Congestion Costs and Infrastructure Development: A Simulation Case Study

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During the last six decades a dense network of motorways has been established in order to reduce travel times in long-distance traffic. More recently, investments have been made mainly for lane extensions thus serving more and more for the reduction of congestion costs.

Various phenomena are at the bottom of the expression congestion costs such as the reduction of travel speed at rising traffic density, disruption of traffic flow above certain traffic volumes and congestion resulting from accidents and road works. Congestion results in an extension of average travel time but also in the necessity to allow for buffer times as certain forms of congestion occur randomly. Despite the random nature of its emergence, the exact determination of congestion cost has an important meaning in the evaluation of economic efficiency of network extensions.

In the present paper the benefit of strategic network extensions for the reduction of travel times and the enhancement of reliability is examined. For this purpose a micro simulation tool is used as it displays the formation of waiting queues as well as the various traffic volumes in the course of the day. The traffic model was calibrated for the German state of Baden-Württemberg and considers passenger as well as freight traffic. The consequences of lane extensions on the systematic and random components of congestion costs are calculated. Benefits are weighed against costs using data from the German Infrastructure cost calculation. It can be seen that a comprehensive upgrade is capable of reducing economic harm caused by congestion as relief from congestion outbalance the costs.

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1. Definitions and state of the art in modeling congestion

There is no general definition for the expression „congestion“. The OECD (2007) summarizes the various efforts taken to define traffic congestion with the sentence: “*Congestion is a situation in which demand for road space exceeds supply”* (OECD (2007), p.28).

A widespread assistance to classify the quality of the traffic flow is the classification of levels of service for transportation infrastructure in the Highway Capacity Manual of the Transportation Research Board (HCM (2000)). There the traffic flow is categorized according to the speed, the possibility to change lanes and the average spacing between two successive vehicles. Based on this work, various classifications of traffic quality have been developed such as the German HBS (FGSV (2009)).

Congestion can be measured with various indicators that can be subdivided into two categories: technical and economical ones. These indicators refer to the two main approaches that are used to describe and explain the emergence of congested roads. An overview of various indicators is given in the COMPETE-study (COMPETE (2007)).

The dependencies between speed, traffic flow and traffic density can be displayed in the fundamental diagram of traffic flow (Koshi et. al. (1983)). From this three dimensional coordinate system, a cross selection can be made to obtain the flow-density diagram, where speed and traffic flow are correlated. Up to a certain value, vehicle density can be increased without the need for concessions to the level of traffic flow. After this critical density is exceeded, additional vehicles can only be placed on a section of road if one is willing to accept a lower traffic flow and hence lower average speed for all road users. Various classifications for sectors in the flow-density diagram are given and along with them, there are explanations how these different states of traffic flow can be reached (c.f. Kühne (2004)).

Kerner (2004) identifies three different phases of traffic flow. Free flow is assumed as long as the flow rate increases although vehicle density also does so. If this is not the case anymore, because a critical density has been exceeded, congested traffic occurs that can be subdivided in the phases of synchronized flow and wide moving jam. In both cases the inflow rate in a road segment is higher than the outflow rate. This has the consequence that a queue of vehicles emerges with the downstream end of the queue moving forward at a slower speed than the upstream end moves backward. In the case of synchronized flow, the downstream end is fixed at a bottleneck on the road (i.e. does not move forward), whereas in a wide moving jam the downstream front is moving ahead.

Nagel and Schreckenberg (1992) developed a set of rules that determines how vehicles move forward on a road. Drivers can accelerate and decelerate depending on their own speed and the distance left to the vehicle ahead of them. With this set of rules, the emergence of congestion on roads that are actually not overloaded can be explained as the result of overreactions of drivers to the behavior of the men in front.

Apart from the mathematical or physical approaches that model the precise flow of vehicles, there are economic or philosophic works that try to explain why there are too many vehicles on the road at a certain point of time at all. Some authors (Larson and Sasanuma (2010), Moinzadeh el. al (1997)) for the case of batch sizes and delivery frequencies causing increased freight transport) argue that traffic congestion is an example for the tragedy of commons as introduced by Hardin (1968). Along with the allegedly free use of roads, individual optimization results in the depletion of a limited resource in the long run. For this reason the adoption of congestion prices is suggested in order to raise consumers' awareness of the limitation of road space at certain locations and times. A very recent review of theoretical as well as practical aspects of congestion pricing has been presented by De Palma and Lindsey (2011).

