An Evaluation of Design Criteria for Operating Trucks Safely on Grades

JOHN C. GLENNON, Texas Transportation Institute, Texas A&M University

This paper is concerned with the evaluation of design criteria relating truck operating characteristics on grades to the implementation of truck climbing lanes. The evaluation is specifically concerned with truck operating characteristics on grades, truck weight-horsepower ratios as they pertain to truck operating characteristics, and truck speed as it is related to truck operating characteristics and design criteria for climbing lanes.

• IN THE DESIGN OF HIGHWAY GRADES consideration is given to the critical length of grade. The critical length of grade is that combination of percentage and length of grade that will cause a designated design vehicle to operate at some predetermined minimum speed. A lower speed is considered unacceptable for safety and operational efficiency. Two alternatives are considered when a designed grade is longer than critical: (a) Adjust the grade line until it is no longer critical, or (b) add an auxiliary truck climbing lane in which slow-moving vehicles can operate adjacent to the main travel lane.

This study was conducted in response to an increasing concern by highway design engineers regarding the validity of geometric design criteria related to safe operation of slow-moving vehicles on highway grades. The report presents a review of current AASHO (1) design criteria and an evaluation of these criteria based on the existing practices. The evaluation was specifically concerned with truck operating characteristics on grades, truck weight-horsepower ratios related to operating characteristics, and truck speed related to operating characteristics and geometric design criteria.

Of all vehicles operating on highways, the large transport trucks have the lowest engine power relative to their weight. Hence, these vehicles are generally the slowest on upgrades and require the longest distances to accelerate. Realistic design of highway grades and acceleration lanes should be based on the performance of these particular vehicles, inasmuch as all other vehicles are capable of better performance.

REVIEW OF CURRENT DESIGN CRITERIA

Design criteria relating truck operating characteristics on grades to the implementation of critical lengths of grade and truck climbing lanes are examined under the following topics: truck operating characteristics on grades, truck weight-horsepower ratios related to climbing characteristics, and design criteria for critical lengths of grade and truck climbing lanes.

Truck Operating Characteristics on Grades

An extensive study (2) of truck performance was conducted from 1938 to 1941 to determine the separate and combined effects of roadway grade, tractive effort, and gross vehicle weight. Data from this study were analyzed (3) to determine the effect of length of grade on the speed of trucks for a wide range in load, grade, and vehicle size.

Paper sponsored by Committee on Operational Effects of Geometrics.

Speed-distance curves were developed for 3 weight classifications: light, medium, and heavy. These curves formed the basis for the 1954 AASHO (4) design criteria for critical lengths of grade.

In 1949, Willey (5) documented the performance of trucks on grades. He developed speed profiles of truck performance on different mountainous grades in Arizona. The observed trucks were classified according to the following gross vehicle weight to brake horsepower (bhp) ratios:

Group	lb/bhp
A	199 and under
B	200 to 299
C	300 to 399
D	400 and over

Willey developed a gradability curve of heavily loaded trucks (combination of group C and group D), which showed the expected average behavior of vehicles loaded to capacity, or nearly so, on various grades (Fig. 1).

Huff and Scrivner (6) used Willey's gradability curves in developing their simplified climbing lane theory. This theory considered the forces acting on a truck ascending a grade to develop the force equation

$$\frac{W}{g}\frac{dv}{dt} = P - W \sin \theta \tag{1}$$

where

W = gross vehicle weight, lb;
g = acceleration of gravity, 32.2 ft/sec^2;
dv/dt = change in velocity with respect to time, ft/sec^2;
P = net driving force on the vehicle, lb; and
θ = the grade angle, deg.

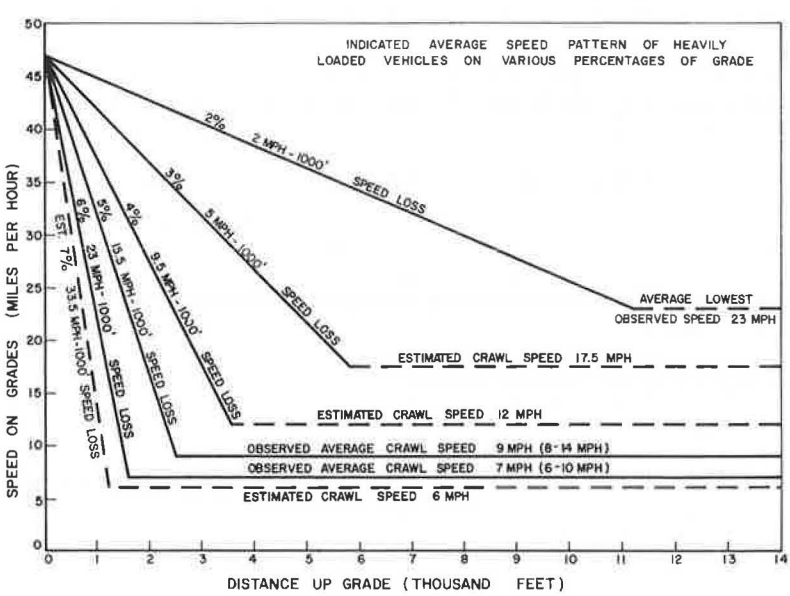


Figure 1. Gradability curves of heavily loaded trucks on different grades.

This equation holds when the driving force needed to impart angular acceleration to the rotating engine parts is neglected. Equation 1 may be rewritten as

$$\frac{P}{W} = \frac{1}{g}\frac{dv}{dt} + \sin\theta \tag{2}$$

The net driving force acting on the vehicle, P, is the total traction exerted by the driving wheels against the road surface, minus wind and road surface resistance.

Engine operation at partial throttle was not considered because the driver's choice rather than highway geometry would then determine the vehicle performance. Therefore, if the truck operates at the highest possible speed and within the manufacturer's recommendations, the total driving force as a function of the velocity only can be approximated if the following assumptions are made:

1. That there is no inertial resistance to angular acceleration;
2. That no wind exists; thereby, air resistance is considered as a function of the velocity; and
3. That there is no change in pavement type or roughness; thereby, surface resistance is considered as a function of the velocity.

It was concluded, therefore, that, although the net driving force must satisfy Eq. 2, it may also be expressed as some function of velocity only.

If a truck operates at maximum sustained speed on any grade, the value of P/W may be calculated from Eq. 2, which reduces to $P/W = \sin\theta$. This value of P/W will always exist at the respective speed, at least approximately, regardless of the value of the acceleration.

