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16. Abstract

Prior to the initiation of this study there had not been a field study of actual truck and recreational vehicle performance, specifically their operating characteristics on critical highway grades, for several decades. The many changes in truck engine displacement and truck horsepower and the noticeable increase in the number of recreational vehicles indicated a need to reassess current climbing lane design practices.

This research study presents current data characterizing trucks (and combinations) and recreational vehicles on grades. Field data collected at several locations in central and east Texas were anlyzed, and speed-distance curves were developed for a range of grade profiles.

From an evaluation of the speed-distance curves for the designated "critical vehicles" (in the truck and recreational vehicle classes), composite critical length of grade charts were devised using a 55 mph approach speed and a range of speed reduction values. Based on this study these revised design charts are recommended for incorporation into current climbing lane design practice.

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SPEED OF VEHICLES ON GRADES

by

C. Michael Walton
Clyde E. Lee

Research Report Number 20-1F

Speed of Vehicles on Grades

Research Project 3-8-73-20

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

August 1975

PREFACE

This is the final report on Research Project 3-8-73-20, "Speed of Vehicles on Grades." In addition to quarterly reports submitted during the project life, a "State of the Art Review" was prepared and submitted (January 4, 1973). The authors acknowledge and extend their appreciation to the many individuals who have contributed to the research. In particular, the study supervisors wish to highlight the graduate research assistants who performed much of the work reported herein: Mark G. Goode, III; Arne Grimstaad; Ragan Broyles; and Abdulla Sayyari. Many undergraduate assistants were associated with the project and special note is given to Thomas Horne, Thomas Chmores, and Gordon Derr.

The administration of the State Department of Highways and Public Transportation, Mr. Harold Cooner of D-8 Design, and D-10 Research section all provided valuable assistance. Mr. Harold H. Dalrymple, formerly of the Center for Highway Research, perfected much of the electronic instrumentation employed in the field studies.

Without the contributions of the above and many others, this research would not have been as productive as we believe it to be.

C. Michael Walton
Clyde E. Lee

ABSTRACT

Prior to the initiation of this study there had not been a field study of actual truck and recreational vehicle performance, specifically their operating characteristics on critical highway grades, for several decades. The many changes in truck engine displacement and truck horsepower and the noticeable increase in the number of recreational vehicles indicated a need to reassess current climbing lane design practices.

This research study presents current data characterizing trucks (and combinations) and recreational vehicles on grades. Field data collected at several locations in central and east Texas were analyzed, and speed-distance curves were developed for a range of grade profiles.

From an evaluation of the speed-distance curves for the designated "critical vehicles" (in the truck and recreational vehicle classes), composite critical length of grade charts were devised using a 55 mph approach speed and a range of speed reduction values. Based on this study these revised design charts are recommended for incorporation into current climbing lane design practice.

KEY WORDS: climbing lanes, vehicle characteristics, trucks, recreational vehicles, vehicle speed-distance curves, weigh-in-motion, car-following.

SUMMARY

Based on the survey of actual operating characteristics of trucks, truck combinations, and recreational vehicles in the field, a set of composite speed-distance curves for a range of highway grades and composite critical length of grade curves for a range of speed reduction values are presented. The charts are based on an approach speed of 55 MPH instead of the older assumption of 47 MPH.

The new design charts reflect for the first time in many decades the collection of data from large samples of actual vehicles operating in the field and not the use of test vehicles. The resultant composite charts are recommended for adoption with integration into current climbing lane design practice.

IMPLEMENTATION STATEMENT

The efficiency and reliability of geometric design criteria, capacity analysis, and safe operation are of paramount importance to every highway engineer. It is necessary to verify these criteria periodically since road user behavior and vehicle operating characteristics are continually changing.

It was the purpose of this study to investigate the speed characteristics of various classes of vehicles operating on selected highway grades. The findings are reflected in an evaluation of current theory and design practice, and recommendations for alteration of standards are made.

The study included an evaluation of the operating characteristics of trucks and classes of vehicles, such as car-trailer combinations, not previously considered, and a resulting methodology for evaluation of the impact of these vehicles on design, capacity, and safety as related to speed characteristics on grades was developed. These findings and recommendations were coordinated with State Department of Highways and Public Transportation (SDHPT) design and traffic survey personnel to expedite implementation into departmental practice as warranted. The same information will be of interest to the Federal Highway Administration and in turn might lead to changes in AASHTO's present design criteria for climbing lanes.

The findings from this research effort have been incorporated in the preliminary revision of Part IV of the SDHPT Highway Design Manual by personnel in D-8 Design. Geometric design standards concerning vehicle operating characteristics on grades have been evaluated on the basis of actual field data. The benefits to be accrued include

(1) more efficient and economical design procedures for climbing lanes, freeway ramps, and other highway grades, based on vehicle operating characteristics;

(2) increased capacity of the highway systems;

(3) increased safety, convenience, and savings to the highway user; and

(4) vehicle operating characteristics of different classes of motor vehicles and vehicle combinations based on data gathered during this project, which will also lead to improved techniques for evaluating existing designs and making capacity analyses.

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CHAPTER 1. BACKGROUND AND LITERATURE SURVEY

The current criteria for the basic design of vehicle climbing lanes have been developed and augmented over the last four decades primarily on theoretical formulation and limited field observation.

The purpose of this study was to obtain new field data concerning operating characteristics on selected grades and relate these data to present and future geometric design standards for highway grades, with particular emphasis on the capacity and safety aspects of vehicle climbing lanes. The results of this project were revised design charts relating length of grade, percent grade, and vehicle performance.

BACKGROUND

Inasmuch as large transport trucks characteristically have the lowest engine power relative to their weight, their performance on grades has been regarded as critical to the safe and realistic design of highway grades. This section presents a chronological review of the development of highway grade and truck climbing lane design criteria.

Before the late 1930's there were few records of significant consideration of vehicle performance on grades. Carl C. Saal initiated the first major study of truck behavior on grades in 1938 and prepared a report in 1939 on the measurement of truck climbing ability on grades (Ref 41). In that report, the author presented and compared four methods for determining the hill climbing ability of trucks. These are

(1) actual grade tests,
(2) theoretical hill-climbing ability equations,
(3) acceleration tests, and
(4) dynamometer tests.

Actual grade tests are made by applying various loads to certain vehicles and observing the speeds that they can maintain. Saal concluded that this procedure is the most satisfactory and gives adequate results since one observes the test vehicle on actual grades, but it is rather laborious and expensive to conduct.

The hill-climbing ability of a truck is computed from engine torque and power curves. The performance formula is derived by equating the tractive effort to the rolling resistance plus the grade resistance, or

$$\frac{T \times E \times R}{r} = (W \times f) + (W \times G)$$

where

T = torque at a given engine speed, in-lb;

E = overall efficiency of the vehicle;

R = total gear reduction;

r = rolling radius, inches;

W = gross vehicle weight, lb;

f = coefficient of rolling resistance, lb/lb of weight;

G = grade, ft of rise/ft.

This formula, Saal concluded, will produce reasonably accurate results, provided that reliable factors for overall efficiency and rolling resistance at various speeds are available.

In the acceleration tests the drawbar effort available at various road speeds over the entire useful speed range is determined. The drawbar pull is a function of the acceleration at a specific road speed and the mass of the truck. Saal concluded that this method will yield accurate results at a reasonable cost.

The dynamometer tests measure the drawbar pull available over the entire useful speed range for each transmission gear. This device can produce accurate results quickly and in usable form, but it has a high initial cost, which limits its use to operations requiring the test of a large number of vehicles quickly.

From road tests conducted from 1938 to 1942 and subsequent theoretical analysis, Saal evaluated and tabulated the separate and combined efforts of grades, tractive effort, and gross vehicle weight on vehicle performance. In a report in 1942 (Ref 42), he suggested two possible ways to eliminate traffic congestion on grades:

(1) by providing facilities to enable faster vehicles to pass slower moving vehicles, including the construction of an additional lane on grades and the construction of highways with longer sight distances; and

(2) by increasing the speed of the slow-moving vehicles, which can be achieved by

 (a) reducing the grade rise,

 (b) increasing the vehicle power, and

 (c) reducing the vehicle gross weight.

Saal stated that each of the three latter methods might be uneconomical. The gross weight reduction would come totally from the payload, which might be uneconomical for the truck operation. An increase in vehicle power would still increase its initial and operational costs. A reduction in percent grade might be uneconomical from the road construction point of view. Consequently, he concluded that the provision of wider surfaces at the points of most serious congestion, which would allow faster vehicles to pass, was the most immediately acceptable solution.

In 1944, J. W. Stevens prepared a report for the Texas Highway Department (Ref 57) on velocity and time loss studies in connection with truck operations on overpass grades. He listed several factors that affect motor vehicle speeds on grades. In general, they were

(1) tractive effort exerted by the vehicle through the driving wheel,

(2) total tractive resistance of the vehicle, which includes rolling and air resistance, and

(3) the accelerating or decelerating forces caused by the grade on which the vehicle is operating.

These factors are related as follows:

$$TE = a(m+k) + GVW(f+g)$$

where

TE = net tractive effort, lb,

a = mean acceleration value, ft/sec^2,

m = mass of the vehicle $\frac{GVW}{32.2}$, lbm,

k = equivalent mass due to rotating parts of the vehicle, lbm,

GVW = gross vehicle weight, lb,

f = coefficient of tractive resistance, lb/lb,

g = rate of grade rise, ft/ft.

Time loss on a grade can be found by calculating the time required for the vehicle to travel the grade and the time required for the vehicle to travel at a given speed on a level road a distance equal to that of the grade. The difference is the time loss due to the grade. Stevens concluded that, where time loss is large, it is necessary to use preventive or remedial measures, such as reduction of grade rise or length, or the construction of an additional traffic lane in order to avoid congestion for the anticipated traffic density, which are similar to Saal's solutions.

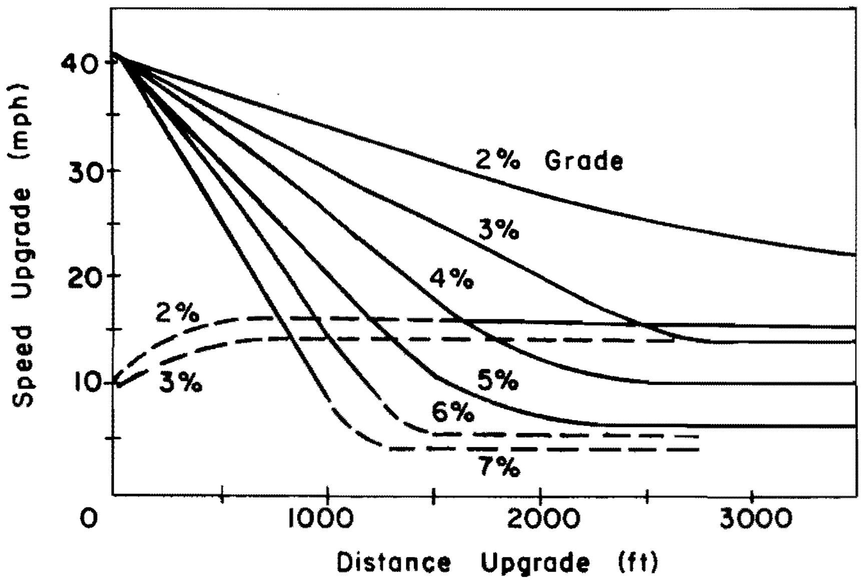
One year later, in 1945, A. Taragin, in a report prepared for the Highway Research Board (Ref 60), developed an equation similar to that used by Stevens. Taragin analyzed the data obtained through Saal's research in order to determine the effects of length of grade on truck speed. His analysis covered a wide range of grades, loads, and vehicle sizes. In the analysis, Taragin developed a series of speed-distance curves, shown in Fig 1, which depicted the effects of various grades - 1 to 7 percent - on truck performance. In the study, trucks were grouped into three weight classifications: heavy, medium, and light, depending on the net force available as tractive effort for the tested vehicles. Taragin's profiles were developed using the equation

$$1/2\left(\frac{W}{g} + K_n\right)\left(V_1^2 - V_2^2\right) \times 1.47^2 + TE \times L = W \times L \times (g+f)$$

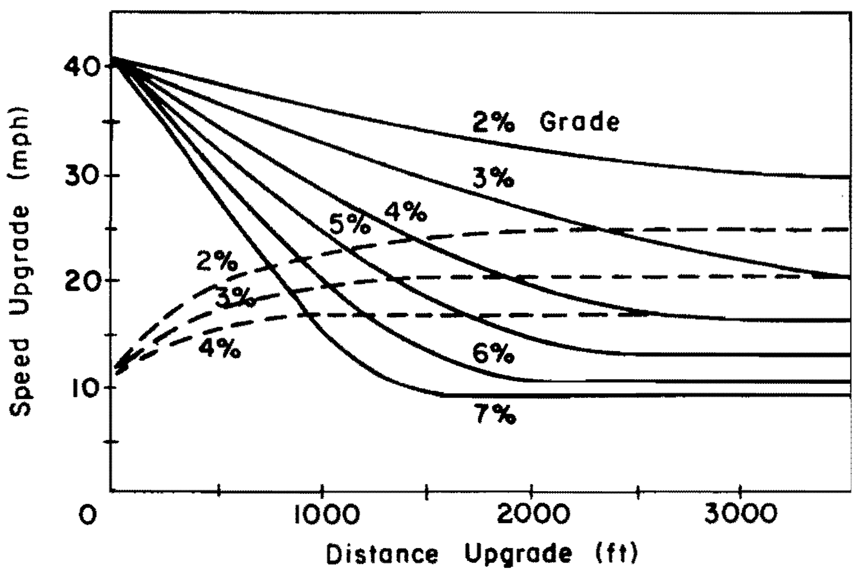
where

W = gross vehicle weight, lb;

K_n = mass equivalent constant, quantified in Saal's report, which compensates for the kinetic energy lost by rotating parts on the vehicle when it is accelerating;



(a) Light motor vehicles.



(b) Heavy motor vehicles.

Note: 40,000-lb Gross Weight Vehicle.

Fig 1. Effects of length of grade on speed of light and heavy motor vehicles (Ref 60).

V_1 = velocity at beginning of grade, mph;

V_2 = velocity at end of grade, mph;

TE = tractive effort, lb;

f = coefficient of tractive resistance;

g = percent grade, ft/ft;

L = length of grade, ft.

The principal assumption is that the change in kinetic energy plus the energy developed by the engine as the vehicle ascends a grade is equivalent to the energy required to overcome the grade plus the tractive resistance. When the tractive effort is greater than the combined effect of the tractive resistance and the grade resistance, the vehicle is accelerating. By solving for length of grade, a set of curves for the design of climbing lanes was derived, given an initial velocity and a percent grade. Taragin's curves formed the basis for the policy on the design of truck climbing lanes adopted by AASHTO (Ref 1) in 1954.

By 1949, William E. Willey (Ref 80) documented the performance of trucks on mountain grades through actual field observation of randomly selected survey vehicles. Grades considered for the survey ranged between 2 percent and 6 percent. The truck traffic in the area was about 10.8 percent of the total traffic. The survey trucks were grouped in two ways. The first classification was according to their weight-to-horsepower ratio; the second was according to their relative weights. Speed profiles similar to those produced by Taragin were developed for each grouping. The four weight-to-horsepower groupings selected were

(1) 100 lb or less/horsepower,
(2) 200-299 lb/horsepower,
(3) 300-399 lb/horsepower, and
(4) 400 lb or over/horsepower.

From the field observations, it was determined that the average approach speed from a level grade was 47 mph. Willey felt that the use of a weight-to-horsepower ratio grouping in the area of 300 or more offered a more consistent and usable classification. He developed gradability curves which represented the expected performance of a fully loaded heavy truck (over 300 lb/horsepower) ascending grades of various percentages (Fig 2). A fuel

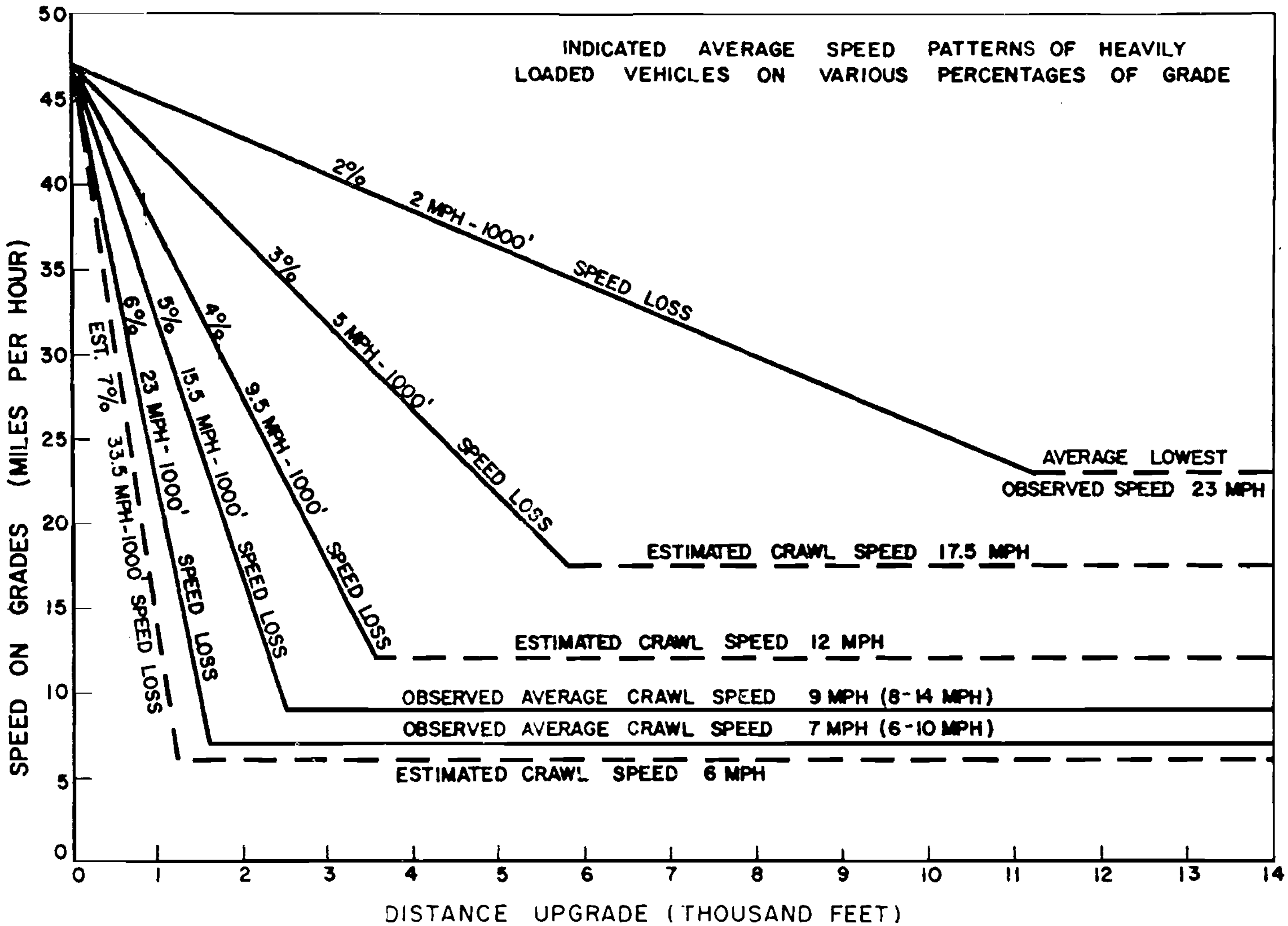


Fig 2. Heavily loaded truck gradability curve (Ref 80).

consumption and time loss study conducted by Saal in 1950 (Ref 43) demonstrated that vehicles of comparable weight-to-horsepower ratios have similar operating characteristics. In the conclusion to that survey, Saal indicated that driver habits, experience, and familiarity with the road had a significant effect on the performance of trucks on grades.

In 1955, T. S. Huff and F. H. Scrivner presented their simplified theory for the motion of heavy vehicles on grades (Ref 30). Using Newton's second law, they derived a general force equation for developing design curves (Fig 3) based on the following assumptions:

(1) There are no wind forces.

(2) Road surface resistance is constant or a function of velocity.

(3) The maximum sustained speed on the grade is used and acceleration is constant.

The mathematical reduction of the motion equation to a form suitable for the construction of speed distance curves is well documented by Glennon (Ref 27).

The design equations are as follows:

$$x = \frac{1}{a}\left[\frac{v - v_o}{g} + (\sin\theta - b)t\right]$$

and

$$t = \frac{1}{a \cdot g} \cdot \ln\left(\frac{a \cdot v + b - \sin\theta}{a \cdot v_o + b - \sin\theta}\right)$$

where

x = distance upgrade, ft,

a = constant,

v = velocity of vehicle, ft/sec,

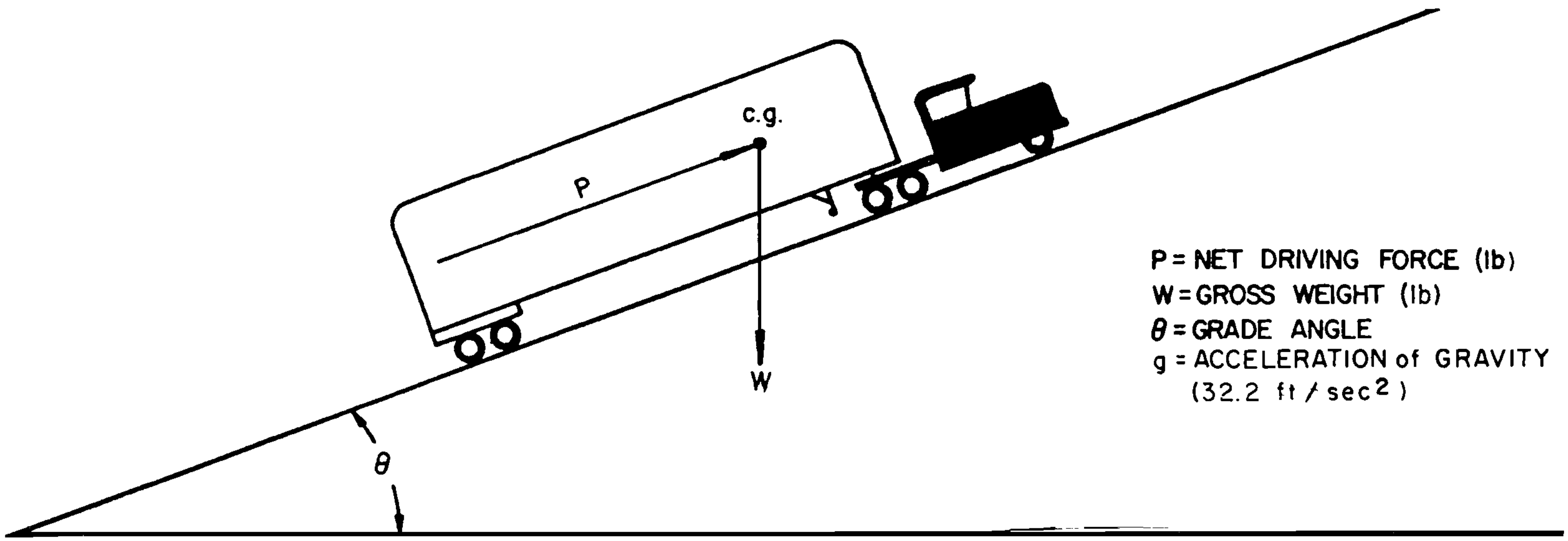
v_o = initial velocity of vehicle, ft/sec,

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

θ = grade, degrees,

b = constant,

t = time for the vehicle to cover the distance, sec.



MASS x ACCELERATION = FORCE

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

Fig 3. Truck ascending grade (Ref 30).

To compare actual truck performance on grades with their theoretical motion equations, Huff and Scrivner conducted road tests with a test truck having a weight-to-horsepower ratio of 391 to 1. Analysis showed that the accuracy of the simplified theory was adequate for use in climbing lane design procedures. Figure 4 shows the curves they developed from road tests.

Willey presented a report in 1955 (Ref 80) on truck congestion on uphill grades. In that report, traffic congestion observed before a planned climbing lane was built was compared with the congestion on the same section of roadway after the climbing lane was built. Willey recommended that such an auxiliary lane should be extended over the crest of the uphill grade for a sufficient distance to allow trucks to accelerate until obtaining the speed of the normal traffic.

Harry C. Schwender, O. K. Normann, and John I. Granum presented a new method of capacity determination in mountainous terrain in 1957 (Ref 48). The report outlined highway capacity analysis procedures for considering the effect of trucks. Truck factors (passenger car equivalencies) were calculated for three basic types of terrain: level, rolling and mountainous. An important conclusion by the authors was that from a capacity analysis standpoint, when an extra lane is provided on a highway section with a grade, traffic delay caused by trucks is reduced to zero (the truck factor equals zero), and the capacity of the normal highway grade section is the same as if there were no trucks. The benefits of providing climbing lanes at certain locations depend on traffic volume, percentage of trucks, length and steepness of the grade, and availability of passing sight distance.

Based on many of the preceding findings, recommendations, and conclusions, the Planning and Design Policies Committee of AASHO presented a new design policy for climbing lane design in 1965. The 1965 edition of the AASHO design procedures for rural highways (Ref 2, p. 193) stated:

> It has been found that trucks which have a weight-power ratio of about 400 have acceptable operating characteristics from the standpoint of the highway user. Such a weight-power ratio will assure a minimum speed reduction of about 15 mph on a 3 percent grade. There is evidence that the automobile industry would find a weight-power ratio of this magnitude acceptable as a desirable goal in the design of commercial vehicles. There is also evidence that the carrier operators are voluntarily recognizing this ratio as an acceptable performance control in the loads placed on trucks of different power with the overall result that the weight-power ratio of trucks on highways has improved in recent years.

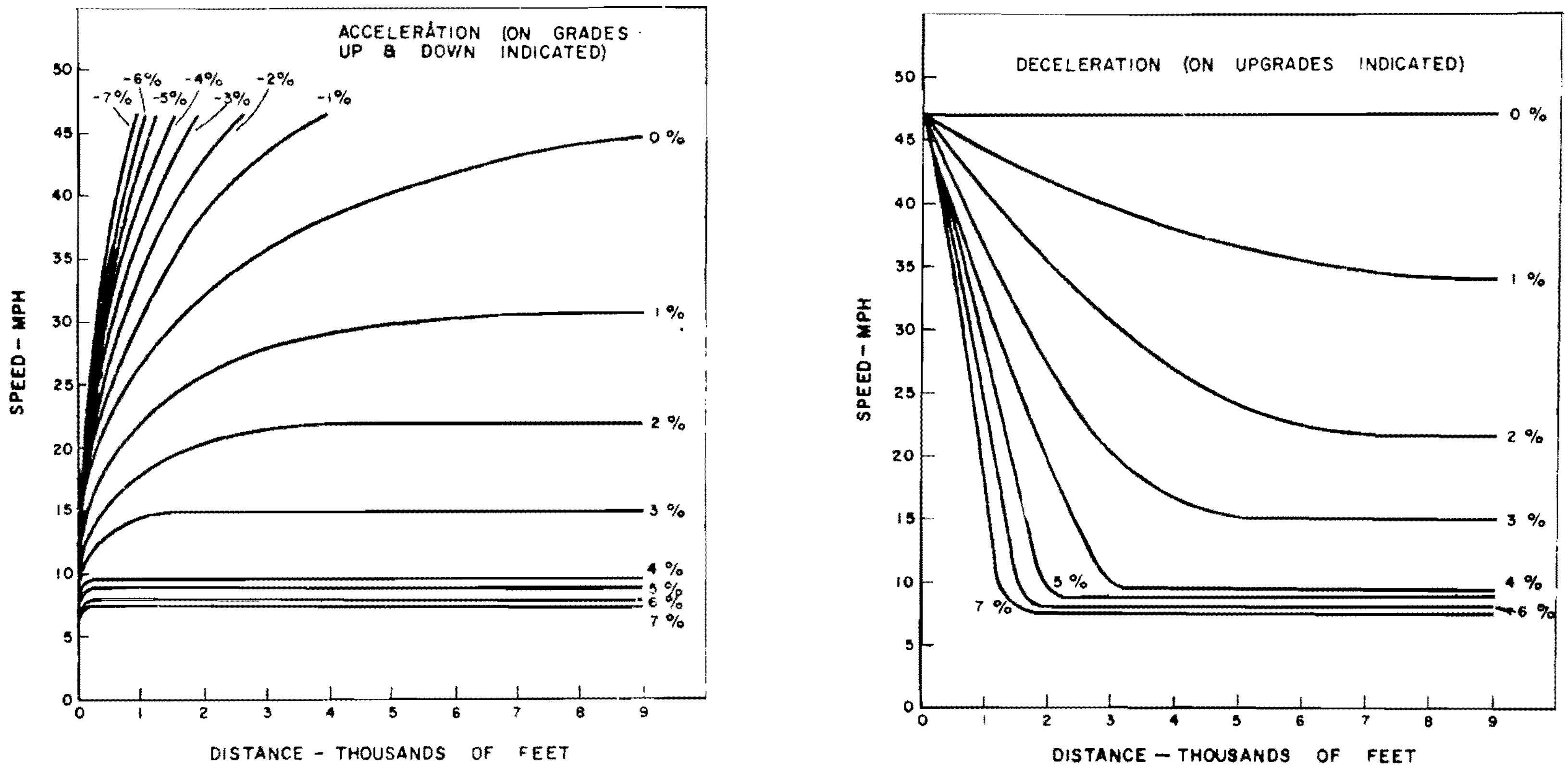


Fig 4. Speed-distance curves from road test of a typical heavy truck operating on various grades (Ref 2).

Cumulative frequency distributions of weight-power ratios of all commercial vehicles weighed in a nationwide brake performance study in 1963 and presented by Wright and Tignor in 1964 (Ref 85) showed that 80 percent of all vehicle combinations with five or more axles had a weight-to-horsepower ratio of 400 to 1 or less. Realizing that there was a trend towards an increase in the number of large trucks, AASHO felt the "prudent" and safe policy to adopt was to use a weight-to-horsepower ratio of about 400 in creating the design curves for determining the critical length of grade. Huff and Scrivner's speed-distance curves became the basis for the 1965 AASHO policy for climbing lane design (Fig 5).

The design chart is used to determine a critical length of grade, given a percent grade and a maximum desirable reduction in speed. The "critical length of grade" is the maximum distance up the grade over which an undesirable reduction of speed of a typical heavy truck will occur. AASHO recommends an allowable speed reduction of 15 miles per hour below the average running speed of the highway as critical. This applies to grades with a level approach. As stated in the policy on design (Ref 2):

> This (15 mile per hour reduction) corresponds to a minimum tolerable truck speed varying from four-tenths of the design speed for 30 mph to six-tenths for 80 mph.
>
> Average running speeds on level sections of highways are about 6 mph lower for trucks than for all vehicles. However, it is known that most truck drivers generally increase speed in approaching an upgrade when feasible, so it can be assumed that the speed of trucks in such instances is the same as for all vehicles.

If it is determined from the design chart that a 15 mile per hour reduction will be reached on a given grade, the AASHO policy on design states that the climbing lane should begin at the point at which the speed of the design vehicle will be reduced to 15 miles per hour below the average running speed. By using the representative acceleration curves (Fig 5) the point at which the extra lane should end can be established: it is that point after the crest of the grade at which the design vehicle will have theoretically regained sufficient speed to enter the traffic stream without hazard or where the sight distance is sufficient to permit passing with safety.

Justification for an auxiliary lane where critical length of grade is exceeded may also be considered from the standpoint of highway capacity.

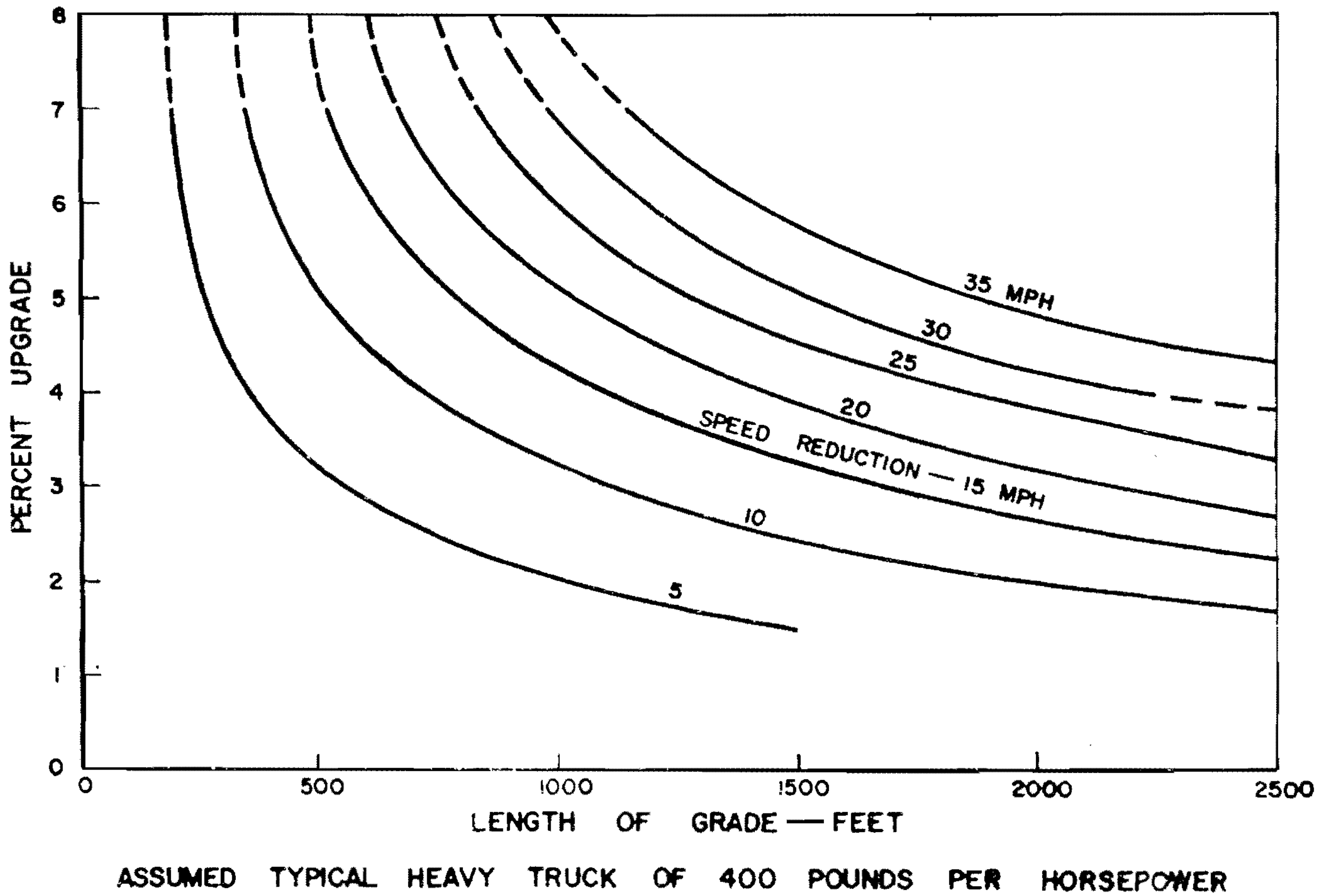


Fig 5. Critical length of grade for design (Ref 2).

Congestion occurs usually when the design hourly volume (DHV) exceeds the design capacity of the individual grade by more than about 20 percent.

The effect that trucks have on capacity is primarily a function of the difference between the average speed of trucks and the average running speed of passenger cars on the highway. Table 1 shows the AASHTO recommended minimum traffic volumes for consideration of climbing lanes on grades for typical two lane roads (Ref 2). However, AASHTO states that there are so many variables involved that few, if any, given sets of conditions can be properly described as "typical." For this reason a detailed analysis of each individual grade is recommended wherever climbing lanes are being considered.

In another study of warrants for climbing lanes in 1967, Williston (Ref 83) determined the effects of upgrades on mixed traffic encountering three different percent grades at separate sites. Vehicle classifications in this study were regular passenger cars, compact passenger cars, panel and pickup trucks, single-unit trucks, and tractor-trailer combinations. Vehicle speed was measured under normal conditions with radar speed-meter equipment. The mean speeds of the various vehicle classifications on the three grades are shown in Figs 6, 7, and 8. Williston plotted the curves from existing warrants on the same graphs.

Williston (Ref 83) observed that truck crawl speeds in the Connecticut region had increased substantially since the establishment of existing deceleration curves, and concluded:

> If trucks in the future continue to increase in speed as much as they have in the past, the need for truck climbing lanes where approach speed is in the category of 50 - 60 mph, such as those found on almost all 4 -,6 -, and 8 - lane expressways, will be significantly reduced.

However, he pointed out that more research was needed on various grades where a lower average approach speed existed. Such data, it was concluded, are needed to establish warrants for truck climbing lanes at lower speed limits for secondary highway systems.

One of the newest publications on climbing lane design is a report by John Glennon (Ref 26) published in 1970. Analyzing design criteria for climbing lanes from a safety aspect, Glennon suggested lowering the 15 mile per hour speed reduction criterion recommended by AASHTO to 10 miles per hour. In effect, this would increase substantially the requirement for additional

TABLE 1. MINIMUM TRAFFIC VOLUMES FOR CONSIDERATION OF CLIMBING LANES ON GRADES ON TYPICAL TWO-LANE ROADS (REF 2)

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			
		T=3%	T=5%	T=10%	T=15%
		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
4	3/4	over 750	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.