On the other hand, congestion is not seen to be totally negative. Downs (2004) argues that utility maximizing individuals accept to be stuck in traffic because they expect the actual purpose of the trip to be worth the wait. This holds true especially for urban areas, where people believe to profit more from the attractions offered by the agglomeration than to suffer from the negative effects of crowding (OECD (2007), p.32f). In reality capacity overloads are only evitable to a certain extent at a reasonable burden. This is especially the case when recurrent congestion occurs due to seasonal or periodical events. The capacity of roads is not designed to absorp all vehicles in the peak hours of a year. It is rather accepted that some congestion is likely to occur. For economic reasons design guidelines allow an overstepping of capacity on 30 hours per year (Natzschka, 2003, p.95).

2. Costs attributed to traffic congestion

Costs that arise from congestion can be manifold. Depending on the scope of the aggrieved parties, they differ in their absolute value. An important decision is whether to constrain the scope on the costs borne by traffic participants on the respective link or to extend it on a rather comprehensive view including costs imposed to parties that are not involved in the traffic situation including the natural environment.

Costs that result from the realization of an additional trip on a congested road and that are imposed to others are referred to as marginal external transport user costs (Nash et. al. (2003)). An established solution to internalize these costs would be the levy of a Pigouvian tax (Pigou (1920)). This tax closes the gap between the average costs of the trip borne by each driver and the marginal social costs that result from also considering the aggravations in traffic flow each trip causes among the other users of the concerned road link. Since the amount of the toll depends on the value of traffic flow and vice versa, it is first necessary to know the demand curve for the particular road section and second the congestion price that is charged in the end has to be determined in an iterative way.

In contrast to congestion pricing, where marginal costs are suitable, the examination of benefits of investment decisions requires the calculation of total congestion costs (Bilbao-Ubillos (2008)). These total costs also comprise external costs shifted to the local residents and the environment in general.

Extended travel time caused by stop and go traffic often results in an extended operating time of combustion engines compared to the free flow case. This mostly ineffective burning of fossil fuels not only yields higher travel costs for the road users but rather also causes additional damage to the environment. Herzog (2011) investigated the potential for saving fuel by driving around congested areas. Fuel consumption also results in air pollution and emission of greenhouse gases.

A cost component that is subject to a very thorough examination is the additional time spent in transit because of congested roads. This time is monetized by multiplying it with the Value of Time

(VoT). Maiwald et. al. (2008, p. 16) label the value of time as one of the best practices to display costs of scarce infrastructure. This goes along with the fact that the main benefits from avoiding or reducing congestion are attributed to the time saved by the road users (OECD (2007), p.138). One of the problems determining the value of time is that it is subject to variations depending on the composition of users, the time of day and other factors (De Palma and Lindsey (2011)). Bilbao-Ubillos (2008) suggests to price the additional travel time resulting from congestion according to the average wage paid in the corresponding area. Apart from the problem, that averages react to sensitive on spikes, obtaining opportunity costs by setting the loss of earnings as a reference value only seems to be appropriate if the trip purpose was to cover the way to or from work. One possibility to account for this imbalance in opportunity costs depending on the activity that could be performed instead of being in transit, are percentaged markdowns according to the purpose of the trip.

In transport networks that operate according to a synchronized timetable, delays in some of the links can result in either missed connections or disturbances that are propagated throughout the whole system. Passenger transit operating under a clockface timetable is mostly carried out by rail in Germany. However, with the planned deregulation of intercity bus lines delay resulting from congestion is likely to be a challenge. As far as freight transport is concerned, delays of shipments can lead to stock-outs and interruption of production processes. In intermodal transport, closing hours of terminals can be missed or the time window for unloading for example at a mixed cargo hub elapses without the expected truck showing up.

Congested transport routes not only shift the estimated time of arrival for passenger trips and consignments of goods. Another problem is the decrease in predictability due to congested roads. This affects passenger as well as freight transport. Anticipating broad fluctuations in travel time could induce passengers or material planners to allow for additional and long time buffers. In the case of passenger traffic, regardless of being individual or public this will lead to higher transit as well as waiting time, both of which are considered to be a nuisance with the latter is priced at a higher hourly rate .The aspect of travel time variability has been reflected in (dis)utility functions by means of the (α, β, γ) – preferences (Fosgerau and Karlstrom (2010)). The two aforementioned authors belong to those who modeled a utility function that evaluates the effect of travel time variability on the decision of a traveler. The function of disutility associated with travel time consists of three components covering tardiness, early arrival and travel time itself with the latter being random and characterized by a distribution function. The parameters (α, β, γ) reflect the marginal costs of travel time (α), earliness (β) and lateness(γ). Given a preferred arrival time, the decision maker chooses his departure time according to the distribution function. Thus, not only earliness and lateness but also the necessity to interrupt a previous activity in order to meet the preferred arrival time causes disutility.

