Speeds and Service on Multilane Upgrades

A. D. St. John and William D. Glauz, Midwest Research Institute, Kansas City, Missouri

This paper presents a sample of design guides for operating speeds and service levels on grades for one-way, multilane traffic including trucks. The design guides are based on computer simulation supported by field data. The guides and supplementary charts enable the user to account for truck populations with different performance characteristics. The paper also discusses traffic characteristics and comfort and safety in upgrade flows. A procedure is described for using the reported results to predict peaking characteristics in upgrade flows.

Trucks on upgrades of multilane facilities reduce capacity and service level. However, no well-established data base or comprehensive model is available to quantify these effects. The 1965 Highway Capacity Manual provides multilane truck equivalence values that are apparently based on some informal traffic observations on multilane facilities plus field studies and equivalence values for two-lane, two-way highways. The manual also presents a conceptual model that is quantified with a small amount of data. This paper discusses the use of field data and analyses to better quantify the effects of trucks in upgrade flows on multilane facilities (1, 2, 3, 4, 5, 6).

METHODS

A microscopic simulation model for unidirectional flow on two or three lanes was developed and computerized. The model was adjusted and validated by using data from the literature and field data collected by ground observers at 22 locations on six grades. In addition, a small amount of data were collected by aerial photography on one grade.

The model duplicates multilane flow features in situations ranging from free-flowing to congested conditions in level terrain, on grades, in the transition regions at grade feet and crests, and at climbing lane additions and drops. Characteristics tested include distribution of flow to lanes, lane change rates, time headways, and speeds. Numerous traffic characteristics are duplicated in the wide variety of terrains because of model logic and without a priori judgments imposed through input.

The program consists of about 8000 statements, is written in FORTRAN IV (except for a small routine in assembly language), and on the CDC 6000 computers requires about 32 000 words of core in addition to the system. User instructions and a complete description of the model, model adjustment, and validation are given in other reports (1, 2, 3, 4, 5, 6). This paper presents major results obtained with the model.

The results from the model tend to confirm a basic postulate of traffic engineering, namely, that the operating speed (and the passenger vehicle average speed) plotted against flow rate exhibits a characteristic shape. And the capacity flow is diminished by slow trucks. Further, the capacity is a nonlinear function of both the percentage of trucks and the local speeds of the trucks.

The design charts described in the next section are based on numerous model results that have been assembled by using the characteristic relations between speed and flow. The curve of operating speed versus percentage of capacity was established first. Then the model was exercised with a variety of flow rates, percentages of trucks, and truck populations on grades. Each case provided an operating speed that was used to read the associated percentage of capacity. The capacity was then estimated as the flow rate divided by the percentage of capacity. The results were assembled into design chart sets.

DESIGN CHART SETS

Design guide chart sets were assembled from the results of numerous simulation model runs. Each chart set consists of two figures that can be used to estimate speed and service for short time periods. Figures 1 and 2 constitute a set for two upgrade lanes on a facility with 121-km/h (75-mph) design speed. Figure 2 shows added lines associated with two examples that are described.

In the first example it is desired to estimate the freeway service level and operating speed on a 2 percent sustained grade with 10 percent trucks in a mixed flow of 1800 vehicles/h. An initial point is located on Figure 2

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at the intersection of the 2 percent grade line and the 10 percent truck line. From the initial point, the horizontal line (1-1) is followed to the intersection with 1800 vehicles/h, and the fan of lines is followed (along 1-2) to the scale for percentage of estimated capacity, which is read as 56. At 56 percent, the service level is C′ and the operating speed is 97 km/h (60 mph). (Service levels are primed to remind the user that the service level depends on operating speed and percentage of capacity. Comfort and safety on grades may not equal that in level terrain.)

In the second example the maximum flow for service level C′ on a rural multilane highway is sought for a 4

Figure 1. Operating speed versus percentage of capacity.

