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ENHANCING THE RESILIENCE OF REAL-WORLD INTERDEPENDENT TRAFFIC SYSTEMS

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Industrialized countries are highly depending on strong traffic infrastructure networks. This is not only caused by increasing national and international freight transport and logistics, but also due to a growing demand for individual mobility. Each of the traffic systems such as railway, road, water or air transport is showing already a high complexity if evaluated separately. The whole infrastructure network can be described at a macro level, consisting of different traffic systems on the meso level. In order to model the linkage between different traffic systems on the meso level, graph theory is used in a specific way. The traffic flow is described with an origin-destination matrix, containing information about capacity and traffic loads. This forms the basis for simulating the consequences for each system of exceptional impacts like natural hazards or technical problems on elements of another system. Identifying critical points or bottlenecks in the different traffic system lead to an enhanced resilience of the overall network on the meso level and to a description of an optimal state of operation in dependence on the boundary conditions. This includes specific measures for the different systems such as bypass on critical system nodes, inter-system connections on crucial points or defined traffic plans for the state of emergency.

Keywords: Resilient infrastructure, interdependencies of traffic systems, origin-destination matrix, critical points in infrastructure systems.

1 Introduction

Traffic infrastructure is of immense importance in public infrastructure systems. Mobility fosters structural transformation and allows spatial, economic and political integration. It guarantees the citizen´s individual mobility and freight logistics. Furthermore, it improves the location quality and enhances the region´s competitive position with impacts for production, services and employment. Traffic infrastructure as prerequisite for mobility, enables specialization and division of labor and thereby increases national economy productivity. To design a reliable infrastructure network, which resists climate change and technical related impacts, it is essential to understand the dependency between the different traffic systems. Examples for impacts are the Icelandic Ash Cloud in 2010, where the Eyjafajallajökull 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 but had enormous effects on the complete network in all 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. Several approaches for investigations on traffic infrastructure derive models focusing on one transport system such as road, railway or air. (Klemt-Albert et al. 2017) 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. In the following approach resiliency with respect to infrastructure networks includes characteristics like capacity of the traffic systems, vulnerability towards hazards as well as conjunctions between different traffic systems.

2 Relevance of Research

2.1 Classification of Infrastructure Systems

Infrastructure is an extensive term with several meanings. Infrastructure is known as the system, which facilitates the supply of energy, flow of goods, telecommunication as well as the waste management for a country, an area, or an organization. It is typically also used for the technical components like streets, bridges, pipes or further special buildings. The following definition is based on the traffic infrastructure and the interlinkage between different traffic infrastructure systems. The traffic infrastructure network can be divided in different meso-level, micro-level an nano-level systems with respect to their specific characteristics such as importance (urban, regional or national), ownership (governmental state-run, city-level or private) and 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.

2.2 *Traffic infrastructure as the backbone of economy*

As shown by the introducing examples there is already a high complexity in single systems, which grows exponentially 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 their impact on the macro-network leads to the identification of crucial sections and their influence on the whole network. Therefore, it is necessary to analyze crucial nodes and neuralgic points and their impact on the different level and systems. However, the optimized value chain is influenced by internal or external impacts to the traffic infrastructure systems. The main destructive impacts can be divided in the following categories using a perspective analysis as shown in Figure 1.

NATURAL AND OTHER HAZARDS	USER	CAPACITY AND DEMAND	REGULATORY
▪ Force major	▪ User behavior	▪ Infrastructure offering	▪ Environmental protection
▪ Seasons	▪ Accidents	▪ Technique and stability	▪ Emission protection
▪ Terrorism	▪ Objective functions	▪ Refurbishment	▪ Nature reserves
▪ Strike action			▪ Traffic regulations

