EVALUATION OF STOPPING SIGHT DISTANCE DESIGN CRITERIA

by

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FOREWORD

This report is one phase of Research Study No. 2-8-68-134 entitled "An Examination of the Basic Design Criteria as They Relate to Safe Operation on Modern High Speed Highways." Other reports published under this research study include: No. 134-1, The Passing Maneuver as it Relates to Passing Sight Distance Standards; No. 134-2, Re-evaluation of Truck Climbing Characteristics for Use in Geometric Design; and 134-4, State of the Art Related to Safety Criteria for Highway Curve Design.

DISCLAIMER

TABLE OF CONTENTS

ABSTRACT

An examination of the state of knowledge was conducted for the purpose of evaluating design criteria for safe stopping sight distance. The evaluation was specifically concerned with driver perception-reaction time, design friction factors, assumed speeds for design, driver's eye height, and object height.

The evaluation was addressed to design criteria as presented in "A Policy on Geometric Design of Rural Highways, 1965," by the AASHO. The major findings were:

- Driver perception-reaction time may be higher than the assumed 2.5 seconds for the higher travel speeds.

- Based on skid trailer measurements on 500 pavements, it was concluded that the AASHO design friction factor values do not represent a critical level of stopping capability.

- The AASHO's "assumed speed for conditions" has no objective basis. Alternative bases are present.

- The present criterion for object height bears no relation to many of the operational requirements for safe stopping sight distance.

- There is a need to design for nighttime stopping sight distance to opposing vehicle headlights on two-lane highways.

SUMMARY

The study reported here was conducted in response to an increasing concern by highway design engineers regarding the validity of current stopping sight distance standards. The report presents a review of the current AASHO design standards and an evaluation of these standards based on the existing state-of-the-art. The evaluation considered the criteria employed in developing the standards including: driver perception-reaction time; design friction factors; assumed speeds for design; driver's eye height and object height. In addition, the report proposes a new philosophy for sight distance design, a philosophy which considers the visual requirements for safety dependent upon operational conditions.

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

1. The commonly used criterion of a 2.5-second perception-reaction for the braking maneuver was based on a subjective extrapolation from laboratory studies. The state-of-the-art evaluation of this report indicates that the perception-reaction time is highly variable and, under critical conditions, could be higher than 2.5 seconds. Because of the trend toward higher speeds and the concomitant degradation of a driver's visual acuity with higher speed, it was surmised that the 2.5-second criterion is questionable for use in designing stopping sight distance for high speed roadways.

2. Based on skid trailer measurements of 500 pavements randomly dispersed throughout one state, it was concluded that the AASHO design friction factor values do not represent a critical level of stopping capability. The AASHO values are representative of the 35th percentile pavement in this state. In other words, 35 percent of these pavements could not provide adequate stopping distance to meet minimum stopping sight distance standards.

3. It was concluded that the use of skid trailer values (which are related to design speed) in the standard stopping distance equation will yield reasonably conservative stopping distance values for use in design. This evaluation was based on 3,900 stopping distance tests which were related to computed stopping distances based on test speed and representative friction factor versus speed relationships for the test pavements.

4. The AASHO Policy's "assumed speed for conditions" has no objective basis. Because of lower friction factors when pavements are wet, the wet condition is the rational basis for design. The AASHO Policy states that it is not realistic to assume travel at full design speed when conditions are wet. However, to arrive at the "assumed speed for conditions," average speeds for dry conditions on horizontal curves (of given design speed) are employed as the critical wet speeds (related to design speed) for stopping sight distance design.

Other basis for determining the "assumed speed for conditions" are presented in the report.

5. A 3.75-foot driver's eye height is employed in the measurement of stopping sight distance design. This height is representative of the distribution of 1960 model automobiles. Although no data are available, it was surmised that this eye height is reasonably representative of current production automobiles. However, an eye height representative of vehicles on the roadway could be lower because of the introduction and high volume sales of automobiles such as the Ford Mustang, the Chevrolet Camaro, and the Volkswagen.

6. Theoretically, a zero object height would provide the safest sight distance design. The six-inch object height used for the measurement of stopping sight distance design was supposedly selected on the basis of diminishing returns in terms of the cost of excavation for crest vertical curves. It is believed a more appropriate balance point is in the range of 0.1 to 0.3 feet as illustrated in Figure 11.

7. It was concluded that the present criterion for object height bears no relation to many of the operational requirements for safe stopping sight distance. There appear to be many operational conditions which require a zero object height for maximum safety, such as either a horizontal curve or an intersection hidden by a crest vertical curve.

8. The report concludes the need to design nighttime stopping

sight distance to opposing vehicle headlights on two-lane highways. It is not uncommon for vehicles to be in the opposing lane even if there are legal restrictions. The opposing driver may be asleep, intoxicated, or otherwise openly violating the restriction.

Recommendations for Implementation

Based on the findings of the report it is recommended that consideration be given to adopting a head-on collision criterion for designing stopping sight distance on two-lane highways. Table 6 of the report lists design values for stopping sight distance that might be considered, using this criterion. These design values were developed using a 2.5-second perception-reaction time, friction factors representing the 15th percentile pavement of Figure 9, and assumed speeds as derived in the report. On the surface, these design values may appear to be very liberal; however, if the opposing driver is either intoxicated or asleep, he may not slow his vehicle at all. In this case, it would be necessary for the other driver to slow and take evasive action in a very short time frame. In applying these values to the design of crest vertical curves, sight distance would be measured from a 3.75 eye height to a two-foot headlight height.

Until the operational requirements for safe stopping sight distance can be defined, it is recommended that the stationary object collision criterion be retained for multilane highways. Table 7 lists design values for stopping sight distance, assuming the critical speed is equivalent to the design speed. Table 8 lists alternative design values using the critical speeds derived in this report. Both tables employ friction factors representing the 15th percentile pavement of Figure 9. In addition, the perception-reaction times for the higher design speeds have been subjectively adjusted upward in accordance with the findings of this report.

Recommendations for Further Research

The report indicates several areas where research would be appropriate. These included:

1. The determination of perception-reaction times in stopping from various speeds for actual highway driving conditions.
2. The determination of the relation between design speed, posted speed, and critical driving speed for wet weather conditions.
3. A thorough analysis of conditional requirements for safe stopping sight distance.

INTRODUCTION

Ability to see ahead is of the utmost importance in the safe and efficient operation of a highway. The path and speed of vehicles on the highway are subject to the control of drivers whose training is largely elementary. If safety is to be built into highways, the design must provide sight distance of sufficient length to permit drivers enough time and distance to control the path and speed of their vehicle to avoid unforeseen collision circumstances.

There has been an increasing concern by highway and traffic engineers regarding the validity of the basic criteria that are fundamental to geometric design standards. A review of references reveals that most of the data which lead to the establishment of these criteria were developed from 20 to 35 years ago. Yet these criteria are being applied to the design of highways intended to serve traffic from 20 to 30 years in the future.

The design standards for stopping sight distance used by the Texas Highway Department (1)* are taken from "A Policy on Geometric Design of Rural Highways," 1965 (2) published by the American Association of State Highway Officials. The design criteria for stopping sight distance presented in the AASHO Policy are based on studies conducted between 1934 and 1953. As such, they may no longer be representative because vehicle, roadway, and driver characteristics have changed. In addition,

* Denotes reference number listed in Bibliography.

there are uncertainties regarding the assumptions employed in establishing the safe stopping distance design standards.

This research study is addressed to an evaluation of the validity of the AASHO Policy's standards for safe stopping sight distance. The method of study employs a comprehensive review of current stopping sight distance standards and an evaluation of the validity based on an analysis of the existing state-of-the-art.

STOPPING SIGHT DISTANCE DESIGN STANDARDS

The Texas Highway Department (1) employs the stopping sight distance design standards presented in the "Policy on Geometric Design of Rural Highways, 1965" (2). Except for some modification of the method of sight distance measuring (explained later in the report) the 1965 AASHO Policy is essentially the same as the first edition of the AASHO Policy (3) printed in 1954. The 1954 edition represented a consolidation and updating of seven separate policies which were adopted during the period 1938 to 1944 and printed as separate brochures. The 1954 edition, as such, represented a significant advancement in the technology of highway design.

This section of the report is addressed to a comprehensive description of highway design standards as presented on pages 134 through 140 and pages 147 through 149 of the 1965 AASHO Policy. This presentation is offered to provide a comprehensive review of the AASHO Policy on stopping sight distance as a basis for an evaluation of its validity.

Stopping Sight Distance Defined

The AASHO Policy defines sight distance as the length of highway ahead visible to the driver. The minimum sight distances available should be sufficiently long to enable a vehicle traveling at or near the likely top speed to stop before reaching an object in its path.

While greater length is desirable, sight distance at every point along the highway should be at least that required for a below-average driver or vehicle to stop.

Minimum stopping sight distance is the sum of two distances: the distance traveled by the vehicle during the period of perception and brake reaction; and the distance required to brake the vehicle to a stop.

Brake Reaction Time

Many studies have been conducted to determine the brake reaction time of drivers. These studies show that the brake reaction time for most people is from 0.5 to 0.7 seconds (2). Some drivers react in a shorter time and some require a full second or more. One of the primary variables is age of the driver, showing a greater reaction time as the driver becomes older (4). The AASHO Policy states:

> For safety, a reaction time that is sufficient for most operators, rather than for the average operator, should be used in any determination of minimum sight distance. A brake reaction time of a full second is assumed herein.

Perception Time

Perception time, as considered here, is the time required for a driver to perceive the need for brake application. It is the time lapse from the instant an object is visible to the driver to the instant he realizes that the object is in his path and that a stop is required. Little is know about the exact time required for driver perception. It varies with the ability of the driver, his emotional and physical condition, and the visibility of the object. At high speeds, perception time may be less than at low speeds because the driver is more alert, however, the longer distances associated with higher speeds may require more time due to the degradation in visual acuity associated with higher speeds (5).

Perception-Reaction Time

Research data on perception time are very limited. Most available data combine perception time with brake reaction time. One study (6) conducted with alerted drivers determined an average combined value of 0.64 seconds, with five percent of the drivers requiring over one second. Under such alert conditions, perception time can be expected to be a small portion of the total perception-reaction time. The study concluded that the driver requiring 0.2 to 0.3 seconds of perception time would require 1.5 seconds for normal highway conditions. In another study (7) with alerted drivers, combined values ranged from 0.4 to 1.7 seconds. Supplemental unpublished data in a study (8) of passing maneuvers showed that a perception time of about one second was required for drivers to analyze and begin a passing maneuver.

The AASHO Policy considers the studies discussed above in arriving at a value for perception-reaction time for use in stopping sight distance design. It states that:

> A significant feature of these comparative tests is that the total perception and brake reaction time for highway conditions may be several times that for

laboratory conditions, and it is evident that perception time is greater than brake reaction time. In determination of sight distance for design, the perception time value should be larger than the average for all drivers under normal conditions. It should be large enough to include the time taken by nearly all drivers under most highway conditions. For such use herein it is assumed that the perception time value is 1.5 seconds, and the total of perception and brake reaction time is 2.5 seconds. Available references do not justify distinction over the range in design speed.

Braking Distance

The approximate braking distance of a vehicle on a level roadway may be determined using the standard formula (see Appendix A for derivation):

$$d = \frac{V^2}{30f}$$

where d = braking distance in feet

V = initial speed in miles per hour

f = coefficient of friction between tires and roadway

In this formula the coefficient of friction, f, is an equivalent constant value representing the entire speed-change interval from V to zero mph. Measurements show that f is not the same for all speeds (9). It decreases as initial speed increases. It varies due to several physical elements such as tire pressure, tire type, tire tread depth, type and condition of pavement, the presence of water, snow, ice, or mud, etc. The several variables are allowed for if the coefficient of friction, f, is computed for each test from the standard formula, $d = V^2/30f$. It thus represents the equivalent constant friction factor.

Design Friction Factors

In developing design values for the friction factor, f, the AASHO Policy considered the results of several investigators (7,10,11). Figure 1 is a reproduction of the curves relating friction factor, f, to vehicle speed illustrated in the AASHO Policy (Figure III-1). For several of these curves, the friction factor, f, was calculated using the standard formula because two of the investigators recorded speed and stopping distance only (7,10).

Curves 1 to 6 in Figure 1 are from a study (10) in which more than 1,000 measurements of forward stopping distance were made on 32 pavements, both in wet and dry conditions. Several types of tires were used. Curves 7 and 8 are representative of several curves developed in a study (11) which recorded friction factors on 50 surfaces tested when dry using three different methods and three types of tires. Curves 9 and 10 from the same study are representative of wet conditions. Curve 11 is the calculated equivalent friction factor for stopping distances, measured (7) on a new high-type pavement; these were the only tests which included stops from 60 to 70 mph. This curve represents an average of all stops measured.

The AASHO Policy in concluding its establishment of design values for the friction factor makes the following remarks:

> Because of lower coefficients of friction on wet pavements as compared to dry, the wet condition governs in determining stopping distances for use

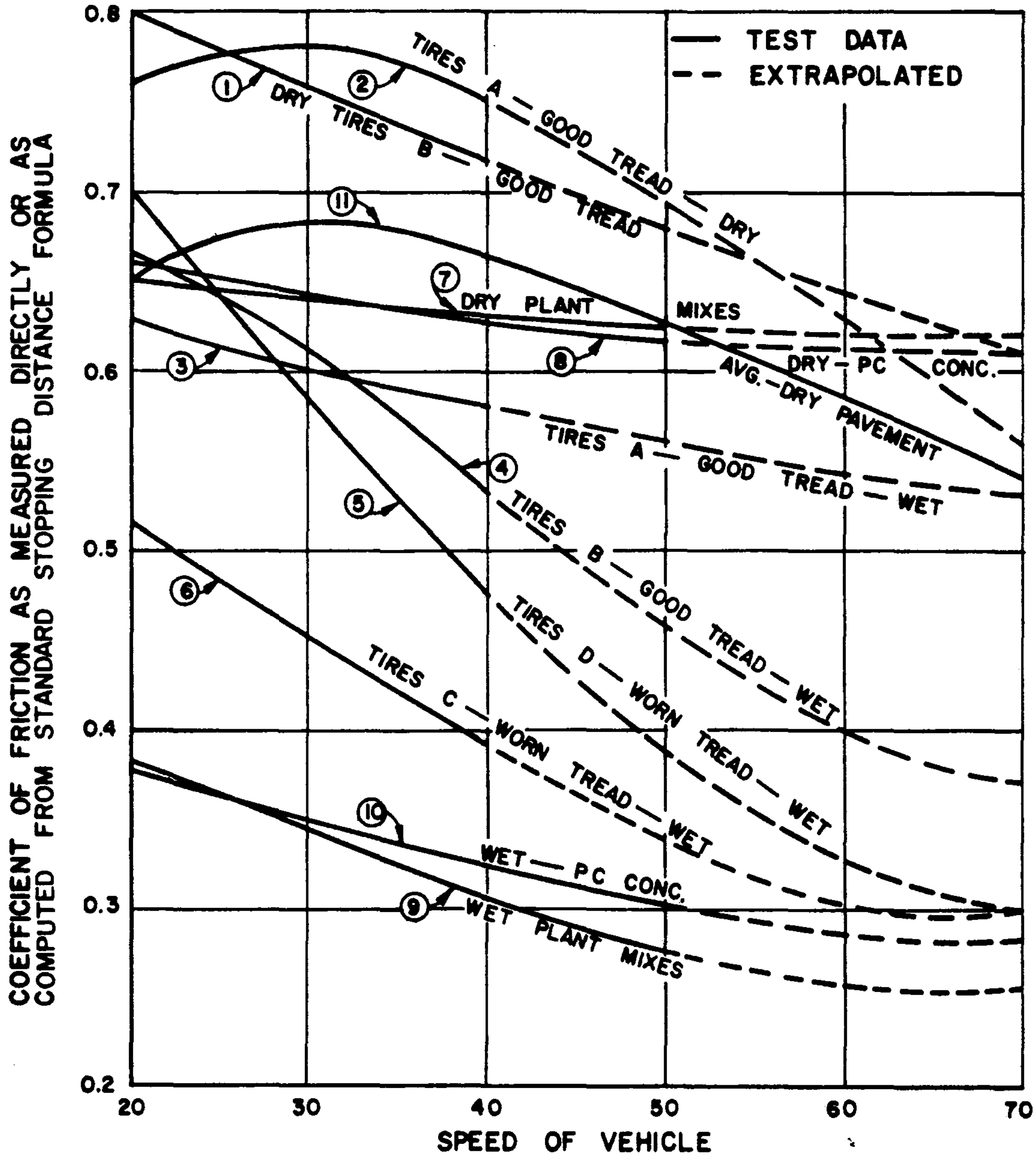


Figure 1 - Relationships Between Friction Factor and Speed for Several Conditions - AASHO Policy (2).