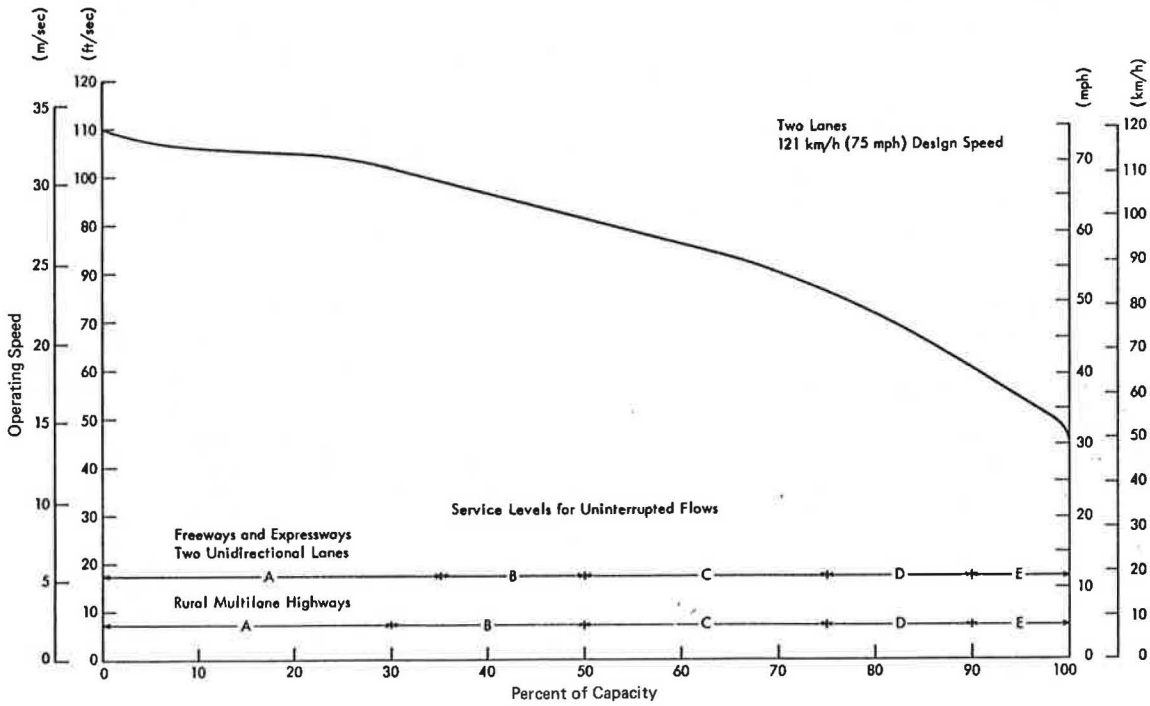
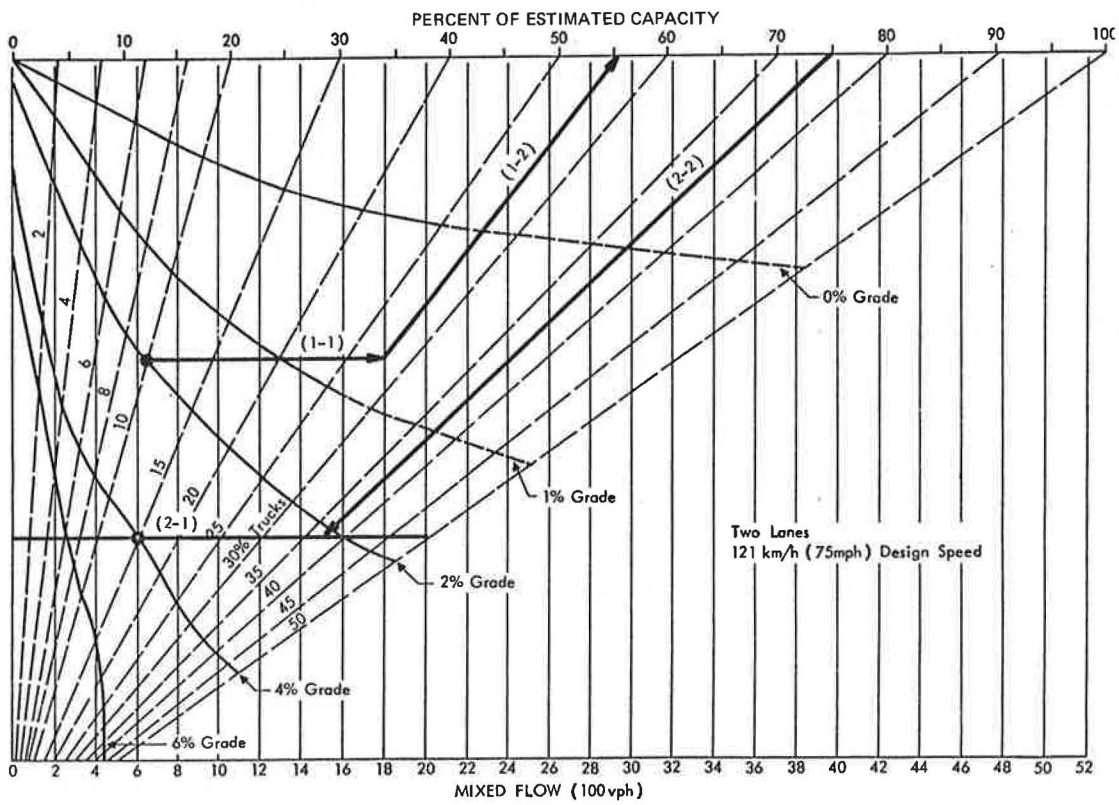