Figure 1. External and internal impacts on infrastructure networks

3 Specific network modeling

A node in the model represented a crossroad or connection point in the project case. The network is modelled as a weighted directed graph in which each edge represented one path between two nodes. (Gross et. al. 2013) To describe different path dimensions (lanes, speed) edges attributes are implemented. (Appert and Laurent 2007) Edges are class-divided into three types characterized by capacity (in user) and maximum speed (in km/h) (see Table 2). Attributes are qualitative to characterize different types. Even if the attributes are exemplary, the ratio is real-world oriented. A region is the start and end of a route through the network. Bottlenecks in infrastructure systems are crucial, if internal and external impacts influence the normal state of operation of the infrastructure system. Especially the limitation in the capacity of bridges, tunnels, intersections or locks can result in far-reaching effects. The aim of innovative solutions for traffic infrastructure and traffic systems are to guarantee an efficient utilization. Most ideas can be classified into two groups – structural enhancement or superordinate traffic flow optimization. Structural enhancement includes solutions like planning tunnels, tubes, cable railway or other transportation means. All structural solutions have in mind to relieve mostly high frequented urban traffic infrastructure. Traffic flow solutions are for example autonomous drivers, car-sharing or software for an ideal approach of a transport mean to get the best benefit. These solutions have in mind to optimize available infrastructure. Since improvement of the infrastructure is limited by investment costs, cost-benefit consideration is needed. The expense is the most limiting factor taking the improvement of the efficiency into account. Appropriate research approaches are needed to evaluate the most efficient solution, especially for the improvement of existing infrastructure systems, paying attention to different objectives of the users.

4 Methodology

The network is the basis for the following simulations. To describe a traffic infrastructure network, it is necessary to define the elements of the network, the composition of the elements and the traffic flow through the network. A network consists of nodes, edges and regions. An edge is the connection between two nodes. The traffic flow through the network is modelled with an origin-destination-matrix (OD) with n by n dimension, where n is number of nodes. Each entry represents the traffic flow from a start node (origin) to an end node (destination). The network is modelled as a directed graph with weighted edges representing the required time to pass each edge. Hence, a user equilibrated network is implemented. According to Sheffi (1985) this optimization problem is formulated as a mathematical problem (see Eq 1).

$$\min z(q) = \sum_a \int_0^{q_a} t_a(\mathrm{w})\, dw \tag{1}$$

Where w is a pair of OD, q_a is flow on edge a and $t_a(w)$ is dependence between travel time and traffic flow. Each route is optimized for a minimum amount of time. This means that a change from a user to an alternative route tends to a higher time of travel (Wardrop 1952). Travel time is calculated using the capacity-restraint-function by U.S. Bureau of Public Roads (1964).

$$t_a(q_a) = t_0 \cdot \left(1 + \alpha \cdot \left(\frac{q_a}{C_a}\right)^{\beta}\right) \tag{2}$$

Where t_0 is travel time in unloaded edge, C_a is theoretical capacity, α and β are absolute terms (common values for $\alpha=0.15$ and $\beta=4$). A higher traffic flow always induces a higher amount of travel time. To optimize the flow through the network additional criteria can be considered like costs, environmental factors or a combination of them. This leads to additional terms in the objective function, which is implemented to calculate the optimum way, based on the origin-destination matrix.

5 Project case

Berlin is the capital city of Germany and with approximately 3,500,000 inhabitants the largest city in Germany. The area of the city is 892 km² (eq. 3,900 inhabitants/km²) quite large in relation to comparable cities like New York City (10,500 inhabitants/km²) or San Francisco (7,000 inhabitants/km²). This results in special requirements for the city´s infrastructure. In the following focus is given on the capital’s passenger mobility modeled by the meso-level systems rail and road. Basically, Berlin`s inner-city infrastructure network can be described by highways, state-run roads and urban streets for the road system and two urban metro-systems, regional trains and a light rail for the rail system. Within the transportation network of Berlin there are some bottlenecks which highly effect the whole mobility of the city. As an important bottleneck the Tegel Tunnel, a highway tunnel near the airport is chosen for the further investigations. Located on highway A111 (the North-South route in Berlin) it is a critical element at the nano-level with significant influence on the everyday mobility and logistics of the capital.

6 Specific network modeling

A node in the model represents a crossroad or connection point in the project case. The network is modelled as a weighted directed graph in which each edge represented one path between two nodes (Gross et. al. 2013). To describe different path dimensions (lanes, speed) edges attributes are implemented (Appert and Laurent 2007). Edges are class-divided into three types characterized by capacity (in user) and maximum speed (in km/h) (see Table 2). Attributes are qualitative to characterize different types. Even if the attributes are exemplary, the ratio is real-world oriented. A region is the start and end of a route through the network.

In this case, every route from a user has to start and end at a region, which is connected to at least one node. All links between two regions are integrated into an origin-destination-matrix (OD). This matrix describes the traffic flow through the network (see Table 1). Traffic flow from region 7 to 4 is represented by the traffic coming from north of Berlin to the city and south of Berlin. This traffic flow is variable and main object of investigation. Traffic flow from 7 to 5 and 6 to 5 is constant and represented as basis traffic.

