ASSESSING NETWORK VULNERABILITY USING THE LOGSUM MEASURE

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ABSTRACT

Abstract in the first language

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MOTIVATION AND OBJECTIVES

In normal state transport networks serve as a backbone of our society carrying passenger and freight traffic. As a result of sudden events such as natural hazards parts of the network may be out of function for a certain time leading to substantial deviations which increase travel time and distance and may lead to mode, destination choice shifts or even cause certain regions to be cut off the rest of the network. However, current research of transport network vulnerability mostly considers only failure induced route choice shift (deviations) including additional travel time and costs. In this paper, the impact of the inclusion of mode and destination choice shifts when evaluating infrastructure vulnerability is systematically analysed.

In vulnerability analysis, every scenario leads to different additional travel time and distance figures. The computation of those figures is particulary time intensive when demand is newly assigned for every scenario. An less computation time intensive alternative is to neglect the volume dependence of link travel times in the failure scenario. This paper analyses the resulting differences of both approaches in order to find patterns that allow later to chose ex-ante the more effective approach when analysing vulnerability.

Taking the opportunity of the data at hand needed to fulfill the objectives mentioned above, the second aim of this paper is to compare different appraisal methods that are usually used for project evaluation, namely cost-benefit analysis and the logsum measure. Given the several dozen of different failure scenarios that were analysed, the focus here lies on analysing the resulting differences between the mentioned appraisal methods.

The remainder of the paper is as follows: The underlying concepts of the different appraisal methods are presented in the literature section. The data section presents both the employed travel demand model and parameters of the appraisal methods. The following section reports on the outcome of the case study for which several dozen scenarios are computed and analysed. Conclusions and advice for further research in the field are provided in the last section.

LITERATURE

Transport network vulnerability analysis

The assessment of transport network failure consequences has attracted significant attention recently. The main focus of the relatively new notion is to assess the impact of a network deterioration to the community compared to the non-failure state of transportation infrastructure. Two strands of research can be distinguished: First, research analysing *ex-ante* possible consequences of transport infrastructure failures intending to detect the most vulnerable parts of the network. Second, research analysing *ex-post* the traffic and behavioral effects of actual transport infrastructure failures.

When analysing consequences of transport infrastructure failures, the research community has not reached a common measure of link failure induced consequences as the several definitions show: Taylor and D'Este (2003) distinguish between connective vulnerability and access vulnerability. The first describes the impact of a loss (or substantial degradation) of a single network link as the increase of (generalized) cost of travel within the network. The latter measures the decrease of accessibility, which in turn can be defined by different measures. Matisziw *et al.* (2007) use a network optimization approach to assess the vulnerability of Ohio's Interstate network in terms of the number of disrupted origin destination relations. Jenelius *et al.* (2006) screened the Swedish national road transport network on indirect consequences using the Swedish passenger transport model. The increase of total travel time caused by single link failures was used as a measure of indirect consequences. They neglected the dependency of travel time on traffic volume but argue that in Sweden link traffic volume plays only a minor role for vulnerability analyses, as most parts of the country are only sparsely populated and increased congestion has therefore only a minor impact on travel times when links fail. To consider travel times to be unaffected by the actual traffic volume might be a reasonable assumption for spatially disperse countries but Knoop *et al.* (2007) showed for the Rotterdam area the need to include capacity constraints when analyzing road network vulnerability in more densely populated areas. This can be done by using traffic assignment models. A major constraint, however, of the use of traffic assignment models for vulnerability analysis is their computational intensity. However, Erath *et al.* (2009) showed that demand shift effects caused by single link failure are usually spatially restricted around the failed link. Failure consequences analysed both using the full network and subnetworks - limited sections of the full network, including their internal and transit demand - turned out to produce consistent results, even for links with long path distances and long detours.

Network disruptions caused by infrastructure failure or maintenance occur relatively seldom. Hence, empirical studies of traffic and behavioral effects after major failures are limited. Hunt *et al.* (2002) evaluated travelers´ response to a 14 month long closure of the Center Street Bridge due to major repairs in Calgary, Canada based on traffic counts and a telephone survey. The most prominent reactions were reported to be shifts of departure time (earlier) and route choice, and, although to a lesser extent, switching modes and destinations. Zhu *et al.* (2009) analysed in an extensive study the traffic and behavioral effects of the I-35W Mississippi River bridge collapse. Based on the analysis of the traffic counts of the remaining Mississippi bridges, they conclude that around two thirds of the previous trips were diverted while one third was subject to either mode or destination choice shifts as those trips 'disappeared'. Based on a regression model analysing the demand on several ramps in the area before and after the collapse accounting for the weekday and month of the observation, no statistical significant drop of total travel demand was detected leading to the assumption that failure induced trip suppression was, if at all, of minor importance. In a accompanying survey 61% of the respondents that considered themselves affected by the bridge collapse indicated to have chosen alternative destinations, especially for shopping and leisure activities. In contrast, only 6% chose an alternative mode and 9% reported to have telecommuted more. The average commuting time before the collapse in the region was 35.62 minutes, compared to 40.18 minutes the day after. However, since in the aftermath commuters became more familiar with the degraded network conditions which resulted in alternated route and departure time choices, the average commuting time reduced to about 38 minutes and remained constant.

