Two-Lane Rural Highways – the German Experience

Prof. Dr. Werner Brilon
Ruhr-University Bochum
Universitaetsstrasse 150
D-44780 Bochum, Germany
Tel: +49 234 322 5936
Fax: +49 234 32 14 151
e-mail: verkehrwesen@rub.de

Dr. Frank Weiser
BBW GmbH
Universitaetsstrasse 142
D-44799 Bochum, Germany
Tel: +49 234 971 9364
Fax: +49 234 971 9366
e-mail: info@bbw-gmbh.de

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ABSTRACT
In Germany a series of investigations has been performed to understand traffic operations on two-lane highways and to make the experiences accessible for traffic performance analysis in practice. As an initial step, observations of traffic flow on several sections of rural two-lane highways have been performed. They led to a set of empirical speed-flow relationships for highways of different characteristics. Using these results, a microscopic simulation model was calibrated. This simulation model was able to produce a comprehensive set of speed-flow diagrams for all kinds of rural two-lane highways. The speed-flow diagrams revealed several unexpected properties: a concave shape of the speed-flow diagrams and non-linear influences of the external geometric parameters like curvature or gradients. The simulated results were then approximated by a simple quadratic equation with the parameters depending on geometric conditions and the percentage of heavy vehicles. Thus, the speed-flow diagrams were obtained for the „German HCM“. In this case the density has been used as a measure of effectiveness for the definition of levels of service. This guideline has successfully been used for three years.
INTRODUCTION

Two-lane highways constitute the largest extent of roads within traffic networks in every country. E.g. in Germany, 90 percent of all rural roads only have two lanes. For planning and design of such a highway, a good understanding of its performance characteristics is essential. Especially the travel speed that passenger cars can maintain under expected peak hour conditions is of primary interest. Therefore, realistic representations of speed-flow relationships for two-lane rural highways are of considerable importance for the layout of regional road networks. In frequent cases with heavy traffic demand the essential questions are: To which extend two-lane highways are able to establish a sufficient traffic performance?

Two-lane rural highways have attracted quite a lot of interest by theory-oriented researchers thirty to forty years ago (e.g. Erlander (1), Jacobs (2), Brilon (3)). Unfortunately, these theories have never found their role as a support for traffic engineering practice. In recent years more practically oriented research on rural highways has been initiated in several countries. These investigations were primarily based on empirical research and simulation and were mainly focused on the applicability for capacity guidelines. In this context, one important report on investigations in two-lane highways has been worked out by Harwood et al. (4) under the NCHRP-project 3-55(3). It only relates to conditions in the US. This research was the basis for the current chapter 20 (Two-lane highways) of the HCM 2000 (5). Here, the level of service (LOS) is defined by the “percent time spent following” (PTSF) as the measure of effectiveness (MOE). Recently, this chapter of HCM 2000 has attracted several comments (6) to improve the methodology for further HCM-editions.

In this situation, additional information about alternative approaches and experiences as they have been developed in Germany and as they have been introduced into the German equivalent to the HCM called HBS 2001 (7) may be of interest, even if the research work has already been finished several years ago (8). Some of the results have also been published in English language before (9) whereas the full report (10) is available in German. Given that two-lane traffic attracts some new interest in connection with the HCM 2000 it may be of interest which solutions have been found in other countries and how they perform in practical application.

As in the US, in Germany there is a strong belief that traffic engineering guidelines should be mainly based on empirical evidence. Of course, for the purpose of extending observed relations into a more general context, also modeling techniques should be used to describe the dependency of MOEs on traffic demand for unobserved situations.

This paper describes the traditional background of two-lane flow analysis in Germany. It then concentrates on the empirical observations of traffic flow followed by modeling considerations using simulation tools. As a result analytical models for speed-flow diagrams on two-lane highways are presented and it is explained how they are used for guideline applications.

GERMAN TRADITION IN TWO-LANE CAPACITY ANALYSIS

For the design process of a highway, in addition to the geometrical design, it has to be shown that the road is able to accommodate the expected future traffic demand and to serve it with adequate performance, both for a new or a redesigned highway. The guidelines for this part of highway planning were formerly integrated into the guidelines for geometric highway design.

