VULNERABILITY ASSESSMENT OF ROAD TRANSPORT INFRASTRUCTURE

A dissertation submitted to

ETH ZURICH

for the degree of

Doctor of Sciences

presented by

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2011
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Abstract

The overall aim of this dissertation is to develop a methodology that allows the assessment of indirect consequences of road network failures that, on the hand can be used to enhance infrastructure management system by the notion of network vulnerability and, on the other hand can be performed with reasonable computational effort. To this end, the dissertation focusses on three different issues: the development of an adaptive failure consequences assessment, the estimation of a statistical model and the evaluation of the relevance of joint failure scenarios when prioritising natural hazard protection measures.

It is demonstrated that based on network and transport demand characteristics, a meaningful link typology with respect to their potential of inducing failure consequences can be obtained based on cluster analysis. For each of those clusters, a separate strategy for failure consequence assessment as been developed. Both key assumptions, namely the use of subnetworks and the omission of assignment for links with low demand, have been successfully validated for the case of the Swiss National Transport Model. Since the concomitant decrease of computation intensity is massive, a network-wide assessment of single link failure consequences including mode and destination choice effects becomes possible.

Based on the variables shortest detour, link type as well as network density and volume a statistical model to evaluate failure consequences is developed. Although the proposed model does not allow to indicate possible failure consequences with high precision given the overall model fit, the results are still relevant for vulnerability analysis. First, the application of the model permits obtaining a first indication of a networks vulnerability structure with considerably lower requirements in terms of data availability and computational effort. Second, the inclusion of vulnerability into infrastructure management systems requires also the indication of failure probability. The level of precision when indicating failure probability based on natural hazard maps in current practice is normally relatively restricted featuring only a couple of ordinal scaled probability categories. The presented statistical model at least meets or
even exceeds such accuracy.

The assumption of single link failures is rather restrictive and especially challenged by threats that are caused by one extreme natural event. The main challenge is the number of potential scenarios that arise when relaxing the assumption of single link failure and allowing that two or more links are in failure state at the same time. The main challenge is to cope with the number of joint failure scenarios with supposably different failure consequences which need to be considered for a comprehensive vulnerability assessment. Based on the mathematical formulation of possible difference between single and joint link failure assessment, a methodology which employs the demand distribution patterns caused by single link failure to reduce the number of relevant joint failure scenarios is developed and applied for a case study. By applying a gradual approach to evaluate the impact of single link protection measures, it is demonstrated that the prioritisation of failure protection measures based on joint link assessment differs on the whole only little from the solution obtained by restricting to single link failures. However, the methodology was able to detect one link that serves as principal detour alternative in case of several other single link failure scenarios as the most effective protection opportunity.

Potential for further research is considered in the improvement of the adaptive failure consequence assessment by employing multi-path algorithm for route search, the consideration of both road and rail network failure and the development of more sophisticated statistical methods for estimating failure consequences.
Zusammenfassung


Das statistische Modell zur Quantifizierung von Streckenausfallskosten kombiniert die Variablen Steckentypologie, Strassennetzdichte sowie Streckenbelastung im Normalfall als erklärende Variablen. Obschon die Erklärungskraft des statistischen Modells beschränkt ist, sind die Resultate für die Analyse der Verletzlichkeit von Strassennetzen dennoch von hoher Relevanz. So ermöglicht die Anwendung des Modells eine erste netzweite Übersicht der Verletzlichkeit, welche hinsichtlich des Datenbedarfs und Rechenaufwands verleichsweise geringe Anforderungen stellt. Berücksichtigt man weiter die Präzision bei der Quantifizierung der Streckenausfallswahrscheinlichkeit, die mit gängigen Methoden meist
nur eine ordinale Skalierung innerhalb einiger weniger Kategorien zu-
lässt, so vermag das statistische Modell diese Genauigkeit zu erreichen
oder gar zu übertreffen.

Die Annahme statistisch unabhängiger Streckenaufälle wird als star-
ke Vereinfachung erachtet und muss im speziellen in Frage gestellt wer-
den, wenn die Gefahren im selben extremen Naturereignis gründen. Sol-
len Netzzustände, welche zwei oder mehrere gleichzeitige Streckenaus-
fälle umfassen, ebenfalls berücksichtigt werden, erhöht sich die Anzahl
potentieller Szenarien aber exponentiell. Aufgrund der zu erwartenden
Differenzen zwischen einzelnen und gleichzeitigen Ausfällen wurde ei-
one Methode entwickelt, die erlaubt die Anzahl der tatsächlich zu berück-
sichtigen Szenarien beträchtlich zu reduzieren. In einer sich auf ein
Teilnetz beschränkte Fallstudie wird gezeigt werden, dass die Priorisie-
run von Schutzmassnahmen sich unter der Annahme von Einzelaufällen
gegenüber Mehrfachausfällen nur leicht unterscheiden. Allerdings wird
auch offenbar, dass Schutzmassnahmen an Strecken berechtigt sein kön-
nen, welche bei Ausfällen anderer Strecken als wichtige Umfahrung di-
nen, hinsichtlich eines Einzelausfalls aber von untergeordneten Relevanz
sind.

Die Verbesserung der adaptiven Bewertungsmethode birgt weiteres
Forschungspotential, insbesondere die Verwendung von Routensuchal-
gorithmen welche ein Bündel sinnvoller, aber sich hinsichtlich des
Streckenverlaufs dennoch deutlich unterscheidenden Routen generie-
ren. Weiter ist die Berücksichtigung von gleichzeitigen Ausfällen im
Strassen- und Eisenbahnnetz sowie die Verwendung verfeinerten Metho-
den bei der statistischen Modellierung von Streckenausfallskosten erstre-
benswert.
Chapter 1

Problem and Objectives

1.1 Motivation: Vulnerability of transport networks

On October 24 2001, two lorries crashed inside the Gotthard road tunnel, a crucial connection between northern and southern Europe and part of the E35 European Highway, about 2 km from the southern entry of the tunnel. The collision set the tunnel ablaze, killing eleven persons and injuring many more, the smoke and gases evaporated by the flames being the main cause of death. In the following two month, the tunnel was closed for cleanup and restoration until it was re-opened for traffic on December 21. Ever since this incident, lorries had to keep a safety distance of 150m reducing the capacity from 5’500 to around 3’000 lorries a day.

Only 30km further north, the same highway was struck by rockfalls on 16 December 2002, 29 April 2003, 21 March 2005, 31 May 2006, and 8 February 2008. In May 2006 on vehicle was directly hit causing two casualties. All other incidents resulted in mere property damage. However, because of restoration work, geological inspections and in the case of May 2006 blasting of an instable rock formation as a protection measure the highway needed to be closed for periods ranging from several hours up to one month (May 2006). Those incidents exemplify not only the relevance of vulnerability of transport infrastructure but also different aspects of vulnerability.

First, we can distinguish between two categories of consequences:

- direct consequences that include casualties, injuries, and damage to infrastructure
- indirect consequences that include the losses induced by the un-
availability of the impaired transport infrastructure, e.g. additional travel time and travel distance and the loss of access to certain areas.

Second, it shows that we have to accept that our transport infrastructure is vulnerable to different types of incidents: natural hazards, human error but also terrorist attacks. Especially the second example shows that even if the risks are well-known and despite the setup of mitigation measures, there is always a residual risk of incidents degrading transport infrastructure. In fact, there is a trade off between the cost of mitigation measures and the reduction of the system vulnerability that can be expected from the respective measures.

This leads to the third point: in the tradition of risk analysis and management, vulnerability should not only be considered as the direct and indirect consequence of transport infrastructure failures but also take into account the likelihood of incidents that may reduce the performance of the system. Only if operationalised in this way, vulnerability of transport systems can be assessed and optimised in an integrated manner.

1.2 Objectives and methodologies for advances in conditional vulnerability analysis

The knowledge of the estimated likelihood of such events and the expected direct and indirect consequences on a network wide scale would allow to optimise the planning and implementation of protecting mitigation measures which advance infrastructure management systems (IMS) substantially. So far, IMS have been developed to collate inspection data specifying the current state of infrastructure objects (e.g. roads, bridges, tunnels), to simulate deterioration processes, to evaluate the consequences of this deterioration, and to develop optimal infrastructure management approaches. However, the current infrastructure management systems’ scope has exposed infrastructure managers to the potentially disruptive force of sudden events such as natural hazard and severe accidents. The neglect of such events can undermine the intended analytically optimal infrastructure management solution. Up to now, two deficiencies have prevented the systematic inclusion of vulnerability into IMS and planning:

- **Probability of failure**: the availability of contiguous hazard maps together with models defining the structures’ resistance against the
1.2. Objectives and methodologies for advances in conditional vulnerability analysis

respective hazards. Data on the structures are usually already available in IMS.

- **Consequences:** The estimation of direct consequences relies on the same data (structures and hazards) as mentioned above. In contrast, the appraisal of indirect consequences needs modeling and economic valuation of transport demand reactions. As for each out of the numerous possible scenarios an estimation of indirect consequences is needed, this involves substantial computation and modeling effort.

It is the key objective of this thesis to enable the implementation of the indirect failure consequences estimation on a network wide scale even with a large transport demand model such as the Swiss national transport demand model. The other missing capabilities of an integrative assessment of vulnerability in transport planning and operation are addressed in a parallel thesis (Birdsall (2008)), especially.

The type of model used to describe the demand reactions in response to network failures best depends on the scenario: short-term failures and failures that result in only minor performance reductions such as lane closure or sections with speed or capacity reductions are most likely to have no impact on routing, not to mention mode and destination choice decisions, but affect the local traffic flow only. Hence, it is advisable to evaluate such scenarios using mesoscopic or even microscopic traffic flow models. In this thesis, it is assumed that the disturbance in response to failures caused by natural hazards is considerable and lasts for several days up to weeks. Thus, it is assumed that all users are aware of the failure and found their best way to adjust their travel demand. The calculus and evaluation of such demand reactions is currently very computationally intensive. This is actually even more relevant when reflecting the vast amount of possible failure scenarios even when assuming only single, mutually exclusive link failures. Therefore, it is an objective of this thesis to develop and evaluate a methodology which allows quantifying failure induced consequences while reducing computation time.

In the literature, the quantification of failure consequences is typically restricted to the user demand reactions in route choice whereas only the cut off of certain parts of the network was proposed to be evaluated differently. In this thesis, the quantification of failure consequences is extended by mode and, as far as the employed transport model allows, also destination choice shifts. Thereby, failure scenarios are evaluated using different degrees of freedom of the demand reaction. The obtained results should not only serve as basis for more efficiency in evaluating
vulnerability but also to enhance the knowledge about the appropriateness of different methodologies in project appraisal.

The quantification of failure induced consequences is usually done by adopting well established methodologies of transport project appraisal. Whereas in the case of failure, not the improvement but the degradation compared to the actual situation is evaluated. Up to now, reduction of different formulations of accessibility (Taylor et al. (2006), Chen et al. (2007), Sohn (2006)), additional travel time (Scott et al. (2006), Knoop et al. (2007a), Jenelius et al. (2006)) and cost-benefit analyses (Berdica (2002)) have been employed to capture the negative social and economic impact of transport network failures. However, the wide spectrum of approaches show that there is no final consensus on how failure induced consequences should be measured. In this thesis, different methodologies to quantify failure induced consequences are applied and their results compared and analysed.

Quantitative infrastructure vulnerability analysis in the way envisaged above is very data demanding and computation intensive. However, relevant data might not always be readily available. Besides, it might also be desirable in certain cases to assess failure consequences less exact but more directly. In this thesis, this is approached by employing a statistical model to estimate a link’s failure consequences. In order to fulfill the objective, such a statistical model combines readily available spatial data with information of the network structure to estimate the parameters that determine indirect failure consequences. Those parameters can then be used to indicate the magnitude of vulnerability without an assignment model.

Given natural hazard scenarios, such as flooding or avalanches, the assumption of single, mutually exclusive link failures is obviously violated. It is the objective of this thesis to evaluate the failure potential of joint link failures. Currently, no indication on joint hazard incidence can be derived from today’s available hazard maps. However, it is clear that the likelihood of joint failure depends on the likelihood of certain spatial hazards to endanger not only one but several links. To cover the last objective of this thesis, different heuristics to detect an upper limit of possible joint failure consequences are evaluated. Thereby, the current lack of adequate joint failure probability and combinatorial blow-up of possible scenarios is approached by making assumptions about the maximum area which is affected by one exclusive natural hazard - e.g. in the case of an avalanche, all unprotected, hillside located links - and by considering an upper limit of the number of jointly failing links.
1.3 Limitations

All proposed and applied methodologies rely heavily on the output of transport demand models which are, in any case, approximations to the real world situation. Failure induced consequences are evaluated by comparing the new equilibrium state with the network in normal state. However, the equilibrium assumption may diverge from the post failure reality - especially for short-term scenarios and for the immediate time after the failure - and the consequences might be underestimated.

In this thesis, for the modeling of the failure induced demand reaction, the same model parameters are employed as when modeling the normal state. It can presently not be stated with certainty whether this assumption is valid, since too few studies focusing on the analysis of transport demand reactions after failures are available. Alternatively, one could try to describe possible reactions using stated preference approaches. The approach employed assumes equilibrium conditions of travel demand and supply. Hence, inertia effects in failure demand reactions are neglected. This leads to an underestimation of consequences. Additionally, it must be expected that in reality the shifting of activities between days might be affected. This remains uncovered unless one would model reactions within a multi-day planning framework. Which of those uncovered effects biases the estimation of failure consequences more distinctively or whether those effects even balance out is hard to demonstrate and remains untreated in this thesis.

Last, the analysis remains restricted to the evaluation of failure consequences within the road transport network, while the rail transport network is considered the substitute or alternative transport option. However, the parallel failure of road and rail infrastructure caused by a joint hazard incident remains uncovered. In a few cases this might result in the underestimation of the effective vulnerability of the transport infrastructure system.
Chapter 2

Definition of vulnerability

The definition of vulnerability depends on the analyst’s viewpoint (Wisner, 2009). Researchers and professionals in the field of disaster management and prevention are interested in the susceptibility of people and communities with their social, economic and cultural abilities to cope with the damage that could occur (Hilhorst and Bankhoff, 2004). For a transport planner, the system of interest is transport. Hence, he or she is interested in how vulnerable the transport system is in case of failure of one or several of components. For a risk engineer, however, the system of interest might be a particular structure such as a bridge, a tunnel or a road segment. For him or her, the field of interest is the vulnerability of the particular structure.

In this chapter, the different usages and definitions of the term vulnerability and related terms such as risk, resilience or robustness are analysed. Thereby, the analysis is restricted to fields that correspond directly to transport, namely infrastructure, transport and social sciences. Biophysical vulnerability, a concept evolving from global environmental change, which describes the extent to which natural systems are vulnerable to adverse effects of climate change are excluded.

Since it is an objective of this thesis to make transport vulnerability analysis compatible with infrastructure management, a field typically tightly related to risk engineering, a framework and terminology that is compatible with both fields is developed.

2.1 Terminology in the field of disaster management

The concept of vulnerability evolved out of the social sciences and was introduced as a concept in response to the hazard-oriented perception
of disaster risk management in the 1970s (Schneiderbauer and Ehrlich, 2004). At that time, it provided an alternative paradigm to the dominance of hazard-oriented strategies at that time which based mainly on technical innovations by stressing the potential of improving the capacities of coping with disasters and resilience. However, the comprehensive review of Birkmann (2006) reveals that no common definition of the term vulnerability has emerged so far, but different concepts are prevalent. To consider all of these concept would go beyond the scope of this chapter. Nevertheless, three exemplary samples shall be presented here: The disaster risk framework (Davidson, 1997) views hazard, exposure, vulnerability, coping capacity and measures as separate features. Thereby, a hazard is defined by its probability and severity while exposure considers the subject that is exposed to a particular hazard. Vulnerability stands for the physical, social, economical, and environmental consequences whereas capacity and measures, e.g. preparation plans cover the social and economical capacity to cope with hazard. The pressure and relief model (Blaikie et al., 1994) combines the first two points of the disaster risk framework with the latter: vulnerability is understood as the magnitude of the consequences of a given natural event’s conditional to the coping capacities. Hence, the framework defines risk as the multiplication of hazard and vulnerability. Finally, the holistic approach to risk and vulnerability assessment (Cardona, 1999) differentiates between physical exposure leading to physical damage denominated as hard risk, and the fragility of the socioeconomic system leading referred to as soft risk.

Naturally, the field of disaster management needs to follow universal approaches when defining hazards, risk and vulnerability as the range of applications is broad and involves e.g. war, nuclear, or natural disasters. However, the essential concept of describing vulnerability as an interplay between hazards, exposure, cope capacity and resilience emerges in the all concepts considered above and is also replicated in the fields of transport and risk engineering.

2.2 Terminology in transport literature

As in the case of disaster management, the term vulnerability is also used in various ways in the transport literature. Jenelius (2010) differentiates between the technological and societal side of an infrastructure system. Within the technological side, the impact of failure of a given infrastructure component is defined as the component’s importance while the combination of importance and the probability of failure is defined as
criticality. On the societal side, the equivalent of importance is exposure which states the failure impact to an individual user while the combination of exposure and the probability of failure is defined as vulnerability. Hence, by summing up vulnerability over all individual users one gets the criticality of a given part of the transport infrastructure conditional on its failure.

In Taylor and D’Este (2003), Taylor (2007), Taylor et al. (2006), and Taylor (2008) the probability of failure occurrence is not considered when indicating vulnerability. It is argued that the measurement of occurrence probability and the resulting consequences is imprecise for many types of incidents. Furthermore, Dalziell and Nicholson (2001) concluded that it is impractical and infeasible to conduct risk assessment for an entire national transport network. Last, the argument is raised that society may consider certain consequences to unacceptable, irrespective of their probability of occurrence. Hence, regardless of the failure probability, the term vulnerability is used to describe the accessibility drop for individual communities caused by a link failure. Links whose failure significantly diminish accessibility are assumed to be critical.

Other authors neither differentiate between the technological and societal side of failure impacts nor take into account the probability of occurrence. However, various terms are used to determine the magnitude of failure impacts, including significance (Sohn, 2006), vitality (Ratliff et al., 1975), and also vulnerability (Murray-Tuite and Mahmassani (2004) and Knoop et al. (2007a)).

### 2.3 Terminology in risk engineering and infrastructure management

In risk engineering, the assessment of a given system’s risk is typically facilitated by considering three constituents (Faber, 2008): Exposure, failure events, direct consequences, and indirect consequences.

Here, the term exposure is used for describing different events acting on the components of the system of interest. Examples of exposures are different types of natural hazards, but also loads that the structure has been designed to serve, such as traffic load for roads or wave loads for bridges can be considered as exposures.

Damages of the system caused by failure events of one or several of its constituents are considered as direct consequences. Direct consequences may comprise different attributes of the system such as monetary losses, loss of lives, damages to qualities of the environment or just
changed characteristics of the constituents.

*Indirect consequences* are defined as the consequences associated with the loss of functionalities of the system caused by the effect of one or more constituent failures. However, the degree of indirect consequences depend on the systems robustness. Robustness can hence be defined as the insensitivity of a system to failure of one of its constituents. It is derived from the understanding that a robust structural system will not lose its functionality despite certain damage of one or several of its constituents. The concept of splitting up the consequences of failure to direct and indirect consequences can be compared with the approach of [Cardona (1999)](#) which proposed hard and soft risk in the field of disaster management. However, it is important to note that direct and indirect consequences are tightly related to the actual definition of the system. As illustrated in Figure 2.2, for each system level both direct and indirect consequences are considered. Indirect consequences should be regarded as direct consequences of the respective higher-ranking system as the loss of functionality propagates.

In the field of infrastructure management, another definition of direct and indirect consequences is prevalent: *indirect consequences* are
defined as transport related consequences of infrastructure failure such as additional travel times (Adey et al. (2003), Birdsall (2008)). At the same time, direct consequences are associated to the respective reconstruction costs and other immediate losses such as fatalities or damage to the environment. Compared to the approach by Faber (2008), the subsystems structure and transport network are not differentiated. Hence, failure events that do not lead to road closure are considered to cause only direct consequences. Furthermore, different authors use the notion of vulnerability ambiguously. Faber (2008) for example sees vulnerability only related to direct consequences and conditional to the probability of hazard: a system’s vulnerability index is defined as the ratio between the risks due to direct consequences and the total value of the considered system. Such a definition prerequestes a quantification of the system’s total value. Birdsall (2008) uses a broader definition of vulnerability and includes both direct and indirect consequences but not the value of the asset. There, the differentiation between vulnerability and risk is as follows: vulnerability is defined as the product of failure probability multiplied by the sum of direct and indirect consequences and is hence conditional to natural hazard. Risk, in contrast, is given by multiplying vulnerability with the probability of hazard that might lead to failure. However, when it comes to the objective of risk engineering, namely the optimal allocation of the resources against hazard exposure, it is agreed that both direct and indirect consequences need to be considered when quantifying the system’s risk. The notion of direct and indirect is only dependent on the actual definition of the system its subsystems. Using the definition of systems by Faber (2008), all unidirectionally linked indirect consequences need to be summed up for any comprehensive and cross-systematical risk quantification. Therefore, one can interpret the system of Birdsall (2008) as congruent with the one described by Faber (2008), at least if the analysis is restricted to the systems transport network and transport infrastructure.
Chapter 2. Definition of vulnerability

2.4 Development of a general framework for assessing and optimising transport infrastructure vulnerability

2.4.1 Definition and mathematical formulation of the general framework

The definition of the system of interest and its constituents is usually given by the decision problem. One of the objectives of this thesis is to facilitate the inclusion of the natural hazard risk in infrastructure management systems. The decision problem is the optimal allocation of protection measures to decrease the risk caused by natural hazards. The framework sketched in 2.2 combines the cross-systematical failure propagation approach of Faber (2008) with the vulnerability definition and terminology of Birdsall (2008).

Mathematically, the framework (Figure 2.2) can be described by the following formulation: the exposure of system \( s \) to hazardous events is denominated by \( p(E_k) \), \( k = 1, \ldots, n_{\text{exp}} \) where \( n_{\text{exp}} \) indicated the number of exposure states to be considered. It is noted that the exposure state \( E_k \) is only one element of the set given by the cartesian product \( \prod_{i=1}^{k} \) of \( k \) types of exposures, e.g. rockfall, avalanches, floods, to be considered as the incidence of different exposure types is not mutually exclusive. Of each constituent \( C_m \) of the respective system, the failure state is given by \( F_{i,m} \), \( i = 1, 2, \ldots, n_{\text{sta}}, m = 1, 2, \ldots, n_{\text{con}} \), where \( n_{\text{sta}} \) is the total number of failure states of constituent \( m \). The combination of individual failure states \( i \) on individual constituents \( m \) for system \( s \) is expressed as \( F_s \).

