Assessing Infrastructure Vulnerability to Sudden Events

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Abstract:

Over the past twenty years, numerous infrastructure management systems have been developed to address gradual failure modes. Unfortunately the management of sudden failure modes within large infrastructure systems (principally: natural hazard induced failures) have not been systematically addressed. This is particularly an issue within liberalized public-private partnerships where the management of and liability for natural hazard vulnerabilities evolves in time.

This paper details a methodology for determining an infrastructure system’s vulnerability to sudden events which 1) assesses a component’s failure potential by superimposing natural hazard and infrastructure network data and applying simple standardized structural failure models and 2) quantifies the cost of a system’s post-failure consequences by calculating the infrastructure system demand redistribution costs. The set of potential failure links are then prioritized as a function of their respective vulnerabilities – their failure potential multiplied by the associated consequences.

Through applying this methodology within a public-private partnership, the public entity can assess and prioritize the infrastructure objects with respect to their vulnerabilities and can thus require the private entity to reduce infrastructure vulnerability, where warranted, by implementing specific mitigation activities or to operate the system within maximum acceptable vulnerability levels. The private entity can likewise quantify and appropriately price their liability to natural hazards. The example herein presented is the application of this methodology to assess a transportation infrastructure network’s vulnerability to avalanche hazards.

Key words: Transportation system, vulnerability, failure assessment, consequence assessment, infrastructure management

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1. INTRODUCTION

1.1 Management of Transportation Infrastructure

Infrastructure systems, such as transportation infrastructure systems, are composed of links connecting geographically dispersed communities, towns and cities. When these systems operate as designed, they form the foundation upon which commerce, trade and the serviced communities’ well-being can flourish. But when the availability of these systems is jeopardized by gradual deterioration (e.g. corrosion induced deterioration) or natural hazards (e.g. avalanche induced link failure), the communities they service can likewise suffer. This potential impact is so great that even the threat of transportation system service interruption can induce the serviced populations to publicly protest or even relocate. Managing and mitigating the impact of the last two risk sources, namely gradual deterioration and natural hazards has been delegated, by default, to the engineering community.

Over the past twenty years great strides have been made to address gradual deterioration of infrastructure objects (e.g. roads, bridges, tunnels), whose progression is extended over multiple decades. The signs and indications of these slow deterioration processes can only be identified and quantified through detailed criterion-based inspections and evaluations. Unfortunately the shear scale of modern transportations systems makes this a formidable task. For example, the federal, state and local roadway systems in the United States of America are comprised of over 6.3 million km of roads and the paved Swiss roadway system is comprised of 161,000 km of roads.

To meet this need, civil engineers have developed infrastructure management systems (IMSs) to collate inspection data, model and predict future deterioration processes, and develop optimal infrastructure management approaches. Example IMSs include PONTIS, developed in conjunction with United States Federal Highway Administration (FHWA) for managing the United States highway infrastructure.

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6 While these total roadway lengths do appear to be considerably different, the road to citizen ratio is almost identical with 47.7 and 46.9 km/citizens respective for the United States of America and Switzerland.
bridges, and KUBA, developed by the Swiss Federal Roads Office to manage road structures on the Swiss Federal Highway System.\textsuperscript{8,9}

1.2 Approaches to Funding Development

Through implementing infrastructure management systems, one can develop optimized management approaches for various foreseeable funding levels and predict the resulting performance. With this funding-performance linked information, engineers can approach political decision makers and infrastructure owners with hard, transparent evidence documenting the implications of their funding policies. Such transparent management approaches can help to induce improved investment in transportation infrastructure. But unfortunately the hidden signs of deterioration combined with semi-rigid taxation and budgeting structures can undermine the political motivation for increasing infrastructure funding resulting in the out-right denial of such funding requests. Thus, it is common for such funding requests to only be fulfilled in the aftermath of a significant deterioration related component failures as were the cases in the British railroad management policies following deregulation-linked deterioration and the Minnesota highway system management following the recent Minnesota I-35 bridge collapse.\textsuperscript{10,12}