Traditionally, speed-flow diagrams had been used as a basis for the design process. For rural two-lane highways as well as for freeways it is a long tradition in Germany that
traffic volumes are measured in “vehicles per hour”. All kinds of motorized vehicles like cars, trucks and motorcycles (not mopeds) are only counted by their number. No “passenger car units” (pcu) are defined. Instead the influence of heavy traffic is expressed by the “percentage of heavy vehicles” (PHV) where each vehicle with a maximum total weight above 3500 kg (= 7720 pound) is considered as a heavy vehicle. The use of passenger car units (pcu) has been tested again for this project (10). The result was that the passenger car equivalents (PCE) for trucks would have to depend on different external circumstances such as curvature or gradient to express the influence of heavy vehicles adequately but even on the traffic volume of the heavy vehicles itself. This was found to create much more complication than the use of PHV. Also the practitioner would expect the pcu-equivalent for a specific type of heavy vehicle being constant instead of depending on various external parameters like degree or length of a gradient.

Percent time-spent-following (PTSF), which is used in the HCM (5), has never been considered as a substantial MOE in Germany. The generation of platoons - and thus of vehicles following one another - is regarded as a compelling consequence of two-lane traffic. Larger values for PTSF are more an expression of driver’s inconvenience; they do not directly express the degree of efficiency of traffic operation. Driver’s comfort is not regarded as a convincing argument in the political context of transportation planning in Germany. Only parameters of safety, system operation quality, or ecological implications are accepted in contemporary public discussion. Thus, the parameter of PTSF would rather be treated with secondary preference in Germany.

In the past the average travel speed (ATS) – i.e. over a longer stretch of the highway (e.g. 5 to 20 km) - of passenger cars has been used in Germany as the preferred MOE. In this definition, the speeds of trucks are not included in the consideration. Reasons for this are: Heavy vehicles above a maximum weight of 7500 kg (= 16500 pounds) are only allowed to drive with a maximum of 60 km/h on rural roads, which is, however, without any importance in practice, since this official rule has been forgotten by nearly everybody. Instead, trucks always behave as they would under the freeway speed limit of 80 km/h, which again means that having good roadway conditions and having free flow, truck speeds up to 90 km/h are usual. These speeds are, however, not much impeded by increasing traffic volumes. Mainly the speeds of passenger cars suffer from higher traffic volumes. Here it is important to know that passenger cars in Germany are restricted in speed by a general speed limit of 100 km/h on rural undivided highways. In reality, these speeds are also exceeded by 10 to 20 km/h by many drivers on highways with an excellent layout under free flow.

For two-lane highways the traffic volume has always been counted as the sum of both directions. Consequently, the average speed as performance measure has always been averaged over both directions.

Before 1980 the speed-flow diagrams in the guidelines were even modified (i.e. they showed a lower capacity than could be expected in reality) to make engineers avoid oversaturated conditions and to guarantee more comfortable conditions for drivers, if these “corrected” speed-flow curves were used for design decisions. This sophistication could, however, not be maintained in present times due to the lack of budget funds and environmental considerations. In our days speed-flow diagrams for the dimensioning of highways are mainly intended to express traffic flow relations in the most realistic way.

Based on this background the federal DOT launched a project (10) to work out the fundament for the current HBS 2001 (7) as far as two-lane highways were concerned. The DOT’s intention was to conduct a critical investigation of the traditional sophistication. As far as its usefulness could be further confirmed, this concept should be given some preference above a completely new formulation of procedures. During the project it became clear, that on
the one hand these preferences could be taken into account. However, some innovative elements turned out to be useful and necessary on the other hand as well.

For the concept of the research project, empirical investigations were intended to play a major role. This included specific local measurements as well as the evaluation of continuous counting data. To achieve more generalized results simulation has been used as a type of modeling technique.

MEASUREMENTS

For the derivation of reliable speed-flow relationships, measurements in real traffic flow were essential. Very high traffic volumes should also be observed as well as a variety of external conditions such as various gradients and curvatures. Altogether, 14 sections of rural two-lane highways were identified where measurements were performed. The higher levels of traffic demand could only be observed on level straight sections. However, steep and curvy mountain roads were also included in the sample.

On all observed sites local measurements have been performed. Here, the traffic was counted for both directions at a point which seemed to be typical for the whole section of the highway by means of video observations over a longer period of time. Furthermore, individual vehicle speeds were evaluated. Both, volumes and speeds were aggregated into 5-minute intervals where the speed was evaluated as space-mean speed. In addition to that, on 10 of the sites travel speeds have also been measured over distances between 1.9 to 4.2 km along sections of the highways under investigation. This was possible by registration number identification combined with travel time assignment to the individual vehicles.