When comparing the mentioned studies, two points stand out: Firstly, that several definitions of failure consequences were employed. This is a result of the different research questions the studies attempted to answer. Nevertheless, it was never analysed how the results differ dependent on the employed vulnerability measure. The most prominent measures, namely generalised cost and accessibility, are also widely used as an evaluation measure in transport project appraisals. Therefore, a comprehensive study of measure induced differences of transport project appraisal is also of interest in this context. Secondly, all present *ex-ante* studies only consider route choice decisions to be influenced by the failure. This might be a justifiable restriction for failures with small consequences or in absence of an attractive public transport alternative. However, as shown by the cited *ex-post* studies, destination and mode choice shift might be of importance as well. This is even more relevant, when public transport is not be affected by a given (natural) hazard and could provide relevant detour alternatives.

COMPUTATION OF FAILURE CONSEQUENCES

Vulnerability and failure 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.

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):

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

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

In this paper, only the quantification of the indirect, transportation related consequences of link failures are of interest.

Expected travel demand reactions

Travelers can react to transport infrastructure failure in four ways:

- Detouring the failed link using the remaining links in service

- Changing the travel mode
- Changing the destination of the activity
- Eliminating the scheduled activity and supressing the trip

The quantification of the failure induced consequences in this paper only covers the first three expected demand reactions. Given the rather dense transport infrastructure network in the case of Switzerland, it is expected that failure induced increase of generalised costs per traveler is too low to force him or her to suppress a planned activity. However, it is planned in further research to challenge this assumption by modeling the remaining demand reaction as well and comparing the results with scenarios that did not include such reactions. Additionally, only the consequences of road network failures are analysed.

Swiss National Transport Model

The calculations here presented are based on the Swiss National Transport model. The Swiss passenger transport model is implemented as a two-dimensionally constrained trip generation and distribution model that describes the network and demand of passenger traffic in the year 2005. It was developed for the Swiss federal office of spatial development (ARE) and the federal roads office (ASTRA) by IVT (Vrtic *et al.* (2005)). The Swiss passenger transport model is implemented on the basis of 2949 small transport demand zones inside the country and 165 increasingly larger zones beyond the borders of Switzerland in order to cover transit demand as well. The calculation of the trip generation considered 17 demand segments according to the undertaken activities, such as commuting, leisure and shopping. Trip distribution and mode choice is implemented as a simultaneous destination and modal choice model Vrtic *et al.* (2007). The model was estimated separately for ten of the seventeen activity purpose pairs, as the samples were too small for the remaining ones. The parameter estimates of the choice model were obtain from Swiss national travel survey Mikrozensus Verkehr Swiss Federal Statistical Office (2001).The usual strong correlations between travel cost, distance and travel time made the estimation of the mode choice parameters of the private motorised and public transport impossible. These were taken from an earlier stated preference study Vrtic *et al.* (2003) together with the parameters for the socio-demographic variables. Table 1 lists the utiltiy parameters used in the Swiss national transport model for each demand segment that are later used to compute both mode shift and logsum differences between failure and non-failure scenarios.

Table 1: Mode choice parameters of the Swiss national transport model

Variable	Work	Education	Business	Shopping	Leisure
Car					
Const	0.46	-0.82	3.37	1.65	1.64
Travel time	-2.92	-2.92	-1.86	-3.19	-1.26
Availability	1.12	1.12	1.15	1.26	0.72
Cost	-0.19	-0.19	-0.025	-0.13	-0.05
PT					
Travel time	-1.66	-1.66	-1.39	-2.01	-0.82
Access	-3.35	-3.35	-2.02	-4.49	-1.95
Headway	-0.87	-0.87	-0.59	-0.39	-0.32
Transfers	-0.52	-0.52	-0.49	-0.35	
Season card share	0.80	0.80	1.75	1.19	1.79
Half-Fare card share	0.89	0.89	0.87	1.04	1.03
Age	0.001	0.001	0.035	0.01	0.007
Cycling/Walking					
Travel time	-0.94	-0.53	-1.623	-0.90	-0.81
Age	0.51	0.69	3.51	2.4	2.36
Destination attractiveness [ln(x/1000)]					
Jobs (D)	0.27	-	0.34	0.38	0.16
Wage earners (O)	0.32	-	0.41	-	-
Education facilities (D)	-	0.09	-	-	-
Residents (O)	-	0.30	-	0.83	-
Sales area (D)	-	-	-	0.17	-
Leisure facilities (D)	-	-	-	-	0.17