This concept can applied both to the system \( 0 \), a road segment, and system \( 1 \), the transport network. Examples of failure states of a system transport infrastructure segment can be weakened supporting structures, destroyed road surface due to rockfall or complete damage of the structure. The consequences attached to the failure are given by the restoration costs but may also include other consequences directly affected by the failure or hazard such as the loss of lives and are summarised by the term direct consequences. Examples of the failure of the transport network are the reduction of maximal speed and increased accident rate due to limited visibility caused by fog, or the closure of roads due to avalanche danger. Here, the associated consequences can either be expressed by an increase of generalised travel cost or the decrease of accessibility to destinations. The former has the advantage that it is measurable by the same unit as the failure costs of the system transport infrastructure segment. The lat-
Figure 2.2: General framework for assessing transport infrastructure vulnerability

ter is a more comprehensive approach as it covers the overall decrease of performance of the transport system in connecting activity locations.

Since the transport network is made up of road elements, it is clear that failure of road segments also affects the transport network, causing an additional source of failure. Therefore, the failure state of constituent $m$ in system 0, $D_{0,m}$, is both dependent on the exposure $E_k$ and the failure state of the road segments $D_{1,m}$. Again, different failure states on different road segments are combined to the system failure state $D_0$. Since the failure state is not only dependent on consequences in system 0 but also system 1, the according consequences are named *indirect consequences*.
2.4.2 Definition of system risk

The definition of risk is given by multiplying probability of failure occurrence with with failure consequences. In order to indicate a composite, cross-systematical risk, all consequences that occur on different hierarchy levels need be included. For the the example of the system definitions transport network and road segments, both direct and indirect consequences need to be included. Hence the composite risk of the transport network against natural hazards is given by:

\[ R_{0,1} = \sum_{k=1}^{n_{\text{exp}}} p(E_k) \cdot p(F_0 \mid (E_k, F_1)) \cdot C_{F_0} + \sum_{k=1}^{n_{\text{exp}}} p(E_k) \cdot p(F_1 \mid (E_k)) \cdot C_{F_1} \]  

(2.1)

2.4.3 Definition of vulnerability, criticality and robustness

As stated at the beginning of the chapter, the definition of vulnerability depends on the analyst’s viewpoint or, translated to the concept of hierarchical systems, on the definition of the relevant system. However, since failure spreads between systems, it is obvious that any definition of vulnerability should also reflect this characteristic. By combining this concept and taking into account the distinction of Birdsall (2008) between vulnerability and risk, the following definition of vulnerability of the transport network against natural hazards evolves (Equation 9.2):

\[ V_{E_k} = p(F_0 \mid (E_k, F_1)) \cdot C_{F_0} + p(F_1 \mid (E_k)) \cdot C_{F_1} \]  

(2.2)

In analogy to the definition of indirect and direct consequences of Birdsall (2008) and Adey et al. (2003), one can define the first summand as indirect vulnerability and the second as direct vulnerability.

The criticality \( C_t \) of a transport network part \( t \) in system \( s \) is given by its failure consequences whereas neither the presence of exposure nor the probability of failure is of relevance.

The robustness of the system is given by the probability that a certain exposure leads to failure. For example, the robustness of the system transport infrastructure segment can be enhanced by reducing the probability of failure due to a given exposure through protection measures (e.g. avalanche barrier). Due to the interrelation of systems, such a protection
also affects of course the robustness of the transport network, of course.

**2.4.4 Limitation of the analysis within the general framework in this thesis**

Failure in the transport network that causes the complete cutoff of network parts, as e.g. the closure of a valley’s single access road, cannot be considered within the system transport network but spreads to systems of higher hierarchy of which the transport network is only one of several system parts (including, but not limited to society and economy. For example, such a scenario can lead to a loss of production as supply lines are cut off. Accordingly, the cost of such failure is best captured in the system economy. The indication of societal or economical failure costs would go beyond the scope of this thesis. Therefore, the indication of vulnerability is restricted to cost occurring within the systems transport infrastructure segment (Birdsall, 2008) and transport network.

Furthermore, the vulnerability analysis presented in chapter 6 and 7 assumes that only a single transport infrastructure segment is in state of failure at one time. This is mainly motivated by two reasons. First, the indication of joint failure probability on several transport infrastructure segments caused by a single exposure is usually not facilitated by current natural hazard analysis based on hazard maps. Second, joint failure needs to be considered for all possible combinations of single transport infrastructure segments for which the probability of joint incidence is not zero. This can lead quickly to an enormous number of different failure scenarios to be evaluated. Similarly, the evaluation of all possible failure states of a given transport infrastructure segment would increase the number of scenarios to be evaluated to a too high degree. As it is assumed that the most important failure state is the complete failure of a transport infrastructure segment to serve transport, only this failure is evaluated.

Last, in the system transport network only failure is considered which is spread from transport infrastructure segments. Failure caused by a combination of exposure effects both on the the transport network and transport infrastructure segments is not covered for two reasons: First, the objective of the analysis is to facilitate the optimisation of protection measures subject to some financial constraints. It is argued that the evaluation of such effects is best facilitated by excluding other influencing factors. Second, direct effects of natural hazards on the system transport network normally only endure for a short period of time (e.g. heavy rain fall). However, the failure caused by such exposure to the system
transport infrastructure segment usually lasts much longer because of the restoration work involved. Therefore, the situation that considers failure of the transport infrastructure segment only is of higher relevance. However, this argument is certainly challenged when considering seasonal differences of the transport network structure. Although the mountain passes do not have the importance they used to have in the past, they can still provide valuable detour alternatives in case of failure of e.g. a tunnel. Therefore, it might be advisable to compute failure costs both for a summer and a winter network. However, all computational efforts presented in this thesis relate to a summer scenario and assuming that all transport infrastructure segments are fully functional.
Chapter 3

A review of network vulnerability literature

3.1 Typology of network vulnerability studies

In its most general notions and based on graph theory, networks are a collection of vertices (or nodes) that are connected by arcs (or links). Networks occur in many and divers fields of research that range from physical infrastructure systems such as communication or transport networks, over biology with the modeling of proteins as networks of amino acids, to social networks which help describing the composition of society. As a result of the ubiquitous prevalence of networks, the science of complex systems tries to identify unifying idiosyncracies of different network typologies.

Since this dissertation focuses on the vulnerability of land-based transport infrastructure, the literature review also focuses on this topic. However, the diversity of infrastructure networks and different fields of scientific research interested in such networks is vast and findings from other fields might be of interest for land-transport infrastructure as well. Therefore, relevant studies from other strands of research are included as well. Inspired by Murray et al. (2008) and Grubesic et al. (2008), this literature review follows a typology and tries to separate those studies according to its objectives and used methodologies. Thereby, the respective merits and shortcomings when assessing network vulnerability are highlighted, building the basis of dissertation’s research directions.
Chapter 3. A review of network vulnerability literature

3.2 Mathematical modeling and optimisation: detection of worst-case scenarios

Mathematical programming approaches are designed to find either minimal or maximal solutions and are applied in diverse fields of research and practice. According to the characteristics of the optimisation problem, a subfield of mathematical programming has emerged. Having their roots in logistics, flow and transportation optimisation are among the most studied fields of applications. The objective function to be optimised in most applications are transport costs or flow of goods. But there is also a field of research focusing on finding those disruption scenarios that impact network performance most. Those studies can be differentiated by the underlying definition of network performance. As the first publications in this context, the proof of the max-flow min-cut theorem by Ford and Fulkerson (1956) merits citation. The assumption of only one network element to be subject to failure has later been relaxed and applied to different problems (Ball et al. (1989), Iida and Wakabayashi (1989), Ratliff et al. (1975), Wood (1992)). Other studies used transport costs instead of flow capacity as the measure to be maximised: Israeli and Wood (2002) developed algorithms that maximise the shortest path between two specified nodes when a certain amount of links can be interrupted, using a mixed integer program. Church et al. (2004) identified a critical set of infrastructure facilities that affect service delivery most in a service supply system by solving newly developed spatial optimisation problems. The same methodology can also be applied to identify how a network is optimally fortified to decrease vulnerability (Church and Scaparra (2007b), Murray (2010b), Murray (2010a)) and has been applied e.g. to a water supply network (Qiao et al. (2007)). A further strand of research takes connectivity as the objective measure. Murray et al. (2007) evaluate scenarios of router loss in telecommunications network using a flow interruption model that measures which router’s loss lead to the greatest decrease of system connectivity and hence unsatisfied demand. Instead of dealing with discrete events/decisions, mathematical programming approaches have also been applied for he calculation of probabilistic network conditions in communication networks (Church and Scaparra, 2007a) and drug trafficking (Cormican et al. 1998).

Bell (2000) introduced game theory as a methodology for vulnerability analysis by formulating a two-player noncooperative game between a router seeking a least-cost path, and a virtual network tester trying to maximise transportation consequences. The minimax optimisation is based on the method of successive averages (Sheffi (1985)) which allows
3.3. Vulnerability of complex systems: graph theory and strategy-specific assessment

the application of the same methodology as a n+m player game covering several origin–destination relations (Cassir and Bell (2001), Bell (2002)) in complex, real-world transport networks (Bell (2006), Bell et al. (2008)). Nagae and Akamatsu (2007) added a weighted entropy term which allows an explicit solution for the minimax problem in the form of a logit path choice model and applied it to the problem of routing hazardous material.

3.2.1 Review of mathematical modeling and optimisation approaches

While mathematical modeling and optimisation approaches have certainly the advantage to find extrema of a particular problem, there are several drawbacks as well. First, real world networks, especially transport networks, are structurally and operationally complex. Approaches that rely on discrete optimisation methodologies can become very computationally intensive with increasing model size when for example networks contain thousands of nodes and links. Furthermore, if the performance of the network depends on demand reactions, as in the case of transport networks, the resulting redistribution effects are a feature that remained unconsidered in all mentioned studies. Second, the focus on worst-case scenarios might restrict the applicability for real world problems as alternative failure scenarios that might be more likely and lead also to substantial losses are neglected. Last, obtained optimisation solutions apply only for the employed disruption assessment measure which in turn relies on the scenario. Therefore for different scenarios respective measures including differing generalisations might be required.

3.3 Vulnerability of complex systems: graph theory and strategy-specific assessment

Graph-theoretical concepts were early on found to be useful for the description of transport network characteristics (Kanskey (1969), Hargre and Chorley (1969)) and its connectivity (Garrison (1960) but were limited by data availability and limited computational power. Further research emerged from the field of complex systems: work in statistical physics has focused on the topology of logical networks. Based on the distribution of the node degree – the number of nodes one particular node is connected with – the typology of exponential, small-world and scale-free networks has been developed (Watts and Strogatz (1998), Barabási
Chapter 3. A review of network vulnerability literature

and Albert (1999), Barabási (2003)). In exponential networks, typical classic random graph models, connections between any two nodes are equally probable. Thus, the number of connections to each node tends to cluster around the average. As a result nodes with significantly higher or lower degrees are rare. Small-world networks show a degree distribution $P(k)$ that peaks at an average $k$ and decreases exponentially for large $k$ (Albert et al. (2000)). Therefore, small-world networks are characterised of clustering between topologically close neighbors. In addition, average path length – number of arcs on shortest path between two random nodes – is short due to a few high degree nodes which connect clusters with each other (Watts and Strogatz (1998)). Scale-free networks in contrast are topologically inhomogeneous as $P(k)$ decays as a power law with $P(k) \sim k^{-\gamma}$ (Albert et al. (2000)). As a result, any random node tends to be attached to a higher-degree node.

Despite the importance of transportation infrastructure networks in daily life, only little literature on transportation network analysis can be found (Erath et al. (2009)). A basic difference to other, often virtual networks is that transportation networks are embedded in real space where nodes and edges occupy precise positions in the three dimensional Euclidian space and edges are real physical connections. Therefore networks are strongly constrained. This impacts the degree distribution the number of edges every node is connected to) which is often used to classify complex networks. Furthermore, the number of long range connections is limited as well, as in planar networks crossings of two edges leads to a new node. Additionally, it is important to reflect that the addition of links for most transport systems is resource intensive. Therefore, direct connections between nodes that are geographically not adjacent are very rare in most transport networks which stops such networks becoming scale-free (Barabási and Bonabeau (2003)). Only in the case of airport networks this is not true. In effect, when taking flights as links and airports as nodes it was demonstrated that airport networks showed scale-free characteristics as the examples of Italy (Guida and Funnaro (2007)) and China (Li and Cai (2004)) illustrate. Small-world properties have been detected for several public transport systems, both on a local (Boston: Latora and Marchiori (2001), Vienna: Seaton and Hackett (2004)) and national scale (Sen et al. (2003)).

However, for road networks node degree is constrained – the junction of Arc de Triomphe in Paris connecting 12 links being among the road network nodes with highest degree. Therefore other approaches to cover centrality have been invented and applied to road networks. As counterpart to the node’s degree but for links, the betweenness centrality has
been defined by Freeman (1977) first. The betweenness centrality measures the number of shortest paths between all nodes which pass through a given node or link. Link centrality is often normalised through division with the number of shortest paths in a network. Another alternative to describe transportation networks was developed by Jiang and Claramunt (2004) turning streets into nodes and intersections into edges, which has been named “dual graph”. The intersection continuity rules were using the street name information. Porta et al. (2006) and Crucitti et al. (2006b) found such a continuity rule unsatisfying because of the lack or just incompleteness of such information in many network databases. Therefore they introduced an intersection continuity model which uses principles of 'good continuation’, based on the preference to go straight ahead at intersections and using basic geometrical information of junctions to detect continuing roads, similar to Hillier’s space syntax (Hillier and Hanson, 1984). Jiang and Claramunt (2004) demonstrated the presence of small-world characteristics using such a dual approach for large street networks. This means that to connect any pair of nodes, generally only a few links are needed as some links act as hubs extending over large parts of the network. Porta et al. (2006) analysed six quadratic cut-outs from six topologically different towns each one square mile in size by the dual approach and found power law characteristics for the degree distribution. However, because main streets (with a high dual graph node degree) are more likely to connect with secondary (or low connected) streets than with streets of the same hierarchical level, significant differences to non-spatial scale free networks were found. Moreover, it became apparent in their work that the cut-outs differ substantially in terms of number of nodes and edges, and they were simply too small to deliver enough cases for a structural distribution analysis. This leads to the main issue of analysing networks by the dual graph approach. All spatial information is lost during the transformation from edges to nodes and vice versa. However, this information is of utmost relevance for failure analysis. First, failure incidences do normally only relate to a specific link location but not to the course of links as the dual approach would suggest. Even more, the effect of the failure is to a great extent depending on availability of detour alternatives which can not be derived from the dual graph.

Crucitti et al. (2006a) started to investigate the primal graphs of urban street networks not only by the common measures of degree distribution or average path length but also by centrality measures which have become a fundamental concept in network analysis since their introduction in structural sociology (Freeman (1977)). They proposed that transportation networks have to be analysed as weighted networks, whereas
the weights are the length of the edges. However, when computing connectivity, the cited studies considered all node to node relations as equally important. Therefore, they neglect the hierarchy that emerges from transport demand and the resulting traffic volumes. However, Yerra and Levinson (2005) proved the emergence of such network hierarchy as an intrinsic property of road transport networks. Erath et al. (2009) showed how transport demand can be used as weight when computing centrality indices for the case of the Swiss road network.

The robustness of networks, mainly of the three main types of complex networks, has been the interest of several studies, many premised on strategy-specific models of nodes or link-based attacks. Albert et al. (2000) simulated the removal of nodes in scale-free networks to determine the attack tolerance in terms of connectivity. They concluded that scale-free networks display an unexpectedly high degree of robustness to random attacks with the ability of the nodes being still connected even under unrealistically high failure rates. However, if the attacks are targeted on the high-degree nodes, these networks are extremely vulnerable as those few nodes play the most important role in assuring the network’s connectivity. As in exponential networks the hierarchy of nodes and links is less distinct, such networks have been found to be less vulnerable both to random and targeted attacks (Crucitti et al. (2003), Holme et al. (2002)). While the main attention of the above mentioned works has been on the number of removals needed to observe the collapse of a coherent network into subcomponents, Latora and Marchiori (2005) proposed the drop of the networks performance caused by the failure of a single component as measure of importance and applied it to the different networks. Additionally, Holme et al. (2002) argued that the network structure changes when important vertices or edges are removed. Therefore, such resistance test have to be performed iteratively. This is even more important when analysing networks were demand distribution is depending on the network structure. Power networks belong to the exponential networks which have been found to have a topologically robust structure. However, the redistribution of loads caused by failure in power networks can lead to cascading effects (Albert et al. (2004) and Zhang (2004)) causing high losses.

3.3.1 Review of vulnerability analysis of complex systems

Strategy-specific approaches are useful for assessing the vulnerability of different network typologies towards identical attack strategies. The re-
resulting insight can then be used to evaluate a network typology that is least vulnerable to e.g. random or targeted loss of network nodes or links. However, there are also several limitations to such an approach: First, comparisons based on strategy-specific approaches are only meaningful if the measure of vulnerability is transferable between and comparable for different networks: for the world wide web for example, connectivity is crucial for the propagation of information while costs are less important as information is propagated at almost the speed of light. For transport networks, detour costs are a more meaningful measure than connectivity, as deviation is more expensive. Furthermore, a loss of connectivity is much less likely for transport networks, typically exponential networks, than for example the world wide web, a scale-free network. Second, not all possible scenarios are evaluated but remain limited within the attack strategy. Hence, no evidence on an upper limit of losses can be derived using the approach. Third, the applied approaches of strategic attacks are often based on the relative importance of the network facilities in the initial state. On the one hand, this eases the computation intensity of those approaches. On the other hand, such assumptions can produce biased results as the network structure and hence the importance of the individual facilities change as the interrelation between the facilities is affected along the process. This particularly applies to systems where the network characteristics are influencing the demand on the network as e.g. like in the case of transport or electric power networks. Therefore the networks structure and the respective demand redistribution effects need to be reevaluated for every step of the strategy’s process. Depending on the complexity of the redistribution process, this can become computationally very intensive. In addition, the logic of the underlying strategy might be of limited relevance in reality. Iterative attacks of the most important or random network facilities might be a meaningful assumption when describing a terrorist network with unlimited resources and scenarios with no additional information, respectively. However, in reality mixed approaches might be more relevant, as e.g. for spatial networks, threats of any nature might occur spatially clustered. Finally, it is important to note that many real-world critical infrastructures bear little resemblance to the theoretical networks assessed in statistical physics (Doyle et al., 2005).
3.4 Detailed transport network vulnerability analysis: scenario-based approaches

Scenario-based assessment approaches evaluate the potential consequences of one particular, well-defined failure scenario or a small set of scenarios. Due to the limited number of considered scenarios, the level of analysis detail is usually high, incorporating detailed information on both direct costs for repairing the facilities and indirect costs of the traffic impact, regional economic interrelations, consideration of logistical dependencies and environmental impacts. Scenario-based approaches can be grouped into two subcategories, according to the time of the analysis: for ex-ante analysis, scenarios are selected according to the expectation of failure likelihood based on to other sources such as hazard maps or high impact. Additionally, the researcher is sometimes concerned with comparing different failure scenarios with each other. For ex-post analysis, the responses to an effective infrastructure failure is analysed. Based on the costs incurred for restoring the failed facility but also its impact on transport via traffic counts and surveys, the overall impact is assessed.

3.4.1 Ex-ante analysis of network disruptions scenarios

The ex-ante analysis of network failure scenarios can be further differentiated according to the employed methodology of the economic assessment. Analysis based on transport models normally considers only additional generalised travel cost. This information can be further processed in regional economic models whose input-output models also cover the interdependencies industrial production.

3.4.1.1 Transport models

Suarez et al. (2005) analysed the impact of twelve different flooding scenarios based on intensity and type of flooding (coastal, riverine and combination of both) on the performance of the transport system in the Boston Metro Area. The analysis is based on the four-stage transport demand model of Boston’s central transportation planning agency both for the current (2003) and future (2025) state. The basic assumptions are that flooded links have zero capacity, flooded regions neither produce or attract trips and shopping trips can be subject to destination choice shift. The different scenarios are then evaluated according to the number of canceled trips, and incurred losses in terms of travel time and distance. However, the resulting consequences are not converted into one
3.4. Detailed transport network vulnerability analysis: scenario-based approaches

As it is expected that the modeled flooding are equally affecting both public and private transport facilities, mode choice effects are not covered by the mode.

Berdica and Mattsson (2007) evaluated 12 different scenarios of network interferences for the road network of Stockholm. The scenarios separately include full and partial (lane) closures in either one or both directions of central bridges, reductions of speed as result of snow-fall and changes of overall transport demand. The assessment is based on the regional transport model that includes 1246 zones and three different time periods. Consequences are monitored in terms of additional travel time and distance and then converted into monetary units using an average occupancy rate and travel time value. Possible shifts in terms of departure time or mode choice were not considered. A main focus is on the applicability of capacity restraint functions for failure scenarios. It is argued that such functional forms are essentially not designed to cover post-failure states as capacity limit is only indirectly covered by the ever increasing link travel times. Additionally, the feature of spilling over backwards on adjacent links is not covered, while at the same time links downstream an overloaded link are experiencing the same overload although in reality vehicles come not through the first overloaded link. Therefore, some of the scenarios were also analysed using so-called Disaggregate Simplicial Decomposition – Implicit Route Storage model (DSD-IRS) (Larsson and Patriksson (1992), Tatieni et al. (1998)). This model exchanges the capacity restraint function for a deterministic queuing time. That way, downstream links from a bottleneck are not punished with increased travel times. However, the problem of the simplification concerning upstream links remains unaddressed. They concluded that for full closure scenarios, the capacity restraint model leads to slightly higher additional travel times. For capacity reductions scenarios, however, those transport demand relations that are directly affected by the capacity reduction show travel times three to four times higher for DSD-IRS model than based on normal capacity restraints functions.

Taylor (2008) uses the Metropolitan Adelaide Strategic Transport Evaluation Model (MASTEM), a multi-modal travel demand model for the metropolitan Adelaide and the according accessibility framework (Primerano and Taylor (2005)) to analyse the consequences of the failure of a freeway tunnel resulting from an incident. The quantification of the consequences derived from on the notion of the inclusive value of a choice set (Ben-Akiva and Lerman (1985)) and the respective consumer surplus as proposed by Train (2003) which takes into considerations the travel times for all modes in normal and failure scenario. In this way,
changes of mode and destination choice are an integrated part of the analysis, although secondary effects of actual mode and destination choice in terms of again changing travel times are not covered. Since both the inclusive value and the consumer surplus can be computed on the level of the modeled zones, spatial analysis was possible showing which parts and socio-demographic groups are affected most by a failure.