The travel speed results were compared with local measurements at locations near the exits or entrances to the sections. A sufficient correspondence could, of course, only be expected on highways with a homogenous geometric design within this section. By some examples (selected as those with the best fit) Figure 1 shows that speed-flow diagrams usually correspond to each other under the presumptions mentioned. Local specifications however can cause some differences. Therefore, the interpretation of locally estimated results as representatives for a longer highway section must be used rather carefully.

Moreover, for several of the test sections also data obtained from continuous counting equipment were available (Figure 2). In one case (B 27), all three kinds of data could be compared (Figure 3). For this example we see that the travel speeds correspond quite well with the continuous counting results, whereas the site of the local measurement does not seem to represent the whole section.

MODELS FOR 2-LANE FLOW

Measurements of any kind can only provide a rather sectional view on highway flow characteristics. The range of influencing parameters which can occur in reality will never be covered completely by empirical results. This is mainly due to the significant effort required for measurements. Usual research funds cannot even pay for the observation of the most important parameter combinations (gradients, curvature, traffic volumes, etc.). In addition, several combinations of parameters can hardly be found in reality, like e.g. a straight road with steep gradient or a winding road in level terrain – both with high traffic volumes. Thus, the whole range of conditions which are usually covered by guidelines cannot be treated when results are only based on measurements. In addition, models must be developed which provide the potential to extend the empirical results to unobserved conditions.

Here, microsimulation is the first choice for a useful modeling technique. Several two-lane simulation models were taken into account such as TRARR (11) or HUTSIM (12).
Finally a German model named LASI (13) was selected for further application. It is a program which is maintained by the University of Weimar based on former developments at the University of Karlsruhe. The program is not sold commercially. Thus, calibrating to the data mentioned above and evaluating had to be performed in close cooperation with the authors of the program. In the end it was possible to represent the original empirical data quite well (Figure 4). Both, on level and straight highways as well as on steep and winding roads the results between measurement and simulation results matched quite well. Thus, the expectation was justified that simulations would rather reveal realistic results also for unobserved cases.

Simulation can generate any number of data points. But for the guidelines an analytical representation of these results is required. Both, measurements and simulation make clear that the shape of the speed-flow diagram for two-lane highways is different from freeway characteristics. Here, on two-lane roads there seems to be a concave shape (i.e. curve is open to the upside) embedded in the results. To represent this effect, a simple quadratic equation provided the best fit to the data points:

\[ v_T(\text{car}) = a + b \cdot \sqrt{q} \]  

where:

- \( v_T(\text{car}) \) : average passenger car travel speed [km/h]
- \( q \) : traffic volume (sum of both directions) [veh/h]
- \( a, b \) : parameters of the model

Meanwhile, Wu (14) has shown that a concave model can also be derived theoretically as a traffic flow model for roads with only one lane per direction. This concave shape was quite unexpected to many traffic experts both from practice as well as from science. Several voices in the discussion were afraid that this shape could only have been induced by the simulation model. This shape, however, becomes also evident looking at measurements over the full range of traffic volumes (e.g. Figure 2 or Figure 3). Also theoretical models come to the same conclusion as Figure 5, obtained from Brilon’s model (3), shows. This theoretical model explains that the concave shape is stamped on the speed-flow diagram by the presence of slower vehicles. The model does also suggest that, in cases of unequal flows in both directions, the volume of the smaller directional flow does not make much difference on the speed averaged over both directions if it is above 200 veh/h.

**FORMULATION FOR GUIDELINES**

To come to speed-flow relations ready for guidelines, a variety of parameters characterizing the geometry of the highway over a longer section has been used for the simulations. One of these parameters is the so-called „class of gradient“ (COG). This is defined by the minimum speed which a fictitious heavy vehicle (BSFZ) could obtain on the section under consideration due to upgrades. The BSFZ is the 15 %-truck; i.e. 15 % of all trucks – according to their power / weight-ratio - will not achieve that speed on an upgrade, whereas 85 % of all heavy vehicles will perform better. Based on evaluations by (15), the 15%-heavy vehicle has a power / weight ratio of 7.1 W/kg (= 3.22 W/pound), where the actual weight of the vehicle and its trailers is decisive for its mass. A speed profile for such a truck is given in (7) and (10). The speed has to be determined following the vertical profile of the highway for both directions. The lowest speed value which is thus obtained, is decisive for the classification of the gradient according to table 1. Thus, the BSFZ is a tool to express the combined effect of the grade and the length of the upgrade by one parameter: the class of gradient (COG).

