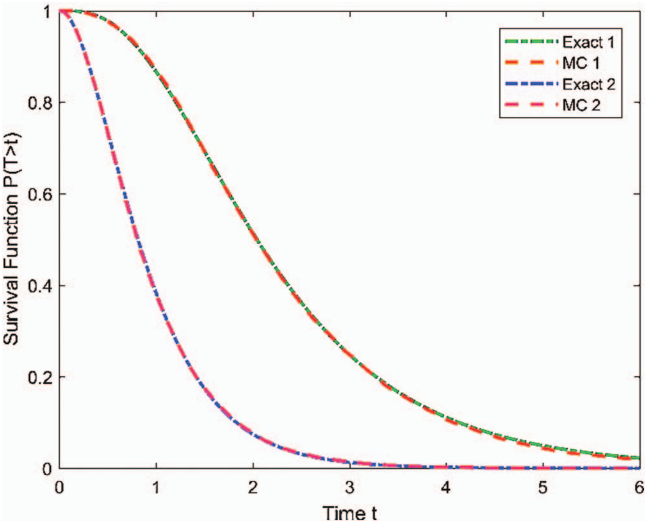

Figure 6. Reliability of the two networks calculated both analytically and numerically

In line with the previous examples, another set of failure times is generated for the dependent failure. For the dependent nodes, the dependent failure times of network 1 are taken also for network 2 if they are smaller; as an example

$$t_{2.24} \sim \min(Exp(\lambda_{2.24}), Exp(\lambda_{1.3})) \qquad (4\text{-}7)$$

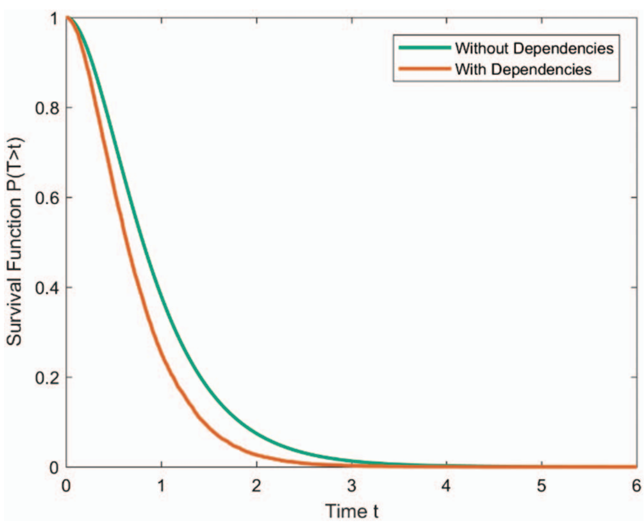

Figure 7. Reliabilities of network 2 with and without dependencies on network 1

The resulting network reliability is shown in Figure 7. It is interesting to see that a reliability analysis of the first network is not required to analyze network 2. In fact, it is sufficient to generate the failure times for network 1 and impose them on the dependent components in network 2. Not having to analyze both interdependent networks together is a key advantage of this method. In addition, since all failures in network 1 are independent, the reliability of this network remains of course as shown in Figure 6.

The decrease in the reliability of network 2 is a direct representation of the consequences of the failures in network 1. This allows for a quantitative evaluation of the consequences of these failures. If the failures are propagated further into an economic network, the consequences can be quantified in terms of economic loss in a rigorous manner. This paves the way to new type of risk analysis with structured calculation of consequences instead of using heuristic assumptions.

CONCLUSION

This report introduced a novel methodology to asses cascading failures between systems. The survival signature approach has clearly shown its advantages over more classical approaches, providing a numerically efficient way of calculating the reliability of interdependent networks. Most importantly, the structure of the system and its probabilistic information are completely decoupled allowing for an easy integration of complex and realistic failure scenarios. Furthermore, the presented method provides a structured approach for a quantitative analysis of consequences of failures, up to an economic loss for a rigorous risk analysis of complex interconnected systems and networks.

References

Aslett, L. J. M. 2012. "ReliabilityTheory: Tools for structural re-liability analysis." R package. www.louisaslett.com.

Aslett, L. J., F. P. Coolen, and S. P. Wilson. 2015. "Bayesian inference for reliability of systems and networks using the survival signature." *Risk Anal.* **35** (9): 1640–1651.

Buldyrev, S. V., R. Parshani, G. Paul, H. E. Stanley, and S. Havlin. 2010. "Catastrophic cascade of failures in interdependent networks." *Nature* **464** (7291): 1025–1028.

