Methodology for assessing the structural and operational robustness of railway networks
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Motivation
Railway networks are critical infrastructures whose non-availability induces immense financial, societal and economic impacts on a national level. The study introduces a method for assessing the structural and operational robustness of railway networks if threatening events such as social, technical or natural hazards occur. But also long-term construction works can put stations or tracks out of service.

Recent robustness studies for other systems solely focus on the structural impacts of removing nodes or links from the networks. This has impacts on the connectivity of the topologies and typically the robustness is quantified by measuring the dynamics of basic topological parameters. This is not sufficient for assessing the robustness of railway networks, since operational data such as line path restrictions has to be considered in both planned and degraded operation. The developed model calculates such states mimicking real-world dispatching efforts and measuring to which extent railway operation is degraded.

Goals and purpose
The study provides essential information to decision makers about the impacts of threatening events on railway transport, which also improves customer information:
- Identification of most critical elements, important rerouting corridors
- Information where to focus protection efforts and the location of emergency units
- Simulation of degraded operation states and their visualisation
- Knowledge about factors contributing to the robustness of the network
- Prioritization of investment efforts and anticipate consequences of reconstructions
- Improve preparedness and recovery times

Methods
Figure 1 shows the structure of the study and the applied methods. Railway networks are represented as multi-level networks comprising several subsystems (Figure 2). Beside the infrastructure topology, operational data such as link capacities, line paths in planned operation and potential turnaround stations are specified. The Control-command and Signalling and Energy subsystem are integrated.

A robustness analysis tool implemented in R allows to manipulate railway networks, to calculate degraded operation states (capacity thresholds of rerouting alternatives are considered) and to measure the extent of degradation combining multiple operational parameters such as the number of served stations or the number of trains.

Application and Verification
The developed method is applied to the Swiss railway network and the tramway system in Zurich in the years 2006 and 2025. For all networks, the impacts of removing single or multiple nodes or links are quantified and compared. Concrete cases are simulated in a sensitivity analysis.

Results
Specific results were discussed with the VBZ for verifying the implemented procedures for calculating degraded operation states that mimic real-world dispatching decisions. The study shows that existing methods for measuring the robustness of networks are not suitable for assessing the impacts of threatening events on railway networks and operational data has to be considered. The front page shows the results, if each node is removed from the Swiss railway network (standard gauge). Summed up over all such removals, red links are less utilized in degraded operation. Green edges are more often traversed and hence are important rerouting corridors. The robustness of all networks can be enhanced, e.g. by adding edges or turnaround alternatives.

Applied Software
R software, igraph package

Contact
Robert Dorbritz, ETH Zurich, Institute for Transport Planning and Systems, HIL F 14.1, Wolfgang-Pauli-Strasse 15, CH - 8093 Zurich, Switzerland

www.ivt.ethz.ch/people/robertdorbritz@ivt.baug.ethz.ch
+41 44 633 68 16