MODEL-BASED ESTIMATION OF CONGESTION-RELATED TRAVEL TIME LOSSES ON FREEWAYS

Justin GEISTEFELDT
Professor
Institute for Traffic Engineering and Management
Ruhr-University Bochum
Universitaetsstr. 150
D-44801 Bochum, GERMANY
Phone +49 234 32-25936
Fax +49 234 32-14151
E-Mail justin.geistefeldt@rub.de

Sandra HOHMANN
Research Assistant
Institute for Traffic Engineering and Management
Ruhr-University Bochum
Universitaetsstr. 150
D-44801 Bochum, GERMANY
Phone +49 234 32-28571
Fax +49 234 32-14151
E-Mail sandra.hohmann@rub.de

Submission date: November 15, 2013

Number of words: 4830
Number of tables and figures: 10
Total number of words: 7330
ABSTRACT
For the economic assessment of road infrastructure investments and the evaluation of operational strategies, the estimation of travel times is of particular importance. The paper introduces a two-component model to estimate total or average travel times on freeways. The model differentiates between travel times in fluid traffic conditions, which depend on the length of the segment, and congestion-related travel time losses, which only depend on the volume-to-capacity ratio of the bottleneck. Based on traffic data from 50 freeway sections in Germany, the total travel time losses due to congestion arising during one year are estimated by macroscopic simulation. With the simulation model, the travel time losses can be related to the volume-to-capacity ratio of the hour in which the congestion was caused. A model function was developed to represent the congestion-related travel time losses in relation to the volume-to-capacity ratio. The application of the model for the assessment of operational strategies is demonstrated for the example of hard shoulder running on freeways.
1. INTRODUCTION

Comparable to the U.S. HCM (1), the German Highway Capacity Manual HBS (2) provides standardized methodologies to evaluate the performance of different kinds of highway facilities. According to the HBS, the volume-to-capacity ratio is used as measure of effectiveness for basic freeway segments as well as merge, diverge, and weaving segments, defining the capacity as a deterministic value depending on the geometric, traffic and control conditions of the segment. Furthermore, speed-volume-relationships are specified to determine average travel times in fluid traffic conditions. The quantification of congestion-related travel time losses as well as the consideration of stochastic influences on both traffic demand and capacity is not performable employing the conventional methods given in the HBS.

In contrast to the methods for traffic flow analysis evaluating the capacity of the traffic infrastructure in a single peak hour, economic evaluation procedures also include the long-term effects of infrastructure investments or operational measures on traffic flow quality. Apart from road safety and environmental effects, the reduction of total or average travel times as well as improvements in the travel time reliability is an essential benefit component (3, 4, 5).

The future German Guidelines for Economic Evaluation of Road Infrastructure Projects will incorporate a detailed approach for the determination of benefits due to travel time savings on freeways. The approach is based on traffic demand time series in 1-hour intervals for a whole year. Travel times are determined with a model consisting of two components. The first component represents the travel time in fluid traffic conditions and consequently depends on the length of the segment under investigation. Additionally, the second component computes congestion-related travel time losses, which are independent of the bottleneck’s length and only depend on the volume-to-capacity ratio.

Within a research project sponsored by the German Federal Highway Research Institute (6), congestion-related travel time losses for 50 freeway sections were analyzed by macroscopic simulations, based on which the hourly travel time losses in relation to the volume-to-capacity ratio can be modeled. The paper describes the methodology and the model derivation. Furthermore, the paper outlines other potential applications of the applied method for quantifying the congestion-related unreliability of travel times on freeways. The standard deviation of the hourly travel time losses in relation to the volume-to-capacity ratio was used as measure of reliability.

2. ESTIMATING TRAVEL TIMES ON FREEWAYS

Calculating travel times based on a functional relationship between traffic volume and mean speed implies that the travel times depend on the length of the segment. This approach is applicable for fluid traffic conditions only. In contrast, congestion-related travel time losses are independent of the length of the section under investigation, because traffic breakdowns usually occur at bottlenecks (e.g. highly trafficked on-ramps, lane closures at work zones or accidents) and the congestion spreads upstream of the bottleneck. Hence, congestion-related travel time losses only depend on the volume-to-capacity ratio, but not on the length of the section downstream of the bottleneck.
The differentiation of travel times in fluid traffic and congestion-related travel time losses can be implemented in a two-component model for the determination of travel times (7):

(I) Travel times in fluid traffic are computed as the quotient of the driven distance and the speed according to the speed-volume-relationship.

