Safety Considerations for Truck Climbing Lanes on Rural Highways

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Data on the speed profiles of trucks on sustained upgrades can be combined with safety estimates to quantify the increased accident rates caused by slow-moving trucks and the changes in accident rate with distance up the grade. Truck performance and speed data were taken from recent field measurements and were evaluated using the truck performance equations presented in NCHRP Report 185. The effect of speed differences on accident rate is based on the relationships developed by Solomon. The results show that there is a pronounced increase in accident rates of passenger cars and trucks in the traffic stream only when a sizeable portion of the truck population falls to speeds of 22.5 mph or less. The results indicate that, from a safety standpoint, there is little apparent need for truck climbing lanes on moderate upgrades (2 percent) or in the first portion of steeper upgrades. However, the results must be interpreted cautiously in light of limitations in the Solomon data that were found during the analysis. In particular, the Solomon data do not show how accident involvement rates change within the very important speed range from zero to 22.5 mph, and these data may represent sections with more intersection- and driveway-related accidents than would typically be found on a sustained grade. Further research is needed to quantify relationships between speed differences and accident involvement rates that are specifically applicable to sustained grades.

It has long been recognized that trucks can cause traffic service and safety problems on steep, sustained grades. Current AASHTO criteria for truck climbing lanes address these considerations through the concept of a critical grade (*1*) (one in which the alignment, truck population, and flow rate may cause an unacceptable reduction in the level of traffic service). Current AASHTO criteria (*1*) define a critical grade as one that is long and steep enough to slow a 300-lb/hp truck by at least 10 mph. The AASHTO Green Book recognizes the potential for collisions between slow-moving trucks and faster vehicles overtaking them, but this effect has not been quantified to provide guidance on where truck climbing lanes may be needed.

The relationship of speed differences in the traffic stream to accidents is well known from the work of Solomon (*2*), who demonstrated that the accident involvement rates of vehicles increase as the deviation of the vehicle speed from the mean speed of traffic increases. Figure 1 illustrates the form of the relationships developed by Solomon. Although the Solomon data were not collected specifically for upgrades, Solomon's results suggest that slow-moving trucks on a steep upgrade should have higher accident involvement rates than faster-moving vehicles. Data on the speed profiles of trucks on grade can be combined with the safety estimates developed by Solomon to quantify the increased accident rates of passenger cars and trucks in the traffic stream caused by slow-moving trucks and the changes in accident rate with distance up the grade. The results obtained from this analysis have some obvious limitations but illustrate an approach that could be used to develop safety warrants for truck climbing lanes. This approach could be used to obtain results more directly applicable to truck climbing lanes if future research could identify relationships between accident rates and speed differentials similar to those of Solomon, but specifically for steep grades.

TRUCK PERFORMANCE ON GRADES

Truck performance on grades is influenced by truck acceleration and speed-maintenance capabilities (typically represented by the truck weight-to-power ratio), by aerodynamic drag (represented by the truck weight-to-frontal area), and by the acceleration and speed preferences of drivers.

The truck population used is that documented in a 1979 paper by St. John (*3*), which was the basis for the passenger car equivalency factors for trucks in Chapters 3 and 7 of the 1985 *Highway Capacity Manual* (*4*). The five-axle truck component of the 1979 truck population was updated with speeds measured by the California Department of Transportation in 1983 and 1984 on sustained 4 and 6 percent grades (*5*). Table 1 summarizes the relative proportions of eight typical ranges of truck characteristics that collectively represent the truck population. The table includes the relative proportion of each truck type determined from the cited sources. The horsepower values used in Table 1 represent the installed net horsepower, which is usually about 94 percent of the engine manufacturer's maximum rated net horsepower. The computations assume that no trucks are present in the traffic stream with weight-to-power ratios outside the range of 50 to 400 lb/hp, as represented by the truck population in Table 1.

The performance capabilities of trucks were computed using the performance equations in Appendix C of NCHRP Report 185 (*6*) together with an improved version of the correction for gear shift delays in Appendix D. The aerodynamic drag coefficients were also reduced to values appropriate for modern truck configurations. The truck performance equations in the NCHRP report allow the determination of the maximum speed of a truck at any point on a specified grade, as a function of truck engine, transmission, aerodynamic drag, and driver characteristics.

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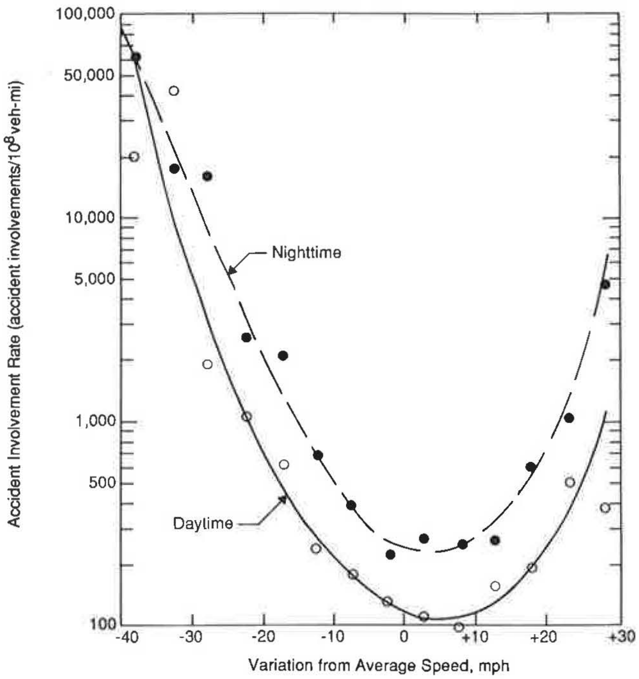

FIGURE 1 Example of U-shaped curves for accident involvement rate versus speed from Solomon (*2*).

