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Capacity effects of variable speed limits on German freeways

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Abstract

Variable speed limits are applied on a number of heavily trafficked freeway sections in Germany. Besides the impact on road safety, variable speed limits harmonize traffic flow at high volumes and hence influence freeway capacity. The paper reports empirical findings obtained for several freeway sections with different speed control conditions in Germany. The capacity of each cross section is determined by analyzing the speed-flow relationship as well as by applying methods for stochastic capacity analysis. The results show that the main effect of variable speed limits is a significantly reduced variance of the capacity distribution function. Hence, the application of variable speed limits leads to a lower risk of a traffic breakdown at moderate volumes. In highway capacity guidelines, this effect can be considered by applying different thresholds of LOS E for freeway sections with and without variable speed limits.

Keywords: Capacity; Traffic Control; Breakdown Probability

1. Introduction

Variable speed limits are applied on a number of heavily trafficked freeway sections in Germany. The major objectives are to increase road safety and to harmonize traffic flow at high volumes by reducing speed differences in the traffic stream. These effects are achieved by using dynamic traffic signs which display flow-dependent speed limits as well as road warnings in case of congestion, bad weather conditions, accidents or other incidents. On some sections, variable speed limits are combined with control systems for hard shoulder running in order to increase the capacity during peak hours.

The positive impact of variable speed limits on road safety was proven in a number of accident statistics. In this paper, the effects of variable speed limits on freeway capacity are analyzed. The focus is on the impact of variable speed limits on the random capacity variability. The paper reports empirical findings from a research project in which the design capacities given in the German Highway Capacity Manual HBS (2001) were revised (Brilon & Geistefeldt 2010). The investigation was based on traffic data samples from a large number of freeway sections with different speed control conditions. The capacity of each cross section was determined by analyzing the speed-flow relationship as well as by applying methods for stochastic capacity analysis based on models for censored data. The capacity obtained in the speed-flow diagram was regarded as an estimate of the (deterministic) design capacity.

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Stochastic capacity distribution functions were derived in order to determine the effect of variable speed limits on the capacity variance.

The paper first describes the methods for capacity analysis that were applied in the study. The specific impact of variable speed limits is then discussed based on a comparison of capacity estimates for freeway sections without a speed limit, with permanent (constant) speed limit and with variable speed limits. Based on these findings, the consequences for the assessment of traffic flow quality are demonstrated.

2. Capacity estimation methods

2.1. Capacity in the speed-flow diagram

The methodology that was developed for the revision of the design capacities for basic freeway segments given in the German Highway Capacity Manual HBS (2001) is based on the empirical analysis of speed-flow diagrams. The volume at the apex of the speed-flow diagram is determined by fitting the speed-flow-density relationship proposed by van Aerde (1995). With this traffic flow model, all traffic states in the fundamental diagram are described by a continuous function. Thus, in contrast to two-regime traffic flow models, the apex volume does not depend on the specification of a speed or density threshold between the fluid traffic regime and the congested flow regime.

Van Aerde's (1995) approach is based on a car following model, which describes the minimum desired distance headway between consecutive vehicles as the sum of a constant term, a term depending on the difference between the current speed and the free speed, and a term depending on the current speed. The speed-density relationship is:

$$d(v) = \frac{1}{\Delta x} = \frac{1}{c_1 + \dfrac{c_2}{v_0 - v} + c_3 \cdot v} \tag{1}$$

where: d = density (veh/km)
v = speed (km/h)
Δx = distance headway between consecutive vehicles (km)
v_0 = free speed (km/h)
c_1, c_2, c_3 = model parameters

The model parameters v_0, c_1, c_2 and c_3 can be calibrated by non-linear regression in the speed-density plane. To receive an even approximation over the whole range of densities, it is useful to divide the empirical data into classes, e.g. with a class width of 1 veh/km. The speed-density function (1) can then be fitted to the average speeds and densities of each class. To receive a good representation of the empirical speed-flow relationship, a sufficient number of data points in the congested flow regime is required. The presence of congested values also indicates that the data sample contains volumes up to the capacity of the analyzed cross section, which is an important prerequisite to obtain a realistic capacity estimate.