Figure 2 shows the relation of P/W to maximum sustained speeds, v, on various grades. The maximum sustained speeds were taken from the gradability curves shown

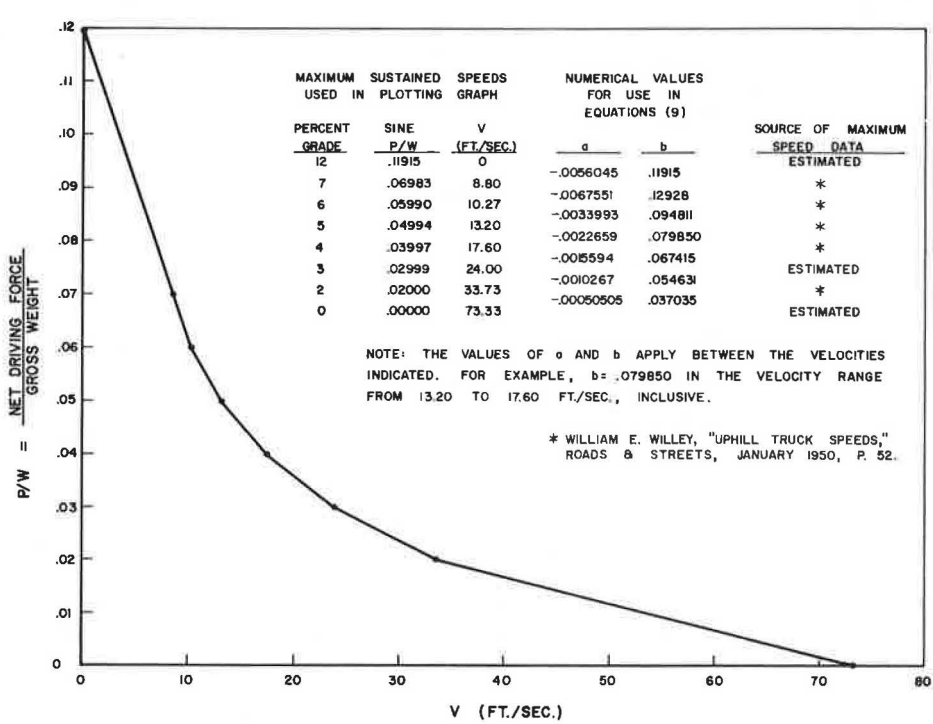


Figure 2. P/W versus maximum sustained speeds on various grades.

in Figure 1. The points shown in Figure 2 were connected by straight-line segments to form a continuous graph. Each line segment was represented by the general equation

$$P/W = av + b \tag{3}$$

where v is the velocity at any point along a line segment, v_n to v_{n+1}, and a and b are constant along the same line segment. By substituting the P/W value of Eq. 2 into Eq. 3, we derive a new general motion equation:

$$\frac{dv}{dt} - gav + g(\sin\theta - b) = 0 \tag{4}$$

where v, a, and b are restricted, as noted earlier.

The position of the truck along the grade may be represented at any instant by its coordinate, x, measured along the direction of the truck. If dv/dt is the change in velocity, v, with respect to time, t, along that line segment, Eq. 4 may be developed into an equation suitable for the construction of speed-distance and time-distance curves. Appendix A discusses the derivation.

$$x = \frac{v - v_o}{2g} + (\sin\theta - b)t \tag{5}$$

where

$$t = \frac{1}{ag} \ln\left(\frac{av - \sin\theta + b}{av_o - \sin\theta + b}\right) \tag{5a}$$

To construct speed-distance by using Eq. 5, where the velocity change involves more than one line segment, requires that the distance or time be calculated over each interval and added in order to obtain total distance or total time. Actually, by utilizing the same assumptions made by Huff and Scrivner in developing Eqs. 5 and 5a, one can derive a much simpler, singular speed-distance. Appendix A discusses the derivation.

$$x = \frac{1}{g} \frac{V_o^2 - V^2}{a(v_o - v) - 2(\sin\theta - b)} \tag{6}$$

In December 1953, Huff and Scrivner (6) conducted a road test of a heavy truck to determine whether these theoretical equations applied to the actual performance on grades. The operating features and data for the truck test are given in Table 1. Eleven grades ranging from 700 to 1,500 ft in length and from 0.16 to 7.62 percent in grade were used in the tests.

Figure 3 shows the data obtained in the tests of the heavy truck. Each computed value of P/W was plotted against its corresponding velocity. The points represent any instant where the acceleration was not zero, and the circles represent any instant at which the truck was operating at maximum sustained speeds. Certain areas, where the points were scattered so as not to represent any consistency, were ignored, and an average line was drawn through the remaining points. This line represented P/W as a function of velocity only.

The data given in Table 1 were also used to compute the maximum sustained speeds according to the SAE procedure (7). These speeds, plotted against the corresponding sin θ, are also shown in Figure 3.

The average values of P/W versus velocity (Fig. 3) were used to develop speed-distance curves for each of the 11 test grades and then compared against the gradability curves developed from the field test. If the curves for each grade coincided, the computed curve

TABLE 1

OPERATING FEATURES OF TEST TRUCK

Feature	Description or Dimension
Vehicle	International R-195 tractor with Hobbs tandem-axle, flat-bed trailer
Dimensions	
Height, ft	7.75
Width, ft	7.75
Gross vehicle weight, lb	57,180
Rated gross vehicle weight, lb	50,000
Gear ratios	
Transmission	6.98, 3.57, 1.89, 1.00, 0.825
Auxiliary transmissions	None
Axle	6.50, 8.86
Total gear reductions	61.84, 45.37, 31.63, 23.21, 16.75, 12.28, 8.86, 6.50, 7.31, and 5.36
Tire size	10 × 20
Net engine horsepower at sea level	146 at 2,600 rpm
Brake horsepower	162 at 2,800 rpm
Altitude, ft	950
Road type and condition	Bituminous, good
Net weight-horsepower ratio, lb/hp	391
Weight to rated horsepower ratio, lb/hp	353

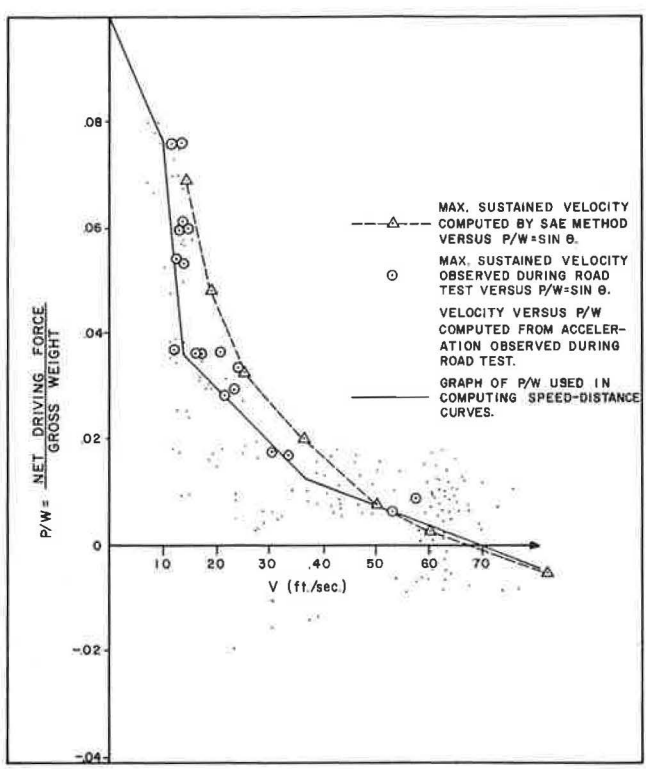


Figure 3. P/W versus velocity as computed and observed.

was considered to be representative of the measured test data; if they did not coincide, the opposite was considered.

A comparison of the computed curves and the measured gradability curves showed a fair amount of consistency. There were, however, 2 major discrepancies:

1. Some irregularity that appeared in the curves was caused by the motion of the truck, especially on some of the upgrade deceleration curves where maximum sustained speeds were reached.
2. The actual maximum sustained speeds were 1 to 3 mph greater than the maximum sustained speeds shown on the computed curves.

It was concluded that, although these discrepancies existed, the gradability curves shown in Figures 4 and 5 (developed through the use of Eq. 5 and Fig. 3) represented the performance of the test truck on grades. Equation 5, therefore, was considered satisfactorily accurate for use in predicting truck operations on grades for design purposes. The gradability curves shown in Figures 4 and 5 are those employed in the 1965 AASHO Policy (1).

