ASSESSING THE RESILIENCE OF TRANSPORTATION SYSTEMS IN CASE OF LARGE-SCALE DISASTROUS EVENTS

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Abstract. So far, only a few studies analyzed the topological and operational disaster resilience of transportation networks, i.e. the ability to maintain transport services even in case of severe disastrous events. This paper presents the disaster resilience analysis results gained for the Swiss railway network (standard gauge) and Zurich’s tramway network. For both networks, the infrastructure topology and the planned operational state such as predefined line paths, line frequencies and capacity limitations of both, stations and tracks were modeled. A disaster resilience analysis and failure spreading simulation tool was implemented using the „R“ software environment for statistical computing. The transport network subsystems „Infrastructure“ and „Traffic Operation and Management“ according to the European directive 2008/57/EC were implemented in order to statistically and numerically analyze the ability to maintain transportation operability in degraded operation due to hazardous events.

The resilience analysis of the infrastructure topologies successfully showed that they share the topological features of the so-called „scale-free networks“: They are highly robust against the failure and removal of (uniformly distributed) randomly chosen network elements. Simultaneously, they are very sensitive towards biased failures of specific „important“ network elements. This observation was also made for many other large real-world systems such as technological, biological, computational or social networks.

While the analysis of network topologies alone may be sufficiently detailed enough for assessing the resilience of most real-world networks, public transportation system resilience analysis additionally has to pay attention to the planned operation state. This study quantifies several operational consequences of blockaded stations and tracks such as rerouting and truncation of lines. The results indicate that the topological importance of stations and the operational one often do not coincide: While in most analysis so far, usually high-degree nodes are considered to be „most important“, for transport networks operational data is essential for finding the most critical elements.

Keywords: public transport systems, disaster resilience analysis, R-software programming, simulation and visualization of blockades, system performance, scale-free networks, planned and degraded operation.

1. Motivation and goals

Throughout the world, societies depend on large-scale, man-made systems supplying nutrition, energy, health, information and transport (Kröger 2008). The non-availability of these critical infrastructures induces immense societal and economic consequences. Transport networks may become non-available due to either planned or unplanned service disruptions. Planned disruptions can be large construction works, while the set of unplanned ones comprises various social, technical and natural hazardous events (Figure 1). There are general hazards threatening many real-world systems and railway-specific ones.

This study focuses on severe hazardous events that may cause failures of entire stations or blockades of connections. All topology elements are in binary states: They can either be used for operation or not.

The paper presents the resilience results for the Swiss railway and Zurich’s tramway network. For both networks, their infrastructure topologies and operational data for planned operation were modeled: Nodes represent stations that are linked if there is a direct connection between them without any intermediate other modeled station. Both, nodes and links may fail due to severe hazardous events such that they are removed from the network. Not only topological dynamics but also operational consequences were analyzed such as the transport services in degraded operation, where lines may either be truncated or rerouted.

The study aims to assess the topological and operational consequences of large-scale failures, to anticipate order of failures and to suggest resilience enhancements for increasing the disaster resilience. This paper summarizes some first results of the PhD-thesis „Railway network stability and the spreading of disastrous events causing system-wide blockades“, written at the Institute for Transport Planning and Systems (IVT). It is sponsored by the Swiss National Science Foundation (SNF).
2. Railway transport subsystems

The railway system is modeled as a multi-level network comprising a set of structural and operational subsystems. According to the European Directive 2008/57/EC, the railway system can be broken down into operational and functional areas as illustrated in Table 1.

For assessing the disaster resilience, the PhD-thesis models and analyzes the connection of the following subsystems: “Infrastructure”, “Energy”, “Command-control and Signaling” and “Traffic Operation and Management”. This paper presents the results gained for the “Infrastructure” and “Traffic Operation and Management”.

