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Traffic Flow on Freeway Upgrades

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ABSTRACT

Traffic flow characteristics on freeway upgrades in Germany have been analyzed. A combination of measurements, analyses of continuous counting results and microscopic simulations has been performed. From these results a macroscopic traffic flow model for freeway upgrades based on a two-stage linear speed-density relation has been developed. All relevant external influences like degree of gradient and length of upgrade together with traffic flow parameters like volume or proportion of heavy vehicles may be included by through specific parameters. Based on this analysis it was found that capacity depends solely the degree of gradient. Capacity is not influenced by gradient length. Velocity, however, is determined not only by the degree of the gradient but by the length of the upgrade (up to $L \leq 4000$ m) as well. Results have been formulated so that they are ready for application in practice, forming, for instance, the basis of the Freeway chapter of the new German Highway Capacity Manual.

INTRODUCTION

Upgrades on freeways impose lower velocities on vehicles, which may lead to capacity losses. While heavy vehicles are affected most severely, steep gradients have an impact on passenger cars as well. As a consequence inclined sections constitute bottlenecks within the freeway network. Therefore, the traffic flow on upgrades is of significant importance for the determination of the required freeway dimensions and for traffic flow qualities within the network. This is the reason why traffic flow on freeway upgrades plays an important role in the current guidelines for highway capacities in many countries.

The American Highway Capacity Manual (HCM, 2000) traditionally describes the impact of upgrades on traffic flow by passenger car equivalents for heavy vehicles, which strongly depend on the grade and length of gradient for different types of vehicles.

The corresponding German guidelines RAS-Q (1) traditionally do not use passenger car equivalents (i.e. pcu values) for freeway traffic flow analysis. They describe traffic volume based on "vehicles / hour" (sum of vehicles over all lanes; with the unit of "1" for motorized vehicles of all types; traffic composition is described by the percentage of heavy vehicles; = vehicles with a maximum weight above 3.5 tons). The measure of effectiveness (MOE) for freeways is represented by the travel velocity of passenger cars over longer sections of the freeway (e.g. 5 km). In the former RAS-Q (1) the impact of upgrades on freeways was described based on Brannolte's investigations (2). However, it was found necessary to recalibrate these relationships for the new guideline HBS (3), which is a German version of the Highway Capacity Manual. These new investigations were embedded in a research project conducted by the authors at the Ruhr University of Bochum on behalf of the German federal DOT (4, 5).

The objective of this research project was to develop speed-flow diagrams representing typical traffic conditions for each combination of length and degree of gradient on German motorways. These curves were to form the basis of the Freeway chapter in the HBS (3). Moreover, criteria for the construction of additional lanes on upgrades ("crawler lanes") had to be developed based on

traffic flow characteristics, traffic safety, and cost-benefit considerations. This paper mainly focuses on the derivation of capacities and traffic flow characteristics for freeway upgrades.

The methods employed include empirical investigations based both on microscopic measurements and continuous traffic monitoring as well as on microscopic simulation. Here the simulation model was calibrated based on empirical data. The results have been analyzed by statistical methods so as to develop models simple enough to be included into a guideline.

EMPIRICAL DATA ANALYSIS

First of all, a series of measurements was conducted at 8 sections of 2- and 3-lane freeway upgrades in different parts of Germany. Travel time measurements were made by video recordings of traffic situations on 5 different freeways, in each case at two points spaced between 2 and 3,6 km apart along the upgrade. Here the gradients varied between 2% and 6%, while the total length of the uphill section varied between 2.5 and 5.6 km. At each section the travel speed between two cross sections (distance between 1.6 and 2.6 km) was evaluated based on license number identification. Each data set contained several 1000 vehicles at traffic flows between 1000 and 3000 veh/h, indicating that free flow conditions were generally observed during measurements. Fig. 1 gives an impression of the range of observed traffic conditions regarding both speed and volume. The highest speeds were observed on the A43 downgrade. This downgrade section had been included for comparison. The low speeds on the A8 were influenced both by the steep gradient (+5.6 %) and the traffic restrictions (speed limit: 100 km/h + truck overtaking prohibition). The results show a clear impact of the degree of gradient on travel speeds.

In addition, a local traffic flow analysis was performed at the upper end of each of the sections under observation. The results are documented in (4). In this paper the emphasis is mainly on travel velocities over extended freeway sections.

Another and much more comprehensive set of data was collected from 5 longer freeway upgrade sections equipped with continuous counting facilities in connection with variable speed limit control devices. In each of these instances, more than two successive measurement points along the whole upgrade section could be analyzed continuously over more than one week (with raw data at 1-minute intervals). As an example Fig. 2 shows a speed-flow diagram from the A43-upgrade ($s = 3.5\%$; a section of the A43 different from that in Fig. 1) based on 5-minute intervals, with an average truck percentage of 8 %. In this context, average speed always corresponds to the space mean speed calculated from local measurements. We see free flow traffic situations and congested intervals at both locations (200 m and 1000 m from the lowest point). The maximum observed volumes, thus, give us an indication of the capacity, which at around 3600 veh/h seems to be identical for both locations. This is regarded as typical for 2-lane (per direction) freeways in Germany. Comparing data points from both measurements shows that capacity is not affected by longer upgrades. At the downstream point (Q7), however, free-flow speeds appear reduced due to the upgrade while on the other hand, congested speeds have increased.

This effect was observed at all of the 5 test sections which all experienced traffic breakdowns during the period of investigation. One rather important result came out clearly: traffic

breakdowns due to an upgrade all occur within a rather short distance from the bottom (i.e. the beginning) of the upgrade – usually on the first 500 m and never further than 1 km from the lower end. Here the data show a classical speed-flow diagram also including congested conditions occurring under sufficient traffic demand (Fig. 3a). On the lower part of the upgrade, speed-flow diagrams show a clear indication of the capacity. Further uphill, the traffic situation may recover and the degree of congestion is significantly reduced. Of course, volumes can never be greater than the capacity at the bottom of the upgrade due to continuity.

As another example for this effect, Fig. 3 shows speed-flow diagrams during afternoon peak hours over one week at the A4-upgrade (5.2 %, 2 lanes) “Tanneberger Loch” in 5-minute data plots. Fig 3a visualizes traffic conditions at a point 850 m from the beginning of the upgrade. We see rather low free speeds and a capacity in the range of 3000 veh/h. In the speed-flow diagrams for points located further uphill - during the same periods - no congestion is observed (Fig. 3 b + c). Fig.4 shows a more detailed analysis of one of the breakdown events shown in Fig. 3 , indicating that the real breakdown only occurred on the initial part of the upgrade section (Q5), whereas at the points further up the hill (Q6 and Q7) no noticeable effects on passenger car travel speeds were observed at the same time. This means that the traffic breakdown caused by the gradient occurred in the lower part of the upgrade section, limiting the capacity of the whole upgrade. Thus, the initial part of the upgrade constitutes the bottleneck for the succeeding freeway section. The capacity of a freeway upgrade does not depend on its length L (with $L > 500$ m). Therefore, the capacity-reducing effect of a freeway gradient becomes manifest even on rather short upgrade sections. However, length does have an influence on travel velocities, since on long upgrades of 500 m and more, the speed of heavy vehicles and to some extent of passenger cars –as well will decrease further along the road.