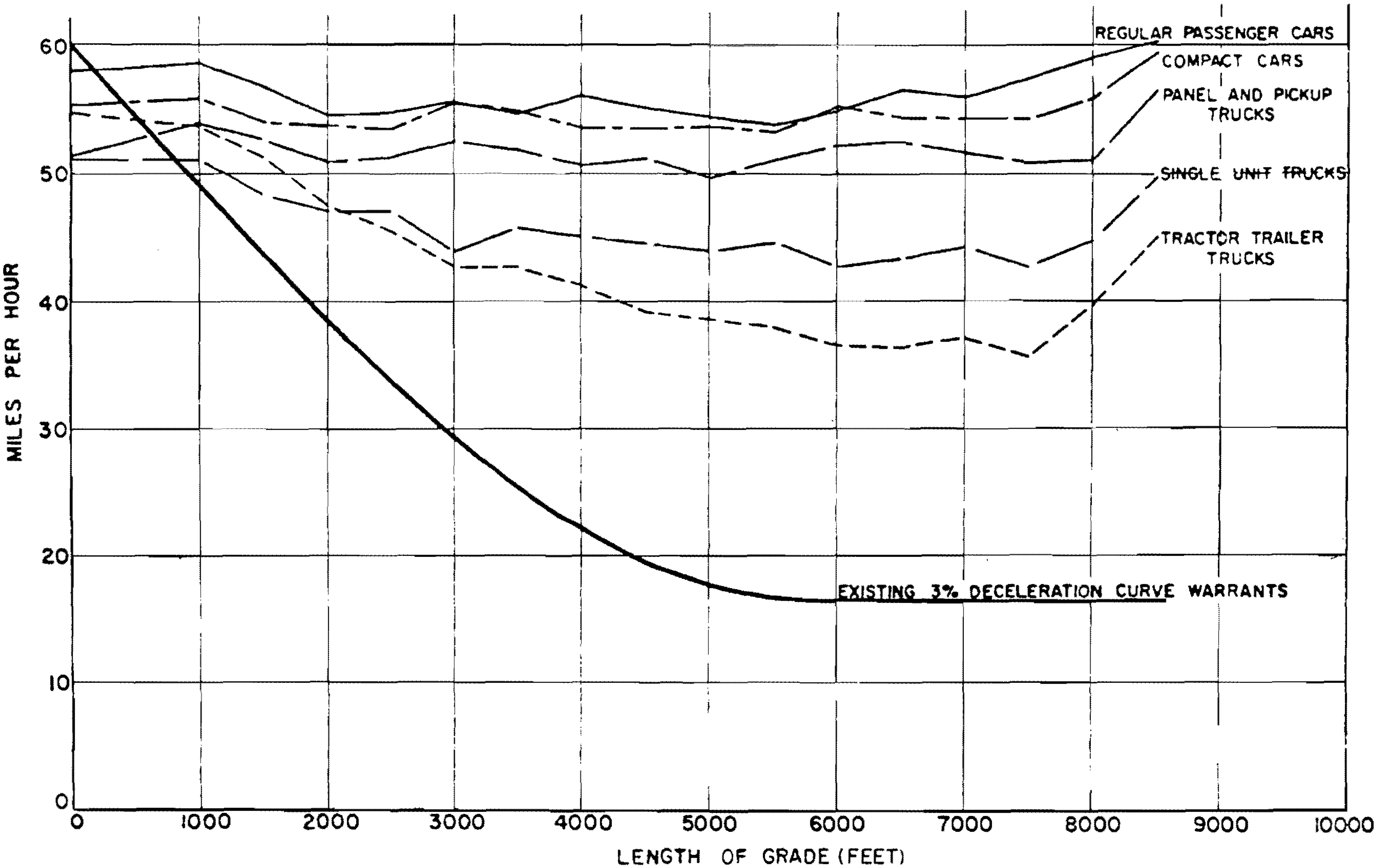


Fig 6. Deceleration comparison curve for a 3 percent grade (Ref 83).

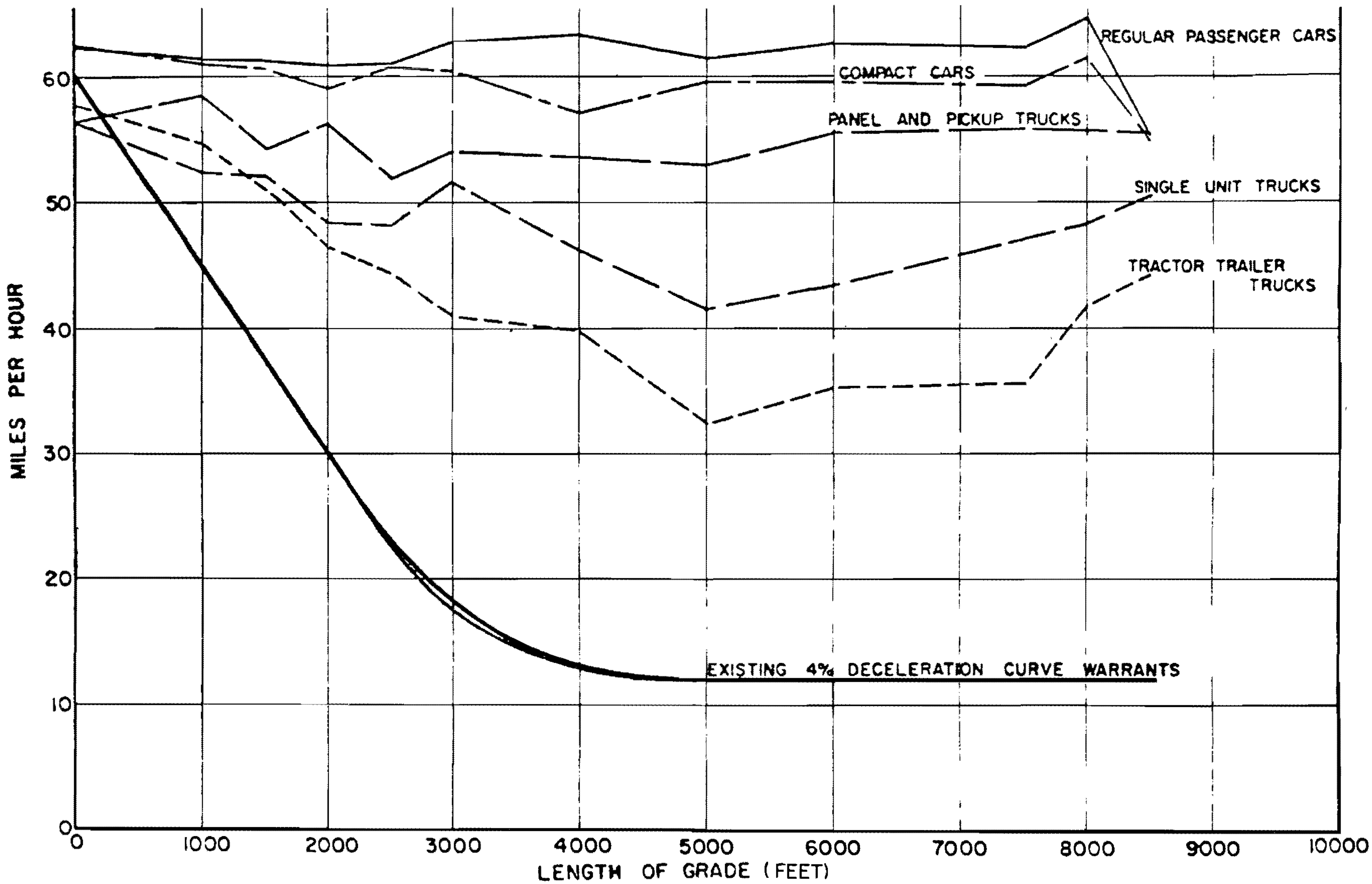


Fig 7. Deceleration comparison curve for a 4 percent grade (Ref 83).

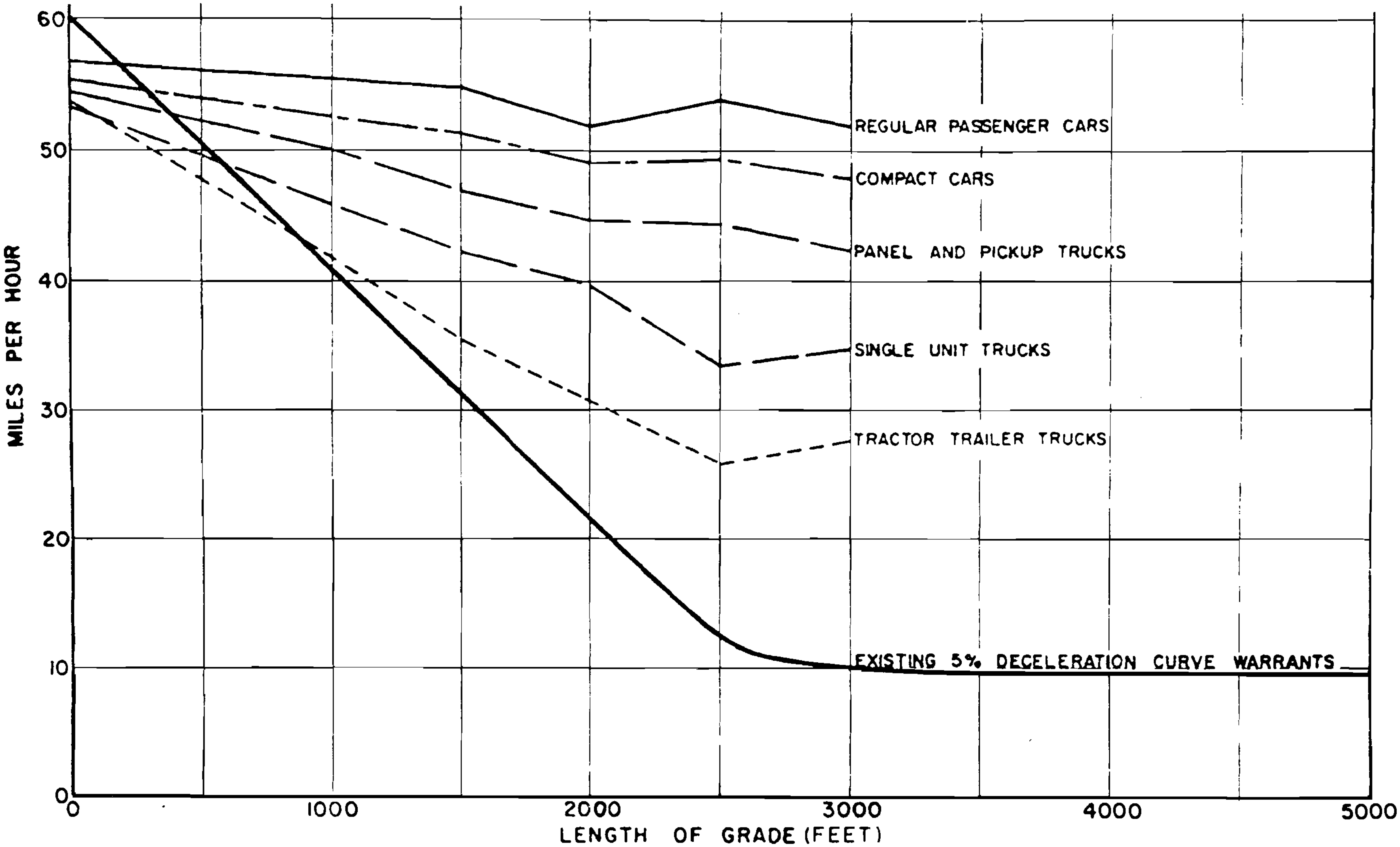


Fig 8. Deceleration comparison curve for a 5 percent grade (Ref 83).

climbing lanes based on current design charts.

Figure 9 shows the accident involvement rate with respect to the variation from the average highway speed.

SUMMARY

Most previous research on truck hill-climbing ability has been directed toward measurement of the elements that affect vehicle performance on grades. In most of the studies, vehicle performance was examined in detail. The roadway conditions including rolling resistance were considered by Taragin (Ref 60) in his theoretical equation. Traffic conditions were considered by Schwender, Normann, and Granum (Ref 48).

The current AASHTO policy is based on data collected in 1954. The State Department of Highways and Public Transportation design policy for climbing lane design is based on the AASHTO policy with more generous tapered sections specified. Figure 10 shows SDHPT acceleration and deceleration curves.

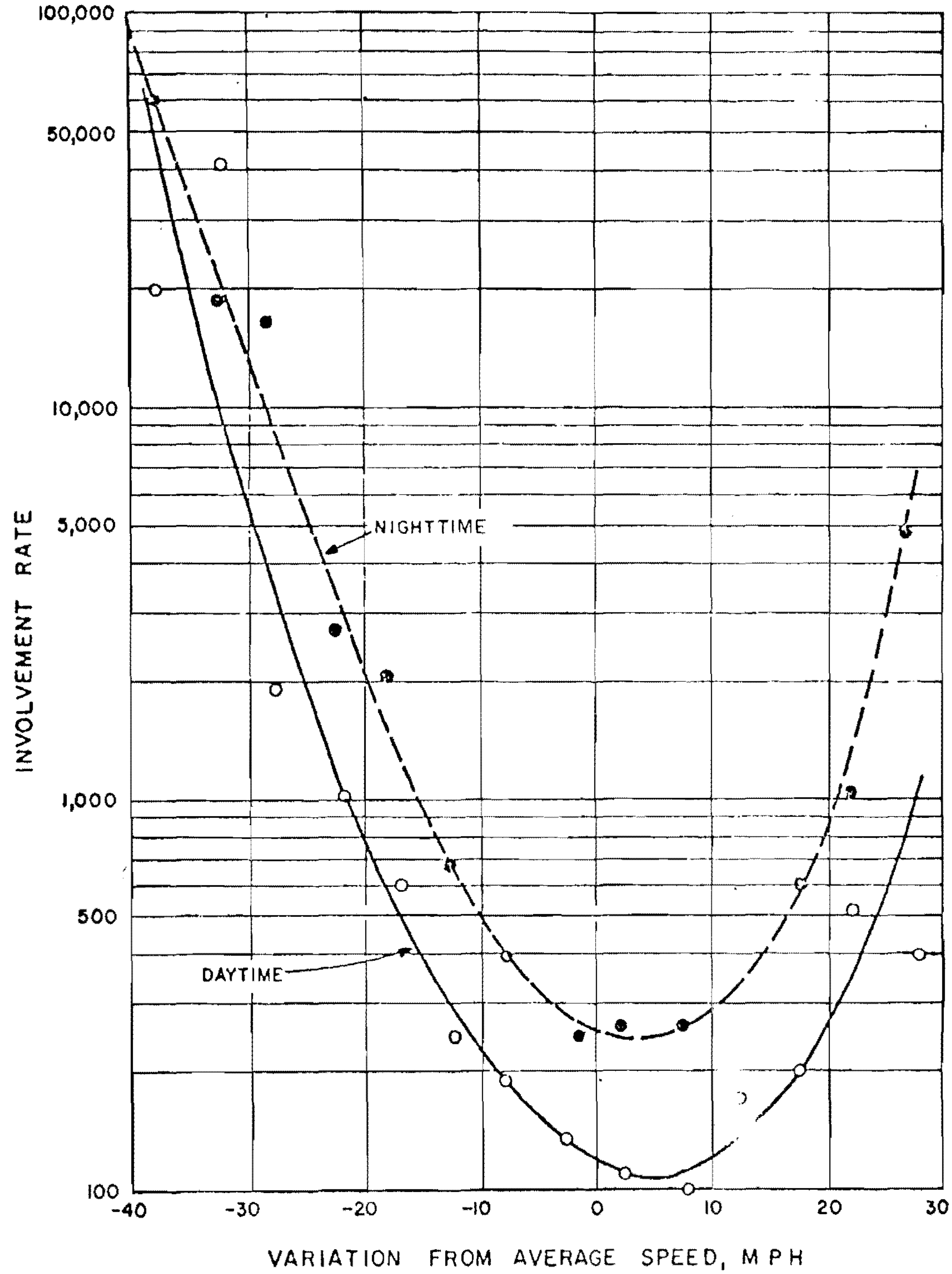


Fig 9. Accident involvement rate by variation from average speed during day and night (Ref 54).

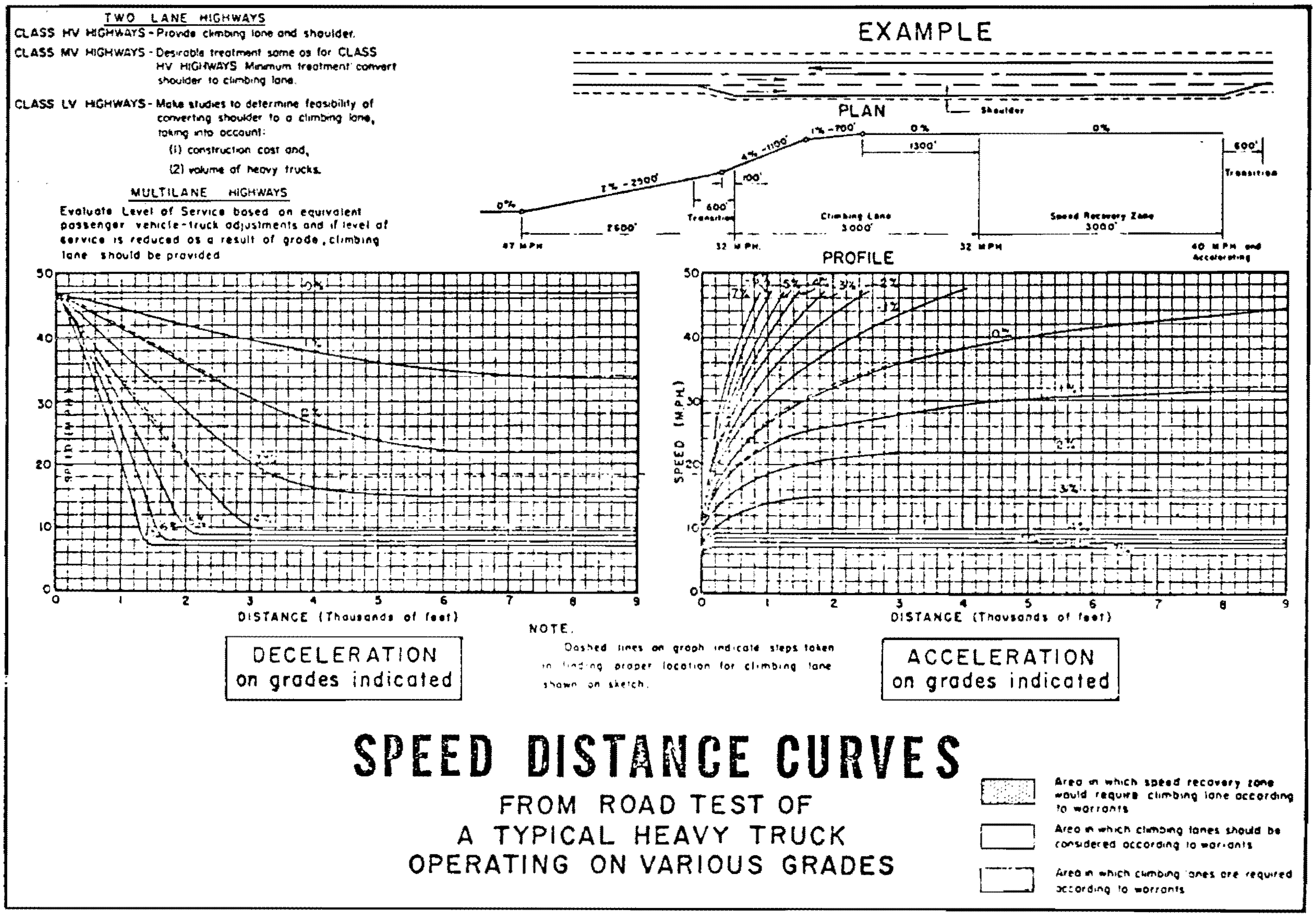


Fig 10. State Department of Highways and Public Transportation climbing lane design procedure (Ref 67).

CHAPTER 2. PHYSICAL ELEMENTS INFLUENCING VEHICLE OPERATION ON A GRADE

The performance of any vehicle operating on a highway differs to some degree from that of every other vehicle. The performance of each vehicle is a function of the interaction of numerous variables associated with four principal elements which govern vehicular motion. These four elements are the vehicle, the roadway, the environment in which the vehicle operates, and the behavioral aspects of the vehicle operator. This chapter contains a brief investigation into the potential influence of each of these four elements on the performance capabilities of a vehicle.

THEORETICAL FORCE SYSTEM

The result of the interaction between the physical elements governing vehicle motion is explained by the theoretical force system which works on the vehicle while it is in motion. This theoretical force system is a dynamic mixture of two principal types of forces: the tractive resistance forces and the tractive effort forces. The tractive effort forces are the pulling forces generated through the power train of the vehicle and delivered to the drive wheels. The magnitude of the force is generally governed by the engine power, transmission gear ratios, and efficiency of the remainder of the drive train of the vehicle. The tractive resistance forces are forces from internal and external sources acting on the vehicle which restrict the movement of the vehicle. The principal tractive resistance forces (Ref 77) are

(1) rolling resistance,
(2) grade resistance,
(3) wind resistance,
(4) inertial resistance, and
(5) the internal resistance from vehicle accessories and vehicle friction.

The resultant of these two principal types of forces is directly related to the ability of any vehicle combination to overcome any given grade.

An analysis of the tractive resistance and the tractive effort forces reveals that each of these forces is a function of one or more factors related to the driver, the vehicle, the roadway, or the environment. It should, therefore, be feasible to represent each of these theoretical forces by data which describe the field performance of selected vehicles operating under a variety of known conditions representative of those expected in the driver-roadway-environment system. In order to design an experiment that will yield the most meaningful data, each of the four basic system elements must be analyzed, and the proper means of representing each must be selected.

DRIVER

The driver is one of the most important and least consistent elements to be dealt with in highway design. Because of the variation of experience, ability, and habits among the multitude of drivers on the road, a realistic representation of driver characteristics in most design procedures is difficult.

In climbing lane design, the effect of driver characteristics can be more crucial than in other areas of design. The complexity and sensitivity of the operation of heavy vehicles with limited pulling capabilities can be a considerable burden on the untrained or inexperienced operator. The performance capabilities and the ultimate speed at which a heavy vehicle can overcome a grade are, in many ways, dependent on the ability of the driver to coax the maximum pulling force from the vehicle (Ref 29). A skilled operator can minimize the speed loss on a grade and thus reduce the detrimental effect of the grade on vehicle operation.

Some of the driver characteristics which are most likely to affect the performance of a vehicle are

(1) the physical abilities of the driver,
(2) his training and experience, and
(3) his familiarity with the vehicle.

The problem of driver inexperience and lack of training can become noticeably more acute when heavier vehicles are operated by a novice. Such is the case in the operation of many types of recreational vehicles and large rental commercial vehicles which require only an operator's license to legally operate the vehicle (Ref 74). Although competent as an operator of passenger cars, an individual may, because of inexperience, not be able to operate heavier vehicles with limited pulling capabilities efficiently. This inefficiency may have a direct, and sometimes dramatic, influence on traffic operation on grades.

VEHICLE

The vehicle itself is another complex and important variable influencing traffic performance on grades. To some extent every theoretical force, tractive effort or tractive resistance, acting on the vehicle is a function of one or more vehicle characteristics. The vehicle characteristics which are most likely to affect the vehicle's performance are

(1) the gross vehicle weight,
(2) vehicle power train characteristics, and
(3) physical dimensions.

Each of these can be further examined.

Vehicle Weight

The fact that the gross weights of trucks and certain recreational vehicles are much higher than those of passenger cars is one of the primary factors leading to the reduction of the operating speed of these heavier vehicles on grades. The greater weight manifests itself in the form of increased rolling resistance, grade resistance, and inertial resistance.

Power Train Characteristics

The ultimate speed maintenance capabilities of a vehicle are dependent on the balance between the tractive effort forces generated through the vehicle's power train and the resistance forces acting on the vehicle. It is therefore necessary that the power output capabilities of the vehicle be identified in order to characterize its hill climbing ability.

The production of the force necessary to move a vehicle is a complex activity. It is, in general, a function of the torque producing capacity of the engine, the gear reduction ratio of the transmission, the number and configuration of axles, and other force diverting variables associated with the vehicle power train (Ref 19).

Physical Dimensions

Although minor in comparison to the effect of certain other vehicle characteristics, many aspects of the physical shape and dimensions of a vehicle can influence its performance capabilities. The characteristics which should be considered are the length, shape, frontal area of the vehicle, and number and configuration of axles. These features generally determine the amount of air resistance to which a vehicle is subjected. For example, the air resistance on a panel truck would be significantly greater than for a flat-bed truck of equal length, due to the difference in trailer shape and surface area.

ROADWAY

The operating characteristics of motor vehicles are also greatly affected by various aspects of the roadway upon which the vehicle operates. In general, the resulting operating characteristics will be a function of the driver's choice of operating speeds under the various roadway geometric conditions and the magnitude of the resistive forces acting upon the vehicle due to these geometric features.

Some of the roadway features most likely to influence vehicle operation are

(1) length and steepness of grade,
(2) cross section features,
(3) horizontal alignment, and
(4) pavement type.

Length and Steepness of Grade

The most significant vertical alignment features in the geometry of a highway in regard to vehicle performance are the length and steepness of the grades. As illustrated by the gradability curve of Fig 4, the speed change rate for heavy vehicles on a grade is directly proportional to the steepness of the grade, and the total speed reduction is proportional to the length of the grade. Typical values for speed reduction rates are given in Table 2, along with the respective crawl speeds.

TABLE 2. SPEED REDUCTION PER 1000-FOOT LENGTH OF GRADE FOR HEAVILY LOADED TRUCK (AFTER REF 2)

Percent Grade	Speed Loss (mph)	Crawl Speed (mph)
2	2.0	23.0
3	5.0	17.5
4	9.5	12.0
5	15.5	9.0
6	23.0	7.0
7	33.5	6.0

Cross section Profile

The effect of several elements of the cross section of a roadway should be considered in evaluating the vehicle operating characteristics. The principal cross section elements (Refs 3, 36, 49, 59, 63 and 64) to be considered are

(1) the number of lanes,
(2) the width of lanes,
(3) the type and width of shoulders, and
(4) the type and condition of the pavement surface.

The restriction of vehicle speed due to variations in the cross section profile should not be expected to influence average vehicle speeds to a great extent, especially where professional drivers are concerned, as with commercial vehicle operation. However, the average driver may subconsciously reduce this operating speed under roadway conditions in which he feels uncertainty. With this speed reduction comes the increased likelihood of vehicle restrictions where passing opportunities are limited. This magnifies the possibility of reduced speeds for the slower commercial vehicles on the approach to a grade and consequently greater speed reduction on the grade itself.

Horizontal Curvature

Horizontal curvature on highways can affect a driver's operation of a vehicle through the restriction of sight distance and the creation of centrifugal forces. Under comparable conditions, the centrifugal force created by the curvature has been shown to cause a significantly greater speed decrease than restricted sight distance (Ref 61). The following quotation (Ref 36) summarizes the effect of horizontal curvature on vehicle speed:

> Curvature does not result in speed reduction until the cornering ratio required to offset the centrifugal force approaches 0.16 of the weight of the vehicle . . . any cornering ratio above 0.16 will result in lower speeds.

In research performed in 1954, Taragin (Ref 61) found that where sight distances were restricted to less than 400 feet, most drivers reduced their speed to one from which they could come to a stop within available sight distances; whereas, for sight distances greater than 400 feet, drivers often exceeded what was considered a safe speed for the available stopping sight distance. Therefore, a sight distance of 400 feet was designated as the minimum allowable which would not influence vehicle speed.

Pavement Types

The type and condition of roadway surfacing can influence vehicle speed because of the variations in surface friction. Since the magnitude of the rolling resistance is proportional to the increase in surface friction, resistances could be expected to increase. Table 3 shows the variation in rolling resistance resulting from several pavement types.

ENVIRONMENT

The environment within which the vehicle must operate is the fourth major factor capable of influencing vehicle performance. The three elements of the environment capable of influencing the vehicle's operating performance are

(1) atmospheric conditions,
(2) traffic conditions, and
(3) land use along the road.

TABLE 3. APPROXIMATE ROLLING RESISTANCE FACTORS OF VARIOUS ROAD SURFACES FOR HEAVY TRUCKS AT NORMAL ROAD SPEEDS (FROM REF 77)

Surface Type	Rolling Resistance Factor[1]
Smooth concrete and asphalt (dry)	.006
Brushed concrete (dry)	.012
Asphalt with sand or chip seal (dry)	.012
Packed snow	.013
Concrete and asphalt (wet)[2]	.015
Packed earth or gravel (dry)	.06
Sand (dry)	.25

[1] On a hard surface, rolling resistance is approximately equal to 50 pounds of drawbar pull for each ton of GVW or GCW.

[2] When water depth is insufficient to create resistances other than those resulting from tire hysteresis and surface adhesion.

Atmospheric Conditions

Many atmospheric conditions can affect the operation of a vehicle. The most dramatic restriction would naturally be the severe atmospheric disturbances, such as high winds, heavy rain, or fog, which would limit the operation of the vehicle by restricting vision, reducing road traction, and causing instability of the vehicle. However, many other less severe atmospheric variables can have a noticeable effect on vehicle operation. These variables are relative humidity, atmospheric temperature, barometric pressure, and altitude. These variables may influence the operation of the vehicle through either restriction of vehicle power output capabilities or negative complication of the driver's reaction.

Current practice within the engine manufacturing industry stipulates that the gross power rating of an engine can be achieved only in operation at standard atmospheric conditions. At present, two standard atmospheric references are in common use within the industry. Both are accepted by the Society of Automotive Engineers. The original standard recognized an ambient temperature of 60 degrees Fahrenheit at sea level as standard atmospheric conditions (Ref 51). A more recent standard, also widely used, recognizes an ambient temperature of 85 degrees Fahrenheit at 500 feet of elevation as the standard atmosphere (Ref 52). Operating differences resulting from deviation from these standards are as a whole very insignificant; however, where extreme deviations do occur, significant variations in performance are experienced. The atmospheric conditions under which a vehicle must operate should therefore be strictly observed.

As a rule, deviations from the standard atmospheric conditions will upset the operating efficiency of the engine in the combustion cycle and will therefore reduce the magnitude of the torque output capable from any given engine. Since the pulling force available is directly proportional to the torque output, any significant variation in operating efficiency from atmospheric conditions could lessen the hill climbing ability of the truck. Therefore, the atmospheric conditions at the time of each test run should be monitored.

Traffic Conditions

Some of the traffic characteristics which need to be recognized are the design hourly volume, the average daily traffic, and the composition of the traffic in the stream. The makeup of the traffic volume will determine what percentage of the vehicles within the traffic stream are within the classes of vehicles whose performance is most likely to be affected by highway grades. With knowledge of the overall volumes and composition of the traffic, capacity analysis techniques and safety criteria can be developed to augment the design of grades.

The distribution of volume and speed among the different lanes also has a significant effect on the operation of the highway and hence the operation of vehicles on the highway. If slow vehicles do remain in the outside lane, when one is provided, their effect on traffic interference will be significantly reduced. The distribution of traffic among lanes should therefore be recorded.

The distribution of vehicle speeds on any roadway will also influence the performance characteristics. Some of the speed characteristics which should be recognized in any test are

(1) the overall average and running speed for all vehicles on the roadway and

(2) the average and overall running speed by type and class of vehicle so that estimates of the speed differential on the highway can be used to analyze possible capacity analysis techniques and the overall safety and efficiency of the highway.

Abutting Land Use

The type or degree of land use along a facility can in many ways influence the operational characteristics of vehicles on the roadway. The principal effect from abutting land use is the natural tendency for the driver to reduce the operating speed of his vehicle due to the increased possibility of conflicting maneuvers from vehicles entering or leaving the roadway. With increases in the density of use of land adjacent to a roadway, the likelihood of obstruction or interference from traffic merging into the roadway from the abutting activities is greater. The driver will, therefore, be more cautious than on facilities with relatively clear roadside areas and will naturally tend to travel at reduced speeds. At-grade intersections or "T"-intersections also raise the possibility of interference and thus reduce vehicle speeds. Therefore, the extent of roadside activities prevalent on a grade should be related to probable vehicle operating speeds on the approach to each grade.

SUMMARY

The performance of every vehicle operating on a highway is a function of the interaction of numerous variables associated with four principal elements which govern vehicular motion. These four elements are

(1) the vehicle,
(2) the roadway,
(3) the environment in which the vehicle operates, and
(4) the driving manner of the vehicle operator.

Identification and evaluation of these elements provided an additional framework for the field study described elsewhere in this report. Each element was described and arrayed for analysis in the mathematical modeling phase of the research.

CHAPTER 3. DATA NECESSARY FOR THE GENERAL EVALUATION OF VEHICLE GRADABILITY

As illustrated in Chapter 2, a wide variety of variables associated with the vehicle, driver, roadway, and environment can influence the performance of a vehicle at any given time. Because of the limiting scope of the conventional force and energy equations, mathematical models used in previous research have not been entirely successful in evaluating the effects of these variables in relation to actual vehicle performance. However, these models might be improved if current experimental data representing actual vehicle operating tendencies under a wide variety of roadway and environmental conditions were available. With this information, the performance characteristics of representative vehicles could be modeled, and a general evaluation of present grade design criteria and methods could be performed.

Collection of the field data necessary to identify adequately the operating tendencies of heavy vehicles on grades is obviously a complex operation due to the numerous combinations of the variables involved. However, a majority of the variables can be represented by field data from three major areas: the pertinent physical characteristics of the vehicles under observation, the speed reduction profile of each vehicle at selected field sites, and the external conditions, geometric and environmental, under which the vehicles operate.

VEHICLE FACTORS

There are many factors in the makeup of a vehicle which can directly influence its operating characteristics on a grade. The three principal factors are

(1) the vehicle type or classification,
(2) the gross weight of the vehicle, and
(3) the vehicle horsepower rating.

Even though not every identifiable vehicle factor can be evaluated in an experimental program, representative information from these three areas should be obtained.

Vehicle Type

A vehicle is generally classified in accordance with its size, shape, and axle configuration. In a field experiment, vehicles should be classified so that any performance variations associated with different classes of vehicles can be identified. The primary elements which should be identified are the number and spacing of the axles, the shape and size of the major vehicle components (such as tractor and trailers), and the frontal area of the vehicle.

Vehicle Weight

The weight of any vehicle is known to play an important role in the gradability of the vehicle. Therefore, the weight of the vehicle and the type of cargo carried should be determined.

The type of cargo carried by each vehicle should be identified so that the effect of certain types of loads on vehicle operation can be determined. For example, it is probable that the shifting action of a fluid cargo would have more influence on vehicle performance than a stable solid load would.

Vehicle Horsepower

The power output element that can possibly be identified in an experimental program is the gross advertised horsepower. This figure gives an estimate of the gross power output to be expected from any engine, as determined by chassis dynamometer testing at the factory. Although the actual horsepower, or net horsepower, that is available to drive the vehicle is known to be less than the advertised horsepower because of power drains from vehicle components and accessories, no practicable method for determining the exact magnitude of the loss for any one vehicle is readily available. Therefore, gross horsepower seems to be the most practical method of representing power output. If an estimate of the net horsepower is desired, the currently accepted practice of subtracting a standard percentage (10 percent) of the gross horsepower as an approximation of the power loss could be used in analyzing field performance data (Ref 31).

SPEED-DISTANCE PROFILES

The second major data grouping to be obtained in an experimental series should be the speed-distance profiles of representative vehicles. From these profiles, relationships between vehicle weight, percent grade, and performance can be established.

The speed characteristics which should be observed in order to perform a thorough examination of vehicle performance characteristics are

(1) the speed of each vehicle upon entering the grade,

(2) the speed reduction rate on successive sections of the grade (deceleration rate),

(3) the crawl speed, or minimum steady state speed, reached during operation on the grade, and

(4) the acceleration characteristics of each vehicle on adjacent level or downgrade areas.

Entry Speed

Monitoring the approach speed of each observed vehicle will enable the determination of a distribution of entry speeds for different classes of heavy vehicles. From this distribution, the validity of currently accepted entry speeds used in design practice can be evaluated.

The entry speed of 47 miles per hour that is now widely used in climbing lane design was originally chosen during Huff and Scrivner's research on the basis that it represented the average speed of trucks on level sections on highways throughout Texas (Ref 30). More recent speed studies by the State Department of Highways and Public Transportation have determined that 47 miles per hour more closely represents the 15 percentile speed of heavy trucks on one level section (Ref 72). The reasonableness of this percentile speed in view of the recent changes in vehicle speed was reviewed and evaluated in subsequent phases of the research.

Observation of the entry speed on a grade will also aid in the evaluation of the effect of various entry speeds other than 47 miles per hour on the deceleration rate on any given grade. The ability of any vehicle to climb a given grade is known to improve as approach speeds are increased, principally because of the increase in momentum (mass times velocity). The momentum of a vehicle on the approach is known to account for a considerable portion of the energy available within any vehicle for overcoming a grade (Ref 60).

The current American Association of State Highway and Transportation Officials policy recommends that where abnormally high or low entry speeds have resulted because of approach conditions, changes in the recommended speed reduction criterion should be allowed (Ref 2). The American Association of State Highway and Transportation Officials policy also states that an increase in the design entry speed of 5 miles per hour be considered for inclines with a moderate downgrade approach and that an increase of 10 miles per hour be considered for steep approach grades. However, no criteria are available to differentiate a moderate approach grade. Better definition of these conditions can be considered after the effect of various entry speeds has been evaluated in light of new field observations.

Deceleration Rate

The deceleration rate experienced by heavy vehicles while operating on a grade must be measured so that the speed reduction occurring on a given length of gradient can be determined. In order that this can be done, a continuous trace of the vehicle's time-position progression on various grades must be plotted. Deceleration characteristics should be determined for upgrades ranging from 1 to 7 percent.

Crawl Speed

The crawl speed is the maximum steady-state speed which a vehicle can maintain during extended operation on a given percent slope. Determination of the crawl speed is desirable so that the speed at which the heavier vehicles will exit any grade can be determined. The speed at which the vehicle will begin acceleration can then be estimated and the necessary recovery distance determined.

Acceleration Rate

Knowledge of the rate at which vehicles with given weight-horsepower groupings are capable of regaining normal operating speeds after reaching the top of a grade is necessary so that the length of a speed recovery zone can be determined. Since the speed at which a vehicle merges into the traffic stream is often more critical than the speed at which it leaves the stream, it is imperative that adequate recovery sections be provided. Current design procedures for climbing lanes call for speed recovery zones of sufficient length to allow the slower vehicles to regain speed equal to the speed used to determine the point at which the climbing lane should begin (Ref 2). The acceleration capabilities of vehicles should therefore be determined by the development of profiles of the time versus distance progression for tested vehicles while on various downgrades. The recovery grades should range from 0 to -7 percent.