Figure 2. Estimated capacities versus percentage of trucks and sustained grade.



percent sustained grade on which the flow will contain 15 percent trucks. The intersection of the 4 percent grade line and the 15 percent truck line is located on Figure 2 and a horizontal line is passed through that point (line 2-1). Figure 1 shows that the upper limit for level C′ is 75 percent of capacity. Figure 2 is entered on the percentage of estimated capacity scale at 75 percent. The fan of lines is followed (along line 2-2) to the intersection with line 2-1. At that intersection the answer is read as 1520 mixed vehicles/h.

Figure 2 and others like it are based on a simple concept that involves the horizontal line passing through the intersection of curves for the percentages of grade and trucks. Service levels A′ (if possible) through E′ are represented along the horizontal line. At the left end, the percentage of capacity is zero and the flow is zero. This is the highest possible service level. At the right of the line, where it intersects the last of the fan of lines, the mixed flow is equal to the estimated capacity. For the second example the estimated capacity is 2020 vehicles/h. The fan of lines actually serves a dual purpose. First, individual lines in the fan identify the intersection of the given percentage of trucks with a sustained grade line. Second, from any point on a horizontal line the fan can be used as a guide to the scale for percentage of estimated capacity.

In the next section the design chart sets are applied to grade feet and crests and to rolling terrain. However, the charts apply to a specific truck population and provide an estimate of the most likely flow conditions during short time periods (2 to 3 min).

VEHICLE POPULATION AND WEIGHT FACTORS

The performance characteristics of the vehicles, especially the trucks, influence the service levels and capacities in on-grade flows. The acceleration and speed capabilities of the trucks in a flow may be as important as the number of trucks. This section presents procedures that can be used to account for the variations in truck populations on different facilities.

The design charts are based on passenger vehicle and truck populations with the characteristics in Tables 1 and 2. The truck population given in Table 2 contains a relatively large proportion of low-performance trucks. The design charts, based on this reference population, will usually provide conservative results (low service levels). A national average truck population, based on data reported by Wright and Tignor (7), is estimated as 26 percent for index 7, 40 percent for index 8, 24 percent for index 9, and 10 percent for index 10.

Because the user may have to contend with a different population, results from the simulation model were used to derive weight factors for adjusting other truck populations to the reference population given in Table 2. The weight factors apply to these four truck types as shown in the following equation.

$$\text{Percentage of reference trucks} = (100/F)(3.16 f_{10} + 1.41 f_9 + 0.14 f_8 + 0.06 f_7) \quad (1)$$

where

F = total flow rate of mixed vehicles,
f_{10} = flow rate of Index No. 10 trucks, and
f_9 = flow rate of Index No. 9 trucks and so on.

