

IMPLEMENTING THE CONCEPT OF RELIABILITY FOR HIGHWAY CAPACITY ANALYSIS

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ABSTRACT

In this paper, a stochastic concept for highway capacity analysis is presented. Instead of constant-value capacities, the capacity of a highway facility is regarded as a random variable. Thus, the stochastic approach provides new measures of traffic flow performance based on aspects of traffic reliability. A methodology for the estimation of capacity distribution functions from empirical data based on statistical methods for lifetime data analysis is introduced. This method is derived for the analysis of freeway capacity. However, it is shown that the stochastic approach is also applicable to intersections. The analysis of data samples from freeway sections in Germany yields that freeway capacity is Weibull distributed with a considerable variance. Based on the stochastic description of capacity, a Monte-Carlo technique is proposed to quantify freeway traffic performance over a whole year. This technique also provides a quantitative assessment for oversaturated conditions.

INTRODUCTION

In the HCM 2000 (1), capacity is defined as the maximum possible expected throughput of the highway element under consideration. For well-defined external conditions, capacity is treated as a constant value. This traditional understanding of highway capacity is used in most of the traffic engineering guidelines around the world (e.g. the German HBS (2)). Most users of such manuals in practice believe in the precision of these guidelines. However, it is obvious that capacities indicated in guidelines do not describe real road facilities performance with a precision up to the last digit. Instead, the given capacities only offer a rough estimation of realistic maximum flows. For a more detailed analysis of traffic flow, however, it is important to consider the extend to which the actual maximum traffic volumes can differ from the given expectations.

For freeways, several authors (3, 4, 5, 6, 7, 8) have already demonstrated that the maximum traffic throughput varies – even under constant external conditions. To determine the variability of capacities, most of these authors observed breakdowns of traffic flow and identified the traffic volume during the time interval preceding the breakdown. This volume, which seemed to cause the breakdown, varied rather significantly. These observations verified that the maximum possible throughput could deviate from given capacities over a remarkably wide range.

In contrast to freeways, high volume traffic flow at intersections is not characterized by random occurrence of traffic breakdowns. Nevertheless, randomness of intersection capacity due to variable driver's behavior and interactions between vehicles is to be expected.

In this paper, a stochastic concept for highway capacity analysis is introduced. Instead of constant-value capacities, highway capacity is regarded as a random variable. The paper presents the mathematical methodology for the estimation of capacity distribution functions from empirical data as well as the consequences for practical application. The whole concept is mainly intended for the analysis of freeway capacity. However, it is shown that the methodology is also applicable to intersections. The stochastic approach provides new measures of traffic flow performance based on aspects of traffic reliability.

TRADITIONAL CONCEPT OF CAPACITY

Although the traditional understanding of capacity is well known to experts, it should be shortly summarized in contrast to the stochastic concept. For freeways, the derivation of guidelines like the HCM (1) or the HBS (2) is based on flow-speed diagrams, which represent measured data. The observed data points are described by useful analytical functions. The volume at the apex of this curve is treated as the capacity, which represents the maximum throughput of the facility. As an example, Figure 1 shows the flow-speed diagram of the two-lane section of freeway A1 north of Cologne, Germany. The traffic flow model of van Aerde (9) delivers a capacity of 3570 veh/h. However, several data points beyond this capacity could be observed. These values cannot be explained by the conventional model in more detail.

Even the conventional approach of traffic flow analysis based on the flow-speed relationship reveals that the capacity significantly depends on the duration of the analysis interval (10, 11). Temporary external conditions like weather or driver population also contribute to different capacities at different times for the same point of the network (11).

STOCHASTIC CONCEPT OF FREEWAY CAPACITY

The HCM (1) defines the capacity as the maximum flow rate that can reasonably be expected to traverse a facility under prevailing roadway, traffic, and control conditions. This definition can be modified without changing too much of the original meaning: Capacity is the maximum flow rate up to which acceptable traffic performance of the facility is achieved and beyond which – in case of greater demand – unacceptable traffic conditions arise. The transition between acceptable and unacceptable flow conditions on uninterrupted flow facilities is called a breakdown. On a freeway, such a breakdown is characterized by a sudden reduction of the average travel speed from an acceptable level of about 70 km/h or more to a much lower value representing congested conditions.

From this definition, it becomes comprehensible that capacity is by no means a constant value. In a critical traffic situation on a homogeneous freeway section, the breakdown can be caused by specific kinds of behaviors of individual drivers together with the local formation of the traffic flow pattern. Thus, not only the macroscopic traffic flow parameters like volume or density determine the breakdown. Also unpredictable events like speed reductions of individual drivers or lane changes may cause a deceleration of following vehicles and, in consequence, a local concentration that could initiate a breakdown. The occurrence of such events has all properties of randomness. Therefore, the traffic volume at which a breakdown is initiated can be treated as a random variable.

To make this concept of randomness of capacity usable, it is necessary to know more about the distribution function of the capacity. The authors have implemented a methodology for the derivation of freeway capacity distribution functions (12, 13). This method is based on statistical methods commonly used for lifetime or failure data analysis. It delivers a numerical solution for the cumulative distribution function of the capacity c , which is considered as a lifetime variable:

$$F_c(q) = p(c \leq q) \quad (1)$$

where $F_c(q)$ = capacity distribution function (-)
 c = capacity (veh/h)
 q = traffic volume (veh/h)

Observations of traffic flow on freeways deliver pairs of values of traffic volumes and average speeds during predetermined observation intervals. For capacity analysis, the following types of intervals are distinguished:

B: Traffic during interval i is fluid, but the observed flow causes a breakdown; i.e. the average speed drops down to a level of less than a specific threshold speed in the following time interval $i + 1$. The volume during interval i is regarded as a realization of the capacity c .

