A STOCHASTIC APPROACH FOR FREEWAY PERFORMANCE ESTIMATION

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ABSTRACT

In this paper, a stochastic approach for freeway performance estimation is presented. The macroscopic model delivers performance indicators like the sum of delays, the delay per driver, the total duration of congestion and the percentage of trips under congested flow conditions. The methodology is based on a comparison of estimated annual patterns of traffic demand and capacity within a Monte Carlo simulation. The performance indicators are calculated based on a queuing model. The estimation of demand patterns considers both periodic and random components of traffic demand. The estimation of capacity patterns is based on distribution functions that represent freeway capacity for specific roadway, traffic, and control conditions. Variable influences like weather conditions and the share of heavy vehicles are considered by varying the parameters of the capacity distribution function. The whole concept is applied to frequently congested freeway sections in Germany. Based on the estimation results, the empirical relationship between different performance indicators is analyzed. The findings are used to derive appropriate target indicator values for freeway traffic management.

1. INTRODUCTION

Due to the increasing gap between traffic demand and road infrastructure supply, congestion has become an everyday feature of freeway traffic flow – particularly in urban areas. In order to achieve a purposive allocation of the limited funds for infrastructural and operational improvements, a precise performance evaluation of both the existing and planned road infrastructure is required. However, conventional performance measures like the “Level of Service” do not adequately represent different degrees of congestion. Therefore, more sophisticated approaches to quantify overload impacts are needed.

The design of road facilities is traditionally based on the analysis of one specific peak hour. The traffic demand during this single peak hour is compared with the capacity to assess the quality of traffic flow. The HCM [1] e.g. proposes to select an analysis hour between the 30th- and 100th-highest hour of a year. However, the analysis of one peak hour cannot reflect the whole life cycle of a road facility. In particular, this concept does not allow for a detailed assessment of overload impacts, as the highest demand values arising during one year are not considered. In order to overcome these limitations, Brilon [2] proposed to assess traffic flow quality over a whole year instead of the analysis of one single peak hour. A basic concept for a Whole-Year-Analysis of freeway traffic flow was implemented by Brilon and Zurlinden [3].

In this paper, the Whole-Year-Analysis concept is used to quantify different indicators representing freeway traffic performance. The model is applied to a number of frequently congested freeway sections in Germany. Based on the simulation results, the empirical relationship between different performance indicators is analyzed. For each indicator, benchmarks for freeway traffic management are proposed.

2. SIMULATION MODEL

2.1. Basic Concept

The Whole-Year-Analysis concept is based on a comparison of annual patterns of traffic demand and freeway capacity within a Monte Carlo simulation. The demand and capacity values are estimated in 5-minute intervals. 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. Incidents (accidents and vehicle breakdowns) are randomly generated based on typical accident and vehicle breakdown rates, respectively. Rainfall events are randomly generated based on monthly values for the probability of rainfall. Extreme weather conditions like heavy snowfall and ice are not considered as these rare events are not a matter of freeway performance assessment in most parts of the world.

2.2. Performance Measures

The performance of road facilities can be described by several measures, which represent different aspects of highway operation like quality of service, traffic reliability, road safety, environmental impacts or economic efficiency. A comprehensive overview of performance measures used in practice is e.g. given by Shaw [4].

The simulation model presented in this paper can be used to quantify a number of performance measures representing the quality of service on freeways. Based on a comparative analysis of different measures in terms of relevance and usefulness for traffic management as well as estimation accuracy, the following indicators were chosen for application:

- Average delay (“time losses”),
- Economic value of average delay (“time costs”),
- Total duration of congestion per year,
- Percentage of trips affected by congestion.

Time losses and time costs can be divided by the distance traveled (vehicle-kilometers) in order to allow for a comparison between freeway sections with different average traffic volumes. Time costs are estimated based on standardized expense ratios e.g. given in [5].

In contrast to conventional performance measures used in traffic engineering guidelines (e.g. density, travel speed, degree of saturation), these indicators can be applied to assess traffic flow quality over longer periods and for all possible degrees of saturation of the system. In particular, the stochastic concept provides an analytical access to a quantitative assessment of different degrees of congestion within Level of Service F.

