A DETERMINATION FRAMEWORK
FOR
WET WEATHER SPEED LIMITS

by

John C. Glennon

Research Report 134-8F

Highway Design Criteria
Research Study Number 2-8-69-134

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FOREWORD

Th is one phase of Research Study No. 2-8-68-134 entitled "An Exa of the Basic Design Criteria as They Relate to Safe Operation on Modern High Speed Highways." Other active phases of this research are; (1) a field study of the passing sight distance requirements of high ed passing drivers, (2) a field study of the degree of path taken in high-speed passing maneuvers, and (3) an evaluation of vehicle paths as a basis for wet weather speed limit values.

This is the eighth project report. Previously prepared reports are;

Research Report 134-1, "The Passing Maneuver as it Relates to Passing Sight Distance Standards"

Research Report 134-2, "Re-Evaluation of Truck Climbing Characteristics for Use in Geometric Design"

Research Report 134-3, "Evaluation of Stopping Sight Distance Design Criteria"

Research Report 134-4, "State-of-the-Art Related to Safety Criteria for Highway Curve Design"

Research Report 134-5, "The Relation of Vehicle Paths to Highway Curve Design"

Research Report 134-6, "Passing Performance Measurements Related to Sight Distance Design"

Research Report 134-7, "Frictional Requirements for High-Speed Passing Maneuvers"

DISCLAIMER

ABSTRACT

This report develops determination charts for wet weather speed limits. These charts are based on a composite of frictional requirements for passing, emergency stopping, and emergency path-correction maneuvers. Determination charts for highway curves are also presented.

SUMMARY

This research was concerned with developing a framework for the determination of wet weather speed limits. Two other study reports (2, 3) have indicated the frictional requirements of vehicles on highway curves and during passing maneuvers. This information, together with considerations of the frictional needs of emergency maneuvers, formed the basis for the proposed wet weather speed limit determination framework.

Frictional requirements for highway curves were related to the degree of highway curve and the superelevation. This relationship was developed from photographic field studies of vehicle maneuvers on five highway curves ranging from 2° to 7° in curvature. The frictional requirements represent the lateral frictional demand of a vehicle path exceeded by only 10 percent of the vehicles.

Frictional requirements for passing were also developed from photographic field studies. Using an impeding vehicle to stage passing situations, passing maneuvers were photographed from a trailing observation vehicle. The frictional requirements for passing represent the vector sum of lateral and forward friction demands. Lateral friction demand is for the vehicle path exceeded by only 10 percent of the vehicles. Forward friction demand was estimated assuming that vehicle acceleration during passing ranges from 40 percent of full-throttle at 40 mph to 60 percent of full-throttle at 80 mph.

Frictional requirements for emergency stopping were related to available stopping sight distance using the standard stopping distance equation. The emergency friction demand presumes stopping to avoid hitting an object on the road that just becomes visible at the available stopping sight distance.

Frictional requirements for emergency path corrections were derived from the minimum vehicle path radius to keep a vehicle on the roadway once a roadside encroachment path has been perceived. These requirements are highly sensitive to the encroachment angle and the initial distance from the edge of the paved roadway. Emergency maneuvers to avoid these circumstances often exceed the skid resistance even on dry pavements. Therefore, the frictional requirements were developed for nominal values of encroachment angle and distance from the edge of roadway.

Using the frictional requirement relationships for passing, emergency stopping, and emergency path correction maneuvers, composite determination charts were drawn as shown in Figure 12 through 15. These charts each have a determination envelope defined by a shaded area. Wet weather speed limits are determined within the non-shaded area.

To use these charts for a specific section of highway requires the following information:

1. Number of lanes
2. Shoulder width
3. Minimum stopping sight distance
4. Skid resistance versus speed relationship

The wet speed limit is determined, on the appropriate chart, by plotting the skid resistance versus speed relationship for the highway section. The wet speed limit is the lower of the two speeds where the skid resistance curve intersects the appropriate sight distance curve and the envelope curve.

The overall wet weather speed limit for a highway section is determined with Figures 12 through 15. Wet weather speed limits for highway curves are determined in a similar manner from Figure 16. Special speed limits for highway curves, of course, should only be applied when they are lower than the limit established for the entire highway section.

IMPLEMENTATION

Because the potential for skidding on wet pavements is so sensitive to vehicle speed, wet weather speed limits are a logical method for reducing wet weather skidding accidents. Although the effectiveness of wet weather speed limits for reducing traffic speeds has not been documented, drivers should tend to comply with limits rationally set for prevailing conditions. Wet weather speed limits would give the driver vehicle control information presently left to his judgment.

The wet weather speed limit determination charts, shown in Figures 12 through 16 are recommended for implementation.

Wet weather speed limits, however, are no panacea for wet weather skidding accidents. The proposed determination charts may require

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wet weather speed limits below 25 mph for some pavements. Obviously, these low speed limits are undesirable and probably ineffective on main rural highways. On the other hand, to set a minimum on wet speed limits at, say, 45 mph, would mean that several highway sections could not satisfy the frictional requirements of traffic.

A minimum skid resistance maintenance program is definitely needed to augment wet weather speed limits. Surface improvements, however, may not be enough for highway sections with very limited stopping sight distances. Therefore, a skidding accident prevention program should also consider reconstruction to improve inadequate sight distances. In addition, if it is desirable to have more highway sections with the higher wet speed limits, addition of paved shoulders should be considered at some locations.

For a comprehensive skidding accident prevention program that includes wet weather speed limits, skid surfacing, and geometric improvements, cost-effectiveness considerations will determine the appropriate application of alternatives for each location.

INTRODUCTION

Slippery pavements have existed for many years. But the causes of slipperiness, its measurement, and its effect on traffic safety were not of great concern before 1950. Although reliable skidding accident data are hard to find, those in existence suggest that the skidding accident rate has increased and has reached proportions that may no longer be ignored. This trend may be partly due to improved accident reporting, but is also undoubtedly a reflection of increased vehicle speeds and traffic volumes. (1)*

More rapid accelerations, higher travel speeds, and faster decelerations made possible by modern highway and vehicle design have raised the frictional demands on the tire-pavement interface. Larger forces are required to keep the vehicle on its intended path. On the other hand, for wet pavements, the frictional capability of the tire-pavement interface decreases with increasing speed. In addition, higher traffic volumes and speeds promote a faster degradation in the frictional capability of the pavement. Figure 1 illustrates how these parameters interact to produce a higher loss of control potential.

From the technological standpoint, the slipperiness problem appears amenable to solutions that either reduce the frictional demand (improved geometric design, and lower speed limits for wet conditions) or increase the frictional capability (improved pavement surface design, improved tire design, and improved vehicle inspection procedures). This research

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*Denotes number in List of References