Firey and Peterson (8) presented an equation that is almost identical to that of Huff and Scrivner:

$$\frac{W}{g}\frac{dv}{dt} = F_T - F_R - W \sin \theta \tag{7}$$

where F_T is the truck engine thrust force and F_R is the truck rolling resistance force.

The engine thrust force, F_T, is zero when the clutch is disengaged and, based on the assumption that the engine torque at wide-open throttle is constant over the operating speed range of the engine, F_T was calculated from the following equation:

$$F_T = \frac{E}{v_{max}} (550) \tag{8}$$

where

E = engine rpm at wide-open throttle and

v_{max} = maximum truck speed attainable in a particular gear setting, ft/sec.

The truck rolling resistance force, F_R, was calculated from the following equation:

$$F_R = \frac{W}{148.5} + 195 \tag{9}$$

This is an empirical equation subject to the constraints of the coasting tests of several heavy trucks as described in another study (9). For significant upgrades, the exactness of F_R in Eq. 9 is not very important because F_T is the dominant resisting force to vehicle motion.

The net force, F_o, acting on a truck was defined by the following equations:

$$F_o = \frac{W}{g}\frac{dv}{dt} = \frac{E(550)}{v_{max}} - \frac{W}{148.5} \tag{10}$$

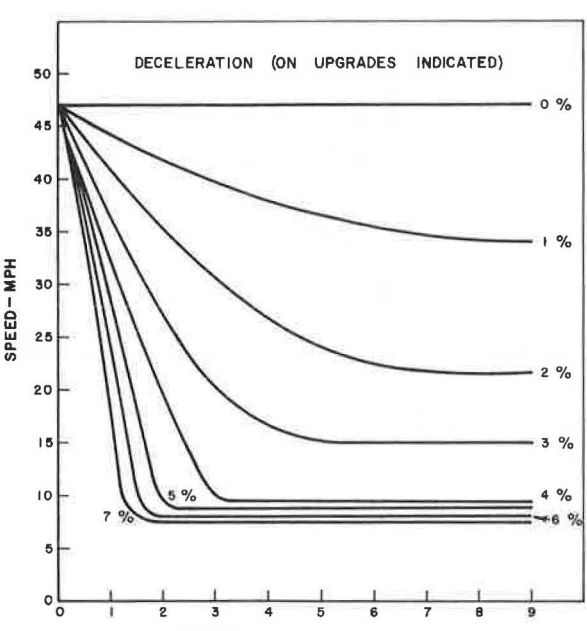


Figure 4. Speed-distance curves for typical heavy truck operating on various grades–deceleration on upgrades indicated.

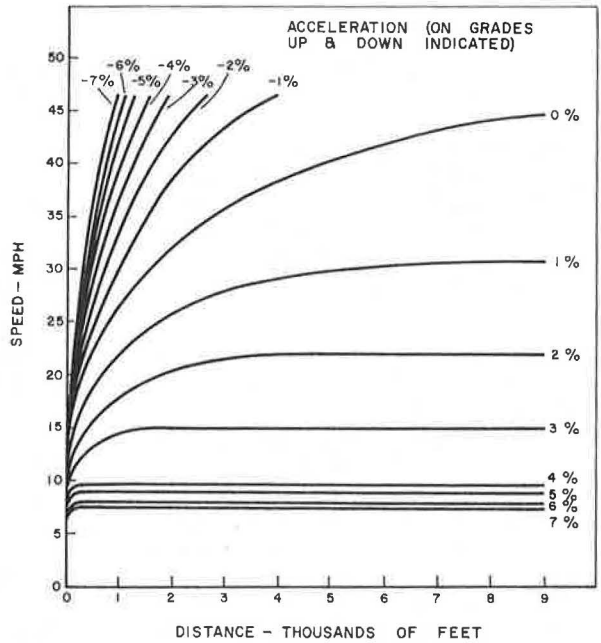


Figure 5. Speed-distance curves for typical heavy truck operating on various grades–acceleration on upgrades and downgrades indicated.

at wide throttle. With clutch disengaged, $F_T = 0$. Therefore,

$$F_o = \frac{-W}{148.5} - 195 - W \sin \theta \tag{11}$$

For computing speed-distance relationships on uniform grades, the following basic physics equations were used:

$$x = v_o t + 1/2\ at^2 \tag{12}$$

$$v = v_o + at \tag{13}$$

Because the acceleration, a, in these equations was considered equivalent to dv/dt and because $dv/dt = F_o g/W$, the following equations were derived for computing speed-distance relationships:

$$x = v_o t + \frac{F_o g t^2}{2W} \tag{14}$$

$$v = v_o + \frac{F_o g t}{W} \tag{15}$$

The velocity versus distance curves on uniform grades was calculated by the following steps:

1. Values were assumed for W, W/H_P, θ, and initial v_o.
2. These values were substituted into the vehicle motion equations (Eqs. 4 and 5).

3. On deceleration curves the first gear shift was assumed to be 0.8 v_o, and on acceleration curves, $v_o/0.8$.

4. An average time of 2 sec was determined (9) to shift the gears, and it was assumed that the vehicle followed the vehicle motion equations for clutch disengagement during the gear shifting interval.

5. Steps 2 and 3 were repeated, and the vehicle motion equations for the clutch disengagement over the gear shifting interval were used.

6. For the second wide-open throttle periods, steps 2 and 3 were repeated, and the terminal speed from step 5 was used as v_o in Eqs. 14 and 15.

7. The preceding steps were reiterated with values of v_o until that value reached the established limitations: 10 mph on deceleration curves, or 50 mph on acceleration curves.

Firey and Petersen developed gradability curves from the foregoing procedure for truck weight-horsepower ratios of 200, 300, and 400. The gradability curve for a weight-horsepower ratio of 400 is shown in Figure 6.

Truck operations can be related to design for highway grades by selecting a design vehicle that represents some lower boundary of operation. Willey (5) was the first to classify truck operating characteristics according to weight-horsepower ratios. Because the weight-horsepower ratios of trucks can be measured in field studies, this measure appears to be best suited as a parameter for determining a design vehicle.

In 1957, Saal (10) studied the relationship between the gross weight of a motor truck and its horsepower. This study indicated that the percentages of trucks in 1950 having a weight-horsepower ratio greater than 400 were as follows: 3-axle trucks, 10 percent; 2-axle truck-trailers with 1-axle semitrailers, 13 percent; 2-axle truck-trailers with 2-axle semitrailers, 41 percent; all other combinations, 57 percent. He also stated that from 1955 to 1958 a 10 percent improvement in the performance ratio of all groups had occurred.

In 1963, Wright and Tignor (11) reported on the 1949, 1955, and 1963 brake studies of the Bureau of Public Roads. Figure 7 shows cumulative frequency distributions of weight-horsepower ratios from the 1963 study for trucks classified by number of axles. Of all the loaded trucks in this study, only 8 percent did not meet the 400:1 ratio accepted by AASHO (1) as a tolerable design performance ratio. Of all the trucks (loaded and unloaded) weighed in the 1963 study, only 5 percent exceeded the 400:1 ratio.