2.3. Demand Estimation

Corresponding to the definition given in the HCM [1], traffic demand is regarded as the traffic arriving at the freeway section under investigation. It is important to consider that time series of traffic demand and traffic volume differ in case of congestion. For frequently congested freeways, traffic volumes observed in short time intervals are hence an inaccurate demand estimate.

In the simulation model, traffic demand patterns are estimated in a two-step process. First, periodic fluctuations of traffic demand are modeled by multiplying measured daily traffic volumes with typical demand patterns for different weekdays. As the duration of traffic jams is usually limited to a couple of hours or less, daily traffic volumes represent traffic demand if no significant spatial shift of traffic occurs. Typical demand patterns describe the share of hourly demand values in total daily traffic. For German freeways, such patterns were derived by Pinkofsky [6]. In a second step, the estimated demand pattern in 1-hour-intervals is transferred into 5-minute-intervals. 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 1 and a variance of 0.1.

2.4. Capacity Estimation

The estimation of freeway capacity patterns is based on the concept of stochastic capacities (cf. Brilon e.a. [7]). In contrast to traditional methodologies e.g. used in traffic engineering guidelines, capacity is regarded as a random variable and not as a constant value. The capacity values in 5-minute-intervals are randomly generated based on capacity distribution functions. Systematic influences on freeway capacity, like road geometry (number of lanes, gradient), truck percentage, weather conditions, and incidents, are considered by varying the parameters of the distribution function. The capacity reduction in case of accidents is estimated by using the corresponding percentage values of the HCM [1]. The capacity drop, thus the difference between freeway capacity before and after a breakdown, is also accounted for.

Empirical capacity distribution functions for specific roadway, traffic, and control conditions can be estimated by applying mathematical methods for lifetime data analysis (cf. Brilon and Zurlinden [3], Brilon e.a. [7]). The capacity is considered as a lifetime variable, and the breakdown of traffic flow represents the failure event. Traffic flow observations on freeways deliver pairs of values of volumes and average speeds during predetermined observation intervals. For capacity analysis, “uncensored” and “censored” intervals are distinguished. An interval i is classified as “uncensored” if the observed volume q_i causes a breakdown of traffic flow, thus the average speed drops below a specific threshold in the next interval i+1. In this case, the volume q_i is regarded as a realization of the capacity c. If traffic is fluent in interval i and remains fluent in the following interval i+1, this observation is classified as “censored”, which means that the capacity c in interval i is above the observed volume q_i. Intervals after a breakdown with an average speed below the threshold are not considered for analysis because volumes observed under congested flow conditions do not contain any information about the capacity in fluent traffic.

To estimate distribution functions based on samples that include censored data, both non-parametric and parametric methods can be used (cf. e.g. Lawless [8]). The non-parametric “Product Limit Method” (PLM) delivers a discrete distribution function, which will only reach a value of 1 if the maximum observed value is uncensored. For a parametric estimation, the function type of the distribution must be predetermined. The parameters of the distribution can be estimated by applying the Maximum-Likelihood technique. For capacity analysis, the Likelihood function is [3]:

$$L = \prod_{i=1}^{n} f_c(q_i)^{\delta_i} \cdot \left[1 - F_c(q_i)\right]^{1-\delta_i} \tag{1}$$

where $f_c(q_i)$ = statistical density function of capacity c (-)
$F_c(q_i)$ = cumulative distribution function of capacity c (-)
n = number of intervals (-)
δ_i = 1, if interval i contains an uncensored value
δ_i = 0, if interval i contains a censored value

A comparison between different function types revealed that freeway capacity is Weibull distributed [3]. The Weibull-type capacity distribution function is:

$$F_c(q) = 1 - e^{-\left(\frac{q}{\beta}\right)^{\alpha}} \tag{2}$$

where: $F_c(q)$ = capacity distribution function (-)
q = traffic volume (veh/h)
α = shape parameter (-)
β = scale parameter (veh/h)

The shape parameter α determines the variance of the distribution. For German freeway sections without a speed limit, the shape parameter amounts to approximately $\alpha = 13$. On sections with variable speed limits, greater values for α were measured, which means that the variance of the capacity distribution is reduced. The scale parameter β is proportional to the mean value of the distribution function. By varying the parameter β, all systematic influences on freeway capacity are considered in the simulation model.