EXTERNAL CONDITIONS

The third grouping of data to be obtained during each field test should include a record of the external factors which influence the operation of the heavier vehicles. The factors to be identified would be the roadway features over which a test was run, the traffic and land use conditions at each test section, the climatic conditions at the time of each test, and the characteristics of the driver of each vehicle.

Roadway Conditions

The roadway features which would be most pronounced in their effect on vehicle operating capabilities are

(1) length and percent slope of test grade;
(2) approach conditions;
(3) recovery area length, slope, and geometry;
(4) horizontal curvature;
(5) cross section geometry; and
(6) pavement type and condition.

Length and Steepness of Grade. Test areas selected must have grades of sufficient length and steepness to cause a noticeable decrease in vehicle operating speeds. An ideal condition would be an incline of constant grade with sufficient length to reduce the vehicle's speed to crawl speed. Since such conditions seldom exist in practice, field sites with various lengths and steepnesses of grade must be used to study the relationship between vehicle operating characteristics and grade.

Approach Conditions. The condition of the approach must be observed so that the effect of approach conditions on the average entry speed to the grade and the ultimate vehicle operating performance on the grade can be identified. The approach characteristics most likely to affect vehicle operation would be the length and percent of the approach gradient, curvature on the approach, and the cross section features of the approach roadway, to include the width and number of lanes and the shoulder conditions.

Recovery Area. The speed recovery zone at each test section is also an important variable to note as the recovery acceleration rate is dependent on the characteristics in the recovery area. Criteria similar to those used in evaluating the suitability of the deceleration grade should be employed for the speed recovery area. Vehicle speed versus distance profiles must be developed for recovery areas with various geometric and traffic conditions.

Horizontal Curvature. In general, the curve sections on most rural highways are designed to carry traffic comfortably at high speeds. The critical conditions discussed in Chapter 2 will occur very seldom. However, since the effect of such sections has not been thoroughly investigated, any curved sections occurring in any portion of the test area, i.e., approach, recovery area, or test grade, should be completely evaluated. The characteristics required to identify any horizontal curves contained within test sections would be the degree of curvature, the sight distance, and the rate of superelevation.

Cross section Geometry. The characteristics of the cross section of the roadway which have been shown to influence vehicle operation are the number and width of available lanes and the condition of the shoulder. Although these features might not physically affect the resistance forces opposing the vehicle, they can, as discussed in Chapter 2, influence the performance of the vehicle operator. Therefore, the geometry of the cross section should be considered for each test section.

Pavement Type. The condition or characteristics of the pavement can influence the amount of rolling resistance to which the vehicle is subjected and the amount of traction produced by the vehicle. Therefore, the type and condition of the pavement at each site should be noted.

Traffic Conditions

The second major external factor to be considered in the tests of vehicle performance is the traffic conditions under which each test is performed. Close records must therefore be kept during each test run on the number of other vehicles in the vicinity of the test vehicle and the speed and behavior of these vehicles. In this manner, the detrimental effect of the presence or interference of other vehicles can be evaluated.

Land Use

Since the presence of roadside activities or conflicting traffic maneuvers is known to affect vehicle speeds, every effort should be made to avoid test sites at which unusual conditions exist. Intersection areas or traffic access zones should not be used in the field study program.

Atmospheric Conditions

Adequate records of the atmospheric conditions during each test should be made. Records of the temperature, relative humidity, and barometric pressure should be made for each series of vehicles tested. Any major variations in these conditions during a test should be noted at the time the change occurs. Prevailing wind direction and velocity for each series of tests should also be noted. In this manner, if significant variation occurs between two series of tests run under otherwise identical conditions, the variations can be referenced to the atmospheric conditions. Severe atmospheric disturbances such as high winds, rain, and fog should be noted as their effect will certainly be significant. Unless high altitude testing of some vehicles is expected to enable some determination of the effect of altitude on vehicle performance, routine testing should not consider the altitude difference between sites.

Driver Data

Driver behavior can have a significant influence on vehicle operating characteristics; therefore, efforts should be made to obtain a profile of the driver of each vehicle tested. This information might be obtained by on-site interviews of a sample of the drivers or by a letter questionnaire sent to the companies whose vehicles are identified in the test. Data obtained on the operator's experience and physical abilities could possibly be correlated with vehicle performance when a definite relationship is apparent.

SUMMARY

Collection of the field data necessary to identify adequately the operating tendencies of heavy vehicles on grades is a complex operation due to the numerous variables involved and their complex interactions. However, a majority of these variables can be represented by data from three major data divisions. These three data divisions are

(1) classification of the vehicle and identification of certain pertinent physical characteristics, such as the gross weight of the vehicle, the shape and size, and rated horsepower output;

(2) speed versus distance profiles on each vehicle during observation within the test area; and

(3) geometric and environmental conditions existing at the test locations chosen.

This phase of the study provided the basis for the field studies and the critical parameters to be observed and analyzed.

CHAPTER 4. SITE SELECTION

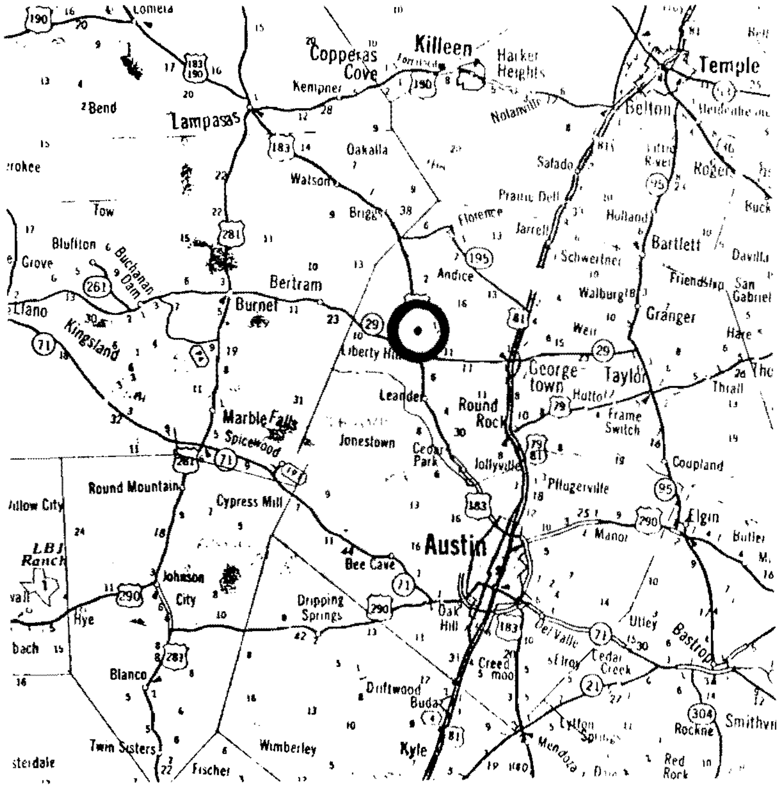
Test sites were selected and characterized on the basis of criteria consistent with the basic parameters associated with the roadway, the traffic, the roadside, and the atmosphere. The search was concentrated in an area surrounding Austin in order to minimize the expense of transporting survey equipment and personnel to the sites. After an evaluation of several grades, test sites were selected for both trucks and recreational vehicles. A detailed description of the test sites and the influencing conditions is given for the truck sites because trucks proved to be the more critical of the two types. Only a brief discussion of recreational vehicle sites is given.

TRUCK SITES

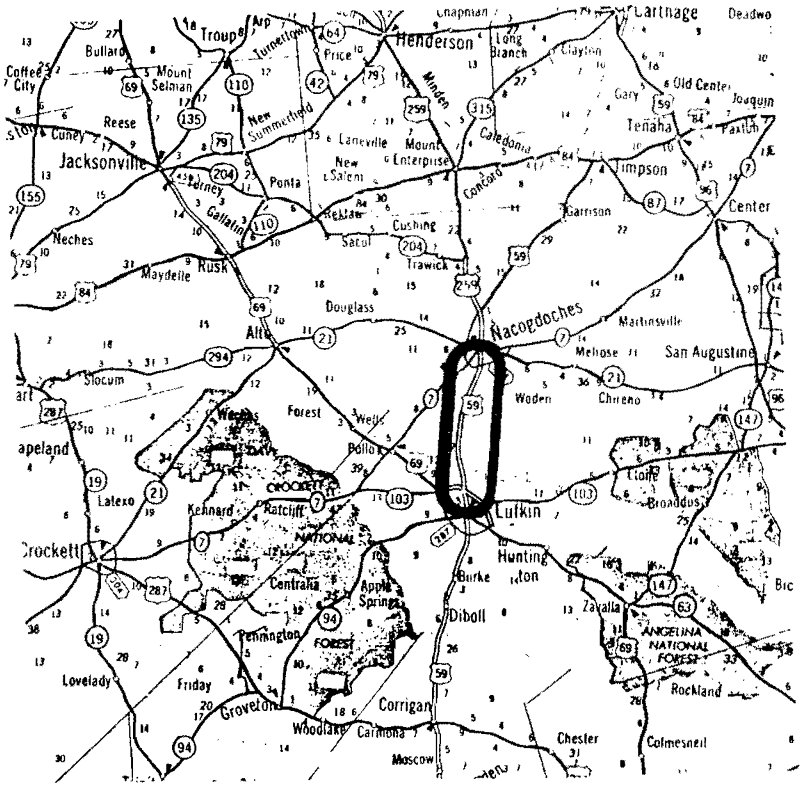
One test site selected was 23 miles north of the Austin city limits on U. S. Highway 183. Four grade sites on U. S. 59 between Lufkin and Nacogdoches near the Angelina River were chosen for observation as a result of inquiries by State Department of Highways and Public Transportation engineers for truckability data on logging trucks in east Texas. The maps in Fig 11 show the relative locations of the grade test sites. Table 4 shows the external conditions for each grade as they existed in the field on the days testing occurred. Not all the desired traffic parameters were available so reasonable estimates were made. SDHPT Planning and Survey Division information for the state was analyzed.

ROADWAY PARAMETERS

Each grade is divided into three distinct areas for analysis of vehicle performance. The first area or section is the approach. Ideally this section should be level so that the entry or approach speed for the vehicle is relatively constant. If the approach section is downhill, the vehicle will be



Site 1, U.S. 183



Sites 2, 3, 4, and 5, U.S. 59

Fig 11. Grade site locations.

TABLE 4. DESCRIPTION OF TEST SITES

	Grades				
	U.S. 183	U.S. 59			
Roadway Parameters	1	2	3	4	5
Length of grade, ft					
Approach	800	400	800	600	700
Grade section	2450	2500	5700	2700	3300
Recovery area	500	350	800	700	600
Steepness of grade					
Approach	0	0	-.5	-.5	0
Grade section*	5	3.4	2.6	3.7	2.6
Recovery area	0	-.5	-.5	-.5	-.5
Horizontal alignment	(All test sites essentially identical with straight horizontal alignment)				
Approach					
Grade section					
Recovery area					
Cross section					
Number of lanes	4	4	4	4	4
Lane width, ft	11	11	11	10	11
Shoulder width, ft	-	8	8	8	8
Median width, ft	-	30	20	20	20
Pavement					
Type	Asphaltic concrete			A.C. overlayed on jointed concrete slab	
Condition	Dry			Dry, but cracked at each joint of the concrete underneath	

*Maximum Cumulative Average Grade

(continued)

TABLE 4. (CONTINUED)

Traffic Parameters	U.S. 183	U.S. 59
Speed (MPH)		
Passenger cars	64.9	67.4
Trucks, single unit, 3-axle	60.9	64.7
Trucks, combination, 3-axle	59.5	60.1
4-axles or more	59.2	60.6
Buses	69.0	67.9
Average daily traffic		
Passenger cars		
Texas	2534	5572
Out-of-state	105	615
Total	2639	6187
Trucks, single unit	925	2000
Trucks, combination 3-axle	11	53
4-axle (2-S2)	23	258
4-axle	-	4
5-axle	193	1087
6-axle	1	6
Sub total	228	1408
Semi trailer-trailer		
5-axle	1	8
6-axle	-	3
Sub total	1	11
Total truck combinations	229	1419
Total all trucks	1154	3419
Buses	7	29
Motorcycles	7	27
TOTAL 24-hour annual average traffic for 1972	3807	9662

(continued)

TABLE 4. (CONTINUED)

Roadside Parameters	U.S. 183	U.S. 59			
	1	2	3	4	5
Abutting land use					
Agricultural (no interruptions)			-		-
Light commercial	-	-		-	
Visual stimuli	-	Occasional signs and driveways			
Conflicting traffic flows	-	Occasional			

Atmospheric Conditions	
Wind: Direction	Not a significant factor
Velocity	Light
Air temperature	75-95° F
Humidity	50-80%
Time of week	Monday through Friday
Time of Day	10 AM to 4 PM

accelerating into the grade; and if the approach is slightly uphill, the vehicle might already be decelerating upon entering the grade.

The actual grade section (test section) over which vehicle performance is most closely monitored starts where the grade actually begins, as determined from the profile plans furnished by the SDHPT.

The grade section is perhaps best described at any one point by the average cumulative grade at that point since this approximates the total effect of the grade on an ascending truck. The average cumulative grade is determined by dividing the grade for each individual 200-foot section by the cumulative number of sections.

Both highways had four lanes. U. S. 183 was undivided, and all sites on U. S. 59 except Site 3 were divided. This section was divided up to the crest but was undivided in the recovery section. Whereas U. S. 183 had no shoulders, U. S. 59 had paved shoulders wide enough to accomodate a stalled passenger car safely. Bridges at the approach to grade 2 and grade 4 on U. S. 59 were only two lanes wide. The pavements on all test sections were asphaltic concrete. The original surface on U. S. 59 was a jointed concrete slab that had shifted. Cracks at each joint had appeared through the asphalt overlay to create a noisy but rideable surface.

TRAFFIC PARAMETERS

The direction of travel of the monitored traffic on U. S. 183 was southeasterly, towards Austin. Grades 2, 3, and 4, on U. S. 59, were on hills running in a southerly direction, towards Lufkin, while Grade 5 was in a northerly direction.

Specific average spot speed data were not available from the SDHPT; however, reasonable estimates from the statewide 1973 speed survey for rural highways (Ref 73) were entered in Table 4. These estimates were made by averaging the speeds obtained from survey stations on 4-lane highways with similar geometric characteristics. Since many other variables affect vehicle speed, this may or may not be a valid procedure. However, if treated only as a rough indicator of highway operation, this information may give some insight into the operations of similar 4-lane highways. The average speeds for all stations in Texas are listed in Table 5.

TABLE 5. AVERAGE RURAL HIGHWAY SPEEDS IN TEXAS, MPH

	Year	
	1972	1973
Passenger cars	64.6	65.3
Trucks - single unit		
Panel or pickup	60.7	61.5
Other	56.6	57.3
Truck combinations		
3-axles	56.7	57.7
4-axles or more	58.0	59.1
Total trucks	58.9	59.8
Busses	63.5	62.1
All vehicles	62.6	63.5

Source: References 72 and 73.

The average daily traffic and directional volumes by class were obtained from the Planning Survey Division of the SDHPT and were for 1972. The counts for U. S. 59 were for both directions (Ref 66).

Fifteen percent of the vehicles traveling over the grades on U. S. 59 were truck-combinations. This represents about 42 percent of all the trucks traveling on that section of roadway. Of that 42 percent, a large number (50 percent of the trucks monitored) carried logs or pulpwood.

On U. S. 183, 31 percent of the southbound vehicles in 1972 were trucks (single-units and combinations). About 21 percent of the trucks were conbinations, the majority (80 percent) of which were 5-axle (3-S2) semi-trailer combinations.

ROADSIDE PARAMETERS

The conditions that exist along the side of the roadway, such as abutting land use, visual stimuli, and conflicting traffic flows, may indirectly or directly affect vehicle operation by distracting or otherwise influencing the driver. At site 1, on U. S. 183, the land on both sides of the roadway is agricultural and there is a small gravel driveway at the top of the hill, past the study zone. A "T" intersection with a seldom traveled farm-to-market roadway exists at the base of the grade, 300 feet from the beginning. Little if any effect is believed to have been created by this intersection since adequate stopping sight distance was provided in both directions. There are no large signboards along the grade to distract the driver. The opposing traffic may have influenced vehicles in the inside lane because the four lanes were undivided; however, all vehicles studied traveled in the outside lane. It is assumed that opposing traffic flow did not have any effect on vehicles tested on the grade on U. S. 183.

Grades 2 and 4, on U. S. 59, have abutting land use that is agricultural in nature. There is a light commercial area at the top of grade 3 visible from almost all points. Grade 5 has light commercial establishments along most of the grade. Crossovers in the median, driveways, and signs exist along all four grades. It is reasonable to assume that all of these interruptions and distractions had some influence on driver behavior. For this reason, test site 1, on U. S. 183, is analyzed separately from sites 2, 3, 4, and 5.

ATMOSPHERIC CONDITIONS

The atmospheric conditions during all tests were similar. The testing took place over a period of time from late June through August in 1973. It was hot (80-90 degrees F) with slight humidity and sunny with scattered clouds. Testing took place during normal working daylight hours, from around 9:30 AM until 4 PM Daylight Saving Time.

Wind usually varied in direction and only slightly in velocity. A wind factor such as this is one of two kinds that can affect truck operations. Natural wind has an average speed in the United States of only ten miles per hour, which barely amounts to a noticeable breeze (Ref 77). As pointed out in a research study report published by Trailmobile, Inc., in conjunction with the American Trucking Associations Foundation, "This kind of natural wind does not appreciably affect the air drag on your trucks or trailers..." (Ref 84). The second type of wind does affect trucks and trailers to a very noticeable degree. This is the "wind" that pushes against, or causes resistance to, vehicles as they pass through the air. At 50 miles per hour a truck or trailer "creates its own wind," a 50 mph wind. Wind tunnel tests conducted by Trailmobile, Inc., at the University of Maryland "proved that correct design and streamlining (of trucks and trailers) increase useable horsepower, decrease air drag, and contribute materially to the economy of operation and ease of handling of truck trailers" (Ref 84).

The wind tunnel tests showed that wind resistance varies as the front corner radius of the trailer is changed. The front design that showed the most wind resistance was the square-corner front. Tests on the square front design showed that 54 hp is required just to overcome wind resistance at 50 miles per hour.

Rounding the two square front corners decreased the wind resistance and the horsepower requirements accordingly. TABLE 6 summarizes the results of four of the more practical of the 7000 combinations of designs tested.

As many truck operators have long contended, the type of trailer side plays a large part in decreasing or increasing wind resistance. A smooth-panel trailer side and a side with horizontal corrugations, when tested in the wind tunnel, both showed a 46.0 horsepower requirement for overcoming wind resistance at 50 mph. A vertical post design for the trailer side resulted in more wind resistance.

TABLE 6. WIND TUNNEL TESTS BASED ON HORSEPOWER REQUIREMENTS AND PERCENT IMPROVEMENT

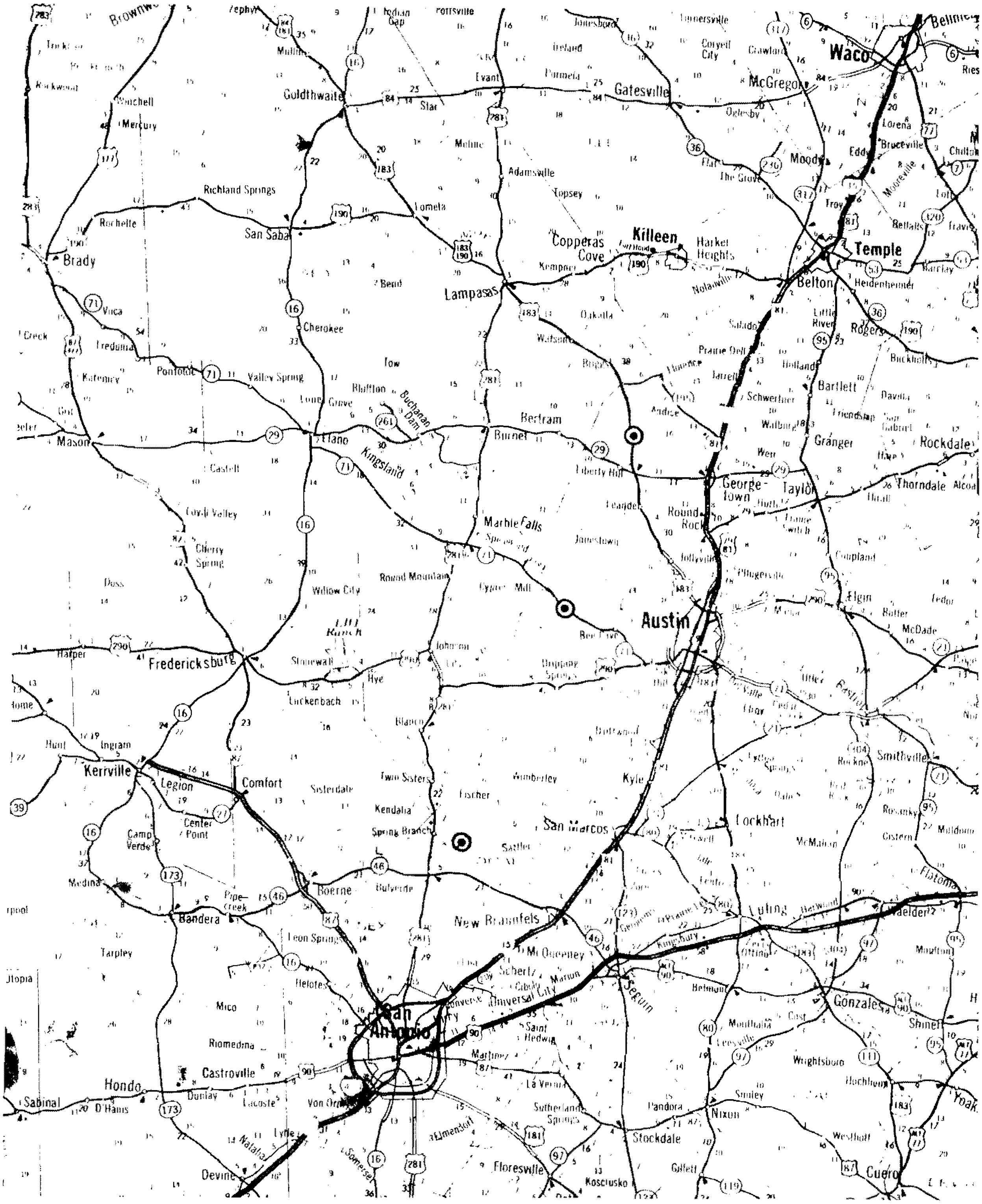
Wind Resistance Speed, MPH	Square Front (HP - %)	18" Radius Corners (HP - %)	6" Radius Corners 6" Radius Roof (HP - %)	18" Radius Corners 6" Radius Roof HP - %)
40	54.0 - 0	48.88 - 14.8	46.7 - 21.1	45.9 - 23.5
50	54.0 - 0	46.0 - 14.8	42.6 - 21.1	41.3 - 23.5
60	54.0 - 0	42.5 - 14.8	37.6 - 21.1	35.7 - 23.5

Source: Reference 77.

As a result of these findings it was concluded that although the natural wind velocity from day to day at each site was not a significant factor, the frontal and side configurations of each vehicle were significant enough to be considered in the final analysis of operating characteristics.

RECREATIONAL VEHICLE SITES

The three sites for this phase of the study were chosen considering the same factors as for the truck sites. The locations of the sites, numbered 6, 7, and 8, are shown in Fig 12. Site 6 is the same as site 1. Site 7 is located on S. H. 71 at the Pedernales River, 20 miles west of Austin. The site is close to Paleface Park, at Lake Travis, where there was a large volume of recreational traffic, especially during the weekends. Site 8 is located on F. M. 3159, 18 miles west of New Braunfels (47 miles south of Austin). This is close to Canyon Dam, and during the weekends there was comparatively heavy traffic, including many vehicles pulling boats to the lake. A summary of specific features for each of these three sites is given in Table 7.



⊙ Site Location

Fig 12. Site locations.

TABLE 7. CHARACTERISTICS OF TEST SITES (REF 73)

Characteristics of Site	Site Location		
	U.S. 183	S.H. 71	F.M. 3159
Highway type	4-lane	2-lane	2-lane
Climbing lane?	No	Yes	No
Approach	Level	Level	Level
Horizontal curvature?	No	Some	Some
Length of test section (ft)	3,600	8,000*	8,700*
Average percent grade (%)**	5	3.9	6.5***
Average daily traffic	1,730	1,670	140

* Test section includes a speed recovery area.

** Average percent grade is computed by weighting each percent grade by its respective length between vertical points of tangency.

*** Two distinct average percent grades: 2.4% and 6.5%.

CHAPTER 5. METHODS OF DATA PROCUREMENT

As discussed earlier, a variety of vehicle performance data had to be obtained by field observation so that current design procedures for grades and climbing lanes could be evaluated. This suggested the need to devise or adapt specialized measuring and recording techniques in order to reliably, accurately, and economically obtain the necessary data.

The techniques and instrumentation used for the field work of this study are discussed in this chapter. The initial part of this chapter presents the methods and a description of the equipment used to monitor the speed-distance progression of each vehicle, and is followed by a discussion of the technique that was used for identifying and classifying the tested vehicles.

GENERAL CONSIDERATIONS

The techniques and instrumentation considered for this experimental program were evaluated in accordance with a number of criteria to determine the practicality of the equipment in the experiment. In general, the equipment had to be relatively economical, practical for operation by project personnel, reliable, and accurate. In addition, the equipment had to be flexible and mobile enough to be used at different field sites and adaptable to the various conditions which may exist. As the system was likely to be used for long periods of time, consideration was also given to the availability of replacement equipment and to the maintenance expected. Finally, the system had to, of course, be inconspicuous to all vehicle drivers so that the vehicles under test would be driven in a natural manner.

SPEED REDUCTION PROFILE

The three principal elements of data necessary for the construction of speed versus distance profiles for each vehicle are

(1) speed reduction (deceleration) of the vehicle,
(2) entry speed for each grade, and
(3) minimum speed reached on the grade.

The speed versus distance profile for each vehicle observed was determined by monitoring the time versus position relationship for each vehicle as it progressed through the test section. To obtain this information several available systems were examined and evaluated (Ref 14) for possible use. Two methods proved to be feasible for use in this study: a photocell technique and a car-following method.

DATA COLLECTION AT SITES 1 AND 6

A vehicle presence sensor (photocell) that was spaced at predetermined intervals (200 ft) was employed for the long grade on U. S. 183. An inexpensive photocell was mounted at the focal point of a small parabolic reflector (from a traffic signal) and connected in the adjacent arm of a Wheatstone Bridge to another photocell located at the edge of the reflector and directed to sense the general light intensity over the roadway. A six-volt battery was used as a power source for the bridge. The reflector was aimed in such a way that a sudden change in light intensity at the focal point of the reflector was produced when a vehicle passed in the lane adjacent to the shoulder. This change was sensed by the photocell and resulted in a change in electrical resistance in one arm of the Wheatstone Bridge. Output from several bridge circuits was accumulated by series connection of the leads and the resultant signal was recorded in analog form on an oscillograph. Examination of the series of bumps on the oscillograph record made it possible to calculate the average speed of a vehicle over each 200-foot section. The reflectors were brought in after each day of data collection since it took only a few minutes to remount them. The Wheatstone Bridge circuits had to be balanced once or twice each day, to account for any varying ambient light conditions. The reflectors were painted green on the outside to minimize any adverse effects on the drivers. At the sites on U. S. 183 (site 1 and site 6) photocell detectors were used and an observer was placed in a position from which he could see any vehicles entering the test section. By a voice phone connection, he gave notice to the personnel operating the oscillograph that was located in the weigh-in-motion van at the crest of the hill. In addition to the speed information, a visual classification of each vehicle was written on the oscillograph record along with the license number. The photocell detection system is inexpensive to construct and can easily be moved from site to site. As used in this study, with nine detectors connected in series, it was sometimes difficult to identify the position of each vehicle from the oscillograph record when several vehicles entered the test section at the same time. This was not a serious problem, however, as the traffic was very light most of the time. The photocell technique was tested for accuracy, using a car with an exact speedometer, and found to be comparable with other accepted methods for speed measurement.

By knowing the actual distance in feet between photocells on the grade and by measuring the distance in millimeters between consecutive signals recorded on the oscillograph paper output, the average speed of a vehicle over a predetermined "track length" was determined. The following equation illustrates the calculation:

$$S_a = .682\frac{Ds}{d}$$

where

S_a = average speed of vehicle over distance between sensors, mph,

D = distance between consecutive sensors, ft,

d = distance between consecutive impulses on the oscillograph output, mm,

s = rate of oscillograph output, mm/sec.

A series of consecutive average speeds over the entire grade constitutes a speed history of that vehicle and can be plotted in a speed reduction profile.

All sensors were camouflaged to minimize their visibility along the roadway and reduce the effect their visibility might have on driver behavior.

Although the photocell sensor system worked well on U. S. 183, a completely different system was developed to fit the different external conditions at the other sites.

DATA COLLECTION AT SITES 2, 3, 4, 5, 7, AND 8

A car-following technique was developed for sites 2, 3, 4, 5, 7, and 8. Three individual cars were used, each manned by a driver and data recorder and equiped with a stop watch, data sheet list, and cassette tape recorder. Stripes painted on the shoulder at 200-foot intervals provided a distance reference for the observer. The observer called out the station number and marked on the cassette tape the precise time the rear axle of the test vehicle was over the station stripe by enunciating the word "point" into the microphone. The voltage impulse created by the distinct enunciation of the word "point" was sufficient to allow the direct transfer of all magnetic recording tapes to oscillograph records for decoding.

These records could then be converted to speed history profiles in exactly the same way as the data collected on U. S. 183.

A comparative study between car-following technique and the photo sensory procedure proved that there was not any loss in accuracy; however, the car-following procedure was much easier to adapt to local field conditions. Therefore, the car-following technique is recommended for any additional comparable studies.

PHYSICAL CHARACTERISTICS OF VEHICLES

The three principal factors which can directly influence vehicle operating characteristics on a grade are

(1) vehicle type or classification,
(2) gross vehicle weight, and
(3) vehicle horsepower rating.

Even though not every identifiable vehicle factor can be evaluated in an experimental program, representative information from these three areas was obtained through the data collection systems used.

The license numbers of the vehicles registered in Texas were submitted to the Motor Vehicle Division (MVD) of the State Department of Highways and Public Transportation for a computer search of registration records. A typical MVD registration printout gives the following useful information:

(1) registered empty vehicle weight,

(2) registered gross vehicle weight,

(3) age of vehicle (model year),

(4) manufacturer of the vehicle,

(5) classification,

(6) vehicle identification number,

(7) name and address of the vehicle owner,

(8) number identifying title on microfilm records, and

(9) whether the engine is diesel or not (trucks).

After a search of registration records was completed, a search of microfilm records was conducted to determine individual vehicle model numbers. With all of this information available, each vehicle could be described in more detail.

VEHICLE CLASSIFICATION

From field observation and MVD records each truck was assigned a particular classification according to axle configuration. The following classes were used (according to SDHPT and AASHTO standards):

Single Unit Trucks

1. 2A 2 axles, single wheels
2. 2D 2 axles, rear dual wheels
3. 3A 3 axles, all single wheels
4. 3D 3 axles, rear tandem dual wheels

Truck Combinations

5. 2-S1 2 axle tractor, single axle semi-trailer
6. 2-S2 2 axle tractor, 2 axle semi-trailer
7. 3-S1 3 axle tractor, single axle semi-trailer
8. 3-S2 3 axle tractor, 2 axle semi-trailer

Because various models, types, loading configurations, and sizes exist within each axle class, a more detailed description of the vehicle by type was used. The following tables show the breakdown of class by type as described by two parameters which affect vehicle performance, frontal and side configuration and area.

Table 8 shows classification by frontal configuration. Configuration is based on tractors pulling vans which run, on the average, three feet higher than the cab and on tractors with trailers other than vans. Usually, all other trailer combinations are lower than the tractor, thus making the frontal configuration of the tractor the governing factor.

Table 9 illustrates the various side configurations. Since vehicle lengths vary only slightly within a particular combination class, the side classifications are designed to include several axle groups each.

Recreational vehicle frontal areas and side areas were also classified as a relative number, from 1 to 10, depending on the size and type of the vehicle. Table 10 shows the basic vehicle type.

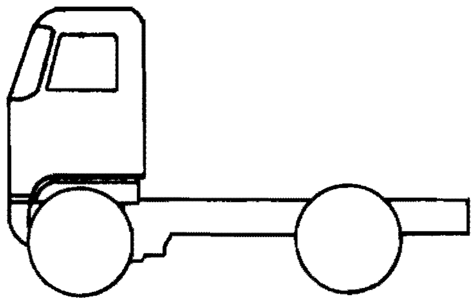
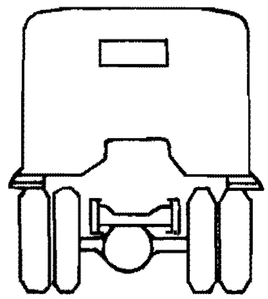
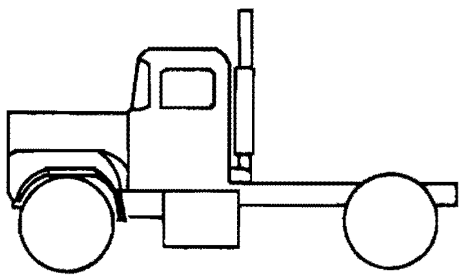
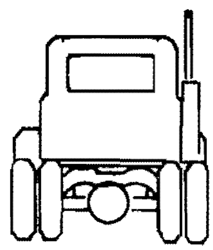
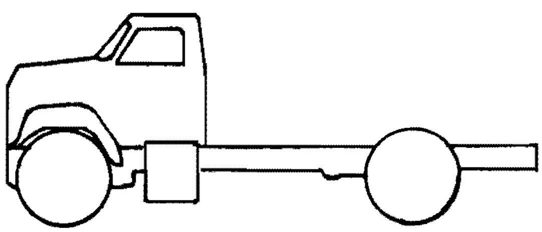
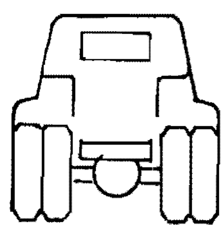
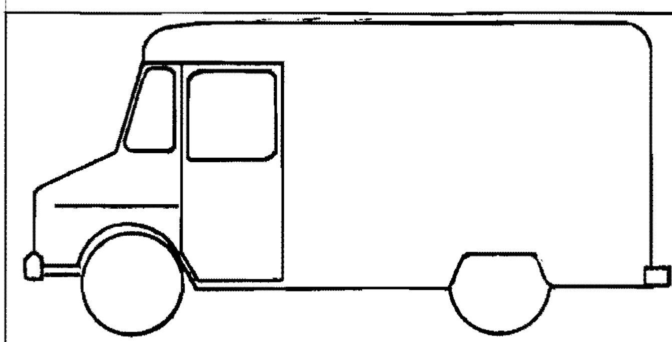
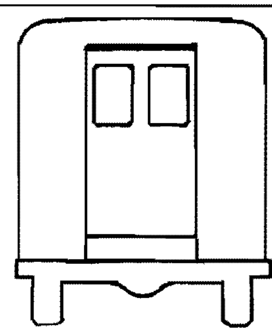
It was considered important to have some kind of measure for comparing the effect of these areas on performance, and it is believed that, by using relative numbers, a valid method for comparison can be obtained.

VEHICLE GROSS WEIGHT

In order to determine the gross weight of each truck, truck-combination, or recreational vehicle in the field, a system that weighs vehicles in motion was used. This in-motion weighing system, developed by the Center for Highway Research at the University of Texas at Austin and the State Department of Highways and Public Transportation for use by the Planning and Research Division of the SDHPT (Ref 67), utilizes special wheel load transducers. Samples of dynamic wheel forces are obtained and can be used to estimate the weight of a vehicle moving at speeds up to 70 miles per hour with an accuracy within 10 percent. Use of this technique does not influence driver behavior, allows on-site weighing, and permits up to 100 percent sampling. The excessive operating costs and time delays associated with a static weighing operation are eliminated.

Basically, the system consists of two loop detectors and two loading pads placed in the outside lane of travel (Fig 13). The loops and scales are connected to a digital computer in a van beside the road. A display console with a special keyboard allows the van operator to classify each truck according to axle arrangement and type. All of the system information is stored on magnetic tape and later transferred to a computer listing.

TABLE 8. FRONTAL CONFIGURATION AND CLASSIFICATION

		Code
		1
		2
		3
		4

(continued)

TABLE 8. (CONTINUED).