There has been a definite trend toward decreasing weight-horsepower ratios of trucks operating on the highways. Figure 8 shows this trend for the 1949, 1955, and 1963 brake studies (11). Another study (12) indicates that there has also been a trend toward more heavy trucks on the highways. The number of heavy trucks (over 26,000-lb gross vehicle weight) on the highways increased approximately 3.4 times from 1954 to 1967 and is predicted to increase 3 times from 1967 to 1980 (12).

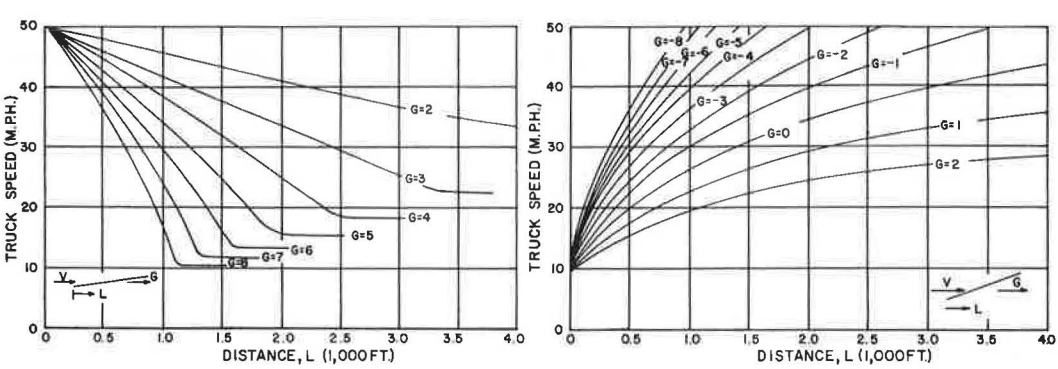


Figure 6. Deceleration and acceleration gradability curves for trucks for weight-horsepower ratio of 400.

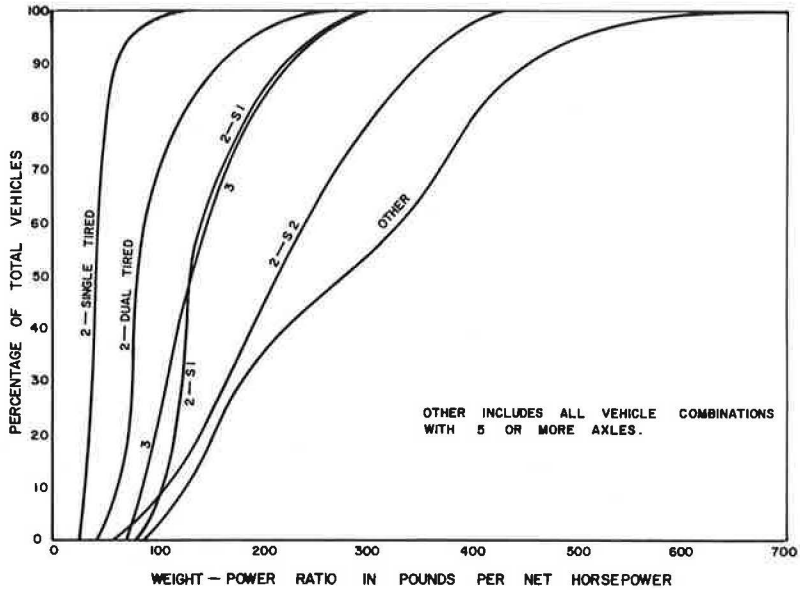


Figure 7. Cumulative frequency distributions of weight-horsepower ratios of commercial vehicles.

In 1968, more International Harvester (IH) trucks were registered across the United States in the heavy category (26,000 lb and over). International Harvester offers 5, 8-cylinder diesel engines to power its 65,000-lb trucks. The weight to net horsepower ratio of an IH truck powered by each of those engines would be 279:1, 298:1, 342:1, 392:1,

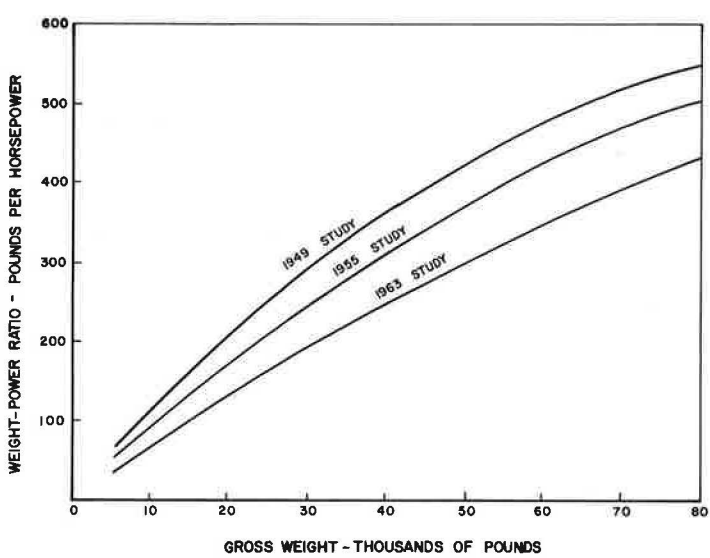


Figure 8. Weight-horsepower ratios based on average data for all types of vehicles from 1949 to 1963.

or 414:1, depending on which model was chosen. Only 1 of the 5 engines offered would be outside the accepted tolerable performance ratio of 400:1 (13).

The AASHO Policy (1) states that trucks with a weight-horsepower ratio of about 400:1 have acceptable operating characteristics from the standpoint of the highway user. It is stated that such a ratio will ensure a maximum sustained speed of 15 mph on a 3 percent grade. There is also evidence that the industry is finding the 400 ratio a desirable goal and is voluntarily accepting it as a performance control, with the result that the weight-horsepower ratios of trucks over the last several years have improved. This improvement is illustrated by the trend curves shown in Figure 8.

Design Criteria Related to Truck Operations

The 1965 AASHO Policy indicates that the average truck speed is approximately 6 mph less than the average passenger car speed on a level highway section. It increases on downgrades of 5 percent or less, and decreases on downgrades of 7 percent or steeper. On upgrades, the maximum sustained speed that a truck can maintain depends on the length and steepness of the grade and the weight-horsepower ratio of the truck. Factors affecting the average speed over the entire section are the truck's entering speed and wind resistance and the skill of the operator.

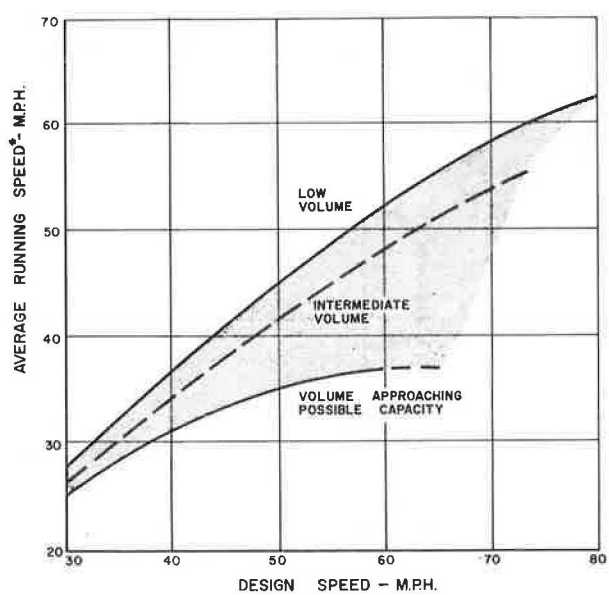
The "critical length of grade" is defined by AASHO (1) as the maximum length of a designated upgrade on which a loaded truck can operate without an unreasonable reduction in speed. If a truck is to operate reasonably on grades longer than the critical length, either the grade must be reduced or an additional climbing lane must be provided.