SIMULATIONS

Measuring traffic flow is an extensive and cost-intensive effort. Moreover, it is difficult to find real-world examples for all the local conditions and combinations of parameters to be described in guidelines to indicate quantitative relations. Both aspects make it necessary to extend the knowledge of traffic flow beyond those cases which can be observed. Therefore, an extrapolation of the observed relations is required. It would be inadequate just to draw measured curves beyond the observed margins. Instead, a set of models is required which incorporate the whole pattern of dynamics within the traffic flow process. The only type of model that can fulfill this requirement is a good and detailed microscopic simulation model. The point is that such a model should be well calibrated and verified for the specific conditions it is supposed to describe, such as applicable traffic rules and vehicle population. At the start of our project, no such model was in sight.

However, the basic concept and flexibility of the VISSIM-model (6) made it possible to use this program to extrapolate empirical results. VISSIM is a microscopic simulation tool which describes vehicle performance and driver behavior in a very detailed manner. By evaluating the interaction of vehicles on the road, it produces all sorts of macroscopic data, such as traffic volumes, local speeds, travel velocities, and many other parameters together with their statistical analyses. The provider of the model (PTV) cooperated with the research team to calibrate VISSIM to the above-mentioned empirical findings obtained on German freeway upgrades.

Results of simulation runs could be evaluated both for travel speeds over the whole length of the upgrade as well as for local speeds at different points along the freeway section under consideration.

Thus, after some calibration work, VISSIM replicated the empirical macroscopic results from all measurements rather well, for both passenger cars and trucks. Fig. 5 illustrates the degree of correspondence between measured and simulated speed-flow data by one rather complicated example (the steepest section with a speed limit and truck overtaking prohibition). Here the variance of truck speeds around the simulated data was much higher than at all the other sites (for more details see also (4)). Fig. 6 demonstrates that VISSIM would also represent traffic characteristics across the whole range of volumes. Here we see a comparison of spot speeds (more precisely: space mean speeds calculated from local observations) which are also shown in Fig. 2. It is obvious that the simulated data shown coincide quite well with measurement results, even up to the highest volumes. Even the effect of reduced congestion (see above) at the uphill point is replicated by the simulation model.

After calibration, VISSIM was employed to produce larger data sets so as to generate speed-flow relationships for all possible combinations of parameters. A series of test applications showed that simulated data from 15-minute intervals produced a rather good representation also for 1-hour counts. As in real life, the VISSIM model provided a significant variation of flow conditions. On average, for each speed-flow diagram around 50 intervals of 15 minutes –each were simulated (see e.g. Fig. 7). Since diagrams for 2-lane and 3-lane (per direction) freeways, for 4 proportions of trucks, for 4 degrees of gradient, for a whole range of lengths, and for different traffic control environments (such as speed limits) were required, the total number of simulation runs ran to several thousands. Each simulated time interval yielded one measurement point in the relevant speed-flow diagram.

As an example, Fig. 7 shows simulation results for different grades on a 2 km long freeway. It can be shown how travel velocity in this section of the road is reduced with increasing volume and grade. Capacity seems to be only slightly affected by a steeper gradient. Such data points (as in Fig. 7) from simulation runs had to be represented by a workable macroscopic traffic flow model.

MACROSCOPIC MODEL

It was necessary to identify a mathematical model able to represent both empirical and simulation results. Here, based on Ponzlet's ideas (7), a 2-stage linear speed-density model was employed. It uses separate linear relations for free flow and congested conditions. The linear speed-density relation yields a parabola for the speed-flow diagram (cf. Fig. 8).

An ANOVA (analysis of variance) was run to identify significant parameters from the simulation results (cf. Table 1). As we can see, the gradient is important only in the congested part of the model. Table 2 shows the parameters for the whole macroscopic model. Thus Table 2 represents the set of equations for the description of traffic flow on German motorways of all possible kinds (Germany has no significant lengths of motorways with more than 3 lanes per direction). Note that the resulting average travel velocity on the freeway section under consideration is the minimum of stage I and stage II velocity, as shown in line 4 of Table 2. For the determination of

a speed-flow diagram the set of equations from Table 2 has to be applied to varying traffic densities k .

As the analysis shows, the length of the upgrade has an impact on local speeds and thus on the overall travel speed. However, as the length of the upgrade increases, speeds converge towards a minimum, which depends on the grade s . Since for the guidelines we are only interested in travel velocities, we may say that one result of the analysis was that beyond a length of $L = 3800$ m travel velocity no longer decreases. Therefore, standard speed-flow diagrams were plotted for lengths of 4 km and above (Fig. 9). The capacities yielded by this analysis depend both on the gradient (s) and the proportion of trucks (Fig. 10) if we look at upgrades longer than 500 m (see also above). We see that both for 2 and 3 lanes, the gradient – if above 2 % - has an influence on capacity. The influence from the proportion of trucks impacts mainly 3-lane upgrades. While this may appear unexpected, it is due to the fact that on the steeper 2-lane upgrades there is usually a truck overtaking prohibition, which is not the case on 3-lane motorways.

The speed-flow diagrams that relate to the equations in Table 2 and/or the two examples in Fig. 9 were not directly adopted in the HBS guideline (3). Instead they were modified into a type of model described by Brilon, Ponzlet (8). This model was derived from a simple queueing analogy. It describes speed v as a function of volume q by this equation:

$$v = \frac{v_0}{1 + \frac{v_0}{L \cdot (c - q)}}$$

where v_0 is the free-flow speed. L and c are parameters of the model (note: c is proportional to the capacity with $c > \text{capacity}$). All three parameters have to be calibrated according to given data, or to the simulation results in this instance. Detailed parameters such as those used in the German HBS (3) are given in the Appendix to Chapter 3 in (3). One drawback of this simplified model is that it cannot be used to describe congested conditions. This model yields no capacity estimates (as does the model in Table 2). Instead, capacity is directly introduced into this model by the calibrated parameter c . The reason for the use of this alternative model in (3) was mainly a desire to get a much simpler set of equations for the HBS (3), even at the price of getting a less precise description. In addition, the model had to be extended to cover speed-limited sections of motorways. Nevertheless, the simulation results as they are described above (see also (4) and (5)) formed the basis for the calibration of the HBS-curves.

The fact that the marginal values for capacities ($L \geq 500$ m) and travel velocities ($L \geq 4000$ m) were obtained at different lengths L of the gradient causes a dilemma, since we now had to use a rather complicated mechanism to interpolate travel velocities for intermediate lengths ($0 < L < 4000$ m). For this purpose, Fig. 11 has been developed. It is part of a procedure which needs some concentration, but for paper and pencil applications it turned out to be the easiest compromise among the other alternatives, offering an easy-to-use diagram together with a sufficiently precise representation of realistic traffic flow behavior.