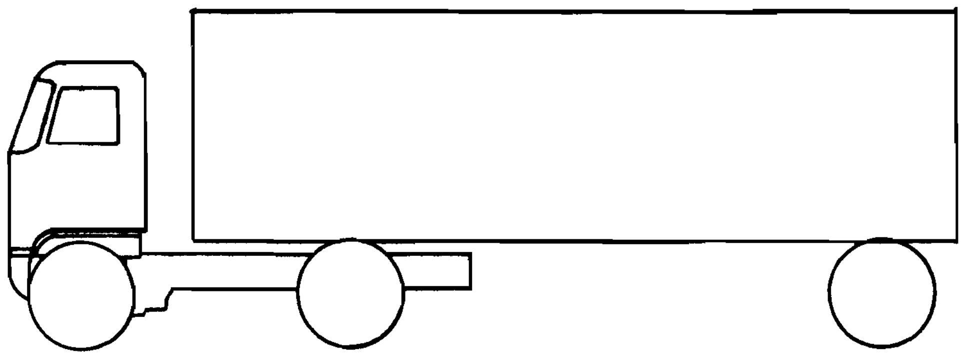
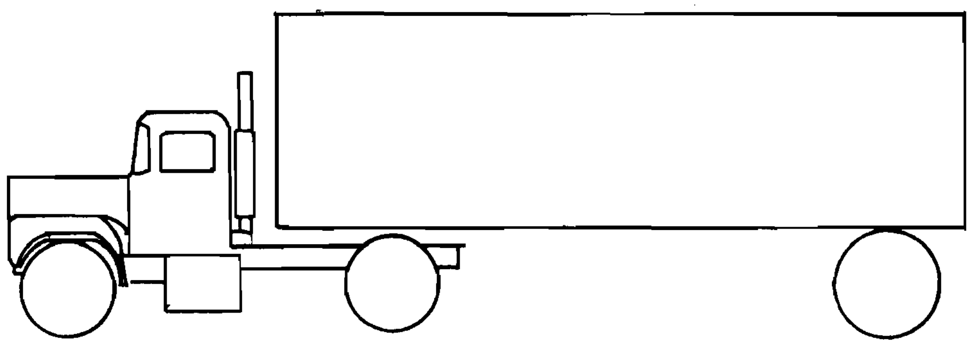
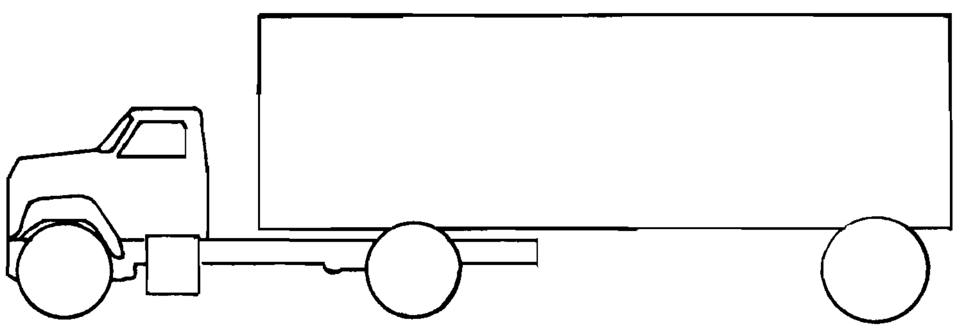
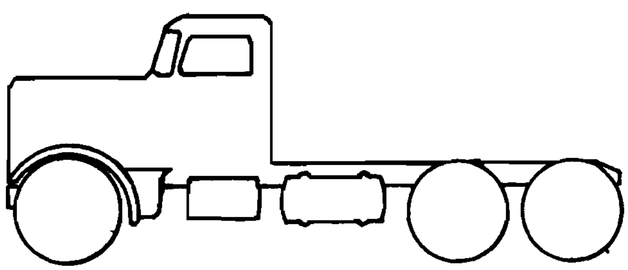
	Code
	5
	6
	7
	8 without van 9 with van

TABLE 9. SIDE CONFIGURATION AND CLASSIFICATION

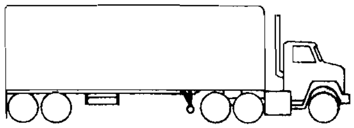
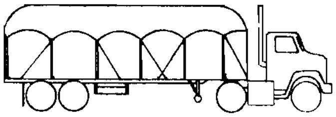
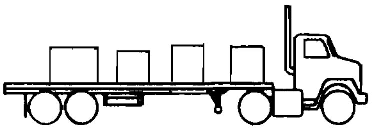
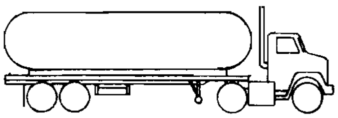
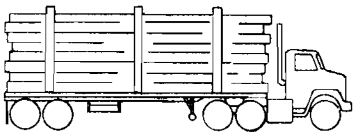
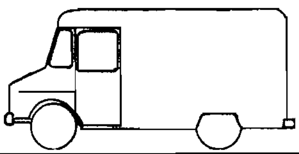
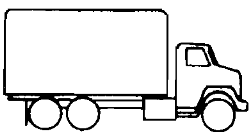
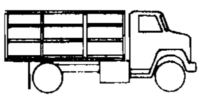
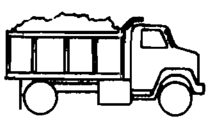
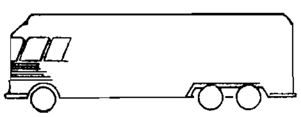
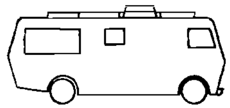
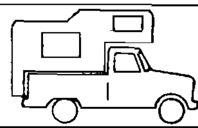
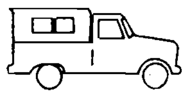
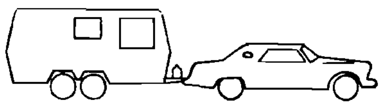
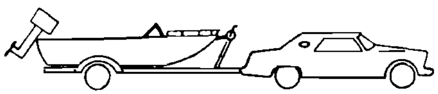
Vehicle Type	Code	
	1	All truck combinations with van trailers or cattle trailers.
	2	All truck combinations with trailers with stake sides.
	3	All truck combinations with flat bed trailers.
	4	All truck combinations with tank trailers.
	5	All truck combinations with logs.
	6	All single unit truck vans.
	7	All single-unit "chassis-with-cab" trucks with vans.
	8	All single-unit trucks with flat beds or stake sides.
	9	All single-unit dump trucks (including concrete mixers).
	0	All busses.

TABLE 10. NUMBER OF SPEED HISTORIES COLLECTED

	VEHICLE TYPE	US183	SH71	FM3159	TOTAL
Motor Home		16	18	2	36
Truck Camper		20	30	1	51
Pickup Cover		16			16
Vehicle Pulling Travel Trailer		19	16	1	36
Vehicle Pulling Camping Trailer		2	6	2	10
Vehicle Pulling Boat Trailer		6	47	31	84
Vans, Rental Trailers, and Cars	MISCELLANEOUS	23	4		27
					260

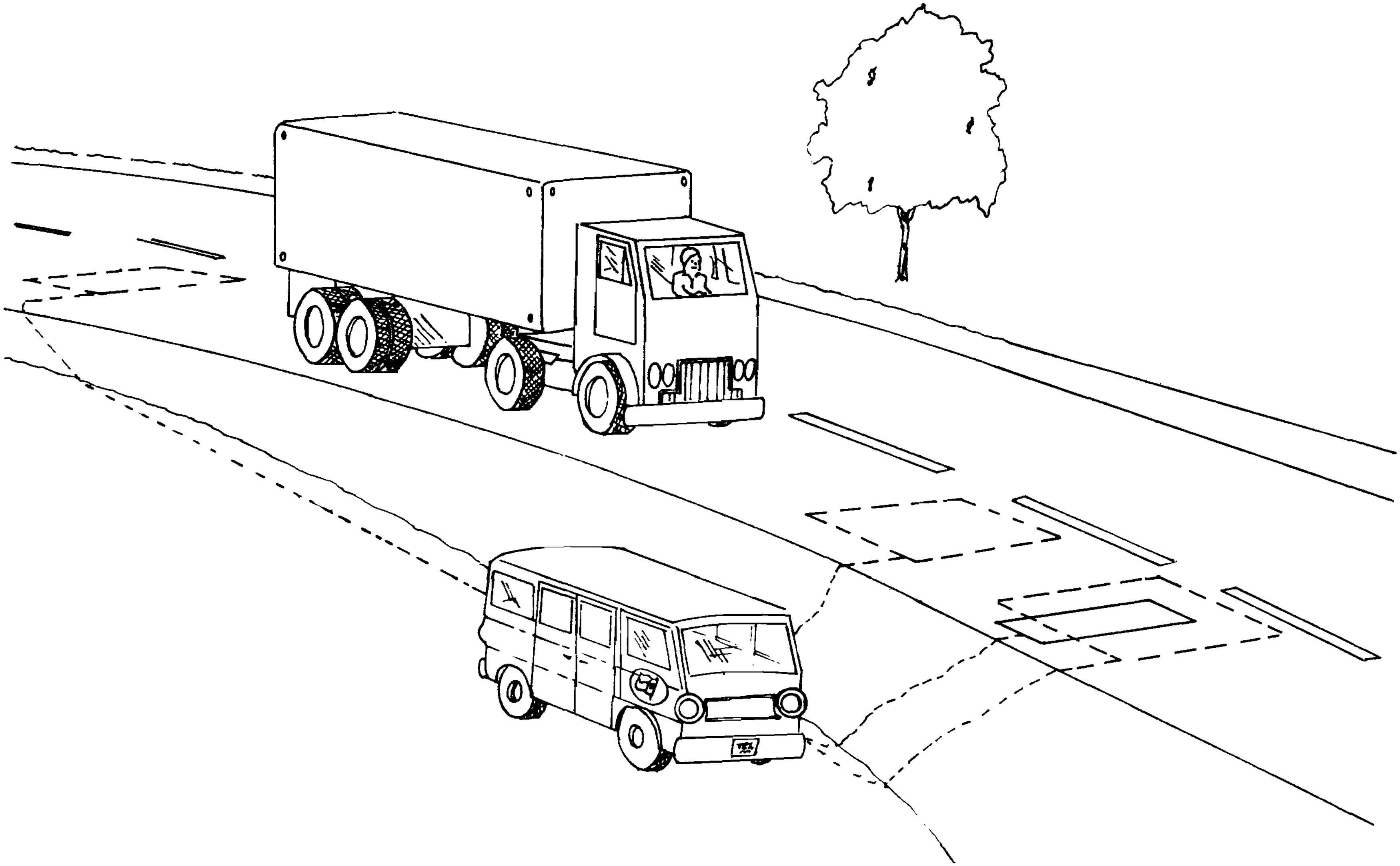


Fig 13. Data collection system on U. S. 183.

The weigh-in-motion system produces the following information for each vehicle:

(1) vehicle speed,

(2) length,

(3) number of axles,

(4) distance between each two axles,

(5) gross weight of each axle, and

(6) gross vehicle weight.

On U. S. 183 (sites 1 and 6) the scales were located past the test section, out of sight of any vehicle on the grade. Vehicles were weighed after passing through the test section. Vehicles traveling south on U. S. 59 (sites 2, 3, and 4) were weighed approximately 3 miles in advance of the first grade. This allowed the selection of particularly heavy vehicles, such as log trucks, for observation.

Vehicles tested at sites 5, 7, and 8 were not weighed by the in-motion system since the results of the previous field studies provided necessary data on the vehicles to estimate vehicle weights. Two methods were used to estimate reasonable weights for vehicles that missed the scales.

The first method was the use of information obtained from a questionnaire mailed to the owner or operator of the vehicle. Names and addresses were obtained from the MVD vehicle registration listing described earlier. Examples of the cover letter and questionnaire are shown in the appendix, Figs A1, A2, and A3.

An attempt was made to inform the vehicle owner that his responses were for research purposes only and would eventually help him, through better climbing lane design. Hopefully, operators responded honestly and as completely as possible to the questionnaire. The gross weight at the time the vehicle passed through the test section as well as the empty weight of the vehicle was requested.

When questionnaires were not returned or when there was no response on weight, a "reasonable" estimate of the gross vehicle weight was made. A basis for estimating the weight was established by examining each vehicle individually and weighting the following factors:

(1) registered gross vehicle weight,

(2) registered empty weight,

(3) description of the vehicle and its load from field data accounts,

(4) estimated horsepower,

(5) speed profile with particular interest in entering speed and eventual crawl speed, and

(6) average of the known weights of other vehicles in the same class.

VEHICLE HORSEPOWER RATING

Gross horsepower is the maximum horsepower output of an engine without any encumbrances, while net is the maximum horsepower output of the engine as installed in the vehicle. This would consider the effect of such encumbrances as the fan belts, alternator, water pump, and other standard accessories. In more recent years this would also include any emission control devices. If an engine were older and/or in a poor state of repair the net horsepower would be affected accordingly.

Because of all the variations in standard equipment, differences in emission controls, and inequities in maintenance procedures, it is difficult to establish a specific net horsepower for any group of vehicles. Most manufacturers advertise and guarantee a specific gross horsepower output for each engine. A net horsepower rating is available only theoretically. However, the gross weight-to-horsepower ratio on which AASHO bases climbing lane design theory uses net horsepower.

For this reason net horsepower was adopted for use in the analysis in this study, and it had to be calculated for practically every vehicle. With a few exceptions, the annually published specifications for all vehicle engines gave gross horsepower. One publication (Ref 53) suggests reducing gross horsepower by 10 percent to get net horsepower. In view of the variations in standard accessories on different models of vehicles, increasing emission control standards for new engines, and the decreasing state of repair on older vehicles, it was decided to use a standard 15 percent reduction in gross to obtain net horsepower for all vehicles tested. This factor provides a margin of safety for design purposes. A good discussion of the differing theories for using gross or net horsepower is presented in Refs 77 and 78.

In order to obtain the horsepower for each vehicle for which a questionnaire was not returned, the model number was checked on official specification tables (Ref 5) by year. These tables provided the standard engine specifications. It was assumed that if not otherwise indicated, the original engine or a replacement of equal horsepower was in the trucks at the testing period.

In all cases this assumption would probably make the horsepower readings less than or equal to the actual horsepower. Since weight-horsepower ratios are only a gross indicator of vehicle hill-climbing ability, it is believed that such estimates are acceptable for the data analysis.

DRIVER VARIABLES

The driver is probably the most difficult element to characterize in developing a complete speed profile of a particular class of vehicle. Drivers of recreational vehicles vary widely in experience, familiarity with a particular type of vehicle, mental ability, and physical coordination. Truck drivers, however, should not have as large a variation in experience and ability. In an attempt to identify more clearly the human aspects of truck-operating characteristics, the field data collection procedures were designed to reduce the influence of driver awareness that he is being monitored and to provide a sample of driver age and experience. One of the questions in the mailed questionnaire asked for the age and years of experience of the driver.

The correlation of all of the factors (gross vehicle weight, net horsepower, vehicle type, vehicle classification, speed reduction profile, and external conditions) into a complete analysis system is described in Chapter 6.

CHAPTER 6. ANALYSIS OF DATA

This chapter deals with the actual data analysis, how it was done, and what results were found. Both sets of data (for trucks and recreational vehicles) were analyzed using the same procedures and techniques.

A stepwise multiple regression analysis was performed on the data. The procedures followed in preparing and performing the analysis include

(1) sample size calculation,

(2) consideration of variables to be analyzed,

(3) determination of speed history groups,

(4) statistical multiple regression analysis to determine "best fit" equations,

(5) selection of equations that best predict and describe the behavior of vehicles on grades, and

(6) speed-distance and critical length of grade curve plotting.

SAMPLE SIZE

A minimum sample of speed history records within a particular group is necessary to guarantee that the results of a statistical analysis are reliable within acceptable confidence limits. The data must be assumed to be normally distributed so that a "students" t-distribution analysis for small samples can be used in estimating a minimum sample size. Using data from the sites, a sample size of 22 vehicle speed histories was determined to provide results that fell within a 95 percent confidence interval (see calculation in Appendix, Figure A4).

VARIABLES

The factors used in characterizing vehicle hill-climbing ability were developed from past research and field observation. A total of 11 factors were analyzed in this study:

(1) length of grade,
(2) percent grade,
(3) approach speed,
(4) weight,
(5) horsepower,
(6) frontal area,
(7) side area,
(8) vehicle length,
(9) driver experience,
(10) age of driver, and
(11) age of vehicle.

As described in Chapter 5, information about each of these factors was collected in a variety of ways. A stepwise regression analysis was performed on the data; in it the speed profile of each vehicle was entered as the dependent variable (Y), and the remaining factors or variables were entered as independent variables (X_1, X_2, X_3 . . . X_n). The length of grade was entered in feet on a cumulative basis with respect to the starting point, which coincided with the vertical point of curvature. Percent grade entered the analysis as a weighted average percent, with respect to the point of curvature. The approach speed was given in miles per hour. Weight represented the gross weight in pounds of each vehicle combination, and the horsepower was given as net horsepower. The frontal area and side area were each given as a relative number, from 0 to 9, depending on the size of the vehicle and the type. A description of the frontal area and side area classifications is presented in Chapter 5. Vehicle length was recorded in feet as estimated by the weigh-in-motion system in the field. Later examination showed that many of the vehicle length records were not accurate. This variable was not used in the final analysis due to a limited sample. The last three variables, driver experience, age of driver, and age of vehicle, are all given in years. Age of driver and driver experience were included in a reduced sample to see what effect these factors would have on the performance of vehicles on grades. It was not possible to obtain information about the age of the driver and driver experience for a majority of the other vehicles and sites.

Several feasible combinations of the original variables, such as squared or cubed terms or cross products (Ref 16), were entered in the analysis in order to find the best possible correlation between the independent and dependent variables. An explanation of the terms used in the development of the equations is given in the Appendix (Fig A5).

MULTIPLE REGRESSION ANALYSIS PROGRAM

The program used for the analysis is called STEP-01 (Ref 16). It computes a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is added to the regression equation. The variable added is the one which makes the greatest reduction in the error sum of squares. Equivalently it is the variable which has the highest partial correlation with the dependent variable partialed on the variables which have already been added; and equivalently it is the variable which, if it were added, would have the highest F value. In addition, variables can be "forced" into the regression equation. "Non-forced" variables are automatically removed when their F values become too low.

Significance of Regression (F)

The "partial F criterion for each variable in the regression at any stage of the calculation is evaluated and compared with a preselected percentage point of the appropriate F distribution" (Ref 21, p. 171):

$$F = \frac{\text{mean square due to regression}}{\text{mean square due to residual variation}}$$

In other words, the variable which is most related to the dependent variable is the one that is included in the equation at each step of the calculation procedure (Ref 16, p. 37).

Correlation (R^2)

An important part of any regression analysis is knowing how much of the variation about the mean $\overline{Y}$ is being explained by the regression. A measure for doing this is given by

$$R^2 = \frac{\text{sum of squares due to regression}}{\text{total sum of squares, corrected for mean}}$$

which tells the "proportion of total variation about the mean $\bar{Y}$ explained by the regression" (Ref 21, p. 26). This ratio can vary between 0 and 1; and the closer the value of R^2 is to unity the better the predictive equation is in explaining the variation. When expressed as a percent, the correlation may be interpreted to mean "the predictive equation explains R^2 percent of the dependent variable behavior" (Ref 21).

Coefficient of Variation (C)

In describing the amount of variation in a population, a measure often used is the coefficient of variation:

$$C = \frac{s}{\bar{x}}$$

where

s = standard deviation of the responses,

$\bar{x}$ = mean of the responses.

The standard deviation is expressed as a fraction, or sometimes as a percentage, of the mean. "A knowledge of relative variation is valuable in evaluating experiments. After the statistics of an experiment are summarized, one may judge its success partly by looking at C" (Ref 50, p. 63).

Predictive Equations

The different vehicle categories were tabulated and prepared for data analysis. Initially, vehicle data from each site were considered separately, and then similar vehicle categories were combined from two or more sites for each set of data. Tables 11 and 12 show the different vehicle combinations, the corresponding vehicle sample size, R^2, C, and the number of independent variables entering the equation. The weighted percent grade is also presented. In order to combine similar vehicles from two or more grades into one equation, it was assumed that slight horizontal curvature differences between each grade would not have any adverse effect on the operating characteristics of the vehicles.

A careful analysis was made of each of the resulting equations before it was entered as representative of that particular vehicle type operating within the given constraints.

TABLE 11. SUMMARY OF PREDICTIVE EQUATIONS DEVELOPED FOR TRUCKS ON GRADES

			Characteristics of Equations					
Equation Number	Site Location	Vehicle Type	Sample Size	R^2	Coefficient of Variation (%)	Length of Section (ft)	Weighted Percent Grade	Number of Variables in Equation
1	US 183	SU-2D	69	.7721	9.9	3,450	4.8	16
* 2	US 183	2-S2	19	.9818	5.4	3,450	4.8	13
3	US 183	3-S2	37	.8944	6.85	3,450	4.8	29
4	US 183	3-S2	127	.8309	10.84	3,450	4.8	21
5	US 59A	3-S2	37	.7837	9.39	2,500	3.5	9
6	US 59B	3-S2	37	.8838	9.66	5,700	2.6	15
** 7	US 59C	3-S2	34	.7106	9.96	2,700	3.7	18
* 8	US 59D	3-S2	20	.6463	8.56	3,300	2.6	18
* 9	US 183 US 59ABC	2-S1	15	.8653	9.6	3,040	4.9	10
10	US 59ABC	2-S2	43	.8657	11.23	3,588	3.1	6
11	US 59A	LOG	37	.8275	9.2	2,500	3.5	14
12	US 59B	LOG	37	.9244	8.5	5,700	2.6	23
** 13	US 59C	LOG	31	.7824	10.7	2,700	3.7	12
*** 14	US 59B	3-S2	26	.9178	7.98	2,900	-2.3	7

* Not considered, sample size too small.

** Not usable, equation invalid.

*** Downgrade.

TABLE 12. SUMMARY OF PREDICTIVE EQUATIONS DEVELOPED FOR RECREATIONAL VEHICLES

			Characteristics of Equations					
Equation Number	Site Location	Vehicle Type	Sample Size	R^2	Coef. of Variation (%)	Length of Section (ft)	Weighted Percent Grade	Number of Variables in Equation
1	FM 3159	Boats	35	.72	8.9	6,500	4.3	11
2	FM 3159	Boats	18	.78	8.0	6,500	4.3	11
3	FM 3159	Boats	18	.83	7.0	6,500	4.3	16
4	FM 3159	Boats (downgrade)	35	.38	11.9	1,600	1.7	3
5	US 183	Truck campers	20	.78	7.7	3,450	4.4	8
6	US 183	Travel trailers	19	.82	7.0	3,450	4.4	9
7	US 183	Boats Rental trailers Camping trailers	15	.82	4.3	3,450	4.4	13
8	US 183	Pickup covers	16	.73	7.9	3,450	4.4	5
9	US 183	Motor homes	16	.82	6.5	3,450	4.4	10
10	US 183	Vans	11	.81	8.7	3,450	4.4	10
11	US 183	Travel trailers Boats Camping trailers Rental trailers	34	.85	6.6	3,450	4.4	10
12	US 183	Motor homes Pickup covers Truck campers	52	.74	8.1	3,450	4.4	8

(Continued)

TABLE 12. (CONTINUED)

Equation Number	Site Location	Vehicle Type	Characteristics of Equations					
			Sample Size	R^2	Coef. of Variation (%)	Length of Section (ft)	Weighted Percent Grade	Number of Variables in Equation
13	US 183	Cars Vans	16	.78	8.1	3,450	4.4	9
14	US 183	Motor homes Travel trailers Truck campers	55	.76	8.3	3,450	4.4	7
15	US 183	Motor homes Truck campers	36	.77	7.6	3,450	4.4	10
16	US 183	Pickup covers Vans Cars	32	.72	8.6	3,450	4.4	10
*17	US 183	Vans Pickup covers	27	.76	8.3	3,450	4.4	9
18	US 183	All categories	86	.75	8.2	3,450	4.4	7
19	SH 71	Travel trailers Rental trailers Camping trailers	27	.70	7.9	6,500	3.9	13
20	SH 71	Motor homes	19	.66	7.4	6,500	3.9	10
21	SH 71	Truck campers	21	.68	7.0	6,500	3.9	12
22	SH 71	Boat trailers	57	.66	8.0	6,500	3.9	12
23	SH 71	Travel trailers Truck campers Motor homes	56	.57	9.0	6,500	3.9	11

(Continued)

TABLE 12. (CONTINUED)

Equation Number	Site Location	Vehicle Type	Characteristics of Equations: Sample Size	R^2	Coef. of Variation (%)	Length of Section (ft)	Weighted Percent Grade	Number of Variables in Equation
24	SH 71	Motor homes Truck campers	40	.50	8.8	6,500	3.9	11
25	SH 71	Boats Rental trailers Camping trailers	68	.60	8.6	6,500	3.9	12
26	SH 71	Travel trailers	16	.73	7.5	6,500	3.9	13
*27	SH 71	Travel trailers Truck campers Motor homes (downgrade)	56	.49	8.8	1,400	.5	9
28	SH 71	Boats Rental trailers Camping trailers	68	.53	8.3	1,400	.5	9
*29	SH 71 FM 3159	Boat trailers	92	.65	8.9	6,500	3.9-4.4	12
*30	SH 71 FM 3159	Boats Rental trailers Camping trailers (downgrade)	103	.47	9.9	1,600	.5-1.7	6
31	SH 71 US 183	Truck campers Pickup covers	57	.65	8.3	6,500	3.9-4.4	12
*32	SH 71 US 183	Truck campers	41	.66	7.8	6,500	3.9-4.4	11

(Continued)

* Equations used to represent operating characteristics on grades for recreational vehicles.

TABLE 12. (CONTINUED)

Equation Number	Site Location	Vehicle Type	Characteristics of Equations					
			Sample Size	R^2	Coef. of Variation (%)	Length of Section (ft)	Weighted Percent Grade	Number of Variables in Equation
*33	SH 71 US 183	Travel trailers	35	.69	8.3	6,500	3.9-4.4	11
*34	SH 71 US 183	Motor homes	35	.68	7.7	6,500	3.9-4.4	14
*35	SH 71 US 183	Rental trailers Camping trailers	20	.68	6.8	6,500	3.9-4.4	14

* Equations used to represent operating characteristics on grades for recreational vehicles.

CHAPTER 7. TRUCK STUDY

After arraying the data, a total of 431 truck speed histories were available for analysis. Table 13 shows the number of vehicles by classification and grade location.

SELECTING THE BEST EQUATIONS

Examination of Table 11 reveals that most of the equations have an R^2 in the range of 75 to 95 percent. When considering an acceptable R^2, it should be remembered that the highly variable human element is being combined with differing vehicle characteristics. By comparison, Table 12 shows that the R^2 range for recreational vehicles is 50 to 80 percent. This tends to add validity to the notion that professional truck drivers have more similar or uniform driving habits than the "amateur" recreational vehicle operators. To show the effect of the human element in vehicle performance, an analysis was made with a reduced sample of 3-S2 semi-trailers on U. S. 183 (see Eqs 3 and 4, in Table 11). A total of 37 questionnaires with driver experience and age of driver information were returned. The equation in which the driver experience and age of driver information were used produced an R^2 that was 5 percent higher and a coefficient of variation 4 percent lower than the equation without driver experience and age of driver.

From these comparisons it can be observed that the human element may have a significant effect on vehicle operating characteristics on grades. The average truck operator tends to drive in a more consistent manner than a recreational vehicle driver; by introducing the human element in the analysis, an additional 5 percent of the variation about the mean can be explained (R^2) and at the same time the relative variation of the error is decreased. It was not possible to incorporate driver experience and age of driver into all of the equations since in the case of U. S. 183 only 40 percent of all the questionnaires mailed were returned, and for U. S. 59 less than 30 percent were returned.

TABLE 13. NUMBER OF SPEED HISTORIES COLLECTED BY LOCATION AND VEHICLE CLASSIFICATION

Vehicle Type	Grade				
	U.S. 183	U.S. 59			
		A	B	C	D
	1	2	3	4	5
SU-2A	15	-	-	-	-
SU-2D	69	-	-	-	-
SU-3A	0	-	-	-	-
SU-3D	7	1	1	1	1
2-S1	12	1	1	1	-
2-S2	19	16	15	12	2
3-S1	2	-	-	-	-
3-S2	127	37	37	34	20
Total	251	55	54	48	23

After carefully analyzing the 14 equations summarized in Table 11, and evaluating such factors as R^2, sample size, length of grade, vehicle type, and coefficient of variation, eight equations were selected to represent the operating characteristics of trucks on upgrades.

Upgrade

The equations selected were T1, T2, T3, T5, T6, T10, T11, and T12. They represent the vehicle operating characteristics of single unit trucks and semi-trailers. Two of the equations, T11 and T12, represent log trucks. All of the eight equations have sample sizes above the minimum of 22 vehicles. Most of the equations have a correlation (R^2) above 83 percent. The coefficient of variation is within 10 for all but one equation.

Downgrade

Of interest to the researchers was the ability of trucks to begin accelerating after cresting the incline. The intent initially was to gather sufficient field data in order to evaluate design charts for determining the length of the extra lane required to provide for adequate and safe merging of trucks into the main traffic stream. In other words, how far should highway designers recommend providing an additional lane with taper beyond the crest of the hill?

The sites selected for the major element of the study, upgrade, did not lend themselves to describing adequately the performance of trucks on a downgrade; therefore, this analysis was eliminated with the recommendation that current design charts be utilized. This is felt to be consistant with current procedures since the length of the additional lane and the taper are much shorter in length than climbing lanes. It is recommended that the practice of continuing the lane beyond the crest be continued with adequate length as determined by the relative safe speed differential between the main stream traffic and merging vehicles.

APPLICATIONS OF PREDICTIVE EQUATIONS

Figures 14-18 show the grade profiles of each hill over which data were collected. It can be seen that the equations have been developed using a range of percent grade of 0 to 6 and a distance of 0 to 6,500 feet. By

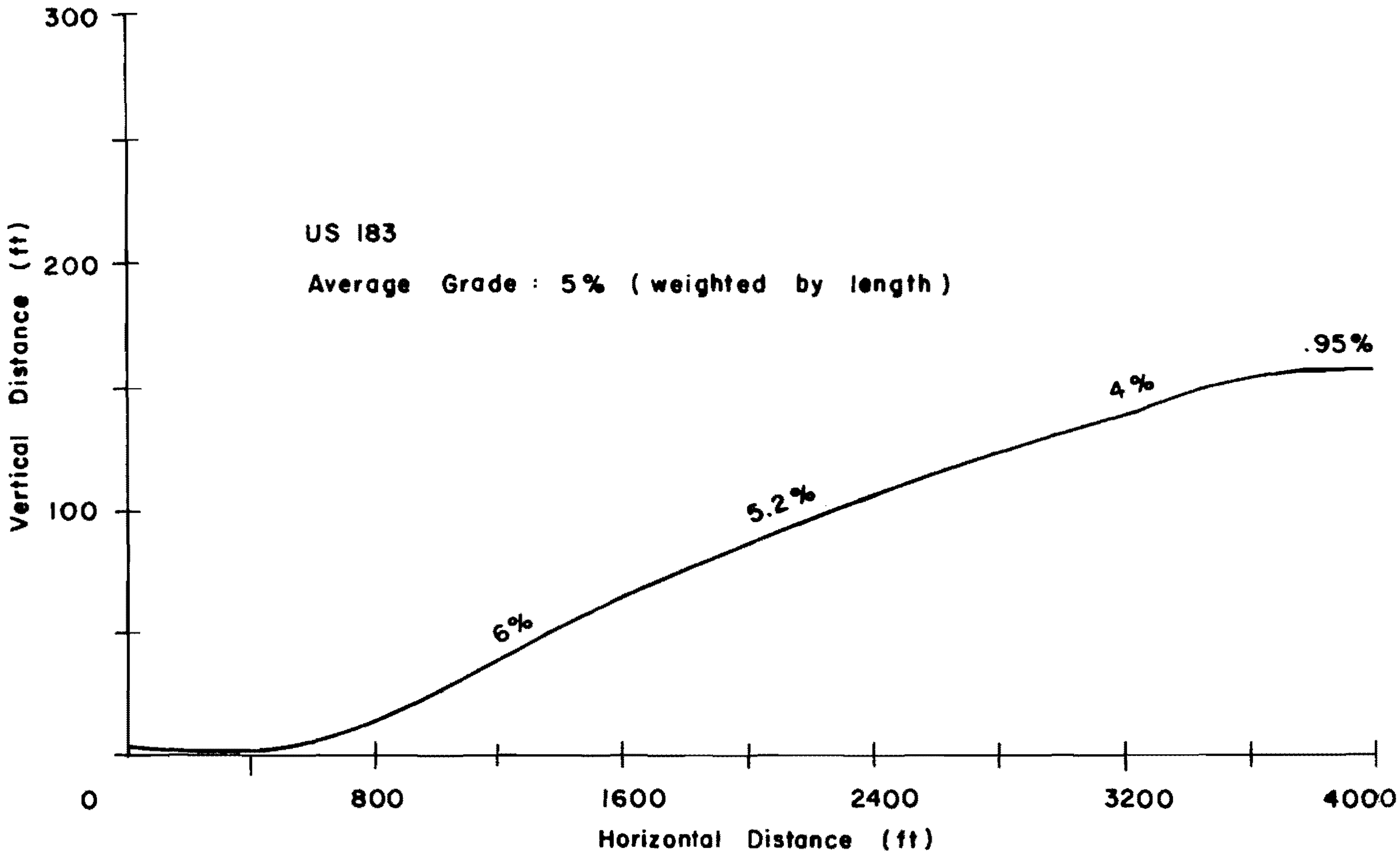


Fig 14. Vertical profile at site 1.

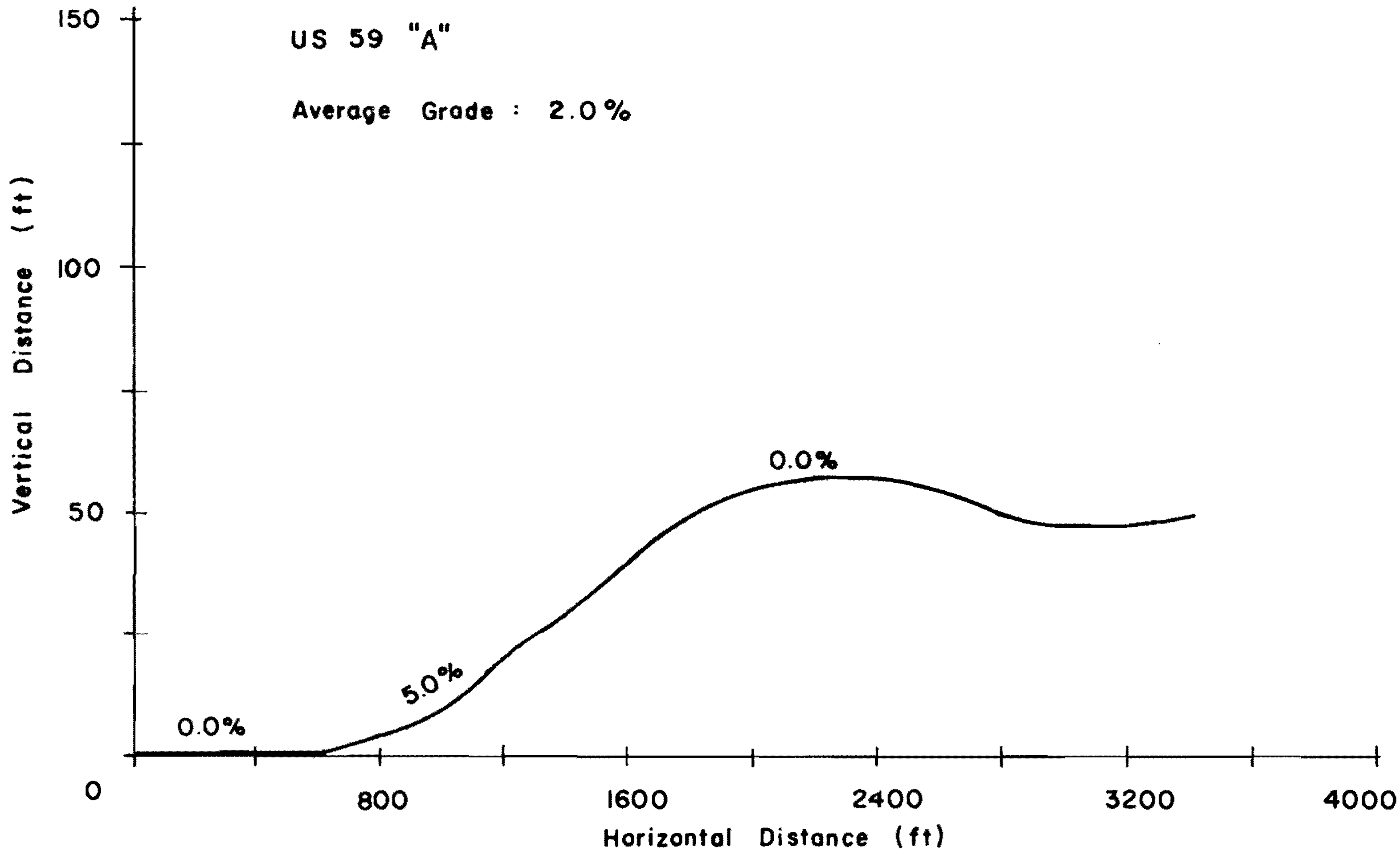


Fig 15. Vertical profile at site 2.

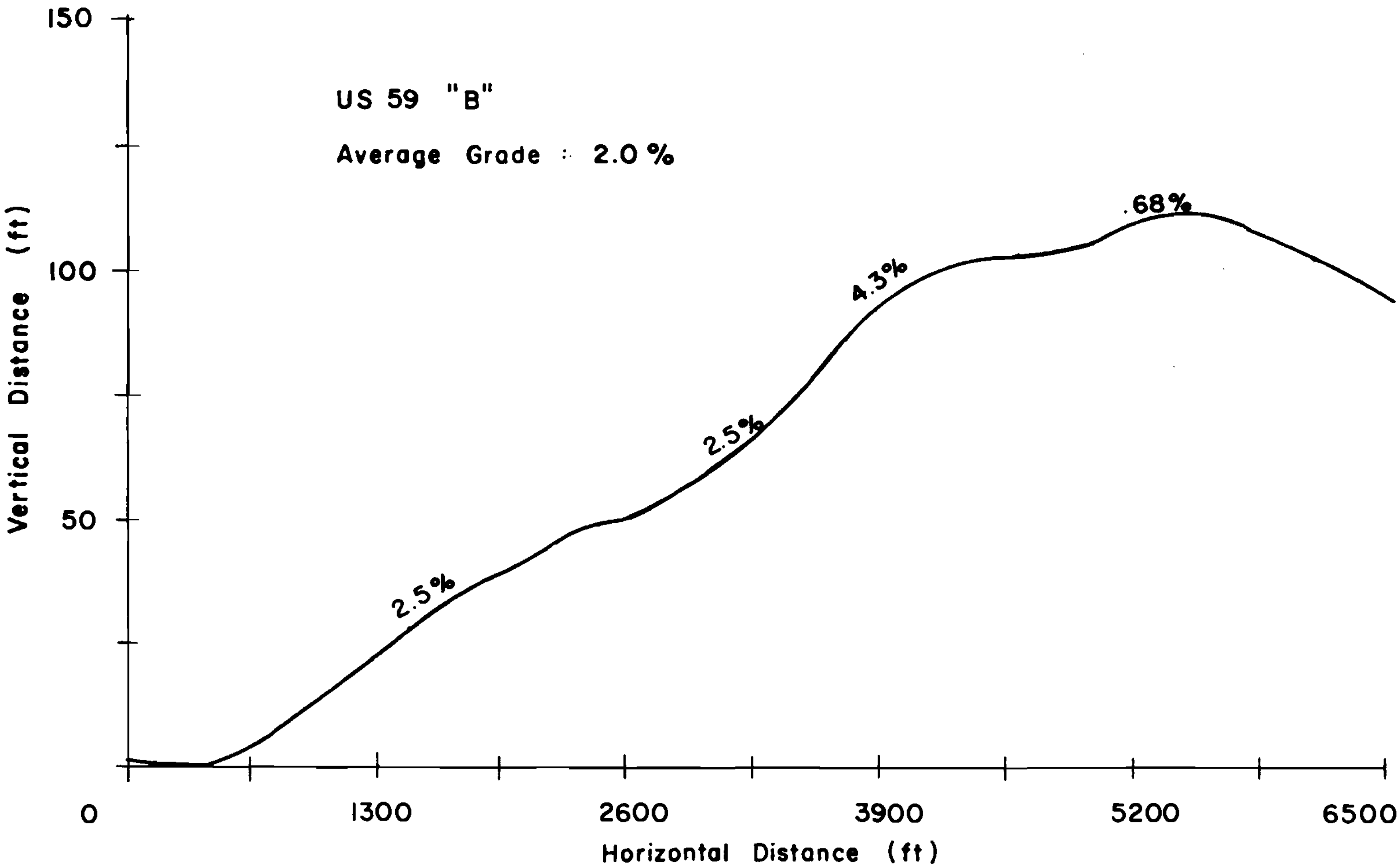


Fig 16. Vertical profile at site 3.