A comparative analysis of deterministic and stochastic capacities for German freeways revealed that the scale parameter of the capacity distribution function in 5-minute intervals can be estimated by multiplying the capacities given in the German Highway Capacity Manual [9] by 1.275. This standardized estimation can be applied if no traffic data for an empirical estimation of the capacity distribution function are available.

2.5. Evaluation of Traffic Flow Performance

The assessment of traffic flow quality is based on a queuing model. The queue length at the beginning and the end of each 5-minute interval is determined by comparing the estimated traffic demand and capacity patterns. The principle is illustrated in Figure 1. The delays in case of congestion are calculated by multiplying the average queue length with the interval duration.

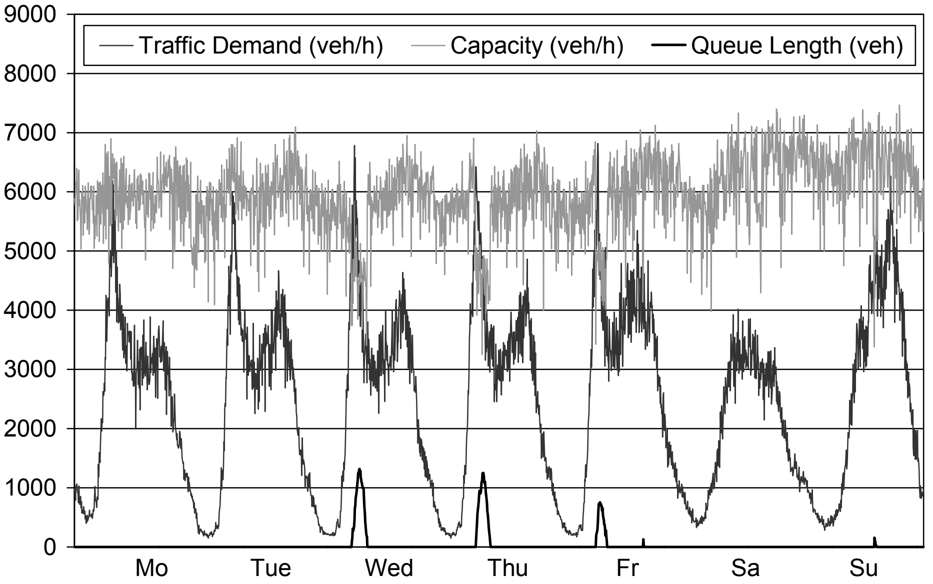

Figure 1 – Estimated traffic demand and capacity patterns and resulting queue length for one week (3-lane freeway carriageway)

The simulation model is mainly intended to quantify overload impacts. However, delays due to the speed-flow relationship in fluid traffic conditions can also be considered with a combined traffic flow model based on standardized speed-flow curves, which are varied in accordance with the random capacity variation (cf. Geistefeldt [10]).

For practical application, the Whole-Year-Analysis concept was implemented in a computer program (KAPASIM). The program estimates annual patterns of traffic demand and capacity with a random generator based on a set of input data. The comparison of traffic demand and capacity patterns is repeated several times in order to obtain average values of the performance indicators. Several subsequent sections of a freeway carriageway can be analyzed. Each section is modeled as a queuing system. The reduction of traffic volumes arriving at the downstream section i+1 in case of congestion in section i is considered by adjusting the demand time series. As the model is based on the principle of "vertical queuing", the spread of congestion is not considered. This means that all congestion impacts are assigned to the section where the traffic breakdown occurred.