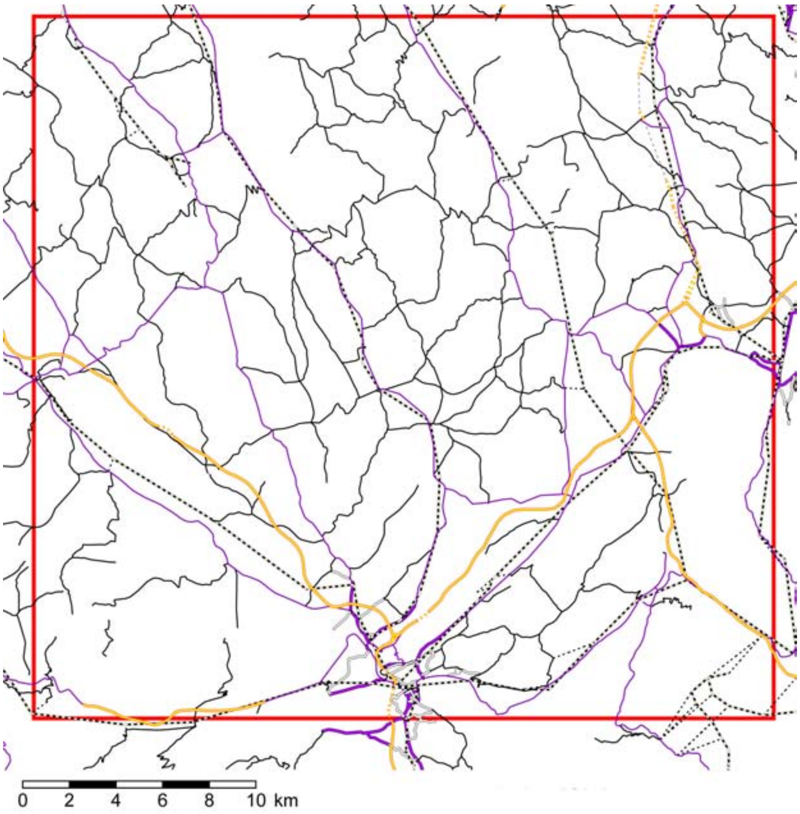
Use of subnetworks

The assignment of the car demand in the Swiss national transport model takes, depending on the the speed of the computer, the number of separate demand segments and the chosen stop criterion of the equilibrium calculation around one hour. 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 (Erath *et al.* (2009)).

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.

Due to time constraints when writing this paper, the analysis covers only one subnetwork. How-

Figure 1: Employed subnetwork for failure consequence analysis



ever, when choosing the subnetwork of interest, special attention was paid to representability in terms of network topology, offer of public transport and the inclusion of different types of spatial structure, namely urban, agglomeration and rural regions.

Figure 1 shows the chosen subnetwork. It consists of 7194 directed links, 2444 Nodes and 463 Zones of which 96 are so-called cordon zones covering the subnetwork's transit traffic.

Implementation of mode choice shift

The road and public transport networks of the Swiss national transport model are covered by two separate, non-corresponding networks. This means that the failure of a road link cannot automatically allocated to the corresponding (bus-) link in the public transport network. Due to the computation time intensity of time-table based public transport assignments it was decided that time-table based information is only considered when computing the utility of the public transport alternative for the non-failure case. This was done using the separate public transport network. For computing the utility difference between normal and failure scenario of the public transport alternative, system-based travel times differences are considered. For this purpose, the road and public transport network needed to be merged as road link failures also might affect busses. Since only utility differences are relevant when computing mode choice by pivot point, it was decided to compute the impact of road link failure to public transport in a simplified manner. Thereby, the utility difference between non-failure and failure state is given by the respective travel time differences of public transport multiplied by the respective parameter of travel time. As the routing of the bus lines on the given road network was not feasible with reasonable effort, it was decided to assign all road links except motorways with a meaningful average bus speed and compute skim matrices based on this speed. The assigned bus speed was taken from an earlier study of average in-vehicle speeds of non-train trips in Switzerland (Hackney (2005)). In addition, the rail links were merged into the network and its nodes connected to the nearest road node. Those connecting links were attributed with a travel time of 5 minutes to account for transfer time losses. The rail links' speed was attributed by the average speed of the rail services leading over the respective link based on a time-table based assignment.

The post-failure transport demand is then calculated using the pivot point method according to equation 2:

$$P_k^1 = \frac{P_k^0 * e^{(V_k^1 - V_k^0)}}{\sum\limits_{m=0}^{M} P_m^0 * e^{(V_m^1 - V_m^0)}} \tag{2}$$

with:

P_k^1	choice probability of mode k in failure state
P_k^0	choice probability of mode k in normal state
V_k^1	utility of mode m in failure state
M	vector of considered modes

Implementation of destination choice shift

Given the failure scenario of natural hazards and failure durations of several days to weeks, it is assumed that work and business destinations are not switched due to the failure. Hence, destination choice shifts are restricted to trip purposes leisure and shopping whose mileage shares amount to 45.6% and 10.6%, respectively. As in the case of mode choice, the post failure demand is calculated using the pivot point method 3:

$$P^1_{k,j} = \frac{P^0_{k,j} * e^{(V^1_{k,j} - V^0_{k,j})}}{\sum_{mj=0}^{MJ} P^0_{mj} * e^{(V^1_{mj} - V^0_{mj})}} \tag{3}$$

with:

$P^1_{k,j}$	choice probability of mode k and destination j in failure state
$P^0_{k,j}$	choice probability of mode k and destination j in normal state
$V^1_{k,j}$	utility of mode k and destination j in failure state
MJ	vector of considered combinations of modes and alternatives

Table 2: Swiss cost-benefit code: deliverables

Deliverable	Relevance to vulnerability
Value of travel time saving, passenger traffic	x
Value of travel time saving, freight traffic	(x)
Accident costs	(x)
Travel time reliability	(x)
Maintenance costs	-
Running costs of vehicles	x
Externalities	-

VALUATION OF FAILURE CONSEQUENCES

Cost-benefit analysis

The Swiss code SN 640 820 "Cost-Benefit Analyses in Transportation" VSS (2009) has been established for the quantification of (dis-)benefits of transport infrastructure projects. The code is the outcome of several comprehensive studies concerned with quantifying costs, benefits and externalities of transportation measures in Switzerland. The full CBA consists of 7 deliverables ranging from changes in travel time and distance and its valuation to externalities such as noise and changes of house prices due to traffic volume differences. As the code is designed to quantify benefits of new infrastructure projects, it can also be used for the reverse, namely to quantify disbenefits caused by infrastructure failure. However, since the failure is assumed to be only temporary, not all of the CBA deliverables are applicable when evaluating failure induced consequences. Table 2 lists the full lists of deliverables and indicates which ones are considered for the quantification of failure consequences when compared with the logsum measure.