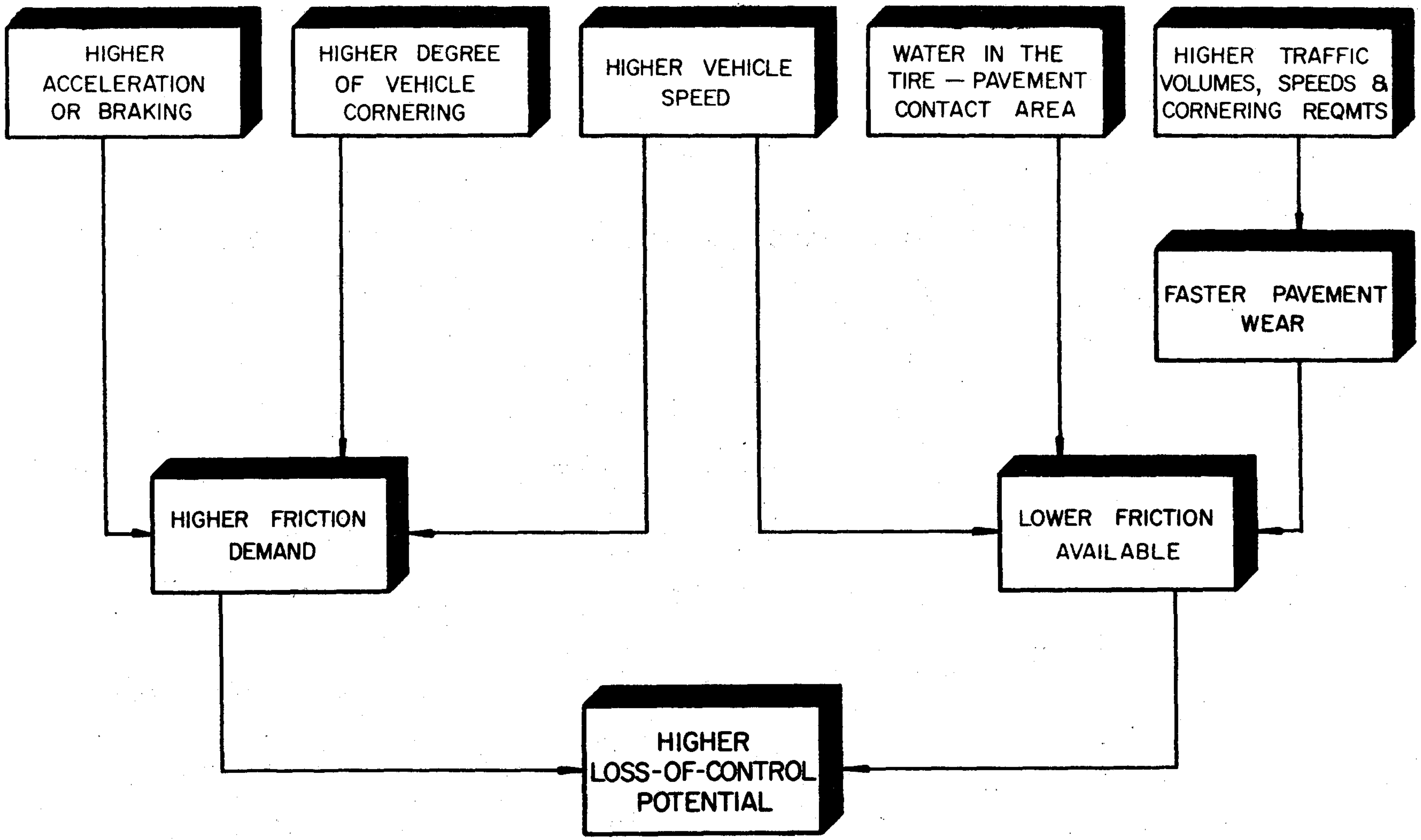


Figure 1. Circumstances Leading to Higher Loss of Control Potential.

is specifically concerned with developing a framework for determing wet weather speed limits. Two other study reports (2, 3) have determined the critical friction requirements of vehicles on highway curves and during passing maneuvers. This information, together with considerations of the frictional needs of emergency maneuvers, forms the basis for the proposed wet weather speed limit determination framework.

SKID RESISTANCE

The tire-pavement friction level at which skidding is imminent depends chiefly on the speed of the vehicle, the degree of cornering path, the magnitude of acceleration or braking, the condition of the tires, and the characteristics of the pavement surface. On wet pavements, speed is the most significant parameter not only because the frictional demand increases as the square of the speed but also because the skid resistance of the tire-pavement combination decreases with increasing speed. Figure 2 depicts a generalization of these relationships showing, for a given degree of cornering or magnitude of acceleration or braking, how the factor of safety against skidding decreases rapidly with increasing speed, until the skid is imminent.

Since the skid resistance on wet pavements decreases with speed, the real problem in a pavement skid-proofing program is to maintain skid resistance levels that will meet the majority of frictional demands for the traffic speeds encountered on the highway. As discussed earlier, higher speeds and more rapid acceleration and braking make the provision of adequate skid resistance increasingly more difficult. Wet weather speed limits, therefore, may be a partial solution to the total problem of preventing skidding accidents.

Skid resistance is typically measured with a locked-wheel skid trailer. The standard ASTM test uses a standard trailer and tire, with measurements made at a test speed of 40 mph. Since pavement texture affects the slope of the skid resistance versus speed relationship,

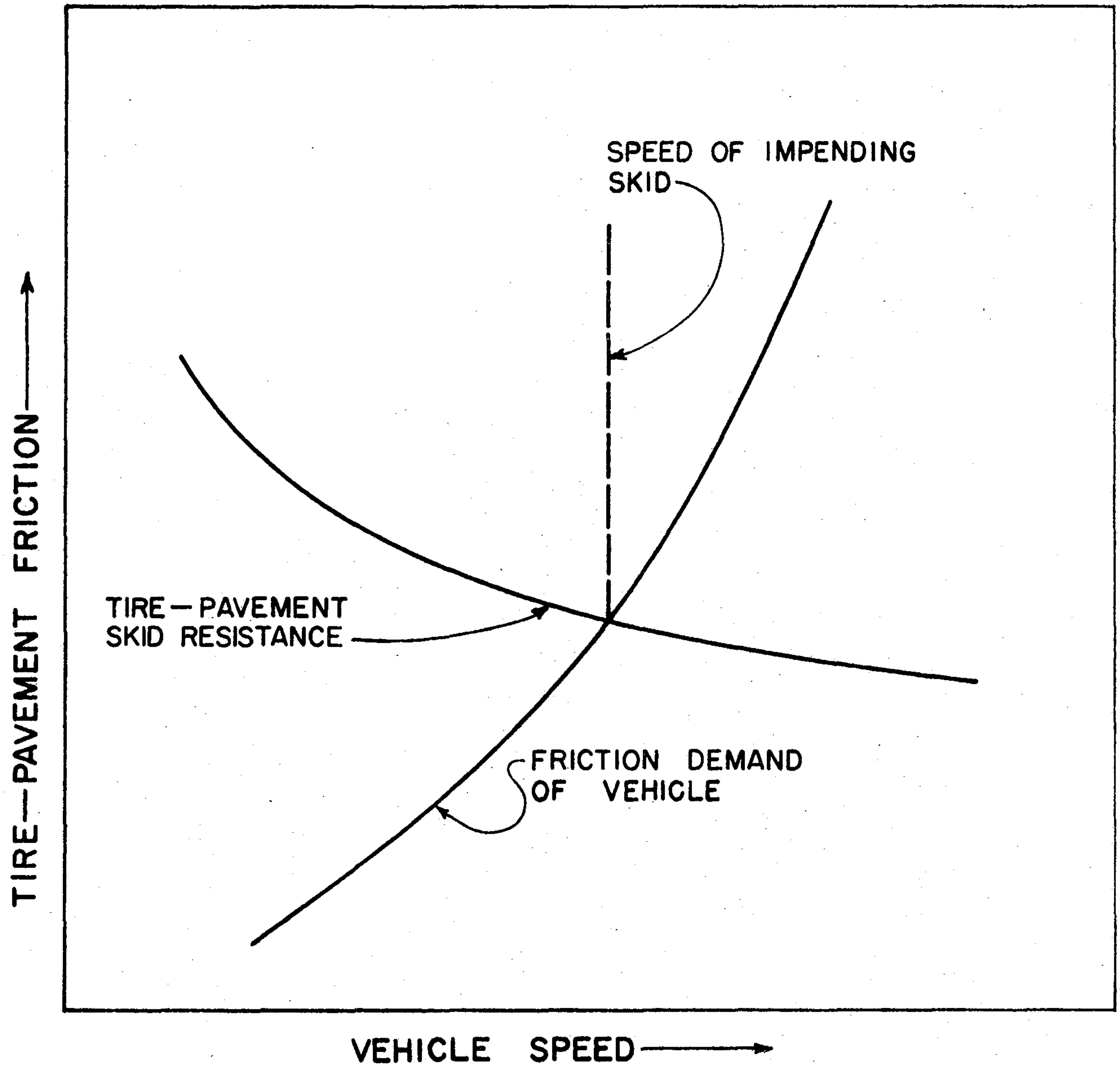


Figure 2 - Relation Between Friction Demand and Skid Resistance

the skid resistance at 40 mph does not give an accurate representation of pavement capability for the higher speeds. For this reason, measurements should be made at a minimum of three speeds to establish the skid resistance versus speed relationship.