F: Traffic is fluid during interval i and the following interval $i + 1$. Thus, the capacity during interval i is greater than the observed volume q_i . This type of data is referred to as “censored data”.

C: Traffic is congested during interval i and the preceding interval $i - 1$, i.e. the average speed is below the threshold value. This interval i provides no information about the capacity. It is not further regarded.

The differentiation of fluid and congested traffic is based on a specific threshold speed, which marks the gap between the upper and the lower branch of the flow-speed diagram. Values between 70 and 80 km/h were found to be fairly representative for German freeways. This threshold value may, however, be different for other types of roads. In some cases, more detailed approaches to identify traffic breakdowns might be required.

The intervals of classification C are not considered for analysis because volumes observed under congested flow conditions do not contain any information about the capacity before a breakdown. Other authors (4, 14) defined the breakdown capacity as the traffic volume measured downstream of a queue at a bottleneck. In consequence, each interval during congestion was regarded as a B-interval. However, the maximum volume in fluid traffic usually differs from the maximum volume observed during congestion (11, 12, 15, 16, 17). Therefore, the consideration of congested intervals seems not to be reasonable.

Statistical methods for lifetime data analysis can generally be applied to estimate distribution functions based on samples that include censored data. A non-parametric method to estimate the distribution function of lifetime variables is the so-called “Product Limit Method” (PLM) by Kaplan and Meier (18). Based on this approach, the capacity distribution function can be estimated by:

$$F_c(q) = 1 - \prod_{i: q_i \leq q} \frac{k_i - d_i}{k_i}; i \in \{B\} \quad (2)$$

where $F_c(q)$ = capacity distribution function (-)
 q = traffic volume (veh/h)
 q_i = traffic volume in interval i (veh/h)
 k_i = number of intervals with a traffic volume of $q \geq q_i$ (-)
 d_i = number of breakdowns at a volume of q_i (-)
 $\{B\}$ = set of breakdown intervals (classification B, see above)

The product within this equation is calculated over all observed time intervals i with a traffic volume $q_i < q$ that were followed by a traffic breakdown. Usually, each observed breakdown is used as one q_i -value, so that d_i is always equal to 1. The distribution function will only reach a value of 1 if the maximum observed volume is a B-value (i.e. a breakdown was following). Otherwise, the distribution function terminates at a value of $F_c(q) < 1$. In this case, the method does not allow estimating the function $F_c(q)$ completely.

To receive a complete distribution function, a parametric estimation based on the Maximum-Likelihood technique can be applied (19). In this case, the type of the distribution function has to be predetermined. A comparison between different mathematical types of functions revealed the best results for the Weibull distribution (12). The Weibull-type capacity distribution function is:

$$F_c(q) = 1 - e^{-\left(\frac{q}{\beta}\right)^\alpha} \quad (3)$$

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

The expectation $E(c)$ and variance $\sigma^2(c)$ of the capacity distribution are given by:

$$E(c) = \beta \cdot \Gamma\left(1 + \frac{1}{\alpha}\right) \quad (4)$$

$$\sigma^2(c) = \beta^2 \cdot \left\{ \Gamma\left(1 + \frac{2}{\alpha}\right) - \left[\Gamma\left(1 + \frac{1}{\alpha}\right) \right]^2 \right\} \quad (5)$$

where $\Gamma(x)$ = Gamma function at point x

The parameters α and β of the distribution function can be estimated by maximizing the Likelihood Function L (or its natural logarithm):

$$L = \prod_{i=1}^n f_c(q_i)^{\delta_i} \cdot [1 - F_c(q_i)]^{1-\delta_i} \quad (6)$$

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 (classification B)
 δ_i = 0, if interval i contains a censored value (classification F)

For the stochastic analysis of freeway capacity, only rather short observation intervals are useful. Otherwise there is only little causality between the traffic volume and the breakdown. Therefore, e.g. 1-hour counts are not adequate. With respect to the availability of reliable loop detector data and in consideration of the use of the results within the Whole-Year-Analysis concept (cf. the following section), an interval duration of $\Delta t = 5$ minutes was found to be a good compromise. However, the methodology is also applicable to 15-minute data.

For the estimation of a capacity distribution function based on data measured at a specific cross section, it should be ensured that all traffic breakdowns observed at this point were caused within the freeway section under observation. At clearly detectable bottlenecks as shown in Figure 2a, breakdowns observed directly upstream of the bottleneck should only be generated due to an oversaturation of the bottleneck itself. Spillback from downstream should not occur since a larger capacity is always available on the succeeding section. At freeway sections without a distinct bottleneck as shown in Figure 2b, traffic breakdowns due to a spillback from downstream should be excluded by analyzing a second cross section downstream of the section

under investigation (17). If the speed data of the downstream cross section indicates congested flow at the time when a traffic breakdown is observed at the measurement cross section, this breakdown event is not considered for capacity analysis.