Some definitions first: The equivalent grade $s_{\text{eq},i}$ (see scale on the right margin of Fig. 11) is defined as the grade of a 4-km section which has the same travel velocity as a section of the grade s_i and a length $L_{\text{eq},i} < 4$ km.

For the procedure, the total length of a motorway to be analyzed must be divided into sections of identical gradients, traffic volumes, truck volumes, and cross-sections in the analyzed direction. This sequence of sections is analyzed by the following steps.

1. We are looking at a freeway section i with gradient s_i . The impact of the preceding section $i-1$ is considered by an equivalent grade, $s_{eq,i-1}$. We begin with a section i which has a gradient of $s_i > 2\%$ and a preceding section $i-1$ with a gradient $s_{i-1} \leq 2\%$ (implying an equivalent gradient of $s_{eq,i-1} \leq 2\%$ and an equivalent length of $L_{eq,i-1} = 0$). The reason is that below $s = 2\%$ no significant influence of the gradient on traffic flow is to be expected. Thus, we begin with sections where the preceding section represents traffic conditions on level freeways.
2. From Fig. 11 we determine the additional length AL_i as the length of a horizontal line starting from the point $(s_{eq,i-1}, L_{eq,i-1})$ and the intersection with the curve of s_i . The equivalent length $L_{eq,i}$ of the section i under consideration is $L_{eq,i} = L_i + AL_i$. If $L_{eq,i}$ is > 4 km, steps 3 and 4 can be skipped. Then $s_{eq,i}^* = s_i$
3. Now we determine the point of intersection between the curve s_i and a vertical line above the length $L_{eq,i}$. The equivalent gradient $s_{eq,i}$ can be obtained for this point on the y-axis at the right margin.
4. We then calculate the resulting grade $s_{eq,i}^*$ by :

$$s_{eq,i}^* = \min \left(\left(\frac{s_{eq,i} * L_{eq,i} - s_{eq,i-1} * AL_i}{L_i} \right); s_i \right) \text{ if } s_i > s_{eq,i-1}$$

$$s_{eq,i}^* = \max \left(\left(\frac{s_{eq,i} * L_{eq,i} - s_{eq,i-1} * AL_i}{L_i} \right); s_i \right) \text{ if } s_i < s_{eq,i-1}$$

5. The resulting grade $s_{eq,i}^*$ can be used to determine the travel velocity on section i from Fig. 8 and the intermediate figures which belong to the full set of speed-flow-diagrams like Fig. 9. Here $s_{eq,i}^*$ replaces the gradient s in these figures. Step 1 to 4 should be repeated for successive sections i with different gradients until we come to a section i with a gradient $s_{eq,i}^* \leq 2\%$.

For negative gradients (downhill sections), travel velocities different from level freeways need not be taken into account. Once again it should be mentioned that instead of a complicated procedure, figures like Fig. 9 and the set of equations listed in Table 2 can be used directly.

EXTERNAL CONDITIONS

Of course, the results obtained in Germany cannot be transplanted directly to other, countries since the technical backgrounds of vehicles, especially trucks, as well as traffic rules may differ. Therefore, the following parameters seem to be of importance for interpreting the results:

- In general, there is no speed limit for passenger cars on freeways in Germany. Only local speed limits may apply, indicated by traffic signs which, however, is the case in large parts of the network.
- Trucks have a general speed limit of 80 km/h, which is enforced by in-vehicle devices. These devices operate usually (and somewhat incorrectly) at a cutoff speed of around 95 to 100 km/h which, thus becomes the usual truck speed. Only under extreme conditions is there a truck speed limit (lower than the general limit) on downhill sections.
- Usually overtaking and passing is prohibited for trucks by signs on 2-lane upgrades (not on 3-lane).
- Average truck horse power is 12 kW/t with a 15 %-percentile of 7.1 kW/t.

CONCLUSION

Traffic flow on freeway upgrades in Germany has been analyzed by combining comprehensive measurements and analyses of continuously recorded data together with microscopic simulation. These results have been interpreted by a macroscopic traffic flow model.

Based on this analysis, it was found that capacity is not limited by the length of a gradient. The limiting impact of the gradient on capacity usually reaches its maximum at a gradient length of around 500 m. Travel velocity, however, is significantly influenced by the degree of gradient and the length of the upgrade (up to $L \leq 4000$ m) as well as by the proportion of trucks.

In its finalized version, the analysis is now ready for use in practice. Its results have been included in Chapter 3 (Freeway Sections) of the new German Highway Capacity Manual HBS (3). The concept of the analysis as a whole might also be applied in other countries, whereas the exact numerical results are linked to Central European conditions.

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FIGURE 11: Diagram showing the cumulative estimated effects of length (for $L < 4$ km) and grade on passenger car travel velocities.

TABLE 1: Significant parameters within the macroscopic traffic flow model describing passenger car travel velocity as a function of total traffic volume on freeway upgrades. An “x” means that this parameter is of significant importance.

| Parameter | | stage I | stage II |
|------------------------------|---------------------------|----------|----------|
| Number of lanes | FS | | x |
| Proportion of heavy vehicles | a_{truck} | | x |
| Degree of gradient | b_{grade} | x | x |
| Length of upgrade section | c_{length} | x | x |
| Traffic concentration | k | x | x |

TABLE 2: Formulas and parameters for the macroscopic traffic flow model for freeway gradients.

| | | stage I | | stage II | |
|---------------------------|---|--|---------|---|---------|
| | | 2 lanes | 3 lanes | 2 lanes | 3 lanes |
| Model | | $v_{P,I}(k) = v_0 + b_{\text{grade}} \cdot c_{\text{length}} + d \cdot k$ | | $v_{P,II}(k) = v_0 + a_{\text{truck}} + b_{\text{grade}} \cdot c_{\text{length}} + d \cdot k$ | |
| | | $v(k) = \min((v_{P,I}(k); v_{P,II}(k))$ $q = k \cdot v(k)$ | | | |
| Parameter | | | | | |
| v₀ | | 141.30 | | 154.88 | 156.13 |
| a_{truck} | Proportion of heavy vehicles | | | | |
| | 5% | | | 0 | 0 |
| | 10% | | | -0.38 | -3.18 |
| | 15% | | | -0.76 | -4.18 |
| | 20% | | | -1.15 | -5.18 |
| b_{grade} | 30% | | | -1.91 | -7.19 |
| | gradient s [%] | | | | |
| | ≤ 2 | 0 | | 0 | |
| | 3 | -1.90 | | -5.39 | |
| c_{length} | 4 | -5.74 | | -13.24 | |
| | 5 | -11.00 | | -20.09 | |
| c_{length} | | $c_{\text{length}} = -1.181 \cdot 10^{-11} L^3 + 2.192 \cdot 10^{-8} L^2 + 3.498 \cdot 10^{-4} L$ $L \leq 3800 \text{ m}$ $c_{\text{length}} = 1$ elsewhere $L = \text{length of the upgrade section [m]}$ | | | |
| d | | -0.6187 | | -1.4516 | -0.9711 |
| v_p | average passenger car travel velocity | | | [km/h] | |
| v₀ | free flow speed | | | [km/h] | |
| a_{truck} | factor for influence of trucks | | | [km/h] | |
| b_{grade} | factor for influence of gradient | | | [km/h] | |
| c_{length} | influence of length (= proportion of speed reduction for a section of length L relative to the maximum speed reduction for the same degree of gradient) | | | [-] | |
| k | traffic density | | | [veh/km] | |
| d | coefficient for the influence of traffic density | | | [km ² /(veh·h)] | |
| q | traffic volume | | | [veh/h] | |