Figure 3 shows a percentile distribution of skid numbers (the assumption being that Skid Number = 100f) versus speed computed from a random sampling of 500 pavements in one state (4). These measurements were taken in 1964 using a modified ASTM standard trailer with standard ASTM test tires. This type of pavement inventory provides the basis necessary to establish a skidding accident program that incorporates minimum skid resistance levels and wet weather speed limits.

Many authorities have questioned the accuracy of skid trailer measurements. Recently, several research studies (5, 6, 7) at the Texas Transportation Institute have shed light on this problem. Results indicate that, with trailer test speeds in excess of 40 mph, measured skid numbers are biased slightly upward, because of inherent difficulties with the trailer's watering system. Water is sprayed, ejected, or splashed on the pavement directly in advance of the test wheel, just before and during lockup. At higher speeds, the watering system does not adequately wet the pavement due to the small time difference between when water contacts the pavement and when the tire is skidded over the wetted segment.

Ivey, et. al. (5), found that skid trailer tests using an external watering source yielded lower skid resistance values that more accurately

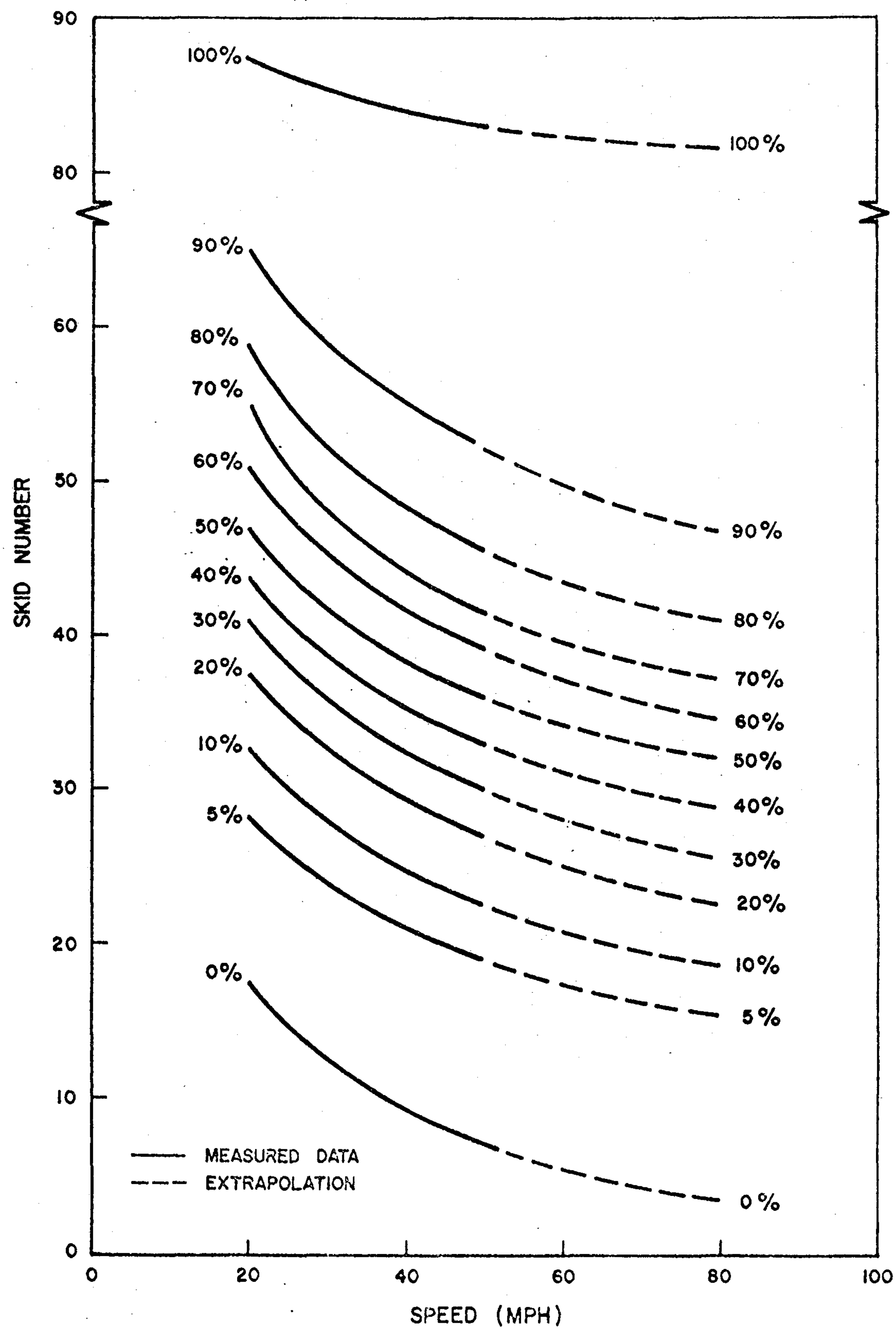


Figure 3 - Percentile Distribution of the Skid Number Versus Speed Relationship for 500 Pavements in One State (4)

predicted the spin-out response of full-scale vehicle skid tests on horizontal curves. These results are inconclusive though, because only two pavements were used. Another research study (6) indicates that a critical level (90th percentile) of vehicle stopping distance was more closely predicted by skid numbers taken with external watering.

Other research (7) using 15 pavement surfaces, showed similar comparisons of the skid numbers for internal and external watering tests. The measured differences, however, were not too substantial, amounting to an average of 0.04 (for SN/100) at 60 mph.

This discussion is not suggesting a change in the skid resistance measuring technique. The standard ASTM skid test currently used still has the advantage of safe and efficient field measurement. What is suggested, though, is that the inaccuracies of the skid numbers be accounted for. Since the difference between measurements for internal and external watering varies between pavement, it is difficult to predict. Perhaps the difference can best be accounted for by providing an adequate safety margin between predicted friction demand levels and measured skid numbers.

FRICTIONAL REQUIREMENTS ON HORIZONTAL CURVES

Recent field studies (2) were conducted to study vehicle behavior on highway curves. A movie camera mounted in an observation box on the bed of a pickup truck was used to photograph the path traveled by sample vehicles. This observation vehicle would begin following a sample vehicle about one mile in advance of the highway curve site. When the curve was reached, the vehicle maneuver was filmed from a position of 60 to 100 feet behind the sample vehicle.

Five highway curves, ranging in curvature from 2 to 7 degrees, were studied. About 100 vehicles were sampled for each site. Each sample was an unimpeded vehicle of randomly selected speed. The speed distribution of sample vehicles was representative of the overall speed distribution at each site.

Each curve site was marked with two-foot stripes placed radially at 20-foot intervals along the centerline. This reference system allowed the determination of the lateral placement of the vehicle at 20-foot intervals by analyzing the movie film on a Vanguard Motion Analyzer. From this lateral placement data, an instantaneous vehicle path radius was estimated at each reference point by calculating the radius of the circular curve through the lateral placement at that point and one point on either side. Since a circular arc is the minimum curved path through three points, the radius so calculated was a conservative estimate of the smallest instantaneous vehicle path radius for the interval.

VEHICLE PATHS

To relate vehicle path radius to highway curve radius, the point where vehicle speed and path radius gave the maximum lateral friction demand ($\frac{V^2}{15R}$ - e) was selected as the critical point for each sample. This point, for most of the samples, coincided with either the point of maximum speed or the point of minimum path radius, or both.

Plotting the relationship between vehicle speed and path radius for these critical points indicated no correlation between these two variables for any of the five highway curves. Therefore, it was surmised that the percentile distribution of critical vehicle path radii found for each curve site could be expected at any speed within the speed range studied. This fact allowed the development of relationships between highway curve radii and various percentiles of critical vehicle path radius. Figure 4 shows this relationship for various percentiles. This figure indicates that most vehicles will have a path radius that is less than the highway curve radius at some point on the curve.