> in design. The coefficients of friction used for design criteria should not only represent wet pavements in good condition but also surfaces throughout their useful life. The values should encompass nearly all significant pavement surface types and the likely field conditions. They should be such as to be safe for worn tires, as well as for new tires, and for nearly all types of treads and tire composition. And, the friction factor should safely encompass the differences in vehicle and driver braking from different speeds. On the other hand, the values need not be so low as to be suitable for obsolescent or bleeding surfaces or for pavements under icy conditions. Preferably, the f values for design should be nearly all inclusive, rather than average; available data are not fully detailed over the range for all these variables, and conclusions must be made in terms of the safest reported average values. The lower curve in Figure III-1B gives the f values assumed for calculation of design stopping distances, recognizing these factors. Comparison with the curves of Figure III-1A shows them to be both practical and conservative.

The Figure, III-1B, depicting the friction factor values for design referred to in the above quote from the AASHO Policy is shown in Figure 2 of this report.

Assumed Speed for Conditions

The AASHO Policy states that it is not realistic to assume travel at full design speed when conditions are wet. It expands on this thought by stating:

> While the degree to which speeds are lower in inclement weather is not known precisely, it is definite that top speeds will be somewhat lower on wet pavements than on the same pavements in dry weather. For use herein the speed for wet conditions is considered to approximate 80 to 93 percent of design speed which, as previously explained, is indicative of the top speeds when pavements are dry. These speeds are the same as average running speeds for low volume conditions as shown in Figure II-16.

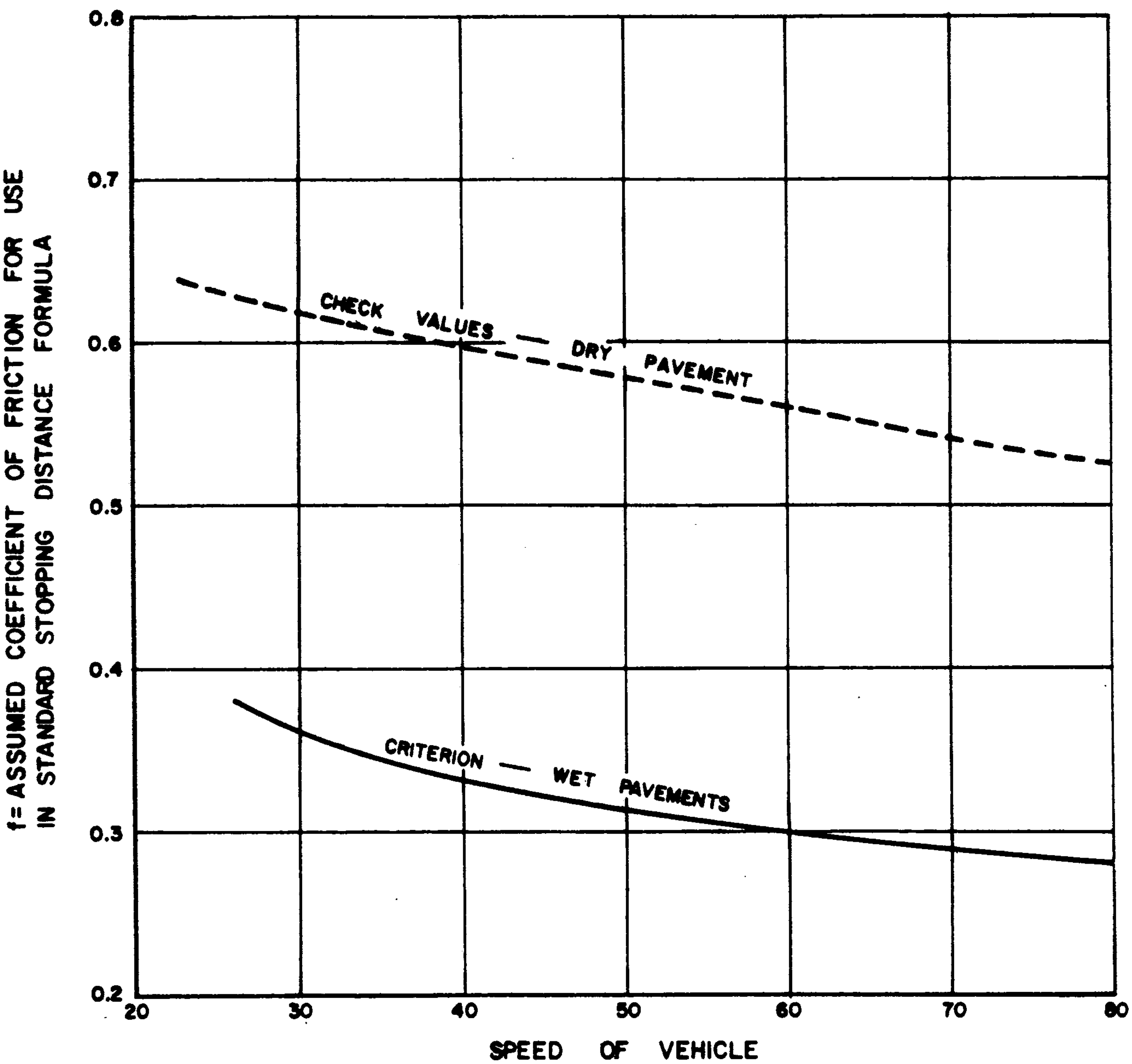


Figure 2 - AASHO Friction Factor Values for
Stopping Sight Distance Design (2).

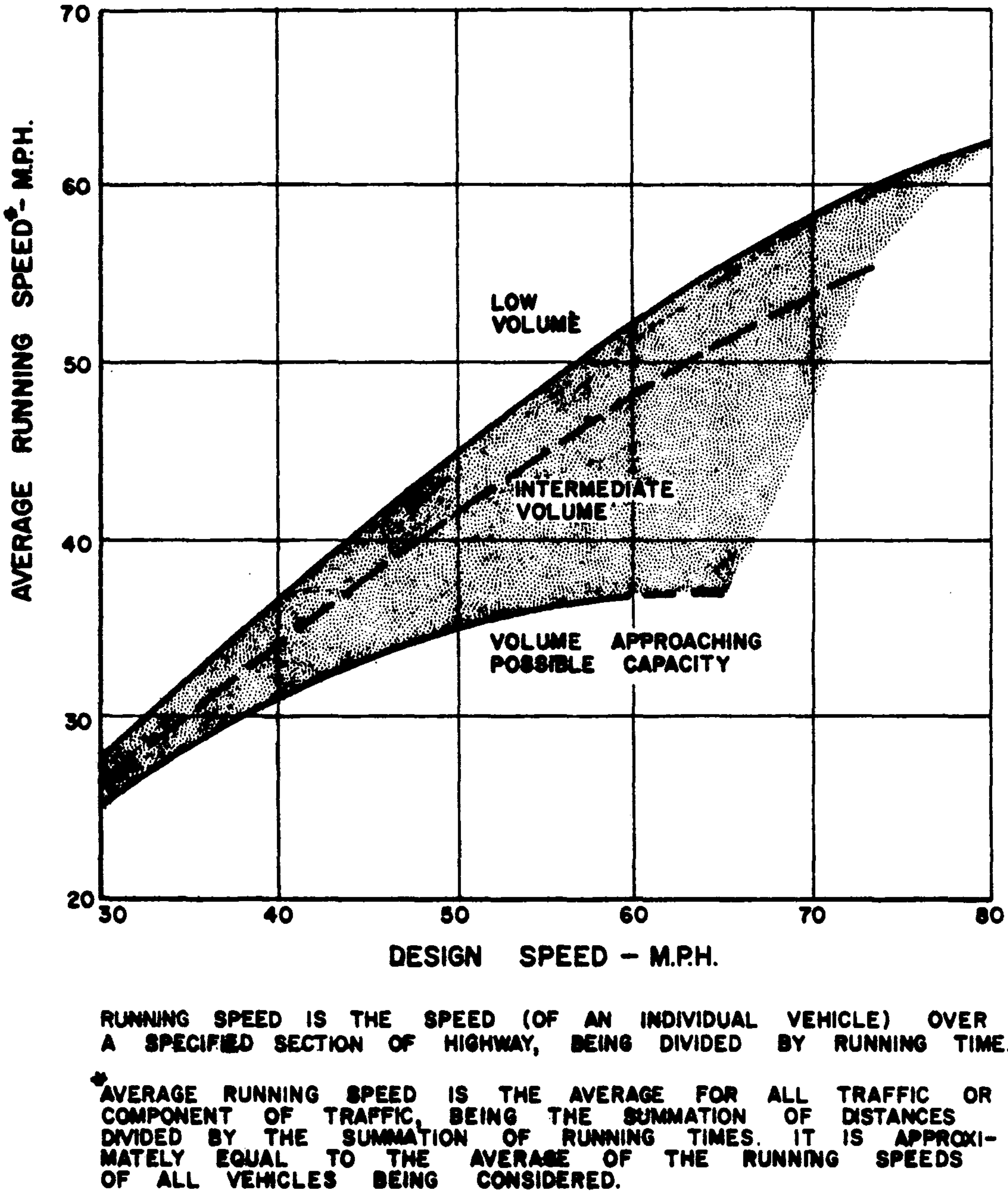


Figure 3 - Relation of Average Running Speed and Design Speed - AASHO Policy (2).

The Figure II-16 referred to in the above quote of the AASHO Policy is depicted in Figure 3 of this report. The AASHO Policy refers to data collected to establish these curves, but does not give a source either published or unpublished. The relationship was supposedly established from data which related average spot speed to design speed on horizontal curves.

Minimum Stopping Sight Distance Design Values

The sum of the distance traveled during the perception and brake reaction time and the distance required to stop the vehicle is the minimum stopping sight distance. Table 1 presents the AASHO Policy design values (and their bases of computation) for minimum stopping sight distance. Comparative check values for dry pavements are shown in the lower part of Table 1. These are computed by use of full design speed and f values for dry pavements as shown in the upper part of Figure 2. Comparison of these stopping distances for dry pavement conditions with those of the design values for wet pavements shows a desirable safety factor over the entire design speed range for dry pavements.

Effect of Grades on Stopping

When a highway is on a grade, the standard formula for braking distance is:

$$d = \frac{V^2}{30\ (f \pm G)}$$

TABLE 1

AASHO DESIGN STANDARD FOR MINIMUM STOPPING SIGHT DISTANCE

Design speed	Assumed speed for condition	Perception and brake reaction: Time	Perception and brake reaction: Distance	Coefficient of friction	Braking distance on level	Stopping sight distance: Computed	Stopping sight distance: Rounded for design
mph	mph	sec.	feet	f	feet	feet	feet
			Design Criteria--WET PAVEMENTS				
30	28	2.5	103	.36	73	176	200
40	36	2.5	132	.33	131	263	275
50	44	2.5	161	.31	208	369	350
60	52	2.5	191	.30	300	491	475
65	55	2.5	202	.30	336	538	550
70	58	2.5	213	.29	387	600	600
75*	61	2.5	224	.28	443	667	675
80*	64	2.5	235	.27	506	741	750
			Comparative Values--DRY PAVEMENTS				
30	30	2.5	110	.62	48	158	
40	40	2.5	147	.60	89	236	
50	50	2.5	183	.58	144	327	
60	60	2.5	220	.56	214	434	
65	65	2.5	238	.56	251	489	
70	70	2.5	257	.55	297	554	
75	75	2.5	275	.54	347	622	
80	80	2.5	293	.53	403	696	

*Design speeds of 75 and 80 mph are applicable only to highways with full control of access or where such control is planned in the future.

TABLE 2

EFFECT OF GRADE ON STOPPING SIGHT DISTANCE
FOR WET CONDITIONS (AASHO POLICY, 1965)

Design speed, mph	Assumed speed for condition, mph	Correction in stopping distance--feet					
		Decrease for upgrades			Increase for downgrades		
		3%	6%	9%	3%	6%	9%
30	28	--	10	20	10	20	30
40	36	10	20	30	10	30	50
50	44	20	30	--	20	50	--
60	52	30	50	--	30	80	--
65	55	30	60	--	40	90	--
70	58	40	70	--	50	100	--
75*	61	50	80	--	60	120	--
80*	64	60	90	--	70	150	--

*Design speeds of 75 and 80 mph are applicable only to highways with full control of access or where such control is planned in the future.

in which G is the percent grade divided by 100, and the other terms are as previously stated. The extent of the grade corrections of the AASHO Policy stopping sight distance design values is explained in Table 2.

Criteria for Measuring Sight Distance

All the material presented previously in this section deals with the design level required for adequate stopping sight distance based on driver and vehicle performance levels. To apply these minimum stopping sight distances in the design procedure, geometric considerations of the highway alignment (both horizontal and vertical), the height of the driver's eye, and the height of the object are required. Sight distance along a highway is measured from the object on the traveled way when it first comes into view (see Figure 4).

The general equations used in the design for stopping sight distance over crest vertical curves are (see Appendix B for derivation):

$$L = 2S - \frac{200\ (\sqrt{H_1} + \sqrt{H_2})^2}{A} \qquad \text{for } S > L$$

and

$$L = \frac{AS^2}{200\ (\sqrt{H_1} + \sqrt{H_2})^2} \qquad \text{for } S < L$$

where L = the length of vertical curve

S = Sight distance in feet

A = Algebraic difference in grade over the crest

H_1 = Height of driver's eye in feet

H_2 = Height of object in feet

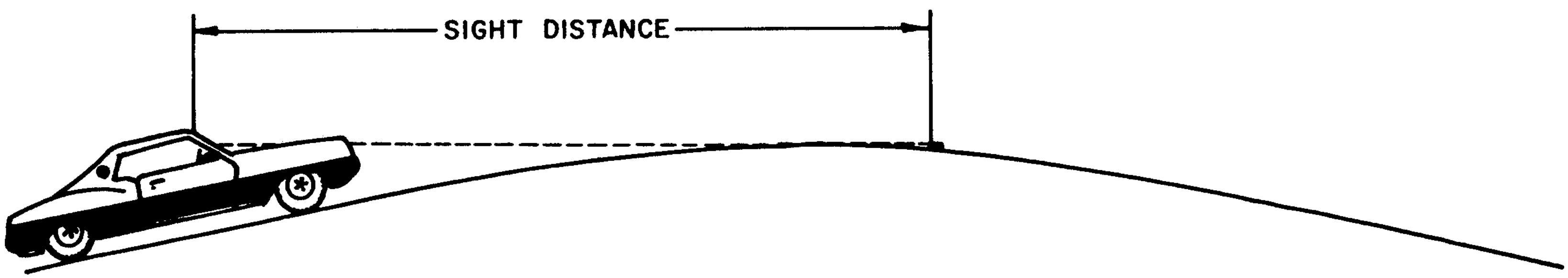


Figure 4 - Illustration of Stopping Sight Distance
Limitation Over a Crest Vertical Curve.