The stochastic methodology for capacity analysis was applied to several freeway sections in Germany (12, 17). For the case of freeway sections without a speed limit, it was found that the shape parameter of the Weibull-type distribution roughly amounts to $\alpha \approx 13$. A constant shape parameter α means that the standard deviation $\sigma(c)$ of the capacity distribution function is proportional to the expectation $E(c)$ (cf. Equations (4) and (5)).

As an example, Figure 3 shows the estimated capacity distribution functions for two cross sections along the ring of freeways around the city of Cologne, Germany. Both sites are geometric bottlenecks according to Figure 2a with a road widening downstream of the observation point. Speed-flow data in 5-minute intervals for the whole year 2000 were analyzed, including 933 breakdowns on the A1 freeway and 834 breakdowns on the A3 freeway. As the highest observed volumes were not followed by a breakdown, the Product-Limit estimation already ends at a cumulative probability of less than 1 in both cases. Nevertheless, the Product-Limit estimations fit very well into the Weibull distribution functions estimated with the Maximum-Likelihood technique. For the two-lane freeway A1, a distribution function with parameters $\alpha = 14.1$ and $\beta = 4532$ veh/h was estimated. For the three-lane freeway A3, the Maximum-Likelihood estimation delivered a distribution function with parameters $\alpha = 12.1$ and $\beta = 7170$ veh/h. Statistical parameters of the estimated capacity distribution functions are given in Table 1.

As the capacity distribution function represents the probability of a traffic breakdown during a single 5-minute interval, even a relatively small function value means that a breakdown is likely to occur within a few intervals. Thus, only a small percentile of the distribution should be used as a design value comparable to capacities given in guidelines like the HCM (1). For the example of freeway A1, the comparison of the conventional capacity estimate as given in Figure 1 and the capacity distribution function for the same section as shown in Figure 3a yields that the conventional capacity estimated based on 1-hour intervals is roughly equal to the 5th percentile of the capacity distribution.

In contrast to constant-value capacities, the stochastic concept of capacity allows for a more detailed assessment of specific impacts on freeway traffic flow. The methodology was e.g. used to investigate differences in performance between dry and wet road surface (12, 17). It was found that on wet road surface the capacity was reduced by around 12 % compared to dry conditions. Also, the effects of darkness were investigated. Contrary to Ponzlet's results (11), it could be shown that darkness did not shift the capacity distributions.

The stochastic approach also provides a theoretical explanation for the dependance of freeway capacity on the interval duration. The fact that the shape parameter α is roughly constant allows for a transformation of the capacity distribution function between different interval durations (13). Based on Weibull-distributed 5-minute capacities (parameters $\alpha_5 = 13$ and β_5), the 60-minute capacities are also Weibull-distributed with an unchanged shape parameter $\alpha_{60} = 13$ and a scale parameter $\beta_{60} = r \cdot \beta_5$, where $r = 12^{-1/\alpha} \approx 0.83 \approx 1/1.2$. Thus, for 5-minute observations, the expected capacity should be in a range of 1.2 times the 1-hour capacity. A

similar empirical ratio between 5-minute and 1-hour capacities was already found by Keller and Sachse (10) or Ponzlet (11) based on conventional capacity estimations.

WHOLE-YEAR-ANALYSIS

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 the limitations of the traditional design methodology, Brilon (20) proposed to assess traffic flow quality over a whole year instead of the analysis of one single peak hour. A basic concept for the Whole-Year-Analysis of freeway traffic flow was implemented by Zurlinden (12). The method is based on a comparison of annual patterns of traffic demand and freeway capacity. The sum of delays over a whole year or the total duration of congested flow conditions during a year are used as measures of traffic flow performance. The sum of delays can be transferred into economic costs and may be applied in cost/benefit-analyses. The estimation of demand and capacity patterns considers both systematic and stochastic components. Hence, the stochastic concept of capacity plays a key role in this approach.

The main features of the Whole-Year-Analysis concept are:

- The comparison of demand and capacity patterns is based on 5-minute intervals.
- Systematic fluctuations of traffic demand are modeled by multiplying daily traffic volumes with typical demand patterns for different weekdays. Typical demand patterns describe the share of hourly demand values in total daily traffic. The required daily traffic volumes can be obtained either from loop detector data for an existing freeway or – if no traffic data are available – by using typical demand patterns over a week and a year, which are available for the German freeway network (21). 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.
- The estimation of annual patterns of freeway capacity is based on capacity distribution functions estimated by applying the stochastic concept presented in the previous section. For the shape parameter representing the variance of the capacity distribution, the value of $\alpha = 13$, which was found to be representative for freeways with unlimited speeds, is applied. All relevant systematic influences on freeway capacity, like road geometry (number of lanes, gradient), weather conditions, and incidents, are considered by varying the scale parameter β of the capacity distribution function. The capacity drop, thus the difference of freeway capacity before and after a breakdown, is also accounted for.
- Incidents (accidents and car breakdowns) are randomly generated based on typical accident and car breakdown rates, respectively. The capacity reduction in case of accidents is estimated by using the corresponding percentage values of the HCM (1).

- 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 should not be an aspect of highway dimensioning in most parts of the world.
- The assessment of traffic flow quality is based on a simple queuing model. The queue length at the beginning and the end of each 5-minute-interval can be determined by comparing the estimated traffic demand and capacity patterns. The delays (“time losses”) in case of congestion are calculated by multiplying the average queue length with the interval duration. Delays due to the speed-flow relationship under flowing traffic conditions can be considered with a combined traffic flow model based on standardized speed-flow curves, which are varied in accordance with the random capacity variation (22).