(II) Congestion-related travel time losses at bottlenecks are computed based on a model depending on the volume-to-capacity ratio.

The total travel time is calculated as the superposition of the travel times in fluid traffic (I) depending on the length of the segment and the congestion-related travel time losses at bottlenecks (II), which are independent of the length of the bottleneck segment:

\[
  t = \begin{cases} 
  \frac{L}{v(q)} \cdot q \cdot \Delta & \text{for fluid traffic conditions} \\
  \frac{L}{v_{\text{crit}}} \cdot q \cdot \Delta + t_{\text{loss}} & \text{for congested traffic conditions} 
  \end{cases}
\]

where:
- \( t \) = total travel time (veh·h)
- \( L \) = segment length (km)
- \( v \) = speed (km/h)
- \( q \) = traffic volume (veh/h)
- \( \Delta \) = interval duration (h)
- \( v_{\text{crit}} \) = critical speed at capacity (km/h)
- \( t_{\text{loss}} \) = congestion-related travel time losses (veh·h)

For the determination of the average travel speed in fluid traffic conditions, the speed-volume-relationship by Brilon and Ponzlet (8) can be used:

\[
v(q) = \frac{v_0}{1 + \frac{q}{L_0 \cdot (C_0 - q)}}
\]

where:
- \( v \) = speed (km/h)
- \( q \) = traffic volume (veh/h)
- \( v_0, L_0, C_0 \) = model parameters

The parameters \( v_0, L_0 \) and \( C_0 \) have the unit of speed, length and capacity, respectively, but do not represent the free flow speed, the segment length and the capacity when calibrated with field data. The HBS (2) provides model parameter values for different types of basic freeway segments depending on the number of lanes, the gradient, the speed limit, and the share of commuter traffic, represented by the location of the segment inside or outside of urban areas. If traffic demand exceeds the capacity, a travel time component depending on the segment length needs to be considered in addition to the congestion-related travel time losses. For this, the threshold speed between fluid and congested traffic can be applied.

For the estimation of congestion-related travel time losses at a bottleneck, a model function depending on the volume-to-capacity ratio is used. The derivation of the model function is described in the following sections.
3. MODELING CONGESTION-RELATED TIME LOSSES

3.1 Whole-Year-Analysis
For the analysis of travel time losses and travel time variability, 50 real freeway (Autobahn) sections in Germany, representing a wide range of segment types with different roadway and traffic demand characteristics, were analyzed. The demand characteristics were determined and classified based on loop detector data. To quantify the congestion-related travel time losses on the 50 analyzed freeway sections for different demand scenarios, a whole-year-analysis with a macroscopic simulation model was applied. The concept for comparing time series of traffic demand and freeway capacity over a whole year was established by Zurlinden (9), cf. also Brilon et al. (10). To account for the stochastic variability of traffic flow processes as well as external influences like weather conditions or incidents, the estimation of demand and capacity considers both systematic and stochastic components.

The calculation of congestion-related travel time losses is based on a deterministic queuing model. The queue length is calculated by comparing the randomly generated traffic demand and capacity values in each 5-minute interval. Travel time losses in each interval are then estimated by multiplying the average queue length with the interval duration. For application, the model was implemented in the software tool KAPASIM using a Monte-Carlo simulation technique (10).

For the derivation of a model function representing the congestion-related travel time losses in relation to the volume-to-capacity ratio, it must be considered that travel time losses due to congestion can already occur at traffic volumes below the design capacity due to the stochastic capacity variability. Also in intervals when congestion dissolves, time losses can coincide with a volume-to-capacity ratio well below 1.0. Therefore, the simulation model was enhanced in order to assign the congestion-related travel time losses to the hour in which the congestion was caused. Through an analysis in reverse chronological order, it is considered that the traffic demand can exceed the capacity several times during a congestion event.