The equation used in the design for stopping sight distance on horizontal highway curves is:

$$S = \frac{R}{28.65} \cos^{-1} \frac{R-m}{R}$$

where S = Sight distance in feet

R = Radius of highway curve in feet

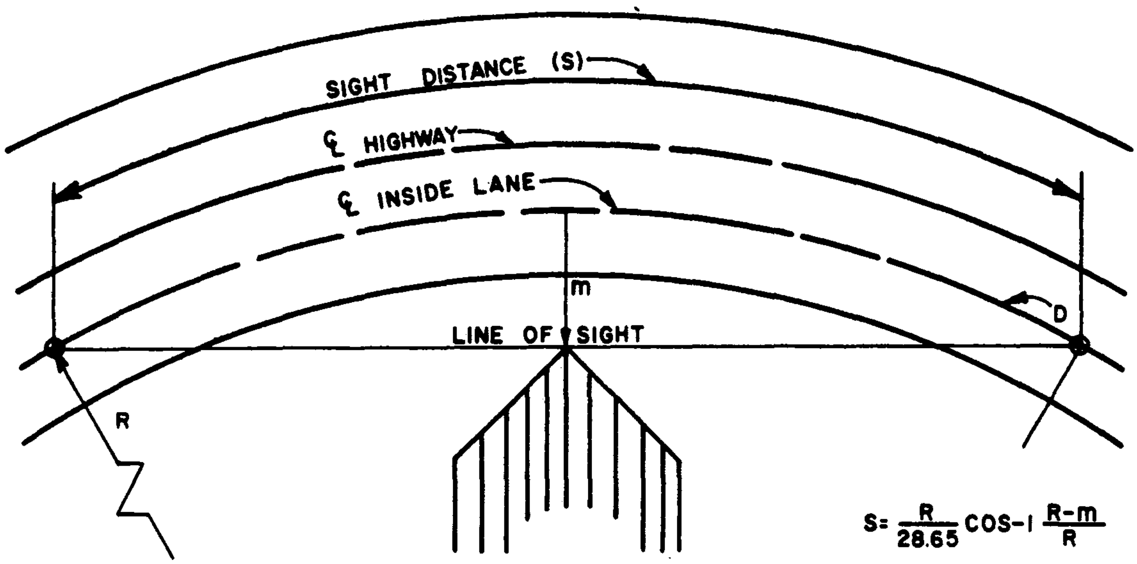
m = Distance in between obstruction and the centerline of the inside lane

Figure 5 depicts this geometry and graphically relates m to the degree of horizontal curve.

The eyes of the average driver in a passenger vehicle are considered by the AASHO Policy to be 3.75 feet above the road surface. In the 1960 model year, the median eye height of drivers in passenger vehicles was reported (2) as being 3.75 feet with a range of from 44 inches to about 49 inches. Because there are few car models in production for which the driver's eye height is above 4.0 feet and an appreciable number no higher than 3.75 feet, the AASHO Policy considers the latter height as appropriate for measuring stopping sight distances.

Stopping minimum sight distance is based on the distance required to stop safely from the instant a stationary object in the same lane becomes visible. On crest vertical curves, this point is limited by some point on the road surface. For horizontal curves, it is limited by a lateral obstruction beyond the roadway on the inside of the curve.

The height of object that should be used to measure stopping sight distance on crest vertical curves has been a controversial



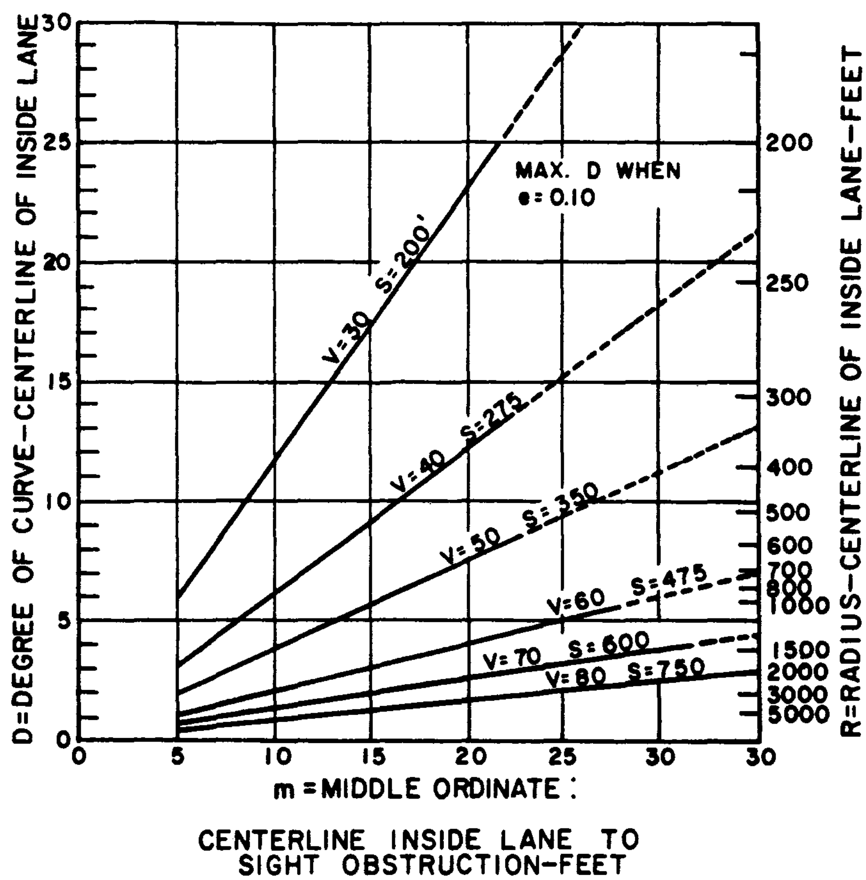


Figure 5 - Stopping Sight Distance Limitation on Horizontal Curves.

subject (2,3). The safest height of object would be zero (i.e., the surface of the roadway would be visible to the driver for the full length of the minimum stopping sight distance). Using this criterion however, would result in long vertical curves requiring considerable excavation costs in many cases. The height should not be more than the approximate two-foot height of vehicle taillights. But such heights would allow questionably short vertical curves, because lower objects on the road such as small animals, merchandise dropped from a truck, or rocks rolled from a side cut, may have to be seen to avoid a collision.

Examination of the required lengths of vertical curves for the minimum stopping sight distance (AASHO design values) in conjunction with various heights of object indicates a significant relationship. The AASHO Policy states:

> Plottings (not shown) of lengths of vertical curves with respect to heights of object, for any one condition of sight distance and algebraic difference in grades, reveal that the required length of vertical curve diminishes very rapidly as the height of object is increased from 0 to about 6 inches; for greater object heights, the reduction in length of vertical curve is progressively less significant.
>
> Substantial economy in construction (as reflected in the depth and volume of excavation due to shortening of vertical curve) is effected by using a 6-inch object instead of the desirable zero value, yet the ability to see or appraise a hazardous situation is not materially altered.
>
> A height of 6 inches is assumed for measuring stopping sight distance on crest profiles.

These criteria for height of eye and height of object represent a departure from the 1954 AASHO Policy. For the 1954 Policy, the height of eye was assumed to be 4.5 feet. Using the same analysis as described above, the 1954 Policy concluded that a 4-inch object height should be used in design.

Using the criterion of 3.75 feet for the height of eye and 0.5 feet for height of object, the general equations for the length of vertical curve may be modified as follows:

$$L = 2S - \frac{1398}{A} \qquad \text{for } S > L$$

$$L = \frac{AS^2}{1398} \qquad \text{for } S < L$$

Figure 6 shows the relation between length of vertical curve and sight distance for various algebraic differences in grade.

The height of object in determining stopping sight distance on horizontal highway curves is not as significant as that on vertical curves. Where the lateral sight obstruction is vertical, all heights of object may be seen at the same distance. Where the obstruction is an inclined cut slope, sight distance is affected somewhat by the height of object, but the effect is not large. For consistency, the AASHO Policy uses the same height criteria as on vertical curves, i.e., 3.75-foot eye height and 6-inch object height.

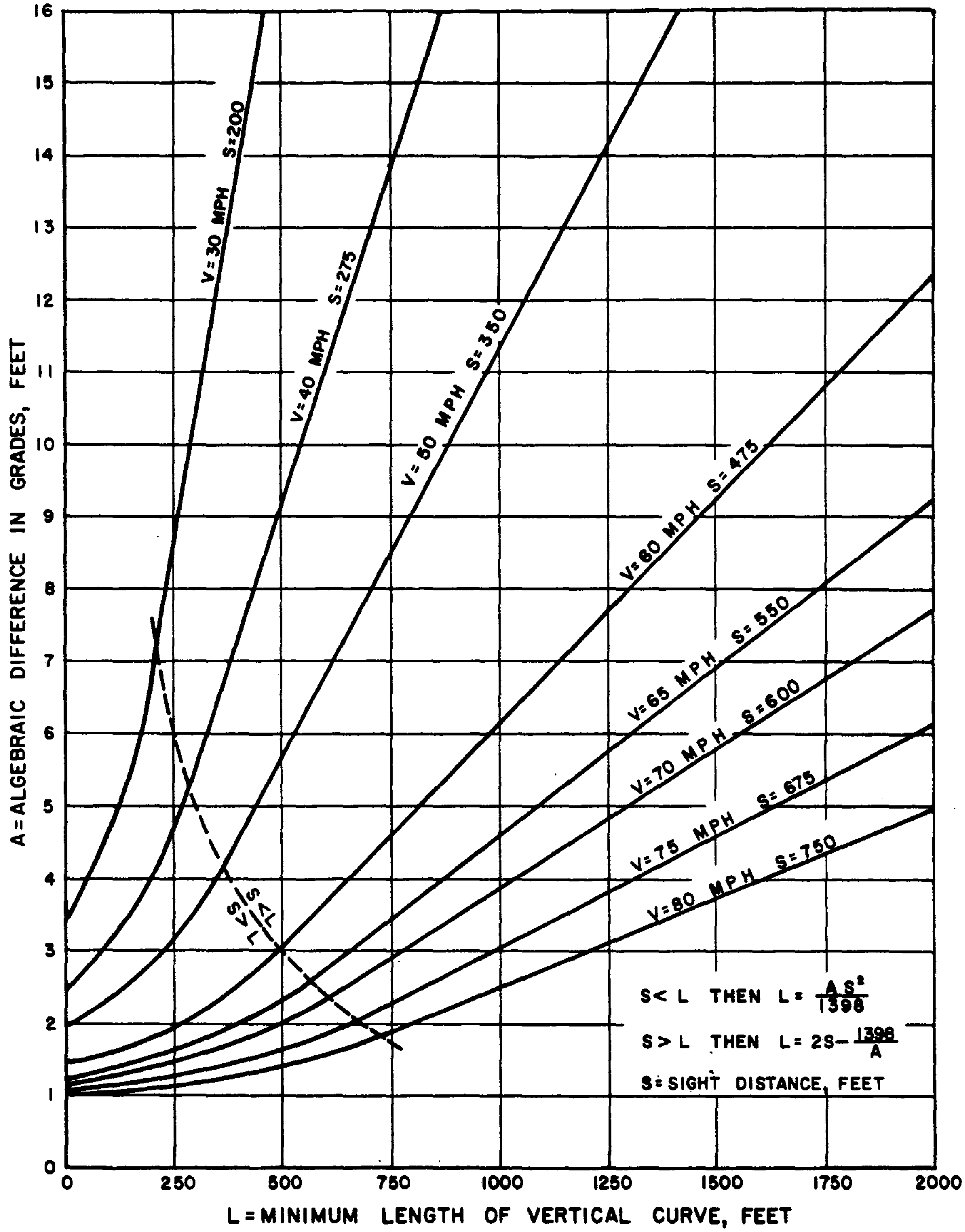


Figure 6 - Relation Between Stopping Sight Distance and Length of Crest Vertical Curve.

EVALUATION OF STOPPING SIGHT DISTANCE DESIGN STANDARDS

This section of the report is addressed to an evaluation of current AASHO stopping sight distance design standards presented in the previous section. Where appropriate, existing knowledge in the form of research references will be brought to bear on the analysis. The discussion includes the evaluation of the validity of the following criteria employed in the AASHO stopping sight distance standards: (a) perception and brake reaction times; (b) the braking distance equation; (c) design values for the friction factor; (d) assumed speeds for design; (e) driver eye height; and (f) object height.

Perception and Brake Reaction Time

The time interval of the stopping process commonly called the perception-reaction time is a very complex phenomenon. It is highly variable dependent on the driver's psychological and physiological characteristics, as well as the condition to be perceived. This may explain the lack of research to measure driver perception-reaction values in actual highway driving situations.

There are, however, conceptual explanations of the perception-reaction phenomenon. For example, Matson, Smith, and Hurd (12) describe the phenomenon as being composed of four elements: perception, intellection, emotion, and volition. Perception time is described as the time interval between the visibility of an object and the recognition of the object through visual sensation by the driver. The intellection time is that interval required for comparing, regrouping and registering new sensations. Emotion is described as a time modifier of perception and intellection dependent on the psychological make-up of the driver. Volition time is that interval necessary to exercise the decision to act. Another conceptual explanation of the perception-reaction process is offered by Baker and Stebbins (13) as illustrated in Figure 7.

Matson, Smith, and Hurd (12) described many variables which affect perception and reaction time including: fatigue, physical disabilities, alcohol, drugs, climatic conditions, light conditions, and driver traits. Another reference (5) states that eye blinking occurs in intervals of 2.8 to 3.8 seconds with a duration of 0.3 seconds or more. The researcher concludes by stating that vision is unreliable for a short time before and after a blink and the modified black out period caused by blinking may vary from 14 to 20 percent of all seeing time.

The most important element in the perception-reaction phenomenon is perhaps the perception of form. Perception of form depends mainly upon a sharp difference of brightness between an object and its background. Color difference is not as perceptible as brightness. Surfaces which differ in hue but not in brightness may be difficult to distinguish. In addition, highway design criteria assume that, as an object first comes into the view on a crest vertical curve, the driver

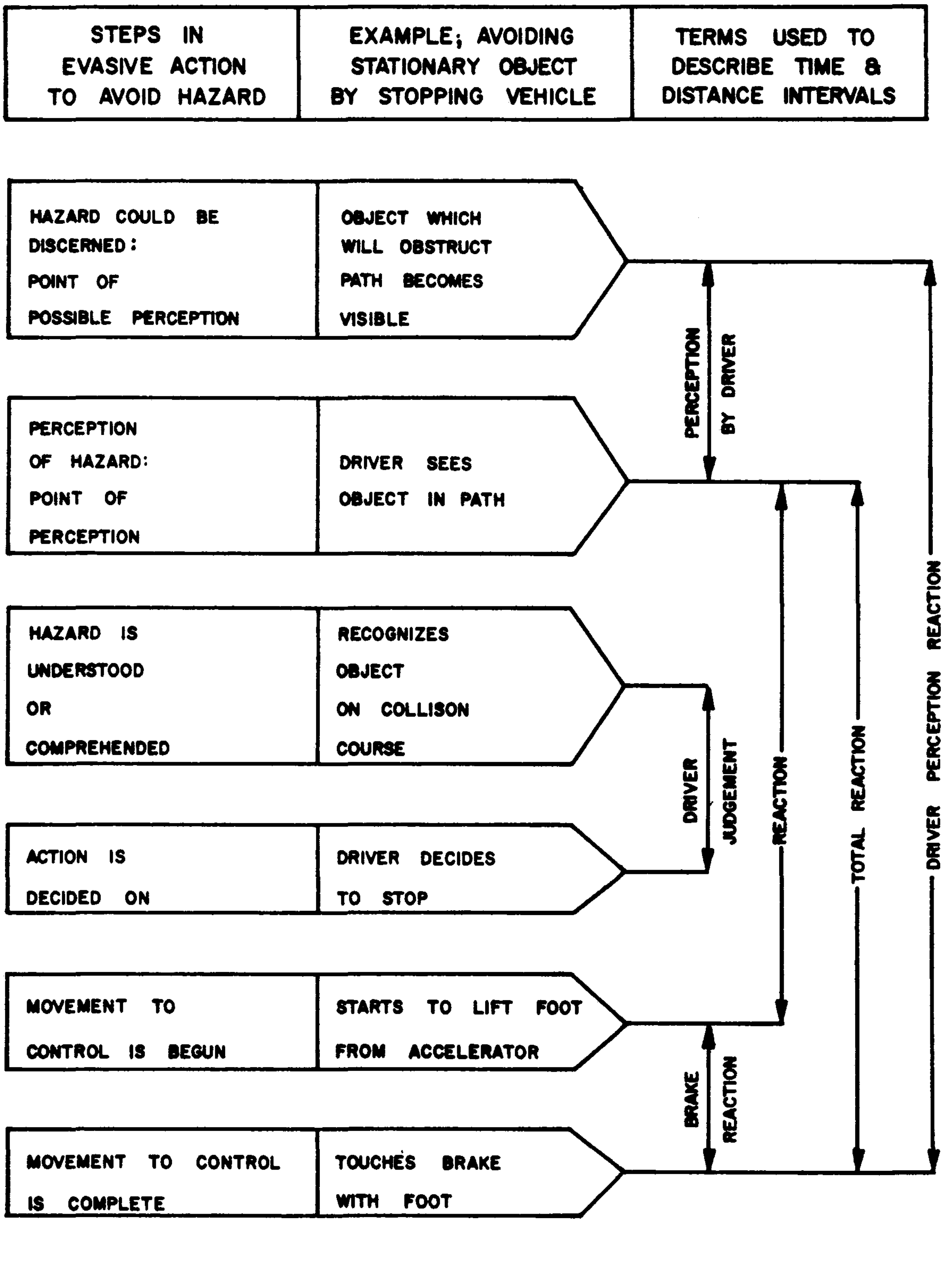


Figure 7 - The Perception-Reaction Process (13).

will perceive it and take appropriate action. Surely the driver has to see more than the first fraction of an object before he can perceive it. At 70 mph, on a vertical curve with 600-foot stopping sight distance (i.e., the driver sees the top of a six-inch object at 600 feet), the driver will not see the whole object until he has traveled 225 feet further.