3. APPLICATION FOR FREEWAY PERFORMANCE ASSESSMENT

3.1. Test Field

The application of the Whole-Year-Analysis concept for freeway performance assessment is demonstrated for a 105 km stretch of freeway A 3 between Limburg and Seligenstadt Interchange in the German Federal State of Hesse. The investigation was carried out as part of a research project on behalf of the Verkehrszentrale Hessen (Hessian Traffic Control Center). The layout of the analyzed freeway is shown in Figure 2. The freeway consists of sections with 3-lane and 4-lane carriageways, including three sections with temporary hard shoulder use. The average daily traffic is between 80000 and 140000 veh/day (sum of both directions). The high share of commuter traffic causes recurrent congestion, particularly on sections in the Frankfurt conurbation.

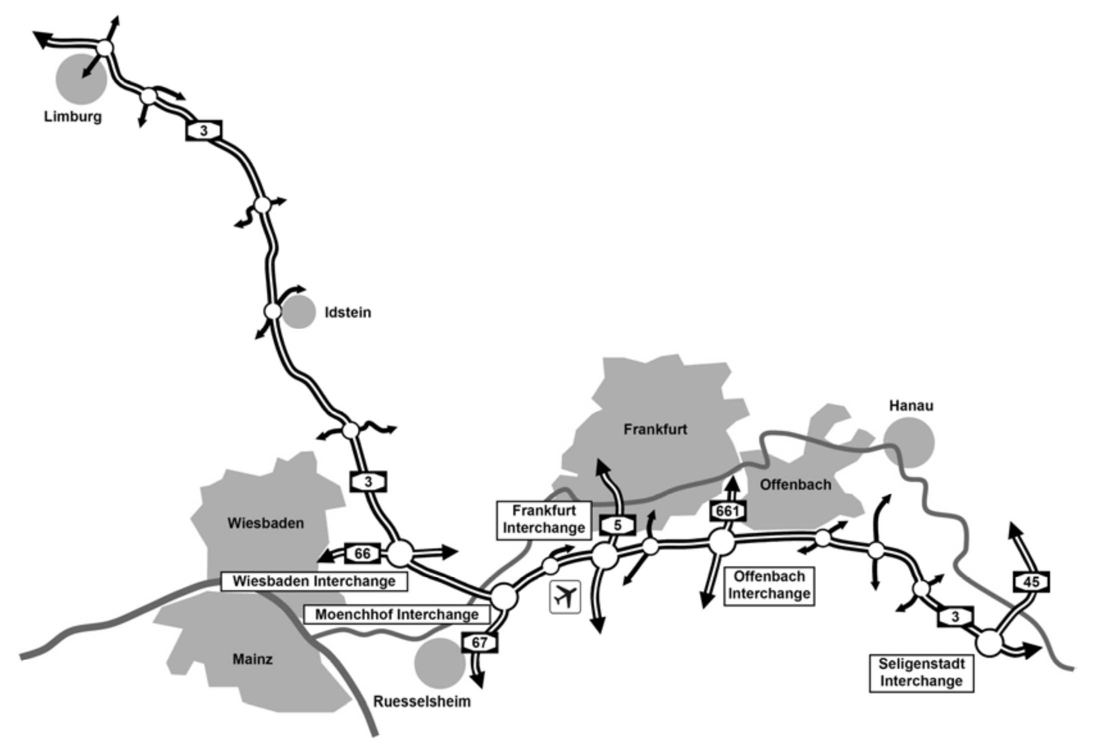

Figure 2 – Analyzed stretch of freeway A 3 between Limburg and Seligenstadt Interchange

A total of 44 carriageway sections in both directions was analyzed. For demand estimation, daily traffic volumes for the year 2005 obtained from loop detector data were used. The capacity of each section was estimated based on the specific geometric and control conditions by transferring the capacity values given in the German Highway Capacity Manual [9] into capacity distribution functions.

3.2. Estimation Results

For the analyzed carriageway sections of freeway A 3, Figure 3 shows the estimated average time losses per distance traveled and the total duration of congestion per year in dependence on the average daily traffic per lane. On sections with a traffic demand of less than about 15000 veh/day/lane, the extent of congestion is rather low. Congestion on these sections is mainly caused by accidents. If the demand exceeds 15000 veh/day/lane, the estimated extent of congestion increases significantly. The maximum average delay on freeway A 3 amounts to 3.2 sec/km, the duration of congestion is up to 300 hours per year.