3.4.1.2 Regional economic models

Transport model based estimations of failure consequences usually rely on the increase of travel distance and time. The respective values are converted into monetary units by taking into consideration average travel costs and time values taken from other studies that focus on the willingness to pay for travel time in-/decreases. However, the assumption of such an approach might be not applicable to large scale disaster such as earthquakes or substantial flood events. The use of regional economic models extends the boundaries of the evaluation system by including a model which covers the flow of goods as production factors. Based on those models, consequences caused by delayed and failed deliveries can be evaluated and included in the analysis. However, this comes at the cost of more complicated and data demanding models, therefore such models have only been used for scenario-based analysis.

Cho et al. (2001) describe and evaluate a scenario of a large urban earthquake in a high level of detail by integrating transportation network models and regional economic models to estimate the costs of a large urban earthquake in Los Angeles. Through the combination of different planning models, both passenger and freight transport demand is covered. An regional input-output model that has also been integrated covers additional losses caused by delayed or failed deliveries. For each scenario, transport demand and its assignment as well as the input-output model ran iteratively till convergence was reached. Different scenarios based on a Monte-Carlo simulation of bridge failures were defined while damage of industrial facilities were based on the EQE International’s Early Post-Earthquake Damage Assessment Tool (EPEDAT). Based on this extensive approach, losses separated by direct structural losses, direct and indirect business losses (from the input-output model) and network losses (additional travel times) could be stated. Interestingly, direct structural (33.5%), direct and indirect business losses (34.6%) and travel related costs (31.8%) stand for similar shares of the total losses. Concerning the travel related costs, about 80.9% of the losses are related to personal travel and only 18.9% to freight.
Further applications of regional economic models are provided by Kim et al. (2002) and Ham et al. (2005). Kim et al. (2002) evaluated the economic impacts of several scenarios of transport corridor failures caused by an earthquake. Ham et al. (2005) estimated the consequences of a single failure or a combination of failures of three important highways in the New Madrid seismic zone in the Midwest region of the United States. Tatano and Tsuchiya (2008) and Tsuchiya et al. (2010) also applied combination of regional economic and transport demand models to analyse an earthquake scenario in Japan. However, due to data availability the economic model covers only nine zones for the whole of Japan.

Additionally, regional economic models have been applied to optimised disaster recovery. Lee and Kim (2007b) developed a spatio-temporal model for network economic loss analysis for unscheduled events that was later applied, to optimise the reconstruction strategy for a large scale disaster (Lee and Kim (2007a)).

### 3.4.2 Ex-post analysis of network disruptions

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 reported were shifts of departure time (earlier) and route choice, and, although to a lesser extent, switching modes and destinations.

The traffic and behavioral effects of the I-35W Mississippi River bridge collapse have been analysed in an extensive study (Zhu et al. (2010a) and Zhu et al. (2010b)). 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 statistically significant drop of total travel demand was detected. This lead to the assumption that failure induced trip suppression was, if at all, of minor importance. In an accompanying survey, 61% of the respondents who 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, in the aftermath commuters became more familiar with the degraded network conditions. This resulted in alternated route and departure time choices reducing the average commuting time to about 38 minutes.

As shown by the cited *ex-post* studies, destination and mode choice shifts might be of importance as well. This is even more relevant, when public transport is not affected by a given (natural) hazard and could provide relevant detour alternatives.

### 3.4.3 Review of scenario-based vulnerability analysis

The main advantages of scenario-based vulnerability analysis are that scenarios that have been identified as important by domain experts because of both their reasonable likelihood of occurrence and substantial impact to society, can be evaluated with relatively complex methodologies. In addition, the results can be used for cost-benefit analyses of protection measures or even for optimisation of the recovery process as it has been shown by Lee and Kim (2007a). A further advantage is that the level of detail employed in such approaches can provide reference to the importance of individual parts of the evaluation in terms of estimated consequences. Such information can then be used to assess the level of detail needed in more comprehensive studies and the possible inaccuracy incurred by the respective simplification. The disadvantages are obviously that only few scenarios can be evaluated. This is certainly a result of the computational burden to assess each scenario. Another reason can be the complexity of the evaluation methodology: on the one hand, different models (such as transport and regional economic models) need to be integrated which can be burdensome depending on the programming interfaces available. On the other hand, such evaluation routines are normally not available in the existing software and need to be programmed first. However, given the substantial effort that is needed to bring the relevant data sources together, it would only be worth and – in terms of work-time invested – consistent to invest in routines that can automatically evaluate different scenarios. Although the selection of the scenarios to be studied usually take expert knowledge into account, the most important scenarios with highest consequences are not necessarily covered. Hence, scenario-specific approaches are not essentially suited for a system wide assessment of vulnerability. Therefore they cannot deliver any indication of the effective allocation of resources within
Simulation based approaches to assess infrastructure failure are motivated by the insight that for any network, a vast amount of possible scenarios exist. At the same time, a priori information regarding the scenario importance in terms of likelihood and consequence are usually not available. Establishing the risk structure of a whole network can become a very challenging endeavor, mainly for two reasons: first, the full enumeration of all possible single failure scenarios – that is on network part, node or link, in failure at one time – can become computationally burdensome even for moderately sized networks because of the complex interrelation of demand and supply. Second, if such an assumption is relaxed, the number of scenarios will be subject of a combinatorial blow-up. The number of possible scenarios is given by the formula of \( k \)-combinations without repetitions which include factorials of the number of the respective network elements. Therefore, a full enumeration of all possible scenarios becomes soon unfeasible even for moderately sized networks. Therefore, most of the simulation-based assessment in literature are restricted to single link failures. Interestingly, most simulation-based approaches of vulnerability analysis are found in the field of transport networks.

### 3.5.1 Employed vulnerability measures

When analysing consequences of transport infrastructure failures using simulation-based approaches, the research community has not found a common measure of link failure induced consequences. This becomes evident by the several definitions that can be found in the literature: 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 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 (see Taylor (2008) for an overview as well as a scenario-based application). Matzziw 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. For the doctoral thesis of Jenelius (2010), the same methodology was applied for area-wide disruptions which were modeled as spatially restricted multiple link failures. Moreover, in Jenelius et al. (2010) apart from measuring the total increase in vehicle travel time as failure consequences, the impact on individual communities as well as the disparity of the distribution among those are evaluated.

3.5.2 Simulation approach

When computing failure induced additional travel time for the Swedish road network, Jenelius et al. (2006) neglect the dependency of travel time on traffic volume. It is argued that in Sweden, link traffic volume plays only a minor role for vulnerability analyses, as most parts of the country are sparsely populated and increased congestion has therefore minor impact on travel times when links fail. While the consideration of travel time being unaffected by the actual traffic volume might be a reasonable assumption for spatially disperse countries, the need to include capacity constraints when analyzing road network vulnerability in more densely populated areas was shown by Knoop et al. (2007a) and Knoop et al. (2008) using the example of the Rotterdam area. In spite of the substantial computational intensity that comes with the use of a mesoscopic traffic simulation, 468 single-failure scenarios were analysed. Furthermore Scott et al. (2006) evaluated single link failures in transport networks by additional travel time due in three generic transport networks using Wardrop’s user equilibrium principles (Wardrop (1952)) and named this evaluation concept “Network Robustness Index” (NRI). Arguing that full link failures are only one of many possible kinds of disruption scenarios, Sullivan et al. (2010) applied the concept of the NRI to evaluate the effects of capacity reductions.

3.5.3 Modeling vulnerability

To ease the conflict between the computational intensity of a full-scale vulnerability evaluation and the problem of systematic network protection that relies on such results, researchers developed different strategies: A first strategy is statistical modeling of vulnerability. Knoop et al. (2007b) attempted to describe and forecast the vulnerable parts of a network with various indicators. These indicators include different mea-
sures of volume and volume/capacity ratio, the number of paths over a link, spillback figures and also a step function to ensure that less traveled but topologically important links are also considered. These indicators were assessed for correlation among each other and rank order with the results of the full assignment. However, the results had no comprehensive explanatory power; especially the rank order test, which evaluates if the indicators rank the same links as highly vulnerable as the assignment, lacked the necessary significance. Additionally, [Scott et al.](2006) showed some significant correlation among the volume/capacity ratio and the NRI. However, the rank order test revealed again important differences between the effectively vulnerable links and those identified by the employed proxy measures.

Another strategy was proposed by [Sumalee et al.](2010) with the application sensitivity analysis to vulnerability analysis. Sensitivity analysis technique deals with the implicit relationship between the input data of a traffic assignment model and the equilibrium network flows based on that given data. Based on gradients of the probit stochastic user equilibrium model ([Clark and Doherty](2002) and [Conners et al.](2007)) vulnerability estimates can be computed based on a single calculation of network equilibrium condition. The model was both applied on the networks of Sioux Falls city and Bangkok metropolitan area. In order to validate the model, the results were compared with the outcome of the respective simulation-based approaches for which a new assignment was computed for every scenario. It revealed that the sensitivity analysis based model results matched the results of the assignment with reasonable accuracy for free flow links and low link capacity degradations (25% capacity reduction). However, for congested links at capacity limit, correlation between the two results becomes substantially less strong.

### 3.5.4 Review of simulation-based vulnerability approaches

The main difference of simulation-based vulnerability approaches compared to scenario-based approaches is the number of scenarios evaluated. The high number of covered scenarios in simulation-based approaches provides a basis for the management and network-wide prioritisation of mitigation and protection measures, but comes at the cost of having less detailed evaluations. However, due to the systematic coverage of possible scenarios, a comprehensive picture of the system’s vulnerability can be obtained uncovering potential vulnerabilities that might not have been identified and evaluated by the scenario-based approaches that rely on...
experts’ ex-ante appraisal. In addition, for the management of large infrastructure systems the relative importance of the individual parts of the system can be equally important as the absolute importance. Here, it can be argued that the relative importance of the individual parts of the system can be evaluated with sufficient accuracy based on simplified evaluation measures.

There are also disadvantages in simulation-based approaches. First, the underlying assumptions of failure impact usually remain the same for all evaluated scenarios. Given the numerous scenarios and hence the wide range of possible impact, those assumptions may not be equally relevant for all scenarios. For example, the neglect of public transport alternative or congestion might be reasonable for failure scenarios with no rail alternative in proximity or in rural parts where congestion is of minor importance. However, such a simplification can lead to a biased result if meaningful detour alternatives are provided by rail or if congestion is a relevant characteristic of the road network. Second, for larger networks and the consideration of more complex demand reactions, the computational burden of simulation-based approaches can become substantial, or when all combinations of single failure need to be included literally infeasible. Even though simulation-based approaches cover usually a substantial amount of possible failure scenarios, it has to be considered that still only a small part of all combinatorially possible scenarios are covered.

3.6 Vulnerability in infrastructure and risk management frameworks

Risk is commonly defined as the probability of occurrence multiplied by the corresponding consequences. In the studies presented above, vulnerability is usually considered as the quantification of infrastructure failure consequences and hence covers only the second part of the risk metric. The probability of occurrence however it hardly covered. The only study that combines both parts is [Dalziell and Nicholson (2001)]: the authors identified a range of possible hazard that can lead to a failure of a particular link of the Central North Island road network of New Zealand. For each hazard and event magnitude, both the frequency of occurrence and the road closure duration were estimated based on historical data using Monte Carlo simulation. The economic losses of closure rely on a scenario-based approach and include increase of generalised travel costs, accident costs and lost user benefit for suppressed trips. Together with
information on costs and characteristics, this information of mitigation strategies was then combined in a cost-benefit analysis to identify the most efficient options for mitigating the vulnerability.

The combination of risk of natural hazards, infrastructure resistance, and possible failure consequences has received very limited attention. Therefore, in this section it is evaluated which sources can be used to quantify the probability of infrastructure failure occurrence. In addition, infrastructure management systems (IMS) are identified as appropriate tools for the management of naturals risks against transport networks.

Over the past twenty years considerable strides have been made to address gradual deterioration of infrastructure objects like roads, bridges, tunnels (e.g. PONTIS [Thompson et al. (1998) and KUBA, Hajdin (2006)].) Infrastructure management systems (IMS) have the objective to minimise the maintenance and reconstruction costs while preserving adequate levels of service. They normally optimise the life-time costs of the infrastructure but only partly take into consideration the costs and benefits for society, e.g. through the inclusion of additional generalised costs for users during the reconstruction of the infrastructure.

IMS rely on databases that include all relevant information about infrastructure objects, their current condition and their construction structure. Thus, they provide comprehensive information on the resistance of infrastructure objects against natural hazards. Since it would be infeasible to analyse the resistance of every single infrastructure object against the relevant natural hazard risks, models have been developed defining the structures’ resistance against the different types and intensities of hazards (Birdsall 2008). However, those models heavily rely on a comprehensive availability of natural hazard maps. A number of such large-scale systematic risk assessment initiatives such as CEDIM (Tyagunov et al., 2005), Riskscape New Zealand (King and Bell, 2005), United States Multi-Hazard platform HAZUS-MH (Federal Emergency Management Agency, 2004) have been implemented for systematically assessing risk from a national viewpoint. In the context of the project StorMe (Federal Office for the Environment (FOEN) (2009)) the Swiss Federal Office of Environment urged the cantonal authorities to establish and make available comprehensive natural hazard maps. The due date of the project has been set to end of 2011. However, large cantons are expected to fail to deliver their contribution by that time (Federal Office for the Environment (FOEN) (2010)).

In order to combine the probability of infrastructure failure occurrence and its consequences in a risk management framework, the failure consequence should be expressed in monetary terms as the cost of cor-
responding protection measures is expected to be monetary as well. In addition, only vulnerability approaches that assess failure consequences on a network-wide scale, namely simulation-bases approaches, are applicable.

3.7 Conclusion: Relevant research directions of road network vulnerability analysis

The objective of this literature review is the identification of research needs in the field of land-based transport infrastructure vulnerability.

Whereas mathematical modelling approaches have the objective to detect the most vulnerable part of the network, graph theory and strategy-specific approaches usually focus on the networks ability to resist a series of failures without being torn apart and still providing a defined level of connectivity. However, they usually lack the ability to consider an inherent characteristic of transport networks i.e. the interaction between network demand and supply. This can be explained by the additional computational complexity the inclusion of these characteristics would evoke. But since congestion effects are expected as particularly important when quantifying the effects of network failures, such an approach would lead to biased results. Nevertheless, several topological characteristics such as clustering coefficient, centrality and network efficiency have been proven to be relevant when assessing the robustness of various types of networks. Therefore, potential is recognised in the application of such measures when analysing transport network vulnerability.

Scenario-based vulnerability analysis relies heavily on the judgments of domain experts about the likelihood of failure occurrence and expectation of its impact: as only a few scenarios are usually evaluated, the likelihood that the most important scenarios with highest consequences will not be covered is substantial nevertheless. The failure scenarios are usually analysed in detail taking into account different demand reactions whereby for example the inclusion of mode and destinations choice effects has proved to be relevant. A substantial part of such an analysis usually is the gathering of the necessary data sets and the development of evaluation models. The actual analysis of the different scenarios is less labor intensive for the researcher but more for the computers running the programmed models. Due to the complexity of the analysis, the computational burden can become extensive and restricts the number of scenarios possible for evaluation. Nonetheless, potential for efficiency gains is recognised both in simplifying the modeling and computing of
failure consequences, mainly by altering the depth of analysis according to the expected failure consequences and automatisation of the assessment process.

The main part of present research in the field of infrastructure vulnerability is restricted to identifying the vulnerability in terms of consequences of an infrastructure failure. However, the results of simulation-based assessment have the potential of contributing to a comprehensive natural hazards risk management. In combination with the outcome of the current systematic large-scale risk assessment initiatives and models of resistance of structure against natural hazards, all components needed for risk management were available. For this purpose, the measure of how failure consequences are quantified must correspond to the need of the risk management framework. As a result of different research questions, quite a range of definitions of failure consequences were employed so far. Within a risk management framework usually only monetary measures are applicable. As it was never analysed how the results differ in dependence on the employed vulnerability measure, a comprehensive study of measure induced differences of transport project appraisal is also of interest in this context. In addition, all present simulation-based studies only consider route choice decisions to be influenced by failure. This might be a justifiable restriction for failures with small consequences or in absence of an attractive public transport alternative but ex-post analysis of network disruptions has clearly shown that, at least in an urban context, alternative modes and destinations are important demand reactions that need to be covered. The corresponding research is presented in Chapter 5 and 7.

Simulation-based approaches are both data and computation intensive which generates a need for statistical models that can be applied without much effort to other networks. Although there have been several attempts to describe transport infrastructure vulnerability using statistical models, no satisfying results have yet been presented. Potential for improvement is recognised in the inclusion of readily available graph-theoretical and transport demand information in such models. The corresponding research is presented in Chapter 8.

Last, simulation-based approaches are usually based on the assumption of single link failures. On the hand hand, this is certainly motivated by the insight that the likelihood of only on network part being subject to failure is by definition at least equally or less likely than any joint failure scenario. However, if the corresponding consequences are more substantial than those of a single failure scenario, the relevance of such a scenario still might be given. Therefore, research potential is identified
in the pre-evaluation of relevant pairs of joint failure based on the characteristics of single failure consequences. The corresponding research is presented in Chapter [9].
Chapter 4

Transport demand models for vulnerability analysis

Scientific models and simulations are often the only possible method of analysis when the real system cannot be engaged for reasons of feasibility, cost, acceptability or availability. Those conditions also apply to the analysis of transport systems. That is why the development of transport models has been and still is attracting major research resources. It is obvious that transport infrastructure vulnerability analysis should make use of those models. In this chapter, the applicability and possible limitations of available transport models are reviewed.

Most transport models have mainly been developed to evaluate different solutions to problems of transport engineering and planning. Such solutions range from small measures such as the coordination of traffic lights to large-scale investments such as the development of motorway networks. As any other model, a transport model is a simplified representation of a part of the real world. By definition, such a model has to focus on certain elements which the modeler considers to be relevant for his analysis. The appropriate use of such a model is therefore restricted by the range of problems and the specific conditions it has been designed for.

The requirements imposed on a transport model used to evaluate infrastructure failure can be derived from observations in the aftermath of actual infrastructure failures. Hunt et al. (2002) analysed the effects of a maintenance related closure of a bridge in Calgary. The most relevant reaction were shifts to earlier departure time and route choice, and, although to a lesser extent, switching modes and destinations. Extensive studies on the traffic and behavioral effects of the I-35W Mississippi River bridge collapse (Zhu et al. (2010a), Zhu et al. (2010b)) revealed that about two-thirds of the traffic has been diverted to other routes. Des-
tination and mode shifts account for the most of the remaining part but also trip substitution through more frequent telecommuting was reported as well. In contrast to the closure of the bridge in Calgary, the failure of the Mississippi River bridge came unexpected. Therefore, it took several weeks for the network to re-equilibrate \( \text{Zhu et al. (2010b)} \). During this period, travelers continued to learn and adjust their travel decisions.

The effects of infrastructure failure are well comparable to what is expected and experienced if new infrastructure is added to a transport network. Since this is an important solution strategy in transport planning, transport demand models have been designed for the evaluation of new transport infrastructure. In the remainder of this chapter, different types of transport demand models and their submodels are presented and their abilities to cover the aforementioned demand reaction are evaluated. Special focus is given to the scalability of those models since it is one objective of this thesis to evaluate a large number of failure scenarios whereas transport demand models usually have been designed for the assessment of a few scenarios only.

### 4.1 Four step transport demand models

In transport planning, transport demand is traditionally modeled according to the four step process (e.g. \text{Sheffi (1985), Ortúzar and Willumsen (2001)}). Transport demand is determined based on the trips taken by travelers or freight on a transport network between various zones of the covered region. These trips are then assigned to the links (i.e. roads) of the network. The four steps shown in Figure 4.1 are:

1. **Trip generation**: For all zones, the number of outgoing and incoming trips is determined. The numbers are obtain based on a trip generation model that takes various structural data of each zone into account (i.e. number of residents, number of working places).

2. **Trip distribution**: This step connects origins and destinations; for each origin it is determined which fraction of its outgoing trips goes to which destination. The result of the trip distribution is a so-called origin-destination (OD) matrix, which specifies the number of trips that go from each origin to each destination.

3. **Mode choice**: These trips can be made by different means of transportation, e.g. by walking, driving, taking the bus, etc. In this step, that choice is modeled.
4.1. Four step transport demand models

Figure 4.1: The four step transport demand modeling process
Source: Based on Meyer and Miller (2001)

4. Route assignment: Each car trip is assigned to a path on the network. These paths are sensitive to congestion: for each link and node a capacity restraint function defines the travel time in function of volume. Typically, it is searched for a user equilibrium (UE): All paths used for a given OD pair should have the same travel time and no unused path should be faster (see also Wardrop, 1952, pp. 325-378).

Four step transport demand models are well suited for simulation-based vulnerability analysis. They include both transport supply and demand, are developed to evaluate the impact of transport infrastructure measures and are, as they represent the current state of practice, - at least in developed countries - readily available at a metropolitan, regional and national level (TRB (2007), Horowitz (2006), Fox et al. (2003)). For these reasons, most of the current scenario- and simulation-based vulnerability analysis studies are based on such models (Suarez et al. (2005), Berdica and Mattsson (2007); Jenelius (2010), Sullivan et al. (2010), Scott et al. (2006), Taylor and D’Este (2003)).
4.1.1 Modeling of route choice effects

Methodologically, four step transport demand models provide the basis to evaluate route, mode and destination choice reactions. However, previous simulation-based vulnerability analysis has usually been restricted to route choice reaction only. Failure of transport infrastructure affects the shortest paths between OD pairs and hence link volumes. In order to obtain a new equilibrium state where all routes between a given OD pair have the same travel time, a new equilibrium assignment needs to be computed. Depending on network size, level of congestion and number of OD pairs, this can be computationally demanding. However, for smaller, regional transport models such an approach can be feasible and has already been implemented successfully (e.g. Scott et al. (2006), Sullivan et al. (2010)). Due to the imposed equilibrium conditions, it is assumed that all travelers are fully aware of the failure and choose their route accordingly so that all used paths for a given OD pair have the same travel time. Originally, this assumption has mainly been motivated by yielding a unique solution to the link flows at equilibrium state which is unique and independent of the initial costs assumed. There are good reasons to expect that equilibrium does not happen in reality, especially after infrastructure failure. However, there are mainly two arguments that support the use of equilibrium conditions. First, if one intends to compare the loss of system performance caused by different failure scenarios, consistency in the use of methods to evaluate such losses is crucial. Equilibrium conditions ensure such methodological consistency. Second, equilibrium conditions have been chosen because their computational efficiency is recognised. Models that cover day to day traffic fluctuations (e.g. Friesz et al. (1994), Zhang and Nagurney (2001)) or have even been developed to depict the evolutionary process after infrastructure failure (He, 2010) are computationally more intensive and usually more data demanding.