The laboratory tests (6,7) previously discussed indicated driver perception-reaction times in the range of 0.4 to 1.7 seconds. As stated in the AASHO Policy, however, these times may be significantly greater for actual highway driving conditions. The AASHO Policy value of 2.5 seconds for perception-reaction time, however, was a rationalization from these studies. From previous discussion in this section it is surmised that the perception-reaction time is highly variable and under critical conditions could be higher than the 2.5-second value.

Figure 8 illustrates how the distance traveled during perception-reaction time varies with speed. It is observed that the required stopping sight distance would not be significantly changed for the lower speeds by increasing the required perception-reaction time by, say, one second. For the higher speeds, however, the distance is significantly increased for a one-second increase. Because of the trend of increased speeds on our highways and because of degradation in visual acuity with higher speeds, the 2.5-second perception time is questionably low for use in designing stopping sight distance for high speed roadways.

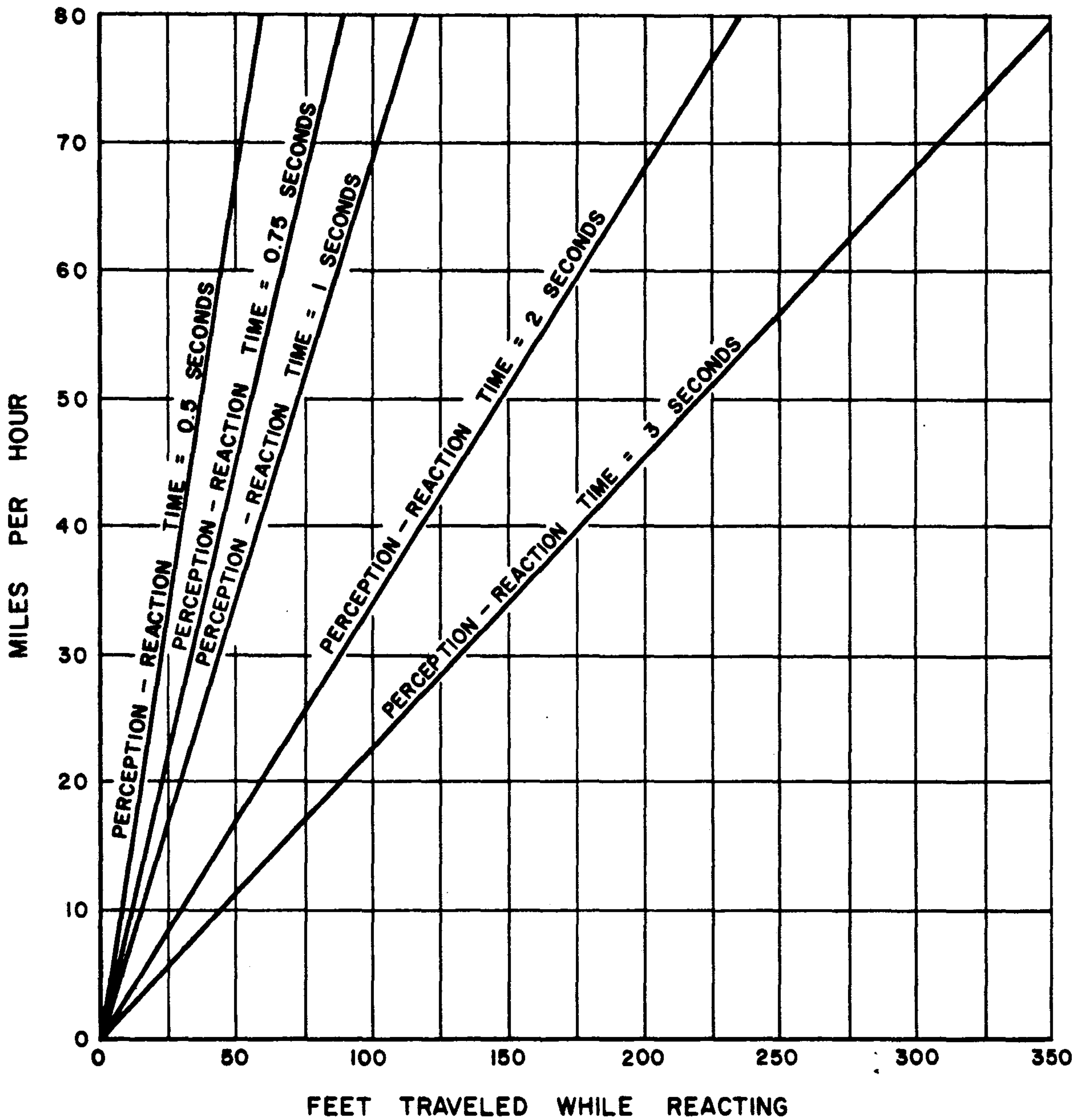


Figure 8 - Distance Traveled During Various Perception-Reaction Times for Various Speeds.

Friction Factor Design Values

The AASHO Policy considered several studies (7,10,11) in determining the design values for friction factors as shown in Figure 2 and Table 1. The friction factor versus speed relationship employed is representative of wet pavements measured in the referenced studies. Because wet values are considerably lower than dry values, the wet values are a rational basis for design. The question remaining is, however, "does this friction factor versus speed relationship represent a typical critical condition?" Figure 9 shows a percentile distribution of skid numbers (skid numbers are considered equivalent to 100f) at various speeds measured on 500 pavements (when wet) randomly dispersed throughout one state (14). These measurements were made in 1964 using a modified ASTM skid trailer with standard ASTM test tires. By referring to Figure 2, it may be observed that the curve that AASHO considers typical represents about the 35th percentile pavement of Figure 9. In other words, 35 percent of the pavements have friction factors lower than the design values. As such, the AASHO values are somewhat high. A more appropriate measure might be the 15th percentile pavement. Table 3 lists the friction factor versus speed relationship for 15th percentile pavement.

Stopping Distance Equation

If the relationship (shown in Figure 2) of friction factor versus speed were indeed a typical critical curve, then there would be no need for a verification of the validity of the stopping distance

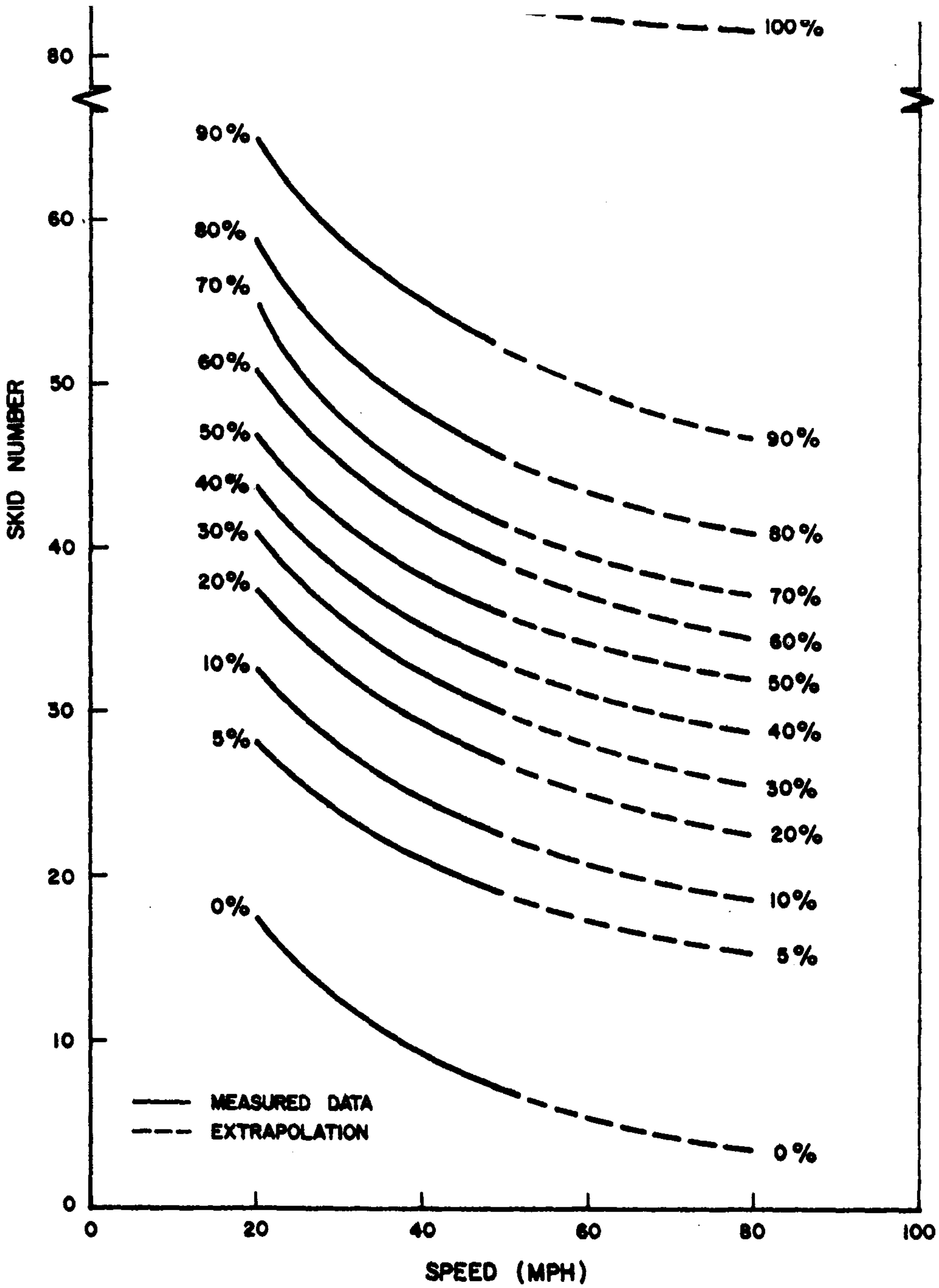


Figure 9 - Percentile Distribution of Skid Number Versus Speed Relationship for 500 Pavements in One State (14).

TABLE 3

FRICTION FACTOR VALUES FOR THE 15TH PERCENTILE PAVEMENT IN ONE STATE (14)

Design Speed	Friction Factor
30	0.30
40	0.46
50	0.24
60	0.23
70	0.22
80	0.21

equation. The reason is that the AASHO Policy employed the equation to compute friction factors from the referenced stopping distance measurements and then using these friction factors, with a safety factor applied, recomputed the stopping distance for design. In reality, this simply amounted to applying a safety factor to the original measured stopping distances.

Because of the apparent need to consider lower friction factors (discussed in the previous subsection), it is necessary to validate the equation for use of skid trailer measurements to compute stopping distance capability. Fortunately, tire quality test measurements (15) were conducted by the Texas Transportation Institute in 1968. These data were available for the analysis presented in Appendix C of this report.

The analysis considered 3,900 stopping distance measurements using several tire brands and tire types conducted on five test pavements of varying friction factor. Friction factors were measured (using the Texas Skid Trailer) on all five pavements periodically during the six months of testing. The analysis presented in Appendix C compares measured stopping distances with the stopping distances computed by using the appropriate friction factor in the standard equation. Although there was considerable variation between measured and computed distances, the analysis illustrates that only ten percent of the trials involved stopping distances greater than that predicted by the equation.

In many of the trials, the vehicle stopped much shorter than that predicted. This variation may be attributed to many variables such as: experimental error, tire temperature, tire type, pavement macrotexture, etc. A considerable portion of the variation was attributed to measurements made on the pavement with the lowest friction factor (Pad 4, approximate f value of 0.20). On this pavement, the stopping distances, in many trials, were much shorter than that predicted by the equation. On the other four test pavements (f values ranging between 0.44 and 0.64), the variation was considerably less than on Pad 4. No explanation can be offered for this phenomenon.

In summary, it appears that employing skid trailer values in the stopping distance equation yields reasonably conservative friction factor values for design purposes. The friction factors thus obtained should provide values of stopping distances which will be adequate for design of almost all conditions.

Assumed Speed for Conditions

The AASHO Policy states that it is not realistic to assume travel at full design speed when conditions are wet. With this reasoning, the Policy subjectively determined that the critical speeds for wet conditions should approximate 80 to 93 percent of design speed, as represented by average running speed for low volume [dry] conditions as shown in Figure 3. The AASHO Policy stated that this curve was developed from field data which related average spot speed to the design speed on horizontal curves. How ironic, that the speeds taken from the curve of Figure 3 were used for stopping sight distance design but not for horizontal curve design (for which full design speed is used for calculations).

It may be true that the critical speed (such as the 85th percentile) for wet pavements on horizontal curves is approximated by the average speed for dry conditions. However, stopping sight distance is also a design consideration on tangent alignment. It is reasonable to assume that low volume average and 85th percentile speeds will be higher on tangent sections than on horizontal curves, especially for the lower design speeds. For free-flowing conditions the horizontal curvature is actually the only feature which limits speed (with the exception of very steep grades). No matter what the overall design speed of a highway may be, the actual design speed of long, level tangent sections on that highway is not limited by the geometry.

There are many variables which affect the spot speed distribution of a highway section including: traffic volumes, percent of commercial vehicles, contiguous design speed, type of facility, amount of roadside development, weather conditions, wet pavements, posted speed limits, etc. (16). Unlimited studies have been conducted to relate traffic speeds to posted speed limits, but no references are available which have measured the relation between critical wet weather speeds and design speed. The Texas Highway Department (17) collected wet weather speed data at 16 sites in 1968. They also collected dry weather data at the same sites. Various speed distribution parameters taken from these measurements are listed in Table 4.

TABLE 4
SPOT SPEED DISTRIBUTION PARAMETERS FOR
WET AND DRY WEATHER CONDITIONS-TEXAS STUDY

	Site Conditions		Wet Weather Speed Parameters			Dry Weather Speed Parameters			
Site No.	No. of Lanes	Posted Speed	50th%	85th%	90th%	Average	50th%	85th%	90th%
1	4	50	45	51	53	51	50	58	60
2	4	60	47	55	57	52	51	58	60
3	4	60	50	58	60	63	61	70	72
4	4	60	55	62	64	59	58	63	66
5	4	60	56	63	65	60	59	65	67
6	4	60	58	68	70	60	60	70	72
7	4	60	60	67	69	66	65	71	74
8	4	60	61	68	69	64	64	70	71
9	4	60	64	71	73	67	66	73	75
10	4	70	52	59	62	61	61	68	70
11	4	70	52	62	64	57	56	63	65
12	4	70	54	61	63	58	57	67	68
13	2	70	54	64	65	59	59	69	70
14	4	70	56	64	65	62	61	70	72
15	4	70	55	64	65	60	60	70	71
16	2	70	56	64	66	61	61	70	71

The speed stations employed in this study were essentially level-tangent sections to limit the variation due to geometric design. Also, measurements were made of free-flowing vehicles only to eliminate variation due to traffic friction. In most cases the overall design speeds of the highways were at or below the posted speed.

From the data presented in Table 4 and from the above description of site and measurement conditions, the following observations are made pertaining to wet weather speeds.