For practical application, the Whole-Year-Analysis concept was implemented in a computer program (KAPASIM) using a Monte-Carlo simulation technique. The program is able to model the annual patterns of traffic demand and capacity and to calculate time losses and the total duration of congested flow conditions during one year. Several subsequent sections of a freeway, each representing a distinct or virtual bottleneck (cf. Figure 2), can be analyzed. As an example, Figure 4 shows the comparison of estimated traffic demand and capacity patterns over one week for a three-lane freeway section.

The Whole-Year-Analysis can be used for a variety of practical applications like the economic analysis of road construction projects, the estimation of the share of different congestion causes (high demand, accidents, road works, bad weather conditions) to improve road management strategies or the evaluation of improved incident management. In particular, the impact of specific geometric, traffic and control conditions on traffic flow can be evaluated. The computer tool KAPASIM was e.g. prepared for application for the optimization of freeway construction zone planning strategies in two German Federal States (Hesse and Saar).

Overall, the Whole-Year-Analysis is an improved method for the economical assessment of freeway planning schemes, since in comparison between two alternative solutions (one of which could be the existing situation), a rather precise estimation of travel time consumption is achieved. Moreover, the method provides an estimation of several other parameters to describe the reliability of freeway operation like the risk of being significantly delayed by congestion or the number of traffic breakdowns. Each of these parameters is given as the expectation over one year. These measures allow for an assessment of traffic performance 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 LOS F.

APPLICATION TO INTERSECTIONS

Although traffic flow at intersections is mainly determined by the deterministic impact of traffic control, intersection capacity is also influenced by the randomness of driver’s behavior and interactions between vehicles. At a roundabout entry, for instance, the number of vehicles entering from one approach (with a constant queue in the entry) at a specific traffic volume on the circle varies from one time interval to the next, as observations show. Since usually the traffic volume departing from a continuous queue on the entry is assumed to be an observation of the capacity, this experience is a clear indication of random variability of the entry capacity.

For the description of this phenomenon, the same concept as described in the previous paragraphs of this paper can be used. Equations (2) and (6) can be applied also on volumes q and capacities c for a movement at an intersection. For the classification of a breakdown, however, a different definition is required. Here, an interval that has an uninterrupted queue on the entry lane(s) is classified as a B-type interval according to Equation (2). Then all the evaluations and estimation techniques can be applied as described above.

As an example, one data set from a larger single-lane roundabout in Sindorf, Germany, is analyzed. For two entries with nearly identical geometric conditions, video observations of several hours were analyzed based on 1-minute intervals. For each interval i , the number of circulating vehicles $q_{c,i}$ (veh/min), the number of entering vehicles $q_{e,i}$ (veh/min), plus the information

$$\begin{aligned} d_i &= 1 \quad \text{continuous queue in the entry (i.e. all headways between entering vehicles} < 4 \text{ s)} \\ d_i &= 0 \quad \text{elsewhere} \end{aligned}$$

were evaluated.

The conventional method to estimate the capacity would be to perform a regression of $q_e = \text{function}(q_c)$ with values obtained during fully saturated intervals (i.e. with $d_i = 1$). The data points for the example together with a linear and an exponential regression are illustrated in Figure 5. Some points represent more than one observation. The diagram illustrates that for one q_c -value, rather different values for the saturated entry flow q_e were observed.

For each q_c -value, the corresponding distribution of the capacity $c = q_{e,\max}$ was evaluated using the Product Limit technique given in Equation (2). The data contain 870 1-minute intervals, including 191 saturated intervals as represented in Figure 5. The results of the Product-Limit estimation are shown in Figure 6. From the fact that all the estimated functions do not continue up to $F(q_e) = 1$, it reveals that in all cases the highest observed entry flows did not occur during a saturated interval. For larger q_c , the distribution function has a tendency towards lower q_e -values. The curves are not sufficiently smooth due to the limited number of oversaturated intervals for each q_c -value.

As an approach to describe the capacity distribution over the whole range of q_c -values by one equation, it was assumed that for each q_c -value the capacity of the entry is Weibull-distributed, since Weibull is the characteristic function type to describe lifetime distributions. The scale parameter β , which represents the expected capacity, should be related to the circulating flow comparable to the findings given in Figure 6. Here, like in many applications for roundabout empirical regression, an exponential relation is used:

$$\beta = A \cdot e^{-Bq_c} \tag{7}$$

where β = scale parameter of the Weibull-distribution (veh/min)
 q_c = circulating traffic volume (veh/min)
 A, B = parameters of the model, to be calibrated

With this, the distribution function for the roundabout entry capacity is

$$F(x) = 1 - e^{-\left(\frac{x}{A \cdot e^{-Bq_c}}\right)^\alpha} \tag{8}$$

The shape parameter α of the Weibull-distribution is also a matter of calibration. With these assumptions, Equation 6 was used for estimating the distribution parameters. The result for the sample under investigation was: $\alpha = 3$, $A = 21$, $B = 0.04$. The Weibull density and distribution functions are illustrated by 3-dimensional plots in Figure 7. The variance of the capacity distribution significantly decreases with increasing q_c . This effect is, however, determined by the assumed formulation of the Weibull-distribution. Possibly the shape parameter α could also be a function of q_c . This might be studied by further empirical work with larger samples.