To determine the critical friction requirement, a percentile level of path radius is needed to assure that very few vehicles will approach instability. The 10% level appears to be a reasonable choice. Using this level would say that only 10% of the vehicles would have a lower path radius at any particular speed. Therefore, to determine the effect of vehicle path radius on the critical friction requirement for a particular curve design, the 10th percentile path radius, R_v,

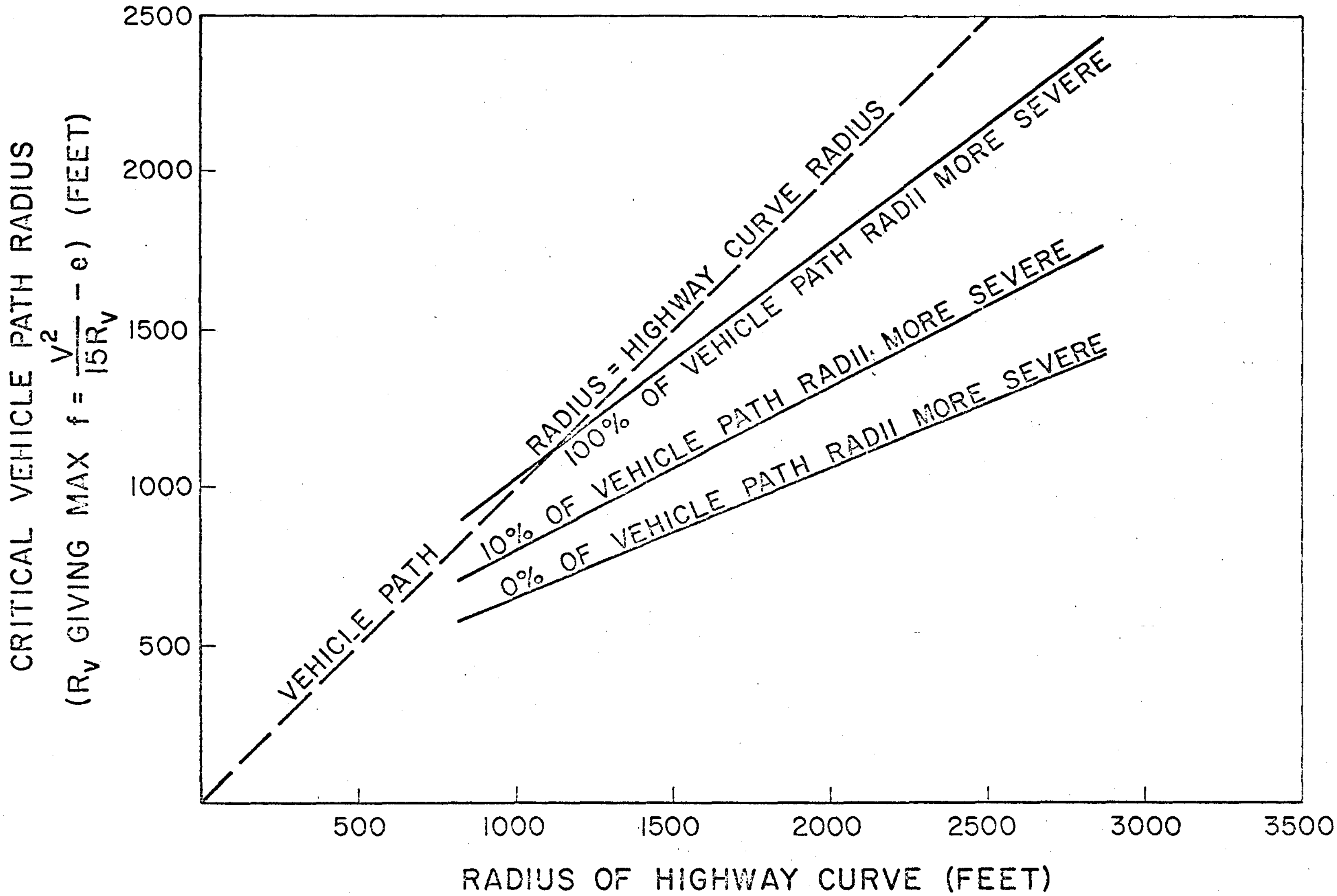


Figure 4 - Percentile Distribution of Vehicle Path Radius Versus Highway Radius (2)

in terms of highway curve radius, R, should be substituted in the centripedal force equation. This 10th percentile relationship is:

$$R_v = 0.524R + 268.0$$

SUPERELEVATION

Because of the need for superelevation runoff, full superelevation is not available near the beginning and end of a highway curve. Depending on design practice, the superelevation at the tangent-to-curve points may be from 50 to 80 percent of full superelevation. Because the field data showed that most vehicles experience their critical path maneuvers near the beginning or end of the curve, the equation of critical friction should reflect this reduced superelevation.

FRICTIONAL REQUIREMENT EQUATION

With the considerations previously discussed, it is possible to write an equation for the frictional requirements on highway curves. Starting with the centripedal force equation,

$$e + f = V^2/15R_v$$

if the derived expression for the 10th percentile path radius, R_v, in terms of highway curve radius, R, is substituted, the following equation results:

$$e + f = V^2/7.86R + 4{,}030$$

If the reduced superelevation at the beginning and end of the curve is approximated by 0.7e and if a safety margin, M_s, is applied, the following equation results:

$$f = \frac{V^2}{7.86R + 4{,}030} + M_s - 0.7e$$

A safety margin is required because of other unaccounted variables that may either increase the lateral force demand or decrease available skid resistance. These variables include vehicle acceleration and braking, excessive water depth, pavement bumps and dips, faulty tires, and winds gusts. In addition, if the derived frictional requirement is to be compared with measured skid resistance, the previously discussed measurement bias must be taken into account.

Because these other variables have not been explicitly evaluated, it is difficult to determine a representative safety margin. It seems, however, that there may be a low probability of the unaccounted variables combining to produce a much more unstable condition than already accounted for by the critical vehicle path and speed. Although there is no supporting data, a safety margin of 0.08 seems to be a reasonably conservative choice. Using this value gives the following equation for the frictional requirements on highway curves:

$$f = \frac{V^2}{7.86R + 4{,}030} + 0.08 - 0.7e$$

FRICTIONAL REQUIREMENTS OF PASSING VEHICLES

Of all the normal (non-emergency) maneuvers performed on our two-lane rural highways, passing probably accounts for the highest frequency of critical tire-pavement friction demands. Not only are passing maneuvers performed at relatively high speeds, but they may also involve critical combinations of lateral and forward acceleration. In addition, the path of the passing vehicle is generally adverse (negative superelevation) to the pavement cross-slope.

Recent research (3) was conducted to determine the frictional requirements of vehicles performing high-speed passing maneuvers. A movie camera mounted in an observation box on the bed of a pickup truck was used to photograph the paths of passing vehicles at two study sites. Passing situations were created with an impeding vehicle traveling at a predetermined speed.

The observation vehicle would move in behind a subject vehicle about two miles upstream from the study site. As the two vehicles approached, the impeding vehicle stationed on the shoulder near the beginning of the no-passing zone, would move out and impede the subject vehicle. Filming was initiated as the three vehicles reached the passing section.

Approximately 2000 subjects were tested. Of this number, about 300 completed passing maneuvers were photographed. Impeding speeds were 50, 55, 60, and 65 mph.

Each study site was marked with two-foot stripes at 40-foot intervals along the centerline. This reference system allowed the determination of the lateral placement and speed of the passing vehicle at 40-foot intervals, by analyzing the movie film on a Vanguard Motion Analyzer. From the lateral placement data, an instantaneous path radius was estimated at each point by calculating the radius of the circular curve through three successive lateral placement points. Since a circular curve is the minimum curved path through three points, the radius so calculated was a conservative estimate of the smallest instantaneous path radius over the interval.

