Comparison of Uncongested Speed-Flow Relationships Using Data from German Autobahns and North American Freeways

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The use of speed-flow data from German Autobahns provides a greater range of free-flow speeds than that available from North American freeways. On the basis of these additional data, three conclusions address current questions about the speed-flow relationship. First, the speed at capacity is not independent of free-flow speed but is higher on facilities on which the free-flow speed is higher; speed approaching capacity is as high as 90 to 100 km/hr on one Autobahn. Second, the range of flows over which average speeds remain constant (at the free-flow speed) decreases with increasing free-flow speed. For example, with a free-flow speed of 135 km/hr, speeds remain constant out to flows of 1,000 passenger car units per hour per lane. Third, for the range of flows in which speeds decrease with increasing flow, the relationship between speed and flow appears to be linear. This means that there is no need to postulate a curved (e.g., quadratic) relationship near capacity, since there is not an increasing rate of decline in speeds at those flows.

The purpose of this paper is to investigate the nature of the speed-flow relationship using data from German Autobahns. Because the range of free-flow speeds on North American freeways is fairly small, free-flow speed data from the Autobahns, many sections of which have no speed limit, can be valuable in resolving three issues that North American data have not been able to answer. The first is the speed at capacity while operations remain uncongested: does it vary with free-flow speed? The second is the flow rate at which speeds begin to decrease from free-flow speeds: does this vary with free-flow speed? The third is the nature of the decrease in speeds for flows exceeding the flow-rate breakpoint: is it linear or quadratic?

The structure of the paper is as follows. The first section provides the context for the issues by providing a brief review of the current status of North American thinking. The second section summarizes the relevant German literature about speed-flow relationships on Autobahns. Because that literature is unable to resolve the issues, the third section introduces analyses of Autobahn data from two different locations. The analyses do not answer all of the questions, but they are able to shed some light on the issues. The final section draws together the results of the analyses in the form of recommendations for resolving some of the open questions about the speed-flow relationships for freeways in North America.

CONTEXT

The 1985 *Highway Capacity Manual* (HCM) (*1*) is heir to the parabolic shape of the speed-flow curve for freeways that appeared in the 1965 HCM (*2*), in that speed at capacity is shown to be roughly half of the free-flow speed for the facility. The shape of the parabola in the 1985 HCM is broader than that in the 1965 HCM, with speeds remaining at or near the free-flow value until quite high volumes, but then speeds fall off precipitously to the low value at capacity. Preparation of a revised Chapter 7 of the HCM (*3*) brought this representation into question, in that the new data collected for multilane rural roads showed that speeds at capacity were only 8 to 10 km/hr lower than the free-flow speeds. In addition, capacity was found to be higher than the 2,000 passenger cars per hour per lane (pcphpl) given in the 1985 HCM for both freeways and multilane rural roads. Both of these results implied that in some respects a multilane rural roadway operated more effectively than a freeway, which clearly did not make sense. Consequently, efforts began to revise the freeway chapter of the HCM to better reflect current conditions in the light of new data.

The new data available were summarized by Hall et al. (*4*), who also proposed a new generalized speed-flow curve for freeways based on those data. However, their proposal was only a representation of the general shape and did not provide the level of detail needed to replace the 1985 HCM curves. In particular, the HCM figure provides curves for three design speeds (70, 60, and 50 mph) and, within the 70-mph design speed, for four-, six-, and eight-lane facilities. The studies reviewed by Hall et al. do not provide the necessary details, either. The magnitudes of speed drops (i.e., the difference between the free-flow speed and speed at capacity) vary from almost nothing in some studies (*5*) to as much as 25 percent of the free-flow speed in others (*6*). An alternative hypothesis was that 80 km/hr is the speed at capacity, as found in several studies.

With the exception of a few older freeways in the northeastern United States, there is not much variation in the design speeds of North American expressways. Given the 55-mph (90-km/hr) speed limit in the United States on urban freeways (where there is the best chance of finding capacity operations) and the 100-km/hr limit in Ontario, it is not likely that a wide range of free-flow speeds will be found in North American data, except perhaps as might reflect local speed enforcement patterns. To some extent this is visible in the studies summarized by Hall et al. (*4*). The apparent free-flow speeds in those studies ranged from slightly above 100 km/hr (60 mph) (*7,8*) through 100 km/hr (*9*) and 95 km/hr (*6*) to perhaps 85 km/hr ["more than 50 mph" (*10*)]. However, the scatter in the results appears to be greater than the range of free-flow speeds, making it difficult to recommend different curves for different speeds on the basis of these studies.