For the evaluation of the curvature \( KU \) the whole highway of total length \( L \) has to be divided into \( n \) elements (straight line, circular line, clothoida) where each element contributes to curvature. Then the curvature \( KU \) of the highway is defined as
\[ KU = \frac{1}{n} \sum_{i=1}^{n} \left| \gamma_i \right| \]

where:

- \( KU \): curvature \([\text{degree/km}]\)
- \( \gamma_i \): turning angle within element \( i \) \([\text{degree}]\)
  
  (degree: measure of the angle, where a whole circle is 360 degrees)
- \( n \): number of horizontal design elements
- \( L \): total length of the highway \([\text{km}]\)

If the horizontal design of the highway is rather inhomogeneous, then these considerations should be made for homogeneous subsections.

In addition to that, overtaking prohibitions by signs or road markings put an additive term on the curvature \((7)\).

In addition to the geometric characteristics the percentage of heavy vehicles as a traffic parameter is varied between 0 and 25 \%, where each vehicle with an allowed maximum weight of 3500 kg (= 7720 pound) or more is regarded as a „heavy vehicle“. This is in correspondence with a more general terminology within German guidelines and traffic regulations.

For each combination of these characteristic parameters one speed-flow diagram has been evaluated by microsimulation. To generate these data, the flows of the two opposing directions were both varied over the whole range of potential values between 100 and 1400 veh/h. The data points (travel speeds averaged over both directions versus the sum of both directional volumes) have been represented by equation 1. With this technique, one speed-flow diagram was achieved for each parameter combination according to table 1 and for each of the heavy vehicle percentages. The results for the parameter combinations marked by shaded areas in table 1 are shown in Figure 6. For the remaining diagrams the reader is referred to \((7), (9), \text{ or } (10)\).

Also here, some of the results were quite unexpected since the external parameters did not show a linear influence on the speed-flow diagrams. In level terrain (COG =1) with medium or high curvature the heavy vehicles do not significantly reduce passenger car speeds (Figure 6, left center). Here, due to the curves, free moving cars also travel at similar speeds as the heavy vehicles, so that the heavy vehicles do not impede cars. On steep gradients (Figure 6, right column), the influence of heavy vehicles is not linear. If there are only very few trucks they already induce a significant reduction of speeds for cars. Further increase of truck traffic then is of minor influence. This result underlines: The influence of one additional truck on traffic performance is not constant – also not for one specific road. It depends both on total volume as well as on the level of truck volume. Therefore –according to the German results - the definition of PCE for trucks is a misleading concept for two-lane highway analysis.

At the outset, the travel speed of passenger cars was the intended MOE. For that case, the LOS had to be defined by a set of speed thresholds. That would, however, mean that in hilly or mountainous terrain a LOS of A or B would never be possible. For steep upgrades high speeds do not occur, even if the road is rather empty. This effect was not desired. Also in a speed reducing environment, (i.e. upgrades or speed limited sections) free flow conditions should mean a high flow performance expressed by an adequate LOS. Consequently, a surrogate for speeds had to be used as the MOE. PTSF was not considered according to the reasons mentioned above. After some experiments and in cooperation with the committee
responsible for the guideline HBS (7) the (fictitious) density $k = q/v_{\text{car}}$ was defined as the MOE for the guideline (7) as a surrogate for the average travel speed. One could argue, that also density (like the PTSF) is related to driver’s convenience. This is, however, not asserted in any official argumentation. The highest achievable density which came out of the measurements and from the simulations seemed to be in the range of 38 – 40 veh/km (in both directions) for passenger car traffic. Beyond this value traffic breakdown occurred. The value of 40 veh/h then was used to limit the upper margin of all speed-flow curves as the threshold to LOS F. Below this value the upper thresholds for other LOS were set by the responsible committee as: 5 (A), 12 (B), 20 (C), and 30 (D) veh/km.

Based on this background, the two-lane highway chapter in the „German HCM“ (7) was formulated.