1. There appears to be a leveling off of the higher speeds as posted speed increases. This is illustrated by the 85th percentile speed variation for 50, 60, and 70 mph posted speeds.
2. There is more variation in the distribution parameters for wet weather conditions than for dry weather conditions. This may be due to variations in rainfall intensity.
3. If it may be assumed that posted speeds approximate design speed, then it appears that the 85th percentile wet weather speed closely approximates the design speed for lower design speeds (less than 50 mph).
4. The wet weather 85th percentile speed averages about 3.0 mph higher than the dry weather average speed. This variation has an indicated regression which would vary from zero mph at lower speeds to 5 mph at the higher speeds.

The AASHO Policy's "assumed speeds for condition" have no objective basis. The question then is what speeds should be used for design. One argument holds that the design speed should be used as the critical design speed for stopping sight distance just as it is used for horizontal curve design. This could be justified on the basis that at some time a highway could be expected to have a posted speed limit either at or above the design speed. In addition, it might be expected that some drivers will exceed the posted limit regardless of weather conditions.

Another basis for critical speeds to use in stopping sight distance design could be derived considering the low volume curve in Figure 3, and the Texas speed data. To accomplish this, assumptions must be made regarding the relationship between average dry speeds on tangents and average dry speeds on horizontal curves. These assumed differences are shown in Table 5, along with the AASHO low volume average dry speeds on horizontal curves, the derived low volume average speeds on tangents, the differences between average dry speeds and 85th percentile wet speeds on tangents (discussed previously) and the derived critical speeds assumed for design. With this method the critical speeds are somewhat higher than those assumed in the AASHO Policy.

Driver's Eye Height

For more than twenty years, the AASHO design policies had based stopping sight distance criteria on a driver's eye height of 4.5 feet above the ground. In 1965, the AASHO Policy adopted a height of 3.75

TABLE 5
A DERIVATION OF CRITICAL WET
SPEEDS FOR DESIGN

Design Speed (mph)	AASHO ave. dry speeds on curves (mph)	Assumed difference between ave. dry speeds on tangent and curves (mph)	Derived ave. dry speeds on tangents (mph)	Assumed Difference between ave. dry speed and 85th percentile speeds on tangents (mph)	Derived 85th percentile wet speeds (mph)
30	28	6	34	0	34
40	36	6	42	0	42
50	44	6	50	0	50
60	52	5	57	2	59
65	55	4	59	3	62
70	58	3	61	3	64
75	61	2	63	4	67
80	64	1	65	5	70

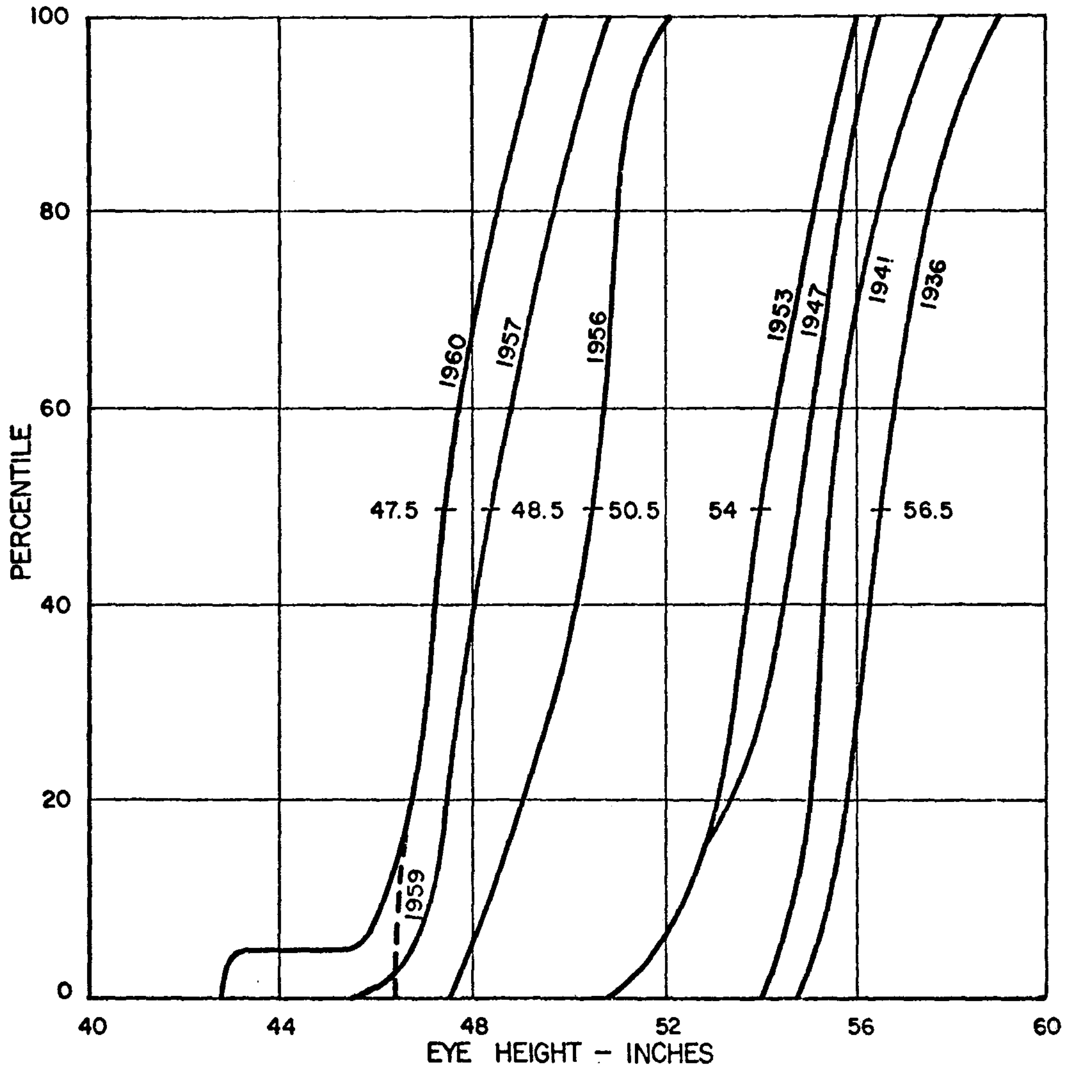


Figure 10 - Percentile Distribution of Driver's Eye Height for Various Model Years (18).

feet. One study (18) which probably influenced this decision was conducted by Stonex. Percentile distributions of "average" driver eye heights are shown for automobiles of various model years in Figure 10. Median driver eye height has decreased from 56.5 inches in 1936 to 47.5 inches in 1960. Stonex surmised that average driver eye heights would not fall below about 42 inches because of the need for automobiles to conform with sight distance constraints of existing highways.

It is believed that the driver's eye height has not been significantly lowered since the 1960 model year. Therefore, it appears that the 3.75-foot eye height may be a reasonably valid criterion for the design of stopping sight distance. However, the percentile distributions shown in Figure 8 are for models and are not distributions experienced on the highway. It is possible that a considerable percentage of driver eye heights on the highway are lower than 3.75 feet because of the introduction and high volume sales of automobiles such as the Ford Mustang and the Chevrolet Camaro.

Object Height

The AASHO Policy considers that a zero object height would provide for the safest sight distance design. The six-inch object height, however, was selected because it represented a point of diminishing returns in terms of the cost of excavation considering the relation between the object height and the length of vertical curve required to provide stopping sight distance for various object heights. This

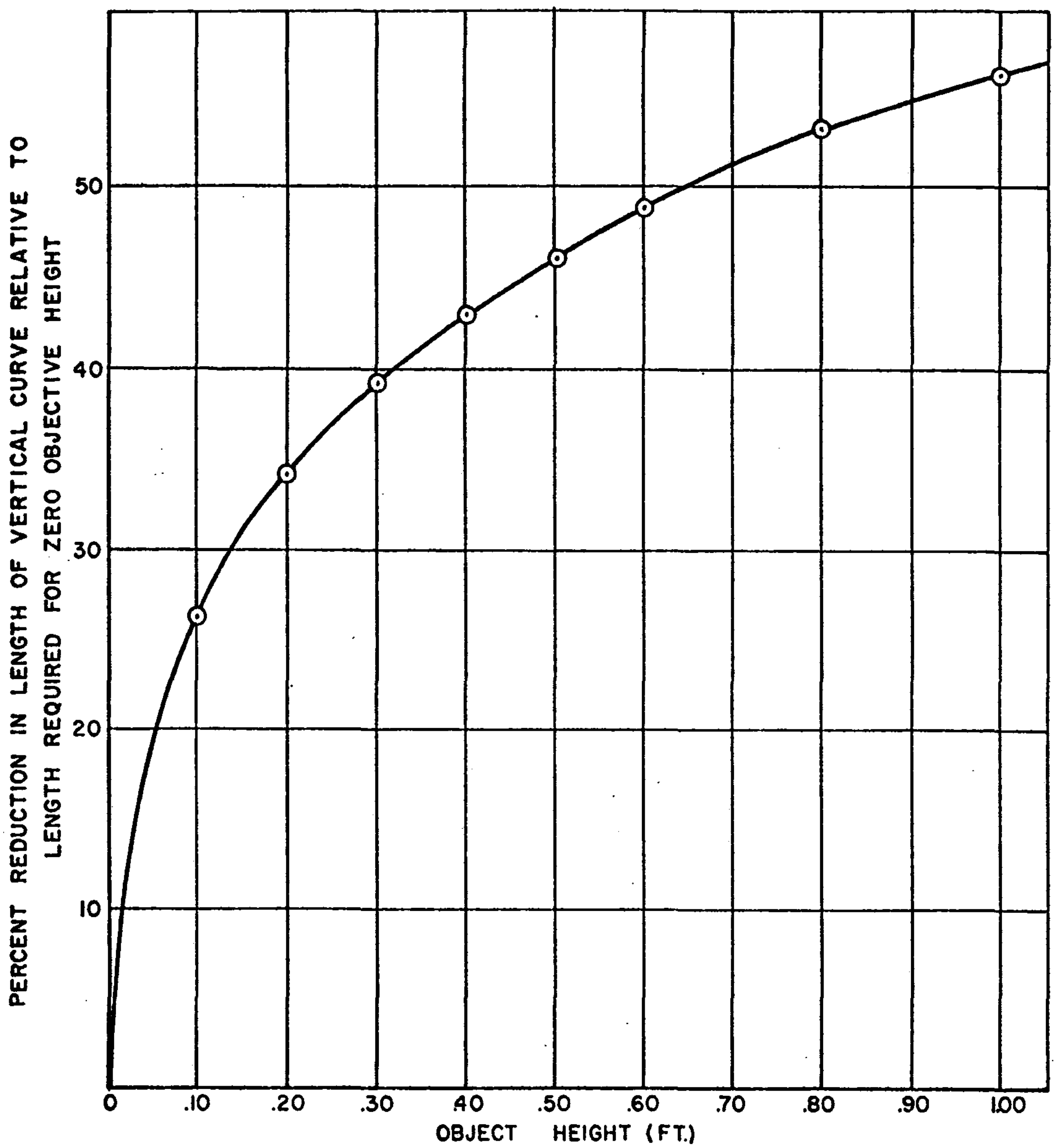


Figure 11 - Relation Between Object Height and Required Length of Crest Vertical Curve for AASHO Policy Stopping Sight Distance Standards (2).

relationship between object height and length of vertical curve is depicted in Figure 11.

This basis for designing vertical curvature may provide safety for most operational conditions, however, it is questionable whether it is entirely adequate for providing relatively high overall safety of operation. There appear to be many operational situations which would require a zero object height for safety, such as either a horizontal curve or an intersection hidden by a crest vertical curve. Therefore, it is concluded that the present criterion for object height bears no relation to many of the operational requirements for safe stopping sight distance. The next subsection discusses a new philosophy of designing for safe stopping sight distance on two-lane highways.

Head-on Collision Criterion for Stopping Sight Distance

At this point, an entirely new philosophy of stopping sight distance design will be offered. On two-lane highways, it is necessary for a vehicle to travel in the opposing lane to pass a slower moving vehicle. Legally, this is only possible where adequate passing sight distance is available and no restrictions are placed on passing. It is well known by traffic engineers and traffic law enforcement officers, however, that no-passing zones are often violated. Considering those drivers who violate no-passing zones and also drivers who wander into the opposing lane because of drowsiness or drunkeness (two characteristics which are all too common, especially at night), it would seem appropriate to design for nighttime stopping sight distance to opposing headlights, allowing for the closing rate of the two vehicles.

It is true that a driver can see the beams of opposing headlights well before he can see the headlights themselves. However, it is not always possible to perceive that the opposing vehicle is in your lane until the headlights are visible. The AASHO Policy states that headlight beam height is approximately two feet from the ground level.

For minimum safety requirements, it appears that the safe stopping sight distances should be doubled for the head-on situation. On the surface, this may appear to be very liberal; however, if the opposing driver is either intoxicated or asleep, he may not slow his vehicle at all. In this case, it would be necessary for the other driver to slow and take evasive action in a very short time frame.

In designing for the head-on situation one is again faced with the problem of establishing critical speeds for design. In this case, the critical speed should be, say, the 85th percentile night wet weather speed. The 1968 Annual Statewide Speed Survey (19) of the Texas Highway Department shows that the nighttime 85th percentile speed is about 2 mph lower than the daytime 85th percentile speed. If the assumptions of Table 5 are accepted, then the 85th percentile night wet weather speed might be derived as 2 mph lower than the 85th percentile day wet weather speeds.

It was previously indicated in this report that the 2.5-second perception-reaction time (assumed by AASHO) is probably low for the higher travel speeds, but that evaluation was based on a stationary

TABLE 6
SAFE STOPPING SIGHT DISTANCES FOR
HEAD-ON COLLISION CRITERIA

Design Speed	Assumed Speed For Condition	Perception-Reaction Time	Perception-Reaction Distance	Friction Factor	Braking Distance On Level	Stopping Sight Distance 1 Vehicle	Stopping Sight Distance 2 Vehicle	Stopping Sight Distance Rounded Design Va
mph	mph	sec	feet	f	feet	feet	feet	feet
30	32	2.5	117	0.29	118	235	470	470
40	40	2.5	147	0.26	205	352	704	700
50	48	2.5	176	0.24	320	496	992	1000
60	57	2.5	209	0.23	471	680	1260	1260
65	60	2.5	220	0.23	522	742	1484	1480
70	62	2.5	228	0.23	557	785	1570	1570
75	65	2.5	239	0.22	640	879	1758	1760
80	68	2.5	250	0.22	700	950	1900	1900