This example should illustrate: The stochastic concept of capacity, which was initially derived for freeway facility analysis, can also be used to estimate the capacity of intersections. This concept provides better plausibility than the assumption of constant-value capacities. For intersections, the same mathematical estimation technique based on the statistics of lifetime data analysis can be applied. If the concept of randomness is accepted, this has also implications for delay estimation, since constant capacities are usually the basis for the derivation of delay formulas (23, 24). Thus, the implications of random capacities on delay distributions should be investigated by further research.

CONCLUSIONS

The stochastic concept of highway capacity presented in this paper seems to be more realistic and more useful than the traditional use of constant-value capacities. The probabilistic approach provides an improved understanding for the variability of maximum highway traffic flows.

A methodology for the estimation of distribution functions of freeway capacity based on the statistics of lifetime data analysis was introduced. It was found that the capacity of a freeway section can be treated as a Weibull-distributed random variable. For German freeways with unlimited speed conditions, the shape parameter of the Weibull distribution seems to be in a range of 13, whereas the scale parameter depends on the specific characteristics of the analyzed freeway section.

The concept of random capacities was included into a Monte-Carlo simulation for a Whole-Year-Analysis of freeway traffic flow. This method delivers parameters like the sum of time losses or hours with congestion. The approach can e.g. be used for the economic appraisal of alternative freeway planning schemes or for the assessment of traffic management strategies.

The stochastic concept of capacity can also be applied to intersections. A distribution function of the entry capacity of a roundabout depending on the circulating flow volume was estimated by applying the new methodology.

Overall, it is expected that the random interpretation of highway capacity offers the potential for improved traffic engineering methodologies. As the capacity distribution function represents the probability of a traffic breakdown at a given flow rate (for the case of freeways), the stochastic method provides measures that describe traffic reliability.

REFERENCES

1. TRB. *Highway Capacity Manual*. Transportation Research Board, Washington D.C., 2000.
2. FGSV. *Handbuch fuer die Bemessung von Strassenverkehrsanlagen (German Highway Capacity Manual)*. Forschungsgesellschaft fuer Strassen- und Verkehrswesen, Cologne, 2001.
3. Elefteriadou, L., R. P. Roess, and W. R. McShane. Probabilistic Nature of Breakdown at Freeway Merge Junctions. *Transportation Research Record, No. 1484*, Transportation Research Board, National Research Council, Washington D.C., 1995.
4. Minderhoud, M. M., H. Botma, and P. H. L. Bovy. Roadway Capacity Estimation Methods Explained and Assessed. *Transportation Research Record, No. 1572*, Transportation Research Board, National Research Council, Washington D.C., 1997.
5. Persaud, B., S. Yagar, and R. Brownlee. Exploration of the Breakdown Phenomenon in Freeway Traffic. *Transportation Research Record, No. 1634*, Transportation Research Board, National Research Council, Washington D.C., 1998.
6. Kuehne, R. D., and N. Anstett. Stochastic Methods for Analysis of Traffic Pattern Formation. *Proceedings of the 14th International Symposium on Transportation and Traffic Theory*, Jerusalem, 1999.
7. Lorenz, M., and L. Elefteriadou. A Probabilistic Approach to Defining Freeway Capacity and Breakdown. *Proceedings of the 4th International Symposium on Highway Capacity*, TRB-Circular E-C018, Transportation Research Board, Washington D.C., 2000.
8. Okamura, H., S. Watanabe, and T. Watanabe. An Empirical Study on the Capacity of Bottlenecks on the Basic Suburban Expressway Sections in Japan. *Proceedings of the 4th International Symposium on Highway Capacity*, TRB Circular E-C018, Transportation Research Board, Washington D.C., 2000.
9. van Aerde, M. A Single Regime Speed-Flow-Density Relationship for Freeways and Arterials. *Proceedings of the 74th TRB Annual Meeting*, Washington D.C., 1995.
10. Keller, H., and T. Sachse. Einfluss des Bezugsintervalls in Fundamentaldiagrammen auf die zutreffende Beschreibung der Leistungsfähigkeit von Straßenabschnitten (Influence of Aggregation Intervals on the Fundamental Diagram for the Description of Roadway Capacity). *Forschung Strassenbau und Strassenverkehrstechnik, No. 614*. Bonn, 1992.
11. Ponzlet, M. *Dynamik der Leistungsfähigkeiten von Autobahnen (Dynamics of Freeway Capacity)*. Doctoral Thesis No. 16, Institute for Transportation and Traffic Engineering, Ruhr-University Bochum, 1996.
12. Zurlinden, H. *Ganzjahresanalyse des Verkehrsflusses auf Straßen (Whole-Year-Analysis of Highway Traffic)*. Doctoral Thesis No. 26, Institute for Transportation and Traffic Engineering, Ruhr-University Bochum, 2003.
13. Brilon, W., J. Geistefeldt, and M. Regler. Reliability of Freeway Traffic Flow: A Stochastic Concept of Capacity. *Proceedings of the 16th International Symposium on Transportation and Traffic Theory*, College Park, Maryland, 2005.
14. van Toorenburg, J. *Praktijwaarden voor de capaciteit*. Rijkswaterstaat dienst Verkeerskunde, Rotterdam, 1986.
15. Banks, J. H. Flow Processes at a Freeway Bottleneck. *Transportation Research Record, No. 1287*, Transportation Research Board, National Research Council, Washington D.C., 1990.