VEHICLE PATHS

The point where vehicle speed and radius gave maximum lateral friction demand $(\frac{V^2}{15R} - e)$ was selected as the critical point. Such a point was found separately for the initial pull-out maneuver and the return maneuver of each sample. These points, for most of the samples, coincided with either the point of minimum path radius or the point of maximum speed, or both.

Plotting scatter diagrams of speed versus vehicle path radius for the two basic maneuvers showed that there was no relationship between the two parameters. This lack of correlation indicated that the percentile distribution of vehicle path radii could be expected at any speed within the speed range studied.

To determine the critical side friction requirement, a percentile level of vehicle path radius is needed to assure that very few vehicles will approach instability. The 10% level appears to be a reasonable choice. Using this level would say that only 10% of the vehicles would have lower vehicle path radii. Therefore, the critical vehicle path radii were found as 1470 feet for the initial maneuver and 1640 feet for the return maneuver.

LATERAL ACCELERATION

Using the values for critical path radius in the centripedal force equation, relationships between critical lateral friction demand and speed can be derived for each basic maneuver. An e value of -0.02 can be used to represent the pavement cross-slope since most vehicle paths were adverse to the cross-slope. The critical relationships, therefore, are:

for the initial maneuver,

$$f = \frac{V^2}{22,050} + 0.02$$

and, for the return maneuver,

$$f + \frac{V^2}{24,600} + 0.02$$

FORWARD ACCELERATION

Although no precise measurements of instantaneous forward acceleration were possible, the data indicated that vehicles were almost always accelerating during the initial maneuver and coasting during the return maneuver. Cursory examination of the data indicated an average acceleration range of 1-3 ft/sec^2 for the initial maneuver. As these are averages over fairly long intervals, instantaneous accelerations could be considerably higher.

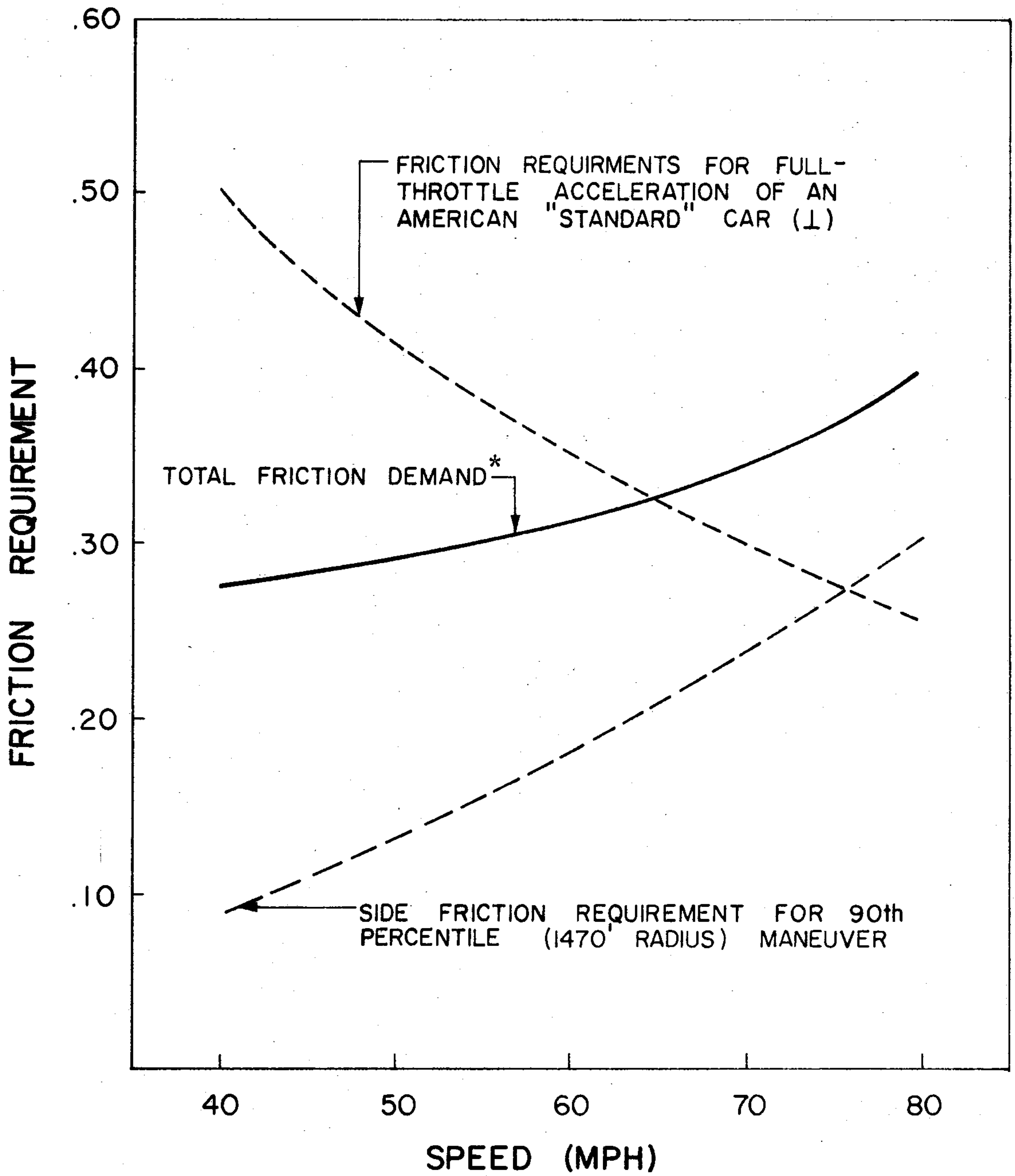
CRITICAL FRICTION DEMAND

The total friction demand is a vector sum of forward and lateral accelerations. Kummer and Meyer (1) reported a relationship between forward friction demand and speed for full-throttle acceleration of an American "standard" automobile. To arrive at a reasonable estimate of the critical friction demand, the instantaneous forward acceleration of the passing vehicle was assumed to vary linearly from 40% of full throttle at 40 mph to 60% of full throttle at 80 mph. For a 4000 pound vehicle, this corresponds to a 6.4 ft/sec^2 acceleration at 40 mph and a 5.0 ft/sec^2 acceleration at 80 mph. For the return maneuver, the only forward friction component is 0.035 contributed by rolling resistance.

By taking the vector sum of the lateral friction demand and the estimated forward friction demand, a critical relation between total friction demand and speed was plotted for both the initial and return maneuvers. Comparing the two plots, it was found that the initial maneuver creates the critical friction demand. The relationship between critical friction demand and speed is shown in Figure 5. A safety margin of 0.06 was used to obtain the total friction requirement.

VEHICLE SPEED

As was found in the analysis of the field data, only about 12% of the passing vehicles exceeded the posted speed limit as the critical point of the initial maneuver. Therefore, the critical speed may be equated with the speed limit for determining minimum skid resistance levels and wet weather speed limits.



*Safety Margin of 0.06 plus vector resultant of side friction requirement and assumed forward friction requirement (ranging from 40% to full-throttle acceleration at 40 mph to 60% of full-throttle at 80 mph).

Figure 5 - Frictional Requirement for Passing

FRICTIONAL REQUIREMENTS FOR EMERGENCY MANEUVERS

Drivers are ocassionally required to perform emergency maneuvers to avoid collisions. These circumstances arise for various reasons including:

1. Another vehicle stopped on the roadway
2. Object on the roadway
3. Animal crossing the roadway
4. Another vehicle crosses or swerves into path
5. Unperceived change in alignment
6. Inattention or other factors place vehicle on roadside encroachment path

There is little doubt that emergency maneuvers to avoid these circumstance are ocassionally so severe that the vehicle exceeds the skid resistance even on dry pavements. It is not feasible to satisfy these severe frictional needs of traffic; however, nominal estimates of the frictional requirements of emergency do have a bearing on the determination of wet weather speed limits. For this reason two emergency conditions will be evaluated: (1) stopping to avoid an obstacle or vehicle in the roadway, and (2) a path correction to avoid running off the roadway.