DESIRED SPEEDS OF TRUCK DRIVERS

Driver speed preferences (also referred to as desired speeds) will determine truck speeds at any location where the desired speed is less than the truck speed capability. The desired speeds of truck drivers were represented in this investigation by a truncated normal distribution that corresponds well with measurements of free speeds on highways with 55-mph speed limits obtained in NCHRP Project 3-33 (*7*). A range of 43 to 67 mph was used for desired speeds of truck drivers, based on a desired speed distribution with a mean value of 55 mph and a standard deviation of 5 mph suggested by field data (*7*). Table 2 presents eight specific desired speed levels drawn from that distribution, ranging from 2.4 standard deviations below the mean (43 mph) to 2.4 standard deviations above the mean (67 mph), which were used to represent the range of speed preferences of drivers. Since driver speed preferences were assumed to be normally distributed, the percentages of truck drivers in each desired speed stratum shown in Table 2 were determined from tables of the standard normal distribution.

ESTIMATION OF TRUCK SPEED DISTRIBUTIONS ON SPECIFIC GRADES

The truck performance capabilities and truck driver desired speeds can be used together to estimate actual speeds on upgrades. The entrance speed of a truck at the foot of the grade is the lesser of the driver's desired speed and the speed capability of the truck on the approach grade. Trucks with excess performance capabilities are assumed not to exceed the driver's desired speed.

Table 3 shows the joint distribution of truck characteristics and driver speed preferences that results from combining the distributions shown in Tables 1 and 2. Each of the 64 entries in Table 3 represents the relative likelihood of a particular

TABLE 1 CHARACTERISTICS OF TYPICAL TRUCKS

	Range of weight/power ratio (lb/hp)	Range of weight/frontal area ratio (lb/ft^2)	Proportion of truck population
Lowest performance trucks	318-400	1161-1460	0.0122
	258-318	942-1161	0.0407
	227-258	829-942	0.0721
	195-227	712-829	0.1050
	161-195	588-712	0.1392
	134-161	489-588	0.1742
Highest performance trucks	105-134	383-489	0.2100
	50-105	183-383	0.2466

TABLE 2 DESIRED SPEEDS OF DRIVERS

	Driver desired speed (mph)	Standard deviations above or below mean speed	Proportion of driver population
Slowest drivers	43-46	-2.4 to -1.8	0.0282
	46-49	-1.8 to -1.2	0.0805
	49-52	-1.2 to -0.6	0.1618
	52-55	-0.6 to 0.0	0.2295
	55-58	0.0 to 0.6	0.2295
	58-61	0.6 to 1.2	0.1618
	61-64	1.2 to 1.8	0.0805
Fastest drivers	64-67	1.8 to 2.4	0.0282

TABLE 3 PROPORTIONS FOR COMBINATIONS OF SPECIFIC TRUCK TYPE AND DESIRED SPEED

Truck weight/power ratio (lb/hp)	Proportion in truck population	Desired speed (mph) 43-46	46-49	49-52	52-55	55-58	58-61	61-64	64-67
		Proportion in driver population 0.0282	0.0805	0.1618	0.2295	0.2295	0.1618	0.0805	0.0282
318-400	0.0122	0.000344	0.000982	0.001974	0.002800	0.002800	0.001974	0.000982	0.000344
258-318	0.0407	0.001148	0.003276	0.006585	0.009341	0.009341	0.006585	0.003276	0.001148
227-258	0.0721	0.002033	0.005804	0.011666	0.016547	0.016547	0.011666	0.005804	0.002033
195-227	0.1050	0.002961	0.008453	0.016989	0.024098	0.024098	0.016989	0.008453	0.002961
161-195	0.1392	0.003925	0.011206	0.022523	0.031946	0.031946	0.022523	0.011206	0.003925
134-161	0.1742	0.004912	0.014023	0.028186	0.039979	0.039979	0.028186	0.014023	0.004912
105-134	0.2100	0.005922	0.016905	0.033978	0.048195	0.048195	0.033978	0.016905	0.005922
50-105	0.2466	0.006954	0.019851	0.039900	0.056595	0.056595	0.039900	0.019851	0.006954

combination of the eight truck performance strata and eight desired speed strata. Because these 64 combinations are assumed to represent all possible truck performance–desired speed combinations, the sum of all entries in Table 3 is 1.0.

Several typical grades were selected for analysis, including sustained 2, 4, and 6 percent upgrades with level (0 percent) approach grades. Truck speeds were calculated on each grade at 200-ft stations until a point on the grade was found where the trucks for all combinations of truck type and desired speed had reached steady speeds. The weight factors in Table 3 were used to assemble a truck speed distribution at each station on each grade using speed strata with a width of 5/3 mph (i.e., 1.67 mph), which was a convenient stratum width for correspondence with the accident data.