Table 1. Attributes of edge types

O/D	…	4	5	…
…	…	…	…	…
6	…	0	250	…
7	…	500	250	…
…	…	…	…	…

Table 2. Detail of an example for OD-matrix

edge type	max. speed [km/h]	capacity [user]
urban road	50	500
highway	100	1000
tram	50	1000

The model is an abstraction of the project case, where the essential parts of the real traffic network are modelled. The traffic network is modelled with urban roads, highway, tram and crossroads . In addition, regions and their connections to the network are considered.

Two types of transportation means are linked (public transport and private transport). In the model each individual user is modelled and is able to use both transport means. The linkage in this model is realized using a park-and-ride system and is implemented as an edge with different attributes. The maximum speed is 5 km/h, corresponding to the speed of walking.

7 Parameter study

In order to find significant data for allocating traffic load that causes network shift, firstly a basic load for the system is adjusted to simulated normal traffic. For specific traffic situations, two scenarios are examined. Load simulation is following the initial values for capacity.

- Constant load, variable capacity (the variable capacity of specific edges simulated a reduced capacity due to an accident or closing tunnel)
- Variable load, constant capacity (the variable traffic load simulated traffic jam)

The variable traffic load simulates traffic jam from commuter traffic from North Berlin to South Berlin. The edge which represented the Tegel Tunnel has a variable capacity to simulate a closing tunnel (see Table 3). It is assumed that transport users choose travel routes to optimize travel time, hence transport users will shift paths or networks when there is a benefit of time to switch their route.

Table 3. Parameter for parameter study

variable load, constant capacity			constant load, variable capacity		
scenario	traffic load (user)	capacity (user)	scenario	traffic load (user)	capacity (user)
1	500	1000	11	2000	1000
3	1000	1000	12	2000	750
5	1500	1000	13	2000	500
7	2000	1000	14	2000	250
8	2500	1000	15	2000	0
9	3000	1000			

6.1 Variable load, constant capacity

For the first four scenarios, the traffic load does not overrun the edge capacity. Hence, all transport users stay on the highway route and no shift to alternative routes takes place. In scenario five to seven, users start to switch from the highway network to the urban road network. In scenario eight and nine these shift increases to avoid a higher travel time on highway or urban road, due to a growing traffic jam.

Figure 2. Use of capacity for scenario 1, 5 and 9

The number of users shifting to tram network, by changing their mean of transport are increasing noticeable at this capacity. To enable switches to public transport, infrastructure like park-and-ride systems or car-sharing are necessary. A switch to an alternative route within the same transport system occurs first at a use of capacity of 150%. Travel time starts at three minutes and rises up to seven minutes for the first use of alternative routes. The shift to a different means of transport occur later with a higher critical value of traffic intensity (250% use of capacity and a travel time of eleven minutes). Different use of capacity for traffic allocation is shown in Figure 2 (scenario 1, 5 and 9).

6.2 Constant load, variable capacity

Scenario 11 is equal to scenario 7. Users switch from highway to urban roads. With a continous reduction of capacity the shift to urban roads increases, also the travel time increases from ten minutes to eleven. In addition, a shift to tram network is assert from scenario 13. By closing the tunnel, which reduces its capacity to 0, traffic splits into a ratio of 2:1 between urban road and tram while travel time rises up to nineteen minutes. Different capacities for traffic allocation are shown in Figure 3 (scenario 11, 13 and 15).

Figure 3. Use of capacity for scenario 11, 13 and 15

8 Conclusion and outlook

A reduction of capacity is more significant for a shift to an alternative route than an increase of traffic intensity. Hence, a closing tunnel is more crucial than a higher traffic load. Travel time increases for the first study case (variable load, constant capacity) nearly linear, travel speed has a nearly convex downwards trend. For the second study case (constant load, variable capacity) the travel time increases with a convex function, travel speed drops with a concave trend.

To define the model as realistic as possible additional factors need to be included. Certainly, travel time is not the only objective for a road user. There are also soft factors like the flexibility, effort, location knowledge, et cetera, which influence the decisions, whether a user changes to a different traffic system or stay on the road regardless a higher travel time. To motivate the user to change the traffic system the attractively of changing the system needs to be raised. The investigation showed the relevance of research in the topic of linked infrastructure systems. The approach and methodology is useful to find efficient solutions to provide a more resilient infrastructure for the future. To develop a useful decision metric, qualitative data will be refined with real-world data in the next step, also including probabilistic traffic load and scenario analysis.

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