AN EVALUATION OF DESIGN CRITERIA RELATED TO SAFE TRUCK OPERATIONS ON GRADES

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SUMMARY

This report is concerned with the evaluation of the state-of-the-art concerning the 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 related to truck operating characteristics and design criteria for climbing lanes.

The following findings may be drawn from the evaluation presented in the report:

1. The truck gradability curves presented in the AASHO Policy adequately describe the performance of a 400:1 weight-horsepower ratio truck on highway grades. These curves were based on studies by Huff and Scrivner (1). Other reports were examined, but no basis was found to change the relationship presented by Huff and Scrivner. The 47-mph entering speed used for these curves is approximated by the 15th percentile speed on Texas highways in 1968. As such the 47-mph speed is a representative lower boundry condition for design.
2. A maximum tolerable truck weight-horsepower ratio of 400:1 is an acceptable design vehicle. Huff and Scrivner's gradability curves represent the performance of this design vehicle on highway grades. The trucking industry seems to have accepted the 400:1 ratio as a performance control; however, this does not account for over-loading conditions which sometimes occur. From all indications of the trends in weight-horsepower ratios of trucks in operation, the 400:1 ratio would appear to have continuing application as a design criterion.
3. From a comparison of accident involvement rates and truck speed reduction on grades, a 10-mph speed reduction of trucks appear to be appropriate as the design criterion for climbing lanes and critical lengths of grades. From Figure 12 in the report, it may be observed that for speed reductions greater than

10-mph, the probability of a truck being involved in an accident increases rapidly with increasing speed reduction.

INTRODUCTION

Of all vehicles operating on our 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.

In terms of highway safety, there has been an increasing concern by highway and traffic engineers regarding the validity of the basic criteria that are fundamental to current geometric design standards. The design criteria for critical length of grade and truck climbing lane designs, as presented in the 1965 AASHO Policy (1)*, are based on studies conducted in the early 1950's. As such they may no longer be representative because of changes in the characteristics of large trucks.

This report is addressed to an evaluation of the validity of the AASHO criteria related to the safe operation of trucks on grades. In performing this evaluation, an examination was conducted on the current state of knowledge concerning truck speed-distance characteristics on grades, truck weight-horsepower ratios, and truck speeds as they relate to safe operations on grades.

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* Number denotes reference listed in the Bibliography

STATE OF THE ART

This section presents a comprehensive picture of the state of knowledge concerning design criteria which relate truck operating characteristics on grades to the implementation of critical lengths of grade and truck climbing lanes. The topics of discussion include: (1) truck operating characteristics on grades; (2) truck weight-horsepower ratios related to climbing characteristics; and (3) 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 in 1938-41 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. Speed-distance curves were developed using three weight classifications: light, medium and heavy. These curves formed the basis for the 1954 AASHO Policy (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 ratios:

Group A - Up to 199 lbs./BHP
Group B - 200 to 299 lbs./BHP
Group C - 300 to 399 lbs./BHP
Group D - over 400 lbs./BHP

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 (see Figure 1).

Huff and Scrivner (6) used Willey's gradability curves in developing their simplified climbing-lane theory. This theory considered the forces

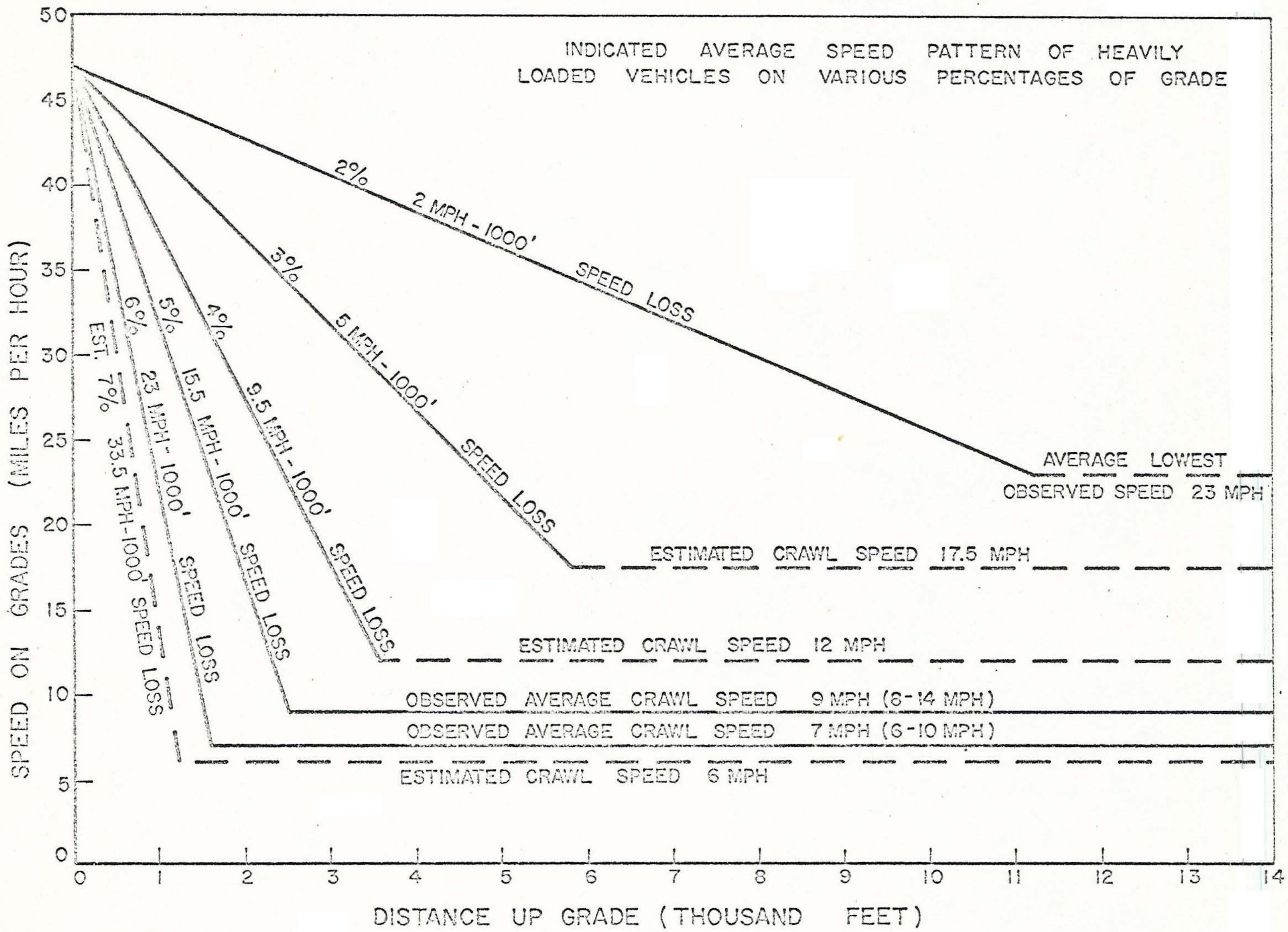


Figure 1. Willey's Heavily Loaded Truck Gradability Curves on Different Grades (5)

acting upon a truck ascending a grade to develop the force equation:

$$\frac{W}{g}\frac{dv}{dt} = P - W \sin \Theta \qquad (1)$$

where

W = gross vehicle weight, in lbs.;

g = acceleration of gravity, 32.2 ft/sec^2;

dv/dt = change in velocity with respect to time, in ft/sec^2;

P = net driving force on the vehicle, in lbs., and

Θ = the grade angle, in degrees.

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:

$$\frac{P}{W} = \frac{1}{g}\frac{dv}{dt} + \sin \Theta \qquad (2)$$

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 it would mean that the driver's choice rather than highway geometry, would determine the vehicle performance; therefore, if the truck operates at the highest possible speed, and within the manufacturer's recommendations, it is possible to approximate the total driving force as a function of the velocity only, if the following assumptions are made:

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

It was concluded, therefore, that although the net driving force must satisfy Equation 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 Equation 2, which reduces to P/W = sin Θ. This value of P/W will always exist at the respective speed, at least approximately, regardless of the value of the acceleration.