If the detoured traffic volume is assumed to be small or there is sufficient capacity of detour paths, the modeled link and node specific travel times change only very little. In such cases it is reasonable to proceed without any additional assignment and update the travel times between OD pairs based on the travel times of the non-failure state and hence neglecting the change of volume. Again depending on the network size, level of congestion and number of OD pairs, the gains in computation time can be substantial. Such an approach has been applied for the Swedish national network (Jenelius, 2010) where, at least for most parts of the network, congestion is not relevant.
4.1.2 Modeling of mode choice effects

Failure of road infrastructure does not only affect individual but also public transport, namely those lines that normally traverse the link subject to failure. The affected lines need to detour which again can impact the operation of the public transport system. There are currently no standard methodologies available to cover such operational impacts which could be taken into account to estimate both the operational and user losses. However, most public transport companies have developed checklists that suggest the operational re-organisation of their lines after failure. Those checklists acknowledge local constraints such as the availability of additional means of transport or trafficability of alternative roads into consideration. Furthermore, those checklists do not follow a common format and are not centrally stored but only available in the traffic control centers of the respective public transport companies. Thus, the inclusion of individual checklists into the transport model involves substantial organisational effort which is prohibitive in this context.

In contrast to the quantification of operational losses, failure induced changes of the public transport system’s level of service can be described in a simplified manner using the transport system-based route search procedure. The basis of the route search is a network composed of all road and rail links that can be traversed by public transport lines. Those links are attributed with specific run times depending on the transport lines traversing it. The additional failure induced user costs are then given by the difference of the shortest routes between the networks with and without link failure in terms of travel time and travel distance. However, mode choice models usually require more data on the service level of the public transport system than is available from the transport system based procedure. Here, incremental demand models such as the pivot-point model (Kumar, 1980) can be applied to estimate post-failure travel demand. This is done on the basis of the pre-failure market shares of each mode and the changes of the level of service variables both for individual and public transport. Thereby it is assumed that of the public transport level of service variables only travel time and travel distance changes.

4.1.3 Modeling of destination choice effects

Trip distribution as part of a four step demand model is typically modeled using an entropy-maximising approach such as the gravity model. Based on the travel cost matrix and the information on trip generation and attraction per zone, the demand matrix is obtained by employing Iterative
Proportional Fitting (IPF). Usually, travel demand is modeled based on several demand segments covering different trip purposes. For each demand segment, individual trip generation and attraction figures are employed while the cost matrix is shared among all demand segments.

Due to the infrastructure failure the cost matrix is altered and an updated trip distribution matrix can be obtained by rerunning the IPF. Behaviorally, such an approach assumes that information both on the cost matrix and zone attractiveness is ubiquitously available and all subjects can alter their travel destinations without restrictions. In reality however, certain destinations such as the working place or location of business appointments cannot be reconsidered based on the failure induced change of the travel cost matrix. Therefore, the modeling of destination choice effects should be restricted to demand segments to which such restrictions do not apply.

In practice, the re-estimation of the trip distribution based on updated cost matrices is only rarely performed. This has several reasons: First, several demand matrices of different demand segments usually are taken together later in the demand modeling process and calibrated to fit traffic counts. Thereby, the quantity structure is altered to fit spatial particularities that are not covered by the trip generation and attraction data. This comes at the cost that the calibrated matrix cannot methodologically consistently be compared with the uncalibrated matrices that have been re-estimated with regard to a new cost matrix. Second, to reach convergence of travel times as used in the trip distribution model and the network assignment usually requires several iterations which increases the computational effort.

4.1.4 Simultaneous modeling of destination and mode choice

The classic four step approach stipulates an iterative strategy with the feedback of updated travel times (see Figure 4.1) for trip generation and mode choice until convergence is reached. However, it has been acknowledged that such a strategy has all the makings of a non-convergent approach (Ortúzar and Willumsen, 2001). Therefore, alternative procedures that combine destination and mode choice with the assignment have been developed and implemented (e.g. Safwat and Magnanti (1988), Florian et al. (2002)). The main disadvantage of such approaches, especially for vulnerability assessment, is that a demand equilibrium, that stipulates the input of the demand generation process to be the same as its output, requires between 4 to 40 times more computation
time than if only route assignment is subject to equilibrium conditions Ortúzar and Willumsen (2001). However, it is supposed that for most failure scenarios only little demand is shifted between modes. For this reason, an iterative strategy can be omitted and thus computing time is saved. Nevertheless, the amount of shifted demand needs to be monitored, and in the few cases of substantial mode shift an iterative computation might become meaningful.

4.1.5 Simultaneous modeling of trip generation, destination and mode choice

Unlike the sequential methodology of trip generation, destination and mode choice, the simultaneous modeling methodology ensures consistency between the three submodels while allowing different behavioral models depending on trip purpose. The EV A model developed by Lohse et al. (1997) is formulated using a Bayesian approach, while employing the information gain criterion and general solution algorithms for solving the resulting non-linear equation systems. Furthermore trip production is subdivided: hard-constraints are applied when trip production only depends on zone characteristics such as the number of working places. Soft-constraints are applied if production also depends on the competition between similar zones, such as shopping locations.

The main disadvantage of such a model in the context of vulnerability analysis is the substantial computation time which is needed to update the model. However, the EV A model requires a consistent choice model for location and mode choice which includes a utility function. The resulting parameters of such a model can be used to evaluate the utility drop caused by the failure without having to compute the effective changes in the demand matrix.

4.1.6 Modeling of trip suppression and unsatisfied demand

In the conventional specification of the four step transport model, trip generation remains unaltered by the iterative process. Such an approach assumes that changes in the network have no effect on trip production and attraction. This assumption is certainly defendable for failure scenarios that cause only small changes in accessibility of each individual zone. In addition, it can be argued that activity and hence travel patterns remain unaltered because of the limited failure duration. In situations, however,
where an individual zone’s accessibility is heavily dependent on the performance of certain infrastructure the situation is different. A village in a valley with only a single access road will be closed off in case of failure of this access road. The assumption of inelastic demand is not applicable in this case. To quantify the disutility of such a situation, Jenelius (2010) proposes the average waiting time to take into account i.e. under the assumption of constant travel demand over time, half of the failure duration. Such an approach seems practicable for shorter durations as it actually covers the primary demand reaction. The monetary valuation of such a measure, however, is not straightforward. Valuation of waiting time as it is used in cost-benefit frameworks (e.g. VSS (2009b) is usually based on stated preference studies. The understanding of waiting time in this context as the interval between the desired starting time and the departure time of a public transport service is different to the failure situation. In a failure situation, activities might for example be shifted so that an in-house activity is brought forward. In such a situation only the disutility of the activity rescheduling should be taken into account. For longer failure duration, activity rescheduling becomes less important but some activities need to be dropped. Here, the utility obtained when normally performing the activity quantifies the failure consequences. However, both measures can only be obtained from an activity-based demand model.

4.2 Activity based demand models

In activity-based demand models (see Feil (2010) for an overview) demand is generated based on complete daily activity schedules for each individual of a synthetic population. The main motivation for such an approach is to overcome limitations of the four step model which mainly arise through the inherent aggregation of individuals and demand over travel time.

Compared to the four step models, activity based models have the following advantages for the assessment of infrastructure failure:

- Depending on the formulation of the activity based model, trip generation can be directly coupled to the travel costs. This allows to include the omission of activities due to infrastructure failure.

- Possible interrelations between trips can be covered. If a work commuter, for example, decides to travel by public transport instead of a car due to the failure, he/she will most likely also use
public transport for further trips during that day.

- Activity based demand models are time-dependent. This is important for the assessment of failures with durations that differ from the time horizon of the four step model. For example, failures that prohibit traffic have different consequences during peak hour than they have during off-peak hours. Furthermore, travelers might respond to a temporal failure by simply rescheduling their activity plans if this causes them less effort than other reactions such as mode or route choice shifts.

- Through the inclusion of individual travelers one can connect travelers’ decisions (e.g. mode choice) with their specific demographic data, making their choices more realistic.

Although activity based demand models provide a sound framework for transport modeling, the assessment of failure consequences on a network-wide scale remains prohibited for two reasons:

First, the assessment of additional demand reactions such as the rescheduling or omission of activities require a utility function that is composed of the positive utility that can be gained through the performance of activities and the disutility of travel. Hence, the utility difference between the pre- and post-failure activity-schedule could be used as the failure consequence measure and would include both travel- and activity related utility changes. The econometric estimation of such a model based on behavioral data, however has not been successfully implemented yet. Although Feil (2010) presents promising results of such a modeling exercise, certain reservations are expressed as key parameters such as the assessment of travel cost being inconsistent with economic theory.

Second, the advantages of activity based modeling can only be maintained when demand remains disaggregated for the assignment. To overcome the temporal aggregation, dynamic traffic assignment needs to be applied. Even though several approaches to go beyond static assignments and produce time-dependent link volumes have been developed (e.g., Kaufman et al., 1991; Astarita et al., 2001; Friedrich et al., 2000), some properties are still not well understood. Daganzo (1998) showed for example that several equilibrium solutions exist for the same OD matrix and the same network. Comparison between two scenarios therefore deserves to be conducted carefully so that differences related to this characteristic can be eliminated. In addition, computation time increases considerably compared to the static, time-independent assignment. There-
fore it is argued that dynamic assignment is only practical for scenario-based vulnerability analysis. To overcome the aggregation of individuals, the travelers need to be maintained as individual entities during the assignment. There are currently two software frameworks available (TRANSIMS (2006), MATSim-T (2011)) which have implemented such a multi-agent approach in transport planning research practice. The main drawback however is their computation intensity. One iteration step of the traffic simulation using the network of the Swiss national transport model with the MATSim toolkit requires about 70 minutes and several dozens gigabytes of RAM (Balmer et al., 2008) and to find an equilibrium state about 50 iterations are needed. Therefore, such an approach is only applicable for scenario-based vulnerability analysis, but computationally far too expensive for a network-wide vulnerability screening.

However, multi-agent activity-based transport demand simulation offer several opportunities for scenario-based vulnerability analysis that are can not be covered by conventional four step models. Based on the activity rescheduling model, effects of failure that last only for a couple of hours can be evaluated more comprehensively than as with classic, four step demand models that require coarse assumptions to be made in that perspective. Additionally, as travel demand is based on the agents’ activity chains, restrictions that may arise in terms of the non-availability of a certain means of transport, such as a car or a bus can be modeled. Finally, all levels of expected demand reactions, including the suppression of certain activities, are covered by the iterative optimisation process and therefore inherently covered.

### 4.3 Freight demand models

Besides the movement of people, the movement of freight is an important component of transport activities. The modeling of freight demand is usually conducted separately from passenger transport modeling but also follows the classic four step model with some adaptations specific to freight. The main differences are the diversity of decision makers in freight (e.g. shippers, carriers, operators), the diversity of the goods being transported (parcels to bulk shipments), additional modes compared to personal travel (e.g. pipelines, demand-dependent block trains) and the limited availability of data.

The first two stages of the freight demand modeling process are fairly comparable to the modeling process for personal travel demand presented above. The only difference is that generation and attraction as well as
distribution needs to be considered separately for different commodities instead of trip purposes and the units used are tonnes instead of persons.

Modal choice is normally treated using multinominal logit formulations based on generalised cost of shipment. Since generalised costs in freight transport usually depend on the volume and the commodity to be transported, interactions are more complex compared to passenger transport mode choice. Further complexity is imposed if multi-modal shipping needs to be covered. Multi-modal shipping has become a common practice as a result of both the increasing use of containers and policies such as the Swiss performance-related heavy vehicle fee.

For the network assignment, the flow of goods needs to be converted into vehicle-units. Road network assignment is typically done jointly with passenger traffic to cover congestion effects, since freight traffic usually is only a small fraction of the total traffic. In order to do this, freight vehicle trips are converted into passenger car equivalents and assigned simultaneously with passenger demand.

The assessment of failure consequences on freight transport can analogously be implemented as for passenger transport. Consequences imposed by route changes can be expressed as increases of generalised cost. Potential mode choice shifts can be modeled similarly to the practice used for passenger transport mode choice modeling. Changes of location choice, in contrast, are only of marginal relevance as the delivery location can usually not be altered. However, due to the minor relevance of freight transport to passenger transport, freight transport models are not always available. Furthermore, due to the interrelation of freight and passenger transport for the assignment freight and passenger transport failure consequences require to be consistent on this level.

## 4.4 Limitations and conclusion

Although the main consequences of failure in transport network, it has to be mentioned that also adverse effects can occur. Given the increase in generalised cost, it is expected that fewer and shorter trips will be made resulting in smaller transport related externalities. Such effects are covered in most existing cost-benefits frameworks. However, with the end of the failure, all presented model concepts would assume that travel demand is characterised as before the failure. In reality however, persons that adapted to the temporary failure situation, might have added new destinations to their mental map, which, given the general increase in generalised cost, are expected to be closer to given locations such as the
residence or workplace. But, the evolution of the mental map can also lead to adverse effects: e.g. while detouring the failed section of the network, new destinations might become known and frequented afterwards in place of already known destination that cause less travel given one’s residential and working place.

It is arguable whether any of the presented models is actually designed for vulnerability analysis. First, the imposition of any sort of equilibrium conditions corresponds to the assumption that everyone is aware of the both the cost of traveling the network and all possible opportunities to perform activities. Especially in the aftermath of failure this might be not applicable and the development of a new equilibrium state might take some time. Therefore, any evaluation that is based on a transport demand model that impose equilibrium conditions tends to underestimate failure consequences.

Furthermore, it is argued that certain failure scenarios cannot be evaluated within the boundaries the transport system but need the inclusion of other system. For example, the loss of production of a company that is cutoff the transport network can hardly be covered by a transport model but needs to be evaluated by models at a higher hierarchy such as the economic input-output model [Leontief, 1986].

Given the need to evaluate failure scenarios on a network-wide scale and the computational intensity of the analysis, only the simpler transport demand models can be considered. When employing those models, the sheer number of scenarios to be evaluated leads to a computation effort that must be considered as impractical. Therefore, an adaptive vulnerability analysis approach is developed and validated in this thesis.
Chapter 5

Measuring indirect consequences of transport infrastructure failure

As presented in Chapter 3, a range of measures to quantify failure consequences were employed so far. However, given the objective of integrating vulnerability analysis in transport infrastructure systems, only monetary measures are applicable. In this chapter, two methodologies of transport appraisal that fulfill this criteria are presented. Special attention is paid both to the description how those methodologies measure failure consequence and how to apply for the Swiss National Transport Model (SNTM) in particular.

5.1 Cost-benefit framework

Changes in the transport system can have various impacts but are, as far as transport infrastructure is concerned, usually linked to considerable expenditure. It is therefore important to assess such impacts in advance. For this purpose, comprehensive methodologies have been developed and summarised into guidelines such as the WebTAG Department for Transport (2011) in the United Kingdom or the NISTRA (Lieb et al., 2003) in Switzerland.

Those methodologies usually include both qualitative and quantitative valuation of possible impacts. Qualitative valuation is needed because the quantitative valuation of certain impacts such as landscape or biodiversity is still difficult to carry out quantitatively. However, based on the development of different econometric techniques such as discrete choice modeling or hedonic pricing, more and more impacts such as the
value of travel time savings or noise can nowadays be valued in monetary terms.

Quantitatively valued impacts, which include both costs and benefits, are then used, together with the cost of changing the transport infrastructure, as the key factors of the cost-benefit analysis (CBA). Guidelines for conducting CBA are typically part of an overarching assessment methodology that also includes qualitative measures. Although the CBA’s coverage of monetarily quantified impacts differs between various authorities, the objective is the same: to compare costs and benefits over the whole life cycle of the infrastructure element.

CBA was originally designed to quantify benefits of new infrastructure projects and usually comprises the decrease of generalised travel cost, increase of traveler safety, and the reduction of environmental impacts. Exactly the opposite performance is expected from transport infrastructure failure. Therefore, it is argued that the CBA methodology can be used to quantify the disbenefits caused by infrastructure failure. However, since the failure is assumed to be only temporary not all of the CBA elements are applicable when evaluating failure induced consequences.

The Swiss code SN 640 820 ‘Cost-Benefit Analyses in Transportation’ (VSS, 2006) has recently been established for the quantification of (dis-)benefits of transport infrastructure projects. The code is the outcome of comprehensive studies concerned with quantifying costs, benefits and externalities of transportation measures in Switzerland. The full CBA consists of 7 elements 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. Table 5.1 lists all elements and indicates which ones are considered for the quantification of failure consequences.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Relevance to vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings of generalised cost, passenger traffic</td>
<td>x</td>
</tr>
<tr>
<td>Savings of generalised cost, freight traffic</td>
<td>x</td>
</tr>
<tr>
<td>Accident costs</td>
<td>x</td>
</tr>
<tr>
<td>Travel time reliability</td>
<td>x</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>-</td>
</tr>
<tr>
<td>Running costs of vehicles</td>
<td>x</td>
</tr>
<tr>
<td>Externalities</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.1: Swiss cost-benefit code: Elements of assessment (VSS, 2006)
Savings of generalised travel cost, both for car and public transport trips, are dependent on trip distance and purpose. For public transport trips not only travel times but also the number of transfers and the transfer time, service frequency and access/egress time are valued in monetary terms. Accident costs are based on accident rates and associated accident costs and they are available for seven link and four node types. As no information on the node type is available in the Swiss national transport model and some nodes serve only modeling related purposes, the indication of node-related accident cost needs to be omitted.

5.1.1 Route choice effects

5.1.1.1 Methodology

Indirect consequences must be quantified in monetary units in order to be integrated 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 into monetary units are suitable. The impact of a link failure in terms of route choice can be expressed as the increase of generalised cost multiplied by the duration of failure. If only route choice effects are considered, the additional generalised travel costs are obtained by multiplying the additional travel time and distance with the willingness to pay for travel time reductions and the incurred average driving costs per distance.

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

$$\Delta TT_l = \sum_i \sum_{j\neq i} w_{ij} (c_{ij}^{(l)} - c_{ij}^{(0)})$$

with

- $w_{ij}$ the marginal utility of travel time,
- $w_{ij}$ weight of relation zone $i$ to $j$, assumed to be the demand,
- $V_{nj}$ travel time from zone $i$ to $j$ under normal network conditions,
- $C_{ij}$ 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

$$\Delta TD_l = \sum_i \sum_{j\neq i} w_{ij} (d_{ij}^{(l)} - d_{ij}^{(0)})$$
Chapter 5. Measuring indirect consequences of transport infrastructure failure

with

\[ d_{ij}^{(0)} = \text{travel distance from zone } i \text{ to } j \text{ in normal network conditions}, \]

\[ d_{ij}^{(l)} = \text{travel distance from zone } i \text{ to } j \text{ in network conditions with link } l \text{ severed} \]

and indirect failure consequences as

\[ CI_i = \Delta TT_l \cdot C_{TT} + \Delta TD_l \cdot C_{TD}, \quad (5.3) \]

with

\[ C_{TT} \quad \text{the willingness to pay for travel time reductions,} \]

\[ C_{TD} \quad \text{the average cost for driving a defined distance}. \]

The relevant figures for Switzerland are the outcome of recent studies [Hess et al., 2008] which provided the basis for the Swiss norm of the value of travel time savings (VSS, 2009b). The values reported in this norm differ for travel distance and trip purposes. Hence, the evaluation of failure consequences needs to be implemented at the level of OD pairs and requires accounting for different trip purposes. The average cost for driving in Switzerland has also only recently been evaluated. The running cost differ between private or business trips and diesel or gasoline cars. Again, the weighted average is used to obtain the driving cost of a generic car trip which equals 0.5 CHF/km (VSS [2009a]).

Since no freight demand model covering all of Switzerland was not available when conducting the research presented here, the analysis is restricted to individual road transport. However, the approach is transferable and only the values indicating the value of travel time saving and cost for driving need to be adapted.

5.1.2 Mode choice effects

In case of failure of a road link, not only private but also public transport might be affected. In order to correctly include mode choice effects, not only the change in generalised cost of private but also public transport needs to be considered.

Mode choice effects can also be covered by the cost benefits framework. However, the mode shift effect of the road network failure needs to be evaluated first. For this purpose, the pivot-point modeling method is employed. This method has been developed to estimate future travel demand based on the knowledge of the current market shares of each mode and the changes in the variables describing the attractiveness of the
5.1. Cost-benefit framework

Considered modes. The incremental form of the multinominal logit mode choice model (Kumar, 1980) is given by:

\[ p'_k = \frac{p^0_k e^{(V_k - V^0_k)}}{\sum_j p^0_j e^{(V_j - V^0_j)}} \]  

(5.4)

with

- \( p_k \) the updated proportion of trip using mode \( k \),
- \( p^0_k \) the original proportion of trips by mode \( k \),
- \( V_k - V^0_k \) the change in utility of using mode \( k \).

Precise modeling of road failure effects on public transport is a laborious task. First, roads are not included in the public transport network, as bus lines are only depicted by the sequence of stops they serve. In order to account for detour effects of bus lines due to road failure, the bus lines need to be routed on the road network. To facilitate this, bus stops need to be matched first to road network nodes. In some situations this might require to split an existing link into two links connected by a node with a bus stop. The actual routing of bus lines on the road network would then be based on a shortest-path search between two stops in a row for a given bus line. Such an approach requires potentially extensive data cleaning. For example, a stop point might be located at a link that is not covered in the road network. This stop point would be assigned falsely which only could be detected by checking the network by hand. Additionally, the rerouting of the bus lines is dependent on operational constraints. If the failure only leads to a small detour, one can assume that the bus line follows the new shortest path between two adjacent stops. Above a certain level, however, the bus operator would probably react by splitting the service into two bus lines. To model this accurately, information on the operators policy would be needed.

Due to those shortcomings, it was decided to model the effects of road link failure to public transport in a simplified manner based on transport system-based assignment (PTV, 2010). The transport system-based assignment does not differentiate between individual types of public transport nor individual lines and calculates exactly one route for each pair of origin and destination. The transport supply only considers the links of a basic network with their specific run times. Since it is assumed that buses can use all road links except motorways to detour some failed link, the basic network comprehends all road and rail links. From the links of this
basic network a graph is constructed which is the basis for a best-route search. Because individual lines are not distinguished, transfer stops with their respective transfer times cannot be included in the search. However, transfer time losses between the rail and the bus system are covered: the rail links were merged with the road network by connecting railway stations to the nearest road node. Those connector links were attributed with a travel time of 5 minutes to account for transfer time losses. The indication of link specific run times of buses on the road network is based on the results of a survey of speeds of non-train trips in Switzerland (Hackney (2005)). The rail links’ speed were attributed based on the results of a time-table based assignment by the demand-weighted average speed of the rail services traveling on the respective link.