In case of freight transport, supply chains are influenced or interrupted. Lean logistic and production systems (c.f. Womack et. al. (1991)) are built on predictable arrival times of shipments. Disturbances in replenishment as well as in distribution affect leveled production lines very quickly. Studies done in New Zealand showed that congestion does not counteract the reduction of stock which is a main principle of lean production, but rather results in an increased frequency of deliveries and thus even reinforce traffic congestion (Sankaran et al., (2005)). Rao and Grenoble (1991) examined the effects of changes in the mean transit time as well as in the standard deviation of the latter on a manufacturer that replenishes parts of his stock just in time. Their model shows that not the increase in mean transit time but in the coefficient of variation (standard deviation of transit time normalized by the mean) is responsible for the increase of safety stock and in-transit inventory and thus the decreased reliability causes the majority of cost increase.

3. Simulation model

The simulation carried out in this article concentrates on the German state of Baden-Württemberg. In this state, the automotive industry as well as their suppliers plays an important economic role. As the automotive branch applies just in time replenishment, reliable and predictable transport respective arrival times are important. Measures to avoid congested roads in this case only consider the supply side, taking into account that the provision of additional traffic area entailed induces traffic in the past decades (OECD (2007), p. 98).

Our simulation model is based on MATSim (Raney et al. (2002); www.matsim.org), which is an activity-based multi-agent simulation tool for transportation. Each agent generates an individual plan; the plan consists of a list of activities, which the agent conducts in a day. Agents execute their plans simultaneously on the physical road network, so called traffic flow simulation or mobility simulation. The system iterates between plan generation and mobility simulation. Each agent has a memory of several plans and evaluates the score of the executed plan at the end of each iteration. For the next iteration the agent can represent its learning ability in the way that it selects the plan of the highest score or modifies an existing plan.

The modeling focuses on the generation of a transportation network for congestion study and building realistic daily travel demand (passenger traffic and freight traffic) using publicly available data for calibration, which are discussed in the following.

3.1. Network

Figure 1: European road network with focus on Germany.

The network of our simulation model is a Europe-wide road network with focus on Germany. In Germany all the freeways and federal roads are considered and in foreign countries only important freeways are included. Every road has the attributes such as free speed, capacity, which can be read and considered as constraints by the MATSim framework.

The street network is not only wide-meshed but also does not contain information about cross-town links. Within city limits, the possible as well as the allowed speed is lower than in the countryside. In order to avoid that too many agents choose to travel on federal roads instead of motorways, the free speed has to be reduced. This is done by assigning an urban share to each link resulting from a linear regression with the population density as independent and the share of each link located within city limits as dependent variable.

3.2. Data preparation for building passenger and freight traffic

The data basis for building the transportation demand is the forecast of the Germany-wide traffic distribution in 2025 (in following forecast 2025) (BVU et al., 2007), which is submitted by the German Federal Ministry of Transport, Building and Urban Development (Bundesministerium für Verkehr, Bau und Stadtentwicklung, BMVBS) commissioned research consortium.

The core of the forecast 2025 is the spatial traffic distribution at the NUTS level in the passenger and freight traffic for the year 2004 (analysis) and 2025 (forecast). For Germany and foreign countries different NUTS levels are applied for different aggregation levels. In Germany the NUTS 3 level is used for the detailed description of traffic flows between two districts, while in foreign countries NUTS 2 or NUTS 1 are applied to describe the international traffic flows. Different Transport modes are included in the Forecast 2025; however, for our purpose only the road traffic is extracted.

The matrix of the forecast 2025 for passenger traffic gives only the total personal trips per year, which is divided in different traffic purposes (work, business, education, shopping and vacation). The final report of mobility in Germany (Mobilität in Deutschland (2008), p.91) provides occupancy rates of passenger cars for different driving purposes. With this information the car trips can be built from the personal trips from forecast 2025 as follows:

$$CT_{ij} = \sum_{all\ k \in X} \frac{PT_{ij}^{k}}{OR^{k}}$$

where:

CT_{ij}: number car trips from zone i to zone j;

X: the set of all possible driving purpose;

k: driving purpose;

PT_{ij}^{k}: number of personal trips with the driving purpose k from zone i to zone j;

OR^{k}: passenger car occupancy rate of driving purpose k.

Because of the daily planning characteristics of MATSim the traffic volume of a normal working day must be determined. Using the counting data offered by Federal Highway Research Institute (BASt, Bundesanstalt für Verkehrswesen; Fitschen et al., 2009) a linear relation is found between the working day traffic volume and the yearly traffic volume:

$$TV_{workingDay} = 0.0028479 \cdot TV_{year} + 150.7763$$

where:

$TV_{workingDay}$: traffic volume of a working day;

TV_{year} : traffic volume of a year.

The forecast 2025 gives tonnage of commodity between two zones. In combination with a truck load matrix (Liedtke et al. 2011) the number of loaded truck trips per day between two zones can be calculated. For our Baden-Württemberg scenario only trips starting or ending in Baden-Württemberg are taken into consideration in the following steps.