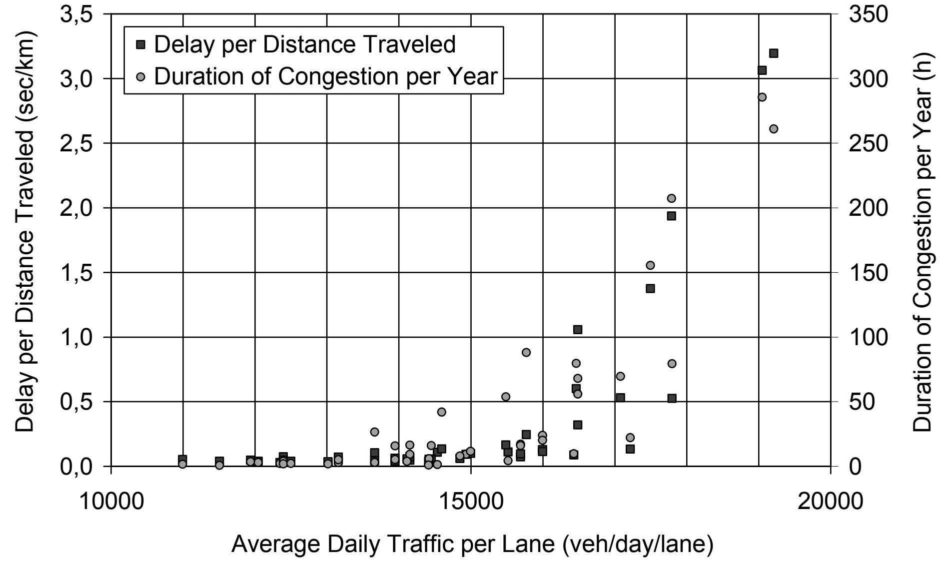

Figure 3 – Simulation results for 44 carriageway sections of freeway A 3: Delay per distance traveled and duration of congestion per year vs. average daily traffic per lane

The maximum performance indicator values were determined for the three-lane carriageway sections in both directions between junctions Hanau and Obertshausen, south-east of Frankfurt. To improve traffic flow during peak hours, the implementation of temporary hard shoulder use is planned for these sections. With the simulation model, the possible effect of this measure was estimated. The adjacent sections between junctions Obertshausen and Offenbach are already equipped with traffic control systems that allow for hard shoulder running during peak hours. Based on data obtained from these adjacent sections, the capacity increase that can be achieved by opening the hard shoulder for running traffic could precisely be estimated for the prevailing roadway, traffic and control conditions. By applying the method described in section 2.4, it was found that the mean capacity of the carriageway is increased by 20 - 25 % compared to the capacity without hard shoulder use. This capacity increase leads to a reduction of the total duration of congestion to less than 50 hours per year in both directions. Even though the additional capacity achieved by hard shoulder use partly results in a shift of congestion to the downstream sections, the total time losses are reduced by more than 50 %, representing an estimated economic benefit of about 1 Mio. € per year.

3.3. Relationships between Different Performance Measures

The estimation results for freeway A 3 were used to analyze the relationship between the performance measures specified in section 2.2. Based on regression analysis, the following findings were established:

- As time costs are calculated by multiplying delays with standardized expense ratios, there is a strong linear relationship between these indicators with a coefficient of determination of $R^2 = 0.988$. Slight deviations from the linear relationship only arise from different expense ratios for different vehicle types (passenger cars and heavy vehicles) and day types (weekdays and holidays).
- The total duration of congestion per year is almost proportional to the percentage of trips affected by congestion ($R^2 = 0.998$). The percentage of trips during congestion can roughly be estimated by multiplying the total hours of congestion per year by 0.028.
- The relationships between delay and time costs per distance traveled on the one hand and the total duration of congestion and the percentage of trips affected by congestion on the other hand are represented by quadratic functions. As an example, Figure 4 shows the relationship between delay per distance traveled and the total duration of congestion. A longer total duration of congestion is usually associated with a longer duration of single congestion incidents and thus with longer average queue lengths. Thus, the average delay per driver increases overproportionally with increasing duration of congestion.