Such an approach however assumes that on every non-motorway link some bus lines are routed. Hence, the failure of any link can result in additional public transport travel times even though in reality the public transport system is not directly affected. Any deviation of this requires bus routing information which was not available when performing the analysis presented here. Therefore, the information on additional travel time by public transport was only used to estimate the potential mode shift from car to public transport but not to account for failure consequences for the remaining public transport users. Such an approach ensures also the comparability of the results that reflect only route choice reactions as thereby also only car demand is used as the relevant quantity.

5.1.3 Destination choice effects

The duration of failure caused by natural hazards is considered to be between a few hours to several weeks. Given this time span, it is reasonable to assume that neither the place of work nor destinations for business trips are subject to adaptation. However, destination for shopping and leisure activities might be reconsidered.

The assessment type to cover destination choice effects depends on the implementation of the transport demand model that is used for the failure consequence analysis. In the case of a classic four step transport demand model, the iterative proportional fitting procedure determining the trip distribution needs to be updated. The SNTM is implemented based on a simultaneous trip generation, destination and mode choice model. Therefore, also destination choice effects can be evaluated based on the pivot point approach. However, since the OD matrices of the SNTM have been calibrated later during the modeling process (Vrtic et al. (2005b), Vrtic and Fröhlich (2010)), the quantity structure of the
final OD matrices does not necessarily correspond to the destination attractiveness that has been used for the simultaneous trip generation, destination and mode choice model. Therefore, the direct application of the pivot point method would lead to biased results. To enable the consideration of destination choice effects anyway, the roots of the non-linear equations describing the destination choice model are investigated based on the MINPACK library ([Moré et al., 1984]) implementation provided by SciPy (SourceForge, 2011). Since this procedure is intensive both in terms of computation time and memory usage, such an approach can only be applied for fractions (subnetworks) of the SNTM.

5.1.4 Suppressed demand

As Jenelius et al. (2006) pointed out, there are cases in which the approach described above is not applicable as some parts of the network might be divided from the rest which lead to suppressed demand $s_{ij}^{(l)}$, defined as

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

Suppressed demand is not considered by the CBA methodology. Therefore, the following simple, trip purpose related approximations of costs caused by suppressed demand are used: Assuming a day’s work activity duration of eight hours at a wage of 50 CHF/h and two trips (to work and back home) in the OD matrix to cover one working day, one gets the value of 200 CHF/suppressed trip. Similar considerations lead to the estimates of 100 CHF, 50 CHF and 25 CHF for business, leisure and shopping trips, respectively. Admittedly, those estimates miss the methodological sophistication of the other assessment approaches. However, the obtain appropriate estimates of trip suppression costs, one would need an economically validated activity scheduling model, which is not available yet.

5.2 Logsum term

5.2.1 Basic methodology

Although it is widely established, the CBA for the quantitative assessment of transport infrastructure measures is under critical review. More
and more researchers argue for the use of the logsum term as an alternative measure (e.g. Bates (2006), Cherchi et al. (2004)). 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 using logsums has been rarely done up to now. It is argued, therefore, that the use of the logsum term is more consistent with the methodology most transport demand models are based on.

By definition, the consumer surplus is the utility – converted into monetary terms – a person receives in the choice situation. It is defined as the denominator of a logit choice probability, divided by the marginal utility of income, plus an arbitrary constant (Train (2003)).

\[
CS_n = \frac{1}{\alpha_n} ln\left(\sum_{j=0}^{J} e^{V_{nj}}\right) + C
\]  

(5.5)

with:

\(CS_n\) the consumer surplus of person \(n\),

\(\alpha_{inc}\) the marginal utility of income,

\(V_{nj}\) person \(n\)’s utility of alternative \(j\),

\(C\) constant representing the absolute value of the utility which cannot be measured.

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.

\[
\Delta(CS_n) = \frac{1}{\alpha_n} (ln\left(\sum_{j=0}^{J^1} e^{V_{nj}}\right) - ln\left(\sum_{j=0}^{J^0} e^{V_{nj}}\right))
\]  

(5.6)

with:

1 failure state,

0 non-failure state.

It is noted that Equations 5.5 and 5.6 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 of the trip distance. An
alternative way that allows to consider the trip distance dependence of travel time is given by Equation \(5.7\):

\[
\Delta(CS_n) = \frac{1}{\alpha_{tt}} \cdot \text{VTTS}_{dij} \cdot (\ln(\sum_{j=0}^{J} e^{V_{nj}^1}) - \ln(\sum_{j=0}^{J} e^{V_{nj}^0}))
\]  

(5.7)

with:

\(\alpha_{tt}\) the marginal utility of travel time,

\(\text{VTTS}_{ij}\) Value of travel time saving corresponding to the distance between \(i\) and \(j\).

### 5.2.2 Route choice effects

If route choice is the only considered dimension of the demand reaction, Equation \(5.7\) collapses to Equation \(5.8\) since only one alternative is available. If the utility of the a route alternative for individual transport is usually given by the travel distance and time, the logsum measures collapses to its CBA counterpart given by Equation \(5.3\):

\[
\Delta(CS) = \sum_{i=0}^{O^0} \sum_{j=0, j \neq i}^{D^0} \frac{1}{\alpha_{tt}} \cdot \text{VTTS}_{dij} \cdot V_{rij}^1 - V_{rij}^0 \cdot w_{ij}
\]  

(5.8)

### 5.2.3 Mode choice effects

Based on the logsum term, the inclusion of mode choice is straightforward and based on the sum of the utilities provided by each available alternative (Equation \(5.9\)). In the case of the SNTM the three considered alternatives \(M\) are car, public transport and non-motorised traffic.

\[
\Delta(CS) = \sum_{i=0}^{O^0} \sum_{j=0, j \neq i}^{D^0} \frac{1}{\alpha_{tt}} \cdot \text{VTTS}_{dij} \cdot (\ln(\sum_{m=0}^{M^1} e^{V_{rijm}^1}) - \ln(\sum_{m=0}^{M^0} e^{V_{rijm}^0})) \cdot w_{ij}
\]  

(5.9)
5.2.4 Destination choice effects

To account additionally destination choice effects, the logsum need to include both mode and destinations as alternatives as given by Equation 5.10:

$$\Delta(CS) = \sum_{i=0}^{O_0} \alpha_{tt} \cdot \text{VTTS}_{d_{ij}} \cdot (\ln(\sum_{j=0}^{D^1} \sum_{m=0}^{M^1} e^{V^1_{ijm}}) - \ln(\sum_{j=0}^{D^0} \sum_{m=0}^{M^0} e^{V^0_{ijm}})) \cdot w_{ij}$$ (5.10)

When applying the logsum term with the weights $w_{ij}$ taken from a calibrated OD matrix, the problem of inconsistent quantity structure as already described in Section 5.1.3 arises and can be addressed in the same way as proposed above.

5.2.5 Differences between the cost-benefit analysis and the logsum measure

There are three main differences 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. Therefore, when comparing the outcome of cost-benefit and logsum analysis, it is 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. Second, concerning the concept of valuation, the cost-benefit analysis is based on actually chosen alternatives rather than the utility provided by the choice of different alternatives as in the case of the logsum term. This can have considerable implications and lead to counterintuitive results as the example given in Table 5.2 demonstrates. For failure scenario I, the utility for car and public transport are -1.5 and -0.5 utility units lower than in scenario 0. If only route choice is considered, the two methodologies are congruent. If mode choice is allowed as additional dimension of demand reaction, one would expect the difference of overall utility between scenario I and scenario 0 to be lower than in the more restrictive case of only including route choice. However, this holds thoroughly only for logsum-based assessment as the example demonstrates. Hence, the evaluation of failure consequences including mode (and destination) shifts differs depending on the employed assessment methodology.

Third, the underlying values of travel time savings of the transport
Table 5.2: Example of calculus difference between CBA and logsum
demand model and the values proposed by the CBA may be inconsistent
since they are usually based on different choice models and different data
sets. Table 5.3 lists the values of travel time savings (VTTS) for the
Swiss national transport model (for parameters see Vrtic et al. (2005b))
and the Swiss cost-benefit code (weighted averages). Except for the trip
purpose work/education, the values are higher for the national transport
model, especially for the trip purpose ‘business’. However, this source of
inconsistency can be excluded when employing the same VTTS values
both for the logsum term as proposed by Equation 5.7 and the CBA based
evaluation as given in Equation 5.3.

5.3 Conclusion

To allow the inclusion of transport network vulnerability in transport in-
frastucture management systems, it is required that the risk of trans-
port infrastructure failure needs to be evaluated in monetary terms. In
this chapter two measures of quantifying indirect failure consequences
that fulfill this requirement are presented and compared. The CBA has
the advantage of being accepted in practice as the underlying method-
ology is clear and easily understandable which supports communication
in interdisciplinary projects. However, the logsum term is the theoreti-
cally consistent approach as it is directly derived from the random utility
model theory on which transport demand model are based. Apart from a
few case studies (see de Jong et al. (2005) for a summary), the practical
impact caused by the differences between the two methodologies have
not yet comprehensively reviewed. Therefore, both methodologies are
applied when evaluating failure consequences of the Swiss road network
as presented in Chapter 7.
Table 5.3: Value of travel time savings: national transport model and CBA (VSS 2009b)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Work/Education</th>
<th>Business</th>
<th>Shopping</th>
<th>Leisure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Car</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time [CHF/h]</td>
<td>2.63</td>
<td>2.10</td>
<td>2.07</td>
<td>2.05</td>
</tr>
<tr>
<td>Transfers [CHF/km]</td>
<td>0.37</td>
<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Headway [CHF/h]</td>
<td>3.88</td>
<td>3.63</td>
<td>3.64</td>
<td>3.64</td>
</tr>
<tr>
<td>Access/egress [CHF/h]</td>
<td>7.58</td>
<td>2.29</td>
<td>1.19</td>
<td>1.19</td>
</tr>
<tr>
<td>Travel time [CHF/h]</td>
<td>16.08</td>
<td>13.23</td>
<td>12.32</td>
<td>12.32</td>
</tr>
<tr>
<td><strong>Bus</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Travel time [CHF/h]</td>
<td>16.08</td>
<td>13.23</td>
<td>12.32</td>
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<td>3.64</td>
</tr>
<tr>
<td>Access/egress [CHF/h]</td>
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</tr>
<tr>
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<td>16.08</td>
<td>13.23</td>
<td>12.32</td>
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</tbody>
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<table>
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<tr>
<th>Variable</th>
<th>Work/Education</th>
<th>Business</th>
<th>Shopping</th>
<th>Leisure</th>
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<tr>
<td><strong>Car</strong></td>
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<td></td>
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<tr>
<td>Travel time [CHF/h]</td>
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<td>2.10</td>
<td>2.07</td>
<td>2.05</td>
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<tr>
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<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Headway [CHF/h]</td>
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<td>3.63</td>
<td>3.64</td>
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<tr>
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<td>2.29</td>
<td>1.19</td>
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</tr>
<tr>
<td>Travel time [CHF/h]</td>
<td>16.08</td>
<td>13.23</td>
<td>12.32</td>
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</tr>
</tbody>
</table>
Chapter 6

Adaptive failure consequences assessment

6.1 Challenges of network wide failure consequences assessment

6.1.1 Objectives

In the conclusion of the literature analysis, the following potential areas of improvement in the field of transport network failure assessment have been identified:

- If the failure of infrastructure is expected to lead to additional congestion, the effects should be covered.
- In order to facilitate vulnerability analysis as part of infrastructure management system, one needs to define all relevant exposures and the respective occupancy probabilities on a network-wide scale, and to estimate both direct and indirect failure consequence in monetary units.
- Mode and destination choice effects should be considered as demand reactions when measuring indirect failure consequences.

It is one of the objectives of this thesis to develop and apply a methodology which addresses these areas of improvement and which can be applied to vulnerability analysis of a large-scale transport network. The devised methodology is applied to the road network of the Swiss National Transport Model (SNTM) (Chapter 7).
Chapter 6. Adaptive failure consequences assessment

6.1.2 Problem

As described above, the basis for failure analysis is preferably a transport demand model. In the Swiss case, such a model has been developed by Vrtic et al. (2005a) and is available from the Federal Office for Spatial Development. The model has been updated to cover the transport demand and supply situations of the year 2005 (Vrtic and Fröhlich, 2010). The owners of the model are committed to continue updating it about every 5 years. This updated model serves as basis for the vulnerability analysis presented in this thesis.

The SNTM has been developed for the assessment of transport infrastructure and policy measures on a national level. It is implemented on the basis of 2949 transport demand zones that represent Swiss municipalities. The main towns of Switzerland are represented by several zones. In addition, 65 increasingly larger zones beyond the borders of Switzerland ensure that through traffic is covered as well. It is designed as a bi-modal transport model with two separate networks for individual and public transport. This means that the road based public transport such as buses is not routed on the road network but its lines are modeled by connecting stop points with virtual crow-fly links. The road network includes 61 134 directed links which are connected by 24 432 nodes. The public transport network includes 39 377 stops which are served by 19 231 lines. In winter, several mountain passes are closed and thus both summer and winter networks have to be considered representing two scenarios when conducting vulnerability consequence analysis. The analysis presented in this work is based on the summer network.

The major problem to fulfill the objectives stated above is its computational intensity. The computation time needed to obtain an equilibrium state for the traffic assignment takes about 80 minutes on an up-to-date personal computer. If it is assumed that the failure of each link in the network constitutes as single scenario, the total computation time for the assignment only would sum up to dozens of months which obviously is infeasible. Thereby, any additional effort that is needed to evaluate changes in travel costs, mode, and destination choice effects is excluded.

6.1.3 Solution approach

One approach to address the substantial computation intensity is the parallelisation of the process. Given the current trend in hardware manufacturing to increase computation power using multi-core CPU, such an approach becomes ever more relevant. Since the assignment is by far
the computationally most expensive process of evaluating failure consequences, parallelisation of this process would be very effective. The static route assignment can be described as a minimum cost multicommodity flow problem with non-linear but convex objectives. Although for this problem different decomposition strategies have been developed (Ory and Mokhtarian (2000), Dos Santos Eleutério (2009), Ferris et al. (1999)), presently none of those are, at least to the author’s knowledge, currently available for solving large scale transport demand assignments.

A second approach to decompose the problem is to distribute the evaluations of single failure scenario to different computing nodes. Because of the commercialisation of cloud computing, access to parallel computing infrastructure has become more and more accessible to a wider audience. This would normally support the argument. However, transport demand models have usually been developed using readily available, proprietary software packages. Generally, such software packages are not compatible with the operating systems which are normally installed to run parallel computing infrastructure. Furthermore, such an approach would not address to root of the problem but would only enable its distribution.

The core of the solution approach is the concept that the analysis of failure consequences should be adaptive to the expected demand reaction. Depending on information on the network topology and the demand characteristics that can be derived from a transport model, the area in which consequences take place, and therefore needs to be modeled can be restricted. For example, it can be assumed that the main demand reaction caused by the failure of a link which serves primarily local traffic does not cause demand reactions on a regional or national scale. Therefore the application of subnetworks which only cover a fraction of the Swiss national transport demand model is tested.

Analogously, the inclusion of congestion effects is not relevant for all failure scenarios. Depending on the characteristics of transport demand and the network topology, one can a priori indicate the need to include congestion effects for failure consequence analysis.

Further potential for improvement in terms of computation time is expected by imposing a less restrictive equilibrium criterion. Usually the equilibrium state is defined by Wardrop’s first principle (Wardrop, 1952). It states that all paths used for a given OD pair should have the same travel time. The usual criteria for terminating the equilibrium calculation process are based on the difference of impedance between a coupled equalisation of routes. For vulnerability analysis however, the criterion of interest is the change of total travel time in the network between two
iterations. The interdependence of those two criteria is therefore investigated.

In addition, it is argued that networks of transport demand models have not been optimised for vulnerability analysis but contain redundant information such as nodes which are connecting only two links. The failure of any of those links obviously leads to the same consequences. Furthermore, failure consequences of some particular links are trivial to assess: either because no demand is assigned in the transport model or because the link belongs to a dead end road and its failure simply would prevent any movement to and from the part of the network being cutoff. Therefore, links with characteristics as just outlined need to be detected before the actual assignment-based consequence assessment.

Last, for the efficient failure consequences assessment, the evaluation process needs to be performed automatically. For this purpose, script routines that can access relevant output of the transport demand model and compute the relevant vulnerability measures using modern software packages for scientific computing are developed.

### 6.2 Network simplifications for failure consequence assessment

**Consideration of undirected links** Typically, an undirected link stands for two directed links, one in each direction. Those two directed links might differ in their attributes such as capacity or maximum speed, but represent a single road. As stated in Chapter 2, Section 2.4.4, it is herein assumed that only scenarios are analysed that include the complete failure of one road and hence both directions at the same time. Thus, all scenarios considered represent the failure of two corresponding, directed links.

**Non-consideration of links beyond the border of Switzerland** The SNTM has been designed to be able to assess infrastructure and policy measures within Switzerland. Beyond the borders of Switzerland, the network resolution is less detailed and does only cover the main roads from which traffic enters and leaves Switzerland. Additional roads that would provide alternatives in case of failure are not covered. Furthermore, with the exception of transalpine traffic, only the demand which is either generated or attracted by Swiss zones is modeled. Therefore, the failure analysis is restricted to the area with sufficient coverage in terms of both supply and demand.
6.3. Analysis of the transport network and demand structure

Links with no demand  Links with zero assigned demand in the transport model are excluded from this analysis since, based on the SNTM, no meaningful failure consequences can be assessed. Of the 20 401 Swiss links, 3293 links carry no traffic, reducing the number of failure scenarios to be evaluated to 17 108. However, it is clear that all links serve some traffic demand. But since demand should be very small, the failure consequences are also considered to be very small as compared to those of links with assigned demand.

Redundant nodes and links  The network contains 5421 nodes within Switzerland which connect only two links. Graph theory describes such links to have a node degree of two. The model would generate the same results, no matter which of the two adjacent links is in failure. In some cases, several nodes of degree two are connected with each other, building a chain of nodes and links. Of such a chain, the failure consequences are the same for any link failure. Therefore, the consequences need to be computed only once and the result can be applied to all the other links of the chain. However, all this does not apply for nodes which are connected to a zone and serve as demand nodes. Here, the failure results differ between each of the two adjacent links.

Cut links  Links whose failure would lead to a cut off of a network part are named cut links. According to the availability of a public transport alternative, two types of cut links can be differentiated. The first type comprises links which are provided with an alternative that detours the failed link by rail. Links of the second type are without such alternatives. Of all 915 cut links in the network with assigned demand, 391 belong the first and 524 to the second category. For links of the first category, vulnerability analysis is based on the number of unsatisfied trips. In the latter case, this analysis is complemented by assuming that the all affected demand would switch modes.

6.3  Analysis of the transport network and demand structure

It is argued that different patterns of link failure can be differentiated based on the characteristics of a given link. Those characteristics include the demand the link serves under normal conditions and the network topology. Three key attributes which have the potential to capture different patterns of failure consequences are identified: the average flow
bundle distance, the shortest route between the two remaining nodes after failure of the connecting link, named detour distance, and the demand volume. In the following, the relevance of those elements for adaptive failure consequences analysis is summarised. Based on a cluster analysis of those attributes, different approaches to evaluate failure consequences in a simplified but accurate manner are developed.

### 6.3.1 Average flow bundle distances

Flow bundles consist of all used paths between a given set of origin-destination pairs traversing a given network element. The flow bundle of a link can serve as reference for the spatial evolution of consequences in case of failure. If a link is mainly traversed by long distance paths, relevant detour alternatives might be available far away from the actual location of the failure. Those alternatives need to be included when performing failure consequences analysis. If a link serves mainly local demand, failure consequences are expected to spread only locally, assumed that local alternative paths are existing.

For example, between Berne and Lausanne two main route alternatives are provided by the motorways A1 and A12 which are very similar in terms of generalised cost. In case of the failure of a link which is part of A1, the newly shortest route from Berne to Lausanne would obviously lead over A12 and vice versa.

Figure 6.1 shows the flow bundle distances and link volumes in the Swiss National Transport Model. Due to the network hierarchy (Erath et al., 2009), mainly only motorway links are characterised by high demand volume and long average path distance at the same time. Routes connecting different valleys in the mountainous regions of Switzerland also serve long distance demand relations in particular, but demand volumes are rather low. Most links, however, mainly serve local demand. Given the availability of local detours (see next section), it is expected that most failure consequences are taking place within a local scale.

### 6.3.2 Detour distance

Another indication of the spatial spread of failure consequences is given by the availability of alternative paths in case of a link failure. Several indicators to quantify such local network characteristics seem to be possible, e.g. local network density or connectivity within a certain radius around the failed link. However, it has been decided for two reasons to take the post failure detour distance between two nodes which, in non-
Figure 6.1: Flowbundle distances and link volumes in the Swiss National Transport Model
failure conditions, are directly connected by one link: first, such a figure is directly related to one given link whereas the other measures are subject to some spatial smoothing. Second, the indication is straightforward and unambiguous while the other measures require the indication of a relevant radius and more extensive data processing.

Figure 6.2 depicts detour distances and link volumes in the Swiss National Transport Model. For most links, the detour distance is below 10km. The detour distance of motorway links is somewhat higher since those links are only connected to the rest of the network by slip roads. By far the highest detour distances result from link failures on mountain passes.

However, the indication of the detour distance does not account for the availability of sufficient capacity on those detours. Furthermore, it is expected that the relevance of local detours becomes less important for links serving long distance origin-destination pairs as described in the section above.

### 6.3.3 Demand volume

When indicating failure consequences, the demand volume that is normally routed over a given link is important for two reasons: first, it acts as a scale factor for any failure consequences. Second, it gives some indication for the likelihood of congestion effects being a relevant part of failure consequences. For these reasons, the link volume has been included in Figures 6.1 and 6.2 as only the combination of volume, flow bundle and detour distance are decisive.

### 6.3.4 Link clustering for scenario adaptive failure consequence assessment

#### 6.3.5 Clustering of links

Based on the link’s characteristics in terms of average flow bundle distance, detour distance, and link volume, a cluster analysis was performed. The main objective of the analysis was the detection of the assessment methodology most appropriate for failure consequences for each link. Given the size of the data set with about 16 500 links, a two-step clustering approach was employed. Cut link and links with no assigned demand have been excluded from the analysis as they already constitute clusters on their own.
6.3. Analysis of the transport network and demand structure

Figure 6.2: Detour distances and link volumes in the Swiss National Transport Model
First, the clustering process was tested without a predefined number of clusters but using the Bayesian information criterion to detect the optimal number of clusters. However, either if an Euclidian or log-likelihood distance measure was selected, it resulted in a two cluster solution. For this reason, it was decided to specify the number of clusters in advance. The most meaningful results were obtained for three to six clusters based on the euclidian distance measure. The results are listed in Table 6.1.