3.3. Agent plan

After the data preparation the agent plan could be constructed. The travel demand provided by the forecast 2025 is performed on all road types; however, our network is a long-distance network, containing only freeways and federal highways. So it is necessary to introduce a long-distance network reduction factor. In the model the number of short distance trips is reduced as follows:

$$f(t_{ij}) = \begin{cases} t_{ij} \cdot \left(b + d_{ij}^{a} \cdot \dfrac{1-b}{d_{max}^{a}}\right), & 0 \le d_{ij} \le d_{max} \\ t_{ij} & d_{ij} > d_{max} \end{cases}$$

where:

t_{ij}: total number of trips between zones i and j;

d_{ij}: travel distance between zone i and j;

b: intercept of the polynomial function, indicates how much of the intrazonal traffic takes place on the trunk road network;

a: indicates the convexity, respective concavity of the function and thus determines how much of the medium distance traffic is carried out on the trunk road network. This parameter is also used to determine the length of the last mile in long distance trips that often occurs on local roads;

d_{max}: the maximum distance above which all trips are assumed to take place on the trunk roads system.

For the generation of an agent plan zone-zone-trips must be converted to node-node-trips (figure 2). In the source zone, trips with a certain destination are distributed equally over all nodes. If one considers an arbitrary start node, the nodes in the destination zone are determined according to a multinomial logit model.

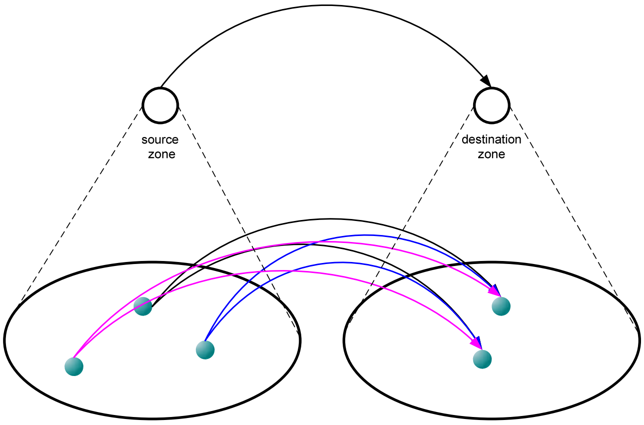

Figure 2: distribution of zone-zone-trips into node-node-trips

The traffic, which is performed between two nodes, has a probability

$$p_{ij} = \frac{e^{-\alpha \cdot d_{ij}}}{C_x \cdot \sum_j e^{-\alpha \cdot d_{ij}}}$$

where:

i: node from the source zone; j: node from the destination zone;

p_{ij}: probability, that the traffic is performed between node i and node j;

d_{ij}: distance between node i und node j;

α: parameter;

x: source zone; y: destination zone;

C_x: the number of nodes in the source zone x.

The parameter α determines, how the difference in the distance to the destination nodes is valuated by the decision maker. For interzonal trips or trips in adjacent zones, differences in the distance between possible destination nodes are more important than in the case of trips to more remote zones. This results from the fact that trips between remote zones are already very long regardless of the actual destination node, so that differences in this last mile are negligible when long journeys are considered. For this purpose, α changes with respect to the approximate distance between two zones according to:

$$\alpha_{d_{ij}} = \alpha_{intra} \cdot \left(0.5 \cdot \tanh\left((-1) \cdot \delta \cdot d_{ij} + d_{local}\right) + 0.5 + \alpha_{inter}\right)$$

where:

$\alpha_{d_{ij}}$: Heterogeneity parameter of the logit function depending on the covered distance d_{ij};

α_{intra}: Heterogeneity parameter for intrazonal and short-distance trips;

δ: Decay parameter, indicates how smooth the curve declines depending on the distance d_{ij};

d_{local}: Determines the maximum length of short distance trips (not identical with the length of the trips due to the properties of the tanh-function);

α_{inter}: Heterogeneity parameter for long-distance trips. The value is closed to zero, as in the case of long distances the last mile is not relevant anymore.

The passenger car agents are categorized into commuter and non-commuter, which have different activity patterns. The departure time for passenger agents is generated according to statistical data (Mobilität in Deutschland (2008), p. 134). However, freight agents' departure time is assumed to be distributed equally between 5am and 8pm and a reduced value during the night. For freight traffic only loaded truck trips are taken into account, complex truck tours are not considered.