Table 1. Sub-division of the railway system into structural and operational subsystems

<table>
<thead>
<tr>
<th>Structural areas</th>
<th>Operational areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure, Energy, Command-control and Signaling (CCS), Rolling Stock.</td>
<td>Traffic Operation and Management (TOM), Maintenance, Telematic Applications for Passenger and Freight Services</td>
</tr>
</tbody>
</table>

3. The „Infrastructure“ subsystem

When representing the infrastructure topology, nodes mimic stations that are connected if there is a direct connection between them. For the Swiss railway network, the infrastructure is modeled on a macroscopic level such that only larger stations are considered. The following data are implemented: adjacency matrices, coordinates of the modeled stations and track lengths (in kilometers). The represented and implemented Swiss railway infrastructure is shown in Figure 5. Figure 6 shows the corresponding one for Zurich’s tramway network.

4. The „Traffic Operation and Management“ subsystem

The representation of the Traffic Operation and Management subsystem (TOM) displays operational aspects such as line paths in planned operational state and additional information such as the time needed for traveling along a link, the track lengths (in minutes) and capacity utilization threshold values such as the theoretical and the operational capacity threshold.

The theoretical capacity utilization value expresses the maximal number of vehicles that may use a specific station or link within a given time interval. This maximal theoretical threshold value is reduced by considering buffer times that allow to run lines stable (operational capacity limit). The TOM subsystem hence considers that - unlike the resilience analysis for many real-world networks such as the Internet or social networks - the predefined line paths and capacity restrictions have to be followed, even in degraded operation as close as possible.

5. Other modeled subsystems („Energy“ and „CCS“)

For railway transport, beside the infrastructure topology and operational key data, the „Energy“ subsystem and the „Command-control and Signaling“ (CCS) subsystem are represented. For the „Energy“ subsystem, substations, railway-owned power plants and the railway high-voltage grid are modeled as 2D-networks.

The „CCS“ installations ensure safe and efficient utilizations of the infrastructure. „CCS“ nodes represent local interlocking devices that are connected with the controlled and signaled infrastructure elements. On the dispositive level, local interlocking devices are connected and supervised by centralized traffic control centers.

Figure 2 illustrates how the overall transport systems are modeled and implemented in the disaster resilience analysis tool: The „Energy“ and „CCS“ subsystem are connected with the infrastructure network via specific interfaces. The „TOM“ subsystem represents (planned) train movements and train service on the infrastructure.
This paper summarizes the results gained for the “Infrastructure” and “TOM” subsystem.

6. Modeling statements and scale-free networks

The implemented tool allows simulating and quantifying the topological and operational consequences of (single or multiple) node or link removals. „R“ is an open-source software and provides basic methods for assessing the topological key data of networks such as transitivity values, node-degree distributions and average shortest path lengths. Other transport-specific features were added. The results verify that both case study networks share the topological of „scale-free networks“, which are characterized by:

- Small average shortest path lengths even for networks comprising many network nodes,
- High degree of regularity, typically measured by the clustering coefficient or transitivity value,
- Existence of hub nodes: High-degree nodes are likely to exist with positive probability.

Scale-free networks are highly robust against the non-biased removal of uniformly randomly chosen nodes. Simultaneously, they are highly sensitive to the biased removal of „important“ nodes. Usually, the degree of a node – that is the number of adjacent nodes – is used to determine the importance of a node. However, also its centrality or betweenness - the fraction of shortest paths connections using a node or link - and other centrality measures can be used to assess the topological importance of a node.

In the implemented tool, the failure of a station causes the removal of the corresponding node and its incident edges. Removing the corresponding link from the infrastructure topology represents failures of a single connection. In the topology analysis for the „Infrastructure“ subsystem, these removals imply changes of several topology parameters that are measured. For the „TOM“ subsystem, the removals cause dispositive measures for degraded operation such as rerouting or truncation of lines. Table 2 shows which potential internal and external failure events may cause node or link removals.