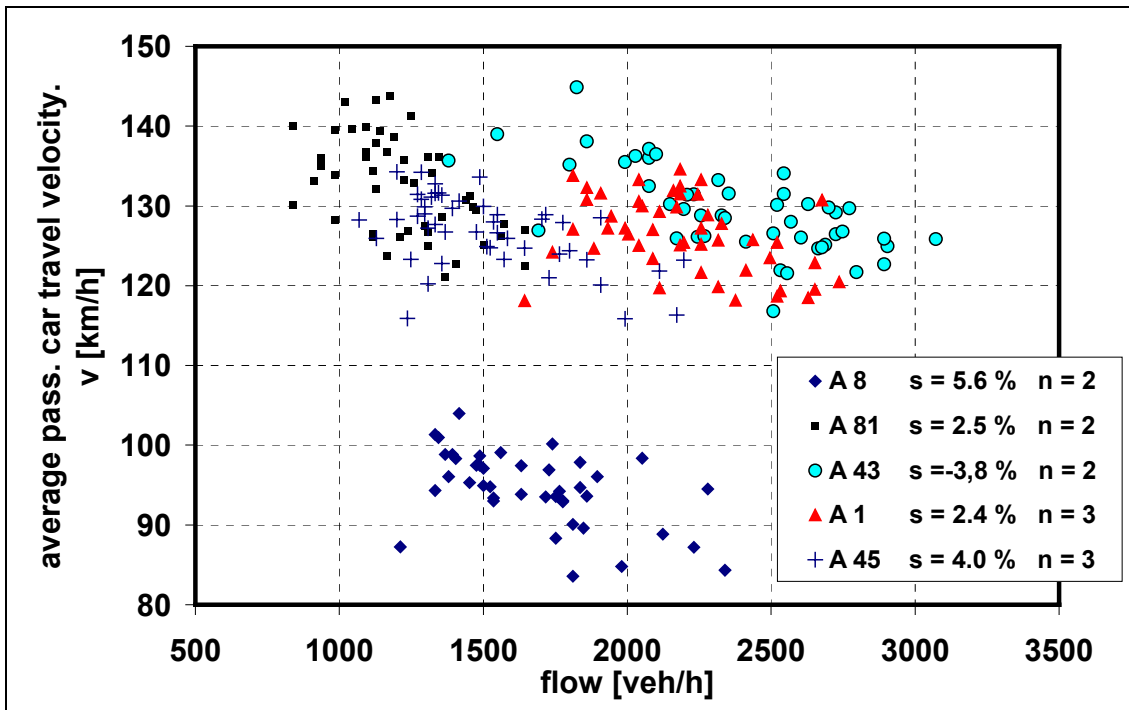


FIGURE 1: Average travel velocity over extended lengths of a freeway versus traffic volume as measured in all test sections, plotted into one graph.

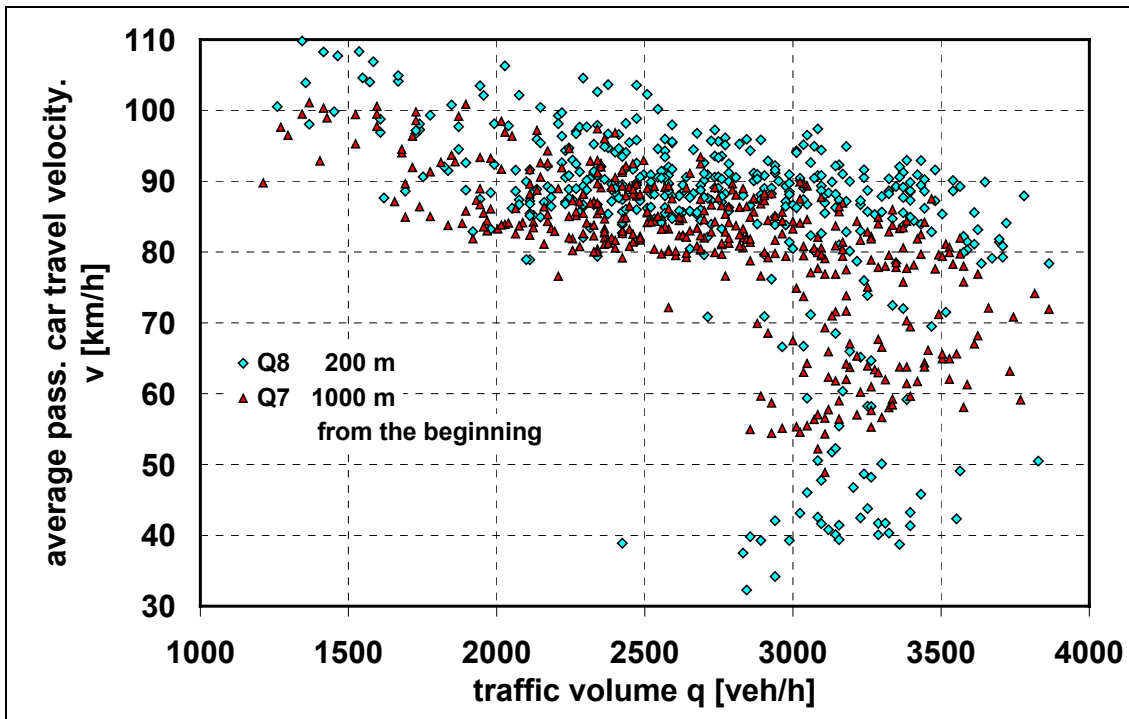
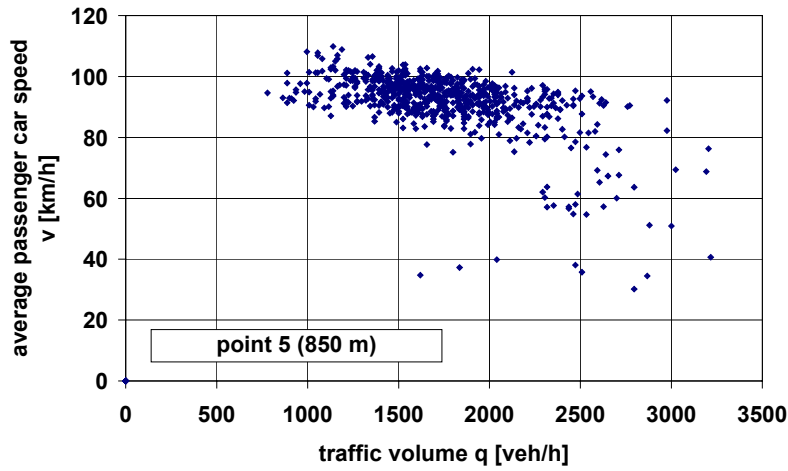
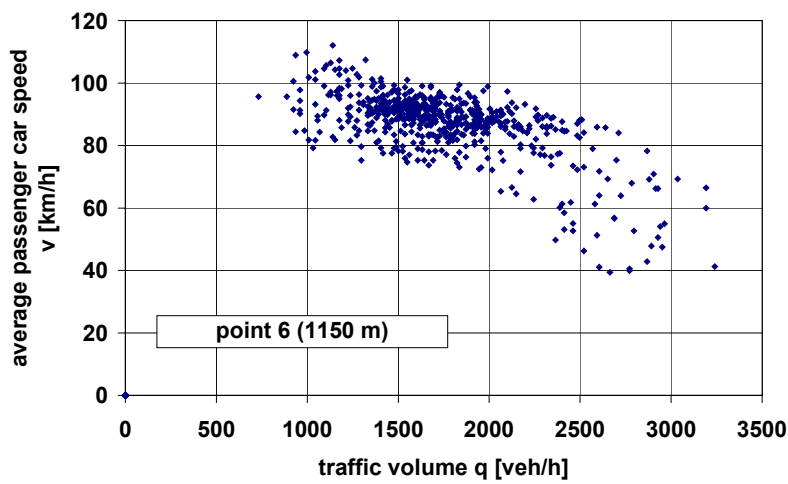