Coolen, F. P., and T. Coolen-Maturi. 2012. "Generalizing the signature to systems with multiple types of components." In *Complex systems and dependability*, 115–130. Berlin: Springer.

Coolen, F. P., and T. Coolen-Maturi. 2015. "Modelling uncertain aspects of system dependability with survival signatures." In *Dependability problems of complex information systems*, 19–34. Cham, Switzerland: Springer.

Coolen, F. P., T. Coolen-Maturi, and A. H. Al-Nefaiee. 2014. "Non-parametric predictive inference for system reliability using the survival signature." *Proc. Inst. Mech. Eng. Part O J. Risk Reliability* **228** (5): 437–438.

Eryilmaz, S. 2010. "Review of recent advances in reliability of consecutive k-out-of-n and related systems." *Proc. Inst. Mech. Eng. Part O J. Risk Reliability* **224** (3): 225–237.

Feng, G., E. Patelli, M. Beer, and F. P. A. Coolen. 2016. "Imprecise system reliability and component importance based on survival signature." *Reliability Eng. Syst. Saf.* **150**: 116–125.

Grigg, C. 1996. "The IEEE reliability test system." Winter power meeting 1996, Paper 96 WM 326-9 PWRS. http://home.engineering.iastate.edu/~jdm/ee553/IEEE-RTS1996.pdf.

Miller, R. G., Jr. 2011. *Survival analysis*. New York, NY: Wiley.

Samaniego, F. J. 2007. *System signatures and their applications in engineering reliability*, 110. New York, NY: Springer.

CHAPTER 5

Enhancing Resilience of Traffic Networks with a Focus on Impacts of Neuralgic Points Like Urban Tunnels

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Abstract: *The European transportation network is the backbone of Europes economic and social collaboration enabling crossnational trading, logistics and mobility. This paper analyses the European transportation network focussing on the socio-economic conditions and on the interconnections between different transportation systems. The whole transportation network can be regarded as a macro-network consisting of several meso-systems such as railway or road. While a resilient network implies the overall functionality and connectivity on the macro-level, resilience and vulnerability necessitate an understanding of the interdependencies on more detailed levels. A framework for the transportation network is developed considering providers and services for the different meso-systems. Furthermore, levels of transportation networks are defined hierarchically. As a real case scenario of random impact at a neuralgic point, the traffic through the airport tunnel at Germanys capital Berlin is analyzed.*

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INTRODUCTION

Industrialised countries are highly depending on a strong traffic infrastructure not only to enable national and international freight transport and logistics but also to meet the growing demands for individual mobility. Each of the traffic systems such as railway, road, water, air transport can be regarded as a meso-level system already showing a high complexity at this level.

Nonetheless, the overall functionality and connectivity of these systems on the macro-level is essential to fulfil the requirements for transportation and mobility of industrialised countries. Hence, the vulnerability of the macro-network cannot be described sufficiently by the resilience of its consisting meso-systems but necessitates a whole and entire understanding of the interdependencies of the different meso-systems. This project aims at enhancing resilience of real world traffic infrastructure modelled as a macro-network consisting of interdependent meso-systems such as railway or road systems. Using real world incidents and modelling their impact on the macro-network can lead to the identification of crucial sections and nodes. Consequently, these model-based variations of the system simulate the reaction to future hazards to conclude in specific measures for the real world traffic infrastructure.

TRAFFIC INFRASTRUCTURE IN GERMANY

Europe's political, economic and social integration is producing a massive increase of passenger and freight transport over the last decades. With respect to density and connectivity a great difference between the provided infrastructures can be observed. For maintaining the European Union`s competitiveness and resources it is essential to mandate a well-running traffic infrastructure. The goal of the Trans-European Transport Networks (TEN-T) is to strongly support the Trans European Internal Market. TEN-T contains of road, railroad, waterway networks, sea and inland ports, airports and terminals. It is built in two phases – the core network (completion in 2030) and the overall network (completion in 2050). Due to the strong economic position and the central location the Federal Republic of Germany plays an important role. Six out of nine corridors in the core network run across Germany as shown in Figure 1.

The North-South axis and the East-West axis of the TNT-T are directly influenced by the performance and operability of the German traffic infrastructure network. Twenty percent of the quantities of goods transported on Europe´s roads run through Germany (Eurostat 2016b).

In addition, Germany's road density with 1.82 km/km^2 is the most dense road system in Europe (USA: 0.67 km/km^2) (Statista 2016b).

Regarding mode share, the road transportation system takes the lead for freight and passenger transportation as shown in the following Figure 2 and Figure 3.