Figure 2 relates P/W to maximum sustained speeds, v, on various grades. The maximum sustained speeds were taken from the gradability curves in Figure 1. The points plotted in Figure 2 were connected by straight line segments to form a continuous graph. Each line segment was represented by the general equation:

$$P/W = av + b \qquad (3)$$

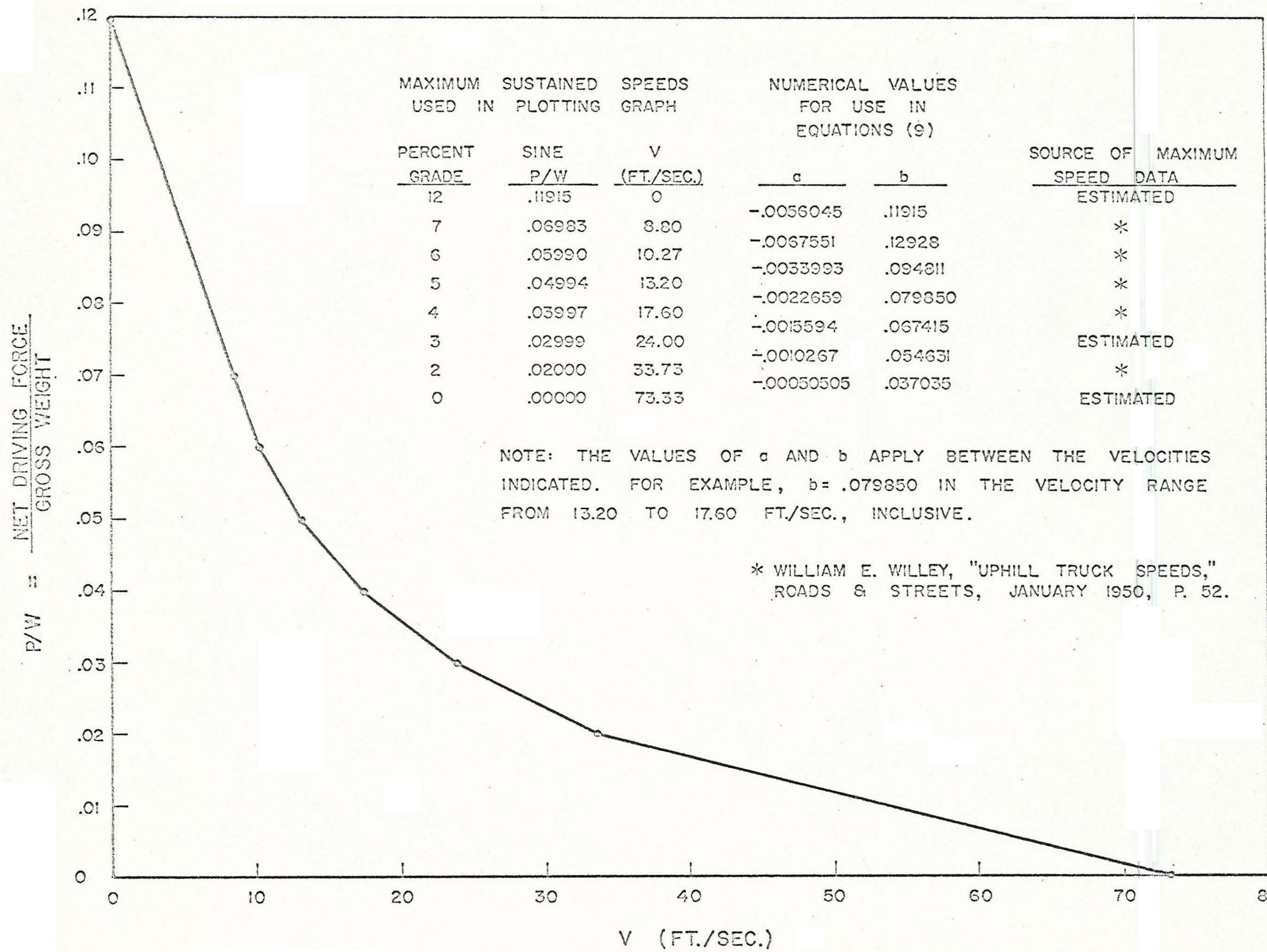
where v is the velocity at any point along a line segment, v_n to v_{n+1}, and a and b are constant along the same line segment. By substituting the P/W value of Equation 2 into Equation 3, a new general motion equation was derived:

$$\frac{dv}{dt} - gav + g(\sin \Theta - b) + 0 \qquad (4)$$

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

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 $\frac{dv}{dt}$ is the change in velocity, v, with respect to time, t, along that line segment, Equation 4 may be developed into an equation suitable for the construction of speed-distance and time-distance curves (See Appendix A for derivation)

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



MAXIMUM SUSTAINED SPEEDS USED IN PLOTTING GRAPH

PERCENT GRADE	SINE P/W	V (FT./SEC.)	SOURCE OF MAXIMUM SPEED DATA
12	.11915	0	ESTIMATED
7	.06983	8.80	*
6	.05990	10.27	*
5	.04994	13.20	*
4	.03997	17.60	*
3	.02999	24.00	ESTIMATED
2	.02000	33.73	*
0	.00000	73.33	ESTIMATED

NUMERICAL VALUES FOR USE IN EQUATIONS (9)

a	b
-.0056045	.11915
-.0067551	.12928
-.0033993	.094811
-.0022659	.079850
-.0015594	.067415
-.0010267	.054631
-.00050505	.037035

NOTE: THE VALUES OF a AND b APPLY BETWEEN THE VELOCITIES INDICATED. FOR EXAMPLE, b = .079850 IN THE VELOCITY RANGE FROM 13.20 TO 17.60 FT./SEC., INCLUSIVE.

* WILLIAM E. WILLEY, "UPHILL TRUCK SPEEDS," ROADS & STREETS, JANUARY 1950, P. 52.

Figure 2. P/W Versus Maximum Sustained Speeds on Various Grades (6)

where:

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

To construct speed-distance using Equation 5, where the velocity change involves more than one line segment, the distance or time must 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 Equation 5 and 5a, a much simpler singular speed-distance may be derived (see Appendix B):

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

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

Figure 3 was developed from 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 presented in Table 1 were also used to compute the maximum sustained speeds according to the SAE Truck Ability Prediction Procedure (7). These speeds were plotted against the corresponding sin Θ in Figure 3.

The average values of P/W versus velocity from Figure 3 were used to develop speed-distance curves for each of the eleven test grades and then compared against the gradability curves developed from the field

TABLE 1
OPERATING CONDITIONS OF TEST TRUCK (6)

Vehicle:	International R-195 Tractor with Hobbs tandem-axle, flat-bed trailer.
Dimensions: (a) Height (b) Width	 7.75 feet 7.75 feet
Gross Vehicle Weight:	57,180 lbs.
Rated Gross Vehicle Weight:	50,000 lbs.
Gear Ratios: (a) Transmission (b) Auxiliary Transmission (c) Axle (d) Total Gear Reductions	 6.98, 3.57, 1.89, 1.00, 0.825 None 6.50, 8.86 61.84, 45.37, 31.63, 23.21, 16.75, 12.28, 8.86, 6.50, 7.31, and 5.36
Tire Size:	10 x 20
Net Engine Hp at Sea Level:	146 hp at 2,600 RPM
Brake Horsepower	162 hp at 2,800 RPM
Altitude:	950 feet
Road Type and Condition:	bituminous, good
Net Weight-Horsepower Ratio:	391 lbs./hp
Weight to Rated Horsepower Ratio:	353 lbs./hp