3.4. Commuter flow

In order to track the fluctuation of traffic loads during a day, the commuter flow should also be taken into consideration. Using the data in forecast 2025 the commuter percentage can be determined for each zone-zone-relation because commuters' travel purpose is "working". Commuters have to be treated separately as they are responsible for the peak traffic in the early morning and late afternoon. The imbalance in the traffic flows was displayed by a logit choice model with the net commuter (in-commuters minus out-commuters) of any two corresponding NUTS3 regions forming the ends of a trip.

3.5. Simulation and model calibration

Due to the limitation of computation capacity, 1% of the total transportation demands are built as agent plan. Our simulation results are calibrated and validated in the way that they are compared with the data offered by Federal Highway Research Institute (BASt, Bundesanstalt für Verkehrswesen; Fitschen et al. (2009)). Two types of data are considered during the comparison, the daily traffic volume and the type of daily traffic load curves. Several model parameters (long-distance network reduction factor, starting travel time distribution, commuter decision rule) are adjusted according to the comparison results. Figure 3 and Figure 4 show the final modeling results for several selected roads in Baden-Württemberg.

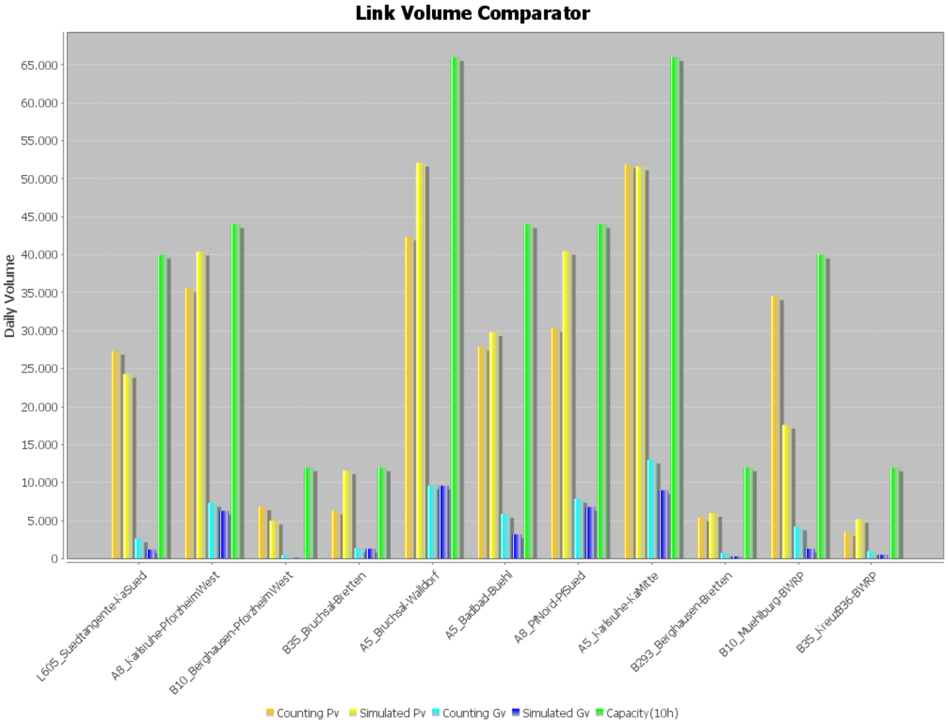

Figure 3: Daily traffic volume on several roads

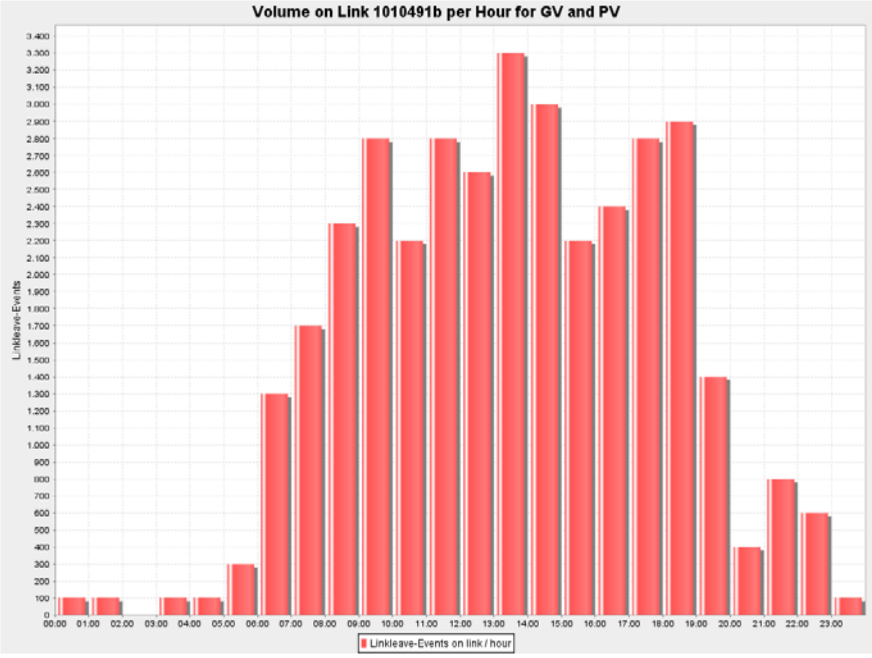

Figure 4: time-dependent traffic load on a link

4. Evaluation results

Among several aforementioned congestion effects the travel time increase is the most important effect of congestion and it accounts for 90% of economic congestion costs (Maibach et al., 2008). Our model has the ability to calculate the travel time of each agent and therefore provides a disaggregated approach to estimate the congestion cost in the long-distance network.