The procedure is illustrated in Figure 1. In the example, the traffic demand exceeds the capacity in three intervals: at 3:05, 4:15 and 4:20 p.m. (marked dots in Figure 1). After the first breakdown, the capacity is reduced due to the capacity drop. The reduced capacity during congestion is represented by the dashed line in the upper diagram in Figure 1. First, the travel time losses due to the overload at 4:20 p.m., which would not have occurred if the traffic had not broken down before, are calculated (lined area). Second, the travel time losses due to the overload at 4:15 p.m. are calculated. The difference between these travel time losses and those due to the overload at 4:20 p.m. is assigned to the interval beginning at 4:15 p.m. (dashed area). In the same manner, the time losses caused by the breakdown at 3:05 p.m. minus the time losses that would have been caused due to the overload at 4:15 p.m. and 4:20 p.m. are determined (dotted area). Finally, the travel time losses caused in 5-minute intervals are aggregated in 1-hour intervals.
3.3 Demand Estimation

The estimation of the demand time series for each section was based on traffic data from automatic loop detectors for one year. Due to the differences between the time series of traffic demand and traffic volume during congestion, traffic volumes in short time intervals (e.g. 1-hour intervals) obtained from detectors do not represent traffic demand in case of frequently congested freeway sections. Therefore, a method to identify traffic demand based on observed traffic volumes is applied. In this study, daily-individual demand patterns are used to model the respective hourly demand volume ([11]). Measured daily traffic volumes are multiplied with daily demand patterns, representing the hourly traffic demand volumes in percent of the total daily traffic. For each day, individual demand patterns are modeled accounting for the variability of the temporal distribution of traffic demand over a day. In contrast to the use of constant daily demand patterns, the use of daily-individual demand patterns allows for a better modeling of real peak demand volumes arising during a year.

The short-term stochastic variability of traffic demand, thus the white noise process of the demand time series, is considered by applying a normal-distributed factor with an expected value of $\mu = 1$ and a standard deviation of $\sigma = 4 / \sqrt{q_D(i)}$ depending on the systematic component of traffic demand in interval $i$, $q_D^i$, cf. ([11]).

Time series and duration curves of traffic demand significantly differ depending on the driver population. On sections with a high share of commuter traffic, time series of traffic
demand show distinct peaks on weekdays and lower values on weekends and during holidays. The duration curve of traffic demand, i.e. the representation of the hourly demand volumes arising during one year sorted in descending order, is usually rather flat at the beginning because the highest hourly volumes are in a relatively small range. In contrast, sections with a high share of recreational traffic show fewer but more distinct peaks during the year, which mostly occur during weekends and holidays. Thus, the duration curve of traffic demand often steeply declines during the first hours.

For German freeways, duration curves of hourly traffic volumes were classified by Arnold and Boettcher (12). Six different types were defined based on cluster analysis. The standardized duration curves of hourly traffic volumes in percent of the AADT are shown in Figure 2.

![Figure 2: Standardized duration curves of freeway traffic demand (adapted from (12)).](image)

In some cases, the traffic demand on the analyzed freeway sections is significantly lower than the capacity even in the highest hours of the duration curve. Due to the relevance of values in the range of the capacity for analyzing travel time losses in this study, fictitious traffic demand scenarios, n30, n50 and n100, were generated for all sections. In scenario n30, the traffic demand in all hours of the year was multiplied by a constant factor so that the 30th hour volume is equivalent to the design capacity of the section under investigation. Hence, the duration curve for scenario n30 shows values above the capacity in the first 29 hours and values below the capacity beyond the 30th hour. In the same way, the demand scenarios n50 and n100 were generated.

### 3.3 Capacity Estimation

The estimation of time series of freeway capacity is based on the concept of stochastic capacities (10, 13). In contrast to deterministic capacities used in traffic engineering guidelines (1, 2), the capacity is regarded as a random variable. The Weibull-type capacity distribution function is:
\[ F_c(q) = 1 - e^{-\left(\frac{q}{\beta}\right)^\alpha} \]  

(3)

where: 
- \( F_c(q) \) = capacity distribution function
- \( q \) = traffic volume (veh/h)
- \( \alpha = 18 \) for freeway sections with variable speed limits
- \( \alpha = 15 \) else
- \( \beta = 1.275 \cdot c_D \)
- \( c_D \) = design capacity (veh/h)