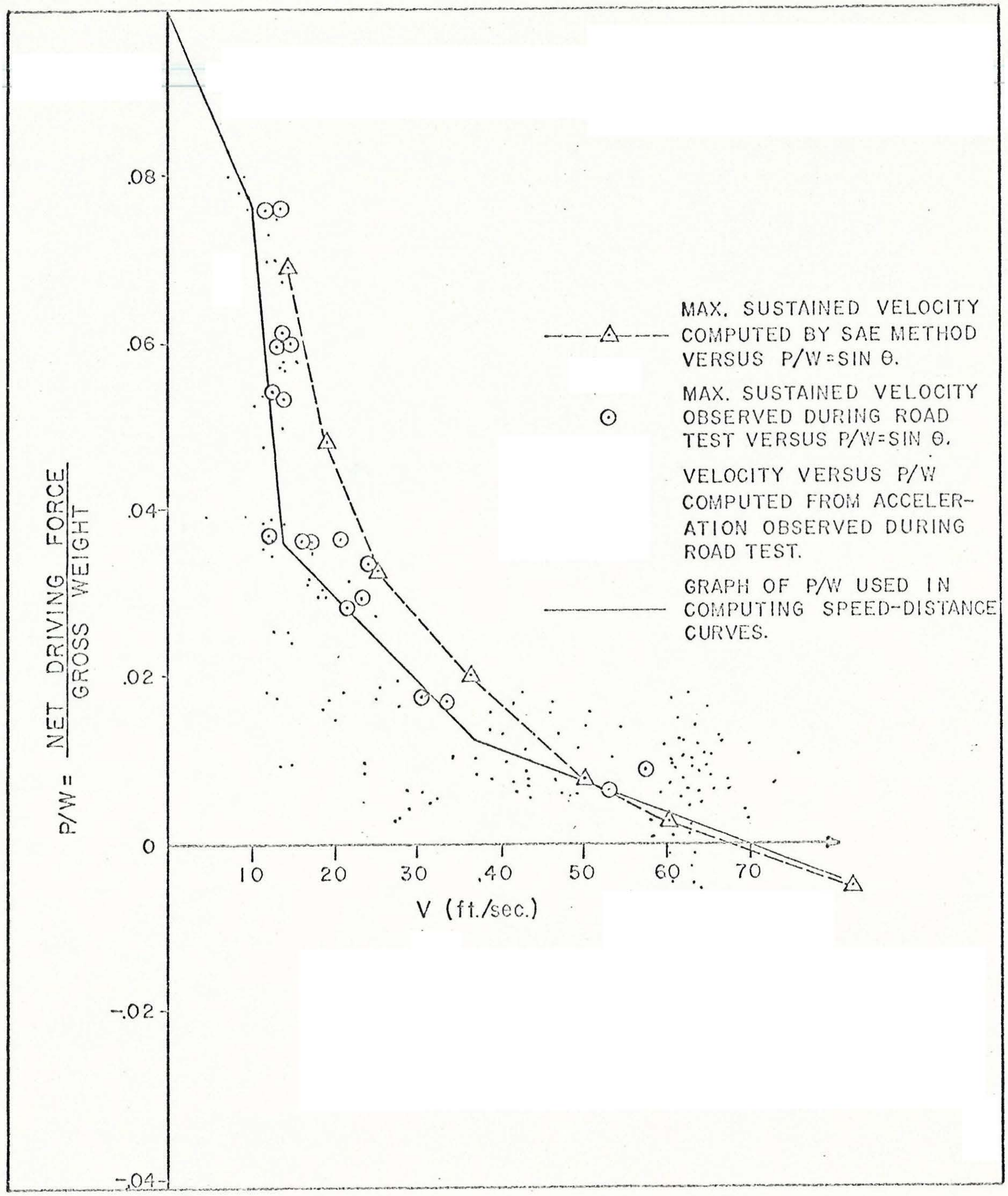


Figure 3. Graph of P/W Verus V for 1953 Road-Test Data (6)

test. If the curves for each grade coincided, the computed curve was considered as representative of the measured test data; if they did not coincide, the opposite was assumed.

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

1. There was some irregularity in the curves, due to 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 the above discrepancies existed, the gradability curves shown in Figures 4 and 5 (developed through the use of Equation 5 and Figure 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 use in design. The gradability curves shown in Figures 4 and 5 are those employed in the 1965 AASHO Policy.

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

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

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, assuming 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:

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

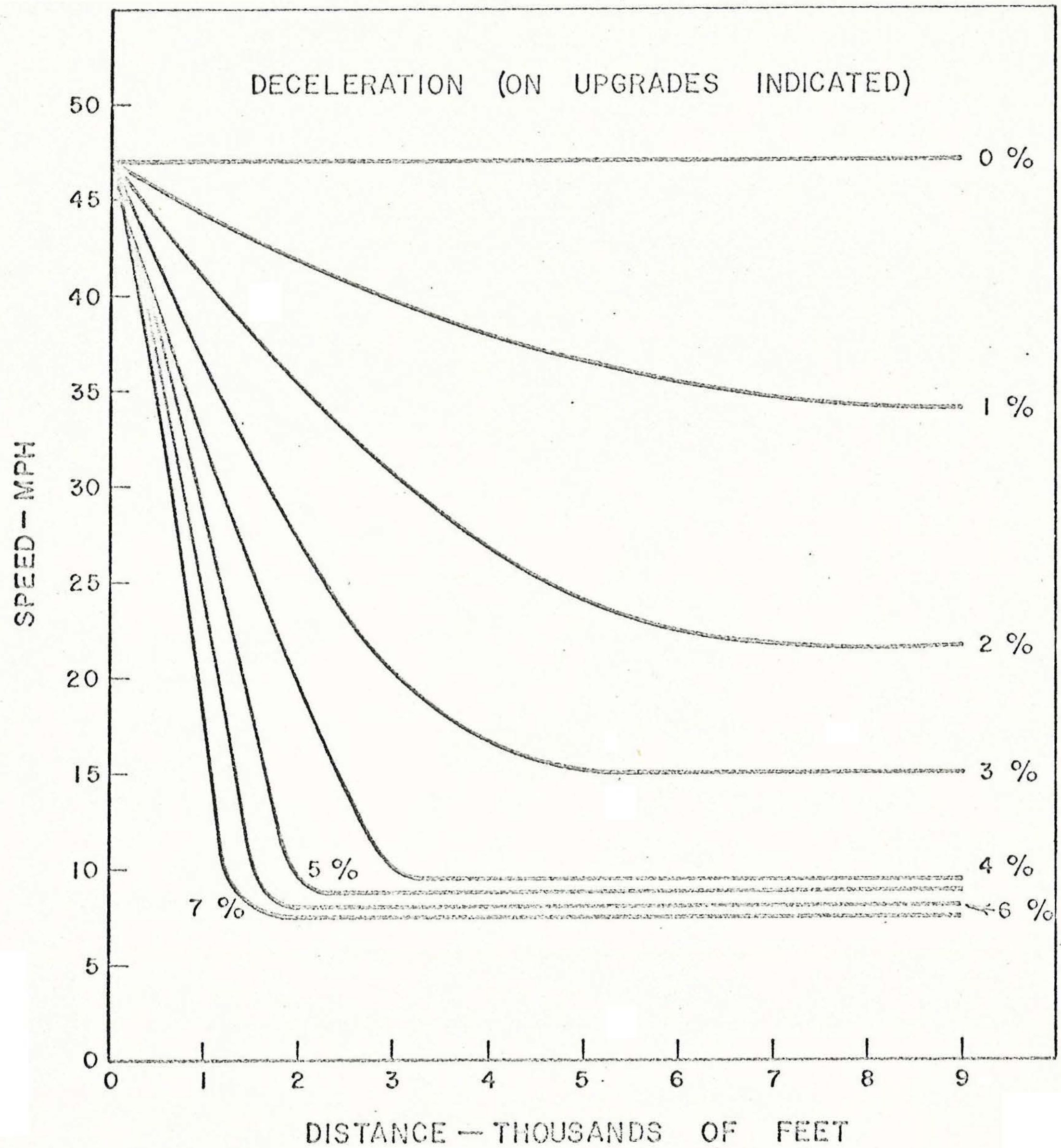


Figure 4. Speed-Distance Curves From Road Test Of A Typical Heavy Truck Operating On Various Grades - AASHO Policy