If no combinations of truck type and desired speed produced speeds in a particular 5/3-mph speed stratum, but speeds were produced in strata on either side, the proportion of truck speeds in the empty strata was determined by linear interpolation. This smoothing of the cumulative speed distribution curves is logically consistent because each type speed combination calculated (except the lowest one—the 400-lb/hp truck with a desired speed of 43 mph) defines the upper speed bound for some portion of the truck population.

PASSENGER CAR SPEEDS

The passenger car speed distribution at all stations on each grade was assumed to be represented by the desired speed distribution shown in Table 2. This approach neglects the moderate decreases in passenger car speeds that are known to occur on steep grades. This common assumption is also made in the *Highway Capacity Manual* procedures (*4*); that is, passenger car equivalents are not calculated for passenger cars on grades.

SPEED DISTRIBUTIONS FOR MIXED FLOWS

The speed distributions in the mixed passenger car and truck flows at each 200-ft station on each grade were obtained by combining the passenger car and truck speed distributions for four different proportions of trucks in the traffic stream: 5, 10, 15, and 20 percent. These speed distributions are all expressed in terms of the proportion of vehicle speeds in each 5/3-mph speed stratum. The use of explicit speed strata in this way is appropriate because Solomon's results (*2*) can then be used to determine the safety implications of the speed distribution expressed in this form.

ACCIDENT RATES AS A FUNCTION OF SPEED DIFFERENCES

In evaluating the need for truck climbing lanes on rural highways, the primary safety concern is the risk of rear-end or same-direction sideswipe accidents involving slow-moving trucks. Steep, sustained grades generally have less than average roadside development and few intersections and driveways, so there is less concern about the potential for angle or turning accidents than at other locations. Climbing lanes may have the potential to eliminate some head-on or opposite-direction sideswipe accidents, but these accident types have no direct relationship to the internal dynamics of the speed distribution in the uphill traffic. Therefore, the accident rate evaluation has been limited to rear-end and same-direction sideswipe accidents which, for convenience, are referred to as rear-end accidents.

Two methods for estimating the accident rate corresponding to a particular speed distribution can be used with Solomon's data (*2*). These methods are as follows:

- *Method 1:* Use data from Table 5, Table 41, and Figure 18 of Solomon's report to estimate rear-end accident rates for all possible combinations of slower and faster speed strata. For example, the Solomon data can be used to estimate the rear-end accident rate per 10^8 veh-mi for a slower vehicle traveling 25 mph and a faster vehicle traveling 60 mph.
- *Method 2:* Use the data in Tables 5 and 41 of the Solomon report to estimate rear-end involvement accident rates (counting each two-vehicle accident as two separate accident in-

volvements) for specific speed strata. In other words, the Solomon data can be used to estimate the rear-end accident involvement rate for vehicles traveling in a specific speed stratum, assuming that the speed distribution of other vehicles on the road is similar to that observed by Solomon.

It was found that by smoothing Solomon's data, Method 2 could be directly used to determine accident involvement rates. However, the assumption (described above) that the speed distribution on the roadway must be similar to that observed by Solomon seems unrealistic for steep grades, so Method 2 appears to be too simplistic for the proposed application. Method 1 requires the assumption that the distribution of flow rates on the steep grades being analyzed is the same as the distribution of flow rates at Solomon's field sites; otherwise, the accident rates would need to be adjusted for the differences in flow rates. This assumption appears more acceptable than the assumption involving speed distributions that must be made to use Method 2. The derivation of Method 1 suggests that, with other factors held constant, accident rate is proportional to flow rate. It would be desirable to have data from steep grades to confirm or refute this relationship. Method 1 has the advantage that it explicitly accounts for the effects of changes in vehicle mix and grade geometrics. Method 1 can be used to determine accident involvement rates only after recasting Solomon's accident data into slower-vehicle–faster-vehicle cells. The available data and the required iterative procedures cannot provide unique results, but do provide very narrow constraints, which ensure results that follow logically from Solomon's data.

Figures 2 and 3 present overviews of the accident rates derived with Methods 1 and 2. For illustrative purposes, Figure 2 assumes that for each pair of slower and faster vehicle speeds, vehicles with those speeds are present in the traffic stream in equal proportions. (This assumption is necessary to illustrate the accident rates in Figure 2; it is not needed for the analyses that were performed.) The most prominent feature in Figure 2 is the consequence of low vehicle speed, particularly below 40 mph. A vehicle traveling less than 40 mph has a much increased likelihood of involvement as either the faster or slower vehicle in a two-vehicle accident. This compounded effect from slow vehicle speeds leads to nonlinearities in accident-speed relationships and illustrates why it is important to use the Method 1 approach, which avoids assumptions about similarities in the speed distributions between the field data (Solomon's) and the calculated speed distribution on grades. Figure 3 presents the rear-end accident involvement rates based on speed strata alone. The foregoing