Outsourcing infrastructure investment to private entities through Public-Private Partnerships (PPP) can circumvent this funding and budgeting hurdle, but adds an additional actor to the process of transforming observed deterioration indicators into optimized management policies. In particular, attempting to implement such policies within a PPP environment can lead to further complications including unequal investment and risk mitigation motivations stemming from the incongruent stakeholder temporal and stakeholder expected performance perspectives. Long-term performance-based management approaches can bridge the PPP owner-contractor separation through specific risk-

\begin{thebibliography}{9}
\bibitem{12} The Economist. 2007. America’s creaking infrastructure – a bridge too far gone. August 9.
\end{thebibliography}
transferring contractual structures including issuing long-term franchises and concessions or by including long-term risk-mitigation benchmarks and requirements directly in the contract documents.13

1.3 Existing Approaches to Failures Caused by Sudden Events

The management of potential natural hazard induced infrastructure failures has not enjoyed a comprehensive or system-wide management perspective. The most common approach is to conduct localized or regional transportation natural hazard risk assessment and mitigation projects, commonly following natural hazard events, resulting in localized management and mitigation approaches. A number of large-scale systematic risk assessment initiatives, including Risk Map Germany14 and Riskscape New Zealand,15 are under development but one platform, the Hazards U.S. Multi-Hazard (HAZUS-MH), developed under the direction of the United States Federal Emergency Management Agency (FEMA), has been implemented for systematically assessing risk from a national viewpoint. But rather than considering specific structures and thus developing specific mitigation recommendations, HAZUS-MH estimates the scope and magnitude of potential losses across geographic regions produced by earthquakes, floods and hurricane induced winds.16 This inability to accurately quantify the infrastructure system elements’ vulnerability to various natural hazards has forced transportation managers to employ a post-event ‘repair following failure’ approach to maintaining the transportation system connectivity.17 This myopic approach leads to general underinvestment in transportation infrastructure natural hazard mitigation activities. Unfortunately when such natural hazard induced transportation network failures occur, the well-being of the affected communities is jeopardized as were the cases in the recent natural hazard induced failures of the German and Swiss train systems.18,19 To move towards more accurately funding and managing

2. MANAGEMENT OF TRANSPORTATION INFRASTRUCTURE INCLUDING VULNERABILITY

A recent Swiss project is working to rectify this vulnerability gap by developing a methodology for determining an infrastructure system’s vulnerability to sudden events. The methodology employs a two branched approach – a civil engineering branch in which assesses a transportation system’s potential failure zones given the documented natural hazard loads and a transportation engineering branch which models the impact of traffic redistributions resulting from potential transportation link failures – Figure 1.

![Vulnerability Assessment Project Structural Diagram](image)

In Figure 1, one can observe that initially a subset of the entire transportation system – the transportation network data – is selected for analysis. This information is used to extract the component data which in combination with the natural hazard data is used within the civil engineering module to identify potential failures. The transportation engineering module then employs transportation network data and the identified potential failures to assess the consequences for each failure state. These failure consequences are multiplied by the potential link failure data to calculate the link vulnerability. This two-branch methodology assesses the location of potential link failures, models the resulting traffic redistribution consequences and calculates the vulnerability of the given component.

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19 Swissinfo. 2007. Heavy rain brings chaos across Switzerland. August 9.
2.1.1 Potential Failure Assessment – General Procedure

This project proposes a four-step procedure to assess the potential failure of the infrastructure objects that make up a transportation network – by answering namely:

1. Is the infrastructure object in question in a geographical area that is exposed to the given hazard load?
2. Is the component affected by the hazard load of a given magnitude?
3. What extent of damage does the hazard load of a given magnitude inflict upon the given structure?
4. What duration and type of service interruption does this extent of structural damage result in?