The shape parameter \( \alpha \), which determines the variance of the distribution, amounts to approximately \( \alpha = 15 \) for German freeways. On sections with variable speed limits, greater values of approximately \( \alpha = 18 \) were estimated reducing the capacity variance (14). The second parameter of the Weibull distribution function is proportional to the mean value of the distribution. A comparison of deterministic and stochastic capacities for German freeways revealed that the parameter \( \beta \) of the capacity distribution in 5-minute intervals can be estimated by multiplying the design capacities given in the HBS (2) by 1.275. Temporary systematic influences on the capacity like rainfall, accidents, and work zones can be considered by adjusting the scale parameter \( \beta \). The capacity drop, which is the difference between the capacity before and after a breakdown, is considered by reducing the capacity by 15% during congestion.

### 3.3 Scope of the Simulation

For estimating the congestion-related travel time losses caused in each hour of the year, a total of 1000 simulation runs with the simulation tool KAPASIM was carried out for each traffic demand scenario. The high number of simulation runs was applied in order to receive a realistic distribution of congestion occurrence in each hour of the year, particularly for the analysis of the variability of travel time losses in section 5. The impact of weather conditions, incidents, and work zones was not considered in the simulations. Hence, the simulation results are valid for fair weather, non-incident conditions. For each section and each scenario, the mean value and the standard deviation of congestion-related travel time losses were calculated.

### 4. TRAVEL TIME LOSSES IN RELATION TO THE VOLUME-TO-CAPACITY RATIO

The macroscopic simulations conducted for 50 freeway sections delivered the relationship between the congestion-related travel time losses and the volume-to-capacity ratio in 1-hour intervals as shown in Figure 3 for three freeway sections based on the demand scenario n50. The three sections differ in terms of geometric layout and traffic demand characteristics (cf. Table 1). Noticeable differences at comparable saturation levels can be identified.
FIGURE 3  Congestion-related travel time losses per segment in 1-hour intervals depending on the volume-to-capacity ratio for three freeway sections.

TABLE 1  Characteristics of the three freeway sections

<table>
<thead>
<tr>
<th>Section</th>
<th>No. of lanes</th>
<th>Location</th>
<th>Duration curve type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 8 Weyarn – Irschenberg</td>
<td>3</td>
<td>Outside urban areas</td>
<td>Type C (miscellaneous traffic)</td>
</tr>
<tr>
<td>A 23 Hanerau – Schafstedt</td>
<td>2</td>
<td>Outside urban areas</td>
<td>Type A (very high share of recreational traffic)</td>
</tr>
<tr>
<td>A 5 Ober-Moerlen – Friedberg</td>
<td>3</td>
<td>Inside urban areas</td>
<td>Type D (mainly commuter traffic without extreme peaks)</td>
</tr>
</tbody>
</table>

In the obtained relationships between the congestion-related travel time losses and the volume-to-capacity ratio, two apparently independent curves emerge. Sorting the simulated data in chronological order reveals that a data point of the front curve (at the highest volume-to-capacity ratios) often entails a data point of the back curve, cf. Figure 4. This fact is due to the allocation of travel time losses to the interval in which the overload occurred as exemplified in Figure 1. Data points of the front curve always appear at distinct peaks, when the traffic demand exceeds the capacity in two or more consecutive hours. In these cases, the traffic demand causes a congestion that can only be dispersed after a long time due to a further increasing traffic demand in proximate intervals. Thus, travel time losses occurring in the following intervals are partially allocated to the interval of the first traffic breakdown.
FIGURE 4 Dynamic illustration of congestion-related travel time losses in 1-hour intervals depending on the volume-to-capacity ratio for an example freeway section.

This example emphasizes that the relationship between the volume-to-capacity ratio and the travel time losses assigned to the hours in which the congestion was caused is substantially affected by the course of the traffic demand time series at peak times. The phenomenon of two apparently independent curves as shown in Figure 4 mainly applies for those demand scenarios in which the traffic demand considerably exceeds the capacity in many hours.