The assessment of traffic flow quality on freeways in the German Highway Capacity manual HBS (2001) is based on the analysis of 1-hour intervals. Correspondingly, 1-hour averages of flow rates and speeds were used for the empirical capacity estimation. If such large time intervals are analyzed, the data points in the speed-flow diagram result from aggregations of different traffic states. Particularly in case of a transformation between fluid traffic and congestion, 1-hour averages may represent a traffic state that never existed in real traffic flow. 1-hour averages tend to be located more in the centre of the parabolic speed-flow scatter plot than e.g. 5-minute observations. As this effect significantly influences the apex volume of the fitted speed-flow curve, 1-hour intervals with unsteady flow conditions were excluded from the analysis. A 1-hour interval is considered as representing unsteady flow conditions if the root mean squared error of the average speeds in the 5-minute intervals within the hour is greater than 10 km/h.

In some rare cases, the application of van Aerde's model delivers a capacity slightly below or even beyond the highest observed volumes. This mainly applies to speed-flow diagrams with a distinct gap between the fluid traffic regime and the congested flow regime. In order to avoid unrealistically high capacity estimates, the apex volume of the fitted speed-flow curve is compared with the 99^{th} percentile of the distribution of all flow rates in the sample. If the apex volume exceeds this threshold, the percentile value is considered as capacity estimate.

As an example, Figure 1 shows the fitting of van Aerde's (1995) model to speed-flow data from a 2-lane freeway carriageway. Here, the apex of the speed-flow model lies well below the 99^{th} percentile of the observed flow rates (dashed line). Thus, the apex volume is regarded as estimate of the design capacity.

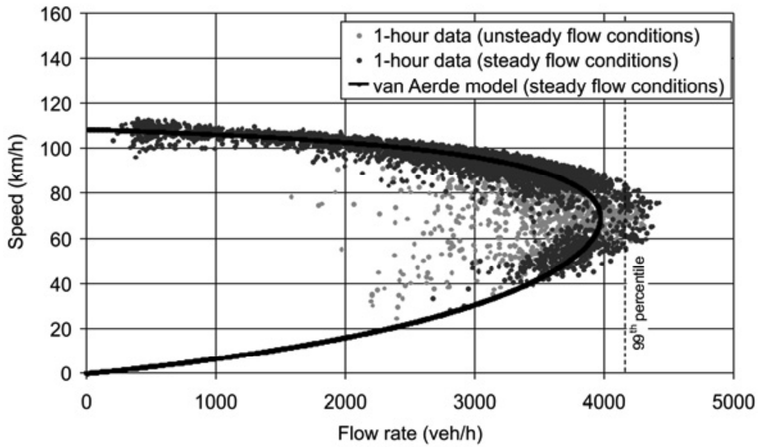

Figure 1 – Capacity estimation in the speed-flow diagram (2-lane freeway carriageway with variable speed limits).

2.2. Stochastic capacity estimation

The stochastic nature of freeway capacity was described in several recent studies (e.g. Elefteriadou et al. 1995, Minderhoud et al. 1997, Persaud et al. 1998, Lorenz & Elefteriadou 2001, Brilon et al. 2005, Brilon et al. 2007). In contrast to the traditional understanding of capacity as a constant value, these empirical investigations show that the maximum traffic throughput of a freeway facility varies – even under constant external conditions. The capacity distribution function represents the probability of a traffic breakdown. Empirical capacity distribution functions for specific roadway, traffic, and control conditions can be estimated by using mathematical models for samples that include censored data (Geistefeldt & Brilon 2009).