GERMAN STUDIES

Because of the absence of any speed limit on many sections of the Autobahns, German data provide an opportunity to investigate

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speed-flow behavior under potentially different free-flow conditions. This section reviews German publications on this topic.

The earliest depiction to consider is the polygon curve from the Green Paper (*11*). This polygon contains three segments for uncongested conditions, which is the part of the speed-flow curve of interest. The resulting polygon can be envisioned as a piecewise linear approximation of the parabolic curve that appeared in the 1985 HCM. However, the polygon was for the most part a generalized curve, without specific numbers assigned to it. The first (leftmost) segment implied a decrease in speeds with each additional vehicle, although only a modest decrease. After the first breakpoint, speeds dropped more sharply. In the third segment (after the second breakpoint) speeds declined even more steeply, to capacity operation.

In a 1990 publication, Heidemann and Hotop (*12*) undertook to specify current parameters for this polygon by fitting it to recent data. They provide a variety of curves, depending on the number of lanes per direction (two or three) and the truck percentage. Their conclusion for a three-lane directional road (i.e., a six-lane freeway) with trucks making up less than 15 percent of traffic is represented as the top line in Figure 1. They found that there was a range of flow over which speeds did not decrease [extending to about 1,200 vehicles per hour (vph) over three lanes, or 400 vph per lane (vphpl)], so they added another segment to the lefthand end of the polygon. However, their data did not extend beyond about 4,000 vph. The part of the curve beyond 4,000 vph was extrapolated by analogy from two-lane data, in order to identify the last breakpoint. The righthand segment of their curve is therefore shown as a dotted line, just as in their paper.

The second representation to be discussed in Figure 1 comes from the publication *Richtlinien für die Anlage von Strassen, Teil: Querschnitte* (RAS-Q), which translates roughly as *Guidelines for the Design of Highways: Profiles* (*13*). In an appendix on level of service (Nachweis der Verkehrsqualität), graphs are included showing a portion of the speed-flow diagram for different roadway cross sections, grades, and percentage of trucks. The small segment in Figure 1 labeled as RAS-Q replicates in its entirety the curve for a six-lane divided freeway, for a continuous grade less than or equal to 1 on which heavy trucks are able to maintain speeds in excess of 70 km/hr (which could include 0 grade), for traffic with 0 percent trucks (roadway type a6ms, Steigungsklasse 1, Lkw = 0 percent).

The third curve in Figure 1 comes from a different part of the *Richtlinien für die Anlage von Strassen*, namely, RAS-W for *Wirtschaftlichkeitsundersuchungen*, or "Economic Assessment" (*14*). The curve shown in the figure is derived from the following equation:

$$V = \{136.5 - 8[\exp(0.235s)]\}[\exp(-10^{-3}\mathrm{KU}) - 0.5 \exp 10^{-3}(Q_p + 2Q_{gv})] \quad (1)$$

where

V = speed of passenger cars,
s = gradient (%),
KU = degree of curvature of roadway section,
Q_p = passenger car rate of flow, and
Q_{gv} = goods vehicles (trucks) rate of flow.

In Figure 1, the curve has been drawn for $Q_{gv} = 0$, $s = 0$, and KU = 0 (i.e., for a straight, level section with no trucks).

The fourth and final curve in Figure 1 is the most interesting. Based on recent data from a number of locations, it is an effort by Stappert and Theis (*15*) to update the curve that lies behind the short segment from RAS-Q. The underlying functional form that they used is the same as that used there, namely, a monotonically decreasing exponential function of the form

$$V = [A - \exp(\mathrm{B}Q)]\,[\exp(-c) - k\exp(dQ)] \quad (2)$$

where

V = velocity,
Q = flow, and
c, d = constant Krummungs factors taking values between 0.2 and 0.003.

On the basis of fitting curves to data for nine sites for Autobahns with three lanes per direction, Stappert and Theis came up with the general curve for this road category, shown in Figure 1. There are