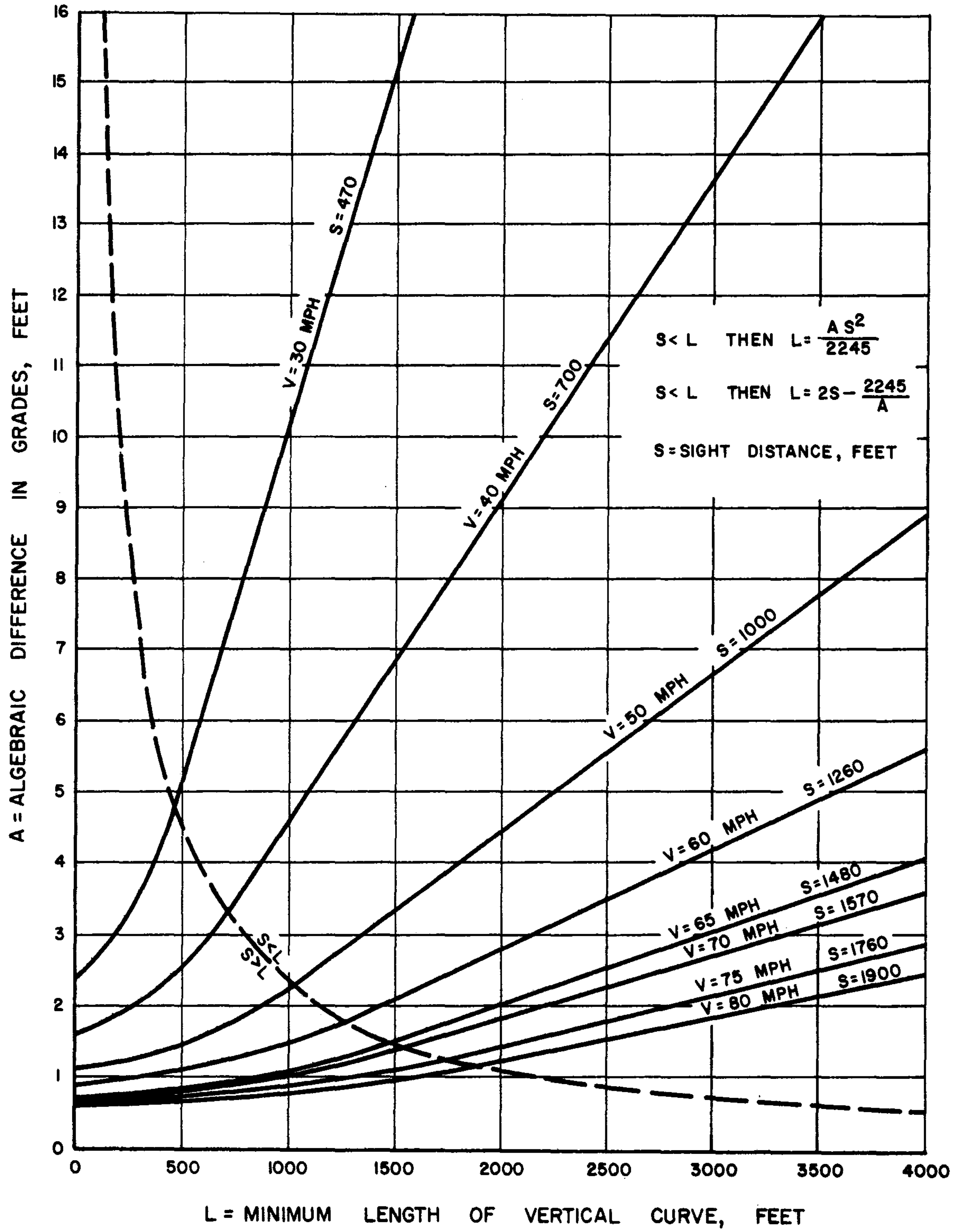


Figure 12 - Relationship Between Stopping Sight Distance and Length of Vertical Curve for Head-on Collision Criterion for 3.75-Foot Eye Height and Two-Foot Objective Height.

object without its own source of illumination. For stopping sight distance design to an opposing vehicle, the 2.5-second perception-reaction time is probably adequate. Table 6 lists the proposed safe stopping sight distances for the head-on collision criterion employing the assumptions discussed in this subsection. The design friction factors represent the 15th percentile pavement as previously discussed (see Table 3). Figure 12 illustrates the relationship between stopping sight distance and length of vertical curve for the head-on collision criterion.

Stationary Object Collision Criterion for Safe Stopping Sight Distance

For multi-lane divided and possibly undivided highways, there is no apparent need for the head-on collision criterion. There are, no doubt, other operational conditions which have respective stopping sight distance requirements. Until these operational requirements can be defined, the stationary object criteria are all that are available.

Table 7 lists stopping sight distances assuming the critical speed is equivalent to the design speed. Table 8 lists stopping sight distances using the critical speeds derived in Table 5. Both Tables 7 and 8 employ the 15th percentile Texas pavement for friction factor values. In addition, the perception-reaction times for the higher speeds have been adjusted upward in accordance with the earlier discussion in this section.

TABLE 7

SAFE STOPPING SIGHT DISTANCES FOR STATIONARY OBJECT CRITERIA (EMPLOYING DESIGN SPEEDS FOR WET CRITICAL SPEEDS)

Design Speed	Assumed Speed for Condition	Perception-Reaction Time	Perception-Reaction Distance	Friction Factor	Braking Distance On Level	Stopping Sight Distance Computed	Stopping Sight Distance Rounded
mph	mph	sec	feet	f	feet	feet	feet
30	30	2.5	110	0.30	100	210	210
40	40	2.5	147	0.26	205	352	350
50	50	2.5	184	0.24	347	531	530
60	60	2.5	221	0.23	522	743	750
65	65	3.0	287	0.22	644	931	930
70	70	3.0	309	0.22	742	1051	1050
75	75	3.5	386	0.21	893	1279	1280
80	80	3.5	412	0.21	1016	1428	1430

TABLE 8
SAFE STOPPING SIGHT DISTANCES FOR STATIONARY
OBJECT CRITERIA (EMPLOYING ASSUMED SPEEDS DERIVED IN THIS REPORT)

Design Speed	Assumed Speed For Conditions	Perception-Reaction		Friction Factor	Braking Distance On Level	Stopping Sight Distance	
		Time	Distance			Computed	Rounded
mph	mph	sec	feet	f	feet	feet	feet
30	34	2.5	125	0.28	138	263	260
40	42	2.5	154	0.26	226	380	380
50	50	2.5	184	0.24	347	531	530
60	59	2.5	217	0.23	504	721	720
65	62	3.0	273	0.23	557	830	830
70	64	3.0	282	0.23	593	875	880
75	67	3.5	345	0.22	680	1025	1030
80	70	3.5	360	0.22	742	1102	1100

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APPENDICES

Appendix A

Derivation of Stopping Distance Equation

The standard stopping distance equation is developed from the following basic physics equations:

$$v = v_o + at \tag{1}$$

$$d = \frac{(v_o + v)t}{2} \tag{2}$$

$$F = ma \tag{3}$$

where

v_o = initial speed in ft./sec.

v = speed in ft./sec. at the end of a given interval, of time, t

a = average acceleration over the interval

t = time of interval in seconds

d = distance traveled, in feet, over the interval of time, t

F = force in pounds

m = mass of vehicle in slugs

Employing these equations to analyzing the stopping vehicle, v_o is taken as the velocity at the point of initial brake application, and the velocity, v, is taken as zero when the vehicle completely stops. Therefore:

$$v_o = at \tag{4}$$

or

$$t = \frac{v_o}{a} \tag{5}$$

and

$$d = \frac{v_o t}{2} \tag{6}$$

substituting for t;

$$d = \frac{v_o^2}{2a} \tag{7}$$

Now considering the average force necessary to stop the vehicle:

$$F = ma$$

and

$$Wf = \frac{W}{g} a \tag{8}$$

or

$$a = fg \tag{9}$$

where

f = coefficient of friction between tires and pavement

g = acceleration of gravity in ft./sec.^{2}

Substituting the value for a from equation 9 into equation 7:

$$d = \frac{v_o^2}{2fg} \tag{10}$$

Changing v_o to miles per hour and replacing g by its value 32.2 ft./sec.^{2}

$$d = \frac{V^2}{30f} \tag{11}$$

where

V = initial vehicle speed in miles per hour

Appendix B

Derivation of Relationship Between Length of Vertical Curve and Sight Distance

Equation for S greater than L

The sight distance configuration for S greater than L is shown in Figure B-1. Use is made of the property of the parabolic curve that the horizontal projection of the intercept formed by a tangent is equal to one-half the projection of the long chord of the parabola. Thus, the sight distance, S, may be expressed by the sum of the horizontal projections.

$$S = \frac{100H_1}{|G_1|} + \frac{L}{2} + \frac{100H_2}{|G_2|}$$

where

H_1 = height of driver's eye in feet

H_2 = height of object in feet

G_1 = tangent grade 1 in percent

G_2 = tangent grade 2 in percent

The algebraic difference in grade, A, is defined as follows:

$$A = |G_1 - G_2|$$

Therefore

$$|G_1| = A - |G_2|$$

and

$$|G_2| = A - |G_1|$$

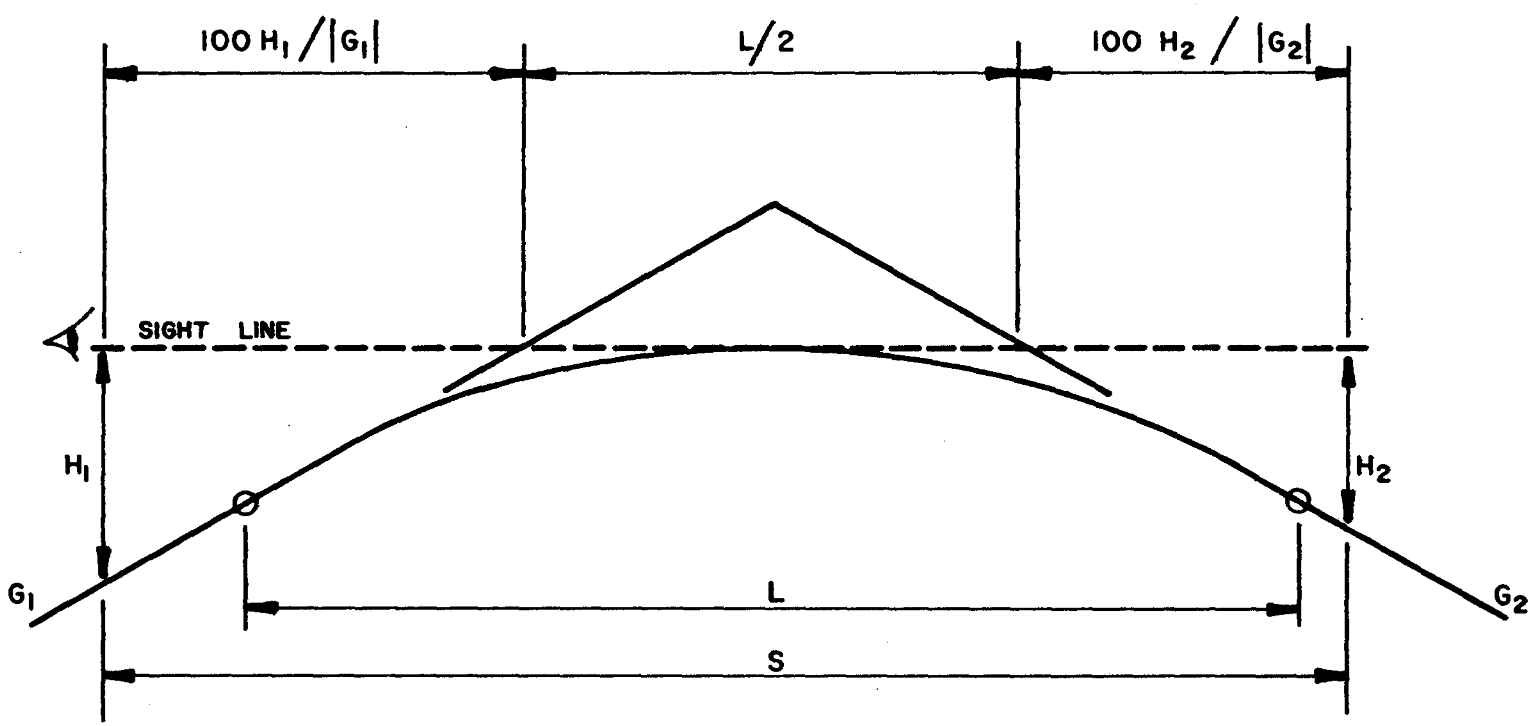

Figure B-1 - Sight Distance Configuration for S>L .

Therefore the equation for sight distance, S, may be written

$$S = \frac{100H_1}{|G_1|} + \frac{L}{2} + \frac{100H_2}{A - |G_1|}$$

The problem is to find the slope of the sight line that will make S a minimum by setting $\delta S/\delta G = 0$

$$\frac{\delta S}{\delta G} = \frac{-100H_1}{|G_1|^2} + \frac{100H_2}{(A-|G_1|)^2} = 0$$

$$\frac{H_1}{|G_1|^2} = \frac{H_2}{(A-|G_1|)^2}$$

or

$$|G_1| = \frac{A\sqrt{H_1}}{\sqrt{H_1} + \sqrt{H_2}}$$

and

$$|G_2| = \frac{A\sqrt{H_2}}{\sqrt{H_1} + \sqrt{H_2}}$$

substituting these values into the original equation for S, the following solution is obtained relating L to S for $S > L$.

$$L = 2S - \frac{200}{A}(\sqrt{H_1} + \sqrt{H_2})^2$$

<u>Equation for S less than L</u>

The sight distance configuration for S less than L is shown in Figure B-2. Use is made of the basic vertical offset properties of

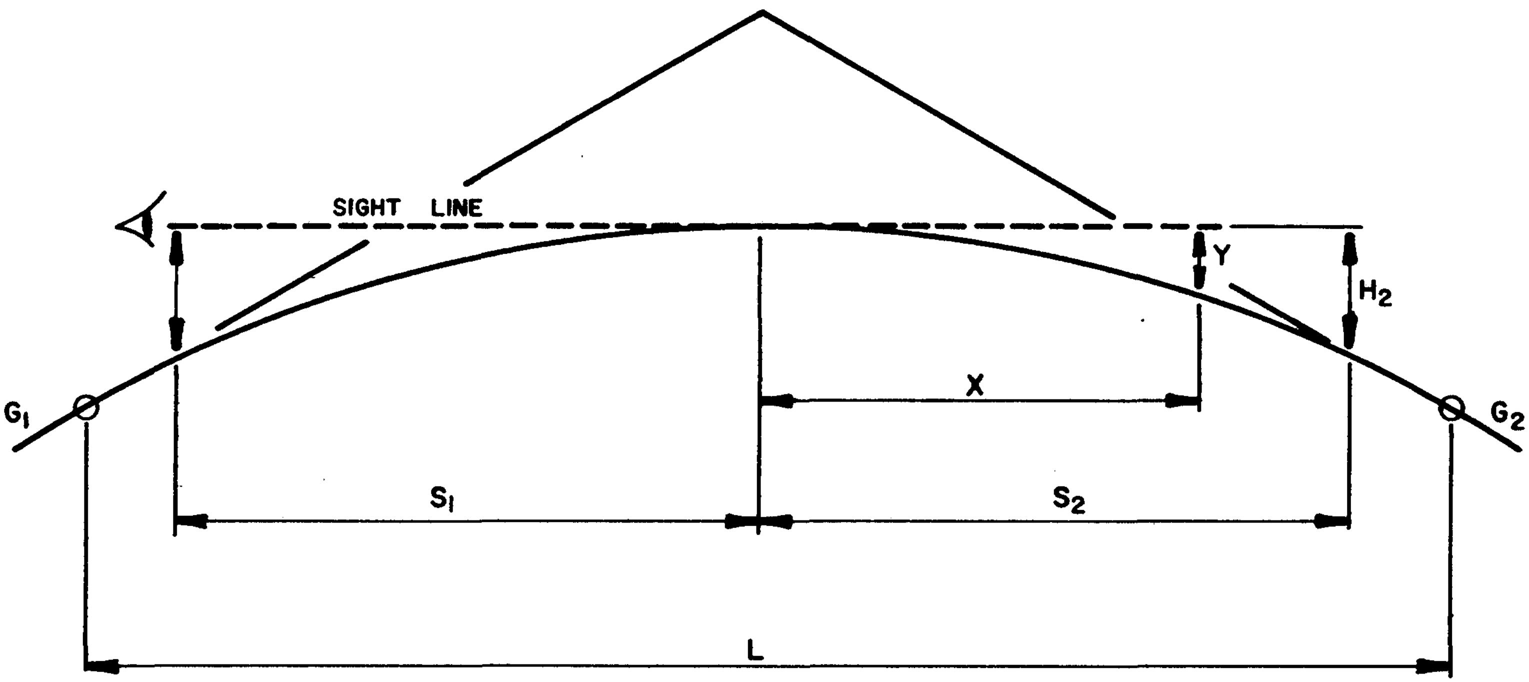

Figure B-2 - Sight Distance Configuration for S<L.

the parabolic curve.

$$y = \left(\frac{2x}{L}\right)^2 C$$

$$C = \frac{AL}{800}$$

therefore

$$y = \frac{Ax^2}{200L}$$

where

y = vertical offset in feet

x = distance from point of tangent in feet

L = length of the parabolic curve in feet

C = mid-curve offset in feet (see Figure B-2)

Applying this relationship to the configuration it can be shown that:

$$H_1 = \frac{AS_1^{\;2}}{200L}$$

and

$$H_2 = \frac{AS_2^{\;2}}{200L}$$

or

$$S_1 = \frac{\sqrt{200LH_1}}{A}$$

and

$$S_2 = \frac{\sqrt{200LH_2}}{A}$$

It can be seen from Figure B-2 that the sight distance, S, is the sum of S_1 and S_2, therefore:

$$S = \frac{\sqrt{200LH_1}}{A} + \frac{\sqrt{200LH_2}}{A}$$

The solution for L in terms of S, for $S < L$, therefore, may be stated as:

$$L = \frac{AS^2}{200(\sqrt{H_1} + \sqrt{H_2})^2}$$

Appendix C

Tire Test Results

The National Traffic and Motor Safety Vehicle Act of 1966 provided for the development of a uniform quality grading system for pneumatic passenger vehicle tires. In order to develop this system, the National Bureau of Standards found it necessary to conduct tests on tires currently in production, to provide the necessary data base. Under contract to the National Bureau of Standards, the Texas Transportation Institute undertook the testing of 95 sets of tires during the period of March through November of 1968 (15). The various sets of tires included in this program are presented in Table C-1. Each set of tires was tested to provide data on tractional characteristics when stopping with locked wheels and to determine loss of traction while driving through curves.