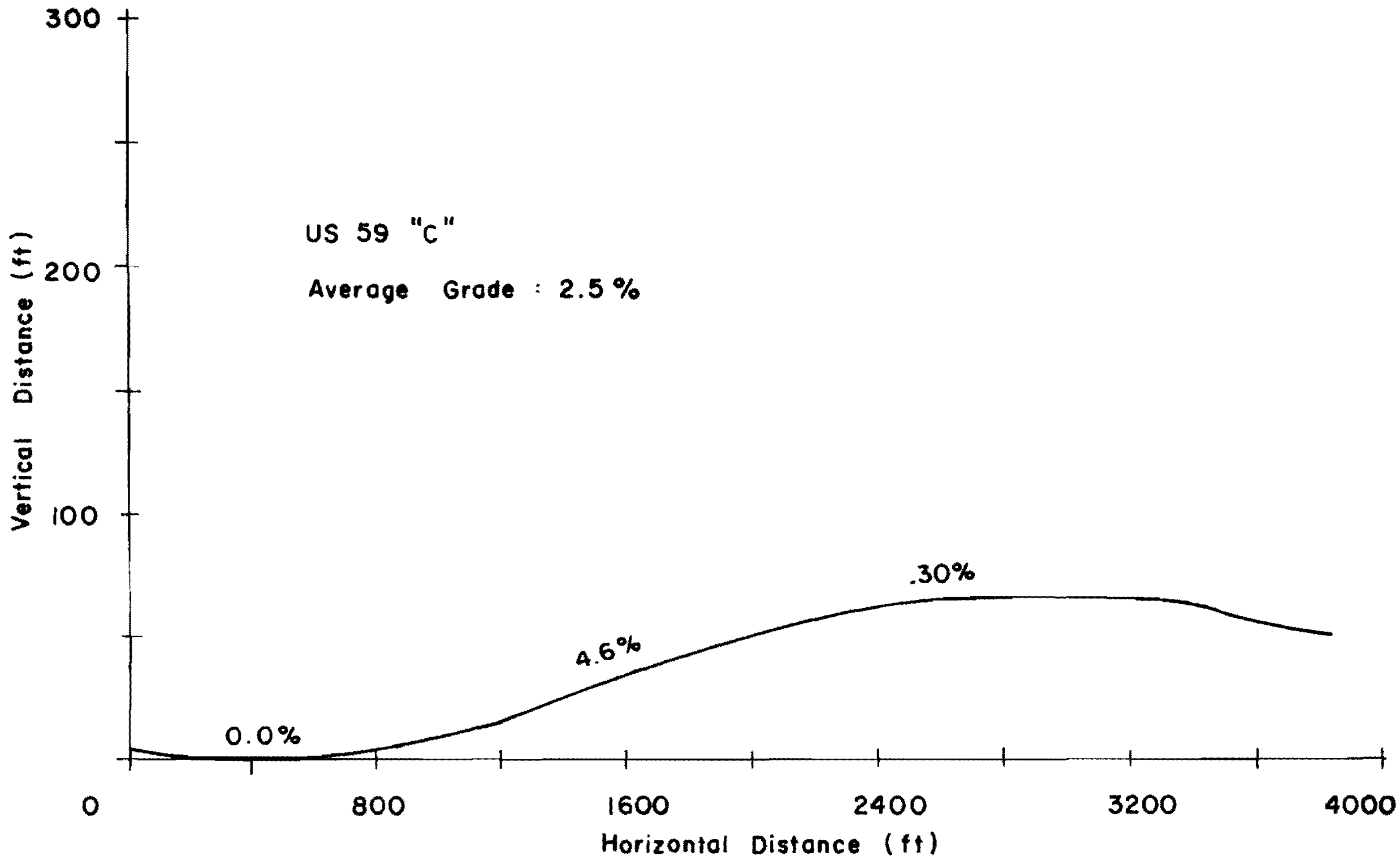


Fig 17. Vertical profile at site 4.

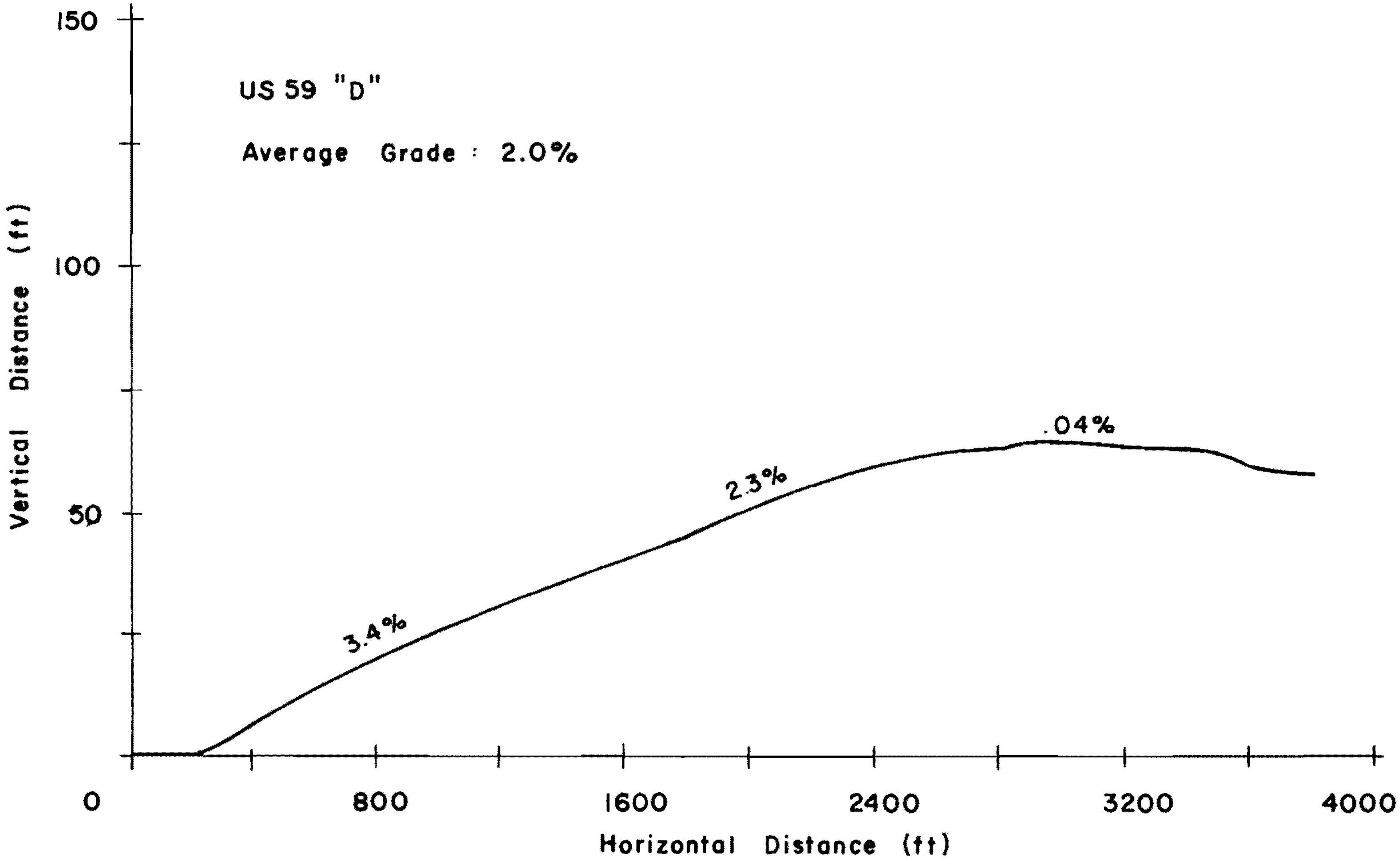


Fig 18. Vertical profile at site 5.

using a weighted average percent grade of the tangent section only and the corresponding distance to represent the characteristics of each site, the resulting range of percentage and distance for each site is determined (Table 14).

Speed Profiles

From the information presented in Table 14 and from weighted average grade profiles for the entire length of each grade, curves were plotted, applying the predictive equations. The average values for the variables in each equation are presented in Table 15. Some of the resulting speed profiles are presented in Figs 19-22. The y-axis represents the speed in miles per hour and the x-axis gives the length of grade in feet (from the vertical point of curvature).

The data for this analysis were collected before implementation of the 55 mph speed limit. State Department of Highways and Public Transportation investigators asked project personnel if this new design criteria could be implemented into the analysis. Research was conducted and it was concluded that the 55 mph design approach speed was justified.

As approach speed was changed within the equations to account for different truck speeds entering a grade, the reliability of the predictive equation dropped. In other words, when the specified approach speed exceeded the limits defined by the standard deviation for that equation, the predicted initial speed also varied significantly. The general shape and total speed loss, however, remained approximately the same for a majority of the curves. The overall complexity of the equations and the nature of the correlation analysis led to the observation that the predictive equations are most valuable when used with approach speeds that fall within the limits of the equation. For this reason, the equations were initially developed using the mean approach speeds, representing one standard deviation about the mean (68 percent of the data). As can be seen from Table 16, 55 mph fell within each particular range.

Table 17 summarizes total speed loss for different classes of trucks and truck combinations. The greatest speed loss was realized by 3-S2 semi-trailer combinations and by log trucks, characterized by equations T3, T5, T6, T11, and T12.

TABLE 14. RANGE OF PERCENT GRADE FOR SITE LOCATIONS

Site	Average Percent Grade*	Distance (ft)	Comments
US 183	6.00	1,500	Upgrade
	5.00**	3,000	Upgrade
US 59A	5.00	1,500	Upgrade
	0.00	1,000	Level
US 59B	2.50	4,000	Upgrade
	3.00	3,200	Upgrade
	-2.87****	2,900	Downgrade
US 59C***	4.00	1,700	Upgrade

*Average percent grade of tangent section only.

**The grade varies from 4 to 6 percent, and 5 percent is used as an average.

***Not used after analysis of speed profiles. Equation inadequate.

****The grade varies from -2.35 to -3.387 percent, and -2.87 is used as an average.

TABLE 15. CHARACTERISTICS OF TRUCKS BY VEHICLE TYPE AND SITE LOCATION USED IN DEVELOPING SPEED-DISTANCE CURVES*

	Site Location	Vehicle Type	Vehicle Characteristics: Approach Speed (mph)	Horsepower (Net)	Gross Weight (lb)	Weight/ Horsepower	Age of Vehicle (years)	Frontal Area**	Side Area**
1	US 183	SU-2D	57.8	166	18,097	108	5.89	3.5	6.4
2	US 183	2-S2	55.9	186	33,194	176	3.76	5.3	2.1
3	US 183	3-S2	61.7	222	46,347	213	3.6	5.3	2.0
4	US 183	3-S2	60.2	212	47,571	230	4.15	4.6	2.3
					46,959				
5	US 59A	3-S2	60.1	202	75,716	367	2.46	2.9	3.9
6	US 59B	3-S2	54.8	200	74,814	375	2.66	3.2	3.6
7	US 59C	3-S2	61.97	204	74,474	367	2.6	3.2	3.6
8	US 59D	3-S2	55.4	218	70,300	327	2.85	4.6	2.3
					73,826	359			
9	US 59ABC	2-S2	49.9	186	68,093	367	4.02	3.0	5.0
10	US 59A	LOG	55.0	191	74,818	392	3.24	2.9	-
11	US 59B	LOG	48.0	195	75,259	378	3.14	2.8	-
12	US 59C	LOG	57.8	195	74,761	385	3.13	2.9	-
					74,946	385			
13	US 183	2-S1	49.9	158	27,297	172	5.17	3.0	5.0
14	US 59B	3-S2	32.8	203	76,284	378	2.61	3.4	3.4

* Values represent an average (the mean) of those vehicles included in the study.

** Given on a scale from 0 through 9 (presented in Chapter 5).

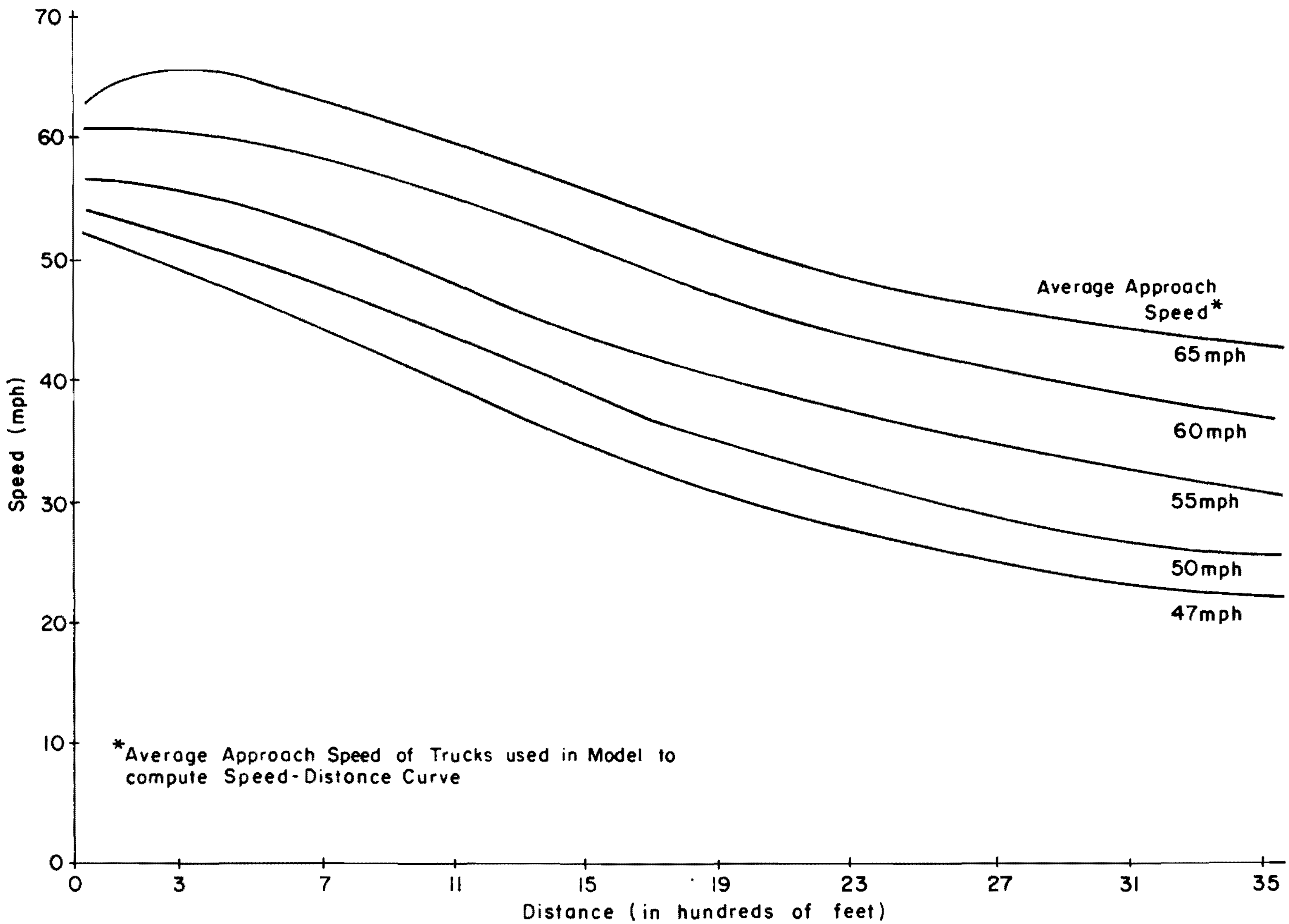


Fig 19. Speed-distance curves for a 3-S2 truck combination on a 3 percent grade.

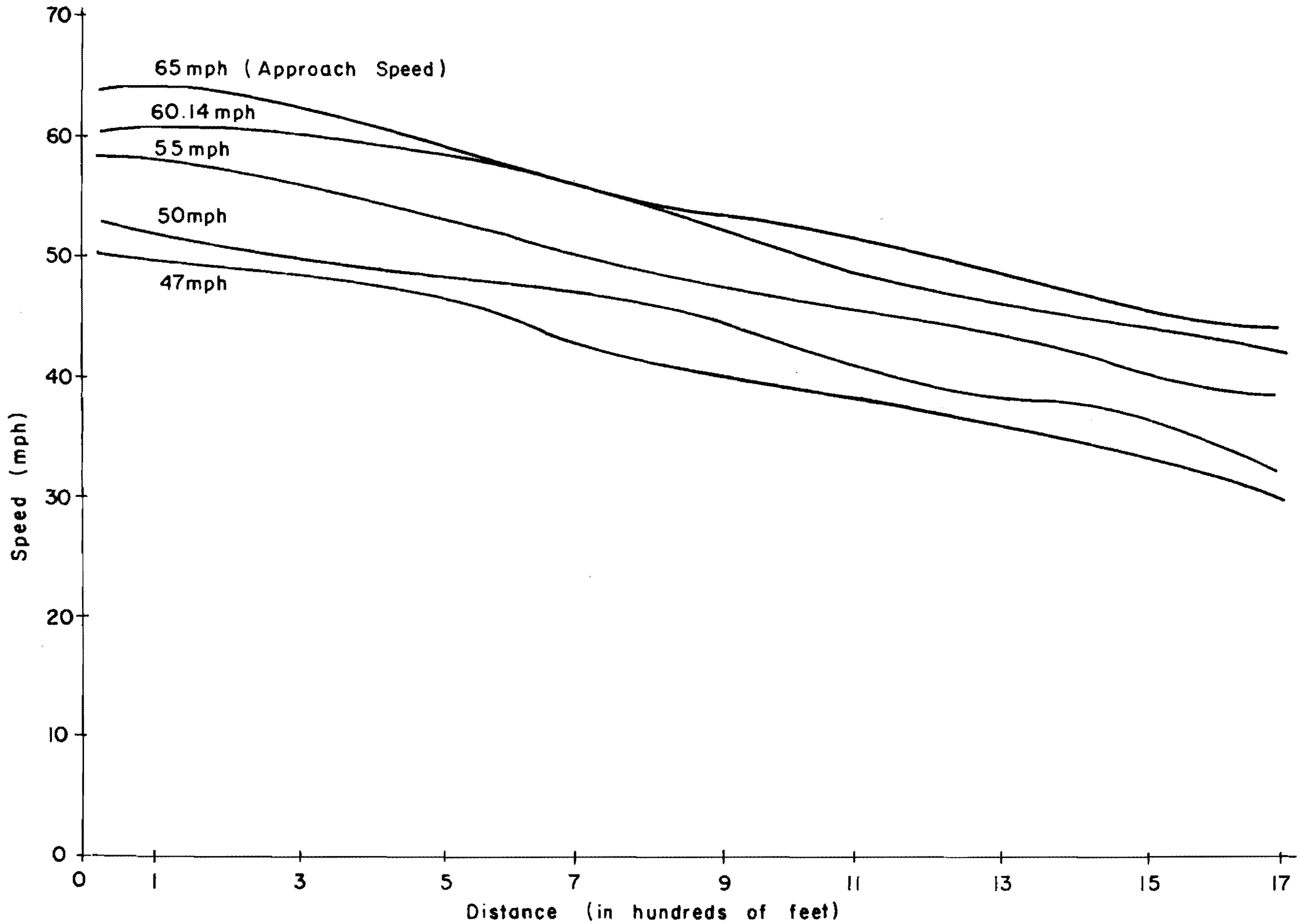


Fig 20. Speed-distance curves for a 3-S2 truck combination on a 5 percent grade.

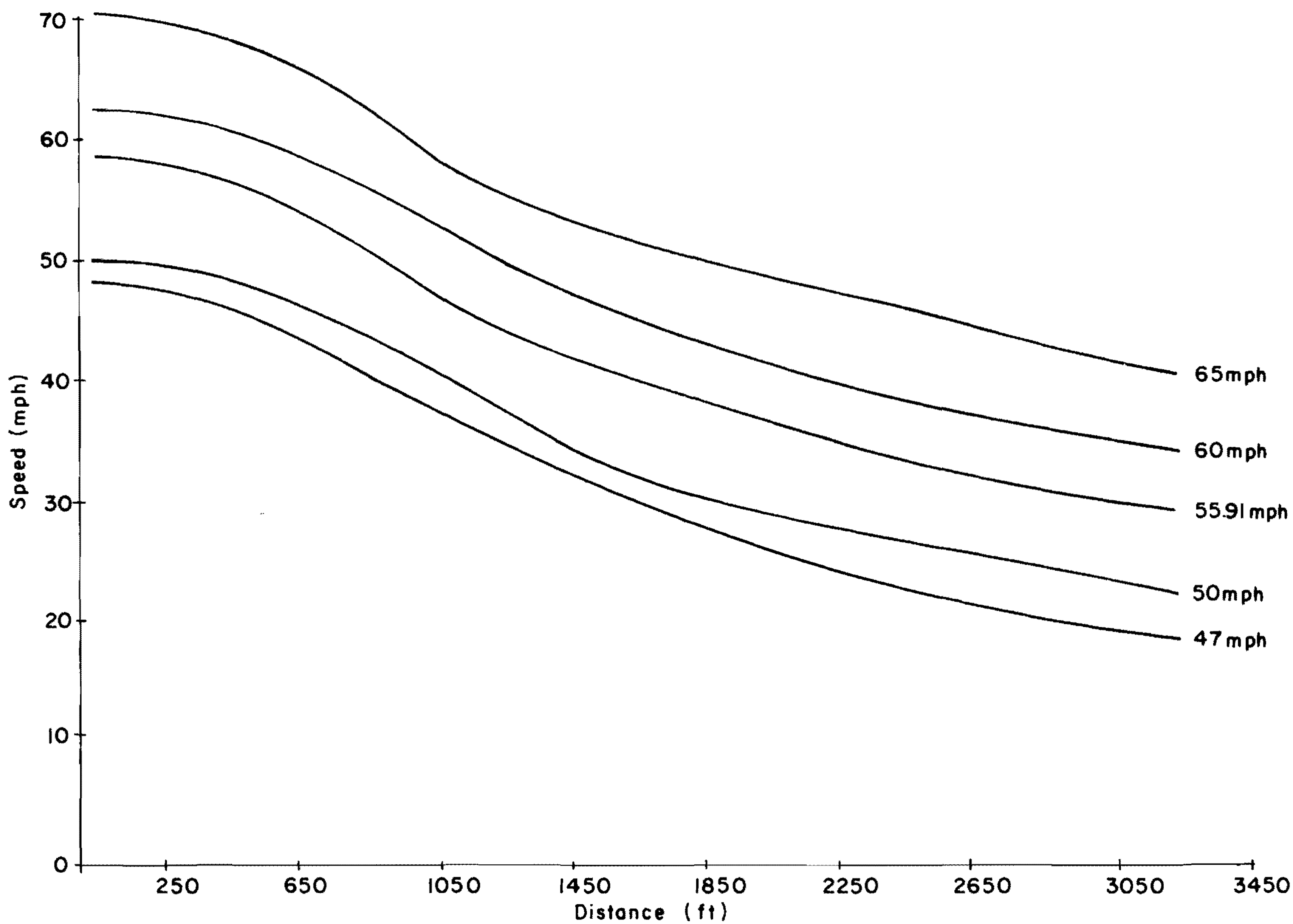


Fig 21. Speed-distance curves for a 2-S2 truck combination on a 5 percent grade.

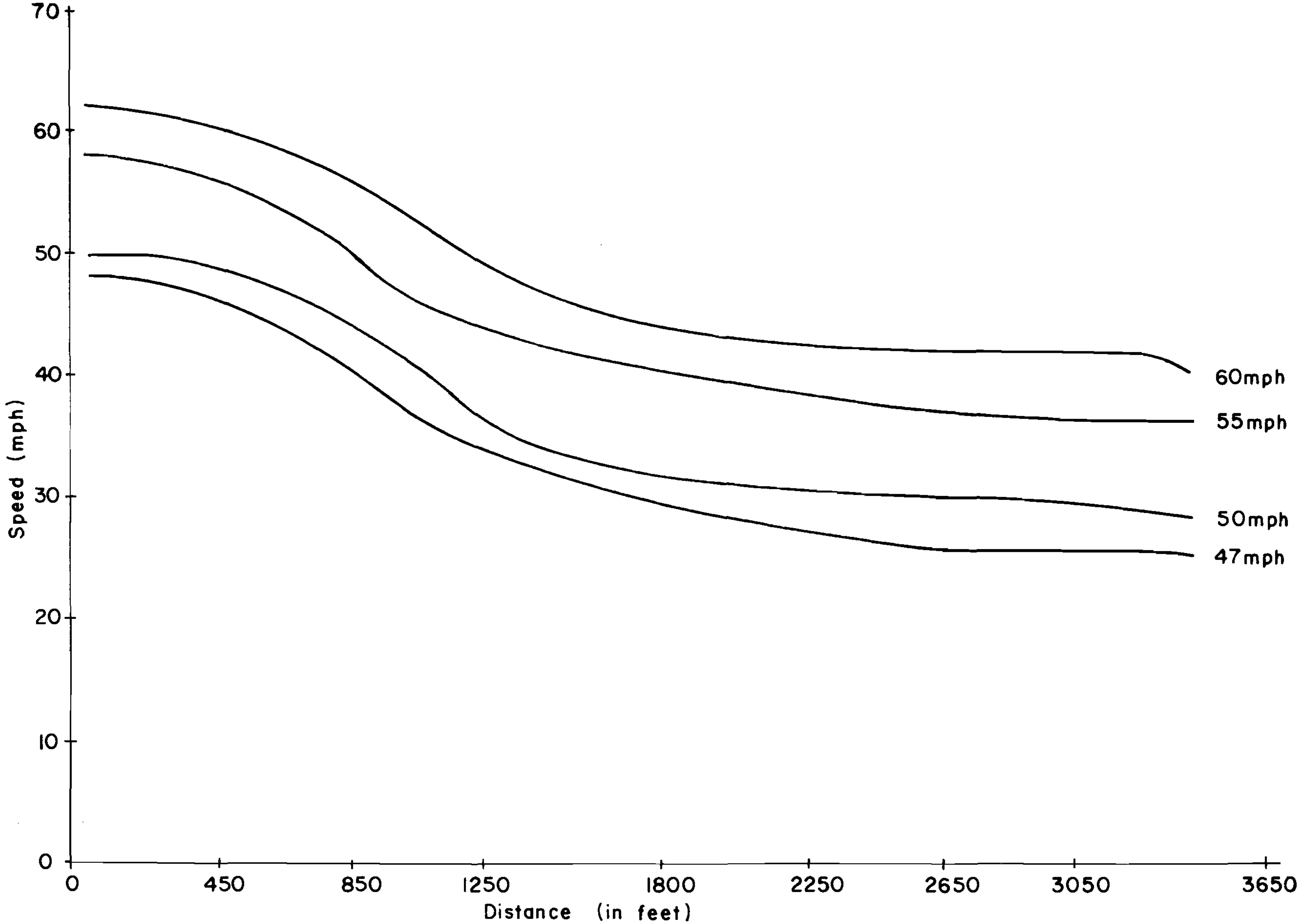


Fig 22. Speed-distance curves for a 2-S2 truck combination on a 6 percent grade.

TABLE 16. APPLICABILITY OF SPEED-DISTANCE CURVES TO VARIOUS APPROACH SPEEDS

Equation Number	Weight/ Horsepower Ratio	Applicable Approach Speed Range	Average* Percent Grade	Figure Number
3	213	55-68	5	23
3	213	55-68	6	23
** 12	378	43-57	2.5	23
** 12	378	43-57	3	Not included in fig
** 11	392	49-62	5	Not included in fig
6	375	48-62	2.5	Not included in fig
6	375	48-62	3	23
5	367	52-69	5	Not included

* Average percent grade of tangent section only

** Log trucks

TABLE 17. TOTAL SPEED LOSS IN MPH FOR DIFFERENT CLASSES OF TRUCKS*

	Vehicle Type				
Average Percent Grade	2D Single Unit	2-S2	3S-2	3S-2 Log	Distance (ft.)
2.5	-	20.7	22.0	23.5	4000
3.0	-	-	26.0	31.5	3200
5.0	-	-	19.9	24.6	1500
5.0	13.5	22.1	38.5	-	3000
6.0	12.5	29.7	42.2	-	1500

*Average speed loss for all approach speeds.

Figure 23 represents truck behavior over selected upgrades presented in Table 14. Figure 23 provides direct comparison between vehicles with different weight/horsepower ratios (213, 375, 378, and 400), varying percent grades (2.5% to 6%), and current design criteria versus criteria developed in this research. The family of curves compare speed versus distance and highlight the difference between current and developed speed-distance relationships. The importance of approach speed is observed by comparing the initial (or entering) speeds given on the figure. Close inspection and comparison with the profiles in Figs 14-18 show that the grades in Table 14 deviate somewhat from each profile in the field. Longer, more consistant grades were created from the existing profiles by changing the grade line within the limits of each equation. This increased the range of profiles available for analysis and provided extra data points for developing critical length of grade curves.

Figure 24 represents the only analysis of truck behavior on a downgrade. As can be seen from Table 15 the equation representing the accleration curve (no. 14 on U. S. 59B) has different variable values from the equation (no. 6) representing the deceleration curve for 3-S2 trucks on U. S. 59B. This was due to the fact that not all the trucks were recorded for the entire length of the downgrade. Therefore, the sample size was smaller and had to be considered separately.

The cumulative distributions of the approach speeds for trucks at each site are shown in Figs 25-29. From these graphs it can be seen that the 85th percentile approach speed is approximately 65 mph. The 85th percentile speed for all trucks on U. S. highways in Texas in 1973 exceeded 60 mph (Ref 73). As mentioned previously, these data were collected before implementation of the 55 mph speed limit. However, even when an approach speed greater than 55 mph is considered, the speed-distance curves presented in Figs 23 and 24 and the critical length of grade curves are still applicable to the speed ranges shown in Table 16.

The average gross-weight-to-net-horsepower ratios on U. S. 59 of 3S-2 combinations and log trucks are 359 and 385 pounds per horsepower, respectively. This compares with an average ratio of 230 pounds per horsepower for all 3S-2 combinations on U. S. 183. Present design procedures are based partly on the assumption that vehicle performance is a function of the weight-to-horsepower ratio. However,

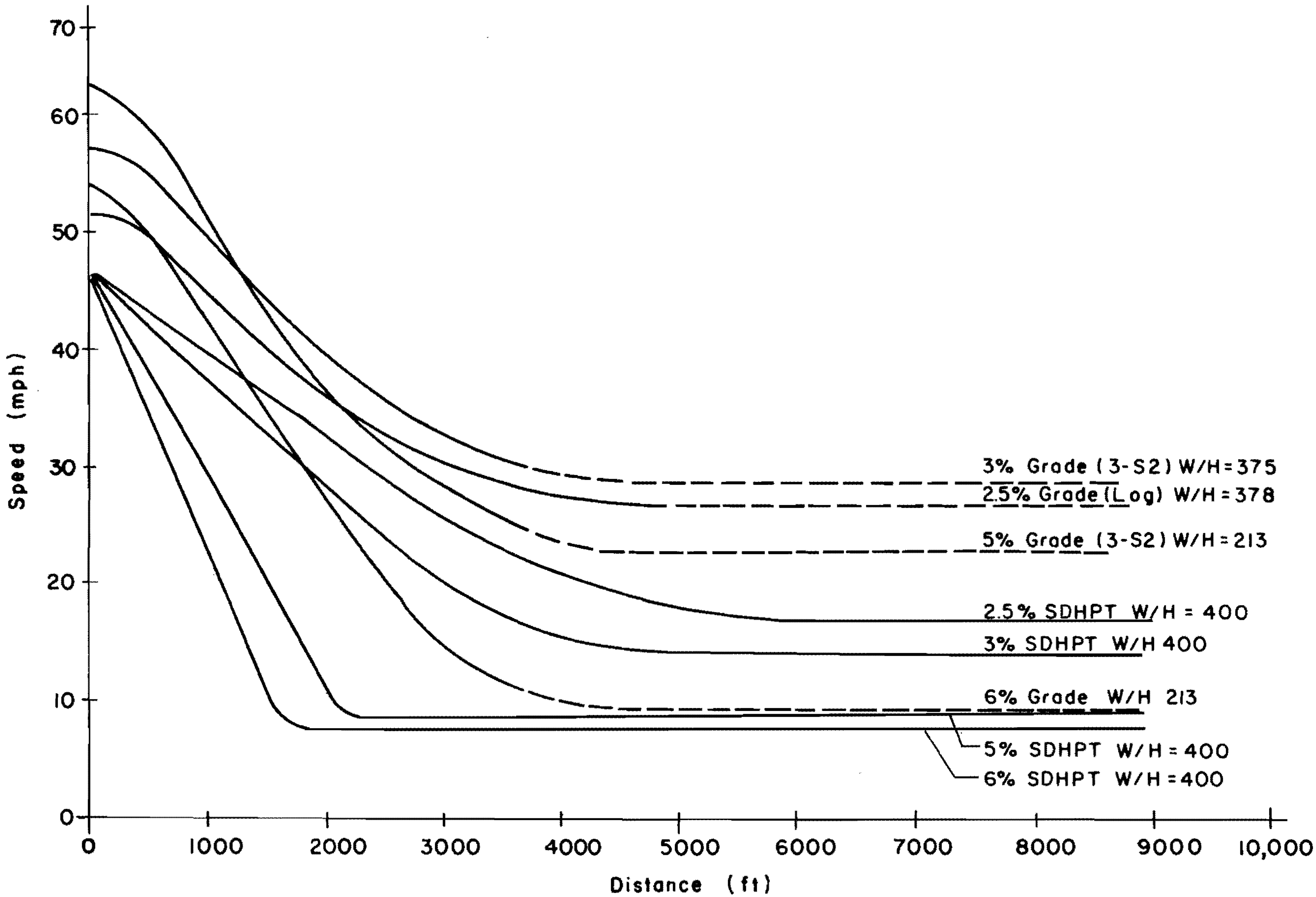


Fig 23. Speed-distance curves for typical heavy trucks as compared with present design curves.

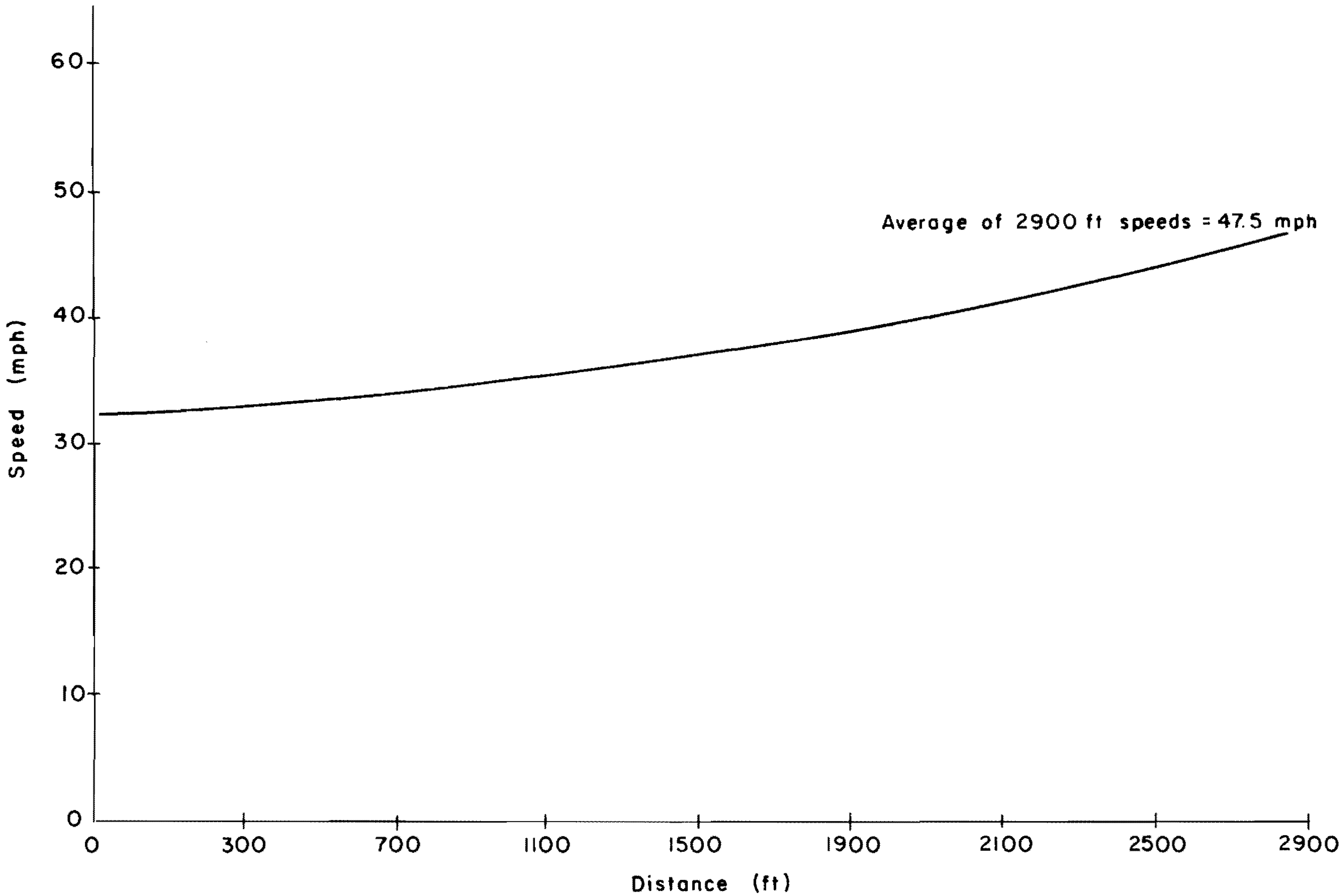


Fig 24. Speed-distance curve for a typical heavy truck on a -2.87 percent grade.