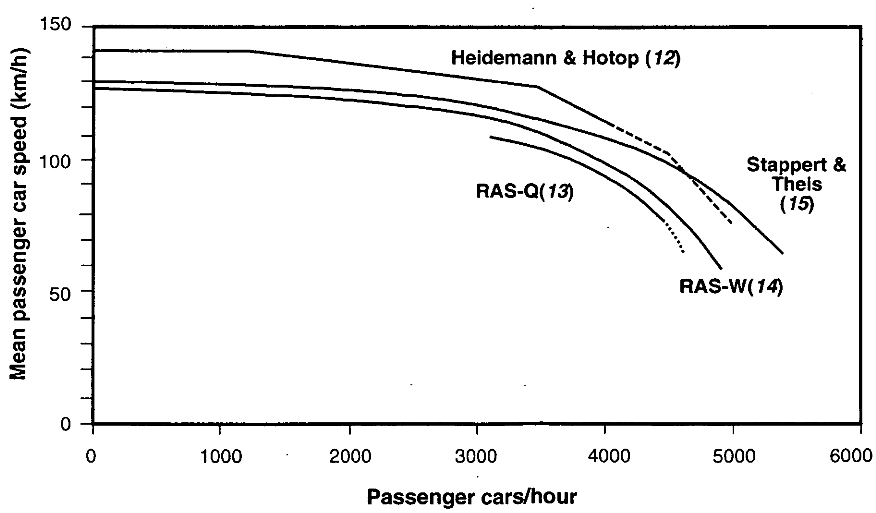

FIGURE 1 Summary of speed-flow relationships in German publications for six-lane freeways (Autobahns with three lanes per direction).

three important comments about their curve, however. The first is that it appears they used only the functional form specified previously and did not compare that function with other possibilities.

The second point is that they too had very little data above a flow of 4,000 vph for the three-lane roads. Their report contains diagrams for four of the nine three-lane sites. There are eight data points above 4,000 vph in those diagrams. Although it is possible that the sites not graphed in their report had higher flows, it appears more likely that they would have included in the report the figures showing highest flows. For the eight "high" flow data points, the mean speed is above 110 km/hr. There is no basis in the data for the 55-km/hr speed shown at a capacity of 5,500 vehicles over the three lanes, nor for the value of 5,500 itself. Those values represent an extrapolation on the basis of the assumed functional shape.

The third point is one that pertains to both the analyses by Stappert and Theis and by Heidemann and Hotop. The data that they used were all hourly counts. For lower flows, the hourly counts can give a good representation of the curve, since operations within a particular hour are likely to be on the same segment of the graph. However, for higher flows there is a good chance that a full-hour count will include data from several segments of the curve (including potentially congested operations) with the result that it will not accurately represent any one part of the curve but instead will average several types of behavior. Figure 2 provides an example of how this can occur. Successive 5-min speed-flow observations are shown, along with the moving average hourly values based on them. There is a brief period of congested 5-min data, which leads the hourly values to appear in parts of the graph where no 5-min operations occurred. Depending on the exact time selected to begin hourly observations, the hourly data may or may not reflect real operations. This point is important for interpreting the German studies, because it is likely that the underlying functional forms that both empirical studies were trying to fit were themselves originally derived on the basis of hourly data.

One of the four-lane freeways (i.e., two lanes each way) for which a graph of data is included in the Stappert and Theis study provides some useful data for the question of speeds at capacity, as well as for per-lane capacity values. On the A43 at Herne, 29 observations exceed a flow of 4,000 vph, with one point above 4,700 vph. All but three of these 29 observations have speeds above 80 km/hr, and 13 are above 90 km/hr. The lowest is 65 km/hr, but the mean would appear to be near 85 km/hr. Hence, there is evidence from the Autobahns that hourly flows in excess of 2,000 vphpl are observed repeatedly and that speeds at these flows are well above the 50 or 60 km/hr suggested by the design guide curves.

In addition to the studies summarized in Figure 1, there is one other recent empirical German study to note, conducted on Highway B10 in Karlsruhe (*16*). The section from which the data come is an urban freeway, roughly 1 km downstream of a cloverleaf interchange and 1 km upstream of a diamond interchange. Figure 3 shows the results obtained in that study, which are not in accordance with any of the curves in Figure 1. In particular, these data show a steady, albeit small, linear decrease in speeds as flow increases, beginning at the lowest observed flows. However, given the nature of the data, all that can be said about capacity is that it is greater than or equal to 3,500 vph (over two lanes), and speed at capacity is likely to be less than or equal to 80 km/hr.

In summary, then, although the conventionally used speed-flow curves for Germany show capacities lower than 2,000 vphpl, and speeds near 50 km/hr at those flows, there are very few data near capacity in the published reports. What data there are at high flows show speeds considerably higher than those portrayed by the German curves, consistent with the recently proposed curves based on Canadian and U.S. data. The data at medium flows are also consistent with the proposed American curves—that is, they show little if any decrease in speed as flow increases (with the exception of the Karlsruhe data). However, the published results in Germany are not adequate to answer the issues raised at the start of this paper.