The pavements used in this test program were specially designed to achieve predetermined coefficients of friction. They included four different asphalt pavements and one portland cement concrete pavement. Each stopping pad was 24 feet wide and 600 feet long, having a cross slope of two inches in 24 feet.

Test Vehicle Description

The automobile used in this test program was a 1968 4-door Bel Air Chevrolet (see Figure C-1). Modification was made to the suspension system, including a change to heavy duty coil springs and heavy

TABLE C-1

CATEGORIZATION OF TIRE SETS TESTED

	Bias Ply	Radial	Wide Oval	Snow	Police	Sae	Wide Slicks	Total
New	20	8	12	11	2	4	1	58
Mileage Worn	13	8	0	0	0	0	0	21
Random Rerun (new and mileage worn)	5	4	2	2	1	2	0	16
							Total.....	95

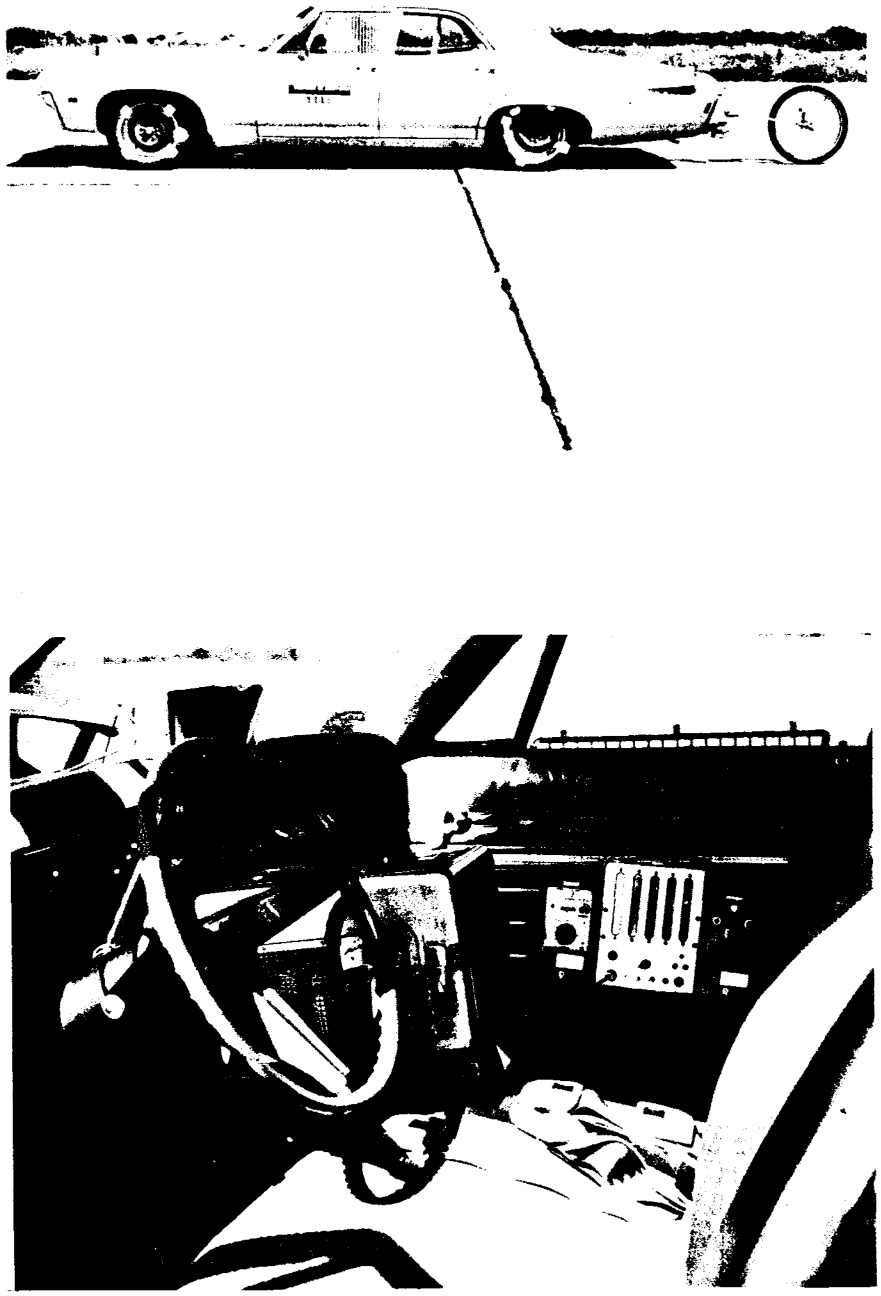

Figure C-1 - Tire Test Vehicle.

duty shock absorbers. Prior to each day of testing, the vehicle height was determined by measuring the height of marks placed on the bumper at each corner of the car. This procedure was established to determine if deterioration was occurring in the suspension system. Air pressure for the automobile tires tested was 24 psi cold.

The tire-test vehicle was equipped to indicate and record the following information:

a. Distance traveled as a function of time;

b. Velocity of the vehicle as a function of time;

c. Rear-wheel lock-up point; and

d. Lateral forces (transverse accelerations).

Distance and velocity data were obtained from a Track-Test fifth wheel assembly attached to the rear bumper. Data were recorded on a Honeywell Visicorder. The AC power required for the Visicorder was supplied by a gasoline engine generator mounted in the trunk.

Description of Test Surfaces

The location of the Texas A&M Research Annex on property that had previously been a jet trainer airfield permitted a wide choice in the specific location of the various test pavements. The study called for the design and construction of four different surface textures produced from selected aggregate and a single grade and type of asphalt cement. A fifth surface was required in the program which consisted of selected portions of the existing portland cement concrete runways. It was expected that these different surfaces would have particular coefficients of friction which would remain constant for the duration of the study.

The preparation of the existing portland cement concrete pad consisted of a thorough cleaning. The other surfaces were to be designed and constructed to provide a range of friction coefficients between 0.20 to 0.60. Pavements were produced which covered a range of 0.18 to 0.64 (as measured with a skid at 40 mph) at the beginning of testing. The spread of these coefficients was reduced during the course of the project to a range of 0.18 to 0.44. The history of friction coefficients over the period of testing is presented in Figure C-2 for each test pavement.

Skid Trailer Measurements

The friction values shown in Figure C-2 were obtained with the Texas Highway Department Skid Trailer (see Figure C-3) run with standard ASTM grooved test tires. The source of water for wetting the pavements was a 4,000-gallon water truck, complete with spray bars and a controlled pumping system capable of producing a uniform flow and distribution of water (see Figure C-4). On each pad, one pass of the watering truck preceded two passes with the skid trailer (one in each direction). The skid trailer's self-watering system was not used.

Friction determinations were made at 20, 30 and 40 mph. For each speed six locked-wheel skids were made on each pad (three in each direction). The points plotted in Figure C-2 represent averages of these six measurements.

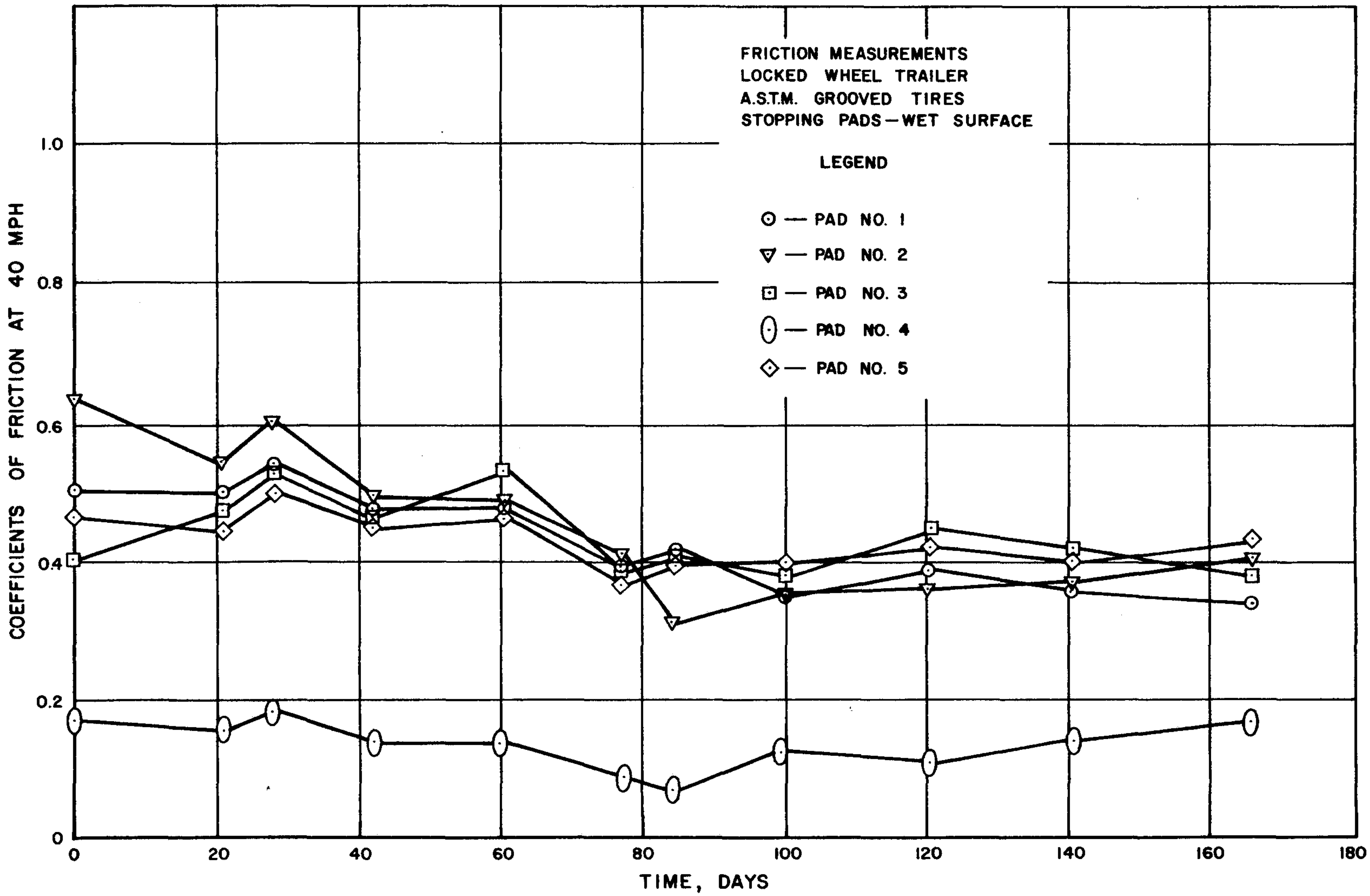

Figure C-2 - Variation of Test Pad Coefficients Over the Period of Testing.

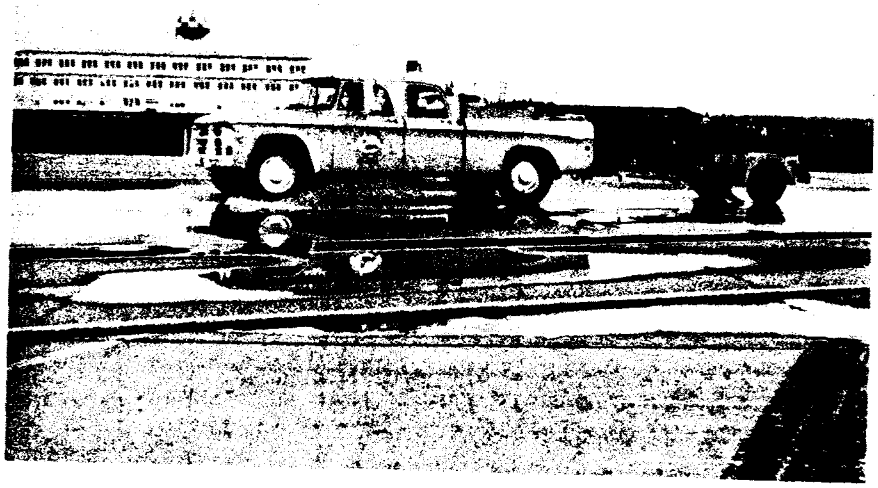

Figure C-3 – Texas Highway Department Skid Trailer.

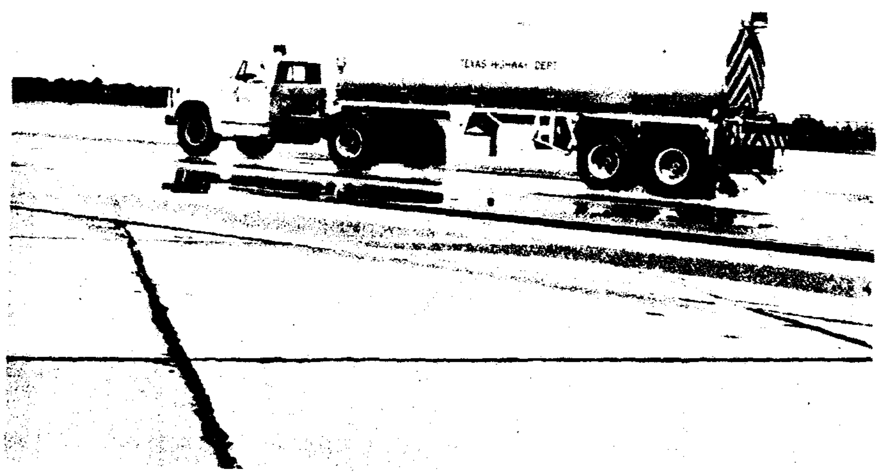

Figure C-4 – Watering Truck.

Stopping Distance Tests

The test vehicle was subjected to four-wheel lock-up four times for each of the speeds shown in Table C-2. Two test trials were conducted in each direction for each pad, tire set, and speed. The speeds shown in Table C-2 were determined at the beginning of the test program so that the driver would not be subjected to extremely unsafe conditions.

On pads 1, 3, 4 and 5 one pass of the watering truck preceded each two passes of the test vehicle (once in each direction). On pad 2, the same procedure was followed except prior to the 55-mph test run, where one pass of the watering truck preceded each trial run. This was necessary because of the nature of the pavement and time consumed by the driver in accelerating to the 55-mph speed.

Approximately 3,900 total stopping distance measurements were made on the following tire set types considered in this analysis: new bias-ply, worn bias-ply, new radial, worn radial, and new wide-oval.

Test Results

For each stopping distance test run, it was possible to associate a computed friction factor for the test speed based on the skid trailer measurements made at 20, 30, and 40 mph. Using the computed friction value and the test speed, it was then possible to compute the predicted stopping distance using the standard equation, $d = V^2/30\ f$. Having a measured stopping distance from the test, it was then possible to

TABLE C-2

LOCK-UP VEHICLE SPEEDS FOR EACH TEST PAD

Pad No.	Lock-Up Speeds (mph)		
1	30	40	50
2	35	45	55
3	30	40	50
4	15	25	35
5	30	40	50

analyze the prediction reliability of the equation, by comparing the predicted values with the measured values.