These questions are answered by employing hazard load-structure combination assessment approach.

2.1.2.1 Component Potential Failure Assessment

To conduct a comprehensive failure analysis, the infrastructure manager must first collect key natural hazard assessment data and transportation network structural data. Transportation network and component data can commonly be located within the associated transportation agency’s files and is comprised of transportation link topographic information and specific structural data. The process of collecting natural hazard data is more complicated, for the engineer must reach out beyond his standard realms of operation and engage natural hazard assessment laboratories and government entities. A surprising amount of natural hazard assessment data has been collected and formulated within the past 20 years, but even when this data is readily available, little has historically been actively employed by the infrastructure management community.

2.1.2.2 Natural Hazard Data Sources

The natural hazard assessment data is commonly separated into three detail and accuracy-based classifications – maximum magnitude natural hazard indication maps, return-period linked hazard identification maps and a database of pervious natural hazard events. Hazard indication maps are large scale maps (1:25000) detailing the regions exposed to a maximum possible event (return period exceeding 1000 years) but do not provide a quantifiable
probability nor event intensity information. Thus hazard indication maps can only be employed to
determine if a component is exposed to a given hazard.\textsuperscript{20} Hazard identification maps are small scale
(1:5000) maps detailing the relative hazard load intensities and are developed for four different return
periods (30, 100, 300 and 1000 years). Within Switzerland,
each canton has been required to produce the hazard
intensity maps for the seven different hazard loads by
2011.\textsuperscript{21} Although the given maps will not be completed for
another four years, this project is employing predefined
hazard loading classes to respectively evaluate the potential
failure of the various structures. Lastly a natural hazard
event inventory documents previous natural hazards and
their associated damage. The Swiss version is (StorMe)
which contains over 17,500 entries.\textsuperscript{22} Where such a database
is actively employed and maintained, the infrastructure
manager can gain a good understanding for the actual natural hazard occurrence probability and
potential impact.

2.1.2.3 Transportation Infrastructure Data Sources

The geographic infrastructure data, including the extent, type and location of the various transportation
links, can be extracted from GIS vectorizations of the respective transportation network and within
Switzerland this geographic vectorization is conducted at a scale of 1:25000.\textsuperscript{23} If a given structure is
exposed to a hazard, key structural information can then be extracted from pre-existing infrastructure

(FOEN).
\textsuperscript{22} Eyer, W. 2007. Rapport explicatif: Cadastre des événements StorMe. Service des Forêts et de la faune, Canton
de Fribourg.
management databases. Within Switzerland such a system for the Swiss Highways System is KUBA which details the structure’s type, key dimensions, design date and construction date.24

2.1.2.4 Potential Failure Assessment

These various data sets are employed in unison to respond to the four analysis questions. 1) A geographic coincidence analysis is conducted between the hazard and component geographic information to determine if the component in question is exposed to the given hazard. 2) If the component is found to be exposed to the given hazard, the pre-defined hazard load magnitudes and key structural information are employed to determine if the component is affected by the potential loads. 3) If the component is found to be affected by the given loading, the post-loading structural response and associated level of failure is calculated. 4) Lastly, if the component experiences a failure, the service interruption duration is estimated from expert opinions and previous documented failures (StorMe). The length of each potential failure and the percentage of each link that experiences failure are then calculated. This failure information is then exported to the transportation engineering consequence assessment module.

2.2 Consequence Assessment

The transportation engineering consequence assessment module focuses on quantifying the actual state of transportation infrastructure following a potential link failure and the impact these failures have on the community.

2.2.1 Existing Consequence Assessment Approaches

Previous consequence studies used primarily two methodologies to assess post-failure consequences: Professor Bell has used a game theory approach and described the problem as a 2-player, noncooperative, zero-sum game between a router, seeking a least-cost path, and a virtual network tester, seeking to maximize single link failure trip-cost.25,26 Within this approach, the objective is to determine the network elements with the largest post-failure consequences. However, when failure

consequences are assumed to be traffic-dependent, which is the case within transportation systems, this approach becomes very calculation and time intensive and thus is only applicable to small networks.