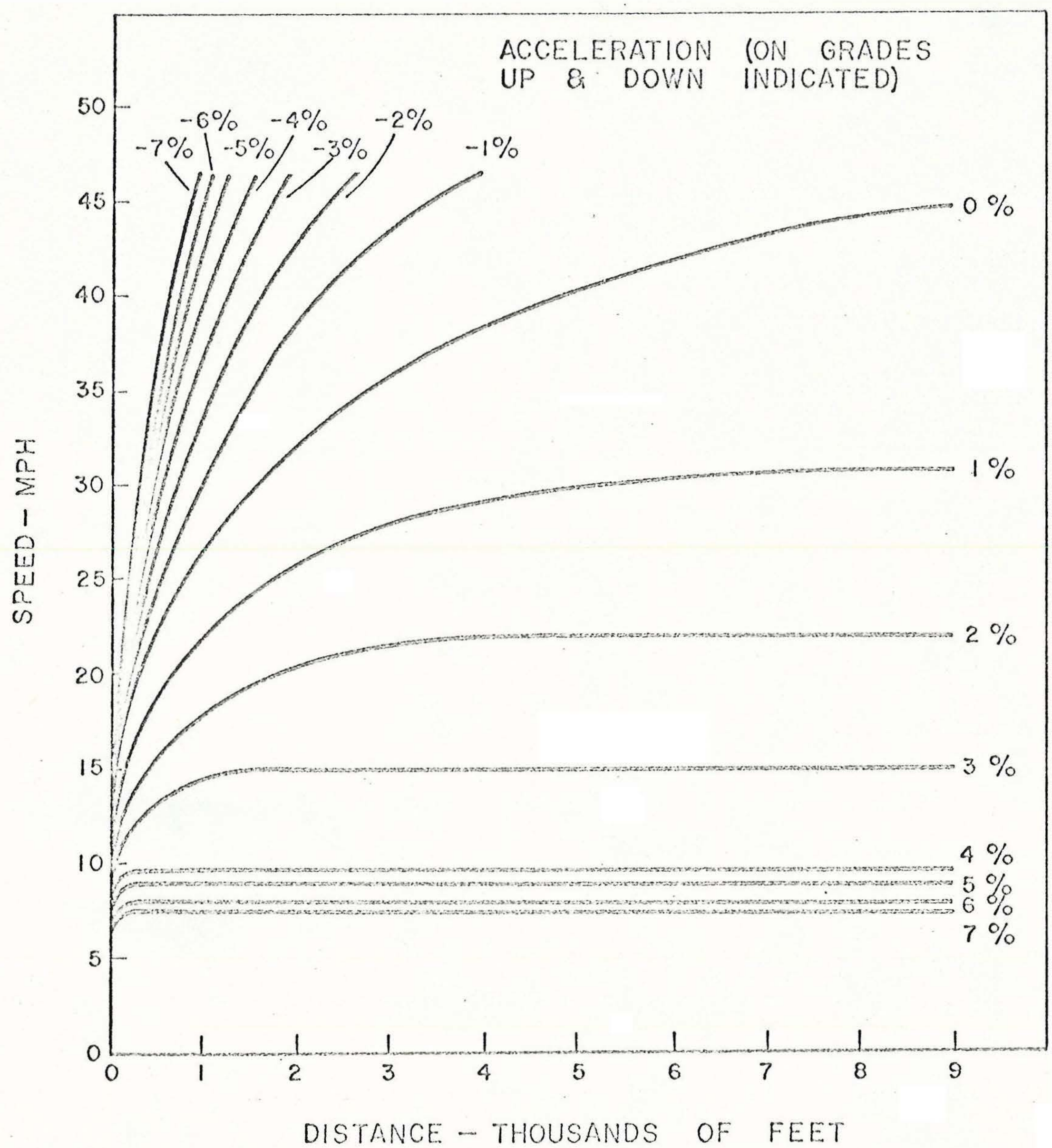


Figure 5. Speed-Distance Curves From Road Test Of A Typical Heavy Truck Operating On Various Grades - AASHO Policy

where;

E = engine rpm at wide-open throttle

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:

$$F_R = \frac{W}{148.5} + 195.0 \qquad (9)$$

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 Equation 9 is not very important because F_T is the dominant resisting force to vehicle motion.

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

at wide throttle;

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

with clutch disengaged, $F_T = 0$; therefore:

$$F_o = \frac{-W}{148.5} - 195.0 - W \sin \theta \qquad (11)$$

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

$$x = v_o t + 1/2\ at^2 \qquad (12)$$

$$v = v_o + at \qquad (13)$$

Because the acceleration, a, in the above 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:

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

$$V = v_o + \frac{F_o g t}{W} \quad (15)$$

To calculate the velocity versus distance curves on uniform grades, the following steps were followed:

1. Values were assumed for W, W/H_p, Θ, and initial v_o.
2. These values were substituted into the vehicle motion equations, Equation 4 and 5.
3. On deceleration curves the first gear shift was assumed at $0.8\ v_o$ and on acceleration curves it was assumed at $v_o/0.8$.
4. An average time of two seconds was determined (9) to shift the gears, and the vehicle was assumed to follow the vehicle motion equations for clutch disengagement during the gear shifting interval.
5. Steps 2 and 3 were repeated, using the vehicle motion equations for the clutch disengagement over the gear shifting interval.
6. For the second wide-open throttle periods steps 2 and 3 were repeated, using the terminal speed from step 5 as v_o in Equations 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 depicted in Figure 6.

In order to relate truck operations to design for highway grades, it is necessary to select a design vehicle which represents some lower boundry of operation. Willey (5) was the first to classify truck operating characteristics according to weight-horsepower ratios. Because

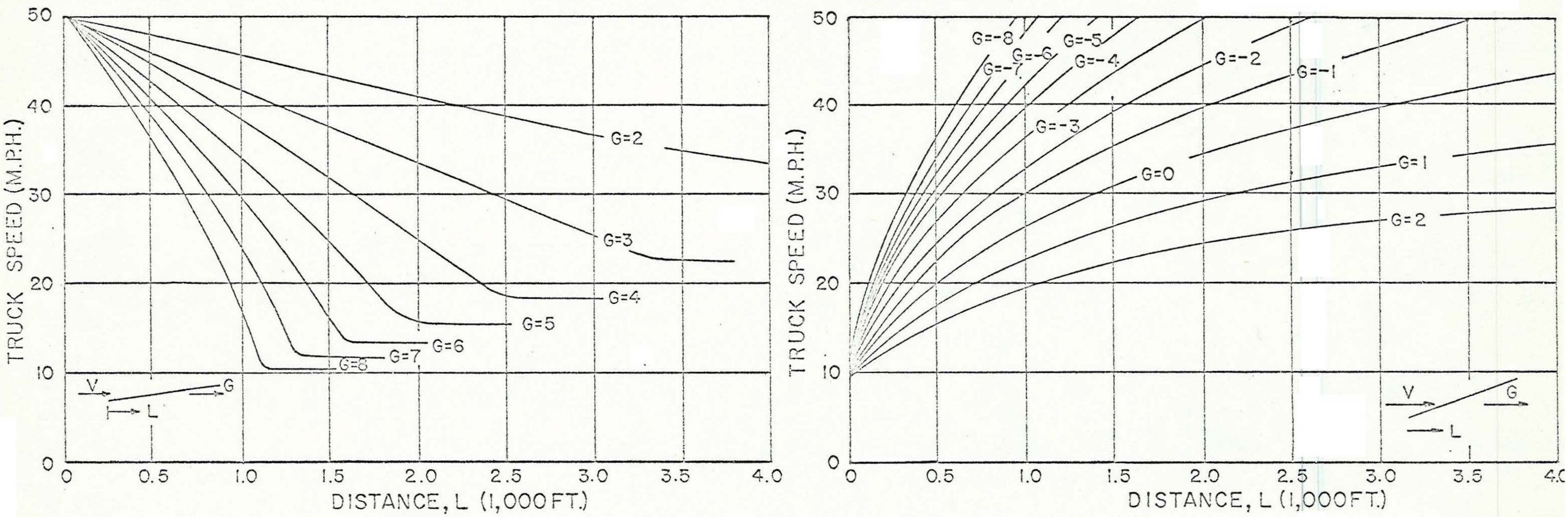


Figure 6. Deceleration and Acceleration Gradability Curves for Trucks with GVW/BHPW Ratio=400 (8).

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 gross weights of motor trucks and their 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 there had been at least a ten percent improvement in the performance ratio of all groups.

In 1963, Wright & Tignor (11) reported on the 1949, 1955, and 1963 Bureau of Public Roads brake studies. 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 eight 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 five percent exceeded the 400:1 ratio.

There has been a definite decreasing trend in 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 pounds, gross vehicle weight) on the highways increased approximately 3.4 times from 1954 to 1967 and is predicted to increase three times from 1967 to 1980 (12).

In 1968, more International Harvester trucks were registered across the United States in the heavy category (26,000 pounds and over). International Harvester offers five, 8-cylinder diesel engines to power its 65,000 pound 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, or 414:1, depending upon which model was chosen. It should be noted that only one of the five engines offered would fall outside the accepted tolerable performance ratio of 400:1. (13)