FIGURE 2: Speed-flow diagram at two points (Q8 and Q7) along the A43 upgrade (3.5 %; 5-minute intervals; space-mean speeds).



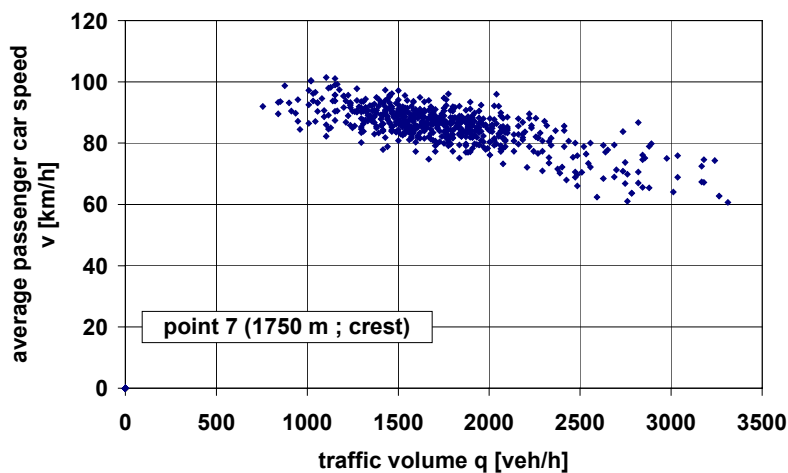
a)

point 5:
850 m distance
from the lowest point



b)

point 6:
1150 m distance
from the lowest point



c)

point 7:
1750 m distance
from the lowest point,
crest

FIGURE 3: Speed-flow diagrams at 3 successive points along the A4 upgrade obtained from continuous counting devices. Each diagram represents space-mean speeds over 5-minute intervals within the same time period.

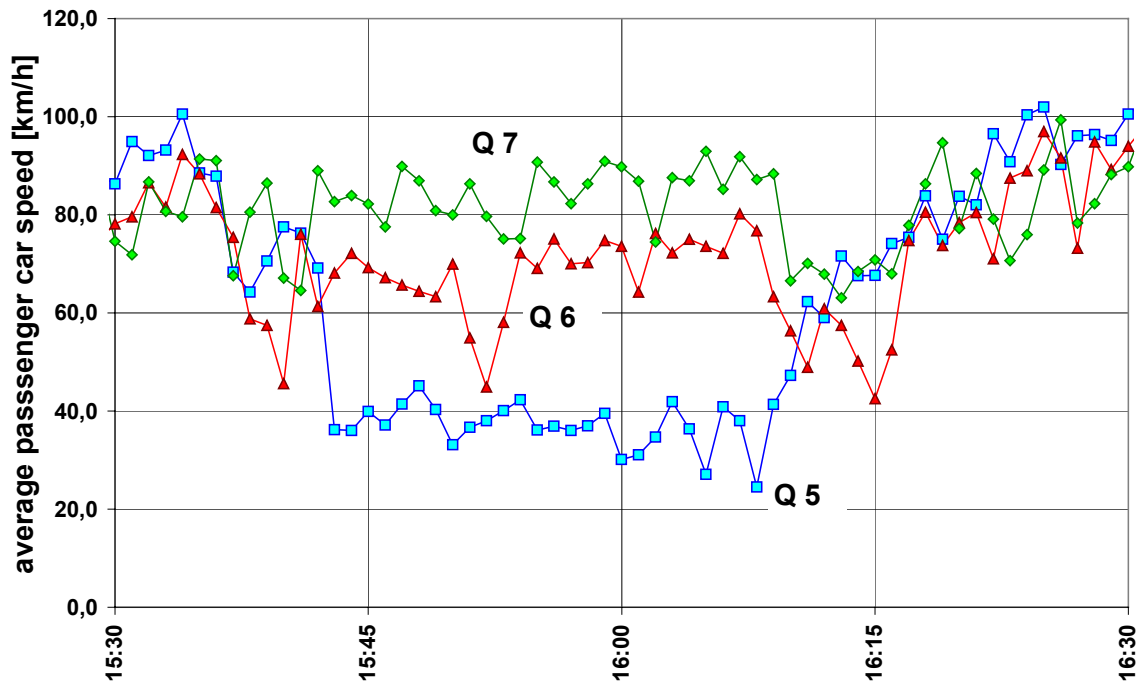


FIGURE 4: Speed pattern over time (space-mean speed; 1-minute intervals) at the A4 upgrade described also in Fig. 3 . The picture shows one of the traffic breakdowns shown in Fig. 3 developing over 1 hour .