Logsum measure

The logsum is a measure of consumer-surplus in the context of logit choice models. In spite of the abundant use of logit models in transport, project assessment is, up to now, only rarely done using logsums (de Jong *et al.* (2005)). By definition, the consumer surplus is the utility, after converting in to monetary terms, that a person receives in the choice situation. It is defined as the denominator of of a logit choice probability, divided by the marginal utility of income, plus arbitrary constants (Train (2003)).

$$CS_n = \frac{1}{\alpha_n} ln(\sum_{j=0}^{J} e^{V_{nj}}) + C \tag{4}$$

with:

CS_n	the consumer surplus of person n
α_{inc}	the marginal utility of income
V_{nj}	person n's utility of alternative j
C	constant representing that the absolute value of utility can not be measures

The change of failure induced consumer surplus is calculated as the difference between the logsum before and after the failure. Thereby, the constants drop out.

$$\Delta(CS_n) = \frac{1}{\alpha_n} (ln(\sum_{j=0}^{J^1} e^{V^1_{nj}}) - ln(\sum_{j=0}^{J^0} e^{V^0_{nj}})) \tag{5}$$

with:

1	failure state
0	non-failure state

It is noted that equations 4 and 5 are only applicable if the marginal utility of income is constant with income which is ensured given the utility form of the choice model in the national transport model. As a result, the value of travel time is independent on the trip distance. An alternative way that allows to take into account the trip distance dependence of travel times as given by external values of travel time savings is the following:

$$\Delta(CS_n) = \frac{1}{\alpha_{tt}} * VTTS_{d_{ij}} * (ln(\sum_{j=0}^{J^1} e^{V^1_{nj}}) - ln(\sum_{j=0}^{J^0} e^{V^0_{nj}})) \tag{6}$$

with:

α_{tt}	the marginal utility of travel time

$VTTS_{ij}$ value of travel time saving corresponding to the distance between ij

Differences between cost-benefit and the logsum measure

There are three main difference between the cost-benefit and the logsum project appraisal: First, the full cost benefit analysis involves a wider range of possible (dis-)benefits of transport measures that outreaches the users' benefits. When comparing the outcome of cost-benefit and logsum analysis, it is therefore important that only those parts of the cost-benefit analysis are taken into consideration that describe the users' benefit, namely savings of travel time and cost 2. Second, concerning the concept of valuation, the cost-benefit analysis is based on the scalar of the demand share of alternatives and its respective utilities rather than the logsum of utilities provided by the choice of different alternatives. This has implications on the valuation of failure consequences given the presence of alternative modes due to the non-linearity of the logit function: if the alternative with highest utility in normal state is more affected by the failure than the other alternatives, then the scalar of the new demand shares of the considered alternatives and its utilities becomes lower than if the presence of alternative modes were neglected. In contrast, a utility decrease of any of several alternative leads always to a smaller drop of the logsum measure as if the presence of further alternatives is neglected or not available. Third, the underlying values of travel time savings may be inconsistent between the two approaches since they are usually based on different choice models of different data sets. Table 3 lists the values of travel time savings (VTTS) for the Swiss national transport model (for parameters see Table 1) and the Swiss cost-benefit code. As the VTTS reported in the Swiss cost-benefit code depend on trip distance and income, the listed values refer to the weighted averages. Except the trip purpose work/education, the values are higher for the national transport model, especially for the trip purpose 'business'.

In order to compare the failure induced logsum drops with the corresponding CBA-based measure, the monetary valuation of the Logsum is based on equation 6. In that way, effects of different underlying VTTS values can be excluded. Additionally, it allows also to take into account the distance dependence of the VTTS.

Table 3: Value of travel time savings: national transport model and cost-benefit code

	Variable	Work/Educuation	Business	Shopping	Leisure
Car					
Travel time [CHF/h]	CBA	31.45	32.24	20.72	22.05
	NTM	15.27	74.32	25.31	25.22
Cost [CHF/km]	CBA	0.14	0.14	0.14	0.14
	NTM	0.18	0.18	0.18	0.18
PT					
Travel time [CHF/h]	CBA	16.08	35.73	12.32	12.01
	NTM	8.70	55.60	15.98	16.67
Access/egress [CHF/h]	CBA	23.44	64.96	10.59	22.79
	NTM	17.56	80.92	35.63	39.71
Headway [CHF/h]	CBA	4.58	9.88	4.39	4.33
	NTM	4.54	23.64	3.07	6.55
Transfers [CHF]	CBA	2.01	3.72	2.03	2.49
	NTM	2.63	20.96	3.90	7.16
Cycling/Walking					
Travel time [CHF/h]	CBA	-	-	-	-
	NTM	4.94	54.00	6.85	16.2

RESULTS

When comparing assignment results based on a complete and an impaired network, the fuzziness of the results caused by the stop criterion defining the equilibrium state must be considered. Travel times between zones that are not affected might slightly differ between the normal and the failure state. Such fuzziness may superpose the effective effect of failures when summing up additional travel time and distance. Therefore, and because of time constraints when writing this paper the following analyses are based on those 100 links, whose failure lead according to a prior study (Erath *et al.* (2009)) to the highest consequences.