For a mathematical analysis of the relationship between congestion-related travel time losses and the volume-to-capacity ratio for all investigated freeway sections and traffic demand scenarios, a model function was adapted to the simulation results via the least squares method. For model fitting, only volume-to-capacity ratios in the range from 0.9 to 1.3 were considered. Volume-to-capacity ratios below 0.9 cause considerable travel time losses only in rare cases. According to the HBS (2), a volume-to-capacity ratio of 0.9 is the threshold value between level of service D and E, i.e. the threshold at which the traffic flow changes from stable to unstable conditions. With regard to the plausibility for the user, travel time losses caused at a volume-to-capacity ratio below 0.9 are not considered. Values over 1.3 are extremely rare and cause travel time losses in a wide range. In the study, these high volume-to-capacity ratios mostly occurred in the fictitious traffic demand scenarios with extreme peaks. For model application, these saturation levels are usually not relevant and therefore disregarded in the following analyses.

To fit the model, different function types like power function and exponential function were tested. For all analyzed freeway sections and traffic demand scenarios, the best results were achieved via the least squares method utilizing the following power function:

$$t_{loss}(x) = A \cdot x^B$$  \hspace{1cm} (4)

where:
- $t_{loss}$ = congestion-related travel time losses (veh-h)
- $x$ = volume-to-capacity ratio
- $A, B$ = model parameters
At a volume-to-capacity ratio smaller than 0.9, travel time losses are not equal to zero due to the variability of traffic demand and capacity within each interval. However, if these travel time losses are neglected, a consistent and continuous course of congestion-related travel time losses in relation to the volume-to-capacity ratio at the threshold between LOS D and E is useful for application. Therefore, both the function value and the gradient of the model function shall be equal to zero at a volume-to-capacity ratio $x = 0.9$. Eq. (4) cannot fulfill this condition.

As an alternative, a shifted power function also showed a high goodness of fit for all analyzed freeway sections and traffic demand scenarios:

$$t_{loss}(x) = A \cdot (x - 0.9)^B$$

(5)

where: $t_{loss}$ = congestion-related travel time losses (veh·h)

$x$ = volume-to-capacity ratio

$A, B =$ model parameters

This formula fulfills the requirements mentioned above and was therefore applied for the following analyses.

Adapting the model function via the least squares method, value in the range of 3 for the parameter $B$ were found for all analyzed freeway sections and traffic demand scenarios. To estimate the model parameter $A$, various differentiations of freeway characteristics were tested, including a differentiation with regard to duration curve types, location of the freeway (inside or outside urban areas), and number of lanes. Table 2 outlines the results for parameter $A$ of the model function according to Eq. (5) gained by least squares method. Depending on the kind of differentiation, a wide range of values for parameter $A$ was determined.

### TABLE 2 Calibrated values of parameter $A$ in Eq. (5) for different freeway characteristics

<table>
<thead>
<tr>
<th>Type of differentiation</th>
<th>Parameter $A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration curve type</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>42000</td>
</tr>
<tr>
<td>B</td>
<td>79000</td>
</tr>
<tr>
<td>C</td>
<td>51000</td>
</tr>
<tr>
<td>D</td>
<td>36000</td>
</tr>
<tr>
<td>E</td>
<td>60000</td>
</tr>
<tr>
<td>F</td>
<td>20000</td>
</tr>
<tr>
<td>Location</td>
<td></td>
</tr>
<tr>
<td>inside urban areas</td>
<td>34000</td>
</tr>
<tr>
<td>outside urban areas</td>
<td>64000</td>
</tr>
<tr>
<td>Number of lanes</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>60000</td>
</tr>
<tr>
<td>3</td>
<td>57000</td>
</tr>
<tr>
<td>4</td>
<td>77000</td>
</tr>
<tr>
<td>without differentiation</td>
<td>60000</td>
</tr>
</tbody>
</table>
Because of different interacting impacts, a precise differentiation with regard to specific freeway characteristics does not improve the model plausibility. With regard to this, $A = 60000$ is suggested to be used as universal parameter. The calibrated model is given in Figure 5. A more detailed determination of congestion-related travel time losses can only be carried out by conducting simulations for each individual case.

![Model function representing the congestion-related travel time losses in 1-hour intervals depending on the volume-to-capacity ratio.](image)

**FIGURE 5** Model function representing the congestion-related travel time losses in 1-hour intervals depending on the volume-to-capacity ratio.