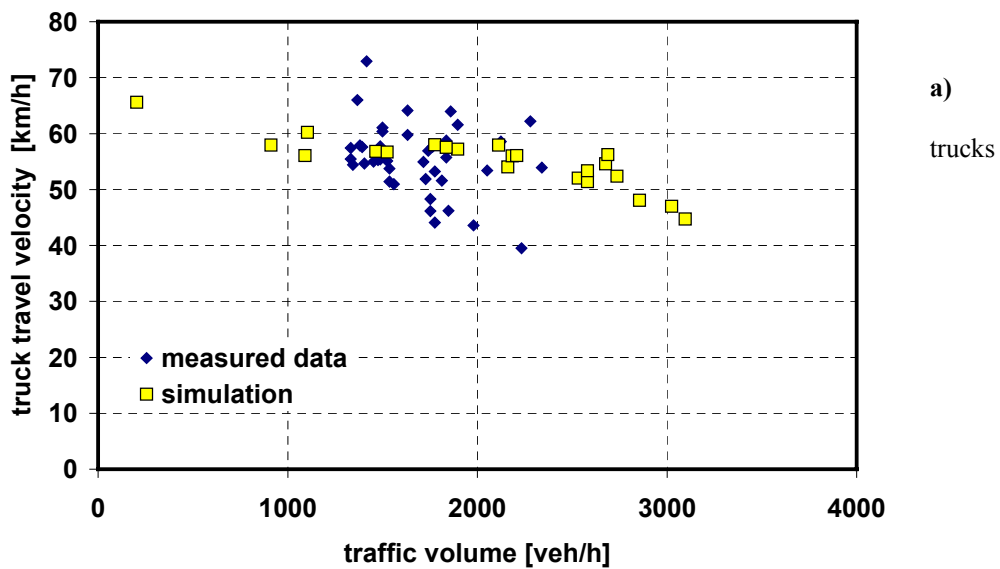
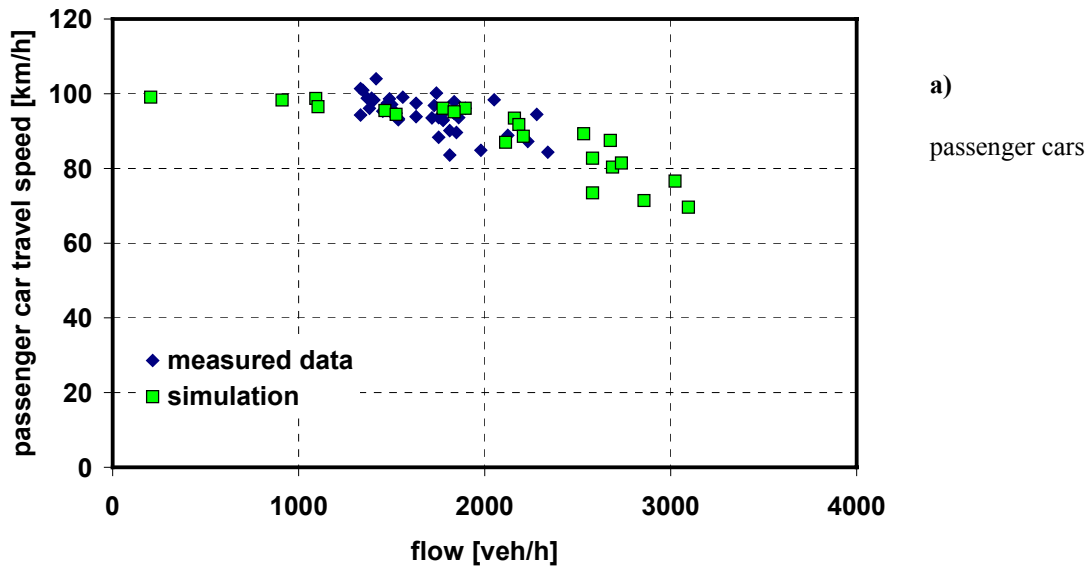


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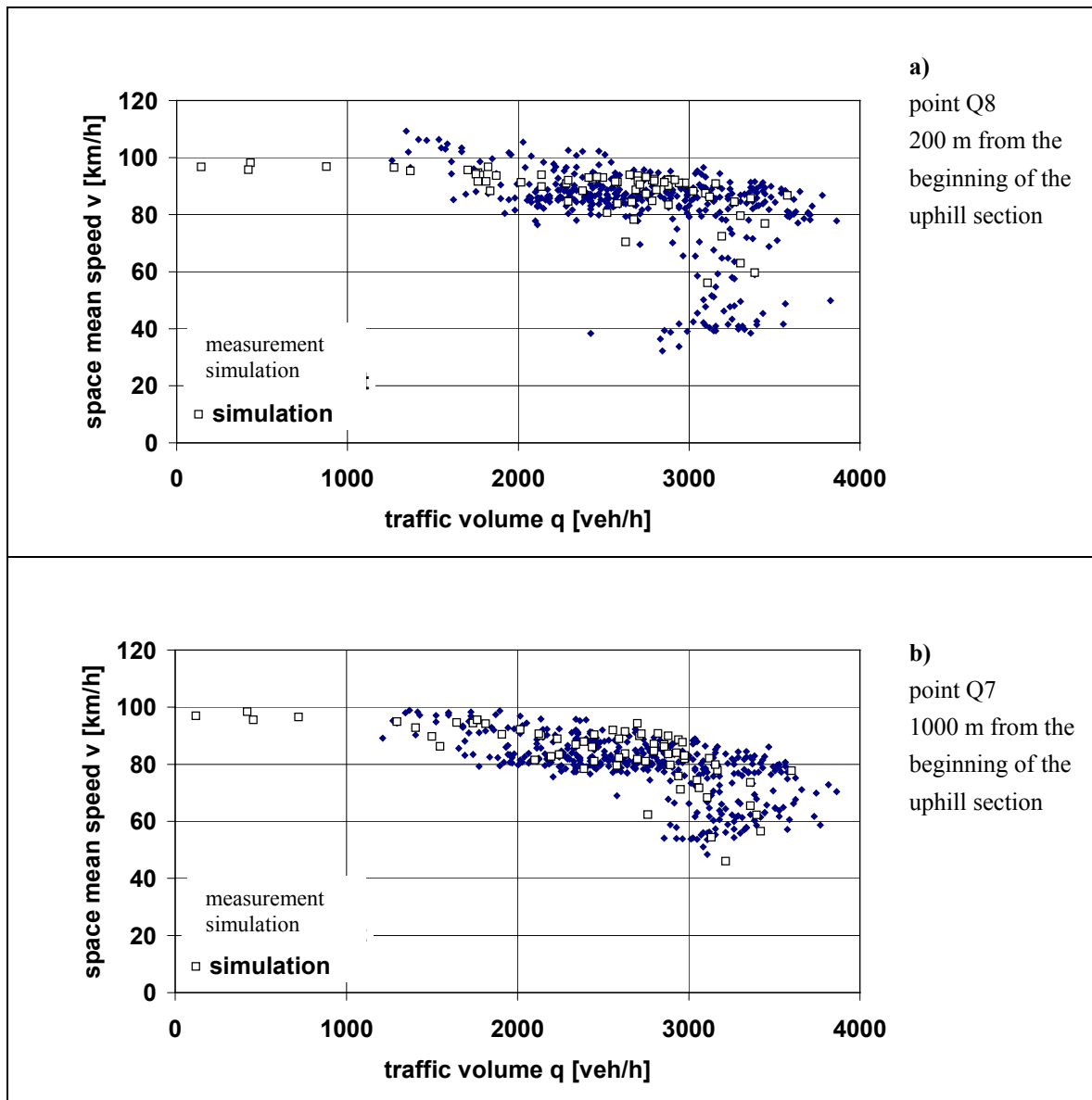


FIGURE 6: Space-mean speed versus traffic volume at 5-minute intervals as an example for the comparison between measurements and simulation results on the A43 upgrade. (2 lanes, grade 3.5 %, percentage of trucks: 8 %; see also Fig. 2).