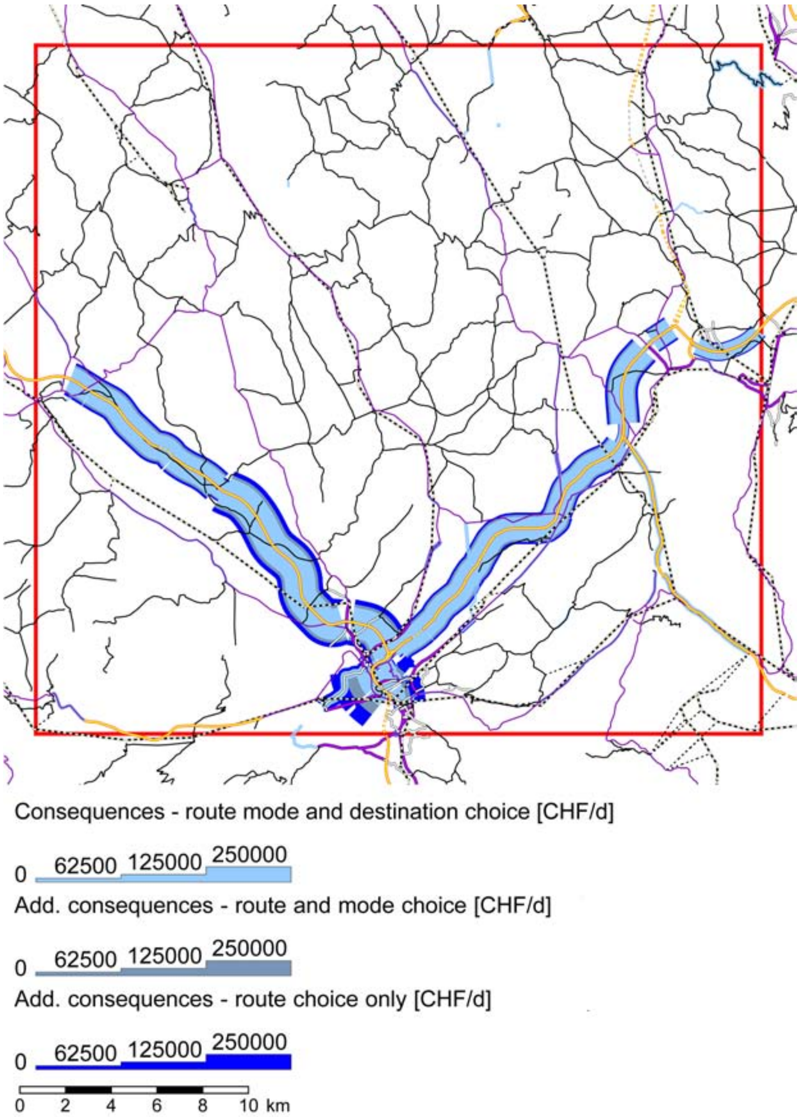
Relevance of mode and destination choice

In former transport vulnerability studies, mode and destination choice shifts have usually been excluded when analysing failure consequences. Generally, this leads to an overestimation of failure consequences since for some travelers it might be more favorable to change the transport mode or the destination of a scheduled activity instead of simply changing routes. The dimension of such an overestimation depends clearly on the quality and availability of alternative modes and destinations as well as the magnitude of failure consequences of a given link: low consequences imply also a low incentive to change behavior.

Figure 2 shows the effects of the consideration of mode and destination choice shifts on failure consequences in the given case study based on the CBA measures of monetarised additional travel time and distance. Inline with the basic considerations above, the highest impact of mode and destination choice shifts are obtained for those links with highest consequences. For example, the estimated failure consequences for the most vulnerable link drop from 3.6 million CHF/d to 1.6 million CHF/d and 1.4 million CHF/d when including mode and mode/destination choice shifts, tively. This particular motorway link has the function of an entry gate respec to the town of Lucerne. Since capacity on detour alternatives is scarce but given the availability of an viable public transport alternative, the consideration of mode choice shifts leads to a substantial decrease of expected failure consequences.

In general, mode choice shifts accounted for the smaller share of reduced consequences although destination choice shifts were restricted to trips with purpose leisure and shopping: on average the inclusion of mode share lead to a decrease of failure consequences of -8.9% compared to -28.8% when mode and destination choice is considered. However, weighted by the failure consequences, the decrease amounts to -25.3% and -40.8%, respectively. The relative reduction of the failure consequences when including mode or mode and destination seems to follow a normal distribution as Figure 3 indicates. Positive values can occur due to the non-linearity of the logit function, as described in the section above. When plotted on the