NEW DATA FROM GERMAN AUTOBAHNS

In an effort to resolve those issues, data from two Autobahn measurement locations have been analyzed. Because data on operations upstream of these points are not available, one cannot be certain that capacity has been reached in the data. Nonetheless, flow values have been observed that are sufficiently high to warrant some tentative conclusions about the behavior of speeds in the vicinity of capacity. In each of the two subsections that follow, the data collection location is described, followed by a description of the analyses that were

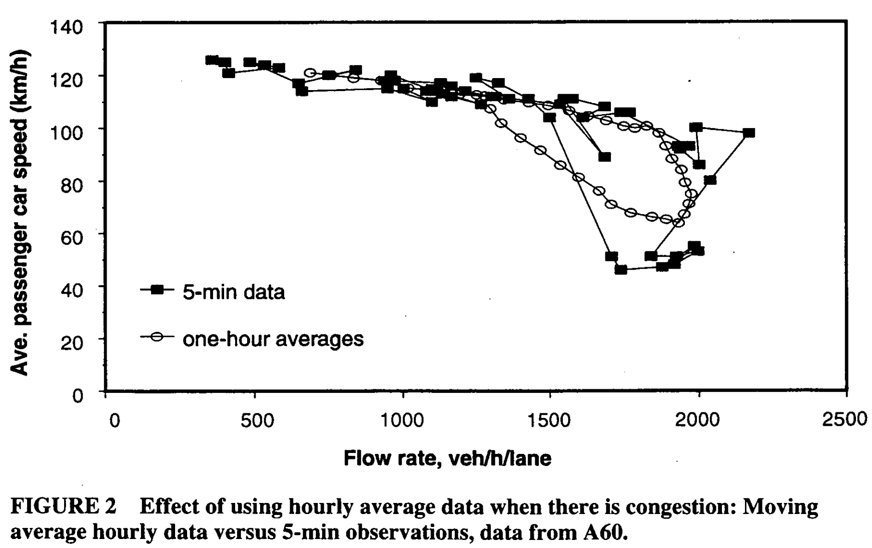

FIGURE 2 Effect of using hourly average data when there is congestion: Moving average hourly data versus 5-min observations, data from A60.

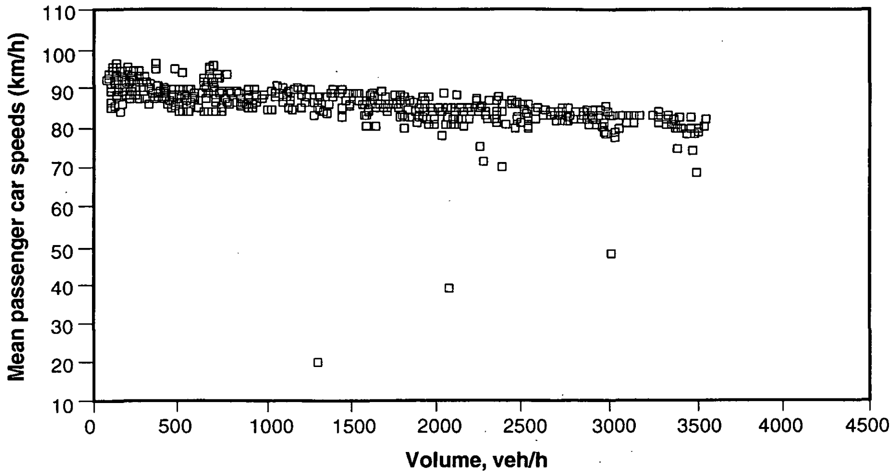

FIGURE 3 Speed-flow data from four-lane urban freeway in Karlsruhe (*16*).

performed. Conclusions from the two analyses appear in the final section of the paper.

A3 at Heusenstamm

The A3 near Heusenstamm, south of Frankfurt, has three lanes in each direction and no speed limit. The measurement location, at km 84, is more than 2 km from any entrance or exit ramps. Because it is sometimes asserted that German Autobahns have a much higher percentage of trucks than do North American freeways, Figure 4 is included to show the daily pattern of traffic volumes together with the truck percentages (for the westbound traffic, i.e., toward Frankfurt). The data in Figure 4 are the actual 5-min counts. There is a fairly steep morning peak in the traffic flow, which is the main focus of the investigation that follows. During this peak, truck percentages fall to their lowest level during the day and are comparable to North American peak-period values. At other times of day, especially at night, the truck percentages are much higher.