A second approach incorporating both the demand and supply side of traffic assignment was recently used to assess failure consequences. The various applications differ mainly in the used type of traffic assignment: Jelenius et al. (2006) neglects the travel time traffic dependency completely. Furthermore, they do consider situations where some parts of the network are completely cut off from the main network. Jelenius et al. argue, in their study of the Swedish transportation system, that link capacity plays only a minor part of road vulnerability analysis for most parts of the country studied (Sweden) is sparsely populated and increased congestion resulting from link failures is only a minor problem. This might be a reasonable assumption for spatially disperse countries but Knoop et al. showed the importance of including capacity constraints when analyzing transportation network post-failure consequences in more densely populated areas by studying Rotterdam.

The bulk of the recent research has considered mode choice and demand as static within the consequence assessment, thereby assuming that each individual would continue life as normal and only change their route choice in the face transportation link failures. The inclusion of mode choice and demand modeling is also neglected within these studies for they would greatly increase the required calculation complexity and would offer only a minor increase in resulting accuracy.

However, the required computational time is still a major constraint of implementing traffic assignment models, even when failure consequences assessment considers are only route changes for every failure scenario has to be calculated separately. For example, the calculation time for one equilibrium assignment of the Swiss road network, which includes over 20’000 links, takes about 30

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minutes on a high performance desktop computer (Xeon 2.4 Mhz, 2 Gb Ram).\textsuperscript{29} Thus alternative approaches have to be developed before these methods can be generally applied across the network. These calculation limitations have also identified by members of the research community who have attempted to describe and forecast the high-consequence parts of a network with various indicators. These indicators include different measures of volume, volume/capacity ratio, the number of paths over a link, spillback figures and step functions to ensure less traveled but topologically important links are considered. Unfortunately the correlation and rank order tests between these indicators and the full assignment assessments have showed no link failure consequence assessment approach.

2.2.2 Post-Failure Consequence Assessment

From the previous research findings and from studying existing transport network model characteristics,\textsuperscript{30,31,32} the methodology for assessing consequences is segmented in two sections: 1) cut link and 2) demand redistribution assessments.

For the cut link assessment (1), the public and private transport networks are merged in order to detect cut links whose failure results in unsatisfied demand. In this merged network two cut-link scenarios are differentiated: 1.1) Only one transport system is linking the community to the rest of the network and a failure completely segregates this community from the network. 1.2) A community is served both by the rail and road networks and a failure in one network produces a cut-off in only one mode, thus the community can employ the mode still in operation to travel to the rest of the network. The economic assessment for the cut-off scenarios necessitate specific and sophisticated regional economic analysis for each scenario, a task beyond the scope of this project. In place of these sophisticated analyses, an assessment approach of cut-off link detection and application of a representative unsatisfied travel demand values is implemented.

\textsuperscript{29} Currently traffic assignment software packages do not support parallel computing.
\textsuperscript{30} ARE. 2006. Erstellung des nationalen Personenverkehrsmodells für den öffentlichen und privaten Verkehr – Modellbeschreibung, Swiss Federal Office For Spatial Development (ARE), Berne.
\textsuperscript{31} ARE. 2006b. Quell-Zielmatrizen im Personenverkehr für das Jahr 2030, Swiss Federal Office For Spatial Development (ARE), Berne.
\textsuperscript{32} ARE. 2006c. Perspektiven des schweizerischen Personenverkehrs bis 2030, Swiss Federal Office For Spatial Development (ARE), Berne.
The consequences of the traffic demand redistribution (2) is quantified by assessing additional travel times, quantifying the associated travel expenses and consideration of the willingness to pay for travel time savings.33,34,35,36