If three clusters are allowed, those clusters can be characterised by featuring either long detour distance, serving high demand volumes of rather long average path distance (indicated as motorway) or serving some demand of rather short average path length (local road). This last cluster is by far the largest. By increasing the number of clusters, those main clusters split up into subclusters. By increasing the number of clusters from three to four, a cluster that can be best described as trunk or main road emerges. When allowing for five clusters, motorways are further differentiated according to the average flow path distance. Finally, a sixth cluster is characterised by both medium detour distance and medium average flow bundle. Members of this cluster stem from both the clusters long average path distance and trunk/main road.

Given those clusters types, the following guidelines to simplify failure consequence assessment are considered. Those proposed simplifications are based either on the spatial restriction of the analysis, the omission of congestion effects or a combination of both:

- Since it can be expected that consequences of local road failures take place in some limited area of the transport network, not the whole network needs to be considered for failure consequence assessment. It is hypothesised that with the use of subnetworks, containing only a spatially delimited fraction of the whole network, failure consequences can be evaluated with a sufficient level of precision.

- In case of failure of a link featuring a long distance detour, the relevant detour alternatives extend over large parts of the network. Given the typically rather low demand figures, congestion is not expected to be of major importance for the indication of failure consequences.

- Congestion effects need to be considered when evaluating the failure consequences of links that serve high demand volume.

- The treatment of the spatial impact of links with high average flow bundle distances is less clear. Depending on the availabil-
<table>
<thead>
<tr>
<th>Name of cluster</th>
<th>Solution with n clusters</th>
<th>Volume [veh]</th>
<th>Path length [km]</th>
<th>Detour dist [km]</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Avg</td>
<td>Std</td>
<td>Avg</td>
<td>Std</td>
</tr>
<tr>
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<td>4</td>
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<td>1427</td>
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</tr>
<tr>
<td></td>
<td>5</td>
<td>1544</td>
<td>1292</td>
<td>106.3</td>
<td>59.9</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1547</td>
<td>1328</td>
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<td>61.3</td>
</tr>
<tr>
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<td>2602</td>
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<td>16.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1454</td>
<td>1298</td>
<td>26.9</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1459</td>
<td>1329</td>
<td>24.2</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1469</td>
<td>1316</td>
<td>25.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Motorway</td>
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<td>13 787</td>
<td>10 691</td>
<td>144.1</td>
<td>108.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>13 642</td>
<td>11 667</td>
<td>162.8</td>
<td>106.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>23 814</td>
<td>9126</td>
<td>81.2</td>
<td>38.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>23 817</td>
<td>8866</td>
<td>93.7</td>
<td>44.5</td>
</tr>
<tr>
<td>Trunk/main road</td>
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<td>7075</td>
<td>2699</td>
<td>31.8</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6319</td>
<td>2927</td>
<td>41.8</td>
<td>27.2</td>
</tr>
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<td>6</td>
<td>6871</td>
<td>2727</td>
<td>35.8</td>
<td>25.4</td>
</tr>
<tr>
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<td>5625</td>
<td>235.5</td>
<td>107.4</td>
</tr>
<tr>
<td>Motorway</td>
<td>6</td>
<td>5311</td>
<td>4637</td>
<td>242.0</td>
<td>110.2</td>
</tr>
<tr>
<td>Medium detour dist.</td>
<td>6</td>
<td>1445</td>
<td>1381</td>
<td>48.6</td>
<td>24.3</td>
</tr>
</tbody>
</table>

Table 6.1: Clustering results
ity of local and distant detour alternatives, failure consequences can emerge only locally or spread over a larger network area. To be sure to include all possibly relevant detour options, assumptions on the network area that needs to be included in for consequence analysis should not be restrictive.

Based on those guidelines, for each cluster a failure consequence assessment strategy is evaluated. Table 6.2 lists for each cluster the potential failure consequences in terms of spatial spread and relevance of congestion effects.

Given the low volume of links belonging to the first cluster, long detour distance, additional congestion effects are not expected to be of importance in case of failure. Due to the rather long detour distances, the spatial spread of failure consequences is considerable.

Local roads are characterised by short average path distances, short detour distances and low volumes. Therefore, failure consequences are assumed to spread only locally and to not cause additional congestion.

Failure of links assigned to the third cluster, named motorways, have the potential to lead to additional congestion. Given the long average flow bundle distances, consequences can potentially take place in some distance to the failure link. If five and more clusters are employed, the cluster long distance motorway splits off. It incorporates links that serve less demand than in the initial motorway cluster but are characterised by long average flow bundle distances. However, it is assumed that failure consequences for both clusters can spread over wide parts of the network and lead to additional congestion. Therefore, the same failure consequence strategy should be employed for both clusters.

Links incorporated by the forth cluster, trunk / main road, are characterised by slightly longer average flow bundle distances than in the case of links of the cluster local roads. Therefore, the spatial spread of failure consequences is expected to be similar. However, due to the difference in terms of demand volume, congestion effects should be included when evaluating failure consequences of trunk roads.

The sixth cluster long distance detour II splits off the first cluster. Both the average flow bundle distance and the detour distance are considerably shorter than in the original cluster long detour distance but still well above the values of cluster trunk / main road.

Figure 6.3 indicates the affiliation of all road links in the SNTM based both on the four and six cluster solution. The two additional cut link clusters have been detected as part of the network simplification process. The comparison of the two figures shows that the clusters long distance motorway and long detour distance II can be considered as subclusters of
6.4 Scenario adaptive failure consequences assessment and its application for the Swiss national transport model

6.4.1 Scenario adaptive vulnerability assessment

Scenario adaptive failure consequences assessment is based on two hypotheses: First, the transport network can narrowed down to a specified sector containing all network parts that might actually be affected by a given failure scenario. Second, congestion effects only need to be considered for links that serve considerable demand under non-failure conditions. The evaluation of congestion effects is the computationally most intensive part of failure consequences assessment. It is supposed that detailed analysis of the demand assignment process might reveal some potential to reduce the computation intensity.

In the remaining sections of this chapter, all preparatory operations and analysis to facilitate the application of scenario adaptive failure consequences assessment for the Swiss national transport model are documented. The actual test of the applicability of the approach and the verification of the hypotheses is covered in the next chapter.

Table 6.2: Potential failure consequence for different link clusters

<table>
<thead>
<tr>
<th>Spatial spread</th>
<th>Congestion effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>Medium</td>
</tr>
<tr>
<td>Long detour dist.</td>
<td>3,4,5,6</td>
</tr>
<tr>
<td>Local road</td>
<td></td>
</tr>
<tr>
<td>Motorway</td>
<td>3,4</td>
</tr>
<tr>
<td>Trunk/main road</td>
<td></td>
</tr>
<tr>
<td>Long dist, motorway</td>
<td>5,6</td>
</tr>
<tr>
<td>Long detour dist. II</td>
<td></td>
</tr>
</tbody>
</table>

The clusters motorway and long detour distance, respectively. However, those subclusters do not have a relevant influence the failure consequence assessment. Therefore, the optimal number of clusters is considered to be four and any further analysis presented herein refers to those four clusters.
Chapter 6. Adaptive failure consequences assessment

Typology: 6 clusters
- Cut link with rail alternative
- Cut link
- Long distance detour
- Trunk road
- Local road
- Motorway
- Rail
- Non-swiss link

Typology: 8 clusters
- Cut link with rail alternative
- Cut link
- Long distance detour
- Trunk road
- Local road
- Motorway
- Motorway long distance
- Long distance detour II
- Rail
- Non-swiss link

Figure 6.3: Clustering of links based on their failure consequence potential in the Swiss National Transport Model

6.4.2 Subnetwork approach

A subnetwork is a limited section of the complete network which is cut out including the internal and the through demand of this section. Ideally, for each link failure scenario, a customized subnetwork would be delimited based on link characteristics such as average path flow distance, detour distance and demand volume. Since the generation of a subnetwork also requires some computational effort, such an approach, however, is not be very efficient. Therefore it was decided to generate a multitude of subnetworks and assign each link to the subnetwork which
facilitates best its failure consequence assessment. Based on the analysis of the transport network structure and the link clustering, the following types of relevant subnetworks are identified.

- The full network needs is employed for failure consequence assessment of links belonging to the cluster *motorway*.

- Two additional subnetworks, one each for the two Swiss mountain ranges, Alps and Jura, were generated to which are employed for the assessment of *long distant detour* link. These mountain range networks were also extended to include parts of the adjacent Swiss plateau where the main freeways are situated to ensure the shortest paths were included (see Figures 6.4 and 6.5).

- The failure consequence assessment of the remaining clusters *local road* and *trunk / main road* is facilitated by automatically generated subnetworks. The design principles of those generic subnetworks are covered by the next section.

**Figure 6.4: Subnetwork to cover failure consequences: Alps**

### 6.4.3 Generation of subnetworks

To generate generic subnetworks four grid layers with 60 km edge length and an offset either or both of half an edge length in x and y axis were
overlaid the Swiss transport model (Figure 6.6). Afterwards, the subnetworks were cut according to the four grids, resulting in 140 subnetworks. This way is assures that from every link the nearest border of its subnetwork is at least 15km away.

Figure 6.7 shows an example subnetwork which represents the surroundings of Lake Neuchâtel. The failure of all colored links is assessed with the depicted network. The colors correspond to the color classification in Figure 6.3. Green links are assessed with the Jura network, yellow and brown links with the subnetwork and blue links with the whole network. The different layers of grey represent the affiliations the other links to the neighboring subnetworks.
Figure 6.6: Grid based generation of subnetworks
6.4.4 Computational intensity of failure consequence evaluation in subnetworks

The computational intensity of traffic demand assignment increases exponentially with the number of links and zones in the network. Since a subnetwork with 60 km edge length includes only a fraction of the links and zones of the whole network, the computational gains are substantial. Figure 6.8 plots the average computation time for each subnetwork based on a rather strict stop criterion with absolute/relative permitted deviation of impedances of 0.1/0.001% and a max. relative gap of $1 \cdot 10^{-4}$. Compared to the computation time for an assignment of the whole network with a less restrictive stop criterion which takes about 50 minutes, the gains are tremendous.

Besides the number of network elements, also the average network load influences the computation intensity. The network load is captured by the indication of the share of links with a capacity/demand ration above 70%. Due to the functional form of the capacity restraint function, even small changes of a link’s assigned volume can change the estimated travel time for traversing that particular link considerably. To reach an
6.4. Scenario adaptive failure consequences assessment and its application for the Swiss national transport model

Figure 6.8: Computation time for assignment by subnetworks [number of links], Stop criterion: absolute/relative permitted deviation of impedances of 0.1/0.001\%, max. relative gap of $1 \cdot 10^{-4}$ equilibrium state, more iterations and hence computation time is needed.

6.4.5 Precision of computation

For most applications of transport demand models, traffic volume per link is the unit of interest, e.g. when comparing traffic counts with model results. Furthermore, the equilibrium state defined by Wardrop [1952] is based on the postulate that all paths used for a given OD pair should have the same travel time. Hence, the commonly employed stop criteria take the deviation impedances of alternative routes into account. For failure consequence assessment, the measure of interest is, however, the sum of generalised travel cost. Other measures such as the Logsum term or network accessibility are also derived from generalised travel cost. Given the number of scenarios that need do be considered for network-wide failure consequences assessment, any potential to decrease the computational intensity of the problem should be utilised. Therefore, not only the assignment parameter of the max. number of inner or balancing iterations but also convergence in terms of generalised cost is tested for the three network types (Full network, Alps network subnetwork). All runs are computed using the transport demand software Visum 11.0 [PTV, 2010].
Chapter 6. Adaptive failure consequences assessment

on a 3.2 Ghz Core 2 processor with 8 Mb RAM. To speed up the assignment process, all failure assignments use the existing paths and volumes of the initial solution of the fully network. This requires to load the initial solution after each assessment. However multiple network modifications and repeated use of existing paths and volumes can result in different routes compared to the result of a new assignment, since for equilibrium assignment numerous possible routes satisfy Wardrop’s principle. For obtaining the initial solution incremental assignment with the demand split into four groups each covering 40%, 30%, 20%, 10%, of the total demand share.

Figure 6.9 shows the development both of additional generalized cost and mean difference volume between two OD pairs for three levels of inner iterations plotted against computation time. The indication of additional generalized cost is based on a assignment with 100 outer an 20 inner iterations. The maximum number of outer iteration has been set to 100. The computation time needed to reach a stable state in terms of generalised cost is for the given example, independent from the number of inner iterations and amount to 80 minutes. However, the variability of additional generalised cost between two outer iterations differs according to the number of balancing iterations. If 5 balancing iterations are employed, an acceptable level of variability is reached quickest. Given the objective of using the results for infrastructure management systems, a precision of some thousands Swiss francs is sufficient. Such precision is best reached using 5 balancing iterations. In order to keep the computational intensity low, the stop criterion in terms of mean volume difference for all further analysis employing the whole network is set to 0.3.
6.4. Scenario adaptive failure consequences assessment and its application for the Swiss national transport model

Figure 6.9: SNTM convergence process

It should be noted, that the failure of a link must not necessarily lead to an increase of generalised travel cost. (Braess, 1969) showed that adding extra capacity to a network can reduce overall network performance, at least when a Wardrop equilibrium state is considered. This can obviously also be interpreted from the opposite direction. By removing capacity, in this particular case given by link failure, the overall performance of a network might improve. However, given the stability of the solution at that point, it must be expected that for less critical links negative values of additional generalised cost are resulting. However, given the stability that is reached with the selected stop criterion, no meaningful detection of such Brass’ Paradoxon examples was possible.

Analogously, the assignment convergence is also examined for the Alps subnetwork. These results are presented in Figure 6.10. The computation time required to reach the equilibrium state is, compared the the whole network, much lower. Additionally, to additional generalised cost varies less. Given the necessary level of precisions, all tested assignment parameters lead to equal results, both in terms of computation time and convergence. However, with 10 or 20 balancing iterations, the final level of additional generalised cost is somewhat quicker reached. Therefore, all further assignments of the Alps network will employ 20 inner iterations with a stop criterion of 0.05 for mean volume difference.
Finally, the convergence process was analysed for three link failures of different cluster typology in the subnetwork depicted in Figure 6.7. The first graph of Figure 6.11 refers to the failure of a motorway link. In terms of convergence of additional generalised cost, all three levels of balancing iterations lead to similar results, although the performance when employing 20 balancing iterations is slightly better. The computation intensity is, compared the full network, substantially lower. At the same time a much higher precision is reached as the low variability of the generalised cost indicates.

The second graph shows the convergence process of a trunk / main road link failure. Here, the setting with 20 balancing iterations performs best. Since the failure of the trunk / main road causes less disturbance in the network, convergence is reached in almost a quarter of the computation time as required for the motorway link failure. The same applies for the link failure of local roads. Thus, for assignments of links in subnetworks, the number of balancing iterations and the stop criterion are set to 20 and $1 \cdot 10^{-4}$ for mean volume difference, respectively.
Figure 6.11: Subnetwork convergence process
6.5 Conclusion

In this chapter, the information on network and transport demand characteristics which can be used to predict failure consequences in terms of spatial spread and the additional congestion. Given the availability of a transport demand model, this information can be generated with reasonable effort. The link typology obtained by the cluster analysis which was employed using the additionally generated link attributes delivered meaningful results. Although one might argue that given overlap of the clustering results with readily available information, such as link type, it need to be stressed that such information normally does not allow to recognise for example link with long distance detours or to differentiate between a local and a main road.

For each of those clusters, a separate strategy for failure consequence assessment has been proposed. Those strategies are based on two hypotheses: First, it is assumed that for most link failures, the spatial spread of consequences is rather restricted. Second, failure induced congestion effects are only relevant for links that serve under non-failure conditions move to a certain demand level.

Based on the first hypotheses, the use of subnetworks for computing failure consequences is proposed. The concomitant decrease of computation intensity is massive. However, it needs to be demonstrated whether subnetwork based results are valid, as the might not consider all effectively available detour alternatives. Similarly, the omission of assignment when evaluating the increase of generalized cost needs to be validated. Both points are addressed in the next chapter which covers the application and validation of the outlined strategies.
Chapter 7

The vulnerability of the Swiss road network

7.1 Validation of the adaptive failure impact assessment

The adaptive failure impact assessment is validated on two levels. The applicability of the subnetwork approach and the neglect of assignment for links with low demand is tested within the whole SNTM.

The relevance of assignment for high volume links as well as mode and destination choice shifts are first evaluated in detail for a representative subnetwork. Based on those findings, the analysis is then extended to the whole network.

7.1.1 Applicability of subnetworks

As the majority of the link failure consequences are assessed with the subnetworks, 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 approach were also assessed with the subnetworks.

Figure 7.1 shows the differences in failure impact between the full network and subnetwork assessment assuming only route choice shifts. Generally, the results calculated by the subnetworks are very consistent with the full network results. In a few cases, the actual assessed consequence level is overestimated 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 of the high network density and the short average path distances, which automatically restricts the spatial scale of the analysis. The outliers are all links that are not provided with a relevant detour with sufficient spare capacity to absorb the rerouted demand within the boundaries of the respective subnetwork. For example, most part of the motorway leading through the south of Canton Ticino, which is characterized by steep mountains, is provided with only one relevant detour in near vicinity. Although such detours are covered in the respective subnetwork, the spare capacity on those detours is insufficient to absorb all of the demand. Hence, substantial additional travel times incur due to additional congestion.

Figure 7.2 shows a histogram of the failure impact difference between subnetwork and full network assessment and the normal distribution according to the respective average and standard deviation. The distribution peaks with the bin containing all values between 0 and 20 000 CHF/d. On average, the actual assessed consequence level is overestimated in these cases because the limited network does not cover all relevant detours. In some cases, this limitation leads to additional congestion effects within the subnetwork which explains positive skewness of the distribution. However, given the average failure impact of 109183 CHF/d for those links (belonging to cluster motorway and assessed with the full network) and the variability of the results due to the rather loose
7.1. Validation of the adaptive failure impact assessment

Figure 7.2: Distribution of the difference in failure impact between full network and subnetwork assessment

stop criterion, the results in general support the applicability of subnetworks. According to the demand structure and the network topology, the spatial spread of failure impact is expected to be most distinctive for such high hierarchy links. For this reason, it is a fair assumption that for other links, the subnetwork approach is expected to cause even less bias.

7.1.2 Relevance of traffic assignment

7.1.2.1 Failure of links serving low volume links

Compared to the additional computational effort of the mode and destination choice shift, the demand assignment is computationally much more intensive and therefore potentially a more important candidate for a shortcut. Based on the clustering analysis, it has been hypothesized that the failure impact of both local roads and long distance detours can be evaluated without additional demand assignment but that time and travel distance matrices are updated only based on post-failure shortest path information.

Figure 7.3 gives an overview of the differences when assessing failure impact either with or without assignment. Only links of the cluster categories local roads (yellow to brown) and long distance detours (green) are covered. In general, the accuracy that that is obtained using updated shortest path information only is sufficient. However, for some links in
urban regions like Basel, Zurich, Lucerne, Berne or Geneva, the difference becomes more distinct as the traffic is rerouted on already congested roads. The traffic demand assignment covers congestion effects by link type specific capacity restraint functions which indicate the relation between traffic flow and travel time. Given the non-linear form of the function, the gradient is ever increasing for additional flow. Hence, even if only little additional rerouted demand is assigned to a link with heavy flow, the increase in travel time can be considerable. However, even in such situation the underestimation of the failure impact when omitting assignment is of negligible magnitude, especially when comparing with the failure impact of links of the categories motorway or trunk/main road.

In general, this applies also for failure scenarios assessed with either the Alps or Jura network, although a few outliers seem to need demand assignment: The Achsenstrasse, for example, is part of the European route 41 connecting Dortmund, Stuttgart and Zurich to the Gotthard. Since it serves under non-failure conditions the highest volume of the category long detour distance, it is, however, not surprising that congestion effects are of certain importance when indicating failure impact.

Other outliers have been detected in the vicinity of border crossings which are modeled in the SNTM as links with low speed and capacity. However, this is considered to be an artefact of the model and should not actually influence the failure impact: first, the implementation of the Schengen treaty involved eliminating the border controls. Second, even under the assumption of actual border control, additional person-
7.1. Validation of the adaptive failure impact assessment

The detection of links, which requires demand assignment for precise failure impact assessment can, at least for the example of the given case study, facilitated by the assessment of failure impact resulting from the shortest-path approach: The *Achsenstrasse* links are by far the most critical ones. Therefore, a two-stage approach is proposed: In a first step all links are assessed based on shortest-path, and in a second step only the links with highest failure impacts are reconsidered employing demand assignment.

Although the reported results suggest that both *local roads* and *long distance detours* can generally be evaluated without additional demand assignment, it is clear for the further analysis in the thesis, the assignment-based results are used.

7.1.2.2 Failure of links serving high volume

When comparing assignment results based on a complete and an impaired network, the fuzziness of the results caused when employing a rather loose stop criterion as proposed above must be considered. This holds especially true if either the whole network is employed (Figure 6.9) or if assessing the failure of high volume links (Figure 6.11). Such fuzziness may interfere the effective impact of failures when summing up additional travel time and distance. Therefore, for the following analysis of the effect of assignment for high volume links a strict stop criterion is employed. To keep computation intensity reasonable, the analysis is restricted to 100 links within a single subnetwork. Those links belong either to the cluster *motorway* or *main/trunk road*. The subnetwork has been chosen to be representative both in terms of network topology and travel demand structure for Switzerland. Based on the findings of this case study, conclusions are drawn how to best assess all other high volume links.

Figure 7.3 shows that the inclusion of assignment and hence congestion effects substantially affects the estimation of failure impact. For motorway links located in the urbanised areas such as Zug or Lucerne, failure assessment that is based on shortest path only underestimates failure consequence up to a factor of three. In practice, besides the effective estimated failure related consequence, a ranking of the most vulnerable links can be of interest, namely when 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
The rank correlation test as well as Kendall's $\tau$ were computed. Both Spearman's $\rho$ as well as Kendall's $\tau$ are highly significant although the effective correlation parameter are rather low with values of 0.49 and 0.36 respectively. When comparing the 20 links with highest failure impact, 70% of the links appear in both lists although the order of the ranking is not consistent. Due to the scale effect of link demand when assessing failure impact, this is not unexpected. However, given that failure impact is log-normally distributed (see Section 7.3 further below), changes in rank order along the long tail of the distribution relate to substantial differences in absolute values.

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.

### 7.2 Relevance of analysis method

In earlier 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.