We define 4 scenarios with different infrastructure capacity: (1) the status-quo road network capacity; (2) the extended capacity with a lane extension for each freeway and each direction; (3) the extended capacity with a lane extension for each road of any type (including freeway and federal road) and each direction; (4) the unlimited infrastructure capacity. In each scenario the agent's travel time can be calculated. The following table shows the travel time difference for several agents in the 4 scenarios, where TT denotes travel time, ref (reference) denotes the first scenario, ex1 (extending only freeways) the second, ex2 (extending all roads) the third and inf (infinite) the fourth. Table 1 shows an extract of the synthetic population that was created in order to simulate traffic in Baden-Württemberg.

Agent Id	**From Node/From zone**	**To Node/ To Zone**	**Passenger car (Yes/ No)**	**Commuter (Yes/ No)**	**Start travel time**	**TT_{ref} (min)**	**TT_{ex1} (min)**	**TT_{ex2} (min)**	**TT_{inf} (min)**
6938	107422 / DE111	107587 / DE122	Yes	No	06:40	36	36	35	33
6939	107426 / DE111	107585 / DE122	Yes	No	09:35	40	37	36	36
6940	107441 / DE111	107586 / DE122	Yes	No	12:15	64	60	42	39
17189	107682 / DE12C	107786 / DE143	Yes	Yes	06:51 / 15:39	118	118	102	101
100358	107581 / DE122	100607 / DE146	No	No	06:52	121	121	117	116
100359	107596 / DE122	100613 / DE146	No	No	05:56	102	102	101	101

Table 1. Agent travel time

We define the congestion cost of each agent as the value of travel time difference between traveling with free speed and traveling within a transportation network with limited capacity. The fourth scenario is the optimal one where each agent moves with free speed and no congestion occurs; it provides the minimum travel time for each agent, and serves as a reference value for calculating the congestion cost in scenarios with limited capacity.

Note, the increase of travel time in scenario 1, 2 and 3 in Table 1 is only due to the high traffic volume at peak hours, which leads to 40% of travel time increase in road networks according to the literature (Zackor et al. (2005)). The other two reasons for congestion are road works and accidents, which can lead to lane closure, lane narrowing and speed reduction and constitute 30% and 25% of travel time increase separately. However, the values of the congest cost and congestion cost savings from our model are without consideration of the effects of road works and accidents and practically they can be more in quantity.

The three components (high traffic volume, road works and accidents) do not only increase the average travel time, but also cause a higher travel time variance due to their random emergence.

Figure 5 shows the impacts of the three components on the mean and the variance of travel time. The green vertical line presents the minimum travel time in scenario 4; the red function is the density function of travel time, which is affected only by the high traffic volume; however, the blue which has both the larger mean travel time and the larger standard deviation shows the actual density function of travel time with impacts of all influencing factors.