16. Hall, F. L., and K. Agyemang-Duah. Freeway Capacity Drop and the Definition of Capacity. *Transportation Research Record*, No. 1320, Transportation Research Board, National Research Council, Washington D.C., 1991.
17. Regler, M. *Verkehrsablauf und Kapazität auf Autobahnen (Freeway Traffic Flow and Capacity)*. Doctoral Thesis No. 28, Institute for Transportation and Traffic Engineering, Ruhr-University Bochum, 2004.
18. Kaplan, E. L., and P. Meier. Nonparametric estimation from incomplete observations. *Journal of the American Statistical Association*, Vol. 53, pp. 457-481, Alexandria (VA), 1958.
19. Lawless, J. F. *Statistical Models and Methods for Lifetime Data*. Wiley, New York, 2003.
20. Brilon, W. Traffic Flow Analysis beyond Traditional Methods. *Proceedings of the 4th International Symposium on Highway Capacity*, TRB Circular E-C018, Transportation Research Board, Washington D.C., 2000.
21. Pinkofsky, L. Ganglinientypen (Typed traffic demand patterns). *Verkehrsentwicklung auf Bundesfernstraßen 2000 – Jahresauswertung der automatischen Dauerzählstellen*. Berichte der Bundesanstalt für Straßenwesen, Issue V 99, pp. 15-32, Bergisch Gladbach, 2002.
22. Geistefeldt, J. Schätzung von Reisezeiten auf Autobahnen unter Verwendung eines erweiterten Verkehrsflussmodells (Estimation of Travel Times on Freeways based on an Enhanced Traffic Flow Model). *Proceedings of the conference HEUREKA '05*, Forschungsgesellschaft fuer Strassen- und Verkehrswesen, Cologne, 2005.
23. Kimber, R. M., and E. M. Hollis. Traffic queues and delays at road junctions. *TRRL Laboratory Report, LR 909*, Crowthorne, 1979.
24. Akcelik, R., and R. J. Troutbeck. Implementation of the Australian roundabout analysis method in SIDRA. *Highway Capacity and Level of Service, Proceedings of the International Symposium on Highway Capacity*, Balkema, Rotterdam, Brookfield, 1991.

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FIGURE 2 Types of bottlenecks.

FIGURE 3 Estimated capacity distribution functions for two freeway bottleneck sections (5-minute intervals).

FIGURE 4 Estimated traffic demand and capacity patterns and resulting queue length for a 3-lane freeway.

FIGURE 5 Example of an empirical regression solution for the capacity of a single-lane entry into a single-lane roundabout.

FIGURE 6 Distributions of entry capacity $c = q_{e,max}$ for different circulating volumes q_c (volumes in veh/min).

FIGURE 7 Estimated Weibull-type density and distribution function of the roundabout entry capacity depending on the circulating volume q_c (volumes in veh/min).

TABLE 1 Statistical parameters of the estimated capacity distribution functions

Freeway	Expected value	Standard deviation	Median	5th percentile
A1 North Cologne	4367 veh/h	379 veh/h	4416 veh/h	3671 veh/h
A3 East Cologne	6874 veh/h	690 veh/h	6956 veh/h	5609 veh/h

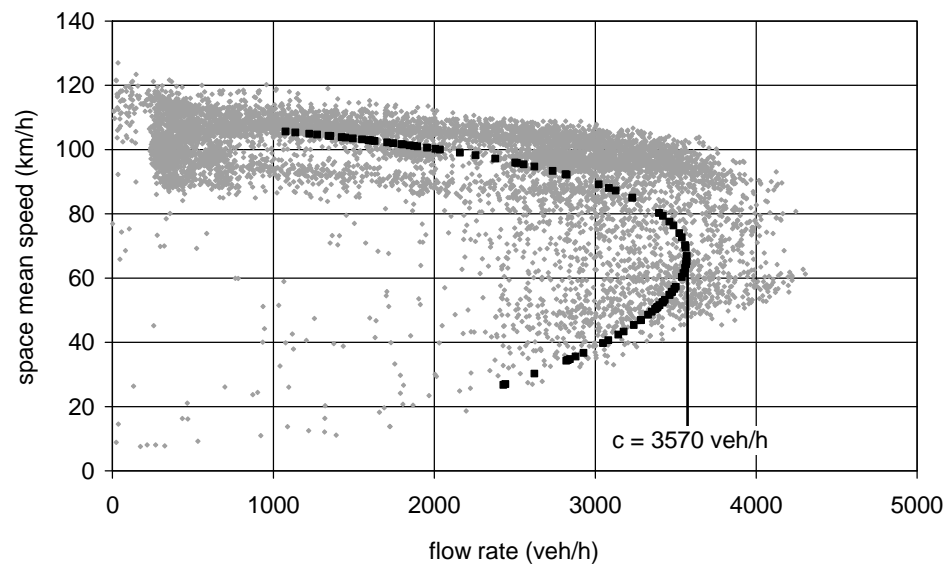


FIGURE 1 Flow-speed diagram of freeway A1 north of Cologne (1-hour intervals).