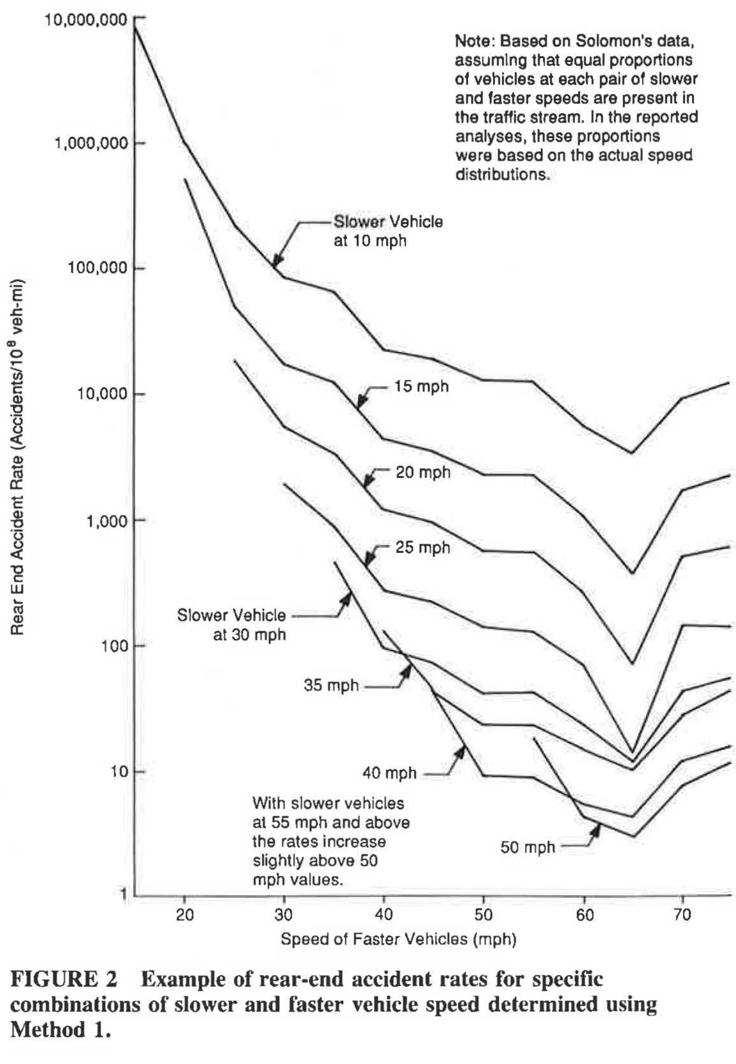

FIGURE 2 Example of rear-end accident rates for specific combinations of slower and faster vehicle speed determined using Method 1.

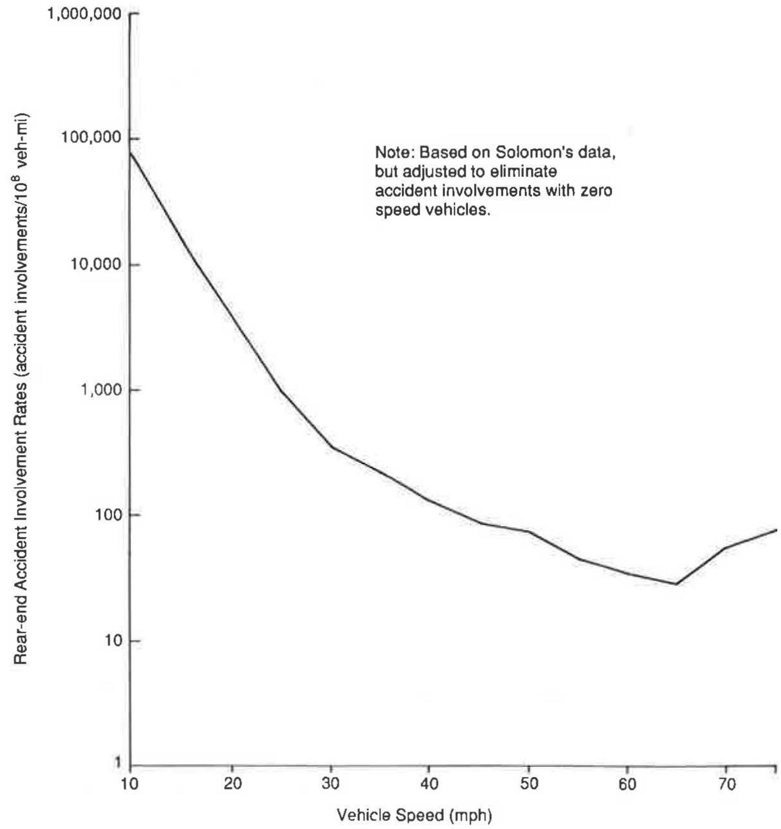

FIGURE 3 Rear-end accident involvement rates as a function of vehicle speed determined from Solomon's data using Method 2.

discussion of Figures 2 and 3 illustrates why Method 1 was found to be more realistic than Method 2, because Method 1 explicitly considers the speed differences in the traffic stream and was used as described below. For simplicity, Solomon's data were combined over roadway types and over day and night.

In Method 1, accident rates were computed for an array in which each cell represented accidents between vehicles in a slower speed stratum (v_i) and a faster speed stratum (v_j).