2.2.3 Potential Simplifications Applied within the Swiss Roadway System

The Swiss National Road Transport Model contains 19’304 links within Switzerland. This network can be simplified for consequence analyses by removing non-junction nodes. However, after this simplification there are still 17’861 links present whose failures each can evoke different results. As the goal of this project is to provide comprehensive failure consequence figures, the calculation time constraints require a more sophisticated methodology than just calculating the full assignment for every failure scenario. The methodology employed herein is a topological pre-analysis of failure prone links. It is assumed that the post-failure demand distribution strongly depends on the topological characteristics, which are a function of the demand origin and destination distribution paths crossing the given link under normal network conditions and the ability of the surrounding network to absorb this post-failure redistributed demand. This approach significantly enhances previous attempts by forecasting the post-failure consequences with volume/capacity based measures.37,38

For example, Figure 2 and Figure 3 respectively show the traffic re-distribution after the failure of the Gotthard-Tunnel and a major Geneva motorway bypass. The Gotthard-Tunnel serves distant origin and destination demands and has few alternative routes (the capacity is limited to the Gotthard pass route which is closed most of the year or the San Bernardino route). By contrast, a link failure in a dense network, like around Geneva, results in mainly local effects as multiple alternatives are present.

33 This has already been extensively evaluated within Switzerland and has resulted in the Swiss norm 641 822.
The figures for the overall delay time and additional travel distance reinforce these findings (Figure 2 and Figure 3). Although nearly three times the number of vehicles are rerouted during an average day for the Geneva case, the additional total travel time is around 50% less than for the Gotthard case. Even more explicit are the figures of additional travel distance, which are a product of the spatial spread of the detour paths.
As calculation time of traffic assignment model increases quadratically with the network size and the post-failure redistribution reach in dense networks is highly spatially limited, the use of subnetworks comprised of only the infrastructure elements within a given perimeter around the failure site turns out to be very effective simplification approach. Subnetworks consider transit demand as well as interior demand and therefore deliver comparable assignment results. Figure 4 compares the sub-network and full-network failure assessment for the Geneva motorway link in terms of additional travel time. The absolute largest deviation (link ‘447’) may be explained as a border effect, for this links is the first motorway after the Swiss-French border and the French network is not as finely modeled as its Swiss counterpart. The deviations mapped at the bottom left side of the diagram are also of minor concern, as these links have only minimal failure consequences. With a calculation time 30 times shorter than the full assignment model, the use of subnetworks appears to be a powerful alternative for post-failure consequence assessment in regions with dense infrastructure. However, further research has to be conducted, to develop a generalized automated measure for determining whether a full- or a subnetwork assessment approach is most appropriate.

A further assessment methodology of employing spatially statistical information is believed to be applicable for modeling the traffic redistribution of low traffic demand routes in more rural regions. As network topology and the demand structure in such regions follow similar patterns, the intention is
to establish a statistical model describing the relationships between the independent variables capacity, demand and network topology and the dependent variable link consequence potential.

2.3 Vulnerability Assessment

With the potential link failures and the associated consequences assessed, the calculation of vulnerability is rather straightforward. Within this methodology, vulnerability has been defined as the multiplication of the probability of failure by the associated consequences. Thus the vulnerability of a given failure is assessed by multiplying the probability of failure by the associated consequences.

3. Gotthard Route Avalanche Vulnerability Case Study

To gain a further understanding for the processes and results of the infrastructure potential failure assessment, post-failure consequence assessment and vulnerability calculation methodologies, consider the possible hazard zones associated with avalanches occurring within the drainage basin on the northern end of the Gotthard Route, Figure 5. Within this region, the roadway network serves two key needs – 1) facilitating a principal north-south European roadway link through the Swiss Alps and 2) providing the only transportation access to a number of small mountain villages and towns.