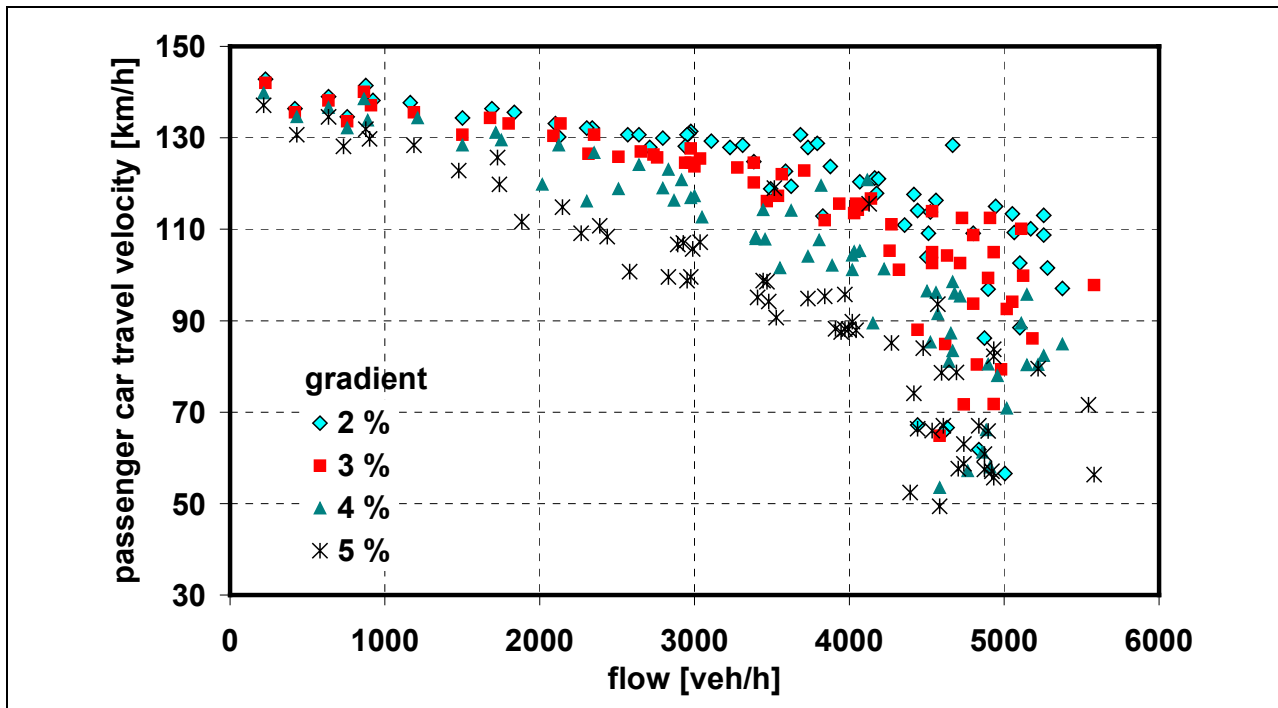
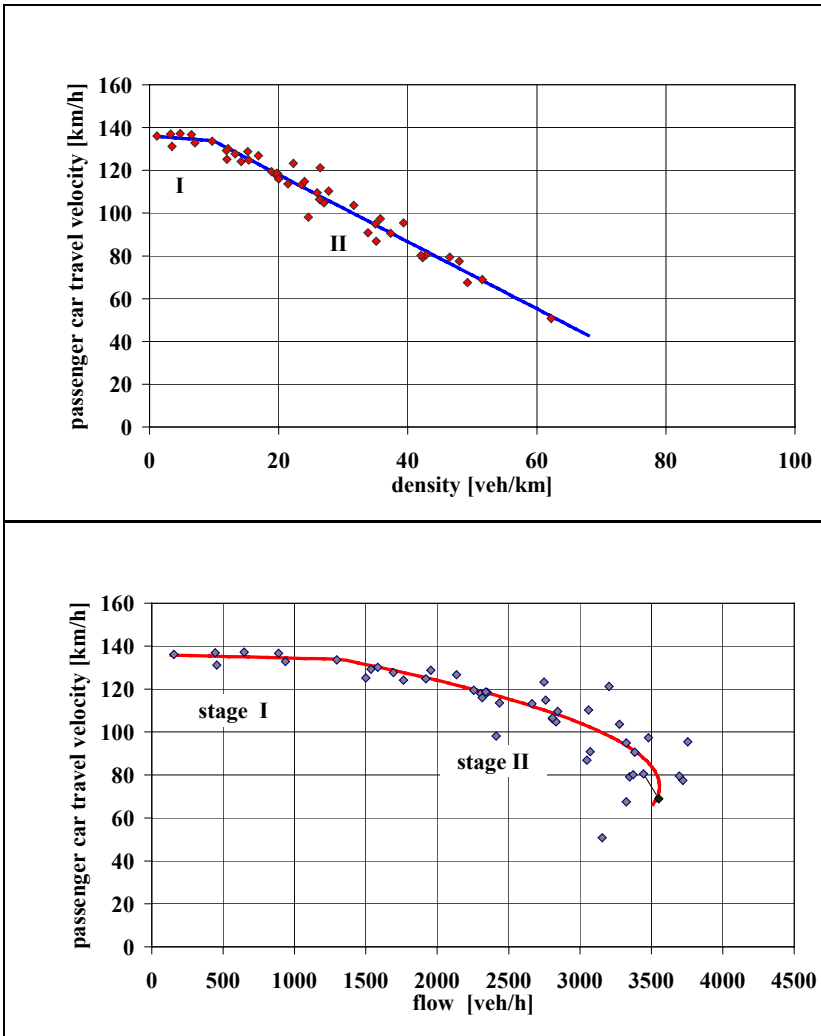