Three days of data were used, for May 29–31, 1990. There are two ways to investigate the data, one based on the German procedure of stratifying the analysis by truck percentage, the other based on the U.S. procedure of converting to passenger car units by means of a passenger-car-equivalent truck factor. Figure 5 is based on the German procedure and shows the mean speed of all vehicles versus volume per lane for trucks less than or equal to 15 percent of the traffic volume. This figure suggests a flat segment out to about 600 vphpl, followed by a linearly decreasing function.

The numerical analysis, however, has been based on the use of truck equivalence factors. Figure 6 shows the data for the morning peak period (5:00 to 10:00 a.m.) for these three days together. Peak-period data were used because most North American capacity analyses have relied on peak period data. In converting from vehicles per hour to passenger cars per hour, a truck equivalence factor of 2.0 was used, since that is the accepted German value, as indicated in Equation 1. Three functional forms were attempted (Table 1): linear, quadratic, and piecewise linear. All performed well, in the sense that the R^2 was quite high (above .75 in all cases) and the root-mean-square (*RMS*) error reasonably low. The quadratic function stands out as being better than the linear, but the coefficient on the first-order term is positive, which is counter-intuitive. None of the piecewise linear models had any slope on flow for the first segment

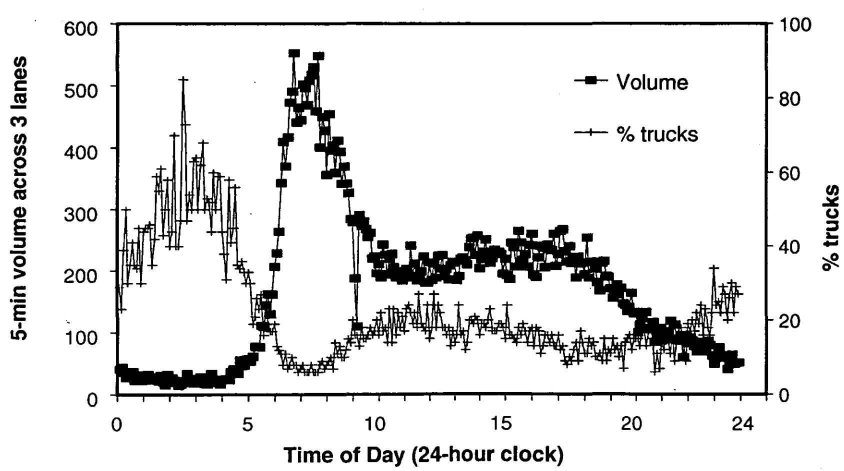

FIGURE 4 Total vehicles and percent trucks versus time of day; from A3 near Heusenstamm, traffic toward Würzburg, May 30, 1990.

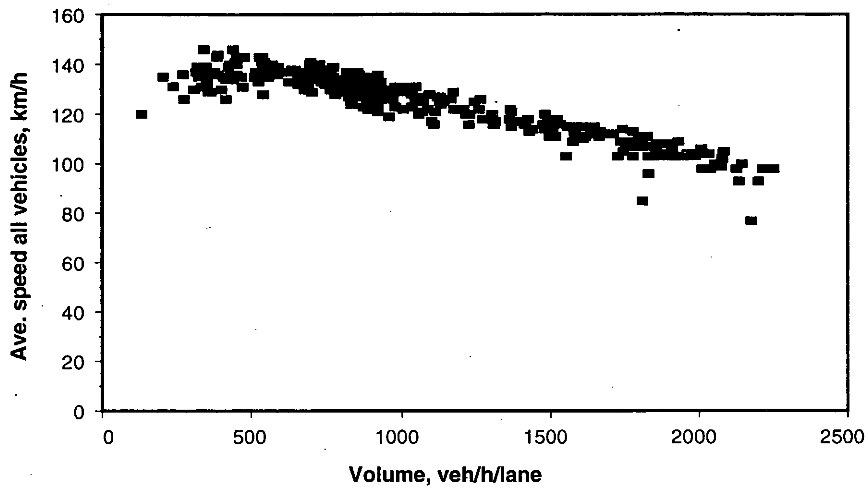

FIGURE 5 Speed-flow data from A3 near Heusenstamm for trucks less than or equal to 15 percent of volume.