Traffic flow observations on freeways deliver pairs of values of volumes and average speeds in particular time 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 greater than 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. The non-parametric "Product-Limit Method" (PLM) by Kaplan and Maier (1958) delivers a set of flow rates and corresponding breakdown probabilities, which form a discrete distribution function:

$$F_c(q) = p(c \le q) = 1 - \prod_{i: q_i \le q} \frac{k_i - d_i}{k_i}; \; i \in \{B\} \tag{2}$$

where: $F_c(q)$ = capacity distribution function
c = capacity (veh/h)

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 distribution function reaches a value of 1 only if the maximum observed volume is an uncensored value, i.e. followed by a traffic breakdown. Otherwise, the distribution function terminates at a value of $F_c(q) < 1$.

For a parametric estimation, the function type of the distribution must be predetermined. The distribution parameters can be estimated by applying the Maximum-Likelihood technique. For capacity analysis, the Likelihood function is (Brilon et al. 2007):

$$L = \prod_{i=1}^{n} f_c(q_i)^{\delta_i} \cdot [1 - F_c(q_i)]^{1-\delta_i} \tag{3}$$

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

An empirical comparison between different function types revealed that freeway capacity is Weibull distributed (Zurlinden 2003, Geistefeldt 2007). The Weibull-type capacity distribution function is:

$$F_c(q) = 1 - e^{-\left(\frac{q}{\beta}\right)^{\alpha}} \tag{4}$$

where: $F_c(q)$ = capacity distribution function
q = flow rate (veh/h)
α = shape parameter
β = scale parameter (veh/h)

The expectation E and variance σ^2 of the distribution are given by:

$$E(X) = \beta \cdot \Gamma\left(1 + \frac{1}{\alpha}\right) \tag{5}$$

$$\sigma^2(X) = \beta^2 \cdot \left\{\Gamma\left(1 + \frac{2}{\alpha}\right) - \left[\Gamma\left(1 + \frac{1}{\alpha}\right)\right]^2\right\} \tag{6}$$

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

The shape parameter α mainly determines the variance of the distribution function. The variance decreases with increasing α. The scale parameter β is proportional to both the mean value and the standard deviation of the distribution function. The scale parameter represents the systematic factors affecting freeway capacity, such as number of lanes, grade, and driver population.

The stochastic concept of capacity is based on the analysis of traffic breakdowns. The pre-breakdown volumes represent the momentary capacity of the facility. As a breakdown of traffic flow is usually a sudden event, only short time intervals (5 minutes or even less) are suitable for the empirical capacity estimation. For greater intervals, the causality between the observed traffic volume and the occurrence of the breakdown is too weak. However, a theoretical approach can be used to transform capacity distribution functions between different interval durations. Based on a capacity distribution function estimated in 5-minute intervals, the 1-hour distribution can be estimated by applying the following relationship (Geistefeldt 2007):

$$1 - F_{c,60}(q_{60}) = \prod_{i=1}^{12} \left[1 - F_{c,5}(q_{5,i})\right] \tag{7}$$

where: $F_c,5(q)$ = capacity distribution function estimated in 5-minute intervals
$F_c,60(q)$ = transformed capacity distribution function in 1-hour intervals
$q_{5,I}$ = flow rate in 5-minute interval i (veh/h)
q_{60} = 1-hour average flow rate (veh/h)

With equation (7), values of the capacity distribution function estimated in 5-minute intervals can numerically be transformed into 1-hour intervals. A Weibull distribution can then be fitted to the transformed values by a least squares estimation. The variance of the 5-minute flow rates during one hour (denoted by $q_{5,i}$ in equation (7)) can be considered by using normal distributed values according to the following equation (Geistefeldt 2007):

$$q_{5,i} = z_{(2 \cdot i - 1)/24} \tag{8}$$

where: $q_{5,I}$ = flow rate in 5-minute interval i (veh/h), i = 1..12
z_p = p-quantile of the $N(q_{60}, \sigma_q)$
q_{60} = 1-hour average flow rate (veh/h)
σ_q = standard deviation of the 5-minute flow rates $q_{5,i}$

The standard deviation σ_q, which represents the variability of the 5-minute flow rates during one hour, has a significant impact on the transformation. The value can be estimated from empirical data. As only the highest volumes are relevant for the capacity analysis, the average value of σ_q for the upper percent of all 1-hour flow rates in the sample is applied.