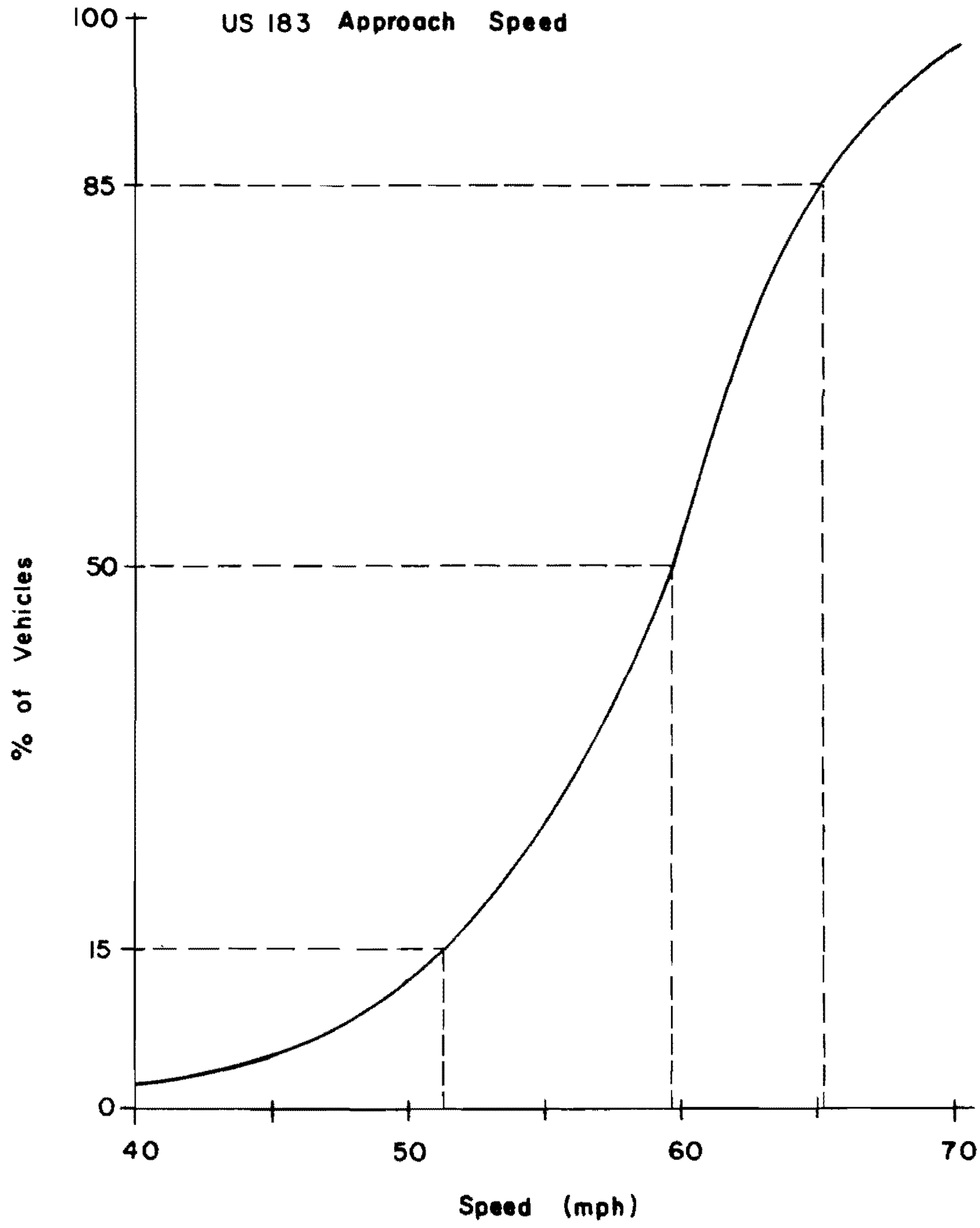


Fig 25. Cumulative distribution of approach speeds for all trucks at site 1.

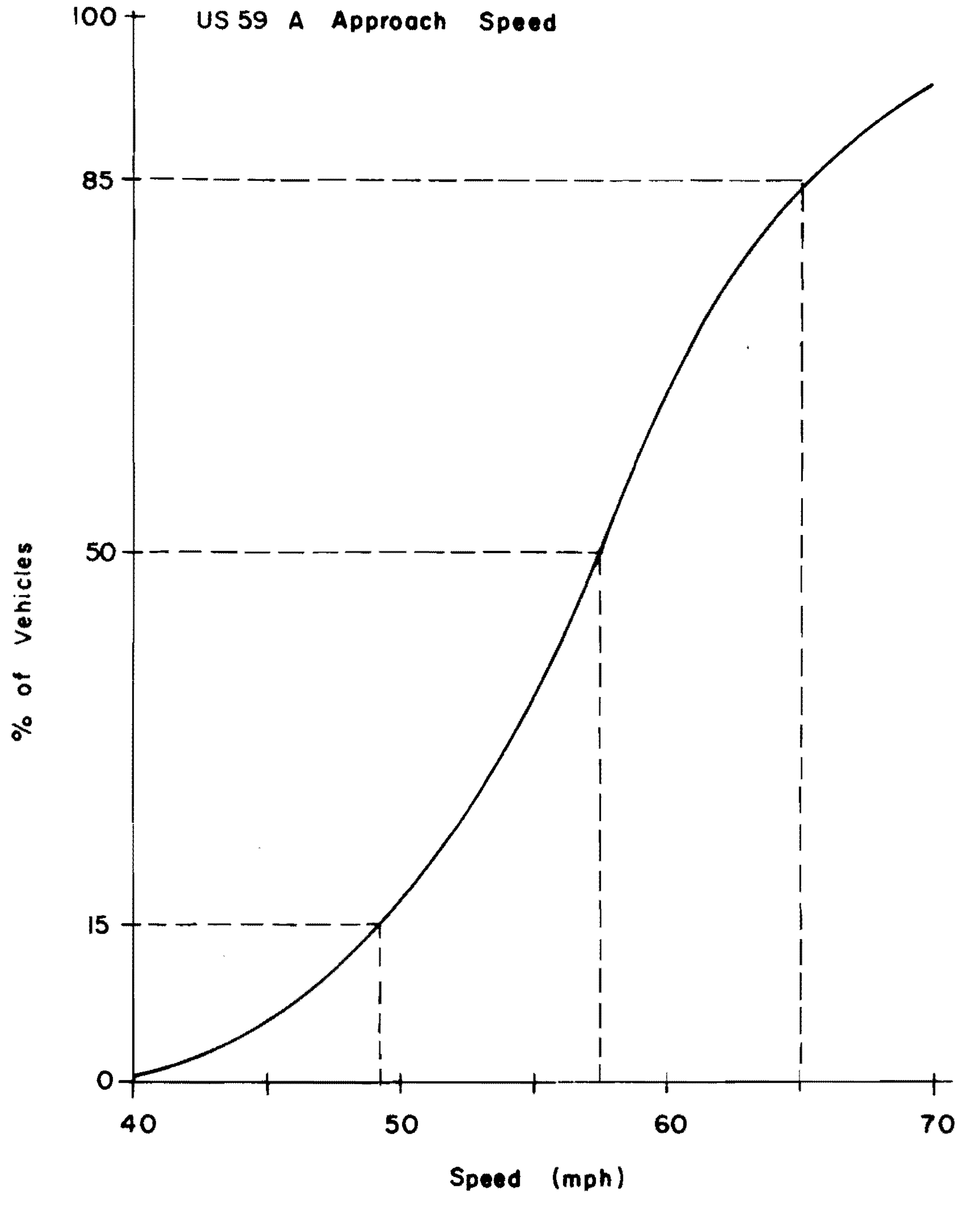


Fig 26. Cumulative distribution of approach speeds for all trucks at site 2.

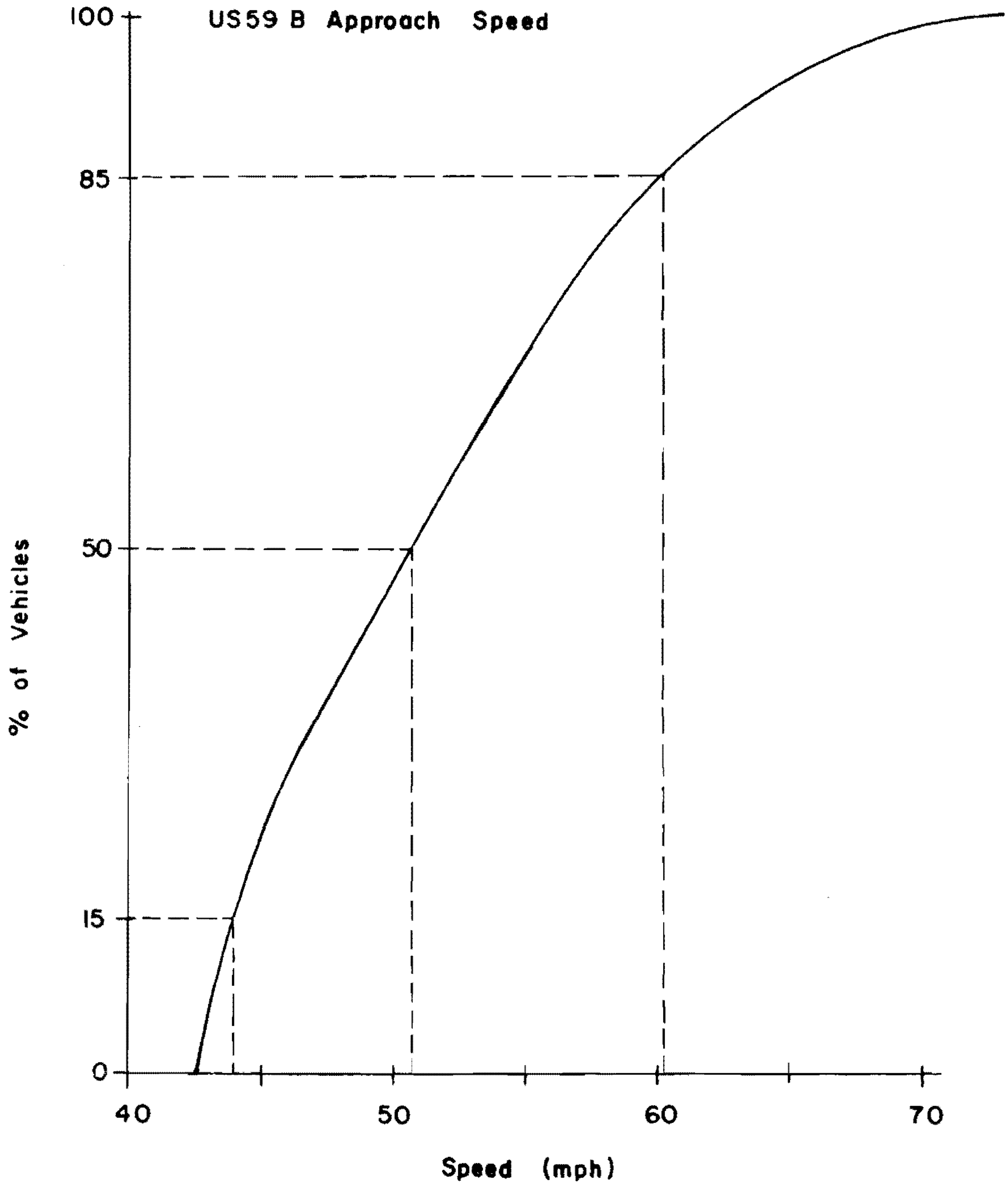


Fig 27. Cumulative distribution of approach speeds for all trucks at site 3.

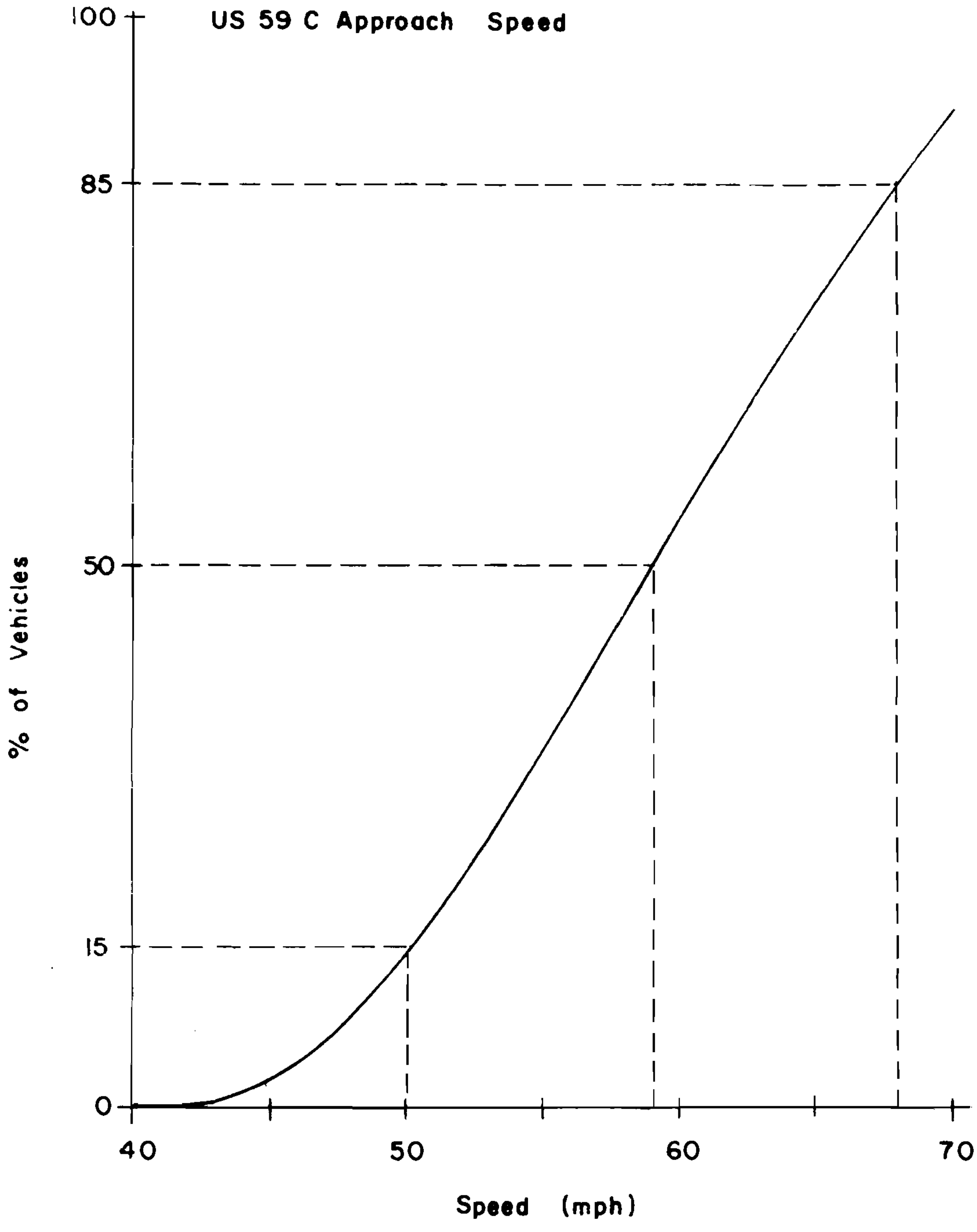


Fig 28. Cumulative distribution of approach speeds for all trucks at site 4.

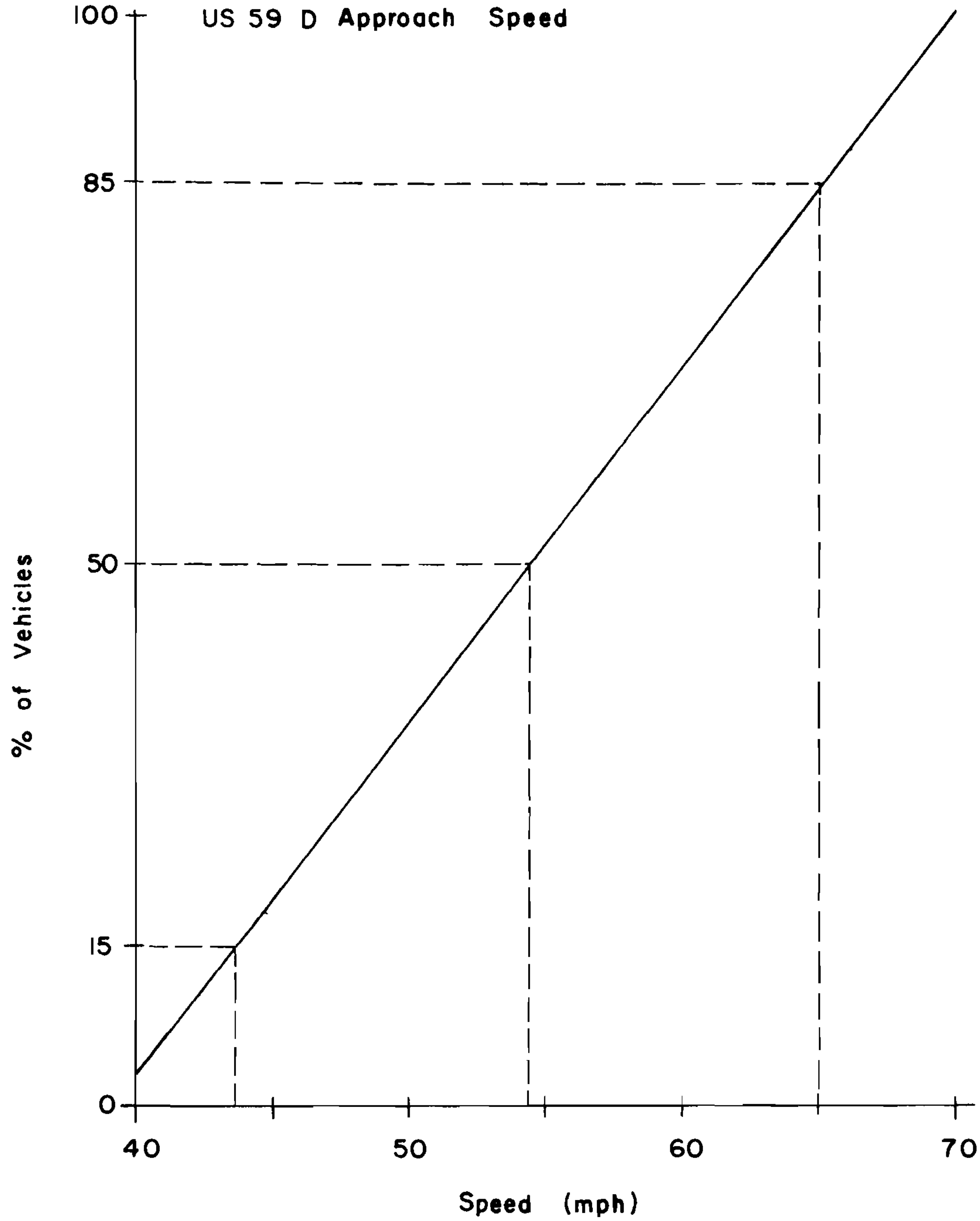


Fig 29. Cumulative distribution of approach speeds for all trucks at site 5.

analysis of Fig 23 shows that there is little difference in the rates of deceleration on the upgrades other than the effect of the entering speed.

CRITICAL LENGTH OF GRADE

As discussed in Chapter 1, the term "critical length of grade" is used to indicate the maximum length of a designated upgrade upon which a vehicle can operate without unreasonable reduction in speed. Using data as presented in Figure 23, a series of critical lengths of grade for 5 mph, 10 mph, 15 mph, and 20 mph reductions in speed are presented in Figs 30 and 31, based on approach speed ranges rather than on specific speeds. The figures cover two speed ranges, 49-54 mph and 52-62 mph. They are representative of trucks with weight-to-horsepower ratios of approximately 370 and 385 pounds per horsepower. Figure 30 was developed from log truck speed profiles. The present critical lengths of grade design curves are presented in Fig 32 for comparison.

The length of grade in feet, starting from the vertical point of curvature, is given on the x-axis and percent upgrade is given on the y-axis. These graphs are representative of all trucks, as they are based on the operating characteristics of the most critical trucks. A reasonably level approach is assumed.

The procedure to be followed in these graphs is indicated in Fig 30. If an average percent grade of 4 is assumed, and an approach speed between 49 and 54 mph the corresponding critical length of grade for a 15 mph speed reduction is 1,240 feet. When the approach speed is in a different range, the critical length of grade is also different. Table 18 shows a comparison of critical lengths of grade between Figs 30, 31, and 32 for a 15 mph speed reduction.

The relationship of approach speed, critical length of grade, and percent grade is not consistent between the two speed range categories. This confirms earlier findings that the distance and percent grade are very important elements in any speed profile for trucks and truck combinations.

From these analyses, composite charts were developed for typical heavy trucks, using an approach speed of 55 mph. Figure 33 shows the critical lengths of grade at different percent grades with associated speed reduction ranging from 5 mph to 20 mph in 5 mph increments.

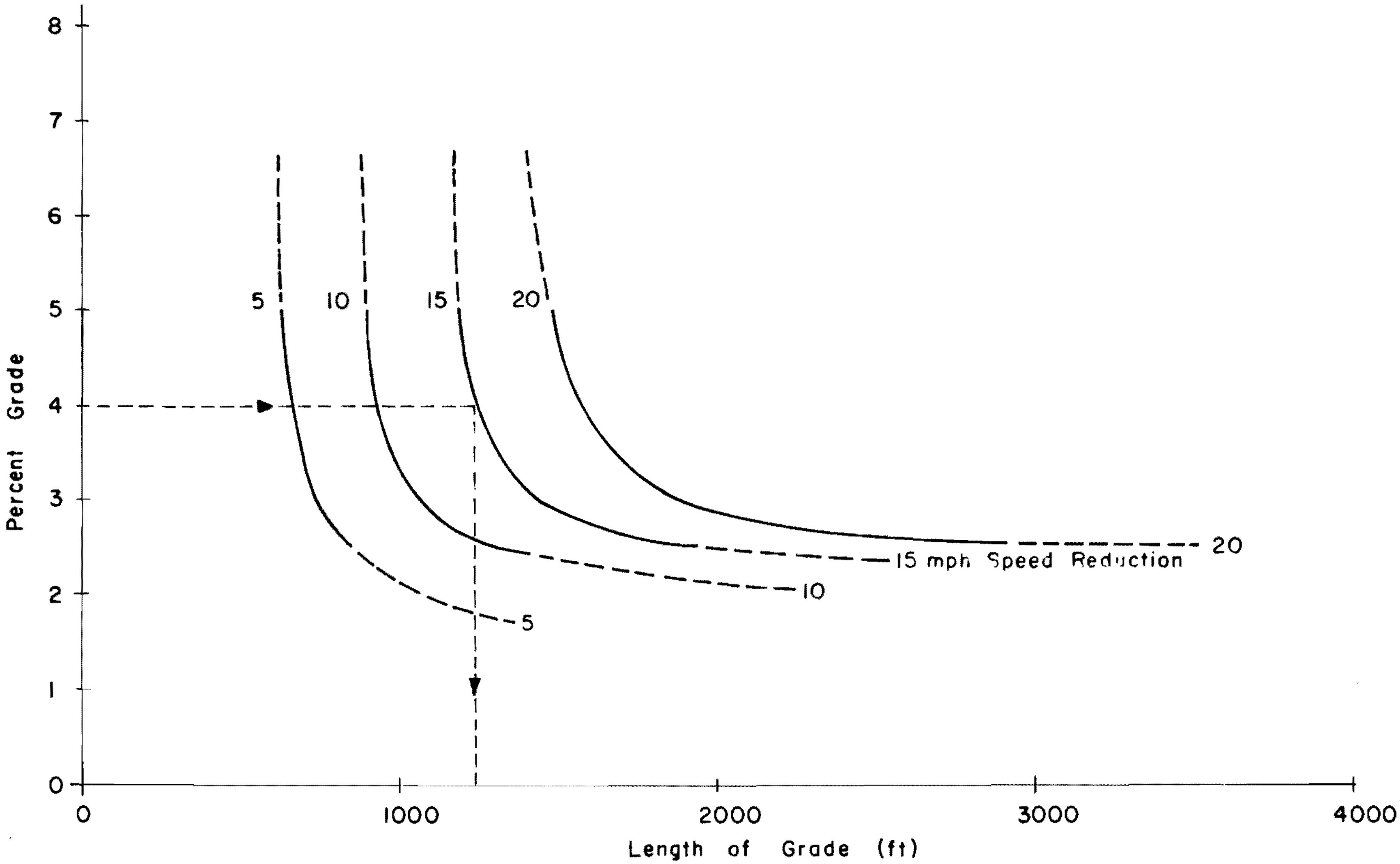


Fig 30. Critical lengths of grade using an approach speed range of 49-54 mph for a truck with a weight/horsepower ratio of 385.

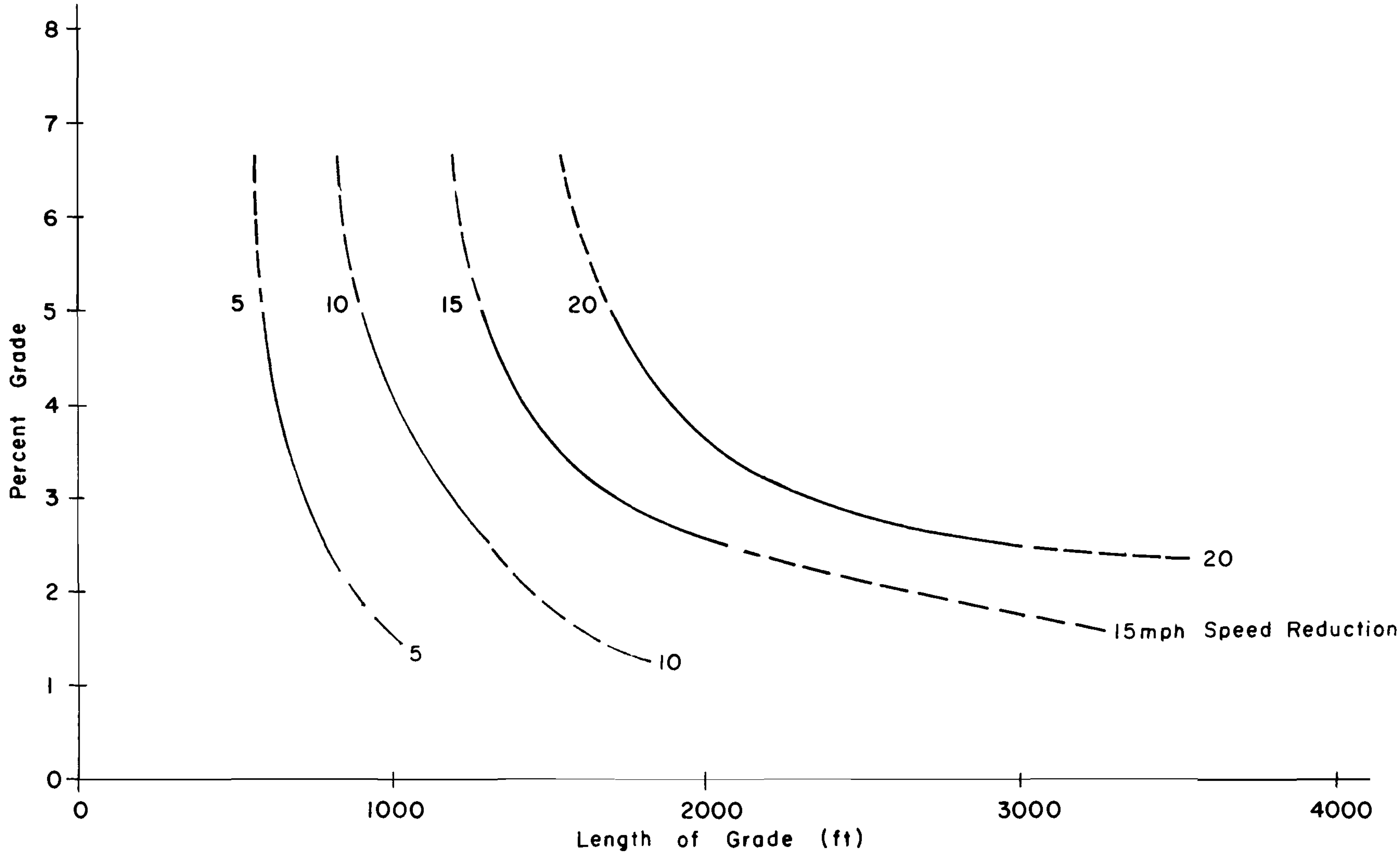


Fig 31. Critical lengths of grade using an approach speed range of 52-62 mph for a truck with a weight/horsepower ratio of 370.

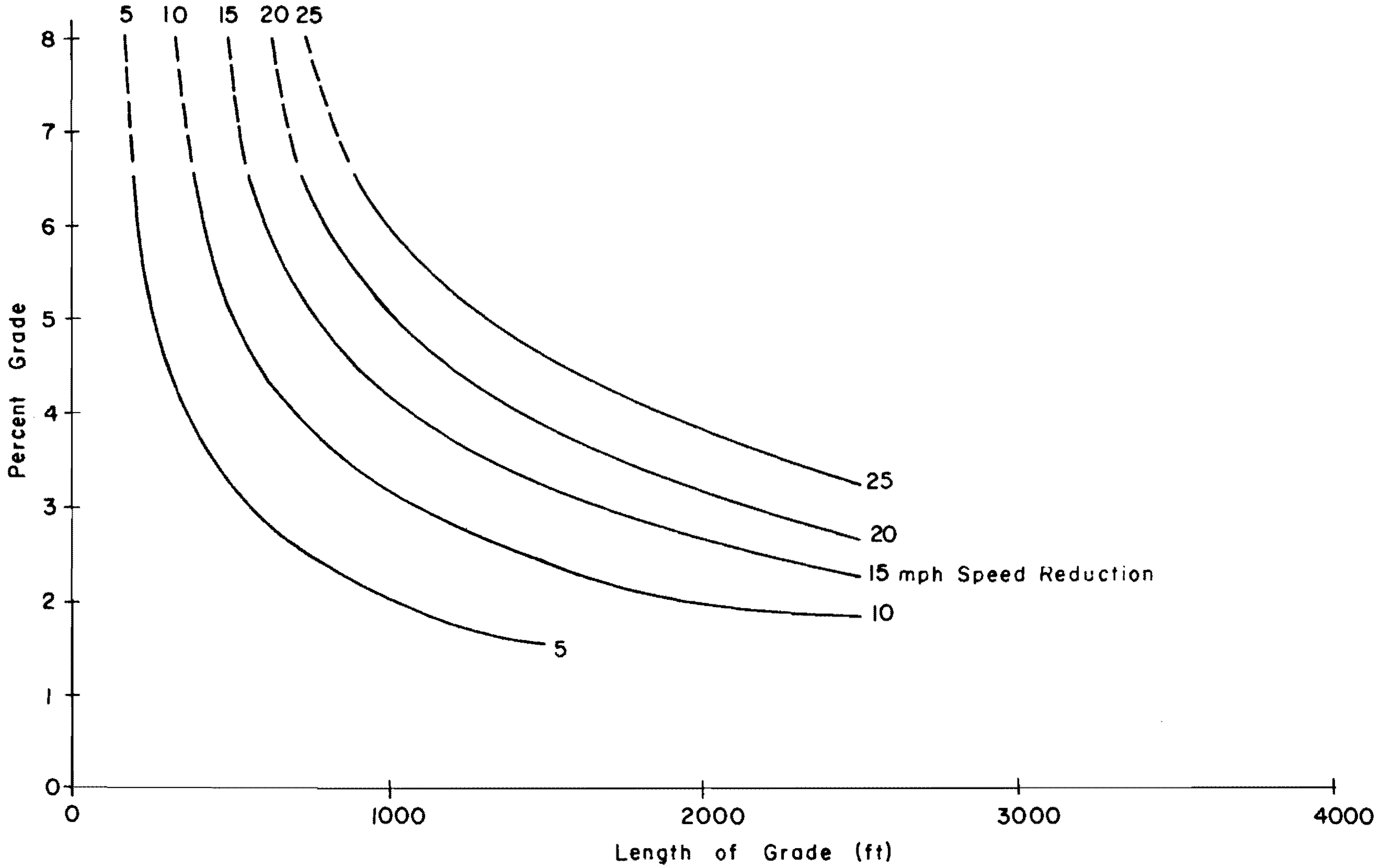


Fig 32. Current critical lengths of grade using an approach speed of 47 mph for a truck with a weight/horsepower ratio of 400.

TABLE 18. COMPARISON OF CRITICAL LENGTH OF GRADE DESIGN CURVES FOR 15 MPH SPEED REDUCTION

Percent Grade	Critical Length of Grade (ft)		
	Fig 30 (49-54 mph)	Fig 31 (52-62 mph)	Fig 32 (47 mph)
2	4,000	2,600	3,000
3	1,420	1,700	1,680
4	1,240	1,420	1,400
5	1,190	1,300	750

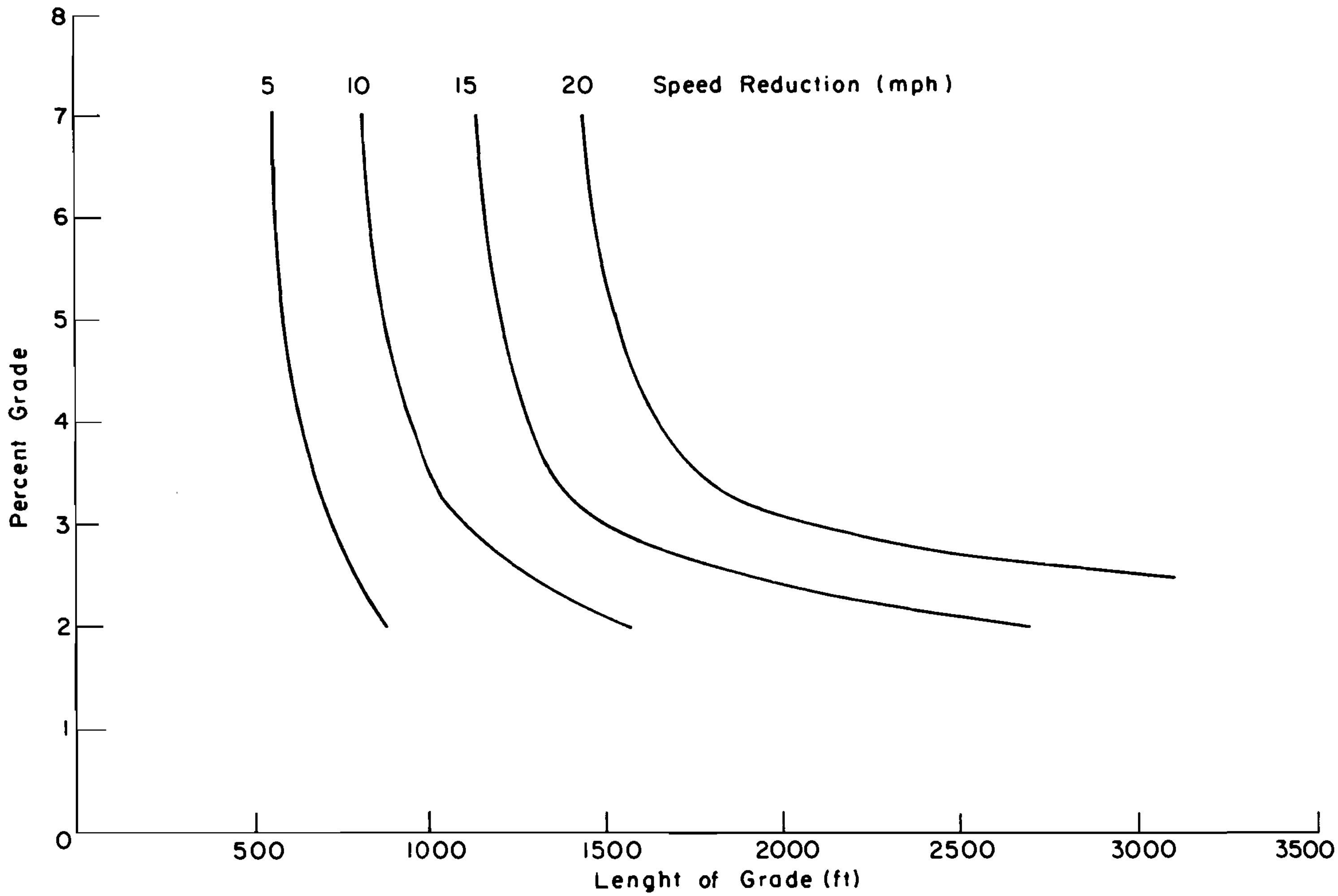


Fig 33. Critical lengths of grade using an approach speed of 55 mph for a composite truck weight/horsepower ratio.