Percentage of reference trucks is in terms of the reference population defined in Table 2. The equation can also be expressed purely in terms of percentages.

$$\text{Percentage of reference trucks} = P_T(3.16 p_{10} + 1.41 p_9 + 0.14 p_8 + 0.06 p_7) \quad (2)$$

where

P_T = total percentage of trucks observed, and
P_{10} = ratio of Index No. 10 trucks to total trucks and so on.

The weight factors are internally consistent; when the weight factors are applied to the reference population, the percentage of reference trucks equals the percentage based on direct counts.

If trucks other than those given in Table 2 are encountered, their weight factors can be approximated by using their speed differences from the slowest observed trucks. (This is an approximation because the speed differences between trucks are not exactly the same on sustained grades of 2, 4, and 6 percent.) The weight factors as a function of speed differences are shown in Figure 3. The slowest truck in a sample (3-min sample) is assigned the weight factor 3.16, or 3.0 in the linear approximation.

Figure 3 provides a means for assigning weight factors to trucks without their first being equated to a truck type. In addition, the strong sensitivity of flow characteristics to the slowest truck in a sample suggests that design chart information can be expressed as a function of the speed of the slowest truck. This representation is shown in Figure 4 as estimated capacity versus the speed of the slowest truck and the percentage of reference trucks.

Figure 4 can be used in lieu of Figure 2 to estimate capacity so that percentage of capacity can be calculated for a design or projected flow. Then, estimates for the service level and operating speed can be read from Figure 1. Figure 4 also can be used for capacity estimates on grades that were not explicitly simulated. The 1 percent grade line in Figure 2 was obtained this way. Figure 4, in conjunction with Figures 1 and 3, can also be used to estimate flow conditions in the foot and crest transition regions when the speeds of the truck sample are known or estimated for these regions.

Figure 4 and similar figures have been used to extrapolate to large truck percentages. The simulation results extend to 20 percent or 30 percent trucks for the grade and lane combinations.

The flow characteristics in rolling terrain should be equivalent to a sequence of foot and crest transition flows. As an example, consider the influence of a short grade on a facility with two upgrade lanes. The alignment has a sag vertical curve at the foot followed by 122 m (400 ft) of 4 percent grade. It is estimated that the truck population, which constitutes 17.5 percent of the peak-hour flow, is slowed to the minimum speeds given in Table 3. When the weight factors are applied, the percentage of reference trucks is

$$\begin{aligned}\text{Percentage of reference trucks} &= 17.5[(0.05)(3.16) + (0.08)(2.72) \\ &\quad + (0.21)(1.61) + (0.33)(0.92) \\ &\quad + (0.33)(0.37)] \\ &= 19.9 \quad (3)\end{aligned}$$

The estimated capacity is read from Figure 4 at 19.9 percent trucks and 13.7 m/s (45 ft/s) for the slowest truck. The estimated capacity is 3420 mixed vehicles/h. Figure 1 may be used to estimate service level. Service near the crest of the short grade will fall below level C′ if mixed flow exceeds 75 percent of 3420 or 2562 vehicles/h.

In the above example, it must be recognized that the service would be depressed over a short section of highway. Variations over time and grade length are discussed later.

An earlier report (1) includes figures similar to Figure 4 for two and three lanes with design speeds of 105, 113, and 121 km/h (65, 70, and 75 mph).

PRECAUTIONS IN THE USE OF DESIGN CHARTS

The design charts are based on a truck population with a large percentage of low-performance vehicles, and the basic curves were drawn conservatively. However, the charts are based on flows during short time periods. They do not include provision for peaking or variance during a design hour. Also, the user should recognize that the charts provide estimates for traffic conditions in relatively short sections of highway, 300 to 600 m (1000 to 2000 ft). Consequently, the truck speeds used are the local speeds and not speeds averaged over the entire grade.

The simulation results indicate that the estimated capacities are not "practical capacities." Temporary local congestions can occur in the on-grade flows over a wide range of percentages of estimated capacity. When 90 percent of estimated capacity is approached, temporary local congestions are almost certain to occur. When flow exceeds 90 or 95 percent of implied capacity, the flow is vulnerable to breakdown. It appears that breakdown on a 2 percent grade will occur in a fashion similar to flows in level terrain with nearly uniform high densities and low speeds. On the 4 and 6 percent grades with trucks present, the maximum flows appear to occur as a sequence of congested and flowing conditions on the grade. Flow breakdown on these steeper grades is probably not a smoothly spreading phenomenon. Instead, if the spots of congestion grow, the storage space on the grade becomes progressively filled with congestion queues.