Table 2. Potential failures that may cause node or link removals

<table>
<thead>
<tr>
<th>Potential failures</th>
<th>Internal failures</th>
<th>External failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Errors (non-biased)</td>
<td>Railway accidents (derailment…)</td>
<td>Natural hazards, accidents at level crossings</td>
</tr>
<tr>
<td>Attacks (biased)</td>
<td>Malevolence: Strike, revenge, sabotage, but also maintenance works</td>
<td>Malevolence such as terrorist attacks</td>
</tr>
</tbody>
</table>

All calculated results are gained using the „igraph“ package that allows to efficiently analyze networks even for very large instances, especially with respect to topological network features such as centrality measures, connectivity parameters and distance measures. It can also be used for visualizing graphs. The implemented disaster resilience analysis and failure implemented phases: data specification (case study network data), disaster resilience analysis and failure spreading simulation methods and the visualization of the results.

The entire concept of the applied methods, working steps and their purposes are depicted in Figure 3. This paper focuses on „Step 1“ and „Step 2“. The arrows indicate both, working steps as full lines, which represent concrete working progress and implemented functions of the tool. Dashed lines show more general proceedings of the PhD-thesis. The last column reveals the purpose of an analysis result.

7. Quantification of the disaster resilience

Formally, the disaster resilience is the ability of social units such as organizations to mitigate hazards, to contain the effects of disasters when they occur and to carry out recovery activities in order to minimize social disruption and to mitigate the effects for potential future disasters (Bruneau et al. 2003). This concept is adapted for assessing the disaster resilience of public transportation systems (⇒ Figure 4). The resilience concept considers prevention, intervention and recovery.

The prevention phase aims to increase the ability of systems to withstand the impacts of disastrous events on the system performance before such an event occurs. Systems should be designed in a way such they are maximally robust and the impacts on the system performance are minimized.

The intervention phase tries to suggest appropriate strategies to positively influence the disaster spreading process during the impacts of them. Catastrophe management and anticipating order of failures are example for intervention measures.

After the occurrence of a disastrous event, large parts of the system may fail such that even the entire network might blockade. Recovery strategies try to regain operability as fast as possible. Usually, recovery measures induce much higher costs than preventive ones. Ex-
periences made in a recovery phase can be used to enhance the disaster resilience before a next occurrence.

The disaster resilience considers four different aspects that are shown in Table 3.

<table>
<thead>
<tr>
<th>Table 3. Disaster resilience elements</th>
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<tr>
<td>Resilience element</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Robustness</td>
</tr>
<tr>
<td>Redundancy</td>
</tr>
<tr>
<td>Resourcefulness</td>
</tr>
<tr>
<td>Rapidity</td>
</tr>
</tbody>
</table>

In graph theory, a network is robust (or error tolerant) if it contains a giant cluster comprised of the majority of network nodes even after a large fraction of its nodes are removed (Albert et al. 2002). Here, a system is robust if the system performance remains at high levels, even in degraded operation. The initial reduction of the system performance when a failure occurs serves as a measure for both, the robustness and redundancy (Fig. 4). The curve of the system performance in temporal dimension is referred to as the „resilience triangle”.

Disaster resilience can either be quantified by measuring the size of the resilience triangle („Approximation 1”) or by measuring the following three values („Approximation 2”): initial impact of a disastrous event, minimal system performance value (a failure may spread and further decrease the system performance) and the moment, when pre-disaster system performance is regained.

8. Visualization of the analyzed transportation networks

Figure 5 shows the representation of the Swiss railway network as implemented in the disaster resilience analysis tool and gives an example of the visualization of a transport network in the „R” software environment. The corresponding illustration of Zurich’s tramway network is shown in Figure 6. Both illustrations contain larger nodes representing a specific subset of nodes: For the Swiss railway system, larger stations where trains may end in degraded operation are highlighted. For Zurich’s tramway network, terminal loops are marked, that have to be at the end of degraded line paths.