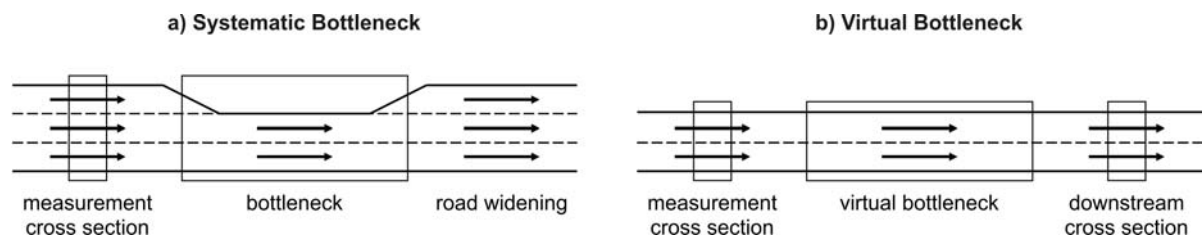


FIGURE 2 Types of bottlenecks.

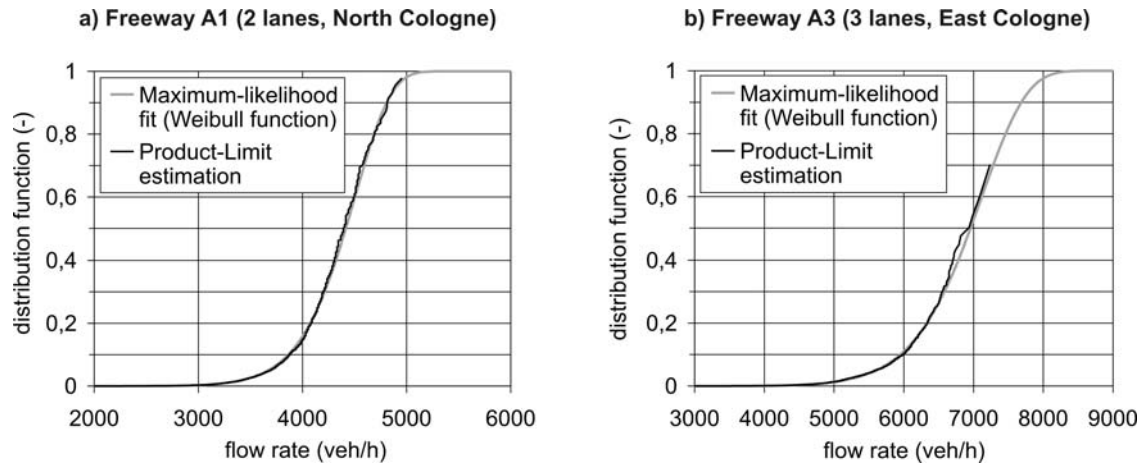


FIGURE 3 Estimated capacity distribution functions for two freeway bottleneck sections (5-minute intervals).

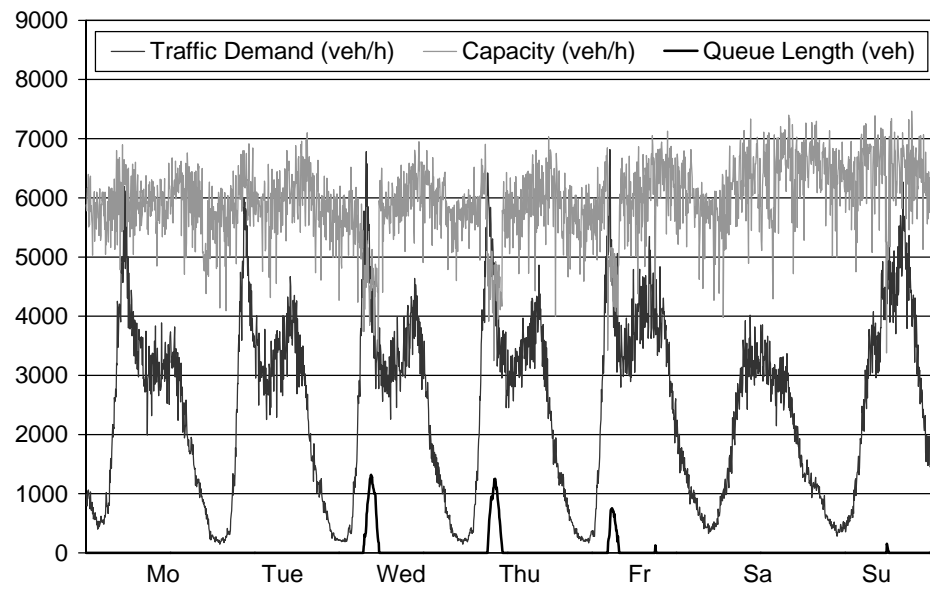


FIGURE 4 Estimated traffic demand and capacity patterns and resulting queue length for a 3-lane freeway.

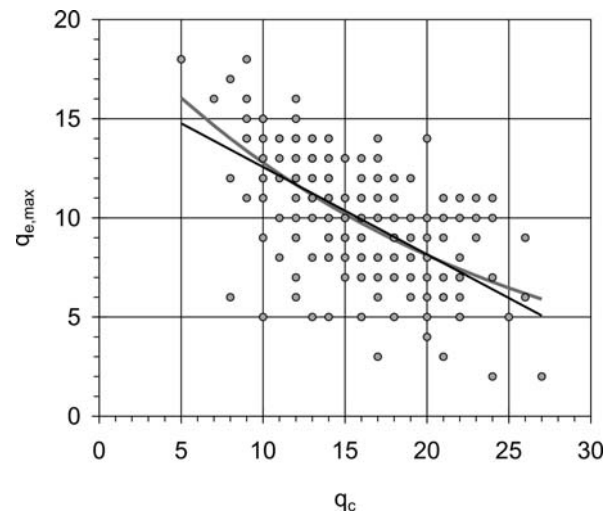


FIGURE 5 Example of an empirical regression solution for the capacity of a single-lane entry into a single-lane roundabout.