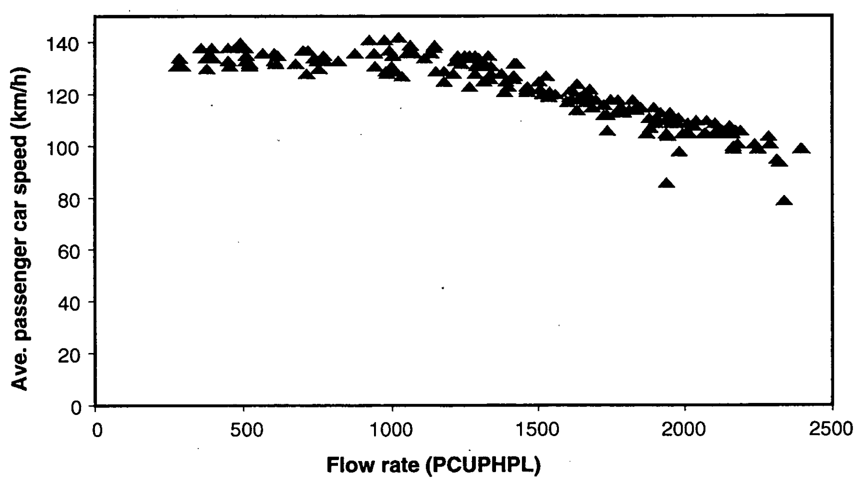

FIGURE 6 Speed-flow data from A3 near Heusenstamm, for three days of morning peak-period data, with flow converted to passenger car units.

of the line, and some performed slightly better than the quadratic. Hence it seems fair to prefer one of the piecewise linear models. The one using a breakpoint of 1,100 vehicles has the highest R^2, but the differences in the R^2 and *RMS* values among several breakpoints were so small that it would be more appropriate to say there is really no difference among several possible breakpoints. The selection of 1,000 vph should probably be made because it is a number that implies approximation, which would be appropriate. The free-flow speed for the equation is 134 km/hr.

A60 near Ginsheim

The A60 near Ginsheim, between Frankfurt and Mainz, has two lanes in each direction and no speed limit. Data were available for the same three days as for the A3. The traffic pattern over the day is similar to that shown in Figure 4 for the A3, so it is not shown here.

Again, presenting the data in the German fashion (Figure 7) suggests a segment with 0 slope out to a flow of perhaps 600 vphpl, followed by a linearly decreasing segment out to capacity. (The nine data points with speeds below 75 km/hr should not be included in the estimation of the function for uncongested data. They are either observations within a queue or queue discharge data.)

Quantitative analysis of the speed-flow relationship was again concentrated on the morning peak period (5:00 to 10:00 a.m.), converting trucks to passenger car units (Figure 8). The first part of Table 2 is based on all of the data in Figure 8. (The nine congested points have been omitted from the figure.) In general, the functions do not fit quite so well as they did for the A3 data: maximum R^2 values are down by about 0.05. In addition, the nature of the piecewise linear function appears to be changing between breakpoints of 400 and 900. The fact that the best R^2 values are associated with quite high flows (1,300 to 1,800 pcuphpl) implies that the data near capacity are affecting the function. Hence, all data above 1,500 pcuphpl (the optimum breakpoint) were deleted, and the

TABLE 1 Results of Analysis of Functions, A3 Data Westbound

Function type	R^2	RMS Error	Equation (all coeff. sig at .00001)	
Simple linear	0.7777	6.09	150 -0.0203 Q	
Quadratic	0.8840	4.41	130 +0.0157 Q - 0.000014 Q^2	
Piecewise linear Breakpoint	(for Q< breakpoint, D=0; for Q =,> breakpoint, D=1)			
400	0.8096	5.65	133 + 20 D	- 0.0222 QD
500	0.8249	5.42	135 + 21 D	- 0.0235 QD
600	0.8466	5.07	134 + 24 D	- 0.0252 QD
700	0.8644	4.77	134 + 27 D	- 0.0267 QD
800	0.8892	4.31	134 + 32 D	- 0.0293 QD
900	0.8928	4.24	134 + 33 D	- 0.0298 QD
1000	0.8963	4.17	134 + 35 D	- 0.0307 QD
1100	0.9000	4.09	134 + 37 D	- 0.0318 QD
1200	0.8993	4.11	134 + 38 D	- 0.0323 QD
1300	0.8986	4.12	134 + 37 D	- 0.0316 QD