The AASHO Policy states that climbing lanes are necessary when the length of a specific grade causes truck speeds to reduce 15 mph or more, provided the volume of traffic and percentage of heavy trucks justify the added cost. Therefore, truck gradability or highway capacity or both can determine the critical length of grade. If truck gradability governs, the AASHO Policy considers that the following factors must be determined or assumed:

1. The size and power of the design truck as well as its gradability data. The 400:1 weight-horsepower ratio is accepted as the national design vehicle; therefore, the gradability curves shown in Figures 4 and 5 are employed by the AASHO Policy.

2. Truck speed at entrance to critical length of grade. The average running speed, as related to design speed, can be used to approximate the average speed of vehicles beginning an uphill climb, as shown in Figure 9 (2). For downhill or uphill approaches, the entering speed should be adjusted accordingly.

3. Minimum tolerable speed at which a truck should operate on the grade. Although no specific data are available on the minimum tolerable speeds of trucks, it seems logical that they would have a direct relationship to design speeds. Minimum speeds of 20 to 35 mph



RUNNING SPEED IS THE SPEED (OF AN INDIVIDUAL VEHICLE) OVER A SPECIFIED SECTION OF HIGHWAY, BEING DIVIDED BY RUNNING TIME

*AVERAGE RUNNING SPEED IS THE AVERAGE FOR ALL TRAFFIC OR COMPONENT OF TRAFFIC, BEING THE SUMMATION OF DISTANCES DIVIDED BY THE SUMMATION OF RUNNING TIMES. IT IS APPROXIMATELY EQUAL TO THE AVERAGE OF THE RUNNING SPEEDS OF ALL VEHICLES BEING CONSIDERED.

Figure 9. Relation of average running speed to volume conditions.

on highways with a design speed of 40 to 60 mph would be tolerable for a vehicle unable to pass on a 2-lane highway, provided the no-passing interval is short. As the volume on a 2-lane highway approaches capacity, the time interval will become more annoying. Multilane highways present more opportunity for and less difficulty in passing; therefore, lower tolerable truck speeds are applicable. In any case, highways should be designed so that trucks can maintain a tolerable speed.

Although all states are not in agreement as to what constitutes the critical length of grade, the most common determining factor is the 15-mph reduction in truck speed below the average truck running speed (1). Some states specify a minimum tolerable speed ranging from 20 to 35 mph instead of the 15-mph reduction. Figure 10 shows the critical length of grade for different speed reductions on specific grades (derived from Fig. 4). The 15-mph curve shown in Figure 10 is suggested by AASHO as a general design guide for establishing critical lengths of grades that are preceded by relatively level approaches. If there is an uphill approach to the grade, the critical length will be shorter; for downhill approaches, the converse will be true.

Climbing lanes may be justified from the standpoint of highway capacity as well as truck gradability. The effect of trucks on highway capacity is primarily a function of the difference in average running speeds between trucks and passenger cars. Passenger car equivalents for trucks at various combinations of running speeds are given in Table 2. By selecting the appropriate values from Table 2 and by using the gradability curves of Figures 4 and 5, one can calculate the design capacity on any grade for a given percentage of trucks.

The AASHO Policy (1) states that climbing lanes may be justified if the design hour volume (DHV) for a highway exceeds the design capacity of that highway by more than 20 percent. Table 3 gives the minimum design hour volumes, including trucks (not passenger car equivalents), for which climbing lanes should be considered.

The beginning of a climbing lane depends on the entering speed of the truck on a grade. The data shown in Figure 4 may be used to determine when a truck's speed has decreased enough to be sufficient cause for the implementation of a climbing lane. The AASHO Policy recommends that the beginning of the climbing lane should be preceded by a tapered section at least 150 ft long.

It is desirable to end a climbing lane when the truck's speed has accelerated to a speed at least equal to that at which it entered the climbing lane. The AASHO Policy states that this may be impractical on many grades because of the long distance required to accelerate to such a speed; therefore, a practical point for ending the lane is

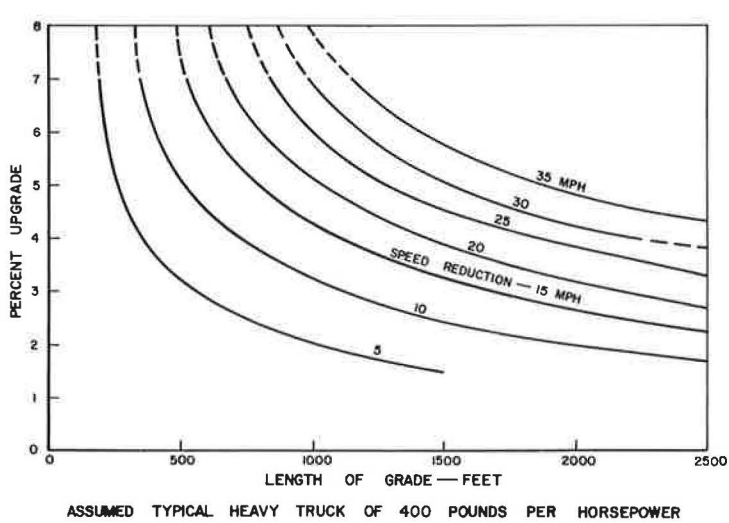


Figure 10. Critical lengths of grade for design.

where a truck can safely reenter the normal flow of traffic. This would be at a point where the sight distance is sufficient to permit passing with safety. The AASHO Policy recommends that a taper of at least 20 ft should be provided to allow the truck to reenter the flow of traffic.

A climbing lane should be at least 10 ft wide, preferably 12 ft. It should be easily distinguishable as an extra lane, and signs should precede the lane to notify trucks that there is a climbing lane ahead (1).

TABLE 2

PASSENGER CAR EQUIVALENTS FOR TRUCKS AT VARIOUS AVERAGE TRUCK SPEEDS AS RELATED TO PASSENGER CARS FOR INDIVIDUAL GRADES ON 2-LANE ROADS

Truck Speed (mph)	Number of Passenger Cars to Which One Truck Is Equivalent		
	45 to 50 mph[a]	40 to 45 mph[a]	35 to 40 mph[a]
35	3.0	2.7	2.5
30	5.0	4.9	3.0
25	8.6	7.6	5.0
20	13.9	11.7	8.8
15	22.9	18.7	15.0
10	40.5	32.5	25.2
5	94.5	75.0	50.0

[a]Average passenger car speed.

EVALUATION OF THE DESIGN CRITERIA

This evaluation of the design criteria for climbing lanes and critical lengths of grade covers the following areas: truck operating characteristics on grades, effect of weight-horsepower ratios on truck operating conditions, truck entering speeds, and speed reduction criteria related to safe operations.