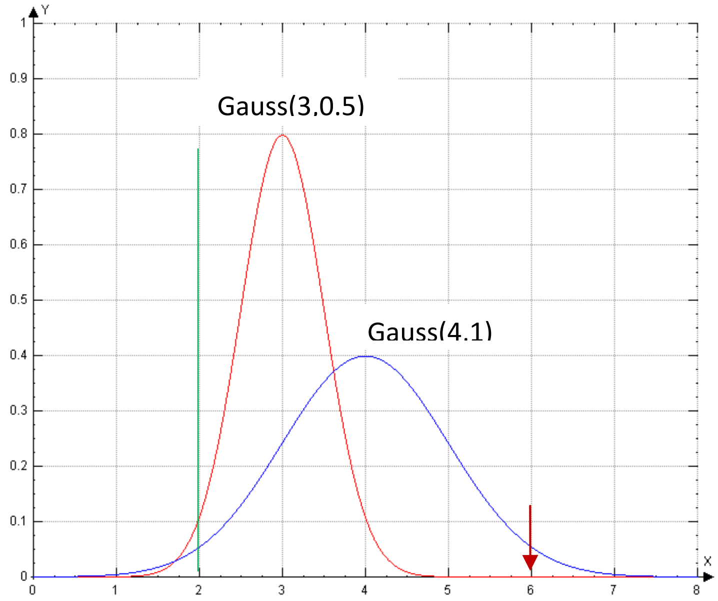

Figure 5. Density function of travel time

Economic theory suggests that different methods of valuation of VTTS (value of travel time savings) should be used for passenger non-work trip (for commuting, shopping and leisure purpose), passenger trips during works (for business purpose) and for commercial freight traffic (Bickel P., Friedrich R. (2006), p.S4). The approach for estimating VTTS for employer's business traffic and commercial freight traffic is based on the marginal productivity of labor. Such an approach assumes that all travel time savings can be transferred to productive output. However, for the VTTS valuation of passenger non-work trip willingness-to-pay evaluation or survey should be conducted that reflects income level, trip purpose, journey length, modal comfort of individuals. Applying the aforementioned methodologies the HEATCO study (Bickel P., Friedrich R. (2006), p.S9-S11) provided the reference VTTS, which is disaggregated in employer's business trip, commute short distance trip, commute long distance trip, other short distance trip and other long distance trip for passenger car traffic and described in Euros per passenger per hour. And for freight traffic the valuation of VTTS is specified in Euros per freight ton per hour. However, for considering VTTS in this study we use a simplification according to data listed in HEATCO study; for passenger traffic the VTTS is assumed to be 10€ per passenger per hour and for freight traffic 40€ per truck per hour.

The travel time deviation from the average travel time in Figure 5 reflects the problem of travel time reliability, which represents the uncertainty of individual drivers about the travel time between any two nodes in the road network. In the case of the blue function in Figure 5 the traveler would budget 6 hours on the way to be 95% sure of arriving at the destination on time. However, in the case of the red function the traveler only needs to budget 4 hours to have the same certainty of a timely arrival. Therefore, the traveler can save 2 hours travel time in the second case; one hour is due to the average travel time reduction from 4 hours to 3 hours; another hour results from the improved travel time reliability, as the standard deviation of travel time is reduced from 1 hour to only 0.5 hour.

In the literature (Chen et al., 2003), the standard deviation and the mean travel time are used to calculate the cost of traversing a route:

$$C = r_1\mu + r_2\sigma\ ,$$

where:

C: total travel cost

μ: mean travel time

σ: standard deviation of travel time

r_1: cost per unit time of average travel time

r_2: cost per unit time of standard deviation

The formula of the travel time savings after the lane extension can be derived as

$$S = r_1(\mu_{ref} - \mu_{ex}) + r_2(\sigma_{ref} - \sigma_{ex}).$$

Our model can deliver a deterministic value for the first part of the above formula, as $r_1(\mu_{ref} - \mu_{ex})$ equals $VTTS \cdot (TT_{ref} - TT_{ex})$. To determine the second part $r_2(\sigma_{ref} - \sigma_{ex})$, we need to do some random experiments in MATSim for scenario 1, 2 and 3 with stochastically generated congestion-inducing incidents, e.g. travel volume fluctuation, accidents and road works. However in our study we make the assumption that $r_1(\mu_{ref} - \mu_{ex})$ equals $r_2(\sigma_{ref} - \sigma_{ex})$. In other words, the monetary value of the average travel time saving is the same as the monetary value of the improved travel time reliability in the case of lane extension.

The calculation of congestion cost associated with travel time increase is very straightforward.

$$CC_{s,i} = 2 \cdot (TT_{s,i} - TT_{inf,i}) \cdot VTTS_i \cdot O_i$$

where:

$CC_{s,i}$: congestion cost for agent i in scenario s;

$TT_{s,i}$: travel time of agent i in scenario s;

$TT_{inf,i}$: travel time of agent i in scenario inf;

$VTTS_i$: value of travel time savings of agent I;

O_i: passenger occupation rate of agent i.

Note, that $CC_{s,i}$ is due to the increased average travel time and the deteriorated travel time reliability in the scenario s in comparison to the optimal scenario (inf). The O_i is 1.5 for each passenger agent (Mobilität in Deutschland, 2008, p.90) and 1 for each freight agent. Table 2 shows examples of values for the $CC_{s,i}$ equation.