To compare the German results with US conditions Figure 7 shows the curves from (7) (for level and straight highways) together with speed-flow diagrams obtained from (5) (chapter 12; base conditions). We see that for the more relevant traffic volumes the differences between the concave shape of the speed-flow diagram compared to the linear relations (HCM) are not very significant, if the free flow speed is adequately adjusted.

CRITICAL CONSIDERATIONS

The largest observed volumes were 2500 veh/h. Also the simulations revealed, that flows far beyond 2500 veh/h (sum of both directions) did not seem to be possible over longer sections of normal two-lane highways. Therefore, the largest observed flows of 2500 veh/h were treated as the maximum possible on straight and level roads. Also under these volumes gaps within the traffic flow still occur. These, however, cannot be filled up due to differences in speed and limited overtaking possibilities. Higher volumes over extended highway sections are only possible under conditions with a more homogenous speed behavior (especially with no speed differences between cars and trucks) than it is the case in Germany.

In this context it is important to know, that also the capacity of one direction is limited to a much lower value than it was originally expected. Both, measurement results as well as simulations showed that the flow on the directional lane for longer sections of two-lane highways is limited to values between 1200 and 1450 veh/h. This seems to be due to the fact that some longer gaps within the traffic flow are characteristic for a two-lane flow with opposing traffic and with a mix of trucks and cars. Also for two-lane tunnels this upper limit for the traffic volume of one direction proofed to be valid. Figure 8 shows a speed-flow diagram for one direction of a two-lane tunnel. This diagram was developed (16) as the representation of tunnel traffic based on comprehensive data analysis for long alpine tunnels. Here a capacity of 1200 veh/h could also be maintained for times of predominant leisure traffic whereas volumes up to 1500 veh/h were observed for commuter traffic.

One point of significant concern is the fact that always the whole cross-section has to be treated to apply the results. In a former paper (9) (there: figure 6) the authors have made clear, that the directional split does not have an influence on the average speed if this is averaged over both directions. There may, however, be some cases where the speed for one direction may become decisive and where, thus, a directional analysis could be preferable. Of course, the simulation results could also be analyzed in this direction. Therefore, analytical equations may be useful which reveal the average travel speed of one direction related to the volume in the same direction with the opposing flow as a parameter. Here it becomes clear that the directional speed is mainly depending on the volume flowing into the same direction. Figure 9 shows such a diagram for the case „level, straight“ (cf. table 1). These curves form an average concerning the relevant range of opposing flows.
Nevertheless, also the opposing flow has an influence on the travel speeds of traffic in one direction, as theoretical models (cf. Figure 5) and also the simulation results showed. The combined effect of flows in both directions on travel speeds over longer sections of the highway lead to more stringent speed-flow relations than a directional analysis concerning the effects of volumes for both directions. This is the main reason why two-way analysis has been recommended as the preferred type of analysis for the guidelines.

Finally, it should also be mentioned that the directional analysis is not too relevant, since in most of the observable cases the volumes of both directions are rather similar. In only 7% of all observed 1-hour intervals the continuous counting equipment detected cases where the directional split was beyond 70:30; these cases included mainly low volumes not relevant for the dimensioning of highways. Also the HCM (5) is emphasizing, that balanced directional distributions of traffic volumes are rather typical for two-lane highways.

The use of the guidelines (7) has been studied by written interviews with several users three years after their introduction. The comments obtained were not very critical. The users expressed their contentment with the practicability of the procedures. No doubts regarding the reliability where raised.

Nevertheless, it should be emphasized that the speed-flow relationships as they have been developed should not be used like a natural law. They can only be treated to describe conditions to be expected on a designed highway under usual conditions. As for freeways, where these effects have been studied in more detail (17), the speed-flow relations as well as the capacities are expected to vary with different driver populations; i.e. the results could differ from site to site and also over time at each specific highway section. Moreover, effects of randomness of capacity might also be essential for two-lane rural highways as they are reported for freeway traffic (17). These open questions should be a matter of further research.

CONCLUSIONS

In Germany, a comprehensive investigation has been performed to develop the chapter on two-lane highways for the „German HCM“ (7). The study is based on the observation of traffic flow on several sections of rural two-lane highways. The measurements were mainly used for a basic understanding of two-lane traffic flow and for the calibration of the microscopic simulation model LASI. The process of calibration was quite successful. Thus, the simulation model has been used to derive representative speed-flow diagrams.