Some of the poorest service levels simulated occurred on the 4 percent grades with two lanes upgrade. The service was depressed in local sections on the grade by a flow feature that might be described as persistent congestion. This congestion was triggered by a single event or a sequence of disruptive events, such as a truck passing a platoon of other trucks. In one case a conservative driver followed the truck performing the pass so that the queue was slow to accelerate when the truck returned to the right lane. In each case a queue 180 to 300 m (600 to 1000 ft) long built up in the median lane. This local spot of congestion did not dissipate; it followed the slow truck up the grade. A flow of higher speed vehicles went through the congestion (with delay), but the congested queue remained with slowly varying length.

In some applications the third upgrade lane may be a climbing lane, which is added near the grade foot and dropped near the crest. The full benefits of the third lane are not realized in the first 240 to 300 m (800 to 1000 ft). Likewise, the benefits are not fully retained during the last 300 to 425 m (1000 to 1400 ft) of the added lane. For volume/capacity ratios of 35 to 85 percent, the operating speeds will be depressed about 2.4 m/s

Table 1. Characteristics of passenger vehicle population.

Simulation Index No.[a]	Percentage in Passenger Vehicle Population	Length (m)	Max Acceleration[b] (m/s^2)	Max Speed[b] (km/h)
1	49.80	5.5	4.5	161.3
3	45.13	5.5	3.6	142.6
5	5.07	5.5	2.5	110.9

Note: 1 m = 3.28 ft; 1 km/h = 0.6 mph.
[a]Indexes 2 and 4 were not used. [b]On zero grade at sea level conditions.

Table 2. Characteristics of reference truck population.

Index No.	Weight Power Represented (kg/kW)	Percentage in Commercial Truck Population	Length (m)	Max Acceleration[a] (m/s)	Performance-Limited Steady Speed (m/s) by Grade[b]							
					0%	1%	2%	3%	4%	5%	6%	7%
7	56	13.5	7.6	3.96	33.1	30.9	28.9	27.1	25.4	23.8	22.4	21.0
8	112	36.5	12.2	2.82	29.4	25.6	22.4	19.8	17.6	15.7	14.1	12.6
9	187 to 261	36.5	15.2	1.73	25.0	20.1	16.4	13.6	11.2	9.5	8.0	6.7
10	>261	13.5	18.3	1.16	18.7	12.8	9.3	7.0	5.3	4.1	3.2	2.4

Note: 1 kg = 2.2 lb; 1 kW = 1.34 hp; 1 m = 3.28 ft.
[a]On zero grade at sea level conditions. [b]At sea level conditions.

Figure 3. Weight factors for trucks versus speed above lowest truck speed.