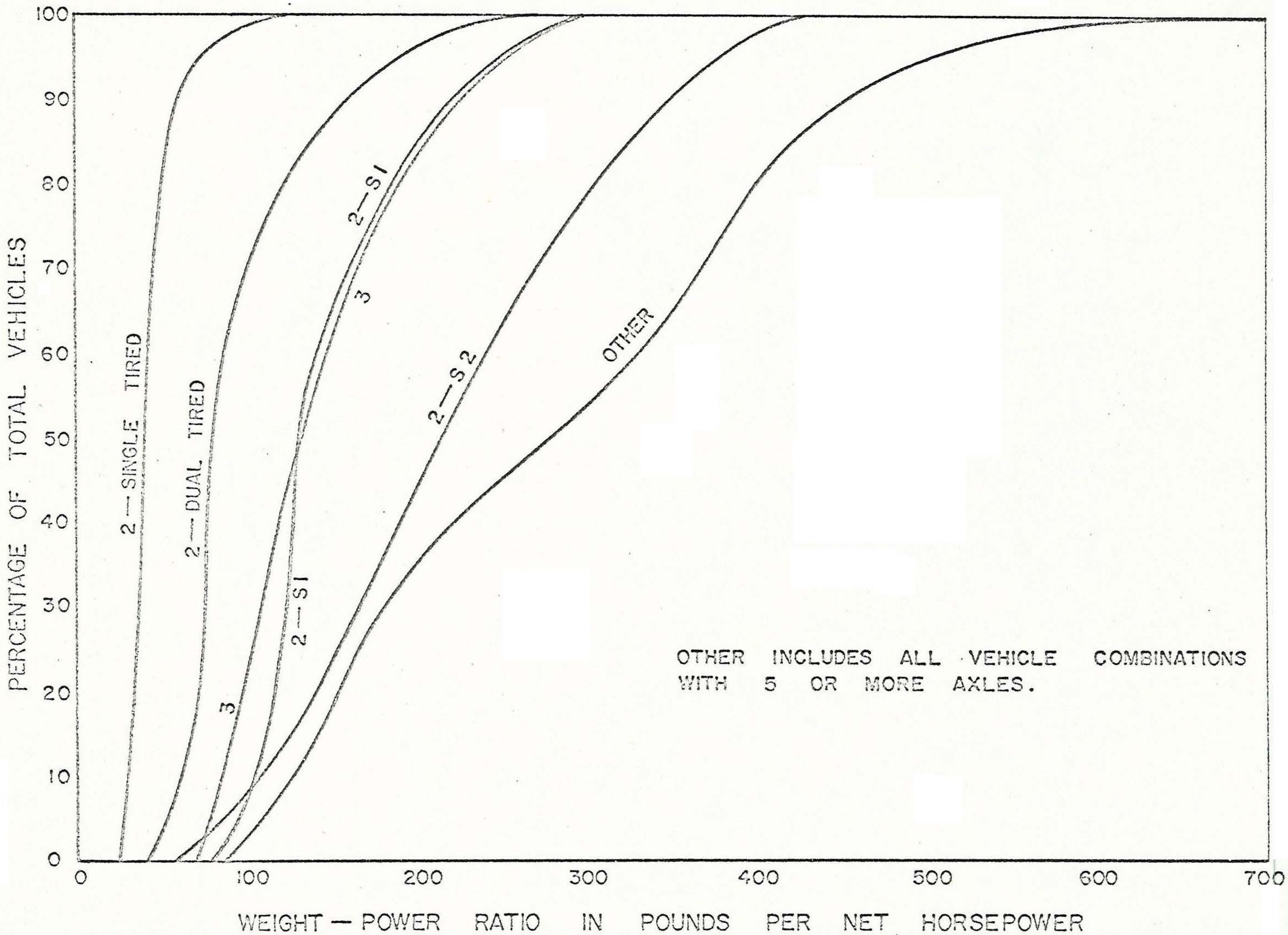


Figure 7 Cumulative Frequency Distributions Of Weight-Power Ratios Of All Commercial Vehicles Weighed In The 1963 Study (11).

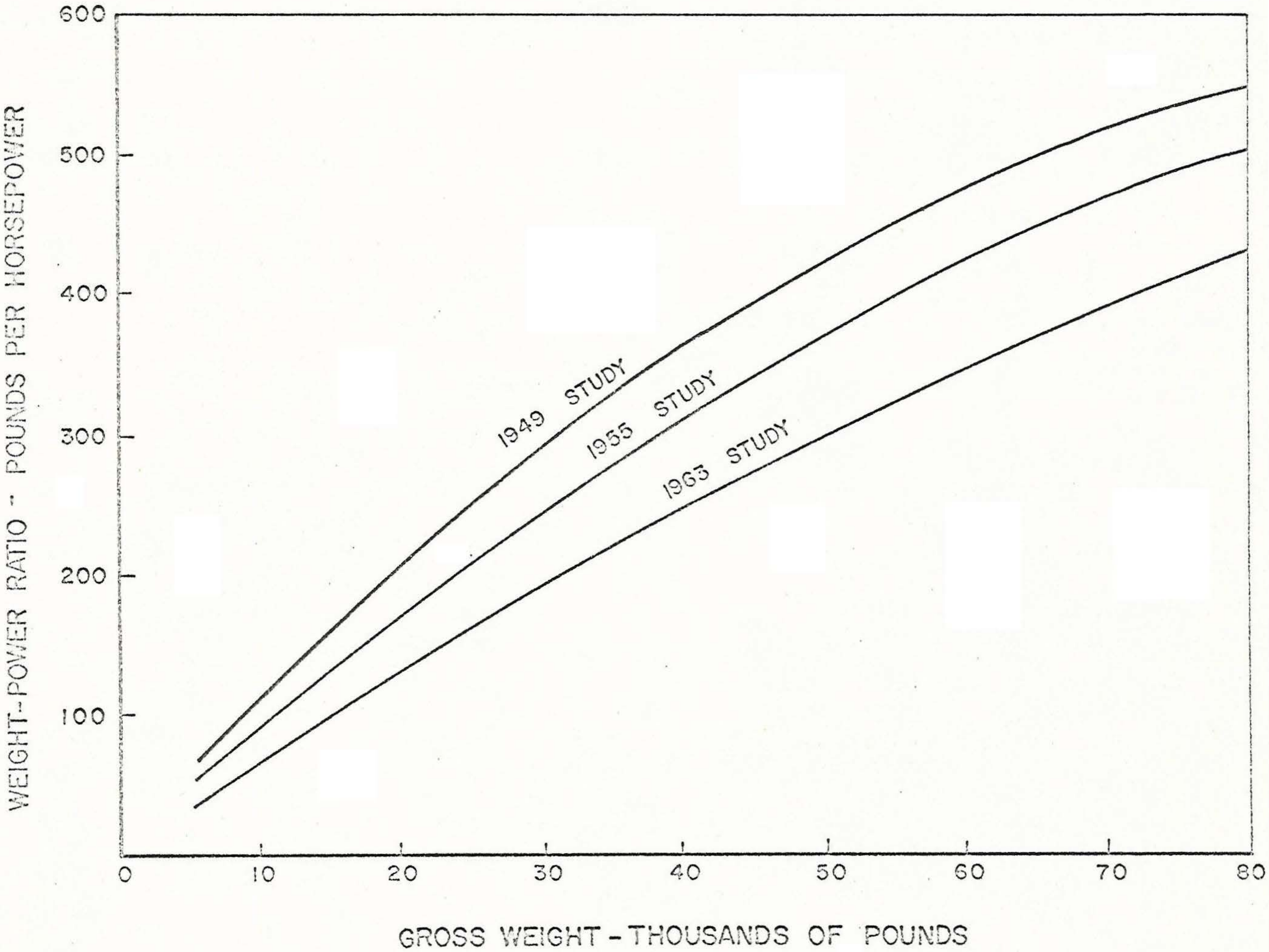


Figure 8. Trend In Weight-Power Ratio From 1949 to 1963 Based On Average Data For All Types Of Vehicles (11)

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 insure a maximum sustained speed of 15 mph on a three 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, resulting in an improvement of the weight-horsepower ratios of trucks over the last several years. 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 five percent or less, and decreases on downgrades of seven percent or steeper. On upgrades, the maximum sustained speed that a truck can maintain is dependent upon 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, wind resistance, and skill of the operator.

The "critical length of grade" is defined by the AASHO Policy as the maximum length of a designated upgrade upon which a loaded truck can operate without an unreasonable reduction in speed. If a truck is to reasonably operate on grades greater than "critical", 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, 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 the gradability data for this truck -- The 400:1 weight-horsepower

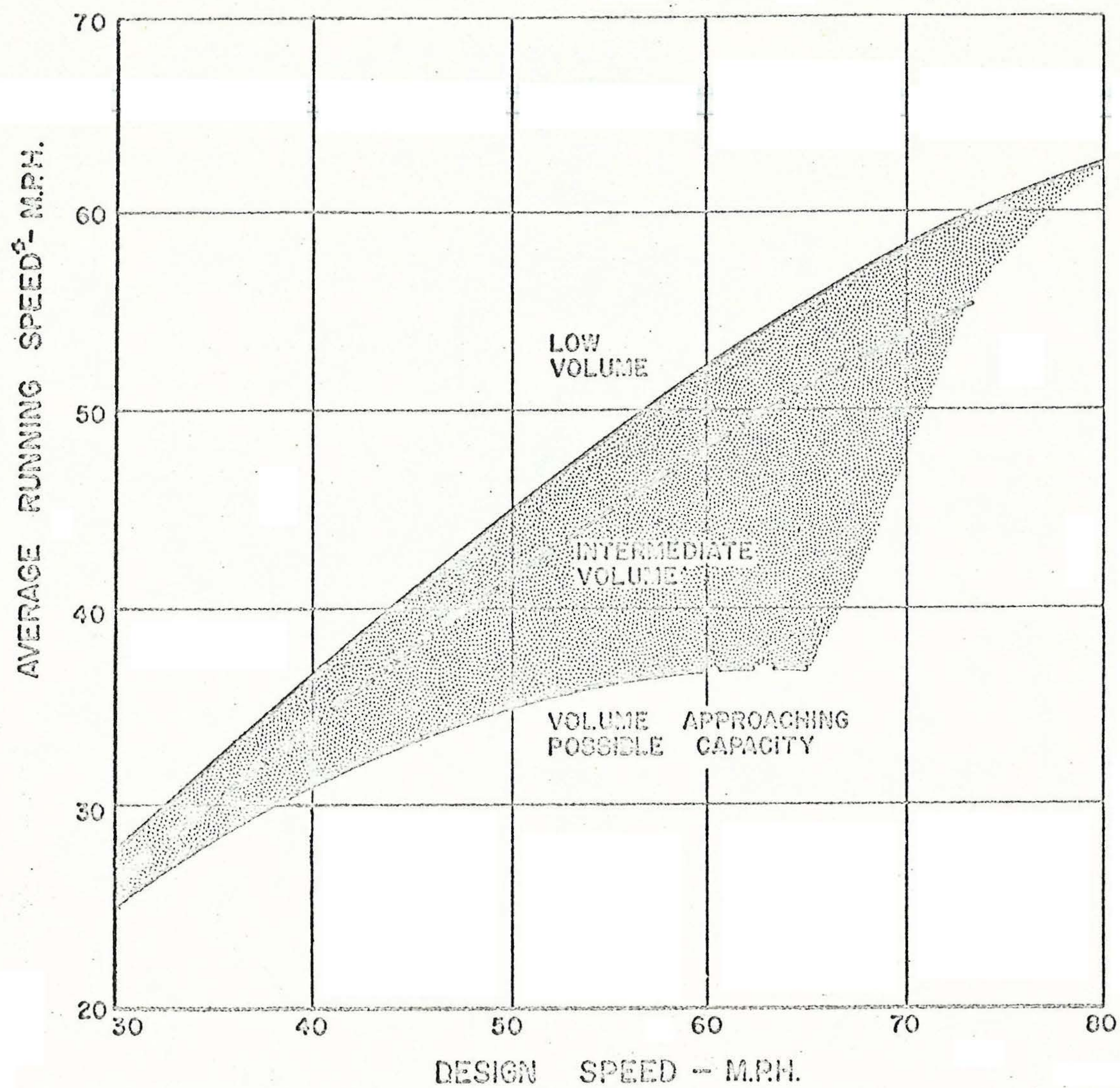
ratio is accepted as the national design vehicle; therefore, the gradability curves presented in Figures 4 and 5 are employed by the AASHO Policy.