The consideration of mode and destination choice effects in vulnerability assessment are expected be to most relevant in urban agglomerations and mountainous regions: in urban agglomerations, public transport alternatives are usually viable and various destinations available. Additionally, in urban areas congestion tends to be a problem and the failure of infrastructure might lead to substantial travel time increases due to additional congestion. In mountainous regions, infrastructure failure can cause large-scale detours and hence considerable increases in generalised cost. If those areas are served by rail, mode shifts are therefore expected to be relevant demand reactions.
7.2 Mode choice

The restriction to route choice effects when assessing failure consequences is equivalent with the assumption of inelastic demand. Depending on the local situation and the type and extent of the hazard that leads to failure of the road infrastructure, other roadways such as rail or waterways might not be affected by a given hazard and provide relevant alternatives. The bias related to the assumption of inelastic demand depends both on the degree of failure induced changes in generalised cost and on the availability and attractiveness of alternative travel modes: if the failure induced change of generalised cost per OD relation is small, the bias incurred by this assumption is also small. However, if alternative modes are available at similar generalised cost, even small changes of generalised cost in the base alternative can lead to relevant demand shifts. In addition, mode alternatives that not have been attractive before might become relevant if the failure induced change of generalised cost per OD relation is substantial.

7.2.1.1 Relevance of mode choice for estimating failure impact

Figure 7.4 shows the effects of the consideration of mode and destination choice shifts on failure impact in the given case study area based on the CBA measures of monetarised additional travel time and distance. In line 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 Mio CHF/d to 1.7 Mio CHF/d and 1.4 Mio CHF/d when including mode and mode/destination choice shifts, respectively. This particular motorway link has the function of an entry gate to the city 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. It is noted that the adaptive failure impact assessment suggests to employ the whole network for most of the links of subject in this case study. The failure impact when employing the whole network are actually considerably lower. However, due to focus of the case study and the restriction that destination choice effects can only be evaluated for subnetworks (see Chapter 5), this shortcoming is accepted.

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 -8.4% compared
Figure 7.4: Effects of mode and destination choice shifts on failure consequences

to -27.9% when mode and destination choice is considered. However, weighted by the failure consequences, the decrease amounts to -23.9% and -39.2%, respectively. The relative reduction of the failure consequences when including mode or mode and destination seems to follow a normal distribution as Figure 7.5 indicates. Positive values can occur due to the non-linearity of the logit function. Failure impact measured by the total sum of generalised cost can be higher if an additional level of choice is considered (see Chapter 5 for a numerical example).

When plotted on the 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
7.2. Relevance of analysis method

Figure 7.5: Scale of failure consequence reduction when including mode and destination shifts

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 impact of the link. Additionally, the relative importance of mode choice compared destination choice increases also with the expected consequences.

In practice, besides the effective estimated failure related consequence, a ranking of the most vulnerable links can be of interest, namely when 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 \( \tau \) were computed and listed in Table 7.1. According to both tests, the correlation of the results are highly significant, whereas the ranking is even the same for the 15 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>
<thead>
<tr>
<th>Kendall’s $\tau$</th>
<th>Mode/Destination choice shift</th>
<th>Sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode choice shift</td>
<td>0.90</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td>Only route choice</td>
<td>0.93</td>
<td>&gt;99.9%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Spearman’s $\rho$</th>
<th>Mode/Destination choice shift</th>
<th>Sign.</th>
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<tbody>
<tr>
<td>Mode choice shift</td>
<td>0.98</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td>Only route choice</td>
<td>0.99</td>
<td>&gt;99.9%</td>
</tr>
</tbody>
</table>

Table 7.1: Effect of mode and destination choice on failure consequences: Rank correlation tests

The case study revealed the relevance of including mode and destination choice effects in vulnerability analysis. Therefore, it was decided to include such effects when assessing the vulnerability of the Swiss road network.

### 7.2.2 Relevance of vulnerability measure

If only route choice is considered, the logsum term according to Equation 5.7 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 7.6) compared to the CBA results. Considering mode as well as combined mode and destination choice effects, the logsum term results are in average -25.4% and -31.0%, respectively below the value based on the CBA approach. Using numerical simulation, it was supported that the logsum is lower than the CBA measure if the most attractive alternative is impaired more by a given failure than the other 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 strongly consistent between both measures (Table 7.2). Again, as in the case of the CBA measure, the indication of the first 15 ranks, both for mode and mode/destination choice are even exactly the same.

Figure 7.7 shows the failure consequences based on the logsum term. As with the CBA measure, the inclusion of alternative modes and des-
7.2. Relevance of analysis method

Figure 7.6: Failure consequences based on the logsum compared the CBA measure

<table>
<thead>
<tr>
<th>Kendall’s $\tau$</th>
<th>Mode/Destination choice shift</th>
<th>Sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode choice</td>
<td>0.88</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td>Mode and destination choice</td>
<td>0.93</td>
<td>&gt;99.9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spearman’s $\rho$</th>
<th>Mode/Destination choice shift</th>
<th>Sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode and choice</td>
<td>0.97</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td>Mode and destination choice</td>
<td>0.99</td>
<td>&gt;99.9%</td>
</tr>
</tbody>
</table>

Table 7.2: Effect of evaluation measure on failure impact: Rank correlation tests
Figure 7.7: Failure impact based on the logsum measure

destinations leads to lower failure consequences. However, the scale of the drop is higher for the logsum term. This results from the property of the logsum term measure, that any increase in generalised travel cost results in a decrease of the logsum measure. This is not necessarily the case when the CBA measure is employed (see Chapter 5). On average, the inclusion of the utility of alternative modes leads to a decrease of failure consequences of -28.3% compared to -47.3% when mode and destination choice is considered. If weighted by the failure consequences, the decrease amounts to -30.9% and -47.9%, respectively. Compared to the CBA measure, the effect of the inclusion of destination choice is substantially smaller.

Since the logsum term can be considered the more consistent assessment measure, at least from a methodological point of view, the indication of failure impact for the Swiss road network will be facilitated by the logsum measure.
7.2.3 Relevance of network resolution

The network used in the national transport model is a simplification of the complete Swiss transportation network and contains only the relevant links for intercommunal travel demand but not all roads. Non considered local roads may provide, in case of failure, relevant detour alternatives. But because of the small capacity and the low hierarchy in the network of these roads this bias is considered to be small. To affirm this assumption, the subsequent case study quantifies exemplarily 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 caused by using a simplified network also links of high hierarchy.

For this case study, the road network of the SNTM of the relevant 30km subnetwork was exchanged with a digital map network, normally used for GPS navigation systems, provided by Navteq. 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 are 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 was detected. One difficulty thereby was that one link of the simplified network was normally represented by multiple links in the Navteq network whereas some of these links can be circumnavigated in proximity and others not. If a majority of the corresponding links in the Navteq-network with a detour in proximity, the link from the simplified was assigned to one such a link and vice versa.

Since a 30km subnetwork is used, the analysis is restricted to the inner 15km square of the subnetwork containing 235 directed links (see Section 6.4.2). 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 time increased by a factor of
Figure 7.8: Failure consequences based on networks of different resolution

The scatter plot reveals the dependence on the detour distance. For links which can be detoured by using adjacent access roads which are not covered in the simplified network, the calculated failure consequences are substantially different. For all other links, however, the results are very comparable. This highlights the importance 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 7.8). Here, the exact location of the failure determines the real failure consequences. On the other hand, it is obvious that local detours are only 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 network as used in the case study on this scale would increase the computation intensity too much and one would not be able anymore to run the analysis on a standard desktop computer.
7.3 Failure consequences in the Swiss road network

7.4 Overview

Figure 7.9 presents the magnitude of the indirect failure consequences by line width for all Swiss links in the Swiss national model. Motorway links and links with long detours which were assessed by the Alps and the Jura networks show 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.

The highest failure impact are identified for the motorway segment between Nyon and Geneve with about 1.1 Mio CHF/d additional generalised cost. In addition, failure impacts of the same magnitude are obtained for the Viaduc de Chillon, the Ponte di Melide connecting Melide and Bissone over the Lake Lugano, the motorway leading to Basel at Schweizerhalle and the section of the A1 around Baregg tunnel.

The links whose failure lead to the highest impacts can be categorized into three groups. First, motorway links serving high demand volume and are well known as bottlenecks such as the motorways leading to Basel, Geneva, Bern and Zurich. Second, motorway links that are not served with detours with sufficient capacity. Examples of such situations are the Achsenstrasse leading along Lake Uri, the Kirchenwald tunnel near Lucerne and two motorway links in the Valais. However, the last two examples show exemplarily how distinct even a small lack of coverage in the network can bias the results. It could be verified that in each case a local alternative given by the Seestrasse in the case of Kirchenwald tunnel and by some access road in the case of Valais is available. If those links

in reasonable time. Therefore, the availability of alternative local detours was only checked systematically for those links with detours within the simplified network longer than 30km. 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. However, the case study showed that the failure consequences can be substantially overestimated even for links with shorter detours than 30km which underlines that the failure consequences should be considered as an upper limit.
Figure 7.9: Failure impact (link width) based on the Swiss National Transport Model
were included in the SNTM network, the corresponding failure impact is expected to drop by at least one order of magnitude. Third, links that are characterised by long distance detours in the mountainous regions. Although some of them are served with a rail alternative, the failure impact is still considerable. Since the probability of natural hazard exposure is usually also more prevalent in this regions, the current practice to fortify those network segments with natural hazard protection measures is verified by the new results. Actually, the failure impact for this category is expected to be even higher if the winter case with closed pass roads is considered. This applies also for the failure impact of the Gotthard and San Bernardino motorway.

In addition, the importance of link volume as a scale factor when indicating failure impact is also obvious. In general, the failure of links with high volume, such as motorways or arterial road in urbanised lead to the highest consequences.

### 7.5 Relevance of mode choice

In Figure 7.10 the relevance of mode choice effects when assessing failure impact in the Swiss road network is indicated. The link bar width is given by the difference of the logsum term between including generalised costs either of all three modes covered by the SNTM (Equation 5.9) or of car only (Equation 5.8). Two findings stand out: First, the inclusion of mode choice is of major relevance when indicating failure impacts of motorways in urban areas. Given the availability of the relevant public transport alternative in those regions, especially the rail system substantially helps to alleviate road failure. Second, in mountainous region the availability of a second transport system helps substantially to alleviate road failure impact. The difference of the risk measure (including failure both the probability of exposure and failure) between the two assessment methods can be used to quantify economic value provided by the redundancy of the rail infrastructure within the transport system. However, this requires that failure probabilities of the two systems are independent which is usually only given if their routes are spatially separated.

The inclusion of mode choice effect is most relevant the motorway link between Geneva and Nyon, which is at the same time the link with highest failure impact. If only route choice is considered as demand reaction, the failure impact is estimated to amounts to 0.68 Mio CHF or about 61% more than if also mode choice effects are considered. Over the entire network, the average reduction amounts to 11.0% if all links is
considered equal, and to 19.8% if the link’s importance is linked to the failure impact.

7.6 Conclusion

In this chapter, the applicability of the adaptive failure impact assessment has been tested at the example of the Swiss road network using the SNTM. Both key assumptions, namely the use of subnetworks and the omission of assignment for links with low demand, have been successfully validated. Furthermore, the results suggest that mode choice effects should be included in failure impact assessment.

In addition, it has been demonstrated that the simplified networks as normally used in transport demand models indeed do not cover some detours that might be relevant for actual failure scenarios. However, the relevance of this bias is considered to be minor for two reasons. First, the bias is strongly correlated to the detour distance. Since the number of links with substantial detour distance is manageable even for a national network, the availability of alternative local detours can be systematically checked for those links. Second, the highest failure impact is obtained for motorway links. As the transport demand model cover normally all main and cantonal roads, it can be assumed that the relevant detours for
motorway failures are included in the simplified network. This assumption proved to be correct for the SNTM except for the two links in the Valais which could have been easily detected.

Furthermore, the result suggest that the initial state of system is of vital importance. In Switzerland, for example, mountain passes are closed during winter affecting the network topology considerably. For example, the impact of failure of the Gotthard tunnel is expected to much bigger in the winter case. In the summer case, the bulk of the traffic is rerouted to the older of the two existing Gotthard pass roads. This highlights two potential shortcomings of the employed methodology. First, network errors, such as the erroneous speeds and distances of the old Gotthard pass roads, that remained undetected when establishing the transport demand model, can bias the estimation of failure impacts. Therefore, the validation of the results is crucial. Second, by employing the equilibrium conditions, it is assumed that all travelers are aware of the failure, know all relevant detour alternatives and the (equilibrium) traffic conditions on those detours. In reality, however, this might not hold, especially for failures of links serving long distance OD demand. Therefore, it must be assumed that the estimated failure impact figures indicate a lower threshold of the actual consequences.

Finally, destination choice effect could only been partially included in the analysis. The quantity structure of calibrated demand matrice does not necessarily correspond with the attraction parameters used to evaluate destination choice shifts, either by CBA using pivot point or the log-sum measure. This mismatch leads to inconsistent and counterintuitive results. Therefore, the computationally intensive operation of finding the roots (attractiveness vector) of the non-linear equations that would lead to the calibrated demand structure was employed. However, due to its complexity and given the hardware at hand for running the analysis procedures, destination choice effects could only be evaluated when subnetworks were employed. Since some of the biggest failure impacts are found in urban areas, and given the results of the case study, the effects of destination choice shift are expected to be considerable. Therefore it might be meaningful to neglect the cluster categorisation and employ subnetworks for the assessment of motorway links in urban areas.
Chapter 8

Statistical modeling of indirect consequences

8.1 Motivation and concept

Using the subnetwork approach, the assessment of indirect failure induced traffic consequences across a national network becomes computationally feasible. For the Swiss case, it takes around two weeks on a fast, currently available personal computer. In addition, significant preparation work is required to generate the subnetworks and evaluation routines. A further, and probably even more crucial prerequisite is the availability of a transport demand model which for example in developing countries is not always given. Hence, it would be desirable to assess link criticality more directly. One approach is to use a statistical model to estimate a link’s indirect failure consequences. Such a statistical model shall combine network topology data such as network density, detour distance and link volume to estimate failure consequences. Based on the resulting parameters, one can impute the magnitude of indirect consequences for other road networks without the need to run traffic assignments. However, the ultimate objective is to facilitate an assessment of failure consequences that does not require any input which is normally only provided by transport demand models. Consequently, a screening of failure consequences can be conducted with comparably low data requirements.

The analysis and models presented in this chapter refer to an earlier stage of the research covered in this thesis. At that stage, only the SNTM (Swiss National Transport Model) for the reference year 2000 [Vrtic et al., 2005a] was available. The style of adaptive failure assessment was not based on the result of a cluster analysis but on link
type. Furthermore, the dimension of considered demand reactions were restricted to route choice and only the CBA measure was employed to indicate failure consequences. Last, the data refer to a winter scenario as the majority of the pass roads are considered closed.

8.2 Application: Modeling failure consequences in the Swiss road network

8.2.1 Failure consequences: explorative data analysis

First, the distribution of the dependent variable is evaluated. As the network plot in Figure 7.9 indicates, the bulk of link failures lead to only minor failure consequences while only the failure of a few links leads to considerable cost. Therefore, it was assumed that failure consequences follow a log-normal distribution. Figure 8.1 shows the histogram of log-transformed failure consequences and compares it with the normal distribution with the parameters mean $\mu = 7.33$ and standard deviation $\sigma = 1.43$ taken from the sample. Although the normal distribution fits the data reasonably well, the formal Kolmogorov-Smirnov test rejects this hypothesis because of the positive skewness. Therefore also other distributions were tested. A Weibull distribution with scale parameter $\lambda = 8377.9$ and shape parameter $\kappa = 0.65$ performed best.

![Histogram of failure consequences](image)

Figure 8.1: Histogramm of failure consequences
8.2. Application: Modeling failure consequences in the Swiss road network

In Figure 8.2, the P-P plots of the data against both the lognormal and Weibull distribution are depicted. Compared with the expected values of the Weibull distribution, a negative skewness can be identified. As the generalized gamma distribution does have the ability to mimic the attributes of either of those two distributions, it was decided to employ a generalised linear model for parameter estimation.

![Lognormal P-P Plot](image1)
![Weibull P-P Plot](image2)

Figure 8.2: P-P plot of failure consequences

### 8.2.2 Independent variables

Table 8.1 lists all independent variables that were employed when developing the statistical model. Some of them have already been used to facilitate link clustering as part of the adaptive failure assessment: link volume has been identified as scale factor of failure consequences as it captures the number of vehicle which are subject to detours in case of failure. The detour distance is considered to be a proxy for the failure induced increase in travel time and distance. However, the relevance of detour distance depends clearly also on the average flow bundle distance. The closer the directly affected OD pairs are located to each other, the more relevant becomes the detour distance as the availability of other, potentially long-range detour options are less likely. The computation of flow bundles for each link requires substantial computational effort and the availability of a transport demand model. At the same time, flow bundles are, due to the network hierarchy, highly correlated with the link type. Therefore, it was decided to use two dummy variables representing different link types as proxy variables for average flow bundle distance: motorway and links with detour distance longer than 30km.
<table>
<thead>
<tr>
<th>Function</th>
<th>Variable</th>
<th>Scale</th>
<th>Link type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Detour distance &gt; 30km</td>
<td>Motorway</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disposed link capacity</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Radii of 5, 10, 15km</td>
<td>Link capacity</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Radii of 5km, 10km, 15km</td>
<td>Number of nodes</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Radii of 5km, 10km, 15km</td>
<td>Number of links</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Radii of 5km, 10km, 15km</td>
<td>Link length</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local density</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flow bundle</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average distance</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Detour volume</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Table 8.1: List of tested independent variables</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
To cover the potential of failure induced congestion effects, different measures of local network density have been generated to be tested in the modeling process. Those include the number of links and nodes, the link capacity and disposable link capacity which is given by subtracting the actual, non-failure link volume from its capacity. Those network density variables have been generated assuming three different catchment areas with radii of 5, 10 and 15 km around each link’s centroid. The generation of the variable disposable link capacity requires the network-wide indication of link volume information. Hence, the availability of a transport demand model is a prerequisite condition for generating this variable. This only partly applies to the variable link capacity as this can also be derived from the link type classification.

During the modeling process several different combinations of the presented set of variables and model forms were tested. Especially the correlations between the different variables needed to be respected. Additional variables were gradually included in the model while always monitoring both the gain in model performance and effects on other model parameters.

8.2.3 Model analysis

The final 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 6.1 but does not require assignment model derived information. Since in the calculation of the failure consequences the volume acts as scale 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 to the network type used in the prior consequence assessment. The data basis is built from link failure of all cases with positive values of additional travel time and indirect failure consequences. The final model has the following structure:

\[
CI_i = C + \beta_1,NT \cdot D_{NT,i} \cdot V_i \cdot TD_i + \beta_2,NT \cdot D_{NT,i} \cdot \left( V_i^2 / C_5^{km,i} \right),
\]

(8.1)

with:

- \( CI_i \) Indirect failure consequences [CHF/day], derived from the assignment solution,
### Table 8.2: Generalised linear model for indirect failure consequences

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\beta$</th>
<th>Std. Error</th>
<th>Wald Chi-Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>810.09</td>
<td>22.78</td>
<td>1265.05</td>
</tr>
<tr>
<td>Alp/Jura $* V_i$ $* TD_i$</td>
<td>25.37</td>
<td>1.41</td>
<td>326.10</td>
</tr>
<tr>
<td>Full $V_i$ $* TD_i$</td>
<td>13.77</td>
<td>0.81</td>
<td>285.75</td>
</tr>
<tr>
<td>Subnetwork $V_i$ $* TD_i$</td>
<td>13.68</td>
<td>0.24</td>
<td>3315.68</td>
</tr>
<tr>
<td>Full $V_i^2$ $/ C_{5km,i}$</td>
<td>0.38</td>
<td>0.04</td>
<td>100.84</td>
</tr>
<tr>
<td>Subnetwork $V_i^2$ $/ C_{5km,i}$</td>
<td>0.26</td>
<td>0.03</td>
<td>96.23</td>
</tr>
</tbody>
</table>

$\varphi^2 = 0.631$, n=13’178

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 a simple and transparent structure. The results presented in Table 8.2 affirm the earlier statement that traffic demand redistribution is spatially restricted, as the included variables describe only the network part adjacent to the studied link.

The parameter for the shortest detour for links assessed with the Alps/Jura network is very similar to the value of travel time savings indicating that demand is primarily shifted from the failed link to the shortest detour. The additional potential of further detours in dense parts of the network reduces dependence on the shortest detour, which is defined as the shortest path distance between the two nodes of the failed link. The term quantifying capacity limitation effects for links assessed with the Alps/Jura network has been omitted since its effect proved to be insignificant and small. 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. Interestingly, the variable link capacity performed slightly better than disposable link capacity. Therefore, and because of its advantage in terms of data requirements, the
variable link capacity is used in the proposed model.

8.2.3.1 Distribution of the errors

The distribution of the error term is normal (Kolmogorov-Smirnov test statistic of 38.72) fulfilling the conditions of the estimation method. The 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 cases with the largest consequences. Those 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. The small number of predicted high failure consequences links, however allows that such cases can easily be identified by checking the presence of local alternatives.

8.3 Conclusion

Although the proposed model does not allow to indicate possible failure consequences with high precision given the overall model fit, the results are still relevant for vulnerability analysis. First, the application of the model permits obtaining a first indication of a networks vulnerability structure with considerably lower requirements in terms of data availability and computational effort than the adaptive failure consequence assessment proposed in chapter 6. Second, the inclusion of vulnerability into infrastructure management systems requires also the indication of failure probability. Hence, it would be appropriate that both components have similar levels of accuracy. However, the indication of failure probability based on natural hazard maps in current practice is normally rather restricted in terms of precision featuring only a couple of ordinal scaled probability categories. The presented statistical model at least meets or even exceeds such accuracy.

The model, however, employs data of a today out-dated transport model. An update based on the results presented in chapter 7 has the potential to validate the results. Furthermore, the scope of dependent variables could be expanded and include failure consequences that reflect mode and destination choice effect. Though, further variables such as the prevalent trip purpose of the traffic normally traversing the failed link might be required to facilitate such model expansion.

The sample of the statistical model presented includes all available cases. If only a random sample was used, the results could be vali-
dated with the remaining cases. Additionally to the analysis of the error term, such an approach might provide further insight about the model’s strengths and weaknesses. In the same vein, it would be interesting to evaluate the models performance when applied to other transport networks. Thereby, especially the model’s sensitivity to network typology in terms supply and demand structure would be of relevance. Finally, the application of advanced estimation methodologies that account for the diverse statistical distributions of both the dependent and independent variable, such as Bayesian interference modeling, is considered to provide potential for improvement when modeling failure consequence. Equally, the methods of spatial statistics would be employed.
Chapter 9

Joint failure vulnerability

9.1 Motivation

The assumption of single link failures is rather restrictive. It is especially challenged by threats that are caused by one extreme natural event. For example, heavy snow- or rainfalls can be considered as the root of natural hazards and they are likely to enhance the probability of mudslides or avalanches not only at a particular location but for a larger region. In the case of floods, joint link failure are even the standard case, as it is likely that several links along the floodplain are affected.