The accident rate array elements for Method 1 were determined as

$$A_e = \sum_i \sum_j [l_{ij} P_i P_j / 10^4] \quad (1)$$

where

- A_e = rear-end and same-direction sideswipe accidents per 10^8 veh-mi,
- $l_{ij} = 10^{10}[a_{ij}N]/[T(p_i p_j)]$ (2)
- a_{ij} = percent of observed rear-end and same-direction sideswipe, accidents involving the combination of the ith and jth speed strata (Solomon),
- N = total number of rear-end and same-direction accidents observed by Solomon = 4,309/2,
- P_i = percent of vehicle-miles in ith speed stratum,
- P_j = percent of vehicle-miles in jth speed stratum,
- T = total vehicle-miles of travel observed by Solomon = 3.671×10^9,
- p_i = percent of observed vehicle-miles in the ith speed stratum (from Solomon), and
- p_j = percent of observed vehicle-miles in the jth speed stratum (from Solomon).

Method 1 uses the concept that accidents between vehicles in the ith and jth speed strata are proportional to the frequency with which their speed difference brings them into potential conflict. There are 43 vehicle speed strata, each 5/3 mph in width, to which Equation 1 is applied. Thus, there are 903 unique combinations of faster and slower vehicle speeds (i.e., [(43)(43) − 43]/2), and Equation 1 involves the summation of 903 separate terms.

Accident involvements as a function of speed were taken from Table 41 of the Solomon report, with night and day values combined. Accident frequencies were set equal to half of the accident involvement frequencies, assuming that each rear-end accident involved only two vehicles. Speed difference data were obtained from Figure 8 of the Solomon report. Although these data are for passenger cars only, most of the vehicles in the mixed flow considered here are passenger cars as well. The important point is that these data properly incorporate the role of speed differences in accident situations. Thus, Table 41 and Figure 8 from the Solomon report provide the raw data for determining the a_{ij} in Equation 2.

The a_{ij} are not uniquely defined by the available data. However, numerical experience with iterations and adjustments indicates that the overall pattern is strongly constrained. In the derivation of the a_{ij} for 5-mph speed increments, it is clear that the vehicles in the highest speed stratum must be the faster vehicle in any rear-end accident in which they are involved, and the vehicles in the lowest speed stratum must always be the slower vehicle. Vehicles in other speed strata may be the faster vehicle in some accidents and the slower vehicle in others. However, because all rear-end accidents were assumed to involve only two vehicles, there must be an equal number of faster vehicle and slower vehicle involvements. In addition, the percentage of involvements by speed stratum are known from the data in Solomon's Table 41. Solomon's Figure 8 provides the percentage of accidents within each speed difference. These assumptions and constraints were used to calculate the a_{ij}, within the added constraint that the a_{ij} must vary smoothly between cells. After the l_{ij} were calculated for the 5-mph speed strata, interpolation was used to obtain values at 5/3-mph intervals that matched the speed distribution data derived earlier.

CALCULATED RESULTS

Upgrade of 2 Percent

Figure 4 shows the calculated truck speed distributions at six locations on the sustained 2 percent upgrade with a level approach. The locations selected for illustrative purposes in this figure are the start of the grade, and stations located 800, 1,600, 3,200, 6,400, and 9,600 ft up the grade. As explained earlier, similar speed distributions were determined at 200-ft intervals on each grade. The minimum truck speed on this grade was about 29 mph, but only about 3.6 percent of the truck speeds would fall below 40 mph.

In the mixed flow with 20 percent trucks and 80 percent passenger cars, the estimated speed distributions for trucks and passenger cars correspond to a rear-end accident rate of 26 accidents per 10^8 veh-mi for the final steady-speed conditions on the upper portion of the grade. Thus, although some trucks decelerate to speeds of 29 mph and some passenger cars travel as fast as 67 mph on the upper portion of the grade, accident rates would be expected to increase by only 1 percent above the accident rate in level terrain. The 2 percent upgrade is simply not steep enough to have a major effect on accident rates.

Upgrade of 4 Percent

Figure 5 shows the estimated truck speed distribution curves at various points on the 4 percent upgrade. The figure shows that on the upper portion of the 4 percent upgrade, 40 percent of the trucks travel at speeds of 40 mph or less, and 5 percent of trucks fall to speeds less than 25 mph. The minimum truck speed on this grade is 18 mph.

Figure 6 shows the safety implications of these speed reductions based on Solomon's accident and exposure estimates for strata of slower and faster vehicles. The figure shows that accident rates do not change appreciably until the trucks are about 2,500 ft up the grade; this is where truck speeds start to drop below 22.5 mph. With 5 percent trucks in the flow, accident rates increase only about 4 percent over the length of the grade, but accident rates more than double with 20 percent trucks in the traffic stream. Finally, the figure shows that at about 7,500 ft up the grade, where trucks reach their steady speeds, the accident rates stop increasing.