Truck Operating Characteristics on Grades

Truck gradability procedures have been developed to predict the performance of trucks on grades in order to establish a design procedure that will enable all vehicles to operate safely on modern highways. Willey (5) documented the gradability characteristics of trucks and classified the observed trucks according to their weight-horsepower ratios. Gradability curves were developed for the heavily loaded trucks on different grades, a heavily loaded truck being one with a weight-horsepower ratio greater than

TABLE 3

MINIMUM 2-WAY DESIGN HOUR TRAFFIC VOLUMES FOR CONSIDERATION OF CLIMBING LANES ON GRADES ON TYPICAL 2-LANE ROADS

Percent Gradient	Length of Grade (miles)	DHV for Various Percentages of Dual-Tired Trucks			
		3 Percent	5 Percent	10 Percent	15 Percent
4	1/3			600[a]	525[a]
	1/2		700[a]	550	450
	3/4		670	500	390
	1	750[a]	640	470	370
	1 1/2	730	610	440	340
	2	710	590	420	340
5	1/3		640[a]	550[a]	480[a]
	1/2	690[a]	620	460	370
	3/4	650	540	380	300
	1	630	510	360	270
	1 1/2	600	490	340	260
	2	600	480	330	250
6	1/3	625[a]	580[a]	480	390
	1/2	570	470	330	250
	3/4	540	430	290	220
	1	530	420	280	210
	1 1/2	520	410	270	200
	2	510	410	270	200
7	1/3	470	410	310	240
	1/2	400	320	210	160
	3/4	380	300	200	150
	1	360	280	180	140
	1 1/2	350	270	170	130
	2	340	260	160	120

[a]Four lanes warranted for DHV over this amount.

Note: Detailed analysis of each grade is recommended instead of using tabular values.

300:1. Although Willey's observations may have been accurate at the time they were made, his report was not documented well enough to allow a verification of the number of heavily loaded trucks observed or the specific weight-horsepower ratio each heavily loaded truck had. No direct comparison of Willey's gradability curves can be made, therefore, with those developed by any of the other prediction procedures.

Huff and Scrivner (6) developed a prediction procedure and compared this theoretical procedure with actual field tests of the performance of a heavily loaded truck with a weight-horsepower ratio of 391. From the field tests, it was concluded that the theoretical procedure compared fairly well with the actual truck performance on grades. Huff and Scrivner's procedure appears to describe the performance of trucks on grades, although their average curve of P/W versus v, derived from the 1953 road test data, ignored some of the field data. The truck gradability curves derived from this procedure have been adopted as part of the AASHO Policy.

Firey and Peterson (8) developed truck gradability curves for trucks with weight-horsepower ratios of 200, 300, and 400. Figure 6 shows the speed-distance curves for the 400:1 ratio.

From a design viewpoint, the controlling factor for climbing lane design criteria is the maximum sustained speed that a truck can maintain on a grade. The higher the sustained speed is, the shorter the climbing lane needed, and the converse is also true. Table 4 gives a comparison of the maximum sustained speeds derived from the various truck gradability prediction procedures presented in this report. Also included are the maximum sustained speeds calculated by the SAE Procedure (7) for Huff and Scrivner's test truck. A considerable disparity is evident among the various prediction methods. The Huff and Scrivner values are the lowest, and the Firey and Peterson values are considerably higher than the others. The Huff and Scrivner values, however, are the only values that were substantiated by using a design vehicle, one that had a representative weight-horsepower ratio. Therefore, the Huff and Scrivner gradability curves adopted by the AASHO Policy are comparatively valid for design.

The Effect of Weight-Horsepower Ratios on Truck Operating Conditions

The weight-horsepower ratio of a truck determines how that truck will operate on grades. The higher the ratio, the more difficulty a truck will have ascending a grade, and the maximum sustained speed attainable will be lower.

There is a definite trend toward a maximum tolerable ratio of 400:1. In 1963, only 8 percent of all loaded trucks had a ratio greater than 400:1. The AASHO Policy states that the 400:1 ratio has been accepted from the viewpoint of the highway user and that the trucking industry has accepted the 400:1 ratio as a performance control. Only 1 of the 5, 8-cylinder engines offered by International Harvester in its heavy trucks would have a weight-horsepower ratio over 400:1. From all indications, it would seem reasonable to accept the 400:1 ratio as a design criteria.

TABLE 4

GRADE VERSUS MAXIMUM SUSTAINED SPEED AS DETERMINED BY DIFFERENT GRADABILITY PROCEDURES

Percent Grade	Maximum Sustained Speed (mph)			
	Willey	Huff and Scrivner	Firey and Peterson	SAE
1	N.A.	33.5	45.3	33.5
2	23.0	22.0	31.1	24.2
3	17.5	15.0	23.0	18.5
4	12.0	9.5	18.5	15.0
5	9.0	9.0	15.3	12.5
6	7.0	8.0	13.0	11.0
7	6.0	7.5	11.8	9.5

Truck Entering Speeds

Truck operating speeds along a highway, obviously, are determined by the profile of that particular highway. Huff and Scrivner selected an entering speed on grades of 47 mph because it was the average speed of trucks on approximate level grades in Texas. Although this no longer represents the average speed, the Texas Highway Department's 1968 statewide speed survey (13) indicates that a speed of 47 mph now represents the 15th percentile truck speed on Texas highways. Because the 15th percentile truck represents a reasonable lower boundary condition, the 47-mph entering speed is

appropriate for design when entry to a grade from a level approach is considered.

Speed Reduction Criterion

Truck speeds may be related to the average running speed of all traffic along a highway. The conclusion in a study reported by Solomon (14) was that, regardless of the average speed on the highway, the greater a vehicle's deviation from this average speed, the greater was its chance of being involved in an accident. The accident involvement rates related to the deviation from the average speed are shown in Figure 11.

The speed distribution of vehicles traveling Texas highways may be obtained from the Texas Highway Department (13). By utilizing this speed distribution and relating it to the accident involvement rates shown in Figure 11, one can obtain the accident involvement rate for 4-or-more-axle trucks operating on level grades. If the reduction in the average speed of all vehicles on a grade is assumed to be 30 percent of the truck speed reduction on that same grade, the accident involvement rates for truck speed reductions of 5, 10, 15, and 20 mph may also be developed (Appendix B).

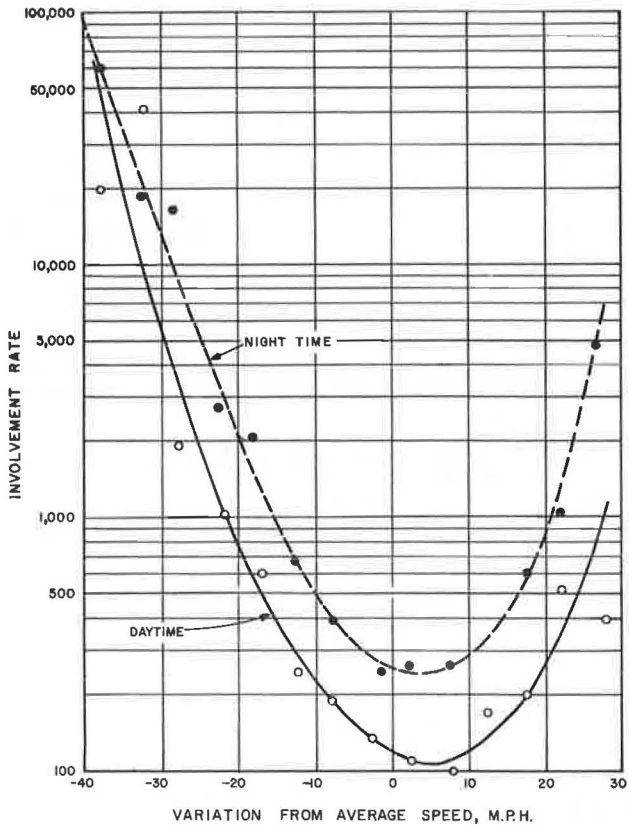


Figure 11. Accident involvement rate by variation from average speed during day and night.