STOPPING

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.

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. This total distance may be approximated by the equation (6):

$$d = \frac{V^2}{30f} + 1.47Vt$$

when d = minimum stopping sight distance; in feet

V = vehicle speed, in mph

f = available friction

t = perception-reaction time, in seconds

Sight distance, when limited, imposes a frictional requirement on the vehicle that needs to stop to avoid a collision. When an obstacle in the road just becomes visible to a driver at a given sight distance, the frictional requirement to bring the vehicle to a stop before hitting the obstacle is:

$$f = \frac{V^2}{30\ (d - 1.47\ Vt)}$$

Using the perception-reaction time of 2.5 seconds assumed for stopping sight distance design standards (8), the frictional requirement can be related to speed for various stopping sight distances:

$$f = \frac{V^2}{30\ (d - 3.67\ V)}$$

As with horizontal curves, a safety margin is required because of other unaccounted variables that may either increase the friction demand or decrease available skid resistance. These variables include excessive water depth and faulty tires. In addition, if the derived frictional requirement is to be compared with measured skid resistance, the previously discussed measurement bias must be taken into account.

Although there is no supporting data, a safety margin of 0.08 seems to be reasonable to account for the unexplained variables. Using this value gives the following equation for stopping friction requirements related to speed:

$$f = \frac{V^2}{30d - 110.25\ V} + .08$$

This relationship is plotted for various sight distances in Figure 6.

TRACKING

When a vehicle has a path that will lead to an encroachment on the roadside, the driver must perform a path correction to stay on the paved portion of the roadway. The frictional requirement for the path correction is highly sensitive to the encroachment angle and the initial distance from the edge of the paved roadway.

Referring to Figure 7, the vehicle having an encroachment angle, θ, is a distance, W, from the edge of pavement when the driver perceives the need for path correction. Since the driver needs time for perception and reaction, the vehicle will be a distance, ω, from the edge of the pavement at the point of initial path correction. The relation between the two distances is dependent on vehicle speed, V, the encroachment angle θ, and the perception-reaction time, t. If t is taken as 1.0

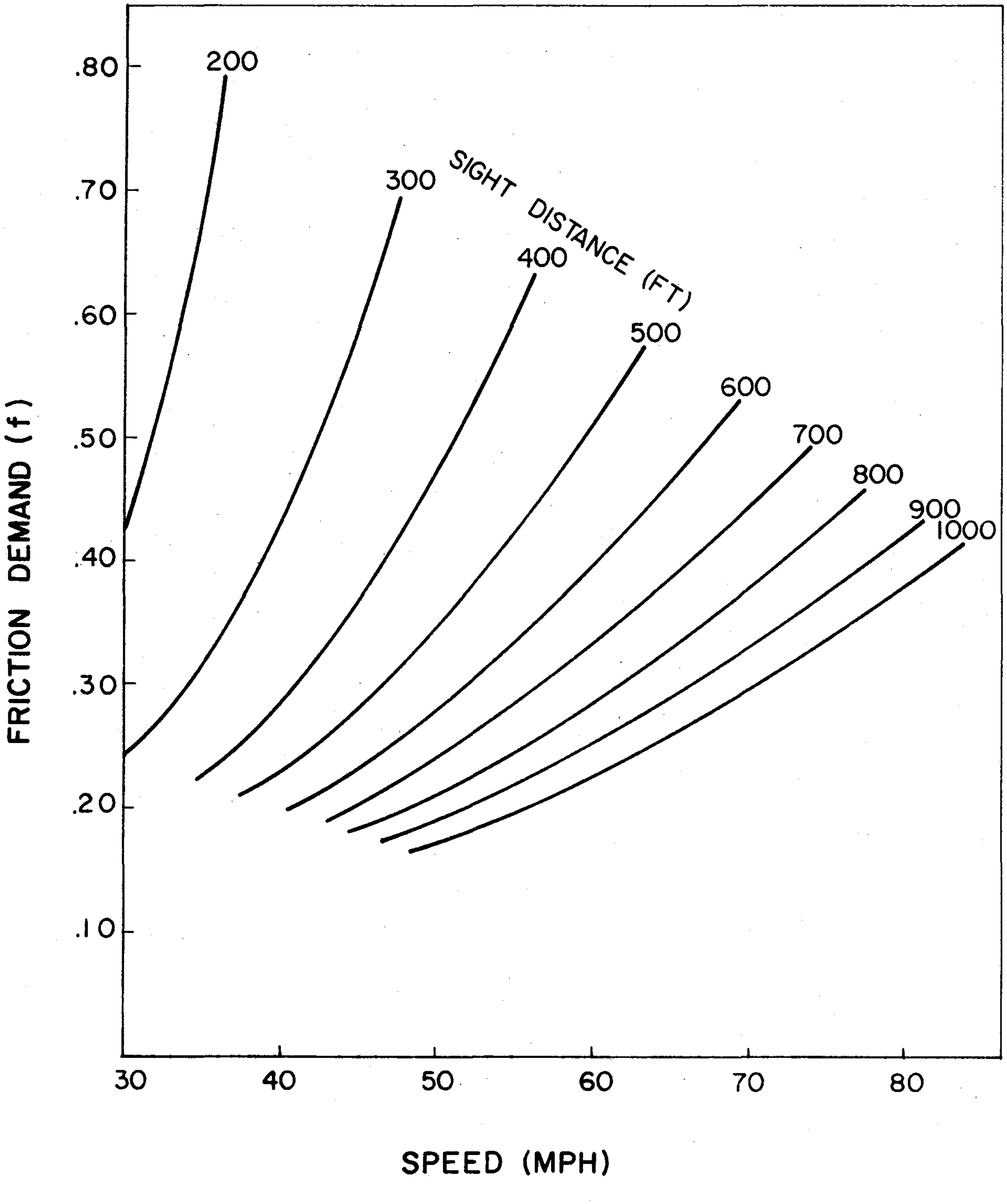


Figure 6 - Friction Requirements for Emergency Stopping with Limited Sight Distance