Agent Id	**$TT_{ref,i}$ (min)**	**$TT_{ex1,i}$ (min)**	**$TT_{ex2,i}$ (min)**	**$TT_{inf,i}$ (min)**	**$VTTS_i$**	**O_i**	**$CC_{ref,i}$ (€)**	**$CC_{ex1,i}$ (€)**	**$CC_{ex2,i}$ (€)**
6938	36	36	35	33	10	1.5	1.5	1.5	1
6939	40	37	36	36	10	1.5	2	0.5	0
6940	64	60	42	39	10	1.5	12.5	10.5	1.5
17189	118	118	102	101	10	1.5	8.5	8.5	0.5
100358	121	121	117	116	40	1	6.7	6.7	1.3
100359	102	102	101	101	40	1	1.3	1.3	0

Table 2. Congestion cost of agents

The status-quo congestion cost is defined as $\sum_i CC_{ref,i}$ and the congestion cost after lane extension is $\sum_i CC_{ex1,i}$ for scenario 2 and $\sum_i CC_{ex2,i}$ for scenario 3. The total savings of congestion cost after lane extension is the summation of the congestion cost savings of all agents,

$$TCCS_{ex1} = \sum_i (CC_{ref,i} - CC_{ex1,i}) ,$$

where $TCCS_{ex1}$ denotes the total congestion cost savings after freeway lane extension. With the simulation results the value of $TCCS_{ex1}$ is €0.45 mil. per working day and €145 mil. per year for

Baden-Württemberg with the assumption that the congestion cost per year is equivalent to the cost of 320 working days. Analogically the value of $TCCS_{ex2}$ is €1730 mil. per year for Baden-Württemberg in the case of the comprehensive lane extension. And the status-quo congestion cost (scenario 1), the congestion cost after freeway lane extension (scenario 2) and the congestion cost after lane extension on all roads (scenario 3) in Baden-Württemberg are €2033 mil., €1888 mil., €303 mil. per year.

The German Federal Ministry of Transport, Building and Urban has commissioned the ProgTrans AG and the Institute of Economic Policy Research (Institut für Wirtschaftspolitik und Wirtschaftsforschung) the development of an infrastructure cost model for charging the road users (ProgTrans/IWW, 2007). With the model the average cost of a lane on the freeways and on the federal roads per year can be calculated, which are denoted as AVC_{al} and $\mathrm{AVC}'_{\mathrm{al}}$. The total cost of lane extension per year in scenario 2 and 3 is straightforward.

$$TC_{ex1} = 2 \cdot AVC_{al} \cdot TL_A$$

$$TC_{ex2} = 2 \cdot (AVC_{al} \cdot TL_A + AVC'_{al} \cdot TL_B)$$

where:

TC_{ex1}: total cost of a lane extension in scenario 2 per year;

TC_{ex2}: total cost of a lane extension in scenario 3 per year;

TL_A: total length of freeways in kilometer;

TL_B: total length of federal roads in kilometer.

AVC_{al} (mil. Euro)	AVC'_{al} (mil. Euro)	TL_A in BW (km)	TL_B in BW (km)	TC_{ex1} for BW (mil. Euro)	TC_{ex2} for BW (mil. Euro)
0.175397	0.102771	1014	4467	356	1274

Table 3. Total cost of a lane extension per year in Baden-Württemberg

The lane extension on the freeway costs €356 mil. and yields congestion cost savings of only €145 mil. according to the scenario 2. However, in the case of a comprehensive lane extension in the scenario 3 the congestion cost savings (€1730) are higher than the costs accruing from an additional lane per annum (€1274).

Costs Scenario	Congestion costs (mil. €)	Congestion costs savings compared with Scenario 1 (mil. €)	Lane extension costs (mil. €)
Scenario 1 (status-quo)	2033	0	-
Scenario 2 (freeway extension)	1888	145	356
Scenario 3 (all roads extension)	303	1730	1274
Scenario 4 (infinite)	0	-	-

Table 4. Congestion costs, congestion cost savings and lane extension costs per year in the 4 scenarios

5. Conclusions

The relatively small relief that an extension of all freeways by one lane brings can be deduced from two facts. First, the extension of capacity supply in the case of a road that has already multiple lanes in each direction is small compared to the doubling of the capacity after adding a second lane to a single lane road. Second, the model does not capture through traffic due to the difficulties arising from determining which of these traffic flows touch the area at all. Long distance through traffic is supposed to traverse the state on either one of the three north-souths or one of the two east-west axes. For this reason, a higher traffic flow is assigned to the motorway network in reality than in our model, as through traffic amounts to about 4% of all passenger car trips and to about 8.5% of the heavy traffic trips on an average day (Modus Consult (2009)). This means that the relatively small improvement will intensify more if this aspect of reality is incorporated.

As far as the overall amount of congestion costs is concerned, the model yields a value that could be assumed to be within the realms of possibility. Sticking to the proposition of Maibach et.al. (2008), the status-quo congestion cost would be around 2.26 bn. €. This corresponds to 0.6% of the annual GDP of the state. Compared to the 0.9% share of the GDP obtained for Germany by the UNITE study (Nash et. al. (2003)) and the statement of OECD (OECD (2007), p.160) that various cost estimates between 1% and 2% of the GDP are too high, and this result fits well in the current literature on this topic.

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