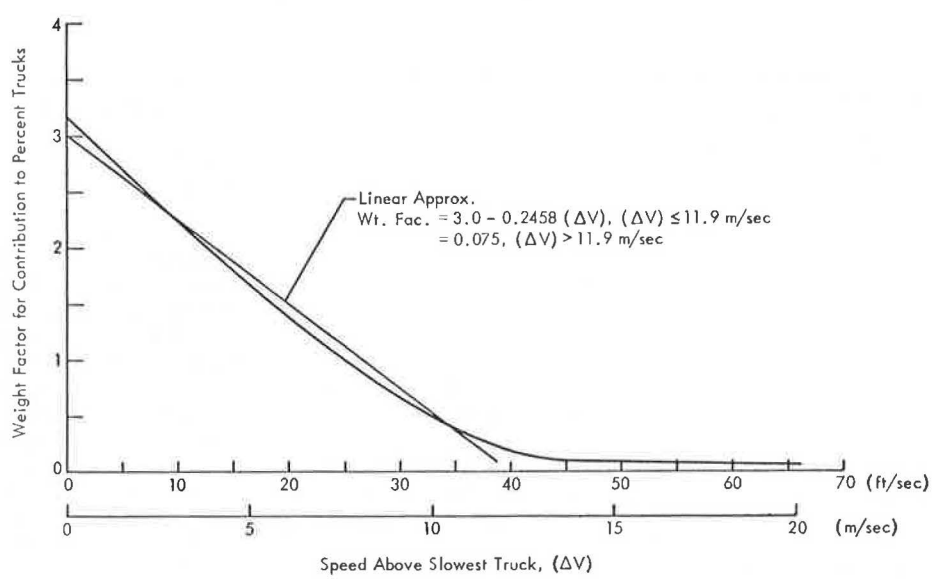


Figure 4. Estimated capacity versus speed of slowest truck and percentage of reference trucks.

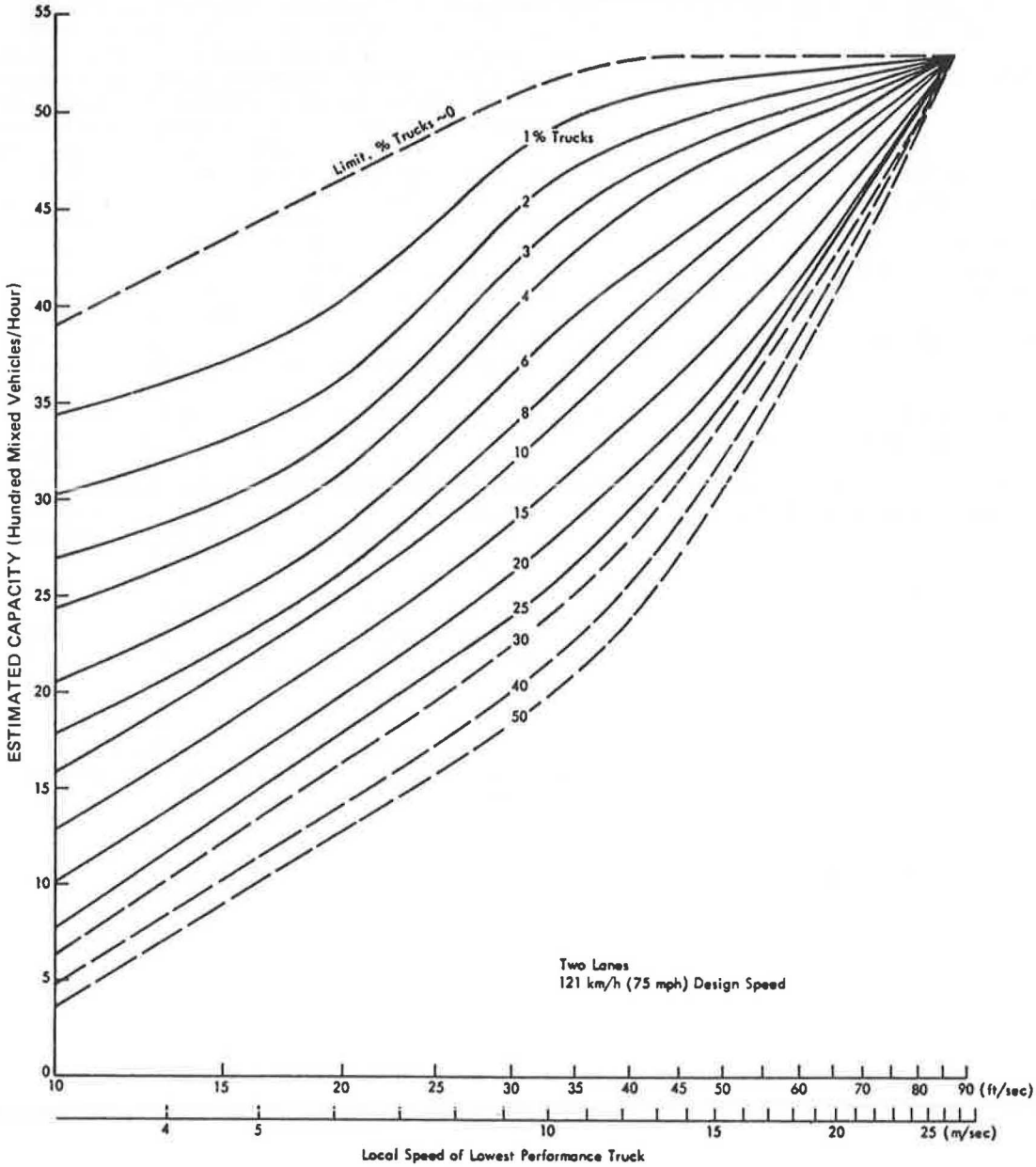


Table 3. Minimum spot speeds of trucks on a short grade and associated weight factors.