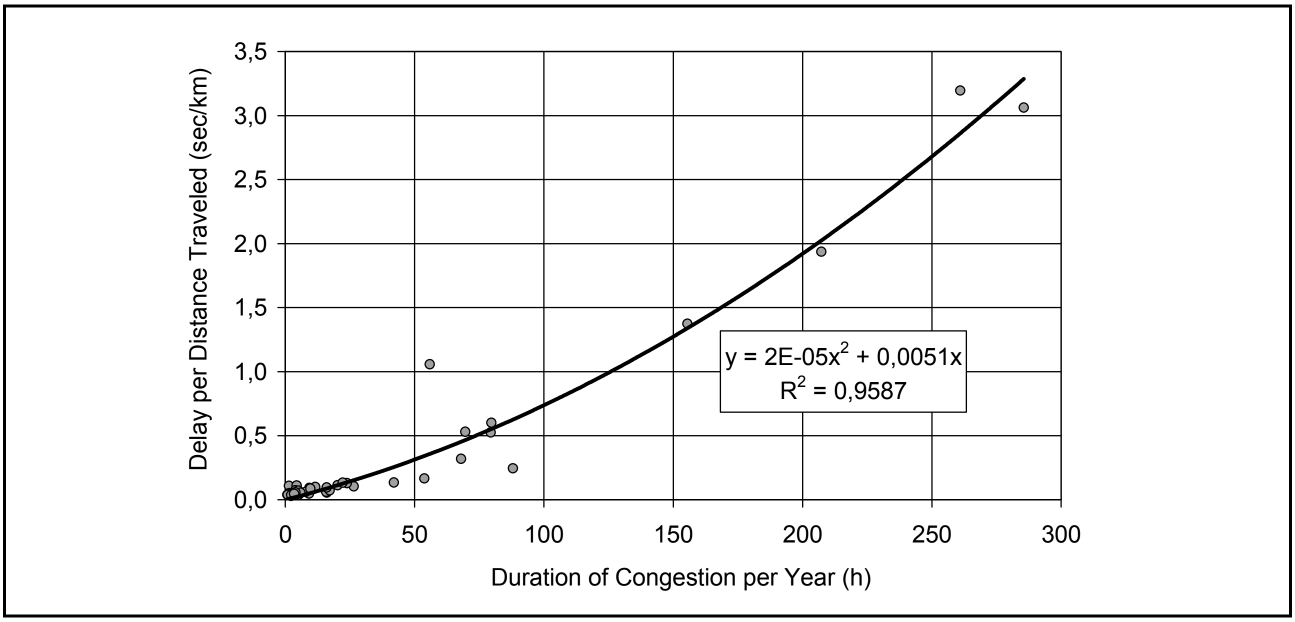

Figure 4 – Relationship between delay per distance traveled and duration of congestion per year based on the simulation results for freeway A 3

3.4. Benchmarks for Freeway Traffic Management

Based on the traffic performance assessment results for the freeway A 3, benchmarks for freeway traffic management are proposed. For each performance measure, benchmarks for a target achievement of 0 % and 100 % are given in Table 1. Between these benchmarks, a linear relationship between the indicator value and the target achievement rate can be assumed. By converting each indicator value into a target achievement rate and calculating a weighted average, a combined performance indicator can be determined.