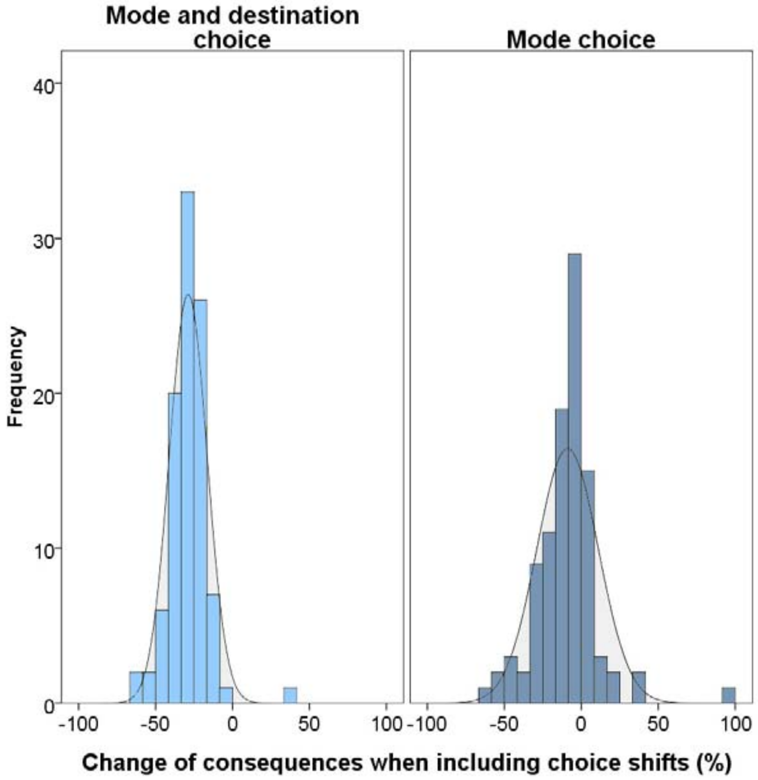
Figure 2: Effects of mode and destination choice shifts on failure consequences



network, no particular pattern was recognized. This was unexpected as for example the failure consequences of links along an existing railway were expected be more strongly affected by the inclusion of mode choice than links without nearby rail alternative. However, it could be confirmed that the importance of the inclusion of mode and destination choice increases with the failure consequences of the link. Additionally, the relative importance of mode choice compared destination choice increases also with the expected consequences.

It can assumed that the detection of the relevant OD-relations for a given link using link flow bundle analysis might lead to a better understanding of the demand on that link and hence an estimation of the importance of the inclusion of mode and destination choice shift. For vulnerability analysis in practice, this would impose additional preliminary analysis effort in

Figure 3: Scale of failure consequence reduction when including mode and destination shifts



order to evaluate the need of mode choice consideration. However, the computational burden for doing so would be disproportionate to the effort of actually computing the mode shift.

In practice, besides the effective estimated failure related consequence, a ranking of the most vulnerable links can be of interest, namely when the only the indication of the most vulnerable links is requested. In order to test, whether the inclusion of mode and destination choice shifts might affect such a ranking, Spearman's rank correlation test as well as Kendall's τ were computed and listed in Table 4. According to both tests, the correlation of the results are highly significant, whereas the ranking is even the same for the 8 links with highest consequences. Therefore it can be stated, that when only the ranking of the most vulnerable links is required, the omission of mode and destination choice shift - as it has been done in previous studies - can deliver sufficiently accurate results, even in urban, congested areas with alternatives modes and destinations available.

Table 4: Effect of mode and destination choice on failure consequences: Rank correlation tests

Kendall's τ	Mode/Destination choice shift	Sign.
Mode choice shift	0.925	>99.9%
Only route choice	0.892	>99.9%
Spearman's ρ	Mode/Destination choice shift	Sign.
Mode choice shift	0.988	>99.9%
Only route choice	0.981	>99.9%

Relevance of assignment

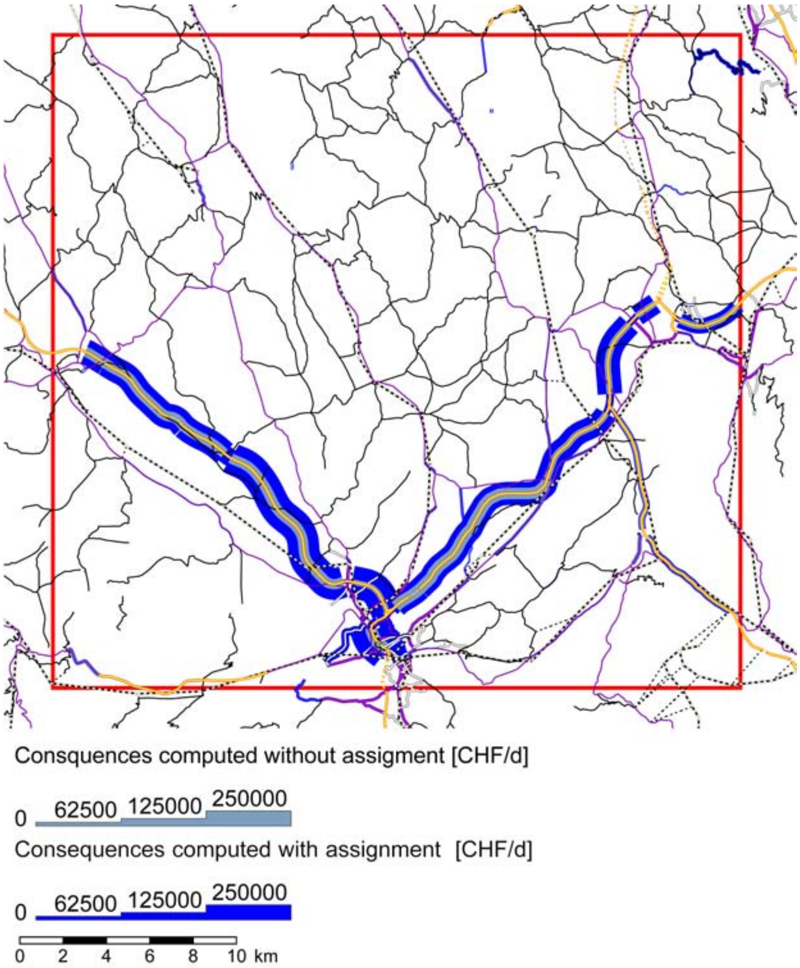
Compared to the additional computational effort of the mode and destination choice shift, the demand assignment is much more time intensive and therefore potentially more attractive to be neglected. Not surprisingly several previous studies focusing on vulnerability neglected therefore the volume dependency of travel speeds. However, as Figure 4 shows, this would have been flawed for the given case study - at least for those links whose failure lead the most severe consequences. Since the capacity of the local alternatives cannot meet the rerouted demand, the failure consequences based on demand assignment are substantially higher than based on demand-independent shortest path search and excluding mode and destination choice effects. However, both Spearman's ρ as well as Kendall's τ are still highly significant although the effective correlation parameter drops to a value 0.49 and 0.36 respectively.