Figure 34 indicates speed-distance relationships for a range of upgrades from 2 percent to 7 percent in 1 percent increments. Again, the approach speed for all grades is 55 mph. From these charts the length of climbing lanes can be evaluated for the percent grade and speed reduction criteria.

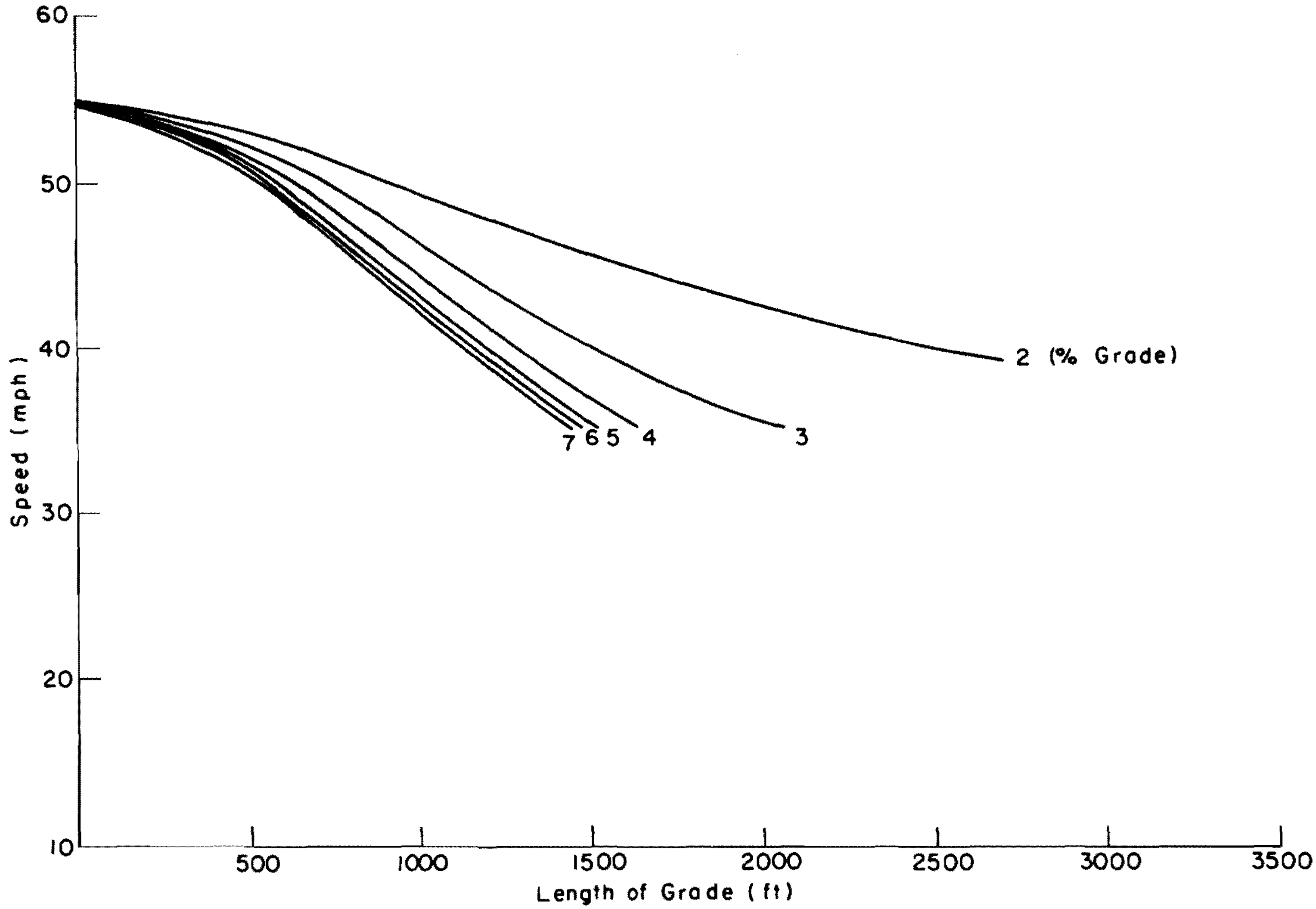


Fig 34. Composite speed-distance curves for a typical heavy truck on selected upgrades.

CHAPTER 8. RECREATIONAL VEHICLE STUDY

This chapter presents the findings of the analyses of the study of recreational vehicles. A total of 260 speed history records were available for analysis. They were collected from three site locations (see Table 10, p 64). It should be noted that 27 miscellaneous vehicles are included as a seventh class. This group includes vehicles pulling rental trailers, regular vans, and passenger cars, and they are included for comparison with other vehicle categories.

SELECTING THE BEST EQUATION

As can be seen from Table 12, p 74, most of the equations have an R^2 in the range from 50-80 percent. As shown in the truck study, the highly variable human element has an effect on a vehicle operating on grade. To reevaluate this observation an analysis was made with a reduced sample of boat trailers from site 8 (see equations 2 and 3 in Table 12). A total of 18 questionnaires were returned with information about the age of the driver and driver experience. These 18 boat trailers were entered in the regression analysis without including these characteristics, and this resulted in an R^2 of 78 percent and a coefficient of variation of 8 percent. Next, driver experience and age of driver were included in the analysis, and this increased R^2 to 83 percent and decreased the coefficient of variation to 7 percent.

After making a careful analysis of the 35 equations in TABLE 12, evaluating factors such as sample size, vehicle type, R^2, and coefficient of variation C, eight equations were selected to represent the operating characteristics of the different vehicle types. Six of these equations represent upgrade characteristics and two equations represent downgrade characteristics.

Upgrade

Six equations were selected to represent the upgrade operating characteristics of the different vehicle categories, RV17, RV29, RV32, RV33, RV34, and

RV35 in Table 12. These equations represent the operating characteristics on an upgrade (a 0 to 7 percent range) for a group of vans and pickup covers, boat trailers, truck campers, travel trailers, motor homes, and rental and camping trailers, respectively. The sample sizes included in these equations are all, except for RV35, well above the warranted minimum of 22 vehicles. The R^2 values range from 65 to 76 percent, and the coefficient of variation values are less than 9 percent.

Downgrade

The equations selected to represent the downgrade are RV27 and RV30 in Table 12. The former represents the operating characteristics of travel trailers, truck campers, and motor homes on a .5 percent downgrade section for 1,400 feet. The latter represents operating characteristics for boat trailers, camping trailers, and rental trailers on a .5 percent and 2.5 percent downgrade for 1,400 feet. Each equation has an R^2 close to 50 percent and a coefficient of variation of 9.9 percent. The single most important variable entering these equations is the approach speed. The downgrade equations were developed using the point on the crest vertical curve corresponding to zero slope as a starting point.

APPLICATION OF PREDICTIVE EQUATIONS

Figures 35, 36, and 37 show that the equations have been developed using a range of percent grade from approximately 0 to 7 percent, over a distance of 0 to 6,100 feet. By using a weighted average percent grade of the tangent section only and the corresponding distance (from vertical point of curvature) to represent the characteristics of each site, the resulting range of percentage and distance from each site is determined (Table 19).

Speed Profiles

From the information presented in Table 19 and the vehicle characteristics for each group, a series of speed versus distance curves were plotted, applying the predictive equations developed. An average of the vehicle characteristics for each group was used (see Table 20). An approach speed of 55 mph was used, as this was found to be the average entering speed for all recreational vehicles in this study. For the downhill speed profiles,

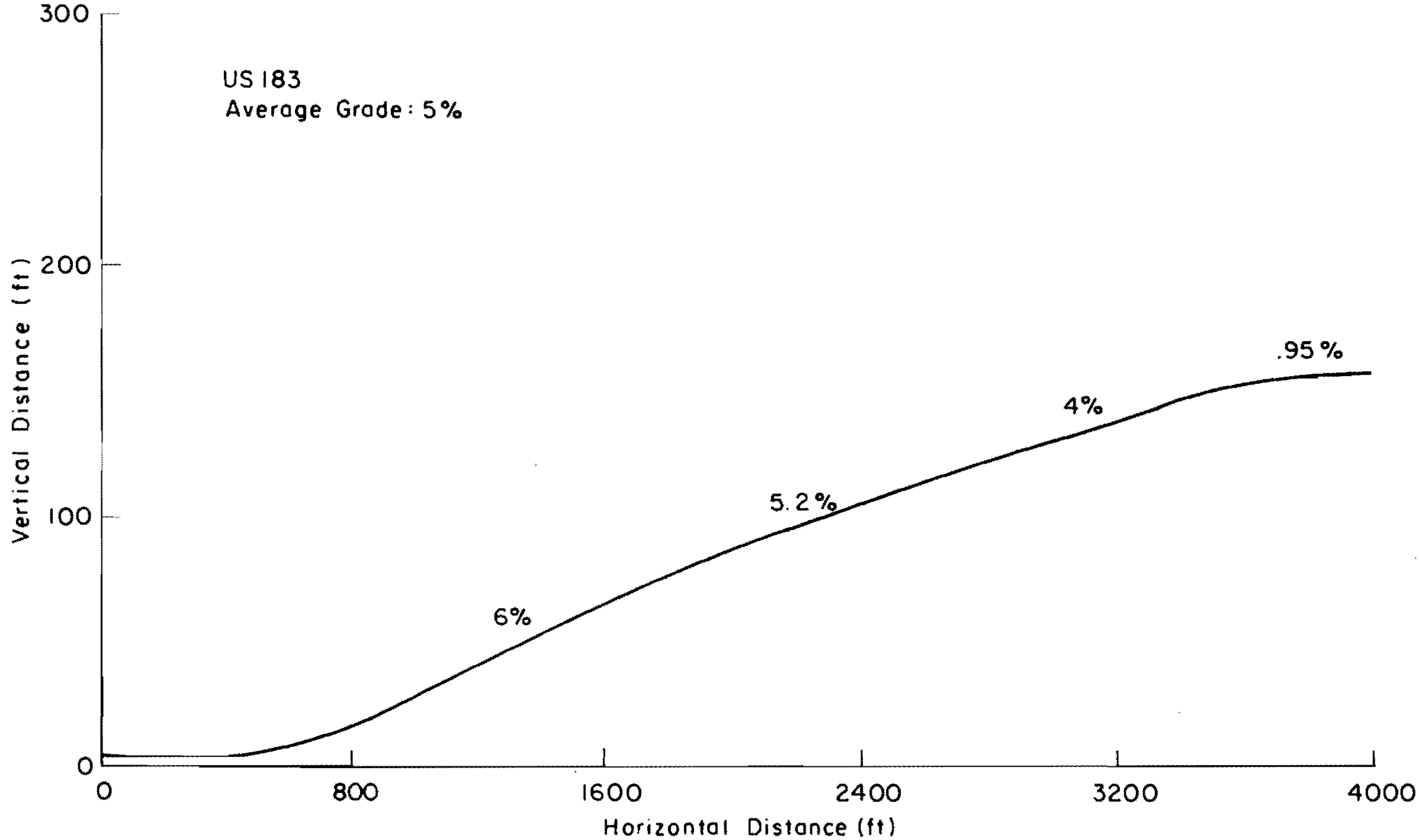


Fig 35. Vertical profile of site 6.

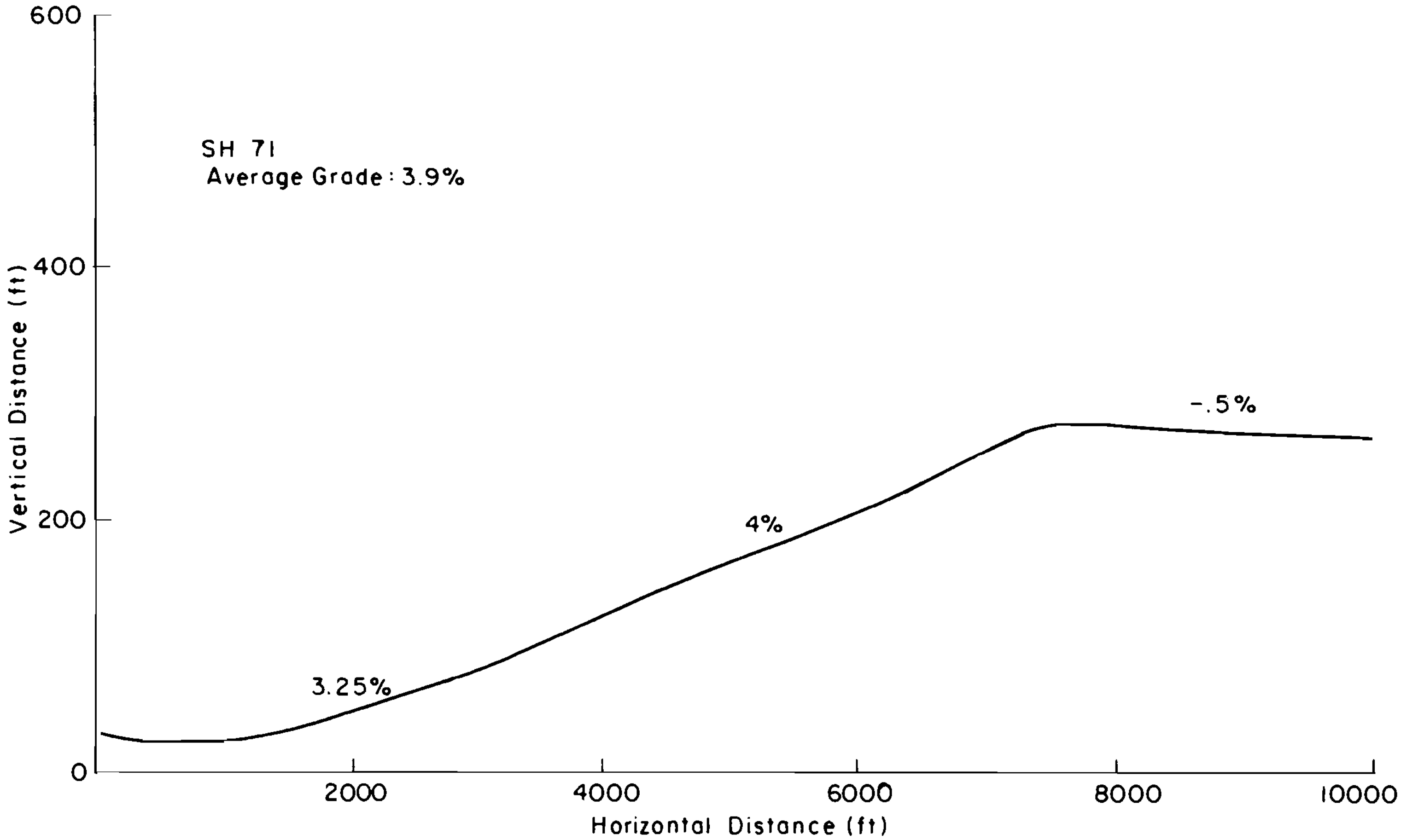


Fig 36. Vertical profile of site 7.

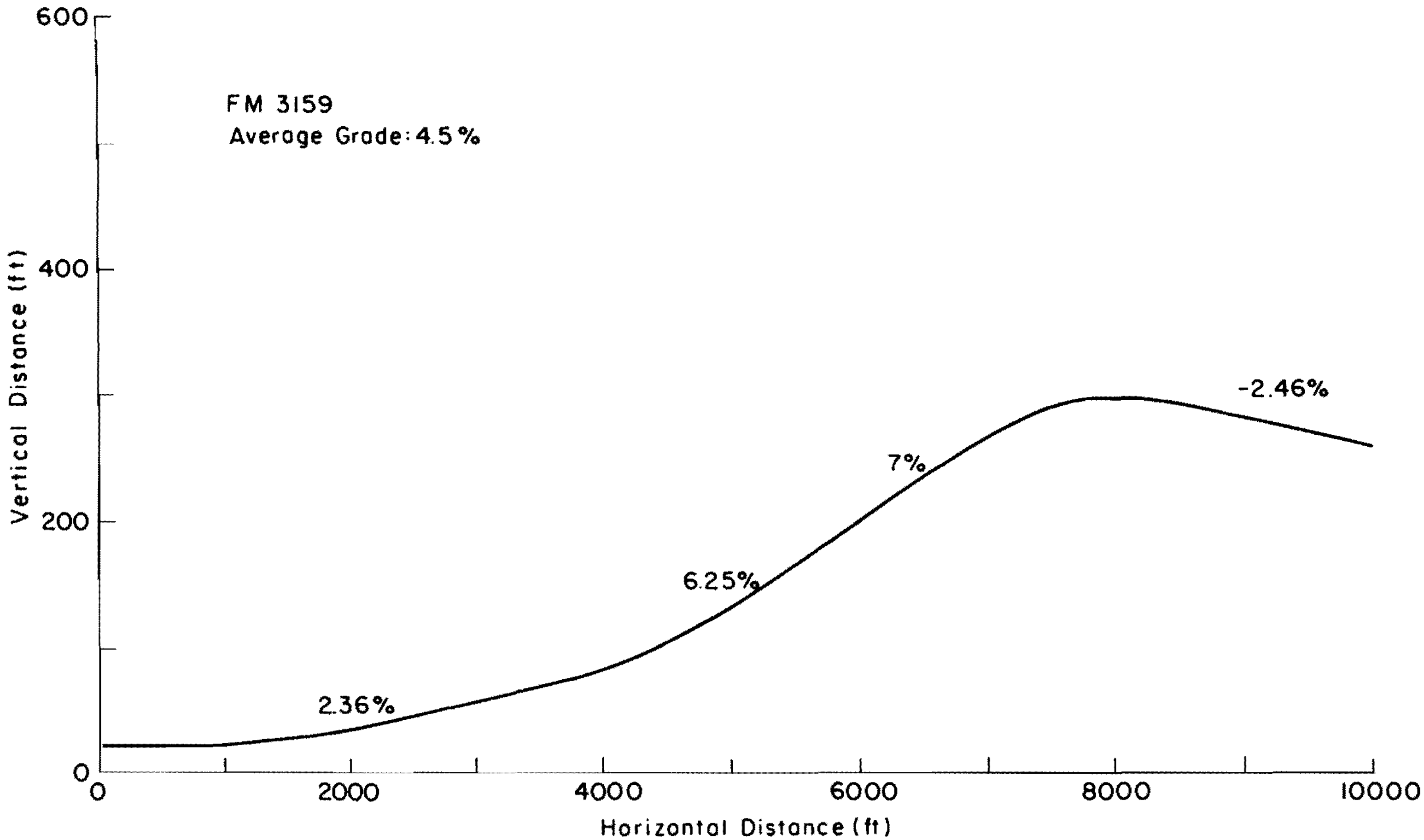


Fig 37. Vertical profile of site 8.

TABLE 19. RANGE OF PERCENT GRADE FOR SITE LOCATIONS

Site	Average Percent Grade*	Distance (ft)	Grade Direction
US 183	6.00	1,500	Upgrade
	5.00**	3,000	Upgrade
SH 71	3.25	2,300	Upgrade
	4.25	3,800	Upgrade
	3.90***	6,100	Upgrade
	-.50	1,400	Downgrade
FM 3159	2.40	2,300	Upgrade
	6.50	3,700	Upgrade
	-2.50	1,400	Downgrade

* Average percent grade of tangent section only.

** The grade varies from 4 to 6 percent, and 5 percent is used as an average.

*** The grade varies from 3.25 to 4.25 percent, and 3.9 percent is used as an average.

TABLE 20. CHARACTERISTICS OF RECREATIONAL VEHICLE CATEGORIES USED IN THE DEVELOPMENT OF SPEED-DISTANCE CURVES*

Vehicle Characteristics	Vehicle Type					
	Truck Camper	Pickup Cover, Van	Camping & Rental Trailers	Boat Trailer	Motor Home	Travel Trailer
Horsepower (net)	175	150	180	185	195	190
Gross weight (lb)	5,750	4,000	5,650	7,500	12,000	8,750
Frontal area**	6	3	2	2	7	8
Vehicle length (ft)	19	15	28	38	26	40
Side area**	5	2	10	3	7	9
Weight-to-horsepower	32.8	26.7	31.4	40.5	61.5	46

* Values represent an average of those vehicles included in the study.

** Given on a scale from 1 to 0.

an average entering speed of 42 MPH was used initially, for comparison. Some of the resulting speed versus distance curves are presented in Figs 38 and 39. The y-axis represents the speed in miles per hour and the x-axis gives the length of grade in feet (from the vertical point of curvature). Pickup covers and vans, and camping trailers and rental trailers were combined into two groups, respectively. They were found to have similar operating characteristics, and any vehicle characteristic presented represents an average of the two types.

The total speed loss for each vehicle group from the different sites is presented in Table 21. Based on these findings, the most critical vehicle category operating on upgrades was found to be the travel trailers, represented by equations RV27 and RV33. For the downhill sections of grades, however, the operating characteristics for truck campers, motor homes, and travel trailers were very similar, with a speed recovery of approximately 1 mph per 300 feet of distance (on a .5 percent downgrade). A more detailed analysis of the upgrade speed profiles for the travel trailers was warranted, and they were plotted using an approach speed of 55 mph. Approach speed and percent grade are the two most important variables in the equation describing the operating characteristics for travel trailers, and the weight-to-horsepower ratio is the third variable, considerably less significant than the first two. In the development of the current design criteria for climbing lane design (Ref 67, Fig 10), the weight-to-horsepower ratio was considered to be very important. These speed-distance curves were based on the operating characteristics of heavy trucks only and did not consider lightweight vehicles.

The speed profiles for the travel trailers were plotted using the range of percent grades given in Table 19 and the vehicle characteristics for the travel trailers given in Table 20. These speed profiles are shown in Figs 40-43. Cumulative distributions of the approach speeds for the recreational vehicles are shown in Figs 44-46. From these graphs it can be seen that the 85th percentile approach speed for all vehicles observed was approximately 60 mph. The average approach speed for all recreational vehicles observed in this study was found to be 55 mph.

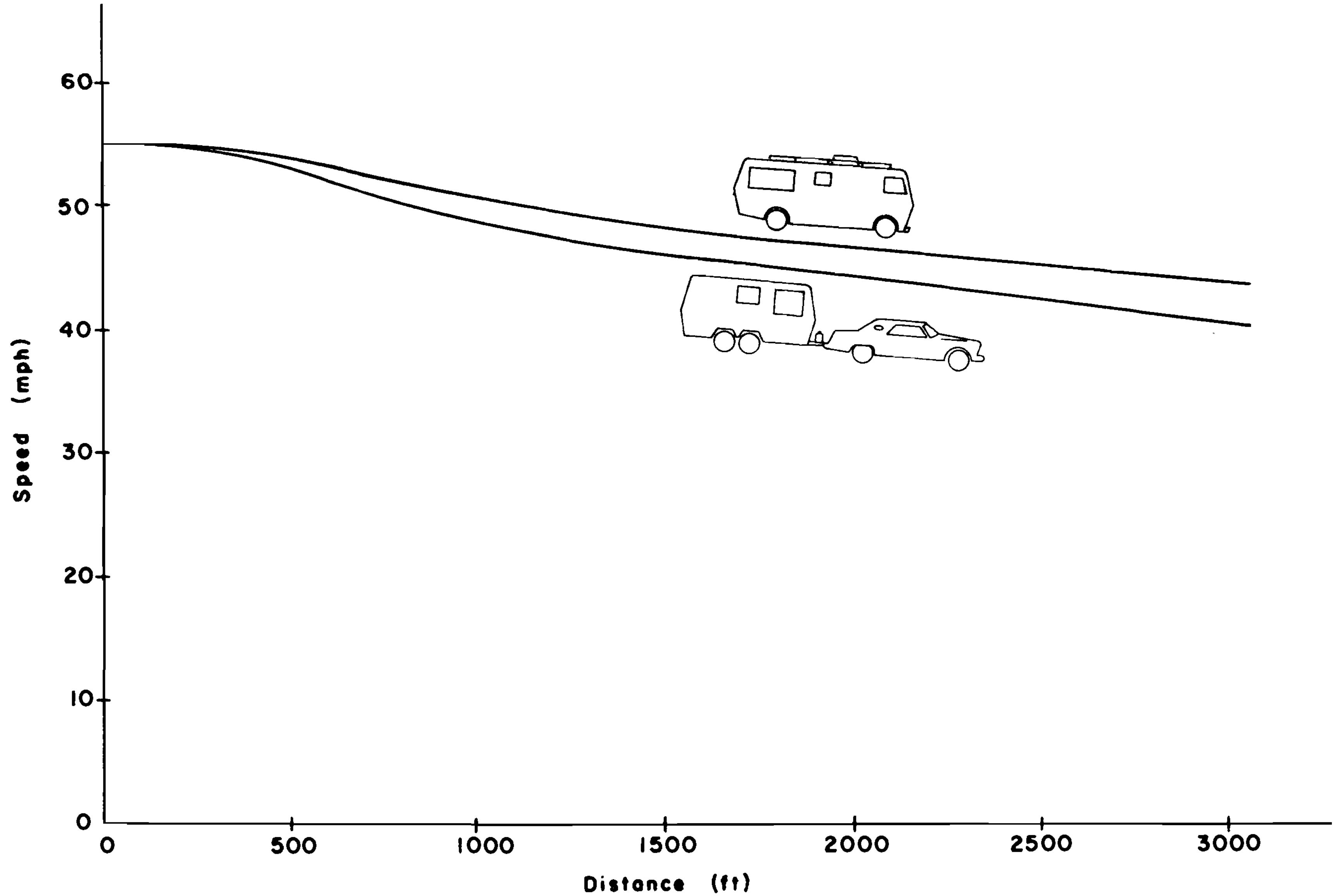


Fig 38. Speed-distance curves for a typical motor home and a typical travel trailer on a 5 percent upgrade.

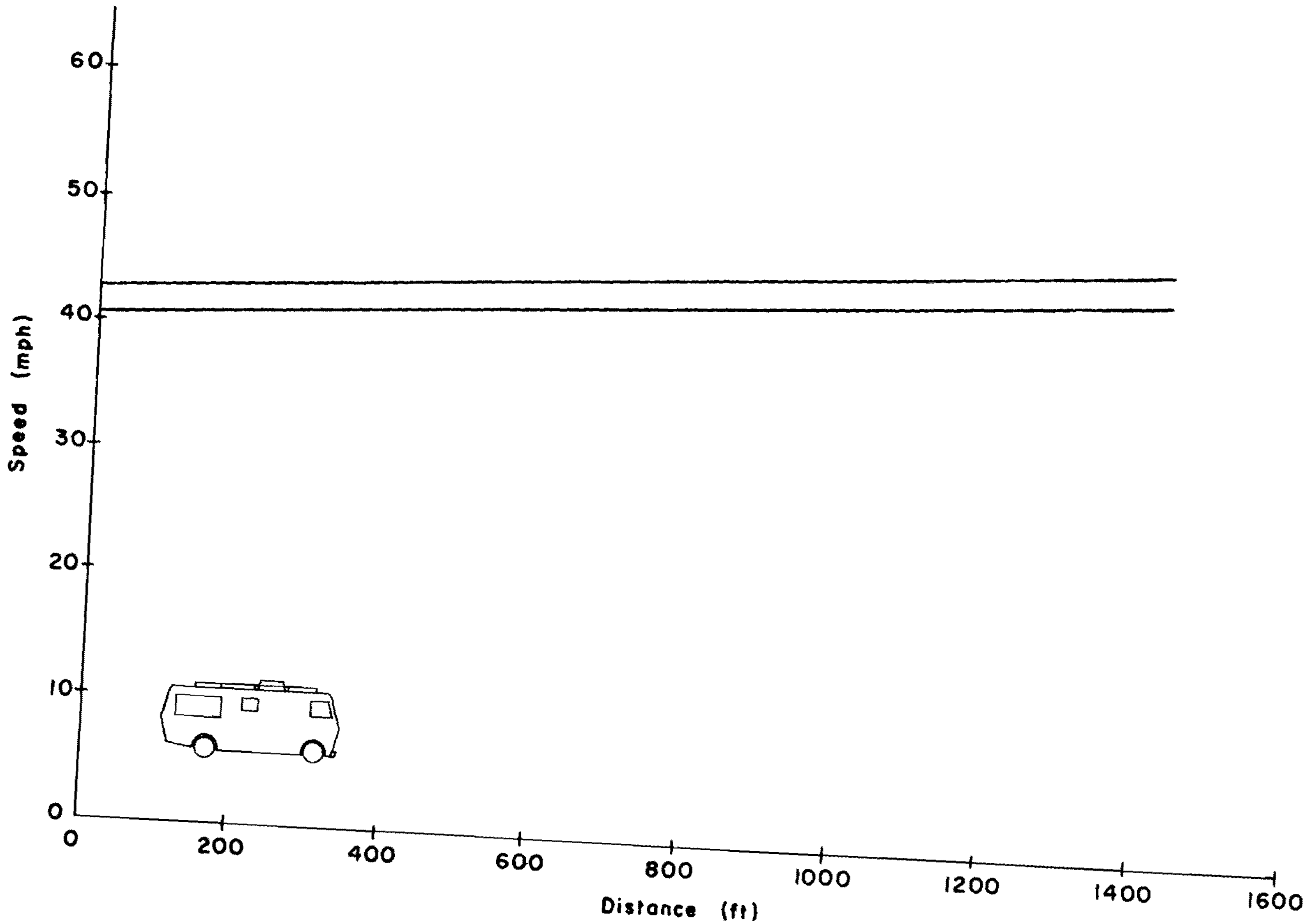


Fig 39. Speed-distance curves for a typical motor home on a .5 percent downgrade.

TABLE 21. SPEED LOSS IN MPH FOR DIFFERENT CLASSES OF RECREATIONAL VEHICLES ON GRADES

	Vehicle Type						
Average Percent Grade	Truck Camper	Pickup Cover, Van	Camping & Rental Trailers	Boat Trailer	Motor Home	Travel Trailer	Distance (ft)
3.9	6.1		6.4	6.7	6.6	10.9	6,100
5.0	8.0	9.0	8.7		11.1	14.1	3,000
6.0	7.9	7.0	7.0		9.0	10.1	1,500
6.5				12.3			6,000
* - .5	4.9			5.7	4.9	5.0	1,400
* -2.5				8.5			1,400

* Represents speed recovery in mph on a downgrade.

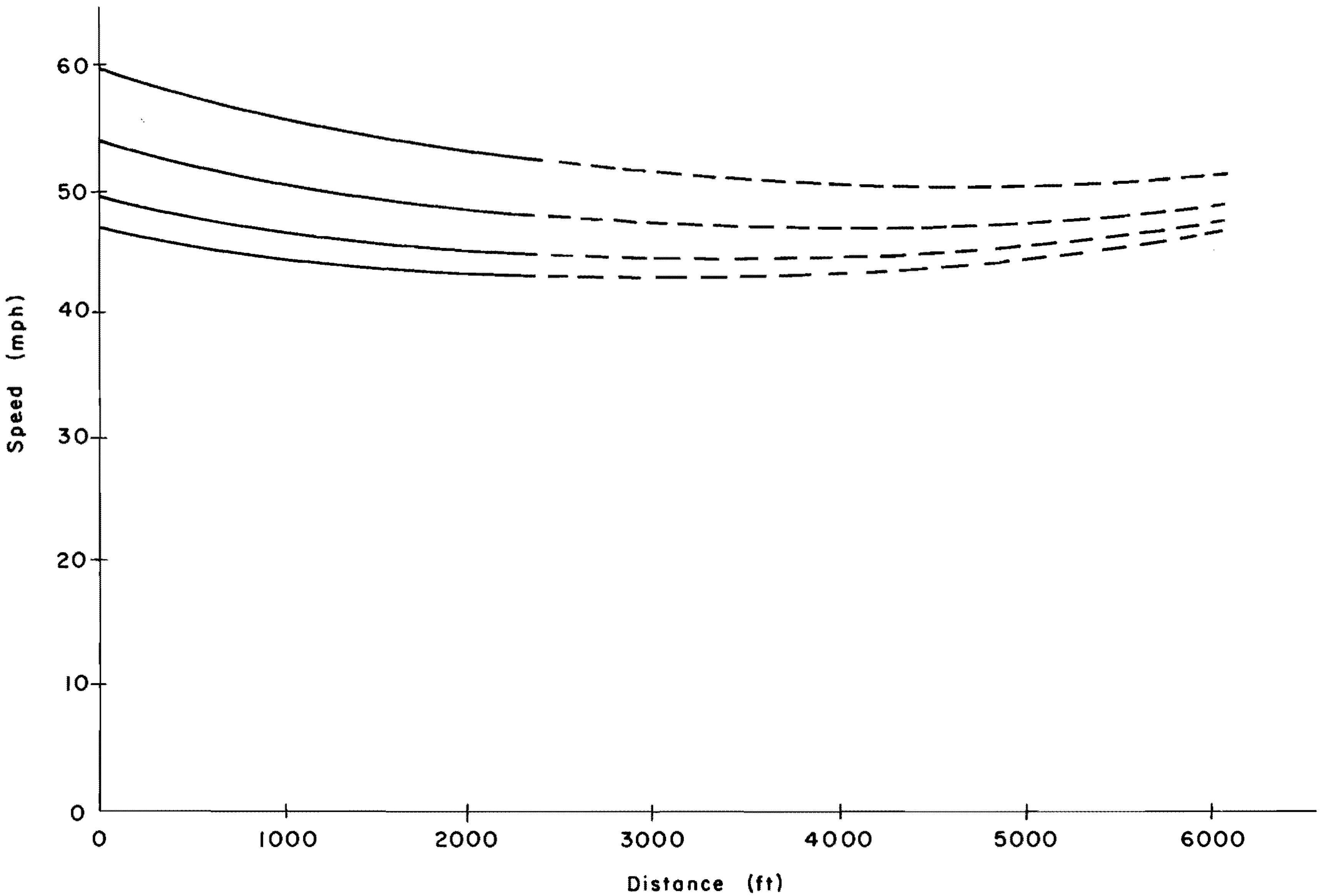


Fig 40. Speed-distance curves for a typical recreational vehicle (i.e., travel trailer) on a 3 percent upgrade.

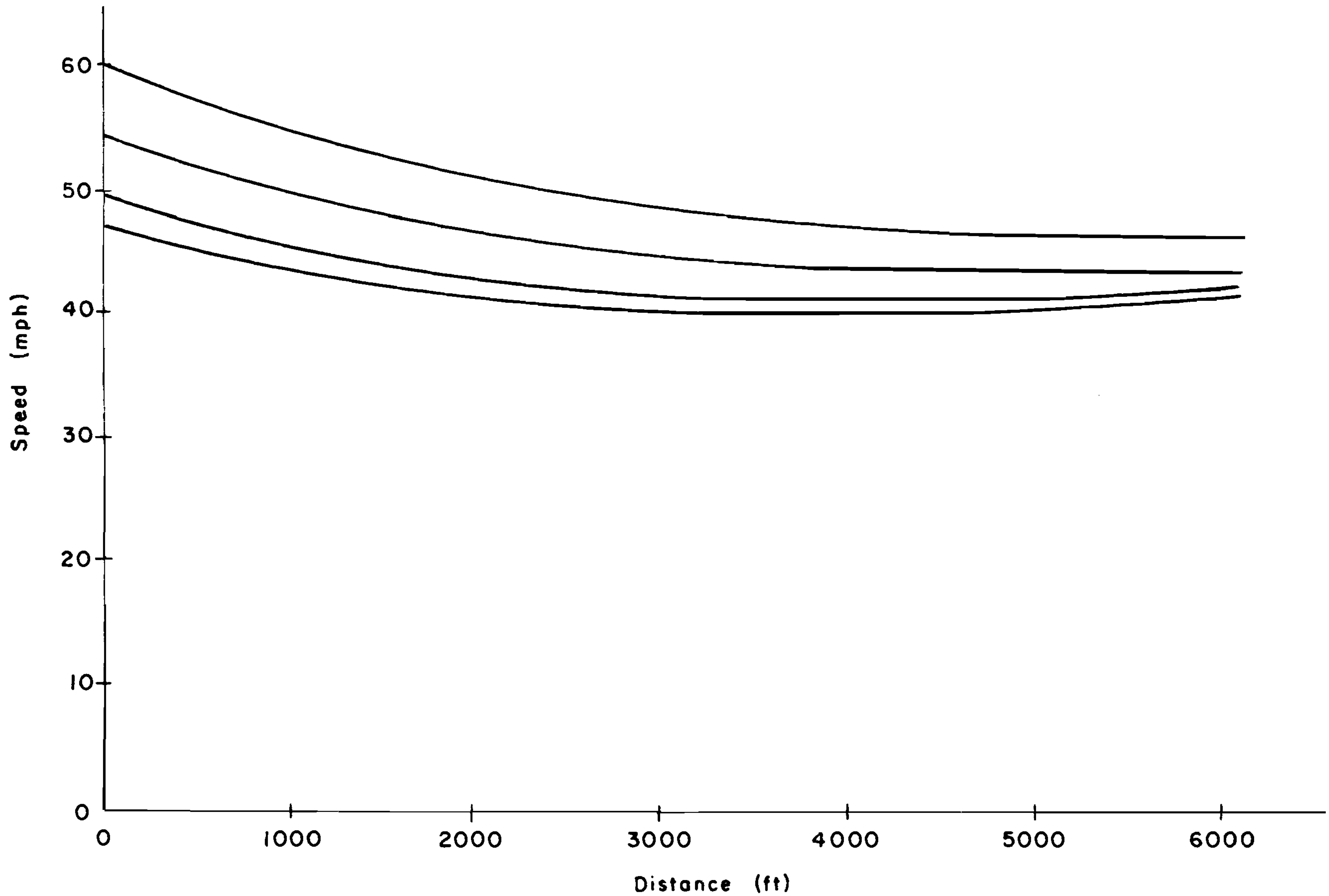


Fig 41. Speed-distance curves for a typical recreational vehicle (i.e., travel trailer) on a 4 percent upgrade.