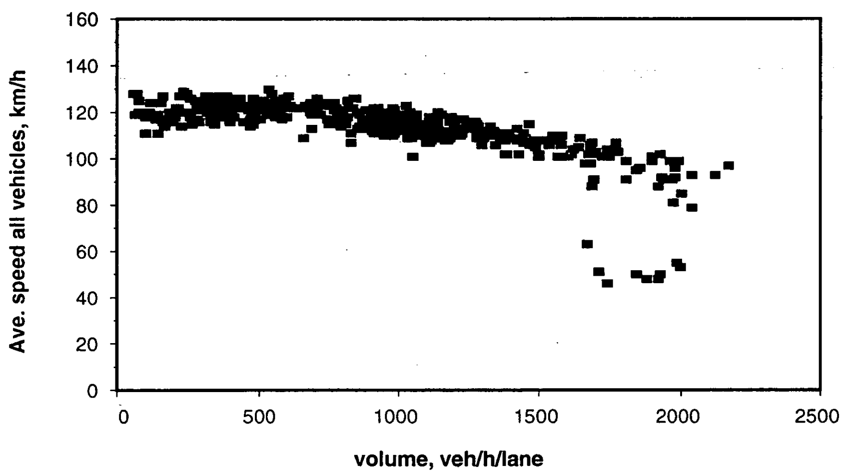

FIGURE 7 Speed-flow data from A60 near Ginsheim, for trucks less than or equal to 15 percent of volume.

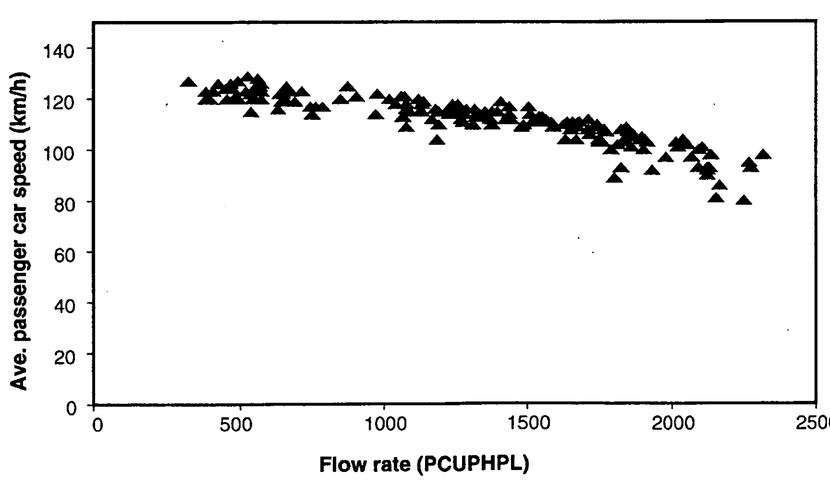

FIGURE 8 Speed-flow data from A60 near Ginsheim, for three days of morning peak-period data, with flow converted to passenger car units.

TABLE 2 Results of Analysis of Functions, A60 Data Eastbound

Function type	R^2	RMS Error	Equation (coeff. sig at .0001 unless noted)
Simple linear	0.7817	4.48	133 -0.0160 Q
Quadratic	0.8329	3.91	124 - 6.328 (Q/1000)^2
Piecewise linear Breakpoint	(for Q< breakpoint, D=0; for Q =,> breakpoint, D=1)		
400	0.7879	4.43	134 - 0.0304Q + 0.0140 QD
			(sig at 0.026)
500	0.7937	4.37	123 + 12 D - 0.0171 QD
600	0.7988	4.31	123 + 13 D - 0.0180 QD
700	0.8064	4.23	123 + 16 D - 0.0193 QD
800	0.8191	4.09	133 + 7 D - 0.0205 Q
900	0.8190	4.10	128 + 13 D - 0.0098 Q - 0.0110 QD
			(sig at .043) (sig at .027)
1000	0.8201	4.09	127 + 14 D - 0.0093 Q - 0.0118 QD
			(sig at .017) (sig at .004)
1100	0.8238	4.05	128 + 15 D - 0.0103 Q - 0.0117 QD
1200	0.8318	3.96	129 + 18 D - 0.0115 Q - 0.0124 QD
1300	0.8359	3.91	128 + 22 D - 0.0109 Q - 0.0149 QD
1400	0.8428	3.82	128 + 27 D - 0.0110 Q - 0.0176 QD
1500	0.8436	3.81	128 + 30 D - 0.0109 Q - 0.0192 QD
1600	0.8426	3.83	128 + 30 D - 0.0107 Q - 0.0191 QD
1700	0.8417	3.84	129 + 30 D - 0.0112 Q - 0.0189 QD
1800	0.8367	3.90	129 + 28 D - 0.0119 Q - 0.0174 QD
			(sig at .001)
Excluding data above 1500 pcuphpl			
linear	0.6043	3.17	128 - 0.0109 Q
breakpoint			
400	0.6079	3.17	122 + 6 D - 0.0113 DQ
			(sig at 0.001)
500	0.6065	3.17	123 + 6 D - 0.0115 DQ
600	0.6109	3.15	123 + 4 D - 0.0106 DQ
			(sig at 0.008)
700	0.6010	3.19	123 + 5 D - 0.0104 DQ
			(sig at 0.044)
800	0.5728	3.31	122 + 10 D - 0.0129 DQ
			(sig at 0.004)