Upgrade of 6 Percent

Figures 7 and 8 show comparable data for trucks on a sustained 6 percent upgrade. Figure 8 shows that rapid increases in the estimated accident rate begin at about 1,800 ft up the grade and that, as in the 4 percent case, accident rates increase

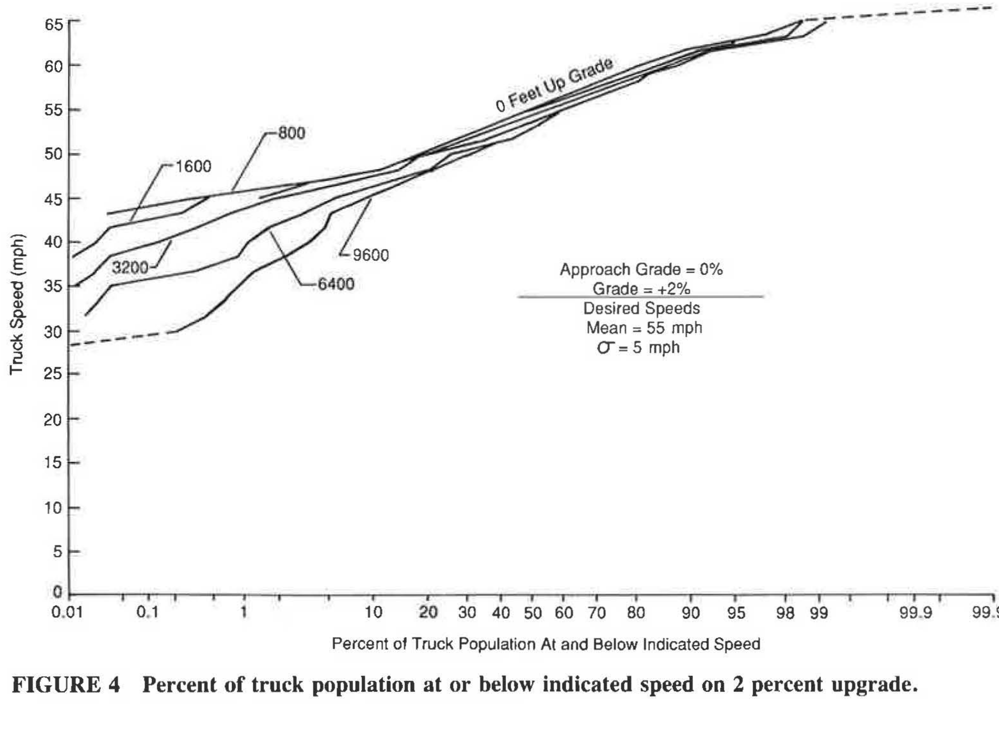

FIGURE 4 Percent of truck population at or below indicated speed on 2 percent upgrade.

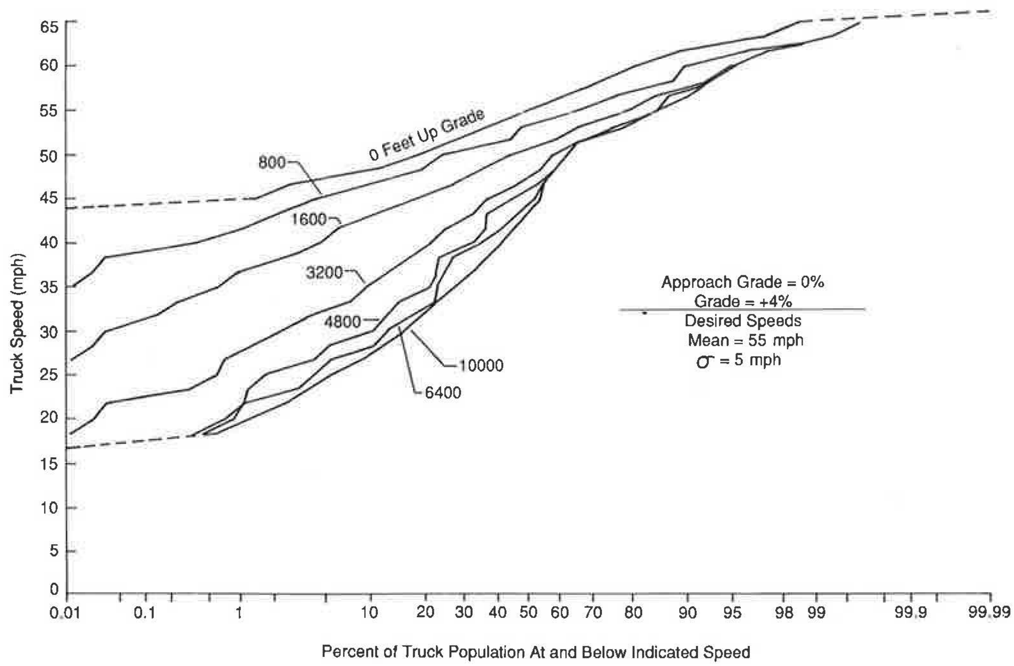

FIGURE 5 Percent of truck population at or below indicated speed on 4 percent upgrade.