The results of the analysis are given in Table 5 and shown in Figure 12. Most states base their climbing lane design on the criterion of a 15-mph reduction of truck speed. The accident rate for a 15-mph reduction is almost 9 times the involvement rate for a 0-mph reduction and approximately 2.4 times the rate for a 10-mph reduction (Table 5). The accident involvement rate increases, in absolute terms, 1,280 from the 10-mph to the 15-mph reduction. This is an increase of more than 5 times the increase from the 0-mph to the 5-mph reduction. This would indicate that a definite consideration should be given to the 10-mph reduction as a climbing lane design criterion, in place of the present 15-mph reduction.

For the steeper grades, thought should be given to further reduction of the speed criterion. A 5-mph decrease in the speed reduction criterion does not substantially increase the required climbing lane length for the steeper grades (Fig. 10). This small increase in climbing lane length would be more than offset by the concomitant reduction of the accident involvement rate. These

TABLE 5

ACCIDENT INVOLVEMENT RATE OF TRUCKS ON GRADES COMPARED TO THE VARIATION FROM THE AVERAGE SPEED OF ALL VEHICLES ON A HIGHWAY

Speed Reduction (mph)	Accident Involvement Rate	Involvement Rate Ratio Related to 0-Speed Reduction
0	247	1.00
5	481	1.95
10	913	3.70
15	2,193	8.90
20	3,825	15.90

same considerations apply on the downstream end of the climbing lane, where it is necessary to allow acceleration of the truck to a speed at which it can safely reenter the normal traffic stream.

In terrain that dictates consecutive climbing lanes at short intervals, consideration should be given to joining the separate climbing lanes to form one continuous lane. This would eliminate the hazardous situation of reentering the truck into the normal flow of traffic and then, in a short distance, removing the truck again.

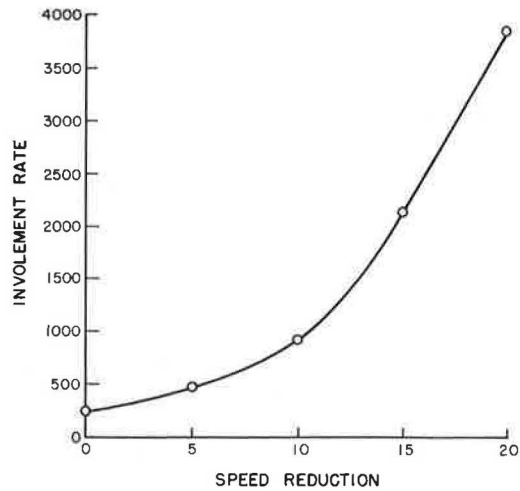


Figure 12. Accident involvement rate of trucks by speed reduction of design vehicle.

SUMMARY AND CONCLUSIONS

Based on this evaluation, which covered several truck gradability studies and prediction procedures, there is no substantiated justification for upgrading the truck gradability curves developed by Huff and Scrivner (2) as employed by the 1965 AASHO Policy (1). These curves were theoretically derived and validated by road tests of a heavily loaded truck with an approximate weight-horsepower ratio of 400:1. The trucking industry appears to have accepted this ratio as a performance control, although this does not account for the overloading occasionally practiced. From all indications of the trends in weight-horsepower ratios of trucks in operation, the 400:1 ratio appears to have continuing application as a design criterion.

The truck gradability curves developed by Huff and Scrivner utilize a 47-mph speed for trucks entering a grade from a level section. This represented the maximum sustained speed of the test truck on a level grade. This speed was the average of all trucks on Texas highways in 1953 and was considered as representative of a critical operating condition. Actually, a more representative critical speed would be the speed that is exceeded by, say, 85 percent of the trucks on the highway. The Texas Highway Department's 1968 speed survey indicated that approximately 85 percent of the trucks exceeded 47 mph. Therefore, the 47-mph truck entering speed is applicable for current design considerations.

The AASHO Policy currently employs a 15-mph speed reduction criterion for determining critical lengths of grades. No objective basis could be found for this criterion. Some existing data were applied to establish an objective basis for a speed-reduction criterion.

Taragin (3) developed a curve that related accident involvement rate to deviation from the average speed of the traffic stream. This relationship showed that the involvement rate increases logarithmically as this deviation increases. This relationship and the Texas Highway Department's 1968 speed survey data were used to compute accident involvement rates for various speed reductions of 4-or-more-axle trucks (Fig. 12). The accident involvement rate related to a 15-mph speed reduction of the design vehicle is almost 9 times that of a 0-mph reduction. The involvement rate increases very rapidly for increases in speed reduction beyond 10 mph. This relationship indicates that a 10-mph speed reduction criterion should be substituted for the present 15-mph criterion.

Highway engineers have been concerned that present design criteria are often responsible for truck climbing lanes that are too short for efficient operation. Operational problems are created for the following reasons:

1. With the present 15-mph speed reduction criterion, the common practice has been to end a climbing lane when the design truck regains a speed equivalent to that speed for which the climbing lane was begun. This practice, for many profile conditions, allows

the ending of the climbing lane shortly over the crest of the hill. This practice can create a lack of adequate operational sight distance to the end of the climbing lane, especially for slow-moving automobile drivers who choose to use the auxiliary lane.

2. Truck drivers find it difficult to maintain desired operation of their vehicles on short climbing lanes and, therefore, are often reluctant to use climbing lanes in areas where they know by experience these auxiliary lanes tend to be short.

Although no investigation was made of the optimum length of truck climbing lanes, the substitution of a 10-mph speed reduction criterion in place of the current 15-mph criterion would alleviate these operational problems.

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Appendix A

DERIVATION OF FORMULAS

Huff and Scrivner's Speed-Distance and Time-Distance Formulas

Through the summation of forces acting on a truck ascending any grade, a basic force equation may be developed:

$$\frac{W}{g}\frac{dv}{dt} = P - W \sin \theta \tag{16}$$

When divided by W, Eq. 16 becomes

$$\frac{P}{W} = \frac{1}{g}\frac{dv}{dt} + \sin \theta \tag{17}$$

If it is stipulated that

$$\frac{P}{W} = av + b \tag{18}$$

then, by substitution, an equation is formed that does not contain P/W:

$$\frac{dv}{dt} - gav + g(\sin\theta - b) = 0 \tag{19}$$

If dv/dt is the change in velocity with respect to time, $\frac{v_o - v}{t}$, and v is the average velocity, $\bar{v}$, then Eq. 19 becomes

$$\frac{v_o - v}{t} - ga\bar{v} + g(\sin\theta - b) = 0 \tag{20}$$

By multiplying by the time, t, and solving for $\bar{v}t$, we may write Eq. 20 as

$$\bar{v}t = \frac{v_o - v}{ga} + \frac{gt(\sin\theta - b)}{ga} \tag{21}$$

Any distance, x, may be measured by the average velocity multiplied by time; therefore, Eq. 21 becomes

$$x = \frac{1}{a} = \frac{v_o - v}{g} + (\sin\theta - b)t \tag{22}$$

which is Huff and Scrivner's first equation.