Figure 5: Considered roadway infrastructure system (orange) and the Gotthard Route (magenta)

3.1 Potential Failure Assessment

To conduct this potential failure assessment, the available key natural hazard and transportation network structural data must be collected. As is commonly the case in large-scale failure assessments,
not all of the desired data is available. In this case, only the hazard indication maps for avalanches, detailing the range of the geographic maximum possible avalanche events and the geographic roadway network data, detailing the extent, type and location of the various transportation links, are available for the entire considered roadway network. The avalanche hazard indication maps were developed by the Swiss Federal Office of the Environment (FOEN) by assessing the local elevation, slope, snowfall and topography to determine where avalanches can form and the extent to which they can flow. In Figure 6 one can observe the shear scale of the avalanche zones and the number of different infrastructure links potentially affected by avalanches. Within this transportation network, the roadways are assumed to have a zero resistance against avalanches and thus when snow or other debris from an avalanche crosses a roadway the roadway experiences a complete failure (i.e. defined in this case as roadway closure).

Figure 6: Considered infrastructure network (orange) and avalanche indication map (red)

The other components within this infrastructure network, the galleries, tunnels and bridges, are assumed to have a complete resistance against avalanches. Thus when an avalanche intersects these components, it is assumed that the snow and debris crosses over or under the given component without compromising the element’s structural integrity or the operation of the associated link. Thus the transportation network is vulnerable to avalanches only where the given avalanche zones cross the studied roadways.
The results of these resistance constraints can be visually seen in Figure 7 where the intersections between the avalanche zones (red) and the roadways (orange) – the potential failure locations – are highlighted in light green. What is of particular interest is that the areas that have already been hardened against avalanche loads, either intentionally or unintentionally, by passing the road through a tunnel, under a gallery or over a bridge. This can be seen in the lower left hand corner of Figure 7 where the avalanche zone intersects the Gotthard A2 highway extending from north to south. Initially the Gotthard highway is a roadway and therefore exposed to the potential avalanches, but as it passes through a tunnel and then over a bridge, it is evaluated as being non-failure prone to the potential avalanches. Additionally, these potential failure locations can be summarized and documented in a tabular form based on their respective link code.

Table 1: Failure prone road link summary in tabular format

<table>
<thead>
<tr>
<th>Link ID</th>
<th>Object Type</th>
<th>Original Length (m)</th>
<th>Failure Prone Length (m)</th>
<th>% Failure Prone</th>
</tr>
</thead>
<tbody>
<tr>
<td>253</td>
<td>Gotthard Route (N.)</td>
<td>5264</td>
<td>1423</td>
<td>27 %</td>
</tr>
<tr>
<td>663</td>
<td>Gotthard Route (S.)</td>
<td>167</td>
<td>167</td>
<td>100 %</td>
</tr>
<tr>
<td>666</td>
<td>Gotthard Route (S.)</td>
<td>3118</td>
<td>1283</td>
<td>41 %</td>
</tr>
<tr>
<td>7722</td>
<td>Gotthard Access Rd</td>
<td>319</td>
<td>300</td>
<td>94 %</td>
</tr>
<tr>
<td>7723</td>
<td>Gotthard Access Rd</td>
<td>4002</td>
<td>1961</td>
<td>49 %</td>
</tr>
<tr>
<td>7724</td>
<td>Gotthard Access Rd</td>
<td>707</td>
<td>459</td>
<td>65 %</td>
</tr>
<tr>
<td>7728</td>
<td>Gotthard Access Rd</td>
<td>3379</td>
<td>3379</td>
<td>100 %</td>
</tr>
<tr>
<td>18556</td>
<td>Maderanertal Rd</td>
<td>2018</td>
<td>669</td>
<td>33 %</td>
</tr>
<tr>
<td>18557</td>
<td>Maderanertal Rd</td>
<td>934</td>
<td>934</td>
<td>100 %</td>
</tr>
</tbody>
</table>
Representative link data including the original link length, the associated potential failure link length to avalanches and the total percentage of each link that is prone to failure can be calculated. Such data for 9 links of the total 108 failure prone links in this case example are included in Table 1. This potential failure link information can be exported to and summarized within a common spreadsheet program.