Figure C-5, C-6, C-7, and C-8 illustrate percentile distributions of the percent difference between the measured friction factor and the computed friction factor, (fc-fm)/fm. From Figure C-5, it is seen that in 90 percent of the 3,900 test trials the vehicle stopped in a shorter distance than that predicted by the standard stopping distance equation. Figure C-6 shows that the equation is somewhat more reliable for the lower stopping speeds. Figure C-7 indicates that new radial and new wide-oval tires have a somewhat better stopping capability than do new bias-ply tires. Also from Figure C-7, it appears that new tires have a somewhat better stopping capability than worn tires (10,000 high speed miles of wear). Figure C-8 shows that for the lowest coefficient pavement (Pad 4) the vehicle stopped considerably shorter than predicted. No explanation can be offered for this phenomenon.

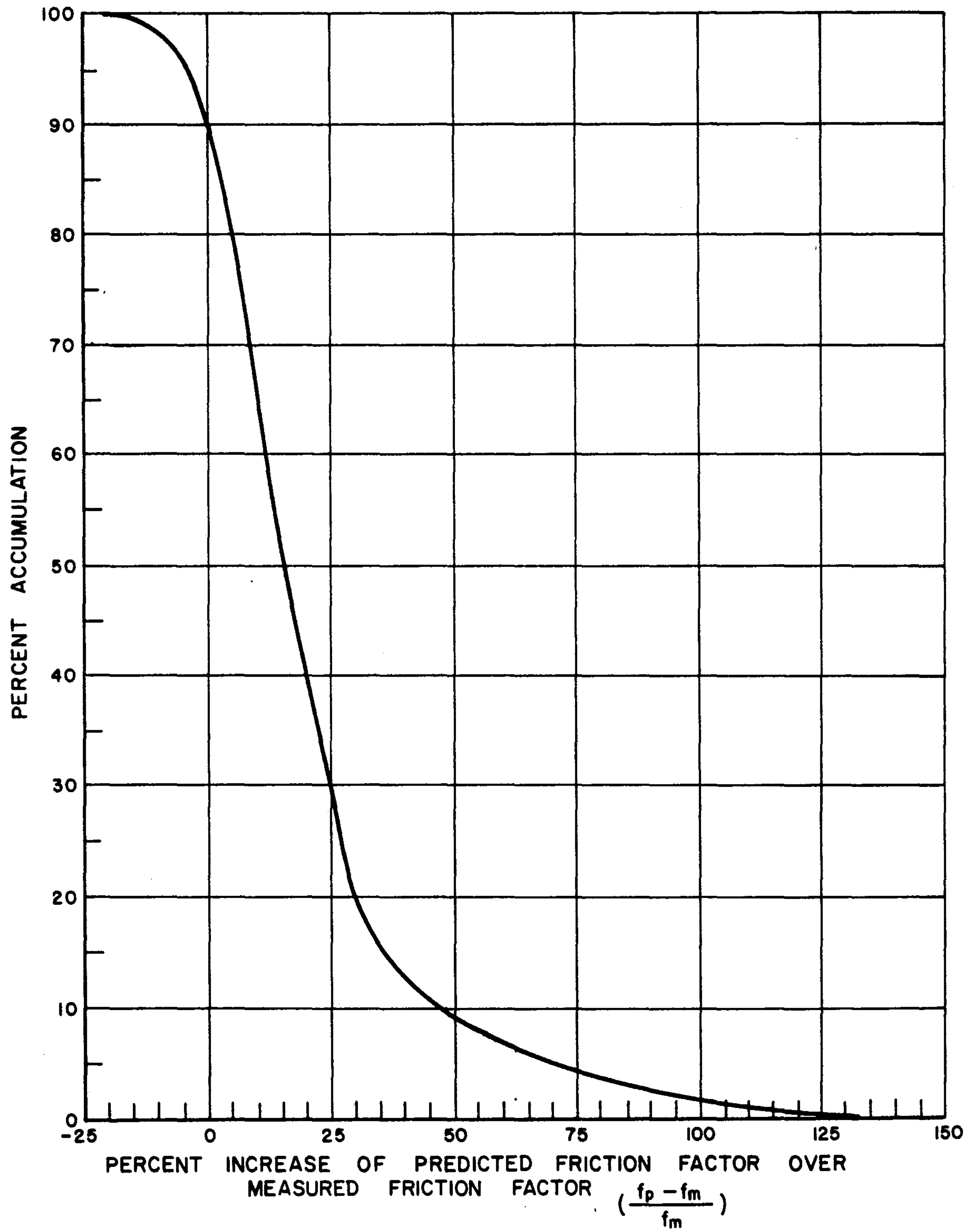

Figure C-5 - Percentile Distribution of Percent Deviation Between Measured and Computed Friction Factors for All Tests.

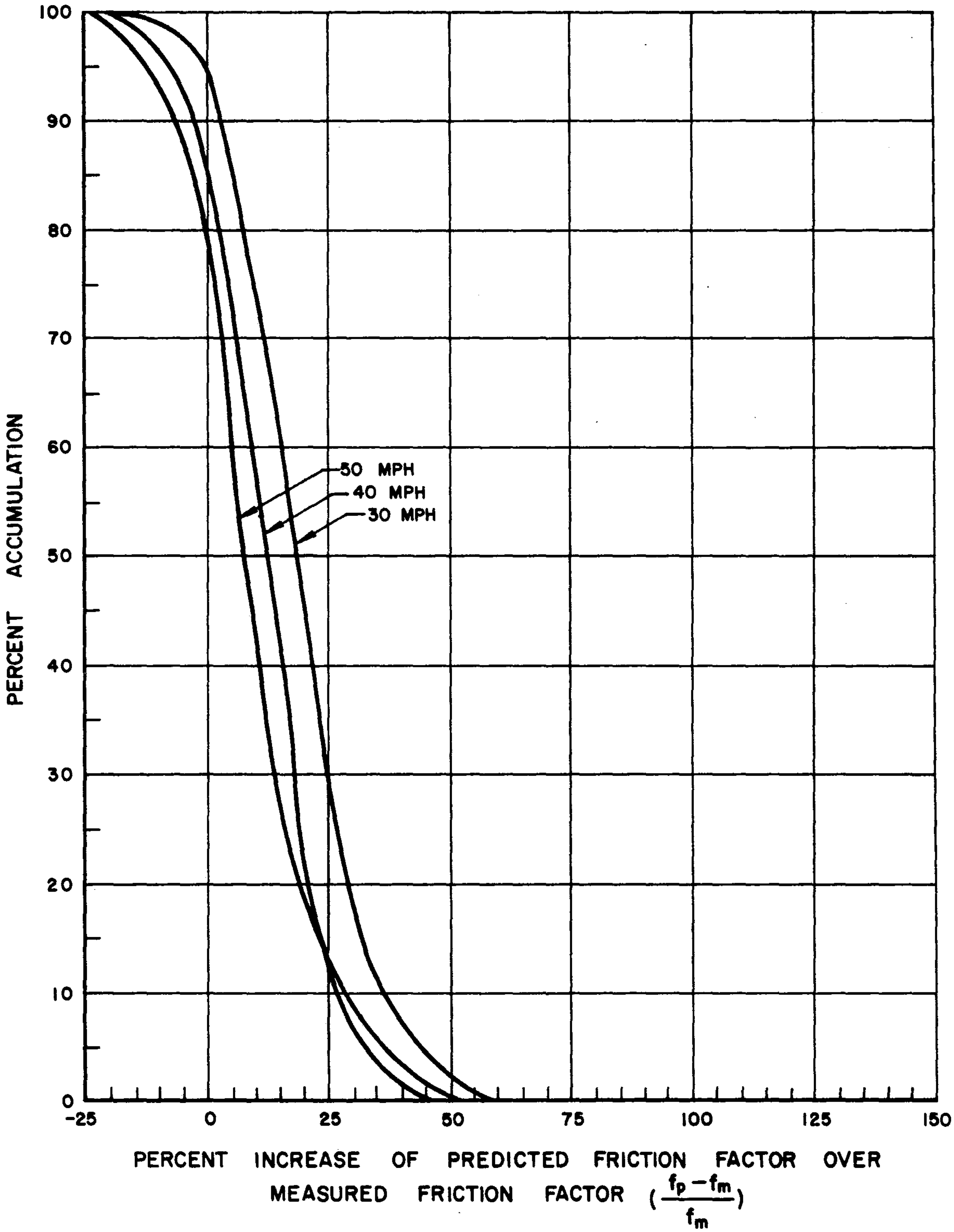

Figure C-6 – Percentile Distribution of Percent Deviation Between Measured and Computed Friction Factors Classified by Test Speed.

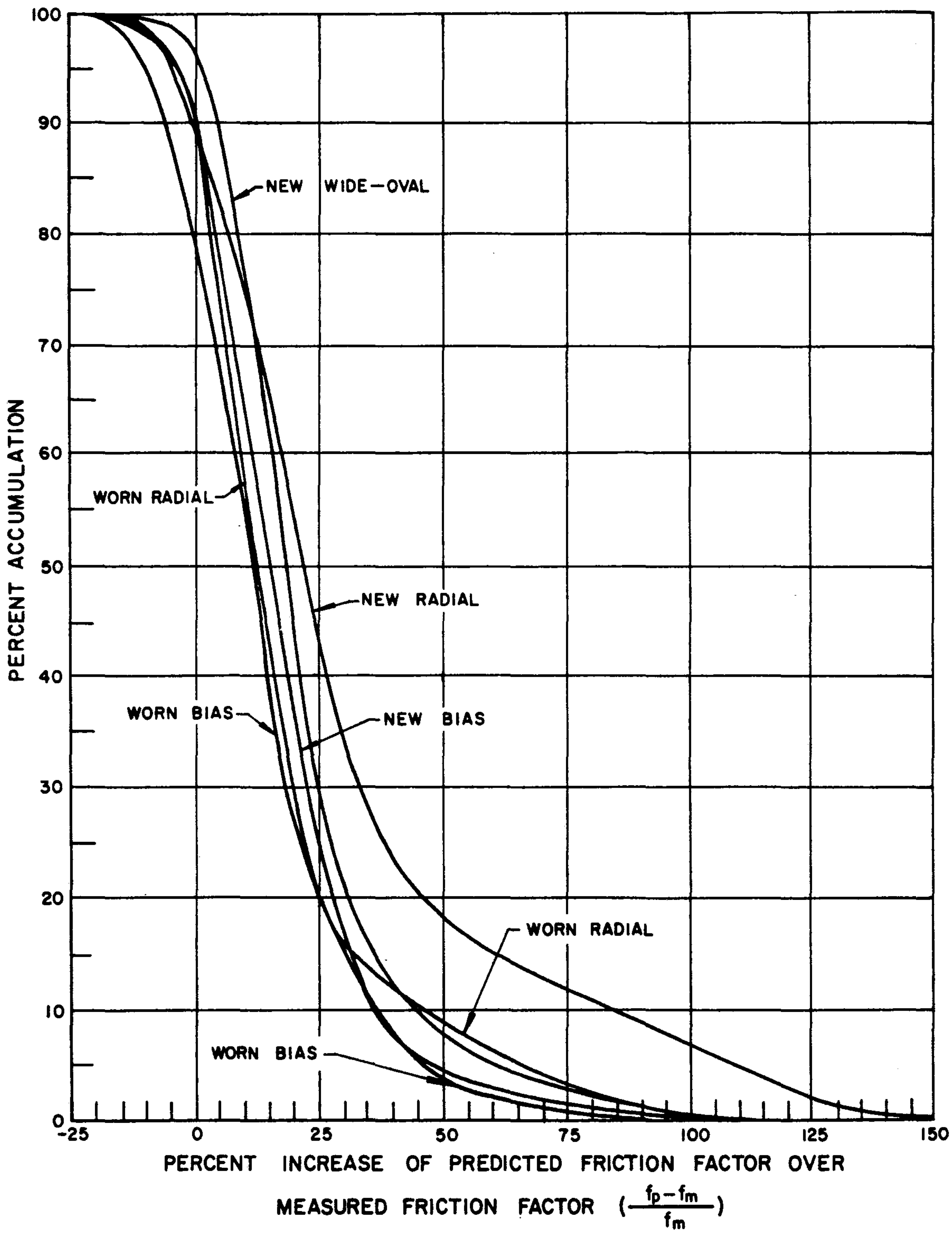

Figure C-7 - Percentile Distribution of Percent Deviation Between Measured and Computed Friction Factors Classified by Tire Type.

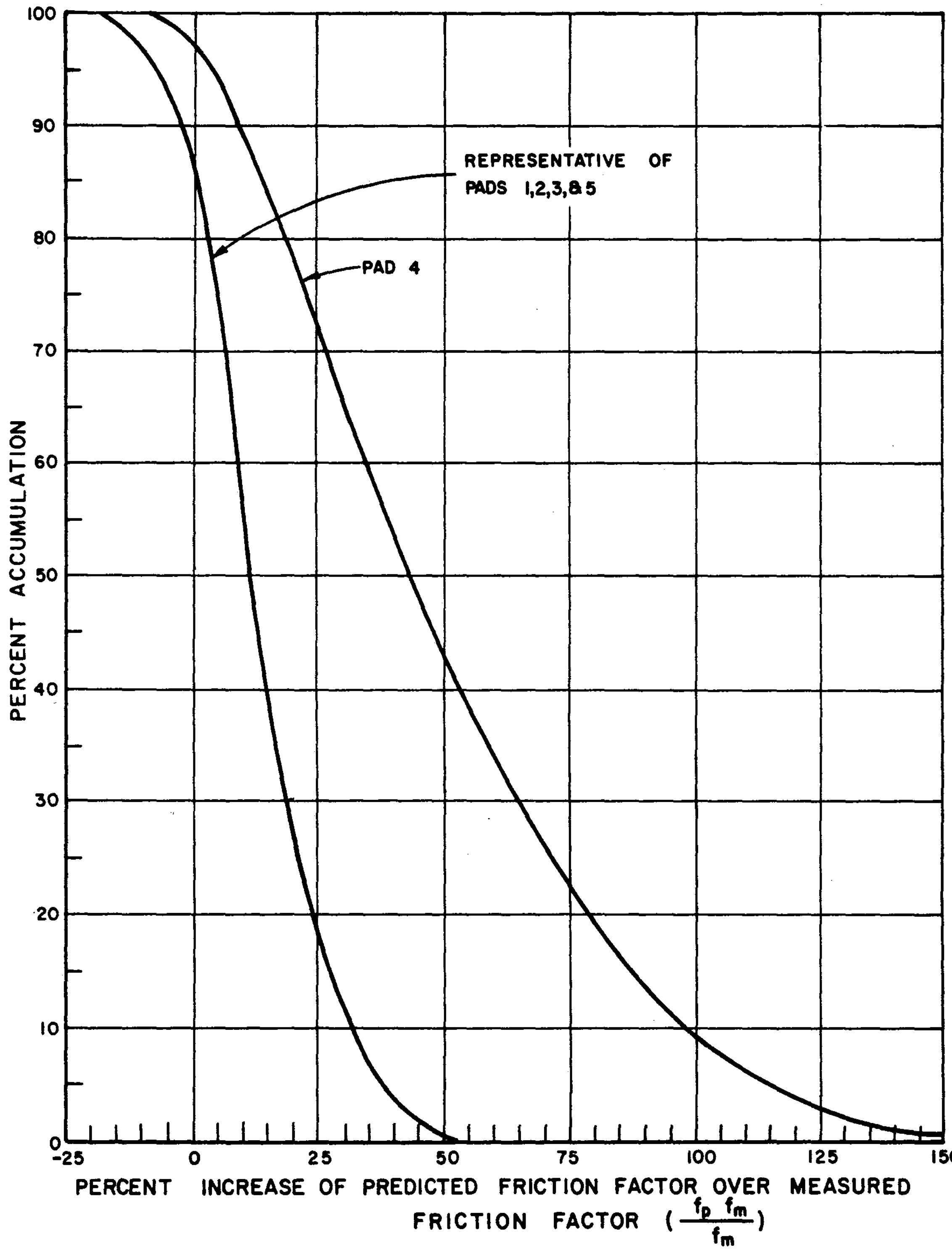

Figure C-8 – Percentile Distribution of Percent Deviation Between Measured and Computed Friction Factors Classified by Pad Number.