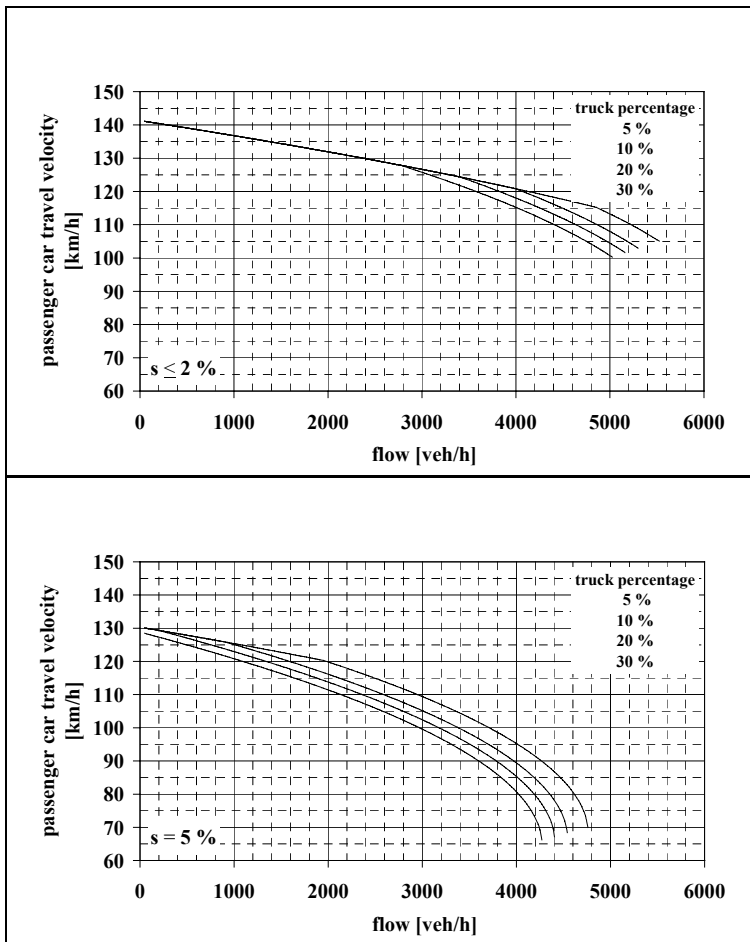
FIGURE 7: Average travel velocity over a 2 km section versus traffic volume obtained by simulation of different gradients on a 3-lane upgrade with 20 % of trucks (5-minute intervals).



a)
linear speed-density
model

b)
corresponding speed-flow
diagram

FIGURE 8: Macroscopic traffic flow model based on a two-stage linear representation for the speed-density diagram (to be applied for 1-hour volumes).



a)
level sections
and upgrades with $s \leq 2\%$

b)
upgrade with $s = 5\%$

FIGURE 9: Speed-flow diagrams for 3-lane (per direction) freeway sections obtained by the macroscopic model for German motorways (to be applied for 1-hour volumes; average travel velocity over sections of > 4 km length).

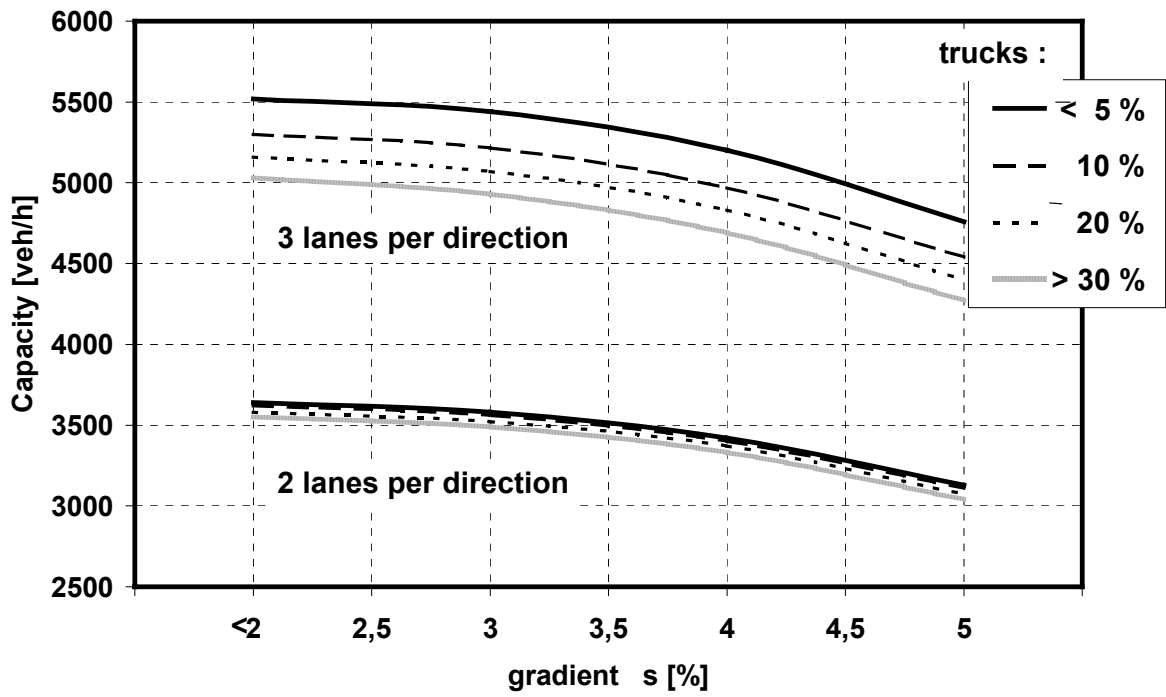


FIGURE 10: Capacities for 1-hour intervals as a function of grade and percentage of heavy vehicles for freeway upgrades.

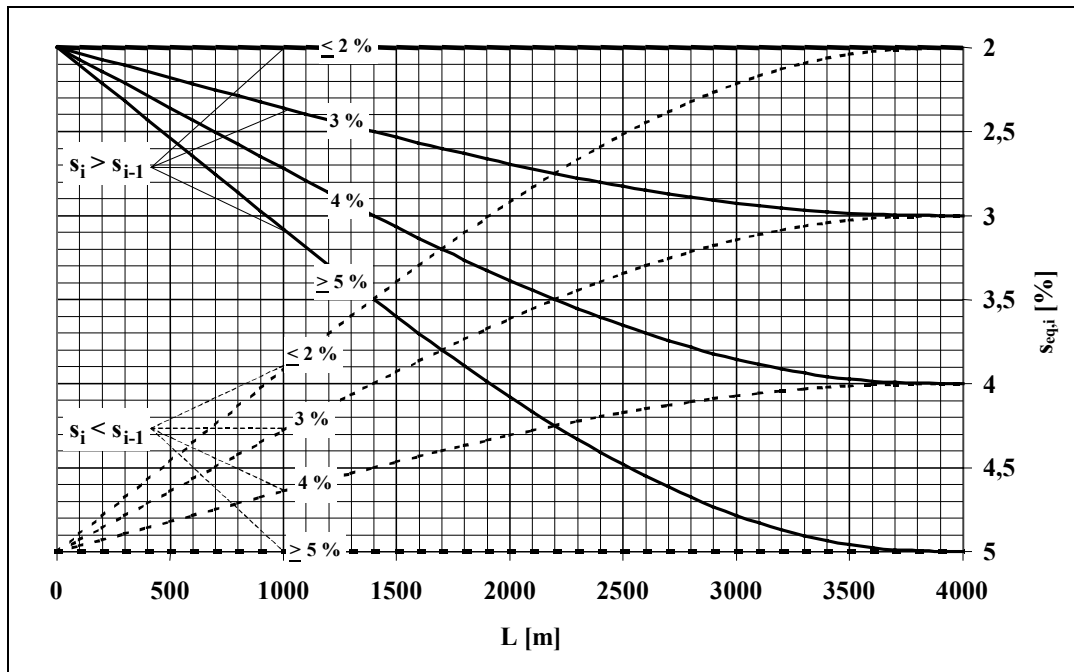


FIGURE 11: Diagram showing the cumulative estimated effects of length (for L < 4 km) and grade on passenger car travel velocities.