Fig 5. Representation of the analyzed Swiss railway topology (standard gauge)

Fig 6. Representation of Zurich’s tramway topology

9. „Infrastructure“ resilience analysis results

The topological analysis of the infrastructure resilience can give a deeper insight in the network processes (Newman 2010). It is the goal to understand the system dynamics, the distribution of flows and the system performance in both, normal and disturbed state. When analyzing the infrastructure topology, line paths are not considered. Instead, shortest path connections are established such that the number of intermediate stops is minimal. Table 4 shows the number of nodes and links for both
analyzed transportation networks as well as the basic topological key values.

The values for the „global efficiency“, „local efficiency“ and „costs“ refer to (Latora et al. 2002). The cost value indicates the fraction of edges present relative to the maximal number of edges that could exist. For both topologies the values are very small, a feature also observed for the Boston underground transportation system. The efficiency values are gained by dividing the geographic distances between any two stations and the shortest path distances in the network between the nodes. For totally connected networks with direct tunnels between all stations, both values coincide (efficiency value becomes 1). (Latora et al. 2002) shows that transportation networks have high global efficiency values while simultaneously being much less efficient on the local level - that is in the subgraphs of the neighbors of a node. This implies that failures of nodes or links may have severe operational impacts on the local level.

<table>
<thead>
<tr>
<th>Topological key parameter</th>
<th>Swiss railway (standard gauge)</th>
<th>Zurich’s tramway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>783</td>
<td>175</td>
</tr>
<tr>
<td>Edges</td>
<td>883</td>
<td>188</td>
</tr>
<tr>
<td>Size [km]</td>
<td>3’716</td>
<td>73</td>
</tr>
<tr>
<td>Mean degree</td>
<td>2.26</td>
<td>2.15</td>
</tr>
<tr>
<td>Mean distance</td>
<td>28.3 hops</td>
<td>13.6 hops</td>
</tr>
<tr>
<td>Diameter</td>
<td>96</td>
<td>32</td>
</tr>
<tr>
<td>Transitivity</td>
<td>0.080</td>
<td>0.045</td>
</tr>
<tr>
<td>Global efficiency</td>
<td>0.678</td>
<td>0.686</td>
</tr>
<tr>
<td>Local efficiency</td>
<td>0.030</td>
<td>0.015</td>
</tr>
<tr>
<td>Costs</td>
<td>0.0001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Both topologies share the topological features of scale-free networks: The networks have small average shortest path lengths and high regularities compared to their random graph equivalents. The degree distribution $P(k) \sim k^{-\gamma}$ decays as a power law $P(k) \sim k^{-\gamma}$ with exponents $\gamma = 3.1$ for the Swiss railway network and $\gamma = 3.0$ for the VBZ tramway network. For most large-scale real world networks the values range between 2 and 4. From the knowledge about other real-world networks with similar characteristics, it can be concluded that the systems are vulnerable for the biased removal of the important nodes, while simultaneously being robust against uniformly distributed ones. This is verified in the following.

Figure 7 shows the effects of successively removing nodes from the Swiss railway topology on the giant cluster size. Uniformly distributed removals are referred to as „random“ removals. Biased ones focus on the degree of a node or its betweenness centrality („BC“), either in the pre-disaster network (called „static“) or the (current) degraded one (denoted as „dynamic“). The effects of the removals on the average shortest path lengths within the largest connected component relative to pre-disaster level are visualized in Figure 8. All figures show the high robustness against removals of randomly chosen elements.

The curve of the system performance for increasing values of removed nodes is depicted in Figure 9. The system performance considers the decreases of the giant cluster size and the relative changes of the average shortest path lengths in the degraded networks by multiplying the relative changes of both.

As an example for the visualization of the calculated results, for the Swiss railway network the nodes whose removal causes the largest decreases of the system performance are shown in Figure 10. Removing large nodes causes more severe reductions of the system performance.
of the „Infrastructure“ subsystem. Thick edges are contained in many shortest paths.