Table 1 – Proposed benchmarks for 0 % and 100 % target achievement

Performance measure	0 % achievement	100 % achievement
Duration of congestion	250 h	10 h
Percentage of trips affected by congestion	7,0 %	0,3 %
Delay per distance traveled	2,50 sec/km	0,01 sec/km
Time costs per distance traveled	0,0050 €/(veh * km)	0,0001 €/(veh * km)

For the total duration of congestion, values of 250 and 10 hours per year were set for 0 % and 100 % target achievement, respectively. 250 hours of congestion per year are roughly equivalent to 1 hour of congestion per weekday. A duration greater than this value is deemed to be an unacceptable extent of congestion for a freeway and is therefore rated as 0 % target achievement. On the other hand, 10 hours of congestion per year can already be caused by a few incidents and hence can hardly be influenced by the operator of a freeway. A duration of congestion of less than 10 hours per year is therefore rated as 100 % target achievement. The benchmarks for the other three indicators were adjusted based on a comparative analysis of the performance indicators in order to ensure that the benchmarks for different indicators represent a comparable extent of congestion.

For the analyzed sections of freeway A 3, Figure 5 shows the relationship between the indicator-specific target achievement rates and the corresponding combined target achievement rate based on the benchmarks given in Table 1. Here, the combined rate was calculated as the non-weighted average of the four single rates. The graph shows that all indicator-specific target achievement rates roughly correspond to the combined rate and hence provide a similar performance estimate.

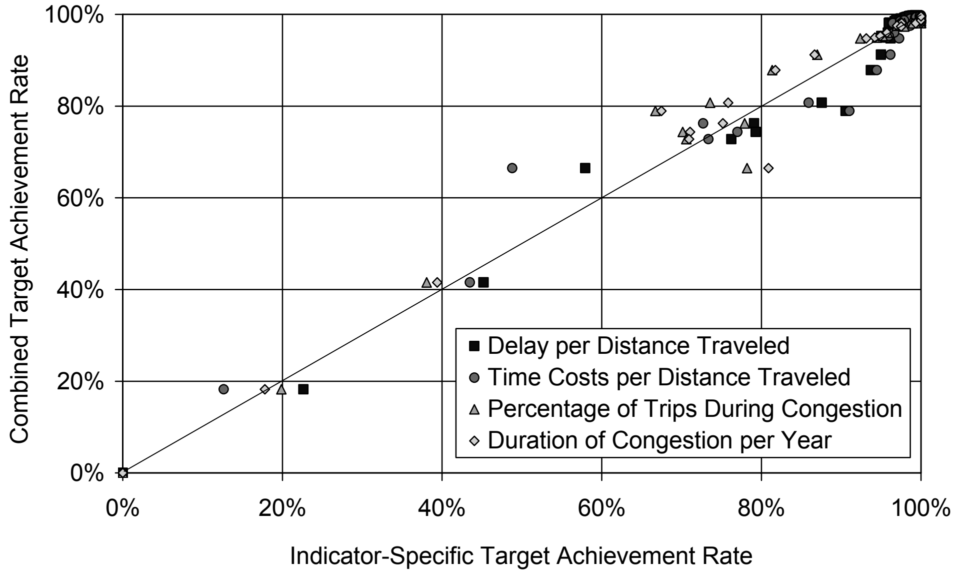

Figure 5 – Relationship between the indicator-specific target achievement rates and the combined target achievement rate for the analyzed sections of freeway A 3

4. CONCLUSIONS

The stochastic approach for freeway performance estimation presented in this paper allows for a detailed assessment of traffic flow quality for all degrees of saturation. By comparing traffic demand and capacity patterns, a number of parameters representing the performance of freeway facilities can be quantified. Each of these parameters is calculated as the expectation over one year.

With the Whole-Year-Analysis concept, a variety of construction and operational scenarios like road widening, temporary hard shoulder use or improved incident management can be analyzed. The model can also be used for theoretical investigations, e.g. for the estimation of the share of different congestion causes (high demand, accidents, road works, weather conditions) or the impact of the highest traffic volumes arising during one year on the total extent of congestion. In particular, the influence of specific geometric, traffic, and control conditions on freeway traffic flow can be evaluated based on corresponding capacity distribution functions.

Overall, the new methodology provides significant advantages for the assessment of freeway traffic performance, especially for congested networks. The concept can be used for the economic appraisal of infrastructure investments or of improved traffic management strategies. Thus, the consequences of both infrastructural and operational improvements can be estimated and compared on the same scale.

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