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 (See Figure 9). For downhill or uphill approaches, the entering speed should be adjusted accordingly.

3. The minimum tolerable speed at which a truck should operate on the grade — Although no specific data is 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 on highways with a design speed of 40 to 60 mph would be tolerable for a vehicle unable to pass on a two-lane highway, provided the no-passing interval is short. As the volume on a two-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 to maintain a tolerable truck 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 presents the critical length of grade for different speed reductions on specific grades (derived from Figure 4). The 15-mph curve in Figure 10 is suggested by AASHO as a general design guide for establishing critical lengths of grades which are preceded by relatively level approaches. If there is an uphill approach to the grade, the critical length will be shorter and, for downhill approaches, the converse will be true.

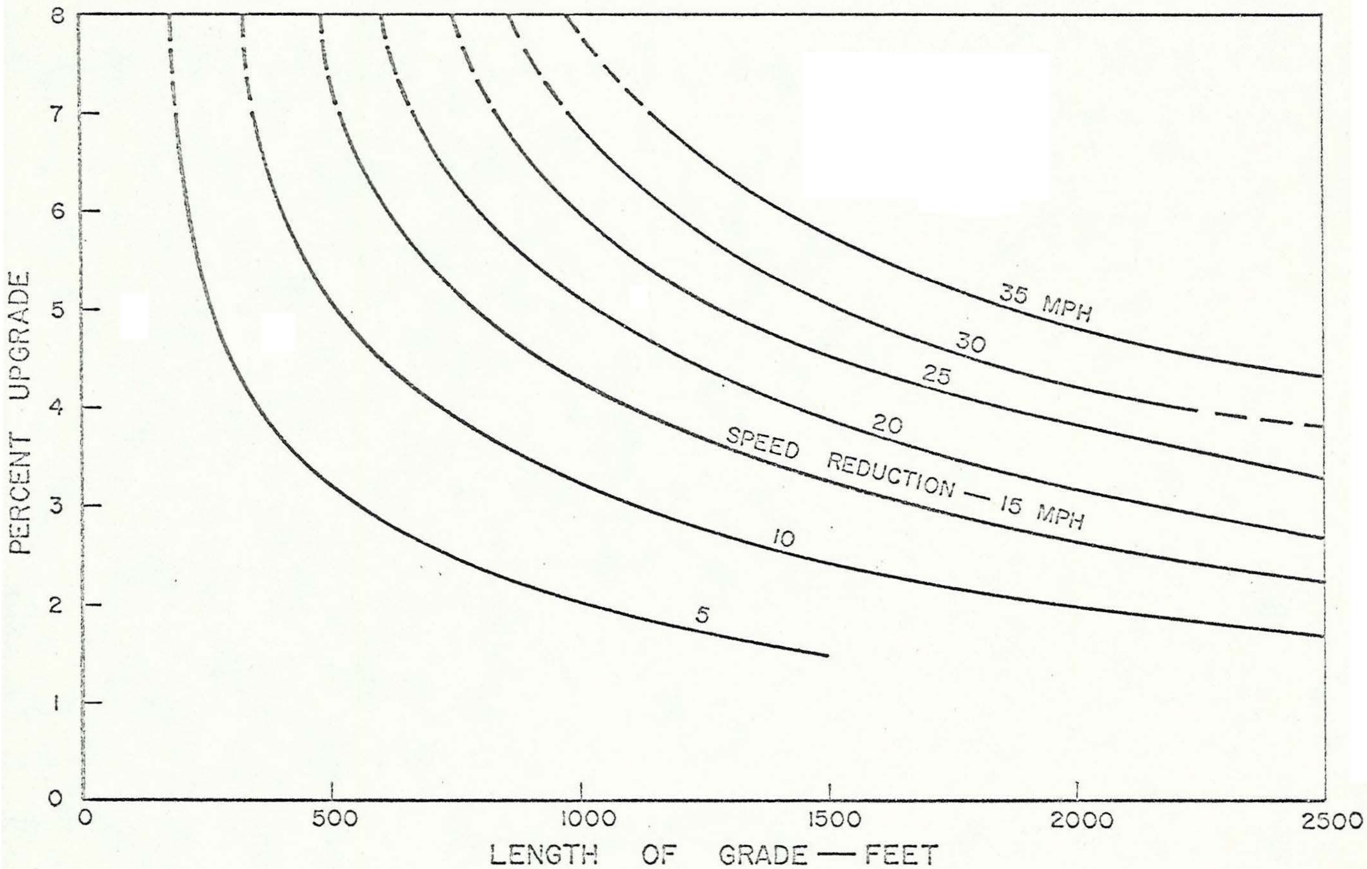
Climbing lanes may be justified from the standpoint of highway capacity, as well as truck gradability. The effect of trucks on highway capacity is primarily a function of the difference in average running speeds between trucks and passenger cars. Passenger car equivalents for trucks at various combinations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



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 - Relationship Between Average Running Speed and Design Speed - AASHO Policy



ASSUMED TYPICAL HEAVY TRUCK OF 400 POUNDS PER HORSEPOWER

Figure 10. Critical Lengths Of Grade For Design - AASHO Policy

TABLE 2

PASSENGER CAR EQUIVALENTS FOR TRUCKS AT VARIOUS AVERAGE TRUCK SPEEDS AS RELATED TO PASSENGER CARS FOR INDIVIDUAL GRADES ON TWO-LANE ROADS - AASHO POLICY (1)

	Number of Passenger Cars to Which One Truck is Equivalent		
Truck Speed, mph	For Average Passenger Car Running Speed of 45-50 mph	For Average Passenger Car Running Speed of 40-45 mph	For Average Passenger Car Running Speed of 35-40 mph
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

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 twenty percent. Table 3 shows the minimum design hour volumes for which climbing lanes should be considered.

The beginning of a climbing lane depends upon the entering speed of the truck on a grade. 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 feet 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 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 feet should be provided to allow the truck to reenter the flow of traffic.

A climbing lane should be at least 10 feet wide, preferably 12 feet. 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 3

THE AASHO POLICY'S MINIMUM TRAFFIC VOLUMES FOR CONSIDERATION OF CLIMBING LANES ON GRADES ON TYPICAL TWO-LANE ROADS

Gradient, percent	Length of grade, miles	Minimum two-way DHV including trucks (not passenger equivalents) for consideration of climbing lane for various percentages of dual-tired trucks			
		3% Trucks	5% Trucks	10% Trucks	15% Trucks
		4 lanes	4 lanes	4 lanes	4 lanes
	1/3	warranted	for DHV	over 600	over 525
	1/2	for DHV	over 700	550	450
		over 750			
4	3/4		670	500	390
	1	750	640	470	370
	1 1/2	730	610	440	340
	2	710	590	420	340
		4 lanes	4 lanes	4 lanes	4 lanes
	1/3	for DHV	over 640	over 550	over 480
	1/2	over 690	620	460	370
5	3/4	650	540	380	300
	1	630	510	360	270
	1 1/2	600	490	340	260
	2	600	480	330	250
		4 lanes	4 lanes		
	1/3	over 625	over 580	480	390
	1/2	570	470	330	250
6	3/4	540	430	290	220
	1	530	420	280	210
	1 1/2	520	410	270	200
	2	510	410	270	200
	1/3	470	410	310	240
	1/2	400	320	210	160
7	3/4	380	300	200	150
	1	360	280	180	140
	1 1/2	350	270	170	130
	2	340	260	160	120

NOTE: Detailed analysis of each grade is recommended in lieu of tabular values.