For the guideline not the average travel speed – as it was initially intended – could be used as the MOE. Instead, the traffic density has been introduced as a surrogate MOE. Here a density of 40 veh/km turned out to be the typical critical threshold where free flow breaks down into congestion.

The speed-flow diagrams have several unexpected properties. The most obvious is the concave shape which first resulted from simulations. It was, however, also confirmed by measurements and theoretical models. The main reason for this effect is due to the difference of the level of speeds between the two classes of cars and trucks. The non-linear influences of curvature and gradients on the speeds are also new and unexpected – however plausible.

The traditional principle to treat both directions of a two-lane rural highway together as one entity – regarding traffic volume as well as average travel speeds – proved to be a consistent concept with a high degree of practicability. Nevertheless, for exceptional cases a directional analysis could be used.

The whole concept developed by the investigations was appreciated by the responsible committee and it was included into the „German HCM“ (7). This is now in use for three years without any complaints. Therefore, the concept – apparently – seems to be an appropriate
methodology for the traffic performance estimation on two-lane highways within the process of highway planning and design.

REFERENCES

**List of tables:**

Table 1: Combination of parameters for the evaluation of speed-flow diagrams

**List of figures:**

Figure 1: Speed-flow diagrams: Comparison between local measurements and travel speed measurements (gray points: local observation; black: travel speed).

Figure 2: Speed-flow diagrams for several 2-lane highways obtained from continuous counting equipment (1-hour intervals) for 4 different sites (horizontal: volume, sum of both directions [veh/h]; vertical: average speed of cars [km/h]).

Figure 3: Speed-flow diagram: Comparison of continuous counting (1-hour intervals), local measurement (5-minute intervals) and travel speed measurement (5-minute intervals) at the same highway section (B 27 near Tuebingen).

Figure 4: Speed-flow diagrams: Comparison between simulation and measurements (= dark points).

Figure 5: Speed-flow diagram obtained from Brilon’s stochastic two-lane flow model (3). (volume = flow in both directions; q-1 = volume for the direction with lower flow) The speed (travel speed) is averaged over both directions. The diagram should apply for a longer highway section with unhindered overtaking and an average free flow speed of 90 km/h.

Figure 6: Speed-flow diagrams for several combinations of parameters (7). Curves are valid for percent of heavy vehicles from 0 % (upper curve) step 5 to 25 %

Figure 7: Speed-flow diagrams obtained from HCM (5) (FFS = free flow speed) and HBS (7) for base conditions, i.e. straight and level highways (left: 2-way-segments; right: directional segments).

Figure 8: Speed-flow diagram for one direction of a two-lane tunnel (7).

Figure 9: Directional speed-flow diagram for a level and straight highway.
Table 1 Combination of parameters for the evaluation of speed-flow diagrams

<table>
<thead>
<tr>
<th>class of gradient (COG)</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>&gt; 55</td>
<td>&gt; 40</td>
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<td>Curvature ( KU ) [degree/km]</td>
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<td>x</td>
<td>x</td>
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<td>67 – 135</td>
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1): The uneven limits of each class are due to the fact that in Germany, for professional use, angles are measured in “gon” where 100 gon = 90 degrees.
Figure 1 Speed-flow diagrams: Comparison between local measurements and travel speed measurements (gray points: local observation; black: travel speed).
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Figure 3  Speed-flow diagram: Comparison of continuous counting (1-hour intervals), local measurement (5-minute intervals) and travel speed measurement (5-minute intervals) at the same highway section (B 27 near Tuebingen).
Figure 4  Speed-flow diagrams: Comparison between simulation and measurements (= dark points).
Figure 5 Speed-flow diagram obtained from Brilon’s stochastic two-lane flow model (3). (volume = flow in both directions; \( q-1 \) = volume for the direction with lower flow) The speed (travel speed for cars) is averaged over both directions. The diagram should apply for a longer highway section with unhindered overtaking and an average free flow speed of 90 km/h.
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Figure 7  Speed-flow diagrams obtained from HCM (5) (FFS = free flow speed) and HBS (7) for base conditions, i.e. straight and level highways (left: 2-way-segments; right: directional segments).
Figure 8  Standardized speed-flow diagram for one direction of a two-lane tunnel (7).
Figure 9  Directional speed-flow diagram for a level and straight highway.