Depending on the network topology and the structure of travel demand, the impact of joint failure scenarios can either be lower, equal or higher than the sum of impacts caused by single link failures. Demand reactions from joint link failures can differ substantially from the simple combination of the respective single link failures. Therefore, it must be assumed that the neglect of joint scenarios affects the allocation of resources and hence makes the relevance of such link-by-link vulnerability analysis questionable. For this reason, implications of relaxing the assumptions of single link failures are evaluated based on a case study and presented in this chapter.

9.2 Problem definition

Under the assumption of mutually exclusive link failures given a hazard scenarios $E$, the indication of the risk of the whole network $R_N$ is simply the sum over the risks of its elements $n$, i.e. links and can be expressed as given in Equation [9.1]. The effectiveness of a natural hazard protection measure is hence only dependent on its ability to protect a given link and does not include that it might part of an important detour alternative in
case of some other links failure.

\[ R_N = \sum_{0 < i \leq n} P(F_i|E) \cdot (CD_i + CI_i) \] (9.1)

If this assumption is relaxed, consequences of network states in which two or more links are subject to failure must be considered as well. Whereas the incidence of joint failure should not affect the direct failure consequences, i.e. cost to restore destroyed infrastructure, this does not necessarily apply to indirect consequences. Only in the most trivial case for which failure induced demand reactions in the transport networks do not interfere, the indirect consequences of a joint failure scenario are simply given by the sum of the individual failure direct and indirect consequences. For all other cases, the joint failure scenario must be considered as a new scenario on its own with consequences being either lower, equal or higher than the sum of the respective single failure consequences.

Under the assumption that only two links, \( i \) and \( j \), are subject to failure at the same time and the vulnerability subject to a given natural hazard event \( E \) can be described as given by Equations [9.2] and [9.3]. Those equations are visualized using set theory in Figure 9.1: the first summand accounts for the independent failures while the two other terms define the intersection.

\[ V_E = \sum_{0 < i \leq n} P(F_i|E) \cdot (CD_i + CI_i) - \sum_{i,j:i<j} P(F_i \cap F_j|E) \cdot (CD_i + CI_i + CD_j + CI_j) + \sum_{i,j:i<j} P(F_i \cap F_j|E) \cdot (CD_i + CD_j + CI_{i,j}), \] (9.2)

which can be simplified to:

\[ R_N = \sum_{0 < i \leq n} P(F_i|E) \cdot (CD_i + CI_i) + \sum_{i,j:i<j} P(F_i \cap F_j|E) \cdot (CI_{i,j} - (CI_i + CI_j)) \] (9.3)

Equation [9.3] can be generalised to cover any number \( n \) of links in
9.2. Problem definition

Figure 9.1: Patterns of joint failure consequences

Joint failure:

\[
R_N = \sum_{0<i \leq n} P(F_i|E) \cdot (CD_i + CI_i) + \\
\sum_{i,j: i<j} P(F_i \cap F_j|E) \cdot (CI_{i,j} - (CI_i + CI_j)) + \\
\sum_{i,j,k: i<j<k} P(F_i \cap F_j \cap F_k|E) \cdot (CI_{i,j,k} - (CI_{i,j} + CI_k)) + \ldots + \\
\bigcap_{i=1}^{n} P(F_i|E) \cdot (CI_N - (CI_{N'} + CI_n))
\]

(9.4)

with:

\(N\) set of all links \(n\) in the network,

\(N'\) \(i, \ldots, n-1\).

The change of the network risk when taking into account joint failure scenarios is determined by the relation of \(CI_I\) and \(\sum_{i' \in \{1, \ldots, n-1\}} CI_{i'}\). Therefore, a natural hazard protection measure on link \(i\) reduces not only
Chapter 9. Joint failure vulnerability

The probability of single link failures, but affects also the probability of all joint failure scenarios that incorporate link \( i \). Equation \( 9.5 \) specifies the risk reduction obtained from a natural hazard protection after including joint failure risk.

\[
\Delta R_i = \Delta P(F_i|E) \cdot (CD_i + CI_i) + \sum_{j:i \neq j} \Delta P(F_i \cap F_j|E) \cdot (CI_{i,j} - (CI_i + CI_j)) + \sum_{j,k:i < j < k} \Delta P(F_i \cap F_j \cap F_k|E) \cdot (CI_{i,j,k} - (CI_{i,j} + CI_k)) + \ldots + \sum_{N \setminus i} \Delta P(F_n|E) \cdot (CI_N - (CI_{N'} + CI_n))
\]

(9.5)

As a result, any failure protection measure at link \( i \) does not only affect the risk \( R_i \) but also the joint failure probability of scenarios that involve \( i \) which in turn are part of other links risk. This means that the implementation of any protection measure changes the network’s risk structure. The cost-benefit evaluation needs therefore to be implemented incrementally (Figure 9.2). In a first step, the protection measure with the best cost-benefit ratio is assumed to be implemented. The network’s risk structure needs then to be recalculated. Thereby, it is assumed that the designated protection measure bans the probability of failure completely. Based on this new risk structure, the second best protection measure is evaluated and so forth. This needs to be continued until either the budget for failure protection measure is exhausted or the cost-benefit ratio of the currently evaluated protection measure is below the value of one. It is, however, not clear that such an incremental approach will be the optimal use of the budget due to the possibly non-linear interactions (see Vitins and Axhausen (2009) for a solution approach to this network design problem and a literature review). Still, it is a good heuristic.

9.3 Challenges

The main challenge of assessing joint failure consequences is the enormous number of possible scenarios. The number of scenarios to be considered is dependent on the number of links in the network and the maximum number of links allowed to be part of a joint failure scenario. Actu-
9.3. Challenges

Figure 9.2: Incremental cost-benefit evaluation for joint failure scenarios

ally, the number of additional scenarios for every increase of the number of links in joint failure is given by the common formula to calculate permutations without repetition:

\[
\binom{n}{k} = \frac{n!}{k!(n-k)!}
\]  \hspace{1cm} (9.6)

with:

- \(n\) the number of links in the network,
- \(k\) the number of links allowed to be part of a joint failure scenario.

As shown in the sections above, the impact of the inclusion of a joint failure event on the network risk depends on two variables: the probability of joint failures and the interdependence of the consequences. Those two factors define the potential to reduce the complexity of the problem.

Concerning the probability of joint failures, it can be assumed that the spatial potential of most natural hazards exposures to affect transport infrastructure is rather restricted. Hence the number of scenarios that actually need to be evaluated should drop considerably, as the probability of a scenarios of two or more spatially distant links shall be considered as almost zero. However, models to estimate joint failure probabilities based on existing natural hazard maps are not yet available. To facili-
tate such models, one would need on the one hand to define the common root, e.g. heavy rainfall, to which of different indications of exposures in hazard maps can be traced back. On the other hand, complex statistical models would be required to capture the probability interference in between different roots and the according natural hazard exposures.

From Equation 9.5 it is derived that the consideration of joint failure events leads to different risk valuation compared to single failure events, if the sum of the combined (single) failure consequences differs from the joint failure consequences. This applies if the traffic redistribution effects of the respective failure combination interdepend, e.g. if the individual failures of the considered links lead to traffic volume shifts on at least one identical link. In case of independence, the joint failure consequences are equal to the sum of the combined failure consequences.

The impact of interacting link failures is assumed to be determined by the characteristic of the interdependence. As illustrated in Figure 9.3, Pattern a) applies to a situation where a series of links serves as rerouting alternatives for both single link failure. Depending on the capacity and the volume of the rerouted demand, congestion effects on those links can occur and lead to joint failure consequences that exceed the sum of the single failure costs. Pattern b) suggests that the links subject to failure serve each other at the same time as rerouting alternatives. In case of a joint link failure, so far unused and hence more expensive rerouting alternatives will become relevant. Therefore, it is assumed that joint failure scenarios that lead to pattern b) show larger failure consequences than the two independent failure events. Pattern c), however, indicates that the joint failures lead to similar rerouting effects as in the case of single failures. Hence, joint failure consequences are expected to be smaller than the sum of the single link failures’ consequences.

9.4 Case study

9.4.1 Approach

In order to assess the bias incurred through the restriction to single link failure scenarios, the following case study joint compares the results of single with joint failure vulnerability analysis. The evaluation of consequences follows the methodology described in chapters 6 and 7. To keep the computational intensity reasonable, the case study restricts to the evaluation of joint failure consequences within a single subnetwork. For this case study, the same subnetwork is used as when evaluating the impact of the mode and destination choice effects as presented in chapter
9.4. Case study

Figure 9.3: Patterns of joint failure consequences

Figure 9.4: Case study work flow

Furthermore, only scenarios with two links in failure at the same time are considered for simplicity and also to obtain a first idea of the change in consequences.
The approach of this case study is visualised in Figure 9.4. Based on the demand redistribution patterns of single link failure scenarios irrelevant joint failure scenarios are excluded. For the remaining joint failure scenarios, the consequences of joint failure are assessed. Those results are then used to apply the incremental cost-benefit evaluation suggested above. In absence of any information both on the natural hazard exposure and the actual failure probability, it is assumed each link has the same probability of failure. No further information on the cost of protection measures is available. Therefore, the comparative cost-benefit analysis is restricted to a prioritisation of protection measures based only on failure consequences. To describe the probability of joint failure a simple model is used: the distance between the centroids of two link is featured in an negative exponential function (Equation 9.7). By employing different parameters defining the decline of probability based on the distance, the stability of the results tested.

\[
P(i \cap j) = e^{-\beta \cdot d} \tag{9.7}
\]

with:

\(\beta\) \hspace{1cm} \text{parameter,}

\(d\) \hspace{1cm} \text{distance in kilometers between the two links.}

### 9.4.2 Results

**Comparison between joint and single link failure consequences** The considered subnetwork contains 551 links to be evaluated for single link failure consequences. According the combinatorial rules, this results in 151,525 possible scenarios with two links in failure mode at the same time which need to be evaluated. For 104,913 of the scenarios (69.2%) the traffic redistribution effects do not interact wherefore the risk evaluation leads to the same results as if only the single failure risk was considered, regardless the probability of joint failure. However, for the remaining 46,612 scenarios the failure consequences were evaluated by the adaptive approach presented above. Traffic assignment was run if the cluster of either one of the two links was *trunk / main road* or *motorway*. The failure consequences are measured by the logsum term including mode choice (Equation 5.9).

The resulting joint failure consequences follow, as the single failure consequences, a lognormal distribution with mean and variance of
9.4. Case study

Figure 9.5: Additional consequences through joint failure

9.44 and 2.01 (single failure consequences 8.53, 1.23). Based on its parameters the two distributions are statistically different (t-test value 7.78, while $t(0.99, \infty) = 2.32$) and the joint failure consequences are on average higher, as expected.

However, given Equation 9.3, the network risk only increases if the inequation $CI_{i,j} > (CI_i + CI_j)$ is fulfilled, i.e. the joint failure consequences are bigger than the sum of the two relevant single failure risk (Pattern a and b). Figure 9.5 shows the distribution of the variable given by $CI_{i,j} - (CI_i + CI_j)$. In 14.0% of the cases the joint failure consequences exceed the sum of the respective single failure consequences. However, due to the log, those 14.0% are important in real terms. Assuming equal probability for all joint failure consequences, the term $\sum_{j:i \neq j} CI_{i,j} - (CI_i + CI_j)$ is positive indicating an underestimation of the network’s vulnerability if only single failure scenarios are considered.

This indicates that the neglect of joint failure might lead to an underinvestment in infrastructure protection measures on those links that serve as an alternative if other links are in failure. The scale of the underinvestment is dependent on two factors: the absolute difference in consequences and the probability of the respective joint failure event.
**Priorisation of protection measures**  As there is currently no methodology available to indicate joint hazard probability based on hazard maps, no information about the actual joint failure probabilities for the employed subnetwork is available. Therefore, the effect of neglecting joint failure when prioritising natural hazard protection measures are tested based on the deterministic assumptions of joint failure probability as described above (Equation 9.7). Thereby, also the effect of different $\beta$-parameters is tested. Figure 9.6 shows the probability of joint failure dependent on the distance between two links for different $\beta$-parameters: the higher the values of $\beta$ are chosen, the less relevant become joint failure scenarios and the more the joint failure prioritisation solution is expected to converge to the single link failure solutions.

Figure 9.7 plots the marginal value of failure protection measures based on single against joint failure assessment. To keep the figure clear, for each series only the 100 links with highest value of marginal protection (based on joint assessment) are plotted. As expected, the prioritisation obtained with a $\beta = -2$ is closest to the single link failure scenarios. However, the value of $\beta$ does not affect the variance of the different solutions but the intercept of the marginal value of protection measures.

Except for one outlier, the prioritisation is, at least for first few ranks, fairly consistent between the single and joint link failure assessment.
This is an important finding as in practice the actual indication of single and joint failure probabilities is subject to a certain bias. Furthermore, infrastructure managers are more likely to have a certain budget attributed for the implementation of hazard protection than to be able to realise all protection measures with cost-benefit ratio above 1.0. The single outlier is detected independently of the employed $\beta$-parameter. This outlier is the Lake Bridge of Lucerne which is the most important of three bridges over the river Reuss dividing the town of Lucerne in two parts of about equal importance. If only single link failures is considered, the link’s failure consequences rank as 23th out of the 551 links. However, as it is the principal detour alternative in case of other link failure as described by pattern B (see Figure 9.3), the link’s availability is crucial in case of failure of several other links.

9.5 Conclusion

In this chapter the problem of evaluating joint link failure has been defined. The main challenge is to cope with the number of joint failure scenarios with supposably different failure consequences which need to
be considered for a comprehensive vulnerability assessment. Based on
the mathematical formulation of possible difference between single and
joint link failure assessment, a methodology which employs the demand
distribution patterns caused by single link failure to reduce the number
of relevant joint failure scenarios has been developed.

Since currently no indication of actual joint link failure probabilities
can be derived from natural hazard maps, a distance-based measure has
been employed to evaluate the relevance of considering joint link failure
in a case study. By applying a gradual approach to evaluate the impact of
single link protection measures, one link that serves as principal detour
alternative in case of several other single link failure scenarios has been
detected as being the most effective protection opportunity.

However, the employed approach required the evaluation of several
thousands joint failure scenarios, despite of the restriction that only two
links are subject to failure at the same time has been restricted to two and
that only a subnetwork of the actual SNTM is employed in the case study.
Potential to facilitate joint failure assessment for larger networks and
more complex failure interrelations is considered in three areas. First,
it is expected that the indication of actual joint failure probability based
on hazard would alleviate the number of potentially relevant scenarios
considerably. Second, the omission of joint failure scenarios with com-
paratively low occurrence probability is considered to scale down the
number of scenarios while not causing significant bias. The similarity
of the solutions obtained with different \( \beta \)-parameters supports this ar-
gument but further analysis to demonstrate this more comprehensively
is recommended. The deterministic, distance-based formulation of joint
failure probability could be replaced with a stochastic model; for exam-
ple with a Monte Carlo simulation that draws from a distance-informed
joint probability density function. Last, a heuristic that identifies reliably
the joint failure scenarios that cause the highest consequences based on
some parametrisation of the redistribution patterns presented in Figure
9.3 might also have the potential to facilitate joint failure assessment.
Chapter 10

Summary and outlook

The overall aim of this dissertation was to develop a methodology that allows the assessment of indirect consequences of road network failures that, on both be used the enhance infrastructure management system by the inclusion of network vulnerability and be performed with reasonable computational effort. To this end, the dissertation focussed on three different issues: the development of an adaptive failure consequences assessment, the estimation of a statistical model and the evaluation of the relevance of joint failure scenarios when prioritising natural hazard protection measures. Following the structure given by these three issues, this chapter gives an overview about the results of the work presented from a more global point of view. Based on this, ideas for future research directions are presented.

10.1 Adaptive failure consequences assessment

It has been demonstrated that based on network and transport demand characteristics, a meaningful link typology with respect to their potential of inducing failure consequences can be obtained based on cluster analysis. For each of those clusters, a separate strategy for failure consequence assessment was developed. Both key assumptions, the use of subnetworks and the omission of assignment for links with low demand, have been successfully validated for the case of the Swiss National Transport Model. Since the concomitant decrease of computation intensity is massive, a network-wide assessment of single link failure consequences including mode and destination choice effects becomes feasible. As transport demand models usually employ simplified networks that do not cover all actually existing detour alternatives, an overestimation
of failure consequences can occur. Such bias is strongly correlated to the detour distance. Since the number of links with substantial detour distance is manageable even for a national network, the availability of alternative local detours can be systematically checked and, if necessary, the network locally amended. Furthermore, it became apparent that the initial state of system is of vital importance. In Switzerland, for example, mountain passes are closed during winter affecting the network topology considerably. Since the probability of natural hazard is also expected to vary according to the season, it is recommended to include such information when expanding infrastructure management systems by vulnerability analysis.

However, the application of the four step transport demand models for failure consequence analysis has limitations. Link failure that leads to a cutoff of some network parts will result in suppressed or, depending on the expected failure duration, postponed demand. Four step transport demand models are not suited to adequately capture such effects but only multi-day activity scheduling would provide a sound methodological framework. However, currently such activity scheduling models are only about to be developed (Märki et al., 2011) and yet have not been validated.

Although the adaptive failure consequences assessment enabled the inclusion of congestion, mode and to some extent destination choice effects, the computational intensity is still considerable. Further potential is considered in the application of a multi-path algorithm (Bell, 2009) which has been developed for risk averse vehicle navigation. Since such an algorithm provides several paths that may be optimal assuming some uncertainty of link availability, its application has certainly the potential to refine the adaptive failure consequences assessment further which may result in a more precise indication of the need to run assignments and the network area to be covered for vulnerability analysis. Furthermore, the analysis is restricted to evaluate failure consequences for individual transport and does not or only partly include failure impacts on freight and public transport. While the assessment of failure consequences on freight transport can analogously be implemented as for passenger transport, vulnerability analysis of public transport is more demanding: Public transport needs to be considered a multi-layer system composed by rolling stock, road and rail network, electric power grid and drivers. For each layer possible sources of failure need to be defined and its impact to other system parts to be evaluated to define the failure state of the whole system. Such analysis is the topic of a current PhD project at IVT (Dobritz, 2011). Only based on comprehensive analysis of the overall
system state, the demand reaction can be evaluated. However, given the relevance of public transport in serving travel demand and the potentially much higher number of failure states, the need for the development of computationally less intensive failure consequence assessment methodologies is apparent. At the same time, such simplified methodologies are likely to be less precise and need to be validated.

10.2 Statistical modeling of indirect consequences

Although the proposed model does not allow to indicate possible failure consequences with high precision given the overall model fit, the results are still relevant for vulnerability analysis. First, the application of the model permits obtaining a first indication of a network’s vulnerability structure with considerably lower requirements in terms of data availability and computational effort than the adaptive failure consequence assessment proposed in Chapter 6. Second, the inclusion of vulnerability into infrastructure management systems requires also the indication of failure probability. Based on the available methods, such indication on a network-wide level is usually only measured using coarse ordinal scales rather than absolute numbers. Hence, it would be appropriate that both components have similar levels of accuracy.

The model, however, employs data of a today out-dated transport model. An update based on the results presented in Chapter 7 has the potential to validate the results. Furthermore, the scope of dependent variables could be expanded and include failure consequences that reflect mode and destination choice effects. Though, further variables such as the prevalent trip purpose of the traffic normally traversing the failed link might be required to facilitate such model expansion.

The sample of the presented statistical model includes all available cases. If only a random sample were used, the results could be validated with the remaining cases. Additionally to the analysis of the error term, such an approach might provide further insight about the model’s strengths and weaknesses. In the same vein, it would be interesting to evaluate the model’s performance when applied to other transport networks. Thereby, especially the model’s sensitivity to network typology in terms supply and demand structure would be of relevance. Finally, the application of advanced estimation methodologies that account for the diverse statistical distributions of both the dependent and independent variable, such as Bayesian interference modeling, is considered to
provide potential for improvement when modeling failure consequences. Equally, the methods of spatial statistics should be employed.

### 10.3 Relaxing simplifying assumptions in vulnerability analysis: joint failure assessment

The assumption of single link failures is rather restrictive and especially challenged by threats that are caused by one extreme natural event. The main challenge is the number of potential scenarios that arise when relaxing the assumption of single link failure and allowing that two or more links are in failure state at the same time. Due to the combinatorial principles, the number of possible scenarios increases exponentially with the number of links that are assumed to be subject to joint failure.

Based on the mathematical formulation of possible differences between single and joint link failure assessment, a methodology which employs the demand distribution patterns caused by single link failure to reduce the number of relevant joint failure scenarios has been developed. Still, the number of scenarios that needed to be evaluated in the presented case study was substantial which makes room for further improvement: Joint failure consequences follow a log-normal distribution with only a few joint failure scenarios having very large consequences. Therefore, great potential is considered in the development of a heuristic that identifies reliably the joint failure scenarios that cause the highest consequences based on parametrisation of the redistribution patterns of single link failures. Further potential to decrease the number of relevant joint failure scenarios is also expected in development of methodologies that allow the indication of joint risk probabilities.
Acknowledgement

I would like to thank my family and friends, who have always supported me throughout my academic career. A very special thank you belongs to my beloved partner Lilia, who was incredibly patient with me. Especially during the last months, when I spent many nights and weekends on my research while she took sincere care of lovely Ellen. In addition, this dissertation would not have been possible without the following important contributions.

Assistance and Guidance  Prof. Dr. Kay W. Axhausen, my thesis advisor, gave me great guidance during my research. Generally granting a lot of freedom during my research, he also ensured that the more promising research directions were indicated well. Prof. Dr. Mike Bell, helped me to see the research topic from different viewpoints and was very helpful in terms of reviewing my work.

Philipp Fröhlich and Milenko Vritc helped me understanding the methodology of the Swiss National Transport Model and were always answering both my naive and more advanced questions of operating Visum.

Michael Balmer built up the \LaTeX- environment with which numerous IVT publications including this thesis were set. Most impressively, he got hardly tired helping me out with problems when setting up papers. Nadine Schuessler and Kirill Müller maintained IVT’s BibTeX database and repeatedly ironed out my at times hair raising mistakes.

Last, but certainly not least all current and former team members of IVT who contributed to the good work environment I enjoyed so much.

Funding  This dissertation was partly funded by the National Research Programme 54 of the Swiss National Science Foundation.

Input Data  The Swiss Federal Office for Spatial Development (Bundesamt für Raumentwicklung; ARE) provided the current versions of the Swiss National Transport Model. Indications of network densities have
been computed with well appreciated help of Michael Löchl from IVT at ETHZ.

**Computational Resources**  The major part of the computation for this work was performed on IVT’s computation server “ngatik,” Adrian Zaugg and Bernhard Riegel did a great job maintaining the server and helping out in case of problems of any sort. Prof. Dr. Kay W. Axhausen has organised the provision of sufficient licenses of the software Visum.
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