Percentage of Truck Population	Minimum Speed (m/s)	Speed Above Slowest (m/s)	Weight Factor (From Figure 3)
5	13.7	0	3.16
8	15.2	1.5	2.72
21	18.9	5.2	1.61
33	21.6	7.9	0.92
33	24.4	10.7	0.37

Note: 1 m = 3.28 ft.

(8 ft/s) after the lane addition and before the drop. The underlying traffic behavior is observed in the model and at field sites.

The reader is also cautioned that the simulation model was exercised for cases extending to 20 to 30 percent trucks. The extrapolation to 50 percent trucks was made when the results from individual cases were summarized to the design charts. The extrapolations that are subject to logical constraints are included in the design charts to emphasize the nonlinearities suggested by available results.

VARIATIONS OF FLOW CHARACTERISTICS WITH TIME AND LENGTH

The data collected on grades and the observation of the flows suggest that 2 to 3 min is a suitable time period for relating the flow characteristics on short sections to the flow rate and vehicle population. Longer time periods will average over characteristics that may be noticeably different. This short period is at variance with the hourly rates and volumes that are normally used in design or evaluation. However, the importance of short-term demands has been recognized for flows on freeways and expressways, and the 5-min interval peak has been employed. Peak-hour factors are used to account for the mean maximum demand during 5-min periods of peak hours. When the period is shortened to 3 min, the peaking will be slightly more severe. However, on grades

(especially on sustained grades) there are additional sources of variance, some of which may be more important than the increased peaking in flow rate.

The design-hour volume for a facility, together with the percentage of trucks, may be the basis for design or evaluation. A peaking factor may be used to account for total flow variations and to estimate the mean maximum flow rate. On a sustained grade, however, the variation of truck flow rates between 3-min intervals may be the source of equal or greater variation in traffic characteristics. In addition, the samples of trucks that arrive in individual 3-min periods may have performance capabilities that are different from those of the truck population sampled during long periods. The simulation results and the comparisons with field data indicate that the size and character of the truck sample have a strong effect on the short-period flow characteristics. Neither of these types of sample-to-sample variations has a pronounced effect on flow characteristics in level terrain.

An additional source of variation for the on-grade flow arises from the presence or absence of disruptive events in the flow. The disruptive events are usually associated with truck-passing-truck maneuvers. This means that the flow characteristics might vary noticeably between different 3-min samples even though each contained exactly the same set of trucks.

All the features discussed above increase the variance of operating speeds measured during 3-min periods on a short section, 300 m (1000 ft), of a grade. When the flow is examined along an extended grade, the same flow features cause a space-wise variation in operating conditions. The space-wise variation is encountered by passenger vehicle drivers who ascend an extended grade in flows that are significantly influenced by slow trucks and who may be forced to make more speed changes and lane changes than would be required for the same overall operating speed in level terrain. As a result the safety and comfort aspects of service on a grade may not equal those in level terrain even when overall operating speeds are equal.

Additional length for a sustained grade appears to have two deleterious effects. First, it increases the likelihood that a region of severely depressed service will exist on the grade at any given time. Second, when spots of persistent congestion arise, they affect the flow for a time proportional to the remaining distance to the crest.

The design charts can be used with an hourly flow rate; the truck population is averaged for the hour to give an estimate of the average operating conditions for the hour. For design and traffic engineering it is more informative to know the distribution of operating conditions. Obviously, the low-service points are most important. The distributions can be constructed by using the design charts and 3-min traffic samples generated with a combination of probabilistic and stochastic techniques.

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