3. Capacity effects of variable speed limits

For the revision of the capacity values given in the German Highway Capacity Manual HBS (2001), a total of 50 freeway sections with different geometric, traffic and control conditions was analyzed by applying the capacity estimation methods described above (Brilon & Geistefeldt 2010). As an extract of these results, the findings related to the influence of the speed control conditions on 2- and 3-lane carriageways are summarized in the following.

Comprehensive results based on a large number of samples could particularly be obtained for 2-lane carriageway sections in level terrain. Figure 2 shows the capacities estimated in the speed-flow diagram for 2-lane carriageways with different control conditions. All sections are located in urban areas and thus have a high share of commuter traffic. The average truck percentage on the different sections varies between 5 and 15 %. The estimated capacities are in a relatively narrow range between 3700 and 4200 veh/h. The average capacities for the groups of sections with permanent (constant) and variable speed limits are slightly higher than the average capacity for the sections without speed limit. Overall, the capacities estimated in the speed-flow diagram correspond well with the design capacities given in the HBS (2001). This shows that the capacity estimation technique described in section 2.1 delivers capacity estimates that are consistent with the HBS design capacities.

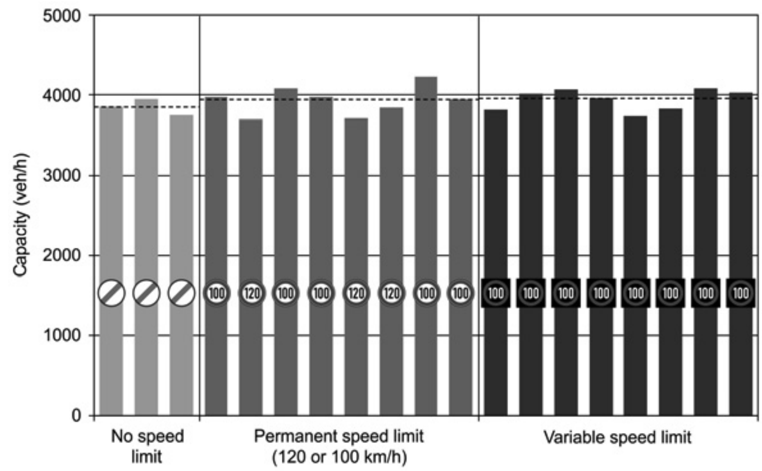

Figure 2 – Capacities estimated with van Aerde's (1995) model for 2-lane freeway carriageways in level terrain with different speed control conditions (the dashed lines represent the average capacities for each group).

In contrast to the capacity estimation in the speed-flow diagram, the methods for stochastic capacity analysis as described in section 2.2 can be used to quantify the random capacity variability, which occurs even under constant external conditions. A high variance of the capacity distribution function particularly incorporates a higher risk of a traffic breakdown at volumes slightly or well below the mean capacity. Thus, systematic differences of the capacity variance depending on the respective control conditions are highly relevant for the assessment of traffic quality on freeways.

To compare the capacity variability of freeway sections with different parameters (and hence different mean capacities), the coefficient of variation, i.e. the ratio of the standard deviation and the expected value of the capacity distribution function, is analyzed. Figure 3 shows the estimated coefficients of variation for a total of 29 freeway sections with 2- and 3-lane carriageways, which are all located in level terrain and within urban areas. The sections are allocated into five groups, each representing specific geometric and control conditions. The vertical lines represent the range of the coefficients of variation for each group, the black horizontal markings represent the median value of each group. The median was chosen as indicator to compare the different section types because it is less influenced by outliers than the arithmetic mean.