For some practical applications, only the detection of the most vulnerable links might be of interest. Interestingly, when comparing the 20 most vulnerable links with both methodologies, 70% of the links appear in both lists although the order of the ranking is not consistent. Therefore, it is argued that for certain applications of vulnerability analysis the omission of assignment is advisable, for example when compiling a list of links whose failure are likely to have high consequences. However, to reliably rank the links' failure consequences and estimate its magnitude in populated regions, the computation of an equilibrium is recommended.

Relevance of failure consequence measure

If only route choice is considered, the logsum term according to equation 6 collapses to the CBA measure. However, when mode and destination choice is included, the failure consequences based on the logsum term are systematically lower (Figure 5) compared to the CBA results. Considering mode as well as mode and destination choice effects, the logsum term results are in average -29.5% and -16.4%, respectively below the value based on the CBA approach. Using numerical simulation, it was verified that the logsum is lower than the CBA measure if the most attractive alternative is impaired more by a given failure than the other

Figure 4: Difference of consequences with/without inclusion of mode choice



Difference of consequences with/without inclusion of mode choice

available alternatives. This is coherent with the fact that most of the links under examination are motorways, whose failure affects car travel times and distances most. However, the scale of the effect is substantial and further (algebraic) analysis is needed towards a more profound understanding of the causes that lead to such results, especially since the logsum term as a project evaluation measures becomes more and more popular (de Jong *et al.* (2005)).

Despite the differences of absolute values, the ranking of failure consequences is fairly consistent between both measures (Table 5). The indication of the first 16 and 7 ranks for mode and mode/destination choice respectively are even exactly the same.

Figure 6 shows the failure consequences based on the logsum term. As with the CBA measure, the inclusion of alternative modes and destinations leads to less failure consequences. However, the scale of the drop is higher for the logsum term. On average, the inclusion of the utility of alternative modes leads to a decrease of failure consequences of -33.5% compared