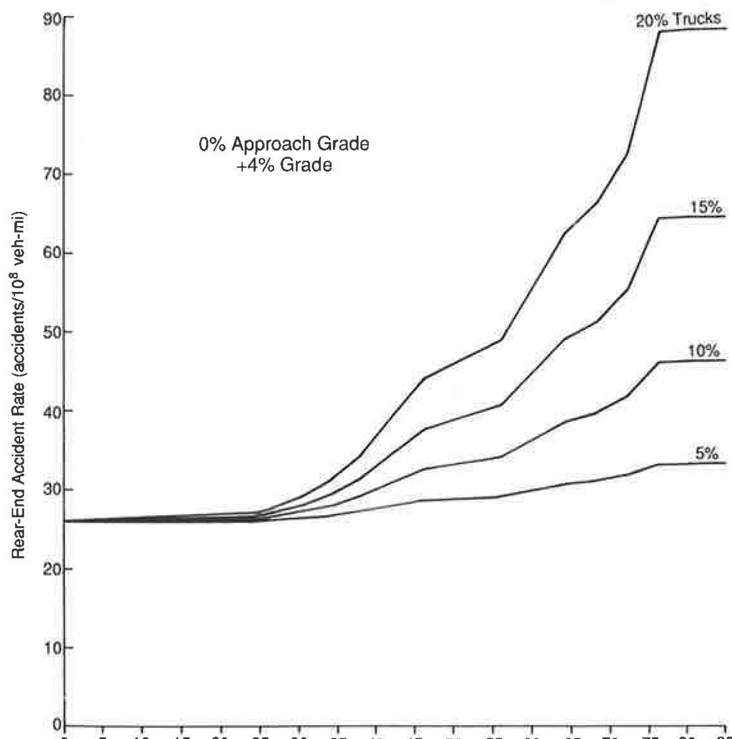

FIGURE 6 Calculated rear-end accident rates on 4 percent upgrade.

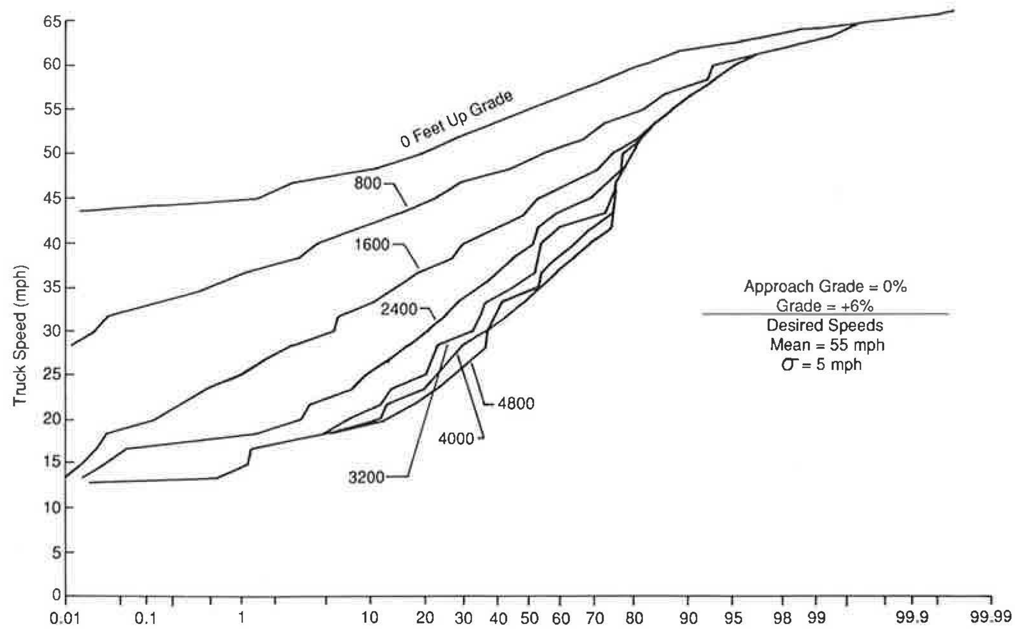

FIGURE 7 Percent of truck population at or below indicated speed on 6 percent upgrade.

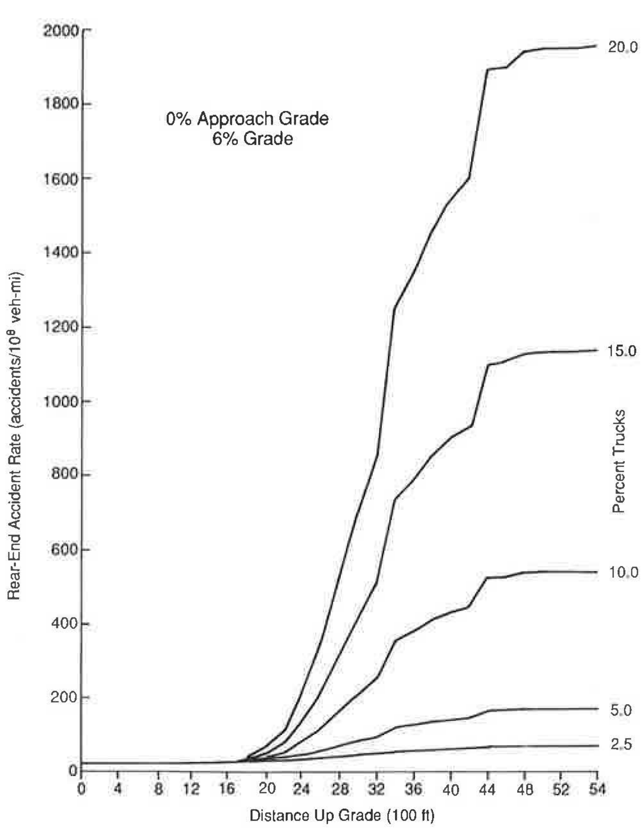

FIGURE 8 Calculated rear-end accident rates on 6 percent upgrade.

nonlinearly with increasing percent trucks. The figure implies that the increase in accident rate with 20 percent trucks will be more than 10 times greater than with 5 percent trucks.