3.2 Accessing the Post-Failure Consequences

To demonstrate the link failure consequence assessment methodology on the surrounding transportation system, the potential consequences of these 9 links are assessed. As the links 18557/18558, 7722/7723/7724 666/663 are connected with non-junction nodes, the network simplification merges these 7 links into three segments, as shown in Figure 8. The potential failures in the Maderanertal valley (the right facing segment) act as cut links and thus lead to unsatisfied demand.

![Figure 8: Local failure prone links presented within the Swiss National Road Transport Model](image)

However, as the Maderanertal is not modelled as a separate traffic demand zone, the transport model reports zero unsatisfied demand. This leads to the conclusion that in cases of unsatisfied demand, the use of geographically more detailed data may be necessary. For this case study, it has been assumed that 300 citizens of Maderanertal are directly affected by this link failure.

For each of these segments it has to be decided whether a full network or a subnetwork assessment is most appropriate. This is accomplished by calculating the demand origin and destination path lengths.
which normally transverse these links, the link demand under normal conditions and the surrounding
network topology (Table 2). The average Gotthard Route link path lengths clearly indicate that
alternative routes may be present beyond the immediate adjacent links, the traffic redistribution
assessment needs to employ a full network assignment. For the Gotthard Access Road, the deviated
traffic demand is easily absorbed by the motorway, minimizing congestion problems and making a
subnetwork simplification a potentially viable option. Both full and sub-network assignments are
calculated and compared (Table 3). Table 3 confirms that a subnetwork simplification approach is
viable for the Gotthard Road Links.

Figure 9 supports the findings presented above by showing that when the northern Gotthard Route
(link 253) fails the majority of the demand switches to the Gotthard Access Road. However, the
reduced subnetwork additional travel distance (Table 3) indicates the post failure full assessment most
probably includes wide ranging detours.

<table>
<thead>
<tr>
<th>Link Number</th>
<th>Object Type</th>
<th>Avg Path Length [km]</th>
<th>Normal Loading (ADT)</th>
<th>Local alternatives available?</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>253</td>
<td>Gotthard Route</td>
<td>484.4</td>
<td>17949</td>
<td>Present, some capacity constraints</td>
<td>Full assignment</td>
</tr>
<tr>
<td>663/666</td>
<td>Gotthard Route</td>
<td>483.5</td>
<td>17997</td>
<td>Present, some capacity constraints</td>
<td>Full assignment</td>
</tr>
<tr>
<td>7722/7723/7724</td>
<td>Gotthard Access Rd</td>
<td>29.3</td>
<td>344</td>
<td>Present</td>
<td>Subnetwork assignment</td>
</tr>
<tr>
<td>7728</td>
<td>Gotthard Access Rd</td>
<td>14.0</td>
<td>949</td>
<td>Present</td>
<td>Subnetwork assignment</td>
</tr>
<tr>
<td>18556/18557</td>
<td>Maderanertal Rd</td>
<td>300 people cut off</td>
<td>not present</td>
<td>Cut Link detection</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Gotthard Link Failure Assessment Results

<table>
<thead>
<tr>
<th>Link Number</th>
<th>Full Assessment</th>
<th>Subnetwork assessment</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Add. Travel Time [h/day]</td>
<td>Additional Travel Dist [km/day]</td>
<td>Add. TT [h/day]</td>
</tr>
<tr>
<td>253</td>
<td>1080</td>
<td>11431</td>
<td>1117</td>
</tr>
<tr>
<td>663/666</td>
<td>1296</td>
<td>28795</td>
<td>1361</td>
</tr>
<tr>
<td>7722/7723/7724</td>
<td>26</td>
<td>2997</td>
<td>23</td>
</tr>
<tr>
<td>7728</td>
<td>58</td>
<td>11153</td>
<td>57</td>
</tr>
</tbody>
</table>
Table 4 lists the failure consequences in financial terms for the different road sections. One can observe that the costs associated with additional travel time are much higher than those caused by the additional travel distance. For the failure consequence assessment this indicates that the accuracy of additional travel time calculations should be more precise than for travel distance calculations.