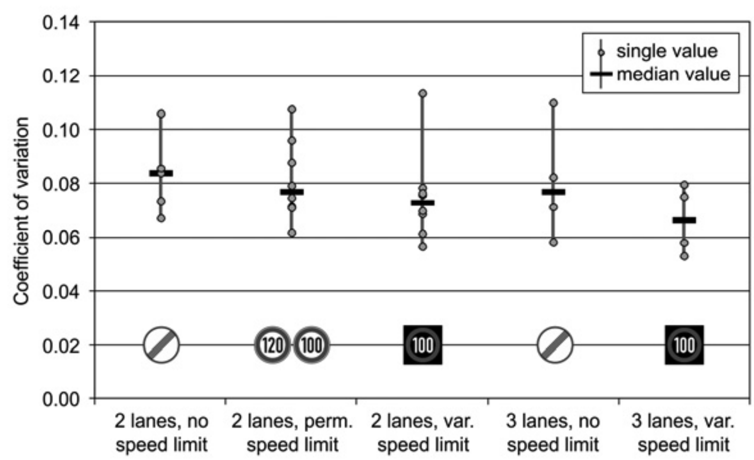

Figure 3 – Coefficients of variation of the estimated capacity distribution functions for 2- and 3-lane freeway carriageways with different speed control conditions.

Figure 3 clearly shows that the median coefficient of variation of the capacity distribution function for both 2- and 3-lane sections with variable speed limits is significantly lower than on uncontrolled sections with the same number of lanes. This confirms former findings e.g. by Schick (2003), which were obtained based on different approaches and different samples. The median coefficient of variation for 2-lane sections with a permanent speed limit (120 or 100 km/h) is roughly between the median values for sections without speed limit and sections with variable speed limits. However, the range of the estimated coefficients of variation within the groups of sections is rather high.

4. Consequences for the assessment of traffic flow quality

The procedures for the assessment of traffic flow quality on basic freeway segments in Highway Capacity Manuals like the HCM (2000) or the HBS (2001) are based on deterministic capacities. The design capacities given in these guidelines account for the systematic impact of the prevailing roadway, traffic and control conditions on the average capacity, but so far do not consider the potential impact of the random capacity variability.

In the German Highway Capacity Manual HBS (2001), the degree of saturation is used as measure of effectiveness for basic freeway segments. The degree of saturation is defined as the ratio of the demand flow rate and the design capacity:

$$x = \frac{q}{c} \quad (9)$$

where: x = degree of saturation
q = demand flow rate (veh/h)
c = design capacity (veh/h)

The degree of saturation was chosen as (surrogate) measure of effectiveness instead of the average travel speed in order to consider that a reduced speed level on uphill sections as well as sections with speed limits does not incorporate a lower quality of traffic flow. If the stochastic variability of capacities is accounted for, the degree of saturation can also be regarded as the degree to which an unacceptable risk of a traffic breakdown is reached. The threshold values for the Levels Of Service (LOS) A through F according to the HBS (2001) are given in Table 1.

Table 1 – Degree of saturation thresholds defining LOS for basic freeway segments in the HBS (2001)

Level of service	A	B	C	D	E	F
Degree of saturation	≤ 0.30	≤ 0.55	≤ 0.75	≤ 0.90	≤ 1.00	> 1.00

The consequences of different capacity variances for the assessment of traffic flow quality on freeways are demonstrated in Figure 4. The graph shows the capacity distribution functions for two 3-lane carriageway sections of the freeway A 3 in Germany. One section (between Obertshausen and Hanau) is equipped with a variable speed limit control system, the other section (between Ratingen-Ost interchange and Mettmann) has no speed limit. The capacity distribution functions were estimated based on 5-minute data and transformed into 1-hour intervals with equation (7). The stochastic capacity estimations for both sections roughly represent average distribution functions for the respective section types. Moreover, both sections have very similar design capacities of approx. 5500 veh/h. The threshold flow rates for LOS C through F according to the HBS (2001), which can be obtained by multiplying the threshold values given in Table 1 with the design capacity, are marked in the diagram. At the upper threshold of LOS E, both capacity distribution functions reach a value of approx. 0.38, which means that a flow rate equal to the design capacity of 5500 veh/h incorporates a breakdown probability of 38 % during a 1-hour interval. At the lower threshold of LOS E (90 % saturation or $q = 0.90 \cdot 5500 = 4950$ veh/h), the capacity distribution value for the section without a speed limit amounts to 0.10, representing a breakdown probability of 10 % during a 1-hour interval. For the section with variable speed limits, the same breakdown probability is obtained at a flow rate of approx. 5100 veh/h, which is a degree of saturation of 92.7 %. Due to the lower capacity variance on the section with variable speed limits, the risk of a traffic breakdown at volumes slightly below the design capacity is significantly reduced. In contrast, the effect of the higher breakdown probabilities at volumes greater than the capacity compared with the uncontrolled section do not affect the traffic flow quality because these high volumes are very rarely reached in reality due to the high probability that a breakdown has already occurred in the preceding intervals at lower volumes.