DISCUSSION OF RESULTS

The increases in accident rate on upgrades presented in Figures 4 and 6, relative to the accident rates shown for level terrain, are undoubtedly larger than those observed in the real world. Nevertheless, the results reported here certainly indicate the manner in which conflicts between slow and fast vehicles increase with increasing percent grade and increasing percent trucks. These results should help guide future research.

The results imply that there is a pronounced rise in rear-end accident rates whenever a sizeable portion of the truck population, 0.5 percent or more, falls to speeds below 22.5 mph. However, these results must be interpreted in light of the limitations of the Solomon data. The Solomon data contain a single category for speeds of accident-involved vehicles greater than zero and less than or equal to 22.5 mph. This broad speed range, coupled with the extremely high accident involvement rate for these lower-speed vehicles, makes it very difficult to determine the exact character of the lower-speed accident rates. This is in contrast to the higher-speed strata, which are only 5-mph wide with much better defined accident rates. Other aspects of the data set raise additional questions.

Solomon's data indicate that 12.7 percent of the rear-end accident involvements were vehicles at zero speed (stopped and presumably waiting for the opportunity to make a turning maneuver). Because the second vehicle in each accident involving a stopped vehicle must be moving, Solomon's data imply that about 25 percent of all rear-end accidents involved a stopped vehicle. This high proportion of zero-speed accidents has not affected the results reported here because all accidents involving a zero-speed vehicle were omitted from the analysis. However, the presence of these zero-speed accidents in Solomon's data implies that the presence of intersections or driveways may be overrepresented in comparison to typical sustained grades. This possibility is reinforced by the accident rates in Figure 2, where two vehicles at generally low speeds are much more likely to be involved with each other than with a higher-speed vehicle.

The concerns discussed about the Solomon data and their applicability to sustained grades occur in the speed range that is most responsible for the large accident rate increases that were calculated for trucks. Thus, the large accident rate increases shown for trucks in Figure 6 and 8 should not be taken too literally. It is likely that they show accident rate increases larger than those that would be observed in the field. Nevertheless, the results have implications that may be useful in deciding where truck climbing lanes are not needed from a safety standpoint.

First, the analysis results show (not surprisingly) that there would be almost no safety benefit to installing a truck climbing lane on a 2 percent grade and that there is little apparent need for truck climbing lanes in the first portion of steeper grades. There are unlikely to be safety benefits from climbing lane installations in the first 2,500 ft of a 4 percent grade or the first 1,800 ft of a 6 percent grade. Thus, it is reasonable to consider introducing the climbing lane on the grade itself, rather than at the foot of the grade.

Second, the potential safety benefits of truck climbing lanes clearly appear to increase with percent grade, length of grade, and percent trucks. Although these findings are not surprising, the nonlinear effect of increasing percent trucks may have important implications. Installation of truck climbing lanes on grades with high truck percentages and high proportions of very low performance trucks may be much more important than is suggested merely by the increased number of trucks. However, these nonlinear effects need to be investigated further to determine whether they are an artifact of the apparent predominance of access-point-related accidents in the Solomon data.

Third, if one accepts the Solomon data as accurate for vehicle speeds above 22.5 mph but potentially misleading for speeds below 22.5 mph, this implies that the current AASHTO truck climbing lane criteria may be overly conservative from a safety standpoint. The truck speed reduction required under AASHTO criteria to warrant a climbing lane was changed in 1984 from 15 to 10 mph on the rationale that the 10-mph criterion was needed for increased safety. However, the data on which Figures 6 and 8 are based clearly imply that there is little, if any, increase in accident rate for vehicles traveling at speeds above 22.5 mph (which is 32.5 mph below the speed limit of most rural highways and the mean speed of trucks on those highways). Thus, it appears that reductions in truck speeds much larger than 10 or 15 mph are needed to produce increases in accident rate large enough to warrant construction of a climbing lane.

With better data on the accident rates actually associated with specific speed differences on grades, it might be possible to develop a formal accident warrant for truck climbing lanes. Thus, there is a need for further research patterned on the Solomon study but focusing on steep grades and with better stratification of the speed range below 22.5 mph.

SUMMARY

In summary, the analyses imply that the Solomon data are not adequate to predict accident rates on steep upgrades, primarily because of the poor definition of accident rates for vehicles traveling at speeds less than 22.5 mph. However, the Solomon data for vehicles traveling faster than 22.5 mph imply that there is little safety justification for truck climbing lanes at locations where essentially all truck speeds remain above 22.5 mph. Of course, traffic service considerations should also enter into the decision to install a truck climbing lane. Furthermore, the truck performance data show that very few trucks would be slowed to speeds of 22.5 mph or below on any 2 percent upgrade, in the first 2,500 ft of a 4 percent upgrade, or in the first 1,800 ft of a 6 percent upgrade. Further research is needed to better quantify the safety effects of vehicle speeds below 22.5 mph, but the Solomon data for this speed range, although flawed, imply that accident rates on steep grades may be more strongly influenced by percent grade, length of grade, and percent trucks than previously thought.

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