analysis run again. In this case, R^2 values dropped even further, and the quadratic function dropped out entirely. (Neither of its coefficients was significant.) The piecewise linear function with a breakpoint at 600 is a viable candidate, but so is the simple linear function. Free-flow speed is either 128 km/hr (linear function) or 123 km/hr (piecewise linear, 700).

CONCLUSIONS

These results provide a positive indication that capacity varies with the free-flow speed of the facility. The A3 data suggest a value between 90 and 100 km/hr for a free-flow speed of 134 km/hr (on a six-lane roadway). The A60 data (for a four-lane road) suggest values above 90 km/hr (before queue discharge effects arise) for a free-flow speed of 123 km/hr. The data discussed by Stappert and Theis for the four-lane A43 at Herne suggested a speed of 85 km/hr for a free-flow speed of 110 km/hr. The higher values are associated with higher free-flow speeds. Thus speed at capacity may not be independent of free-flow speed. The implication for speed-flow curves in the HCM is to support the new curves in Chapter 3 (*17*) which show different speeds at capacity for different free-flow speeds. Although the effect appears to be present in these German data, some studies referred to earlier provide contradictory results. In particular, the works by Persaud and Hurdle (*6*) and Hurdle and Datta (*9*) contain high speeds at capacity even though they do not have particularly high free-flow speeds.

With regard to the flow rate at which speeds begin to decrease from free-flow speeds, the German data suggest that the range of flows over which speed is constant can vary, depending in part on how the data are analyzed. Figures 5 and 7 suggest only a short range of constant speeds, out to about 600 vphpl when speed is averaged over all vehicles. The analyses in Tables 1 and 2 suggest a larger range when flow is converted to passenger cars and speed is averaged over only passenger vehicles. Nevertheless, there are some clear indications even in these analyses that higher free-flow speeds are associated with a lower value of flow for the breakpoint than in North American studies. Heidemann and Hotop's curve in Figure 1 has a breakpoint at about 400 pcphpl for a free-flow speed of 143 km/hr. Table 1 suggests a breakpoint of about 1,000 pcphpl for a free-flow speed of 134 km/hr. The lowest breakpoint in the new Chapter 3 for the HCM is 1,300 pcphpl, for a free-flow speed of 70 mph (115 km/hr). One interpretation is that the constant speeds seen across a wide range of flows on North American freeways are probably an artifact of the presence of a speed limit that is considerably below the speed at which drivers could travel comfortably. This interpretation receives some support from Heidemann and Hotop's analysis (*12*) of sections of the Autobahn with speed limits, in that they show the constant speed segment continuing to higher volumes when there is a posted speed limit. For example, on a six-lane road with a speed limit of 80 km/hr, the constant speed segment extends to 1,300 pcphpl.

These data have not been adequate to resolve the final issue raised at the start of this paper, namely, the nature of the decrease in speeds for higher flows. The analyses with the Autobahn data (especially for the A60) suggest that a linear function in this range is entirely adequate and that there is no steeper decrease in speeds at the highest observed flows. However, if the highest observed flows are not at capacity, then it remains possible that there is a steeper decline in the last few hundred vehicles per hour of flow, which the data in Figure 8 suggest. Nevertheless, given the large range of flows with decreasing speeds (from 500 to 2,000 vphpl), a linear function appears reasonable.

In summary, then, the analysis of German data supports the general picture proposed by Hall et al. for the uncongested portion of the speed-flow curve and adds some detail to the general picture in a way that is consistent with the depiction in the recently approved version of Chapter 3 of the HCM (*17*). The one difference between these data and the depiction of speed-flow relationships on freeways in the new Chapter 3 of the HCM is that only a linear trend was observed in these German data, although it is possible that capacity flows did not occur in the data. Certainly these few sites are not enough to settle the matter decisively, but they do provide useful confirmation for the new Chapter 3 curves, which in several key aspects appear to have been developed with minimal empirical support.

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