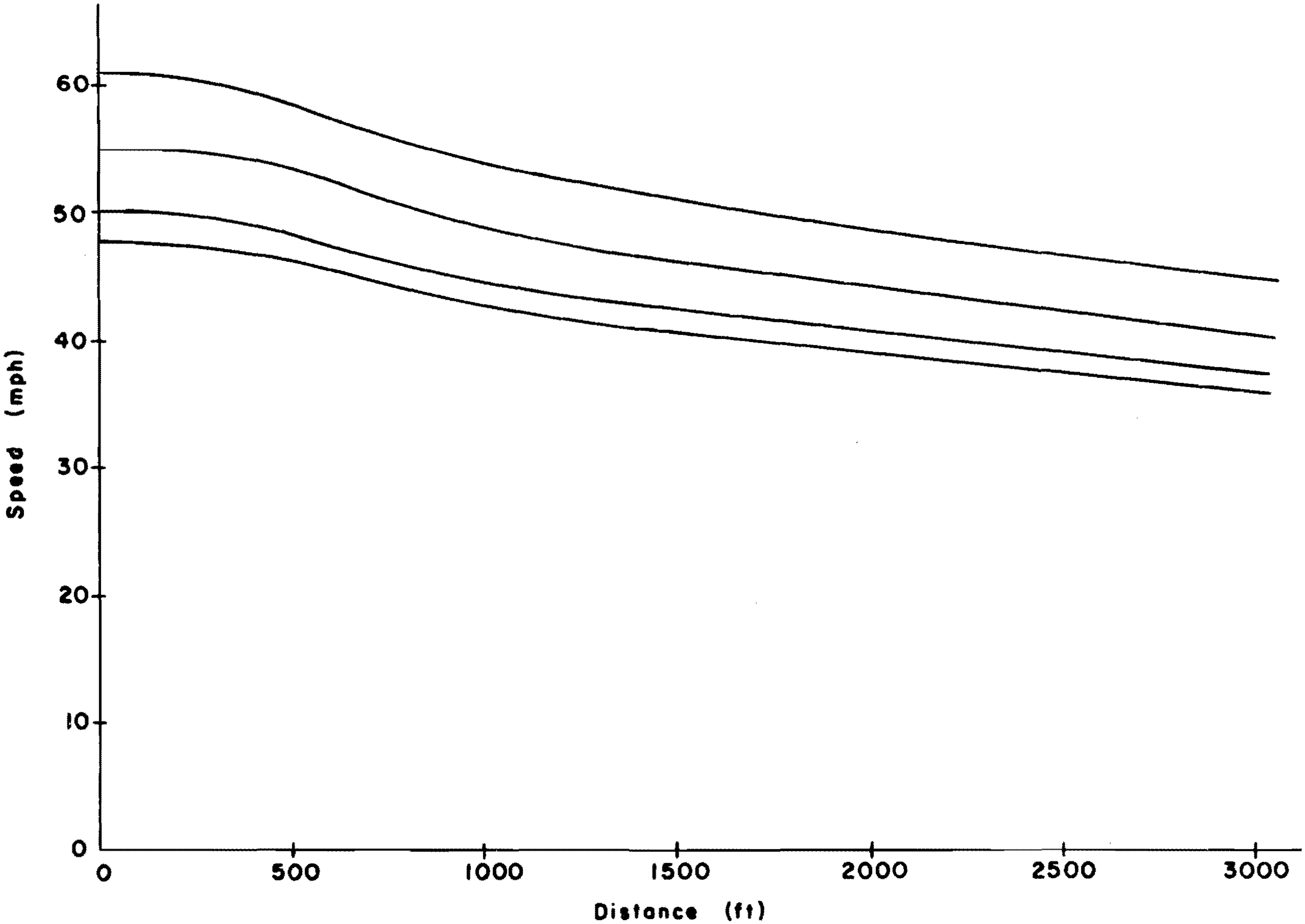


Fig 42. Speed-distance curves for a typical recreational vehicle (i.e., travel trailer) on a 5 percent upgrade.

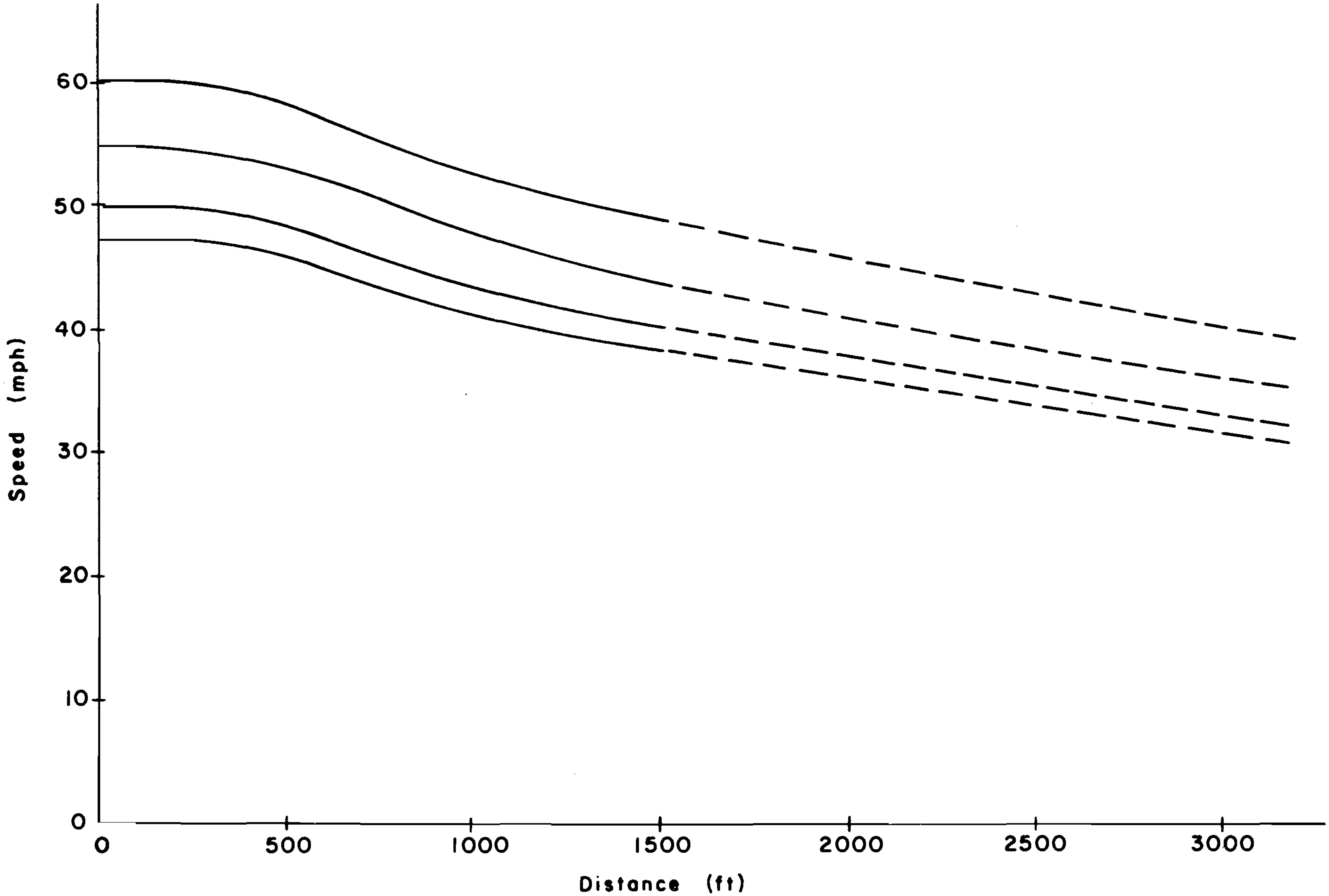


Fig 43. Speed-distance curves for a typical recreational vehicle on a 6 percent upgrade.

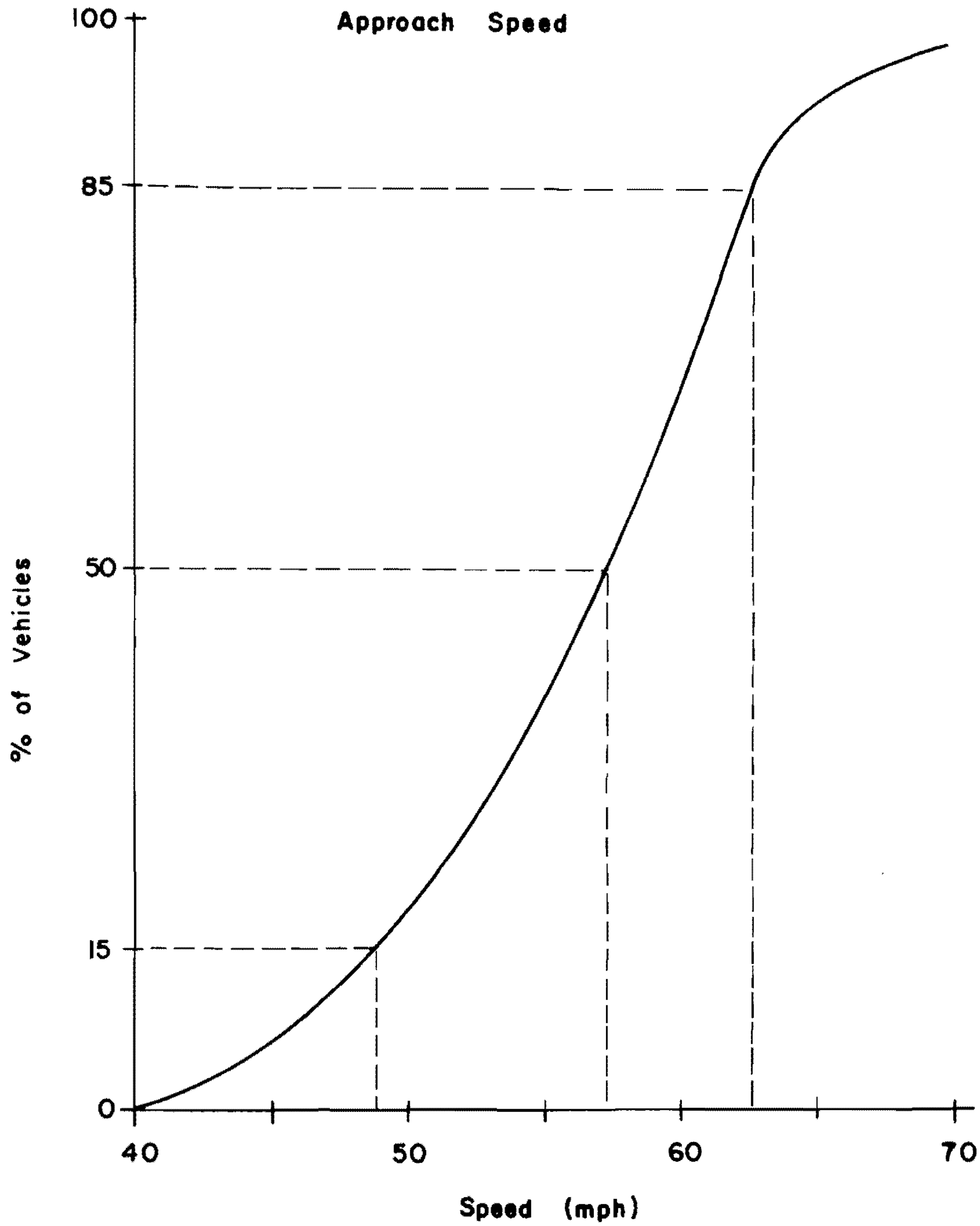


Fig 44. Cumulative distribution of approach speeds for recreational vehicles at site 6.

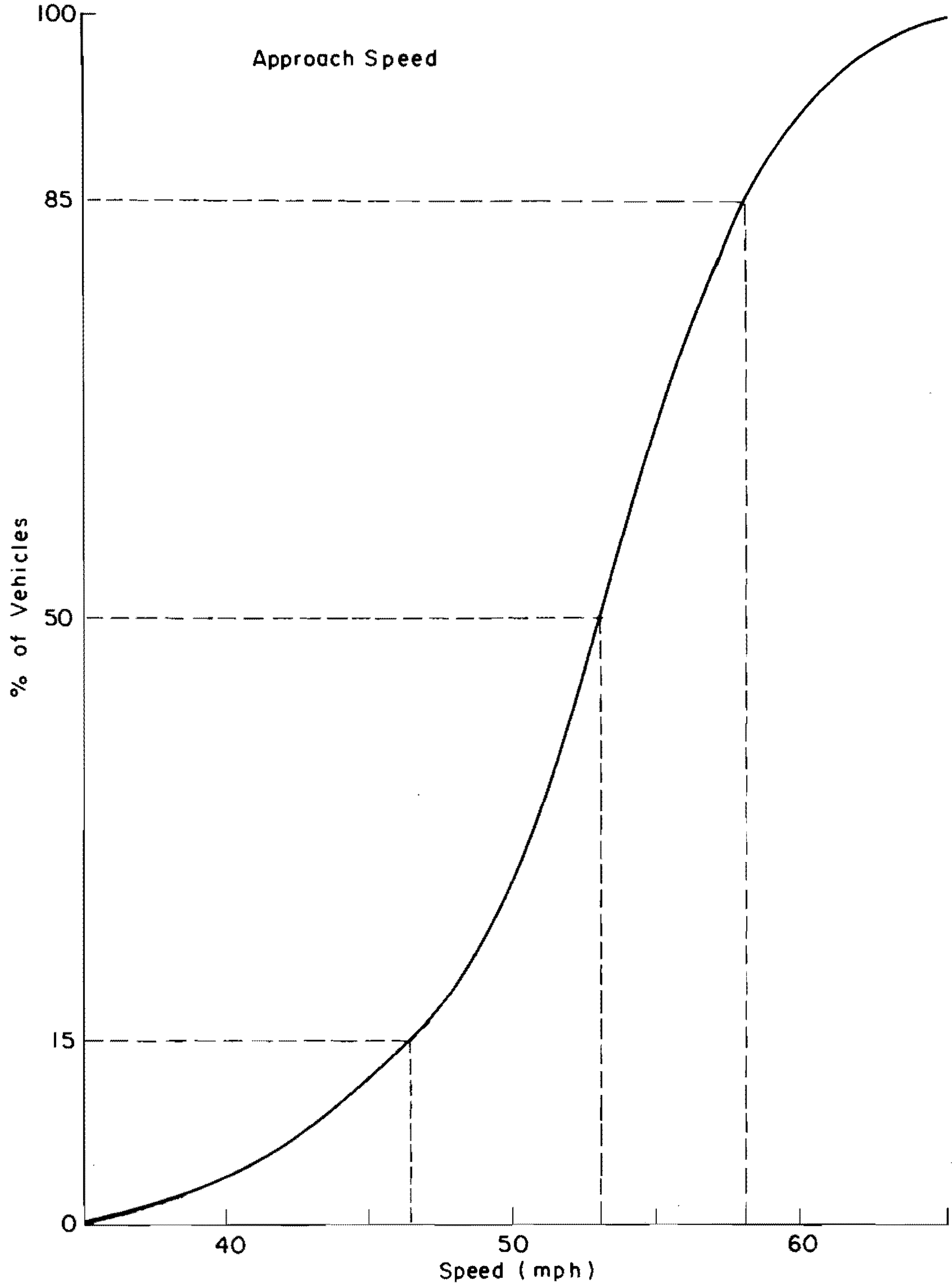


Fig 45. Cumulative distribution of approach speeds for recreational vehicles at site 7.

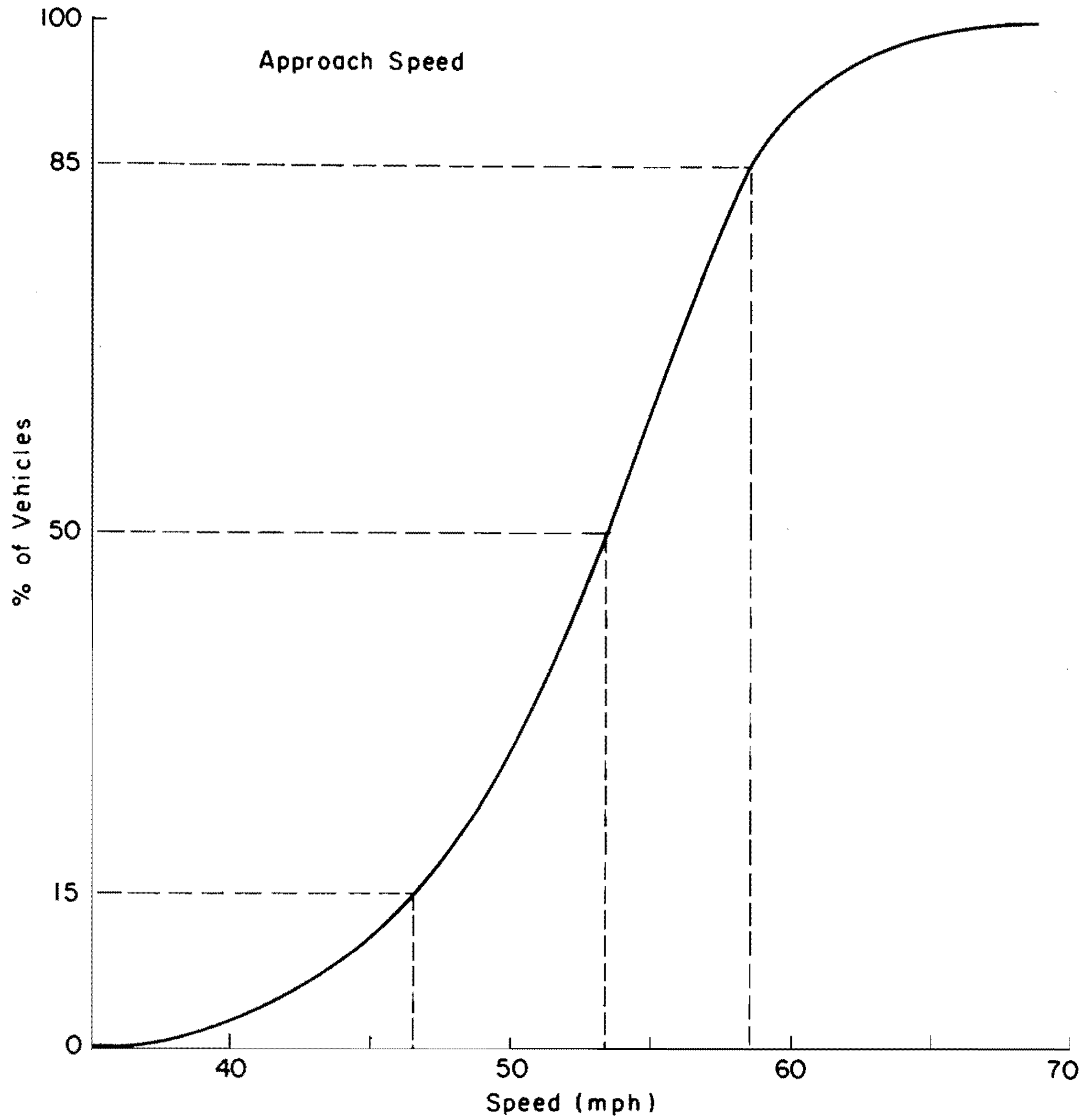


Fig 46. Cumulative distribution of approach speeds for recreational vehicles at site 8.

CRITICAL LENGTH OF GRADE

The term "critical length of grade" is used to indicate the maximum length of a designated upgrade upon which a vehicle can operate without an unreasonable reduction in speed (Ref 1). This is part of the criteria for determining if a climbing lane is warranted and is currently taken as a 15 mph reduction in speed from average running speed. There has been, however, discussion about reducing this limit to 10 mph, due to traffic accidents (Ref 26). Another factor to consider before deciding whether a climbing lane is warranted or not is the level of service (Ref 1). If the design hourly volume exceeds the design capacity on a particular grade by more than 20 percent and the critical length of grade is exceeded, a climbing lane is currently warranted.

Using the data presented in Figs 40-43, a series of critical lengths of grade for 5 mph, 10 mph, and 15 mph speed reductions are presented in Fig 47, based on an approach speed of 55 mph. The length of grade in feet, starting from the vertical point of curvature, is given on the x-axis and percent upgrade is given on the y-axis. This graph is representative of all recreational vehicles as it is based on the operating characteristics of the most critical recreational vehicle category. Fairly level approach is assumed. The procedure to be followed in using this graph is indicated by the arrows in Fig 30, p 105.

Figure 48 indicates speed-distance relationships for a range of 3 percent to 6 percent in one percent increments. The approach speed for all grades is 55 mph. From these charts the lengths of climbing lanes can be evaluated for the percent grade and speed reduction criteria based on an assumed typical recreational vehicle.

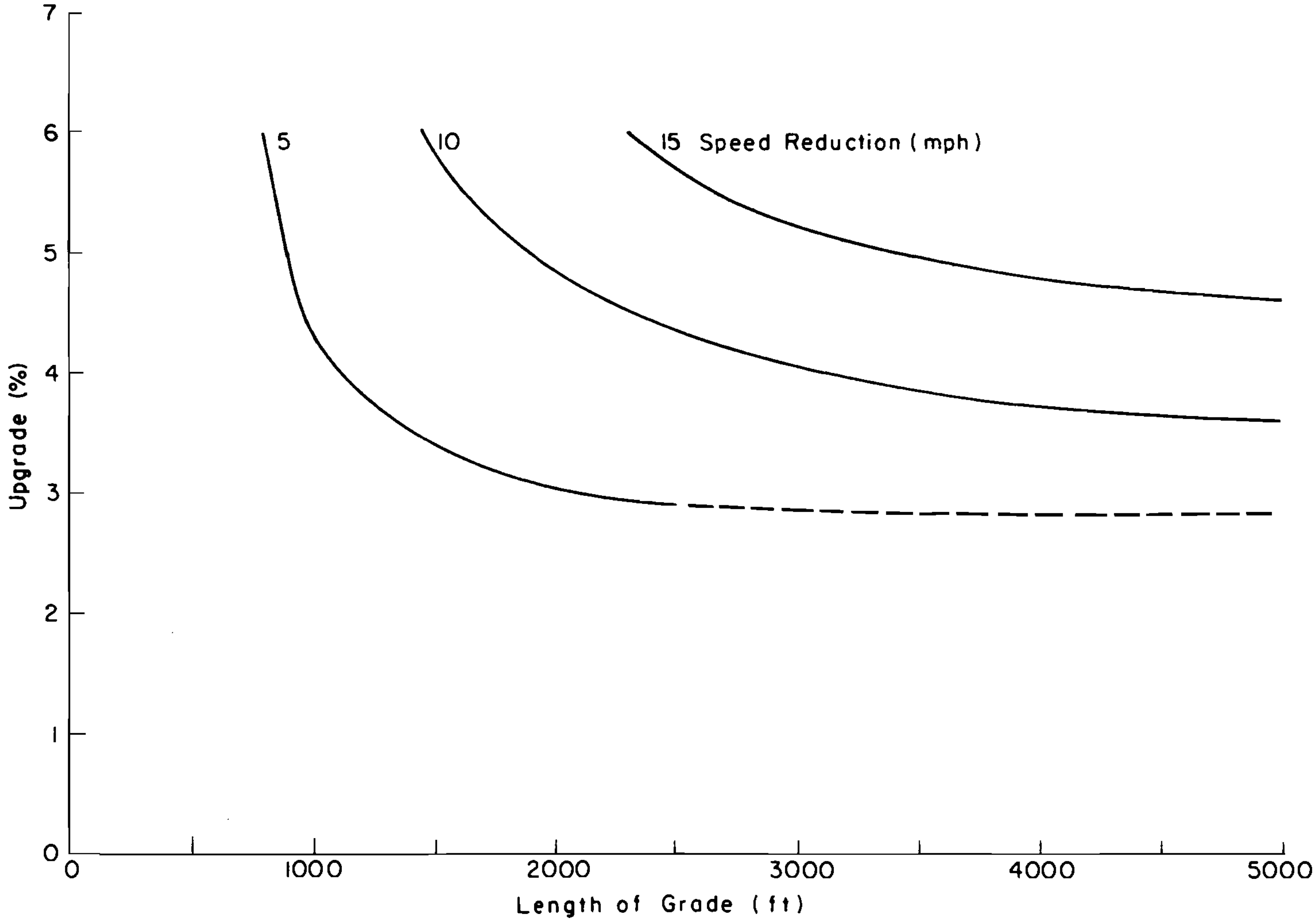


Fig 47. Critical lengths of grade using an approach speed of 55 mph (assumed typical recreational vehicle).

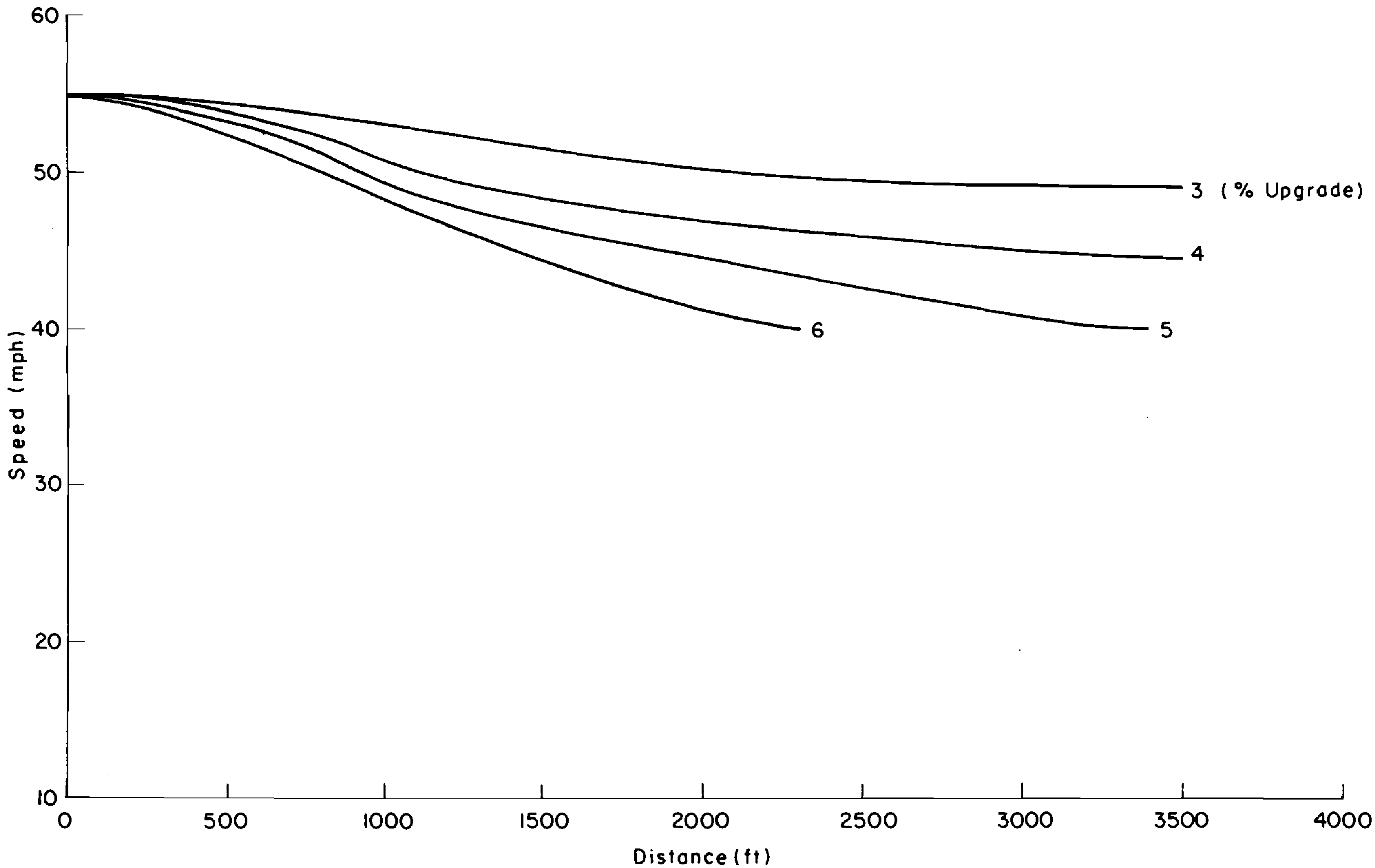


Fig 48. Speed-distance curves for a typical recreational vehicle on selected upgrades.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to obtain new field data concerning motor vehicle operating characteristics on selected grades and relate these data to current and future geometric design standards for highway grades, with particular emphasis on the capacity and safety aspects of vehicle climbing lanes.

To attain this objective, the research project was subdivided into five phases, encompassing a two-year time frame.

Phase 1. Collection, Review, and Compilation of Literature. Literature relating to the operating characteristics of motor vehicles on vertical curves was gathered.

Phase 2. Collection of Data at Selected Field Sites. This phase involved the design of a field data collection experiment, development of data collection techniques, and selection of data collection sites.

Phase 3. Analysis of Data. The data generated and compiled from the field observations were analyzed and tabulated for comparison with current climbing lane design criteria. In addition to analyzing truck operating performance on grades, special attention was given to recreational vehicles.

Phase 4. Methodology Recommendations. From the analysis of data in the previous phase a series of design charts was developed on the basis of vehicle classification, weight-to-horsepower ratio, approach speed, speed reduction, percent grade, and length of grade. These series of figures provide the highway designer with flexibility for evaluating design criteria for existing highway situations with more analysis tools than were previously available.

Phase 5. Conclusions and Recommendations. The findings and recommendations cited herein provide revised climbing lane design criteria based on the analysis of actual field data on the operating performance of trucks and recreational vehicles on selected representative grades within the State of Texas.

CONCLUSIONS

An extensive state-of-the-art review of the performance characteristics of trucks and recreational vehicles on highway vertical curves indicated the need for verifying the effectiveness of current climbing lane design standards. Because of the complexity of obtaining actual field data on various types of these vehicle classes there had not been any extensive field studies for over twenty years, and the work performed at that time may not reflect the actual operating characteristics.

For this study, speed and weight data for trucks operating on existing highway grades were collected in field studies at four sites, three located in the vicinity of Austin and one near Nacogdoches. The data on recreational vehicles were obtained at three sites on major recreational routes surrounding Austin. Two different data collection techniques were employed: photo sensitive devices and car-following. The weigh-in-motion system was used at one site near Austin and at the Nacogdoches location. A questionnaire was also employed, to survey the owner of the vehicle on attributes of the vehicle and driver information. An approximate 40 percent return of the questionnaire enabled the researchers to test the significance of driver experience in relation to vehicle performance.

From the speed history records speed-distance curves were developed using a stepwise multiple regression analytical technique. As many as 12 selected roadway, vehicle, and driver variables were used in an attempt to explain the observed speed variation of each class of truck, truck combination, and recreational vehicle (classification of which was developed by the researchers in this study).

Two classes of trucks with particular characteristics were found to experience greater speed losses than others: 3-S2 semi-trailer combinations and log trucks with typical weight-to-horsepower ratios of 370 and 385 respectively. These vehicles were used as the critical vehicular type in developing truck climbing-design charts. Concerning the recreational vehicles, the most critical category was found to be vehicles pulling travel trailers. This category currently enjoys the largest share of the recreational market and is considered to be representative of the operating characteristics of all recreational vehicles.

In both classes of vehicles, approach speed was found to have a significant effect on the vehicle operating characteristics on grades. A set of speed ranges was devised for critical lengths of grade analysis.

Composite design charts (Figs 33, 34, 47, and 48) were developed with an approach speed of 55 mph, a range of speed reduction values in mph, percent grade, and length of grade in feet. By comparing them directly with the currently accepted design charts, one can observe that in some instances there is a significant difference in the resultant length of climbing lane required for a given speed reduction constraint. It can be observed that for specific grades the new composite design charts using a speed reduction limit of 10 mph yield length of grade figures similar to those obtained by using current design charts with a 15 mph speed reduction limit. The new design values yield performance characteristics which are more indicative of the actual vehicle behavior than previous data and design charts. It is observed that consideration of recreational vehicles is not as critical as that of trucks in the design of climbing lanes. However, it is suggested that on certain routes, such as designated recreational routes, with a low percentage of trucks, where a truck climbing lane may not be warranted, sufficient recreational vehicle traffic may indicate a demand for an additional lane. This situation can be evaluated utilizing the design charts developed herein.

RECOMMENDATIONS

Based on the findings of this research the following recommendations can be made:

(1) The composite critical length of grade and speed-distance curve charts (Figs 33, 34, 47, and 48) should be considered for application in the evaluation of the need for and design of climbing lanes for trucks and recreational vehicles respectively.

(2) An approach speed of 55 mph should be used for evaluation and design of climbing lanes.

Further evaluation and study are recommended in the following areas:

(1) 10 mph versus 15 mph speed reduction criteria - there are strong cases for both, but the safety aspects associated with the 10 mph speed reduction suggestion are balanced against the resultant requirement to reevaluate existing climbing lanes, design, and construction of additional facilities, and the current austerity program and priorities for other facilities within the state; at this time this appears to be more of a policy decision than a design procedure; it is suggested that a program of continuing the 15 mph reduction, while not an ultimate, or ideally the "best," case, is at least a compromise providing better safety to the traveling public than previously provided;

(2) current warrants for climbing lanes, in view of the findings of this study;

(3) the performance of vehicles on downgrades - in relation to recreational vehicles, an acceleration of 1 mph per 300 feet of .5 percent downgrade was observed in this study; additional information would be required to evaluate the requirements for terminating a climbing lane;

(4) vehicle equivalencies - further analysis should be made to facilitate capacity and level of service analysis; many questions remain concerning the effect of various vehicles on capacity. Current studies being conducted elsewhere may provide additional guidance in this area;

(5) roadway signing and marking of climbing lanes;

(6) effect of driver behavior and experience on vehicle performance - from our limited sample relating to the driver, this factor proved to be significant in contributing to the explanation of the vehicle performance on grades.

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APPENDIX

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN
AUSTIN, TEXAS 78712

Dear Sir:

The Center for Highway Research, The University of Texas at Austin, in cooperation with the Texas Highway Department and the Federal Highway Administration, is conducting research which will result in improved design standards for climbing lanes on rural highways. In recent years, several public agencies and many road users have expressed concern about the length and location of these extra lanes on hills, therefore, a new evaluation of current design practice is being undertaken.

The research study will involve extensive observation of trucks and recreational vehicles operating on grades of various length and steepness. In order to evaluate the relationship of different vehicle characteristics and driver techniques to the geometry of highway grades, it is necessary to have certain information concerning the vehicle that can be obtained only from the owner or driver.

We realize that you may not have available all the information that we are asking for, but any information that you can give us will be of great help.

We, therefore, ask for a few minutes of your time to answer the questions on the enclosed form and drop it in the mail. Your cooperation will make it possible for us to design and construct better, safer highways at the least possible cost to you, the taxpayer. Thanks for your help.

Sincerely yours,

Clyde E. Lee

Clyde E. Lee
Director

CEL:mlw
Enclosure

Fig A1. Cover letter.

CENTER FOR HIGHWAY RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

QUESTIONNAIRE*

A truck registered in your name with license number _______ was observed going ____, 1973, between _____ _____. The estimated gross weight of the vehicle was _______ lbs.

1. What was the gross weight of this vehicle? __________lbs.

2. What is the approximate empty weight of this vehicle? _______ lbs.

3. What is the manufacturer's rated gross horsepower of the engine presently in the truck? _______ h.p.

4. Has the engine been changed since the purchase of the truck? ___ yes
   ___ no

5. How often does this truck travel this route? ___ once a week
   ___ once a month
   ___ other (specify)

6. Approximately how many miles per year does this truck travel? _______ miles

7. What is the age and years of experience of the driver? _____ years old
   _____ years of experience

8. If possible, can you give us some information about the full throttle torque by the engine, the range of gear-reduction ratios, and the net horsepower of the engine delivered to the clutch?

9. Please comment on the state of wear of the engine, and the physical condition of the tractor-trailer combination as a whole.

*THIS INFORMATION WILL BE USED ONLY FOR RESEARCH PURPOSES RELATED TO THE GEOMETRIC DESIGN OF HIGHWAY GRADES.

Fig A2. Questionnaire for truck survey.

CENTER FOR HIGHWAY RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN

QUESTIONNAIRE*

A vehicle registered in your name with license number ________ was observed towing a trailer ____, 1973, between __________ ______.

1. What make and year is the trailer? ______________________
2. What is the approximate weight of the trailer? ________ lbs.
3. Approximately how many miles per year does the trailer travel? _______ miles
4. What is the manufacturer's rated gross horsepower of the engine presently in the vehicle? _______ h.p. or cubic inches displacement? _____ cu. in.
5. Has the engine been changed since the purchase of the vehicle? ___ yes
   ___ no
6. Approximately how many miles per year does the vehicle travel? _______ miles
7. What is the age of the driver? ____ years old
8. For how many years has the driver been operating a vehicle-trailer combination? ___ years
9. Please comment on the state of wear of the engine, and the overall physical condition of the vehicle-trailer combination as a whole.

*THIS INFORMATION WILL BE USED ONLY FOR RESEARCH PURPOSES RELATED TO THE GEOMETRIC DESIGN OF HIGHWAY GRADES.

Fig A3. Questionnaire for survey on travel trailers, camping trailers, and boat trailers.

$$t = \frac{\bar{X} - \mu}{s\sqrt{n}} \qquad \text{(Ref 30)}$$

where

t = the deviation of the estimated mean from that of the population, measured in terms of $s/\sqrt{n}$ as the unit,

$\bar{X}$ = sample mean,

μ = population mean,

s = sample standard deviation, and

n = sample size.

Assumptions:

(1) $X - \mu = 2$ mph is acceptable,

(2) $s \approx 4.5$ mph (based on data collected from U.S. 183 and U.S. 59, s ranges from 2.3 to 5.5),

(3) $n = 15$ initially.

From Ref 50 (Table A4, p 549), for $15 - 1 = 14$ degrees of freedom, $t = 2.145$ for a 95 percent confidence interval. Solving for n ,

$$n = \frac{t^2 \times s^2}{(\bar{X} - \mu)^2} = \frac{(2.145)^2 \times (4.5)^2}{(2)^2} = 23.29$$

Fig A4. Determination of sample size.

For $22 - 1 = 21$ degrees of freedom, $t = 2.080$:

$$n = \frac{(2.080)^2 \times (4.5)^2}{2^2} = 21.90$$

Therefore, any sample size equal to or greater than 22 will be acceptable with a 95 percent confidence interval.