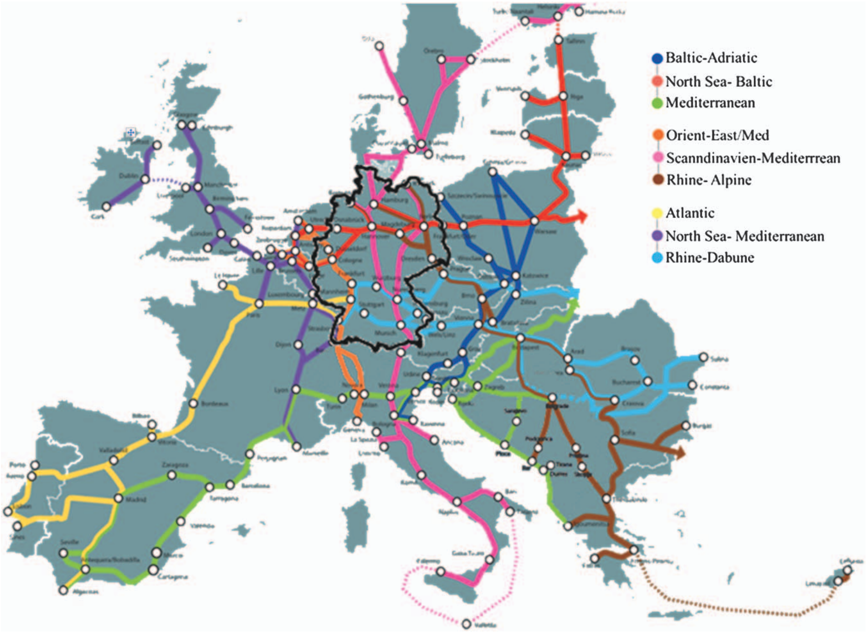

Figure 1. Transeuropean Traffic Transport Networks TEN-T following European Comission 2016

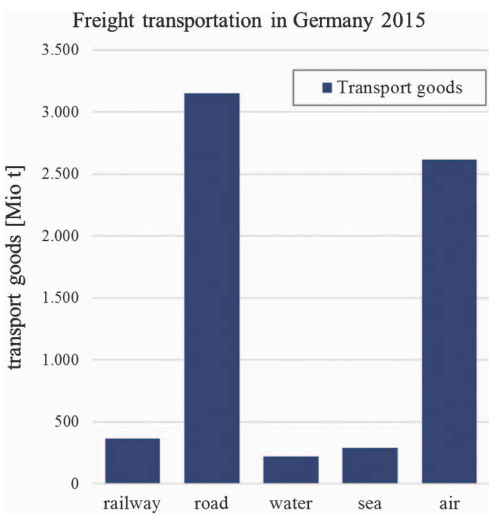

Figure 2. Freight transport in Germany (Statistisches Bundesamt 2016)

In 2015, more than 3 million aircraft movements have been registered in Germany, which corresponds to 33.9% of all 28 European States (Deutsche Flugsicherung 2015).

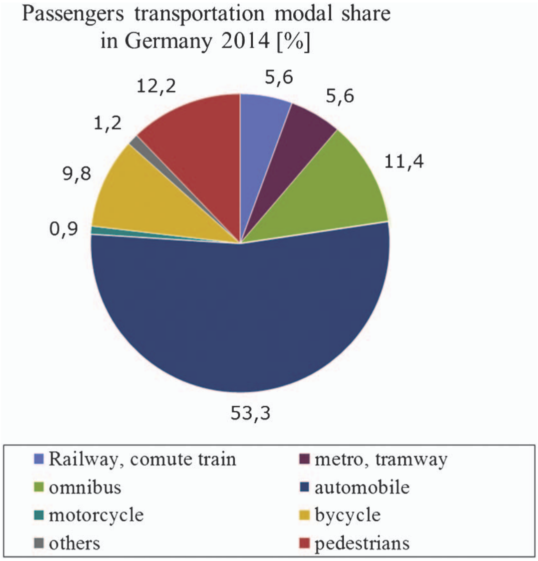

Figure 3. Passenger transport in Germany (Bundesministerium für Verkehr und digitale Infrastrukturen 2016)

The European railway network is 131,168 km long, whereby the German railway network is the longest national network of Europe (38,836 km) and about 25% of the whole European railway system (World Bank 2016, Statista 2016a). Furthermore, with 5,700 Stations and 40,000 trains the German railway system is the most important network of Europe (Deutsche Bahn AG 2016). Especially with a capacity of 112,629 tkm freight transport volume (26.6% of the whole European network and transportation rate of 4.0 bill. people it became one of the most developed and powerful railway network of the world (Deutsche Bahn AG 2016).