To demonstrate the practical applicability of the derived travel time estimation model for the assessment of freeway operational strategies, the impact of dynamic hard shoulder running was analyzed for the example of a three-lane carriageway. The congestion-related travel time losses are determined with and without the application of temporary hard shoulder running for different values of the annual average daily traffic. In the example, a capacity of 5500 veh/h without hard shoulder running and 6800 veh/h with hard shoulder running, according to the HBS (2) design capacities for freeways inside urban areas with 10% percent heavy vehicles, is assumed. A typical demand time series for urban areas with a distinct morning peak on weekdays was used as input value.

By applying Eq. (5), the total travel times over one year were determined depending on the average annual daily traffic (AADT). The results in Figure 6 show that a considerable decrease of the total travel time losses is achieved for an AADT above 60000 veh/d. The economic value of the travel time savings, i.e. the difference between the curves, can be compared with the investment and operational costs for the implementation of hard shoulder running.

Based on the whole-year-analysis simulation, models to describe the impact of other operational strategies affecting the mean value and/or the variance of the capacity distribution function can be derived in the same way. Also the effects of temporary impacts on the capacity like accidents and incidents including the effect of different incident management strategies can be modeled based on random incident scenarios considered in the simulation.
5. VARIABILITY OF TRAVEL TIME LOSSES

To analyze the variability of congestion-related travel time losses, the variance and the standard deviation of travel time losses caused in each hour of the year were determined. In the simulation model, the variability of the simulation results only arises from the stochastic variability of 5-minute capacities and traffic demand volumes in the 1000 simulation runs, whereas the 1-hour demand volume is constant in each hour of the year. Thus, a relationship between the standard deviation of congestion-related travel time losses and the volume-to-capacity ratio in 1-hour intervals can be determined. Consider that the standard deviation of the total travel time losses caused in 1-hour intervals does not exactly represent the travel time reliability experienced by individual drivers, but can be regarded as a measure of the operational reliability of a freeway.

Figure 7 shows the estimated relationship between the standard deviation of congestion-related travel time losses and the volume-to-capacity ratio. As in Figure 3, the results are illustrated in 1-hour intervals for the demand scenario n50 for three example sections. Again, noticeable differences between the sections can be identified.
FIGURE 7 Standard deviation of congestion-related travel time losses in relation to the volume-to-capacity ratio for three freeway sections.

The relationship between the standard deviation of travel time losses and the average travel time losses is shown in Figure 8 by combining the data from Figure 3 and 7. The variance of travel time losses is proportional to the average travel time losses. Therefore, the relationship of the variability of travel time losses to the volume-to-capacity ratio shows a concave course of the curve which can be described with a root function (cf. Figure 8).

FIGURE 8 Standard deviation of congestion-related travel time losses in relation to the average travel time losses for three freeway sections.
6. SUMMARY AND CONCLUSIONS
Travel times on freeways consist of travel times under fluid traffic conditions depending on the segment length and congestion-related travel time losses at bottlenecks, which are independent of the bottleneck’s length. The average travel time under fluid traffic conditions can be calculated based on flow-speed-relationships. For the determination of travel time losses at bottlenecks, a model function is introduced that allows for a calculation of congestion-related travel time losses in relation to the volume-to-capacity ratio in 1-hour intervals.

The whole-year-analysis concept was used to analyze the traffic performance at 50 freeway sections. Based on the results of macroscopic simulations, a model function was developed. In contrast to empirical analyses of travel times on freeways, the macroscopic simulations allow for assigning the travel time losses to the interval in which the congestion was caused. Moreover, the random variability of congestion-related travel time losses and the associated reliability of traffic flow can be ascertained.

The simulation results show significant differences in the appearance and course of travel time losses for the analyzed sections. These differences cannot be definitely explained by the specific geometric, traffic and control conditions of the freeway. Thus, a pragmatic approach is suggested. A uniform model function representing the relation between congestion-related travel time losses and the volume-to-capacity ratio will be part of the future German Guidelines on Economic Evaluation Procedures for Road Infrastructure Projects.

ACKNOWLEDGEMENTS
The paper is partly based on research sponsored by the German Federal Ministry for Transport, Building and Urban Development, represented by the Federal Highway Research Institute, under project no. 03.440/2008/AGB. The contents of this paper solely reflect the views of the authors.

REFERENCES