Their second equation may be derived by first solving for dt in Eq. 19.

$$dt = \frac{dv}{g(av - \sin\theta + b)} \tag{23}$$

If Eq. 23 is integrated from t_o to t,

$$\int_{t_o}^{t} dt = \frac{1}{g}\int_{v_o}^{v} \frac{dv}{av - \sin\theta + b} \tag{24}$$

and, because $(\sin\theta + b)$ is constant over any interval v_o to v, then Eq. 24 becomes

$$t = \frac{1}{ag}\int_{v_o}^{v} \frac{adv}{av + (-\sin\theta + b)} \tag{25}$$

Then,

$$t = \frac{1}{ag}\ln\left[av + (-\sin\theta + b)\right] - \frac{1}{ag}\ln\left[av_o + (-\sin\theta + b)\right] \tag{26}$$

or

$$t = \frac{1}{ag} \ln \frac{av - \sin\theta + b}{av_o - \sin\theta + b} \tag{27}$$

Simplified Speed-Distance Formula Using Huff and Scrivner's Assumptions

A simplified speed-distance formula may be derived by using the same assumptions made by Huff and Scrivner. If dv/dt is the change in velocity with respect to time and v is the average velocity, Eq. 19 becomes

$$\frac{v_o - v}{t} - ga\bar{v} + g(\sin\theta - b) = 0 \tag{28}$$

When divided by the average velocity, $\bar{v}$, Eq. 28 becomes

$$\frac{v_o - v}{\bar{v}t} - ga + \frac{g(\sin\theta - b)}{\bar{v}} = 0 \tag{29}$$

Any distance, x, may be represented by an average speed times time, $\bar{v}t$; therefore, Eq. 29 becomes

$$\frac{v_o - v}{x} - ga + \frac{g(\sin\theta - b)}{\bar{v}} = 0 \tag{30}$$

Solving for x and substituting $\frac{v_o + v}{2}$ for $\bar{v}$, we may write Eq. 30 as

$$x = \frac{1}{g} \frac{v_o^2 - v^2}{a(v_o + v) - 2(\sin\theta - b)} \tag{31}$$

Appendix B

ANALYSIS OF ACCIDENT INVOLVEMENT RATES OF 4-AXLE TRUCKS ON GRADES

An analysis was made of accident involvement rates to ascertain whether the 15-mph speed reduction design criterion is adequate for determining the critical length of grade. In a report by Solomon (14), accident involvement rates were related to average running speeds of vehicles on a highway. The conclusion was that, regardless of the average speed on a highway, the greater a vehicle deviated from the average running speed of all vehicles, the greater was its chance of being involved in an accident. The involvement rates as they relate to the deviation from the average running speed of all traffic along the highway are shown in Figure 11 of this report.

Each year the Texas Highway Department reports the speed distribution of all vehicles traveling on the highways in Texas. This survey is made by recording the actual speed of vehicles at 31 strategically located speed-survey stations across the state. In 1968, the speeds of 48,253 vehicles were checked, 35,776 of which were passenger cars and 3,284 were 4-or-more-axle trucks.

The following assumptions were made to facilitate the analysis of accident involvement rates:

1. That the statewide average speed determined by the Texas Highway Department was the typical average speed of all vehicles operating on level grades along a highway.

2. That the statewide speed distribution for 4-or-more-axle trucks determined by the Texas Highway Department was the typical speed distribution for this type of truck operating on level grades along a highway.

3. That the involvement rate for each category would be multiplied by the daytime involvement rates versus deviation from the average speed (Fig. 11). The daytime rates were employed because they were lowest and were considered to be conservative for this analysis.

4. That all 4-or-more-axle trucks decelerated in the manner shown in Table 6.

5. That the average speed reduction of all vehicles on a grade was 30 percent of the average truck speed reduction on that same grade.

TABLE 6

ASSUMED SPEED REDUCTION OF 4-AXLE TRUCKS ACCORDING TO SPEED CATEGORIES FOR VARIOUS SPEED REDUCTIONS OF THE DESIGN TRUCK

Truck Speed Categories (mph)	Speed Reduction of Design Truck[a] (mph)				
	0	5	10	15	20
30 to 35	0	8	13	18	23
35 to 40	0	7	12	17	22
40 to 45	0	6	11	16	21
45 to 50	0[a]	5[a]	10[a]	15[a]	20[a]
50 to 55	0	4	8	12	16
55 to 60	0	3	6	9	12
60 to 65	0	2	4	6	8
65 to 70	0	1	2	3	4
70 to 75	0	0	0	0	0
Avg. speed of all traffic	59.4	57.9[b]	56.4[b]	54.9[b]	53.4[b]

[a]Design truck operates within the 45 to 50 mph category.
[b]Assumed average speed of all traffic on grades is calculated by subtracting 30 percent of the design truck speed reduction from the average speed, 59.4 mph, of all vehicles on level grades.

The following procedure was used to determine the accident involvement rates on grades:

1. The average speed of all vehicles on level grades and the speed distribution categories were obtained from the data reported by the Texas Highway Department.

2. The midpoint of each speed category was subtracted from the average speed of all vehicles to determine the difference.

3. The deviation in speed from the average for each category was used to determine the involvement rate for that category from the daytime involvement rates versus speed variation (Fig. 11).

TABLE 7

ACCIDENT INVOLVEMENT RATE OF 4-AXLE TRUCKS WITH AN ASSUMED SPEED REDUCTION ON GRADES OF 15 MPH BELOW THE SPEED ON LEVEL GRADES

Average Speed (1)	Truck Speed Categories (2)	Midpoint (3)	Difference From Average (4)	Percent of Total 4-Axle Trucks (5)	Involvement Rate (6)	Percent of Trucks × Involvement Rate (7)
54.9	12 to 17	14.5	-40.4	0.9	100,000	90,000
	18 to 23	20.5	-34.4	3.9	17,000	66,300
	24 to 29	26.5	-28.4	6.1	3,700	22,570
	30 to 35	32.5	-22.4	18.3	1,180	21,594
	38 to 43	40.5	-14.4	19.8	350	6,930
	46 to 51	48.5	- 6.4	37.4	175	6,545
	54 to 59	56.5	+ 1.6	10.0	118	1,180
	62 to 67	64.5	+ 9.6	3.4	123	4,182
	70 to 75	72.5	+17.6	0.2	200	40
Total				100.0		219,341

Involvement rate = 219,341/100 = 2,193

Notes: Col. 1. Average speed of all vehicles on level grades less 30 percent of assumed reduction in truck speed on grades: 59.4 - (0.3)(15) = 54.9.
Col. 2. Truck speed categories as determined by subtracting the assumed truck speed reduction in Table 6 from the speed categories established by the Texas Highway Department.
Col. 3. The midpoint of each truck speed category.
Col. 4. Difference of the average truck speed from the average speed (col. 1 minus col. 3).
Col. 5. Percentage of total 4-axle trucks in each speed category as determined by the Texas Highway Department.
Col. 6. Involvement rate taken from Figure 15.
Col. 7. Product of the percentage of total 4-axle trucks and the involvement rate for the speed differential for each speed category (col. 5 times col. 6).

4. This involvement rate for each category was multiplied by the percentage of 4-or-more-axle trucks within each speed category to obtain the weighted involvement rate.

5. All weighted rates were totaled and divided by 100.

6. The same procedure was followed, with one exception, to determine the involvement rates on grades that would cause a truck speed reduction of 5, 10, 15, and 20 mph. The average speed on the grade was established by subtracting 30 percent of the truck speed reduction from the average speed of all vehicles on level grades. All other steps, 2 through 5, were exactly the same. An example of the calculation procedure is shown in Table 7 for the 15-mph speed reduction.