![Fig 10. Most important network nodes with respect to the system performance of the degraded network (Swiss railway infrastructure network)](image)

10. Measuring the „TOM“ (operational) resilience

So far, the analysis of the infrastructure subsystem resilience considered all available route alternatives for degraded operation. However, shortest paths do not always coincide with pre-defined line paths that have to be kept. Generally, there are two basic operational measures for degraded operation: The failure of a link or station may cause lines to be locally rerouted and/or to be truncated. Figure 11 shows the entire set of implemented operational measures for degraded operation.

![Fig 11. Dispositive measures for degraded operation implemented in the „R“ disaster resilience analysis tool](image)

The „TOM“ system performance has to consider additional measures compared to the infrastructural one. In degraded operation, the connectivity or the capacity utilization may be reduced. Figure 12 shows the values used for measuring the operational consequences of disastrous events on the transport operation and how they are combined.

![Fig 12. Quantification scheme for the system performance for infrastructure resilience and „TOM“ subsystem resilience](image)

The consequences of failures on the capacity utilization in the degraded network consider:
- Sum of additional track-kilometers per line in degraded operation,
- Number of additional vehicles needed for degraded operation,
- Additional edges utilized above theoretical threshold value,
- Additional edges utilized above operational threshold value.

11. „TOM“ resilience results

Figure 13 shows the comparison of the capacity utilizations of tracks in planned and degraded operation if lines are rerouted or truncated according to the scheme illustrated in Figure 11. Thick edges are of high importance for rerouting lines.

![Fig 13. Comparison of capacity utilization in planned and degraded operation for Zurich’s tramway network](image)

A visualization of the locations of the corresponding stations and links where both value differ significantly is depicted in Figure 14. It can be seen that there are stations whose importance significantly increases if operational aspects are considered. Hence, topological analysis is not sufficient for assessing the consequences of failures in networks, where flows have to follow pre-defined line paths such as in transportation networks.
The analysis results help to identify the most critical network elements from an operational point of view.

Fig 14. Operational importance of stations and connections of Zurich’s tramway network

12. Next steps

The next steps of the PhD-thesis are:

- Represent „Energy“ and „CCS“ devices and measure the consequences of failures of those units on the operational system performance.
- Suggest, implement, and quantify the effects of resilience enhancements.
- Verification of the results by real-world scenarios.

13. Conclusions

The Swiss railway system and Zurich’s tramway system were modeled, represented, and implemented in order to assess their disaster resilience - that is the ability to withstand disastrous events causing the failure of stations or a blockade of tracks. Two different aspects of the disaster resilience can be analyzed: the infrastructural one that does not consider any operational data such as line paths, track and station capacities and frequencies of the lines. On the other hand, the operational resilience can be assessed giving information about how, to which extent and where the system performance is reduced in degraded operation. Also the routes that are important for rerouting lines and alternative line paths can be identified.

Both analyzed infrastructure networks share the topological features of scale-free networks: they are highly robust against the uniformly distributed removal of randomly chosen nodes and links. Simultaneously, only a very few „important“ nodes and links, i.e. high-degree nodes, nodes or edges with high centrality values, may destabilize the infrastructure networks, such that the network disintegrates and shortest path lengths are significantly enlarged.

If operational aspects are considered, the importance of some edges and nodes may be changed such that some stations become important for operations that are not necessarily also important for the infrastructural network and vice versa.

The introduced scheme of how to measure the system performance in both, normal and degraded operation allows to categorize the network elements according to the effects of their failure on the operation in disturbed state: The failure of elements may either primarily affect the connectivity of the network, the capacity utilization of the network, both simultaneously or none of them significantly. The implemented tool can calculate alternative paths in degraded operation and measure several aspects such as the number of additional track kilometers used or the number of vehicles needed for operating all lines, for all potential single or multiple failures. Additionally, for each station or link blockade can be determined if lines can still be operated or not, or whether they are truncated or have to be rerouted.

This information can be used for anticipating the consequences for even multiple failures and for quantifying the disaster resilience of networks. This may be helpful for enhancing the disaster resilience and to test several counteractions.

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