EVALUATION OF THE DESIGN CRITERIA

The purpose of this section is to evaluate the design criteria for climbing lanes and critical lengths of grade. This will include an evaluation of the state-of-the-art in the following areas:

1. Truck operating characteristics on grades,
2. The effect of weight-horsepower ratios on truck operating conditions,
3. Truck entering speeds, and
4. The speed reduction criteria as it relates to safe operations.

Truck Operating Characteristics on Grades

Truck gradability procedures have been developed to predict the performancé 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 300:1. Although Willey's observations may have been accurate at the time they were made, the report was not documented well enough to allow a verification of the number of heavily loaded trucks observed or what 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 truck ability prediction procedures.

Huff and Scrivner (6) developed a truck ability 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 ratio's 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, the smaller length of climbing lane that is needed, and the converse is also true. Table 4 lists 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 using the SAE Procedure (7) for Huff and Scrivner's test truck.

It can be seen from Table 4 that there is considerable disparity among the various prediction methods. The Huff and Scrivner values are the lowest, while the Firey and Peterson values are considerably higher than the others. The Huff and Scrivner values, however, are the only values that were substantiated using a design vehicle, one which had a representative weight-horsepower ratio; therefore, it appears that 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 eight 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. This can be shown by the fact that International Harvester offers only one out of five 8-cylinder engines for its heavy trucks, which would result

TABLE 4

GRADE VERSUS MAXIMUM SUSTAINED SPEED AS DETERMINED BY DIFFERENT GRADABILITY PROCEDURES

Grade	Willey	Huff and Scrivner	Firey and Peterson	SAE Procedure
%	MPH	MPH	MPH	MPH
1	NA	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

in a weight-horsepower ratio over 400:1. From all indications, it would seem reasonable to accept the 400:1 ratio as a design criteria.

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 Highway. Because the 15th percentile truck represents a reasonable lower boundry condition, the 47 mph entering speed is appropriate for design, when considering entry to a grade from a level approach.

Speed Reduction Criterion

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

The speed distribution of vehicles traveling the Texas Highways may be obtained from the Texas Highway Department (13). By utilizing this speed distribution and relating it to the accident involvement rates presented in Figure 11, the accident involvement rate may be obtained for 4-or-more-axle trucks operating on level grades. By assuming the reduction in the average speed of all vehicles on a grade 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 (See Appendix C).

The results of the analysis are presented numerically in Table 5 and graphically in Figure 12. It should be noted that most states base their climbing lane design on the criterion of a 15-mph reduction of

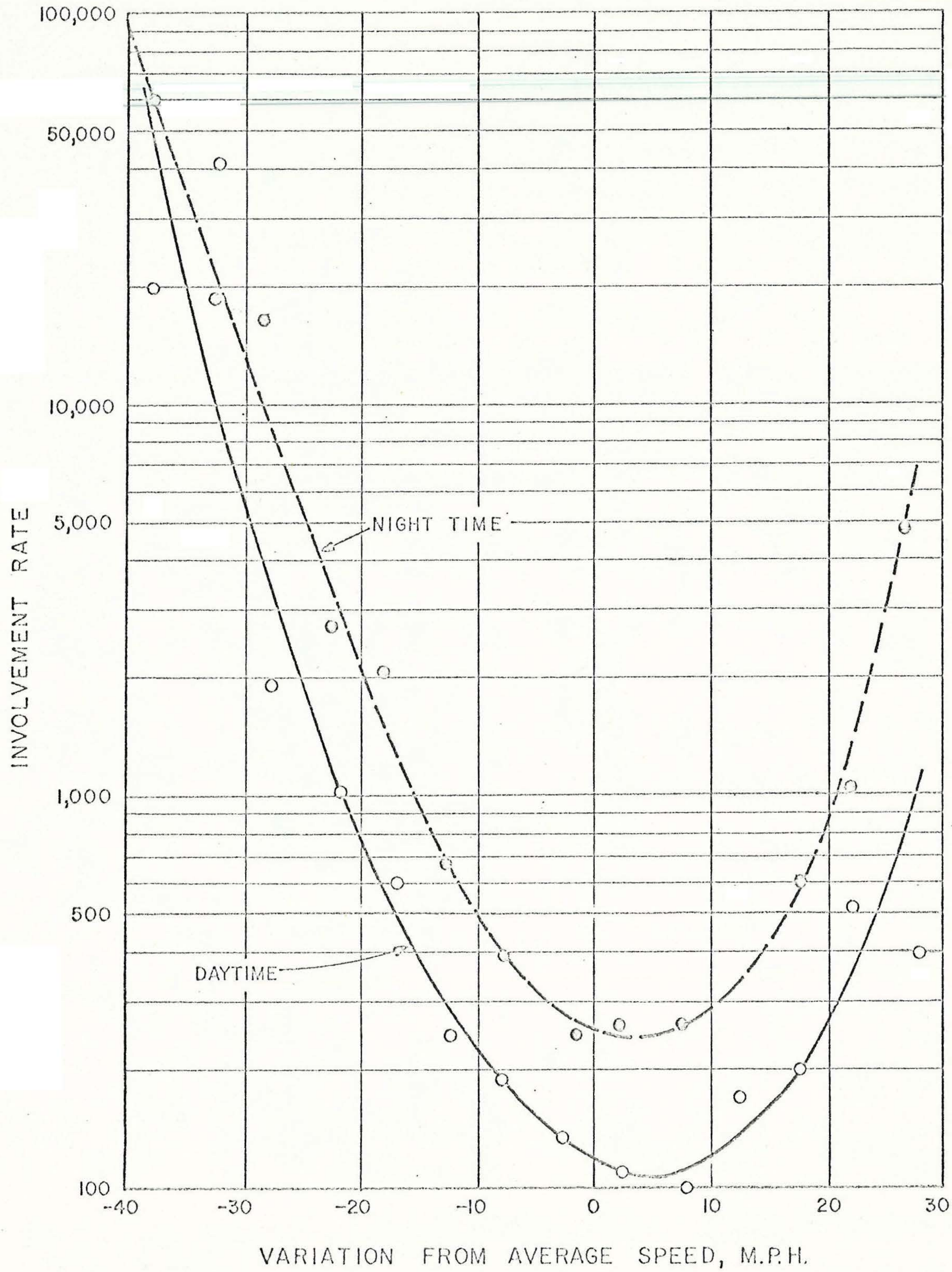


Figure 11. Involvement Rate By Variation From Average Speed On Study Section, Day And Night (14)

TABLE 5

Accident Involvement Rates On Grades Compared To The Variation From The Average Speed Of All Vehicles On A Highway

Speed Reduction	Accident Involvement Rate	Involvement Rate Ratio Related To 0 Speed Reduction
0	247	1.00
5	481	1.95
10	913	3.70
15	2193	8.90
20	3825	15.90

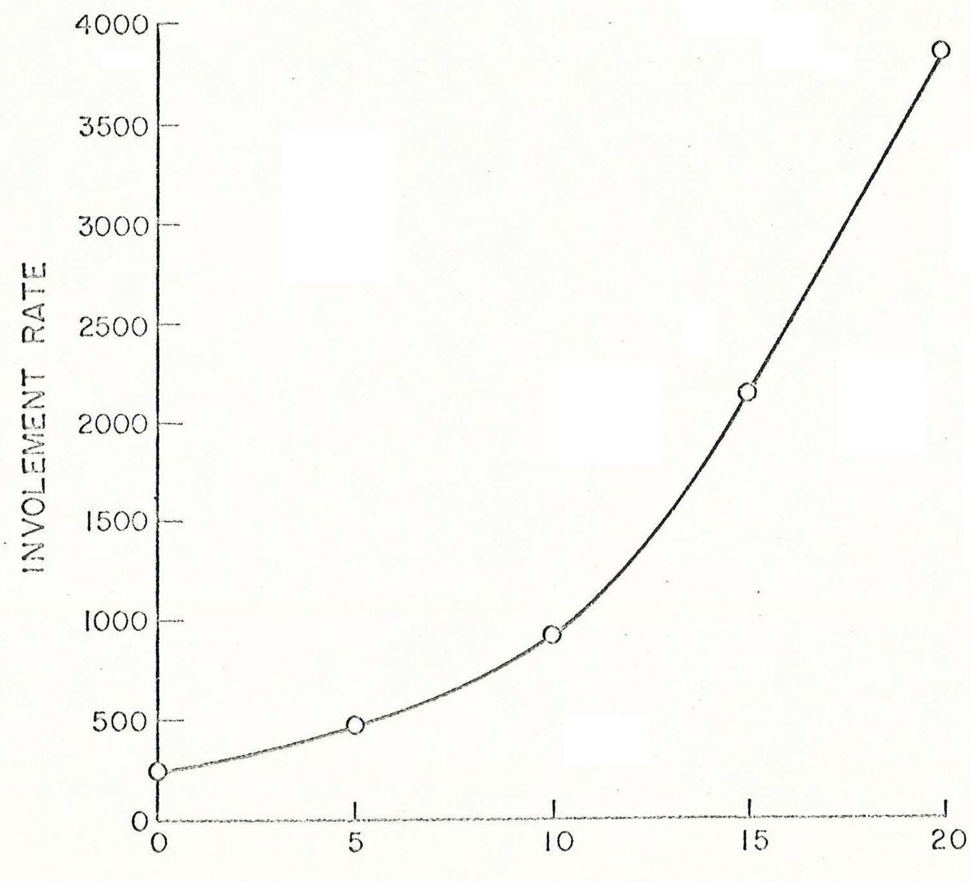


Figure 12: Truck Accident Involvement Rate Related to the Speed Reduction of the Design Vehicle.