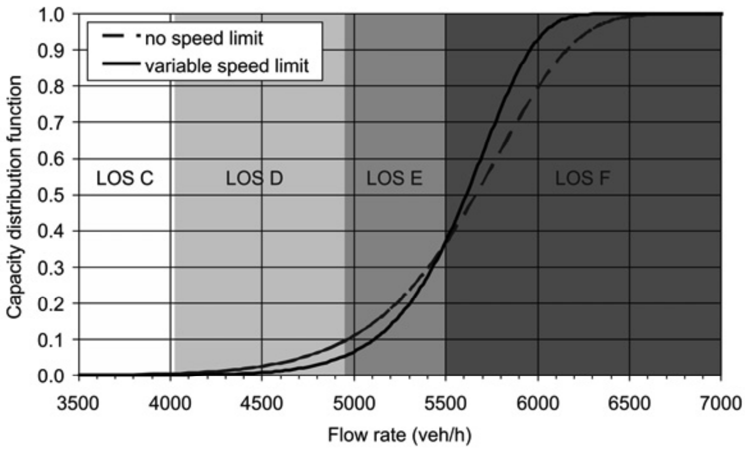

Figure 4 – Capacity distribution functions for 3-lane carriageway sections with and without variable speed limits.

LOS E is commonly defined as an instable traffic flow condition in which small disturbances can cause a major disruption of the traffic stream. On freeways, the probability of a traffic breakdown can be regarded as the parameter that most appropriately represents the degree of instability. The example illustrated in Figure 4 shows that a reduced capacity variance results in a narrower range of instable flow rates. For the assessment of traffic flow quality, this effect can be considered by adjusting the lower threshold of LOS E. According to this, the threshold degree of saturation between LOS D and E shall be shifted from 0.90 (cf. Table 1) to 0.92 for sections with variable speed limits in the forthcoming edition of the German Highway Capacity Manual. The concept of applying different thresholds for LOS E could also be implemented in other procedures for the assessment of traffic flow quality based on different measures of effectiveness (like traffic density as used in the HCM).

5. Conclusions

The analysis of traffic data samples from freeways with different control conditions (no speed limit, permanent speed limit, variable speed limits) in Germany shows that the main effect of variable speed limits is a significantly reduced variance of the capacity distribution function, whereas the mean capacity is – on average – only slightly higher than on uncontrolled freeway sections with similar geometric and traffic conditions. Hence, the application of variable speed limits leads to a lower risk of a traffic breakdown at volumes slightly below the mean capacity.

The implications of the reduced capacity variance on sections with variable speed limits for the assessment of traffic flow quality can be considered by analyzing the empirical relationship between the quality of service and the corresponding breakdown probability. In the level of service (LOS) concept used in highway design guidelines, instable traffic conditions with traffic volumes slightly below the capacity are represented by LOS E. For freeways, the probability of a traffic breakdown can be regarded as the most appropriate measure of instability. By adjusting the lower threshold of LOS E, systematic differences between the capacity variance on freeways with different control conditions can be considered. The concept of applying different thresholds of LOS E for freeway sections with and without variable speed limits will be implemented in the forthcoming edition of the German Highway Capacity Manual HBS.

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