The economic and environmental advantage of the usage of waterways is the relative favorable cost per tkm. The German waterway network has a length of 7,350 km, with 75% rivers and 25% water channels (Bundesverband der Deutschen Binnenschifffahrt 2016). In comparison to all 28 European States the length of the German waterway network mounts up to 16.9% of the European network (Statista 2016c). In addition, traffic density is much higher in Germany since 39.2% of European freight transported on water is shipped on German waterways (Eurostat 2016a).

METHODS OF MODELING

Several approaches for investigations on traffic infrastructure derive models focusing on one transport system such as road (Demsar et al. 2008, Mattson and Jenelius 2012, Iida 1999), railway (Angeloudis and Fisk 2005, Liu and Tan 2013, Stoilova and Stoev 2015) or air (Wilkinson et al. 2011). Demsar identified critical locations in a spatial network by applying dual graph modelling with connectivity analysis and topological measures at the street network of Helsinki (Demsar et al. 2008). Derrible et al. used graph theory to compare different subway systems with respect to their attractiveness for people (Derrible and Kennedy 2011). Angeloudis et al. also compared the world´s 20 largest subway systems and give an approximation by an evolutionary network with an associated exponential degree distribution (Angeloudis and Fisk 2005).

Looking at other disciplines, Minor et al. evaluated the connectivity of habitat patches of songbirds by using graph theory to model the fragmented landscape. An interesting work, which can be also applied to infrastructure, is provided by Cornelis et al. using fuzzy weighted graphs to describe shortest paths (Cornelis et al. 2004).

A differentiated and particular picture of modelling traffic infrastructure with different approaches is given by Mattson et al. (Mattsson and Jenelius 2015).

Svendsen et al. give a first approach how to describe interdependencies between completely different networks such as financial services, energy and health care. Due to the various sectors he is not aiming at a flow or exchange between the modelled networks (Svendsen and Wolthusen 2007).

However, the cross-system connectivity and overall functionality of the whole transportation network consisting of different traffic systems is not investigated further. So far, the approaches for modeling infrastructure networks do not focus on how impacts on one traffic system affect other systems. But regarding resilience and vulnerability of traffic infrastructure networks interconnections between different traffic systems are essential and will be taken into account in the following approach.

FRAMEWORK FOR MODELING TRAFFIC INFRASTRUCTURE

Traffic infrastructure systems rail, road, water and air are equally used for the mobility of passengers and the industry for freight transportation. These two dimensions are augmented by providers such as infrastructure owner, infrastructure maintenance, supplier for rolling and mobile stock services as well as influences like regulations and internal/external impacts. For the dimensions transportation system, mobility/logistics and provider/influences a framework is defined by the Cuboid Transportation Network. The Cuboid forms the basis for investigating resilience of the holistic transportation network and impacts on socio-economic structures.

A comprehensive model of traffic infrastructure includes the multidimensional dependencies described by the Cuboid Transportation Network (Figure 4). Furthermore, for modeling traffic infrastructure consisting of different systems it is essential to define a clear hierarchy allowing comparability with respect to the required level of detail.

As shown in Figure 5 the real-world traffic infrastructure can be regarded as a macro-network consisting of interdependent meso-systems. Each of the traffic

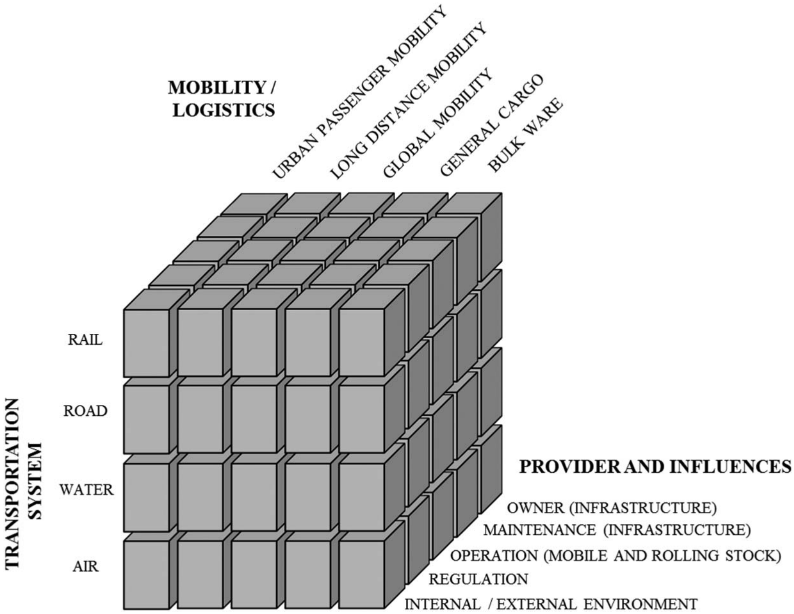

Figure 4. Cuboid Transportation Network with multidimensional dependencies

systems such as railway, road, water or air transport can be regarded as a meso-level system with their own specific characteristics. These transport systems can be divided in different micro-level systems with respect to their specific characteristics such as