Figure 5: Failure consequences based on the logsum compared the CBA measure

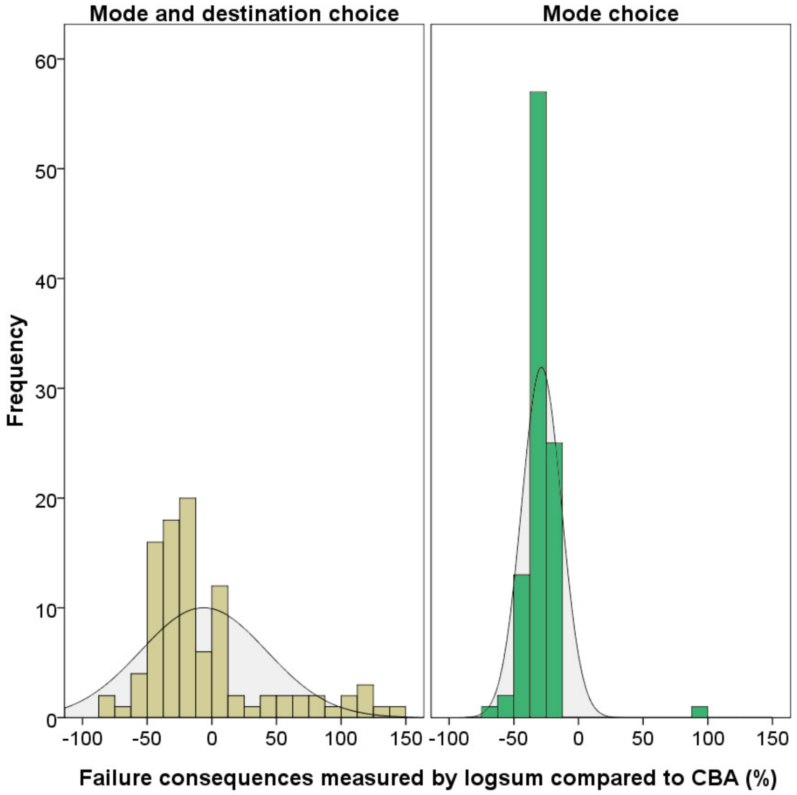
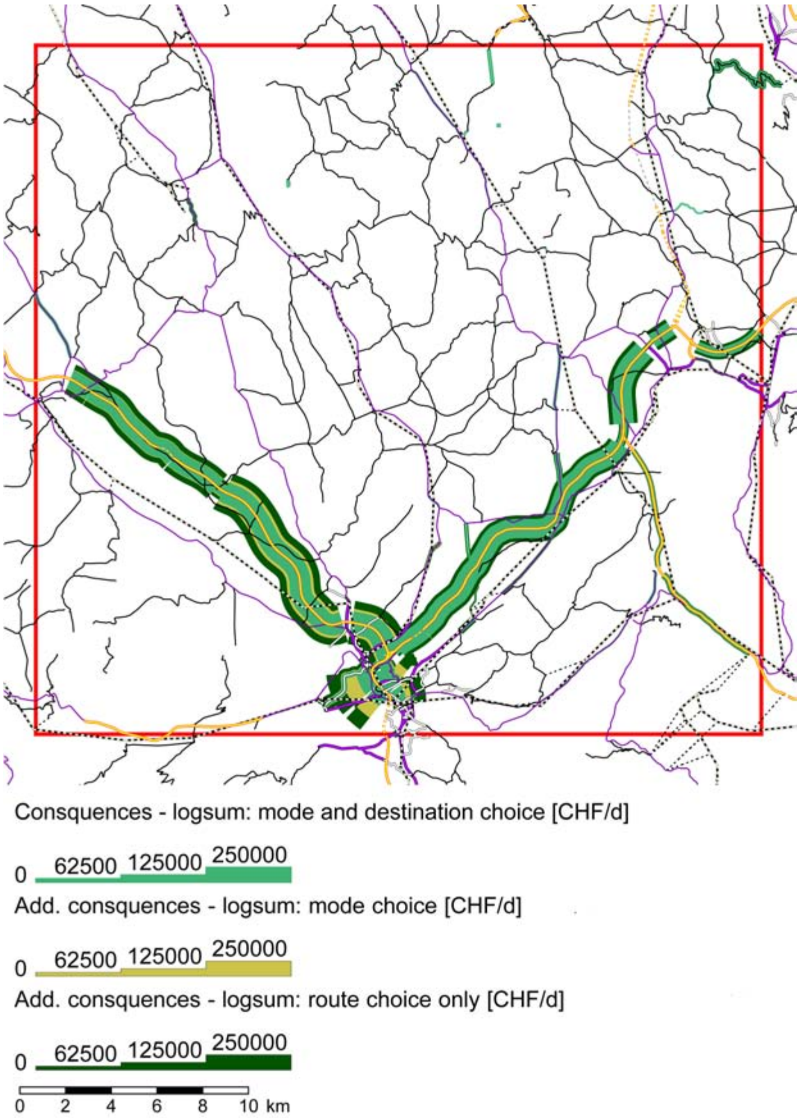


Table 5: Effect of evaluation measure on failure consequences: Rank correlation tests

Kendall's τ	Mode/Destination choice shift	Sign.
Mode choice	0.725	>99.9%
Mode and destination choice	0.874	>99.9%
Spearman's ρ	**Mode/Destination choice shift**	**Sign.**
Mode and choice	0.878	>99.9%
Mode and destination choice	0.970	>99.9%

to -37.8% when mode and destination choice is considered. If weighted by the failure consequences, the decrease amounts to -49.6% and -44.9%, respectively. Compared to the CBA measure, the effect of the inclusion of destination choice is substantially smaller.

Figure 6: Failure consequences based on the logsum measure



CONCLUSION

The impact of the inclusion of mode and destination choice shifts on failure consequences was evaluated based on 100 single link failure scenarios in a subnetwork of the Swiss National Transport Model. The failure consequences - the monetary valuation of additional travel time and distance - decrease substantially when mode and destination choice reactions are allowed. In general, mode choice reactions account for a higher share of such reductions. However, for failures leading to high consequences, mode choice becomes more relevant. Since the considered area is well served by public transport alternatives, the scale of the decrease is considered to be above average. However, given the small and homogenous sample of link failures considered (mostly motorway links), more extensive analysis is needed in order to model the impact of the built environment on the importance of mode and destination choice shift when evaluating the effects of road network failures.

To save computation time and/or because of the lack of a transport demand model, the volume dependence of link travel times sometimes is neglected in vulnerability analysis. According to the results presented in this paper, in populated areas this leads to substantial underestimation of failure consequences for the most vulnerable links. On the other hand, the most vulnerable links can also be detected based on free flow travel times. Hence a two-stage approach is proposed if only failure consequences of the most vulnerable links are needed. In the first instance, the failure of any link in the network is screened by computing failure consequences based on free flow travel times. In the second instance, equilibrium based failure consequences are only computed for those links above a certain percentile. Since failure consequences follow a power law distribution, it is supposed that the relevant threshold percentile can be chosen rather high. However, a more extensive database with failure consequences based on both methods will be needed to attain more precise results on the relation of the level of such a threshold and the chance of including the most vulnerable links.

The comparison of CBA and logsum based assessment revealed that CBA leads to higher failure consequences. However, using the logsum term, the relative decrease of the failure consequences is smaller when additionally destination choice is considered. Although it was shown what fundamental circumstances can lead to such results, further (algebraic) analysis is needed towards a more comprehensive understanding.

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APPENDIX

Appendix A