<table>
<thead>
<tr>
<th>Link Number</th>
<th>Full Assessment</th>
<th>Costs per Unit</th>
<th>Overall Cost [CHF/d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>253</td>
<td>1080</td>
<td>11'431</td>
<td>19.37</td>
</tr>
<tr>
<td>663/666</td>
<td>1296</td>
<td>28'795</td>
<td>19.37</td>
</tr>
<tr>
<td>7722/7723/7724</td>
<td>26</td>
<td>2'997</td>
<td>19.37</td>
</tr>
<tr>
<td>7728</td>
<td>58</td>
<td>11'153</td>
<td>19.37</td>
</tr>
</tbody>
</table>

3.3 Calculating Vulnerability

The vulnerability of each segment is then calculated by multiplying the failure probability (1) by the total segment failure consequence cost. From this it can be seen that the vulnerability of the southern segment of the Gotthard Route (links 663 & 666) to the avalanche hazard is higher than the vulnerability of the northern segment of the Gotthard Route. Likewise the two Gotthard Route segment vulnerabilities far exceed the Gotthard access route and the Maderanertal Road.
vulnerabilities. Thus the Gotthard Route (N & S) should be prioritized over the Gotthard Access Roads and the Manderanertal Road vulnerabilities even in the face of potential cut links and unsatisfied demands.

Table 5: Segment vulnerability assessment

<table>
<thead>
<tr>
<th>Link Number</th>
<th>Segment Name</th>
<th>Failure Probability</th>
<th>Consequences (CHF/d)</th>
<th>Vulnerability (CHF/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>253</td>
<td>Gotthard Route (N)</td>
<td>1.00</td>
<td>25948</td>
<td>25948</td>
</tr>
<tr>
<td>663 &amp; 666</td>
<td>Gotthard Route (S)</td>
<td>1.00</td>
<td>37765</td>
<td>37765</td>
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<tr>
<td>7722, 7723, 7724, 7728</td>
<td>Gotthard Access Rd</td>
<td>1.00</td>
<td>1826</td>
<td>1826</td>
</tr>
<tr>
<td>18556 &amp; 18557</td>
<td>Maderanertal Rd</td>
<td>1.00</td>
<td>6021</td>
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</tr>
</tbody>
</table>

4. CONCLUSION

Managing infrastructure systems is no small feat and from the industry’s experience with managing gradual failure modes, one can see that a systematic and semi-automated management framework is required. When the management scope is enlarged to include managing sudden failure modes (particularly natural hazard induced failure modes) applying a similar systematic framework is necessary. This paper proposes such a semi-automated vulnerability assessment methodology to compute the component failure probability, the associated consequences and the component vulnerability. Within public-private partnerships, specific vulnerability mitigation activities or maximum acceptable vulnerability levels can be included in the PPP contractual documents to achieve a more uniform investment and risk mitigation motivations across the various stakeholders.

The proposed methodology can be further refined within the potential failure branch by developing and employing natural hazard identification hazard maps and by conducting a detailed component failure potential assessment. On the consequence branch, the considered network can be minimized by using the average path length and the local residual capacity with only a minor reduction in accuracy but additional test cases are needed to define the general indicator path length and circumjacent infrastructure threshold levels. Likewise, research is also needed to quantify the economic impact of unsatisfied demand before it can be directly compared against traffic redistribution costs.

ACKNOWLEDGEMENTS

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