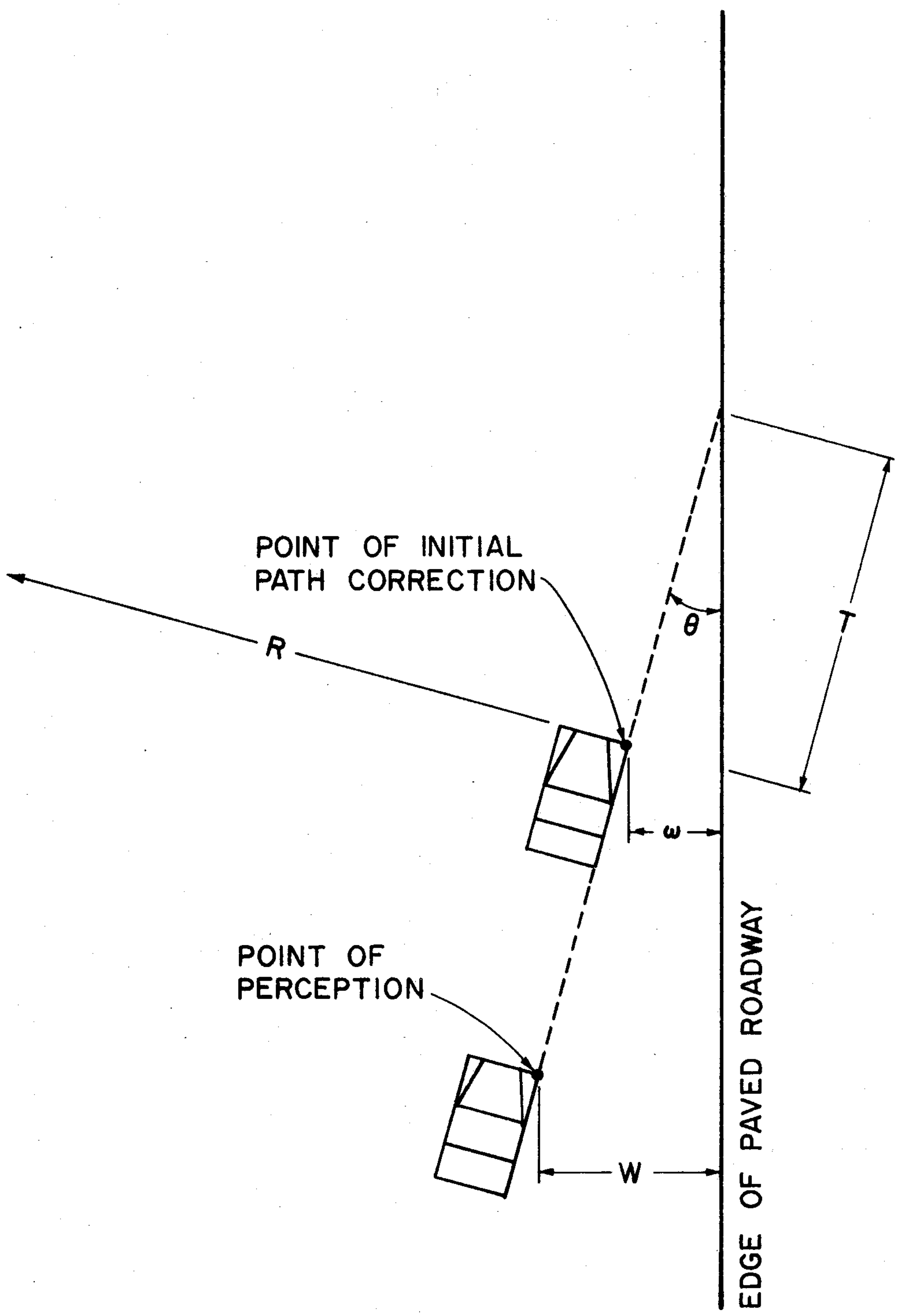


Figure 7 - Assumed Encroachment Trajectory

second, the two distances are related as follows:

$$\omega = W - 1.47V \sin \theta$$

where the distances, ω and W, are in feet and the speed, V, is in mph.

The least severe correction path of the vehicle is tangent to the edge of the roadway and tangent to the encroachment line at the point of initial path correction. The radius of this path is developed as follows:

$$R = T \cot \frac{\theta}{2}$$

$$T = \omega/\sin \theta$$

$$T = (W - 1.47V \sin \theta)/\sin \theta$$

$$\cot \frac{\theta}{2} = \sin \theta/(1 - \cos \theta)$$

$$\therefore \quad R = (W - 1.47V \sin \theta)/(1 - \cos \theta)$$

To obtain the friction requirement relationship for this type of maneuver, the derived value for R and a cross-slope of -0.02 are substituted in the centripedal force equation:

$$f = \frac{V^2 (1 - \cos \theta)}{15 (W - 1.47V \sin \theta)} + 0.02$$

In applying this equation, the distance W is a function of paved shoulder width and vehicle placement in the travel lane. Therefore, the frictional requirement varies with shoulder width. Three typical shoulder widths are examined; zero, six, and ten feet. Since average vehicle placement is closer to the centerline for smaller shoulder widths, the respective W's for these three conditions were assumed to be five, ten, and thirteen feet.

To obtain the frictional requirement for these three conditions, encroachment angles must be assumed. A comprehensive study of vehicle encroachments on freeway sections was done by Hutchinson and Kennedy (9). Figure 8 shows the cumulative percentile of encroachment angles found in the study. From this figure, encroachment angles less than six degrees appear to be conservative for estimating the emergency path of correction maneuvers. Also it is expected that the vehicle would have a chance to have a higher encroachment angle as the shoulder width increases. Therefore, the nominal emergency conditions were assumed as follows:

Shoulder Width (ft.)	Distance from Edge of Roadway (ft.)	Encroachment Angle
10	3 + 10 = 13	5^{o}
6	4 + 6 = 10	4^{o}
0	5 + 0 = 5	3^{o}

The frictional requirements for these nominal emergency maneuvers are shown in Figures 9, 10, and 11. Also plotted are conditions very close to the nominal condition, to show the extreme sensitivity of the relationship.

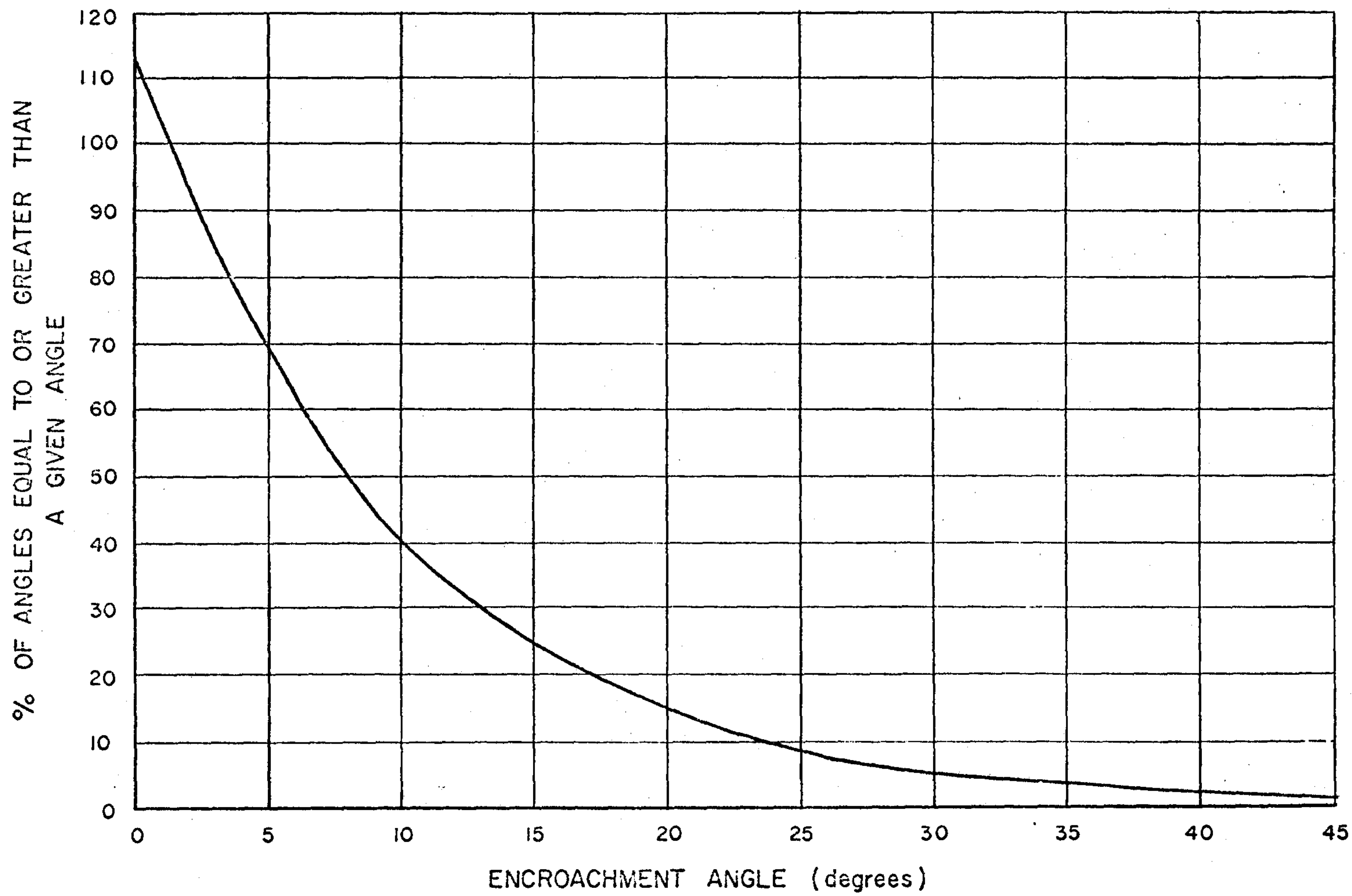


Figure 8 - Distribution of Encroachment Angles (9)