- Importance: urban, regional or national
- Ownership: governmental, state-run, city-level or private
- Technique: e.g., overhead catenary, third rail, light rail, not electrified or train gauge

Hence, the segregation at the micro-level depends on the focus and aim of the investigation. The systematology allows degrees of freedom within the classification, while the principle hierarchy defines a precise borderline to ensure comparability. With regard to bottlenecks single structures on the nano level need to be described more closely such as tunnels or bridges within the road system or locks and ship lifts within the water system. Thus, their impact on higher level systems and on the whole network can be evaluated.

In order to develop an adequate model of the macro-network, heavy impacts, which have already occurred at meso-level traffic systems, are analysed with respect to their implication on the macro-level. There are different ways to quantify the performance of the infrastructure network on the macro level. In case of passenger transport, one of the main optimization goals is to reduce the summation of traffic time of all individuals. A traffic infrastructure system could

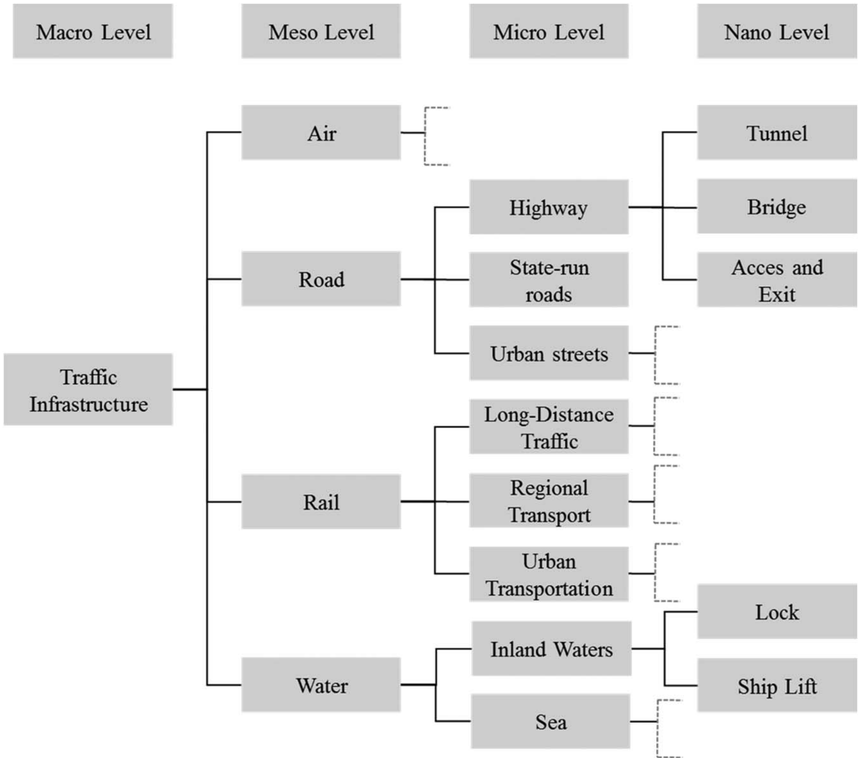

Figure 5. Traffic infrastructure hierarchy

be described the more resilient, the less the increase of the overall travel time of the individuals, caused by impacts on a lower level, is. The same applies for goods of the industry, to keep the supply chain going. Another aim, especially important for freight traffic, could be to reduce the overall cost to move through the network.

Examples for impacts on the meso level are the Icelandic Ash Cloud in 2010, where the Eyjafjallajökull volcanic eruption effected a collapse of the European air traffic leading to overcharge road and railway systems. Another example is the simultaneous strike of German train drivers and pilots in 2014. The strike concerned in the first place only air transport and railway respectively but had enormous effects on the macro-network in all meso-systems. It culminated in an economic struggle of specific industry branches when supply chains collapsed due to overload of the truck transportation system with congestions on the roads and simply a lack of sufficient trucks.

As shown by these examples there is already a high complexity in single systems which is exponentially growing by the connection of the systems to a holistic infrastructure network.

Designing resilient structures or finding solutions for resilient design requires the identification of network sensitives. Using real world incidents and modelling