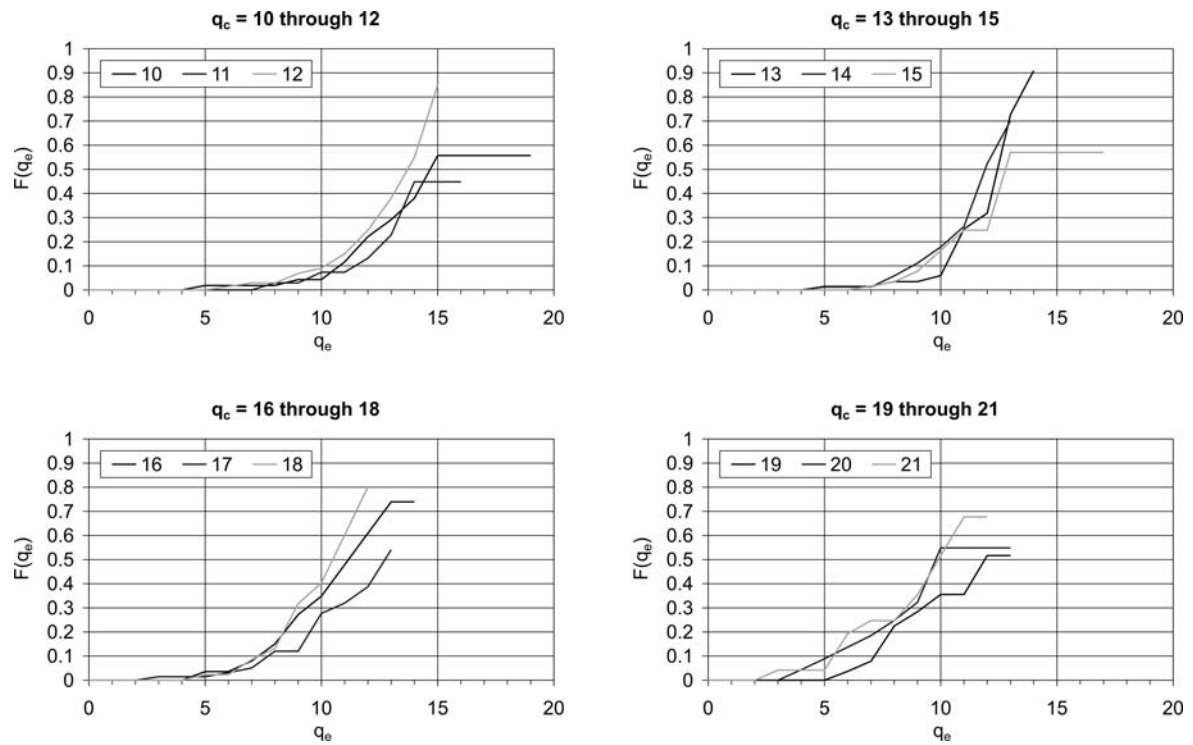


FIGURE 6 Distributions of entry capacity $c = q_{e,\max}$ for different circulating volumes q_c (volumes in veh/min).

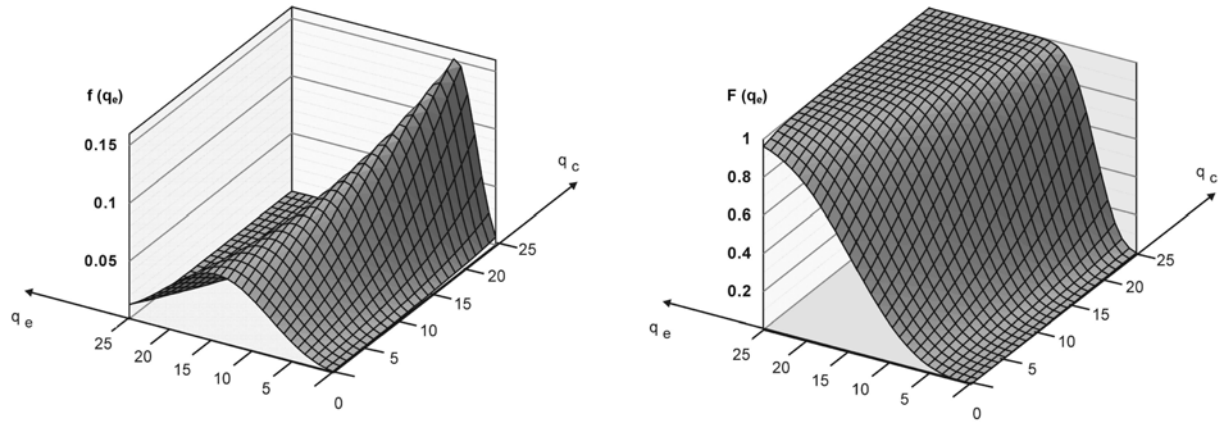


FIGURE 7 Estimated Weibull-type density and distribution function of the roundabout entry capacity depending on the circulating volume q_c (volumes in veh/min).