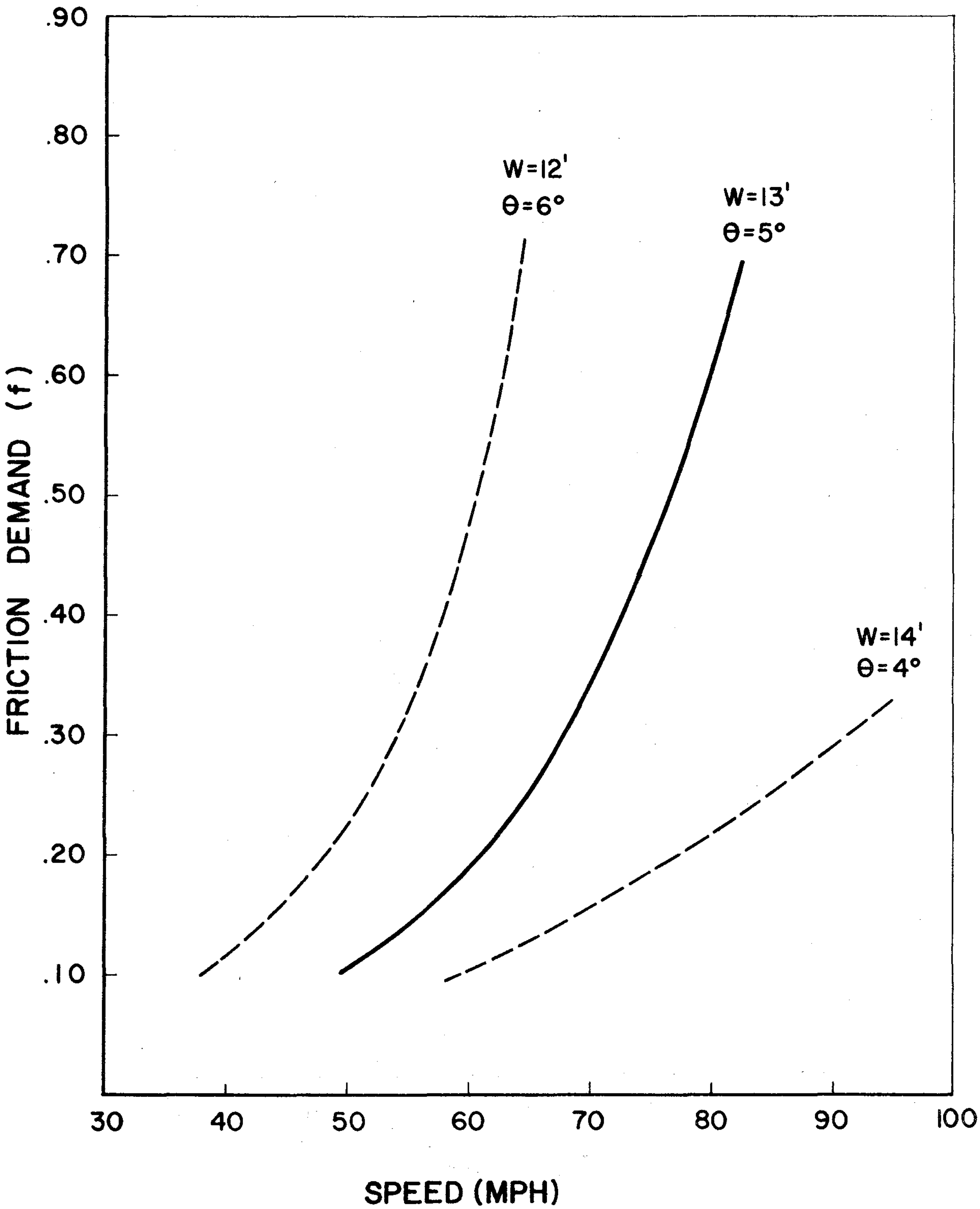


Figure 9 - Frictional Requirement for Emergency Path Correction on a Highway with a 10-foot Paved Shoulder

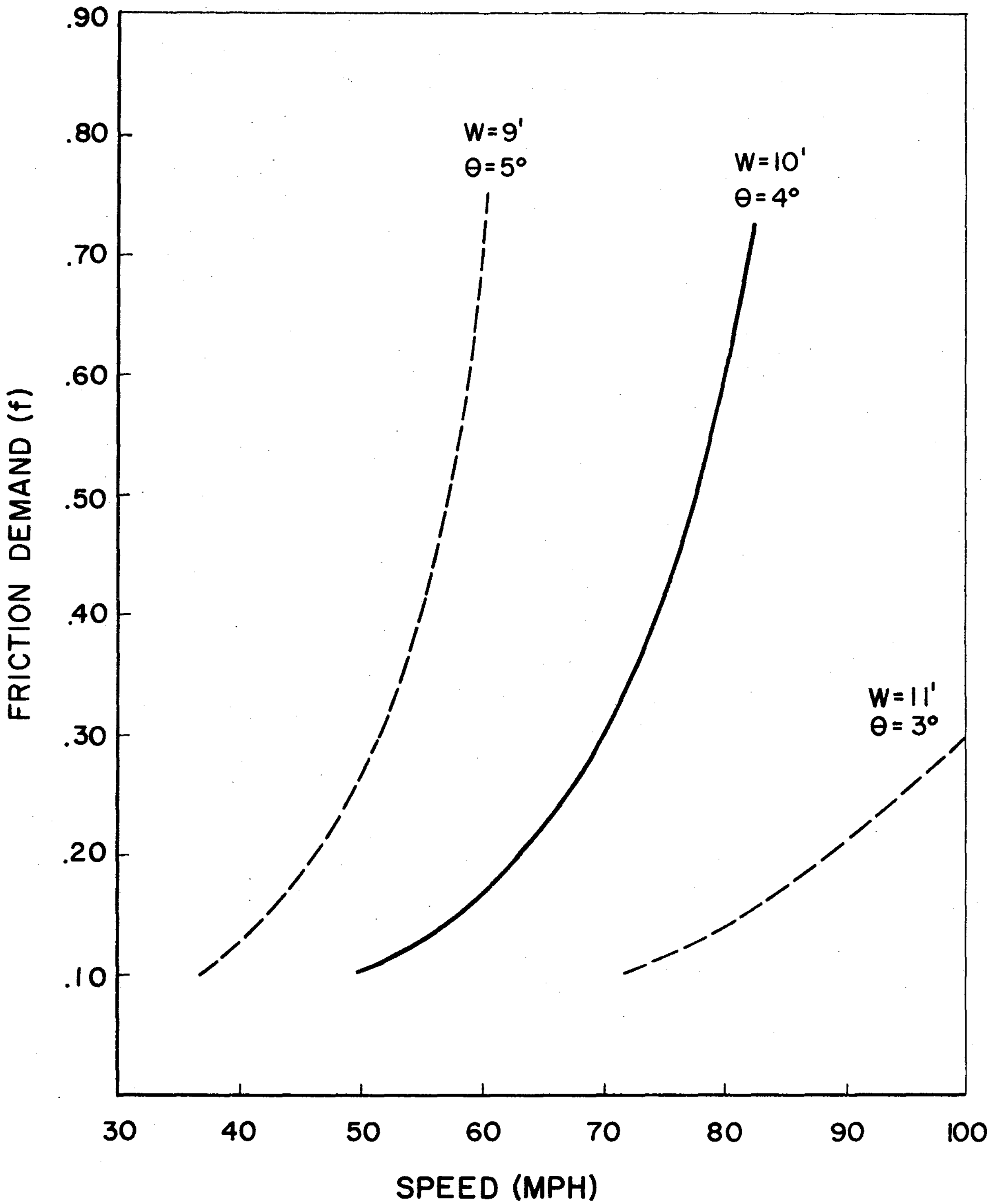


Figure 10 - Frictional Requirement for Emergency Path Correction on a Highway with a 6-foot Paved Shoulder