truck speed. From Table 5, the accident rate for a 15-mph reduction is almost nine times the involvement rate for a zero mph reduction and approximately 2.4 times the rate for a 10-mph reduction. The accident involvement rate increases, in absolute terms, 1,280 from 10-mph to the 15-mph reduction. This is an increase of more than 5 times the increase from the zero 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. From Figure 10, it may be observed that a 5-mph decrease in the speed reduction criterion does not substantially increase the required climbing lane length for the steeper grades. This small increase in climbing lane length would be more than offset by the concomitant reduction of the accident involvement rate. These 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 which 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 in to the normal flow of traffic and then, in a short distance, removing the truck again.

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Appendix A

The Derivation of Huff and Scrivner's (6) 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:

$$\frac{W}{g}\frac{dv}{dt} = P - W \sin \Theta \qquad (1)$$

Dividing by W, Equation 1 becomes:

$$\frac{P}{W} = \frac{1}{g}\frac{dv}{dt} + \sin \Theta \qquad (2)$$

If it is stipulated that:

$$\frac{P}{W} = av + b \qquad (3)$$

Then by substitution, an equation is formed which does not contain P/W:

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

If $\frac{dv}{dt}$ is considered as the change in velocity with respect to time, $\frac{v_o - v}{t}$ and v is the average velocity, $\bar{v}$, then Equation 4 becomes:

$$\frac{v_o - v}{t} - ga\bar{v} + g\ (\sin \Theta - b) = 0 \qquad (5)$$

By multiplying by the time, t, and solving for $\bar{v}t$, Equation 5 may be written:

$$\bar{v}t = \frac{v_o - v}{ga} + \frac{gt(\sin \Theta - b)}{ga} \tag{6}$$

Any distance, x, may be measured by the average velocity multiplied by time; therefore, Equation 6 becomes the following:

$$x = \frac{1}{a} = \frac{v_o - v}{g} + (\sin \Theta - b)t \tag{7}$$

which is the first equation of Huff and Scrivner.

The second equation of Huff and Scrivner's may be derived by first solving for dt in Equation 4:

$$dt = \frac{dv}{g(av - \sin \Theta + b)} \tag{8}$$

If Equation 8 is integrated from t_o to t:

$$\int_{t_o}^{t} dt = \frac{1}{g}\int_{v_o}^{v} \frac{dv}{av - \sin \Theta + b} \tag{9}$$

and since $(\sin \Theta + b)$ is constant over any interval v_o to v, then Equation 9 becomes:

$$t = \frac{1}{ag}\int_{v_o}^{v} \frac{adv}{av + (-\sin \Theta + b)} \tag{10}$$

Then:

$$t = \frac{1}{ag} \ln \left(av + (-\sin \theta + b)\right) - \frac{1}{ag} \ln \left(av_o + (-\sin \theta + b)\right) \tag{11}$$

or;

$$t = \frac{1}{ag} \ln \frac{av - \sin\theta + b}{av_o - \sin\theta + b} \qquad (12)$$

Appendix B

The Derivation of a Simplified Speed-Distance Formula Using Huff and Scrivner's (6) 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, Equation 4, Appendix A, becomes:

$$\frac{v_o - v}{t} - ga\bar{v} + g\,(\sin\Theta - b) = 0 \qquad (1)$$

Dividing by the average velocity, $\bar{v}$, Equation 1 becomes:

$$\frac{v_o - v}{\bar{v}t} - ga + \frac{g(\sin\Theta - b)}{\bar{v}} = 0 \qquad (2)$$

Any distance, x, may be represented by an average speed times time, $\bar{v}t$; therefore, Equation 2 becomes:

$$\frac{v_o - v}{x} - ga + \frac{g(\sin\Theta - b)}{\bar{v}} = 0 \qquad (3)$$

Solving for x and substituting $\frac{v_o + v}{2}$ for $\bar{v}$, Equation 3 may be written:

$$x = \frac{1}{g}\,\frac{v_o^2 - v^2}{a(v_o + v) - 2(\sin\Theta - b)} \qquad (4)$$

Appendix C

An Analysis of 4-Axle Truck Accident Involvement Rates on Grades

This Appendix presents an analysis 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 for the Department of Commerce by Solomon (14) accident involvement rates were related to average running speeds of vehicles on a highway. It was concluded that regardless of the average speed on a highway, the greater a vehicle's deviation from this average running speed of all traffic, the greater 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 12 of this report.

Each year the Texas Highway Department's Planning Survey Division 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. The statewide average speed determined by the Texas Highway Department was assumed to be the typical average speed of all vehicles operating on level grades along a highway.

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

3. The involvement rate for each category was multiplied by the daytime graph of involvement rates versus deviation from the average speed (See Figure 15). The daytime graph was employed because it represented the lowest involvement rates and is considered to be conservation for this analysis.

4. All 4-or-more-axle trucks were assumed to decelerate in the manner shown in Table C-1.

5. The average speed reduction of all vehicles on a grade was assumed to be thirty percent of the average truck speed reduction on that same grade.

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 mid-point of each speed category was subtracted from the average speed of all vehicles to determine the difference from the average speed of all vehicles to determine the difference from the average speed.

3. The deviation in speed from the average for each category was used to determine the involvement rate for that category from the daytime graph of involvement rates versus speed variation (See Figure 12).

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 which 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, 2-5, were exactly the same. An example of the calculation procedure is shown in Table C-2 for the 15-mph speed reduction.

TABLE C-1

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, mph* 0	5	10	15	20
30-35	0	8	13	18	23
35-40	0	7	12	17	22
40-45	0	6	11	16	21
45-50	0*	5*	10*	15*	20*
50-55	0	4	8	12	16
55-60	0	3	6	9	12
60-65	0	2	4	6	8
65-70	0	1	2	3	4
70-75	0	0	0	0	0
Average Speed of All Traffic, mph	59.4	57.9**	56.4**	54.9**	53.4**

* Design truck operates within the 45-50 mph category.

** 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.

TABLE C-2

Involvement Rate Of 4-Axle Trucks With An Assumed Speed Reduction On Grades Of 15 mph Below The Speed On Level Grades

1* Average Speed	2* Truck Speed Categories	3* Mid Point	4* Difference From Average	5* Percent Of Total 4-Axle Trucks	6* Involvement Rate	7* Product 5x6
54.9	12-17	14.5	- 40.4	0.9	100,000	90,000
	18-23	20.5	- 34.4	3.9	17,000	66.300
	24-29	26.5	- 28.4	6.1	3700	22,570
	30-35	32.5	- 22.4	18.3	1180	21,594
	38-43	40.5	- 14.4	19.8	350	6,930
	46-51	48.5	- 6.4	37.4	175	6,545
	54-59	56.5	+ 1.6	10.0	118	1,180
	62-67	64.5	+ 9.6	3.4	123	4,182
	70-75	72.5	+ 17.6	0.2	200	40
				100.0		219,341

Involvement Rate = $\frac{219,341}{100}$ = 2193

1* Average speed of all vehicles on level grades less 30% of assumed reduction in truck speed on grades; 59.4-(.3)(15) = 54.9

2* Truck speed categories as determined by subtracting the assumed truck speed reduction found in table C-2 for the speed categories established by the THD's Planning Survey Division

3* The mid-point of each truck speed category

4* Difference of the average truck speed from the average speed, 1 minus 3

5* Percentage of total 4-axle trucks in each speed category as determined by the THD's Planning Survey Division

6* Involvement rate taken from Figure 15

7* Product of the percentage of total 4-axle trucks and the involvement rate for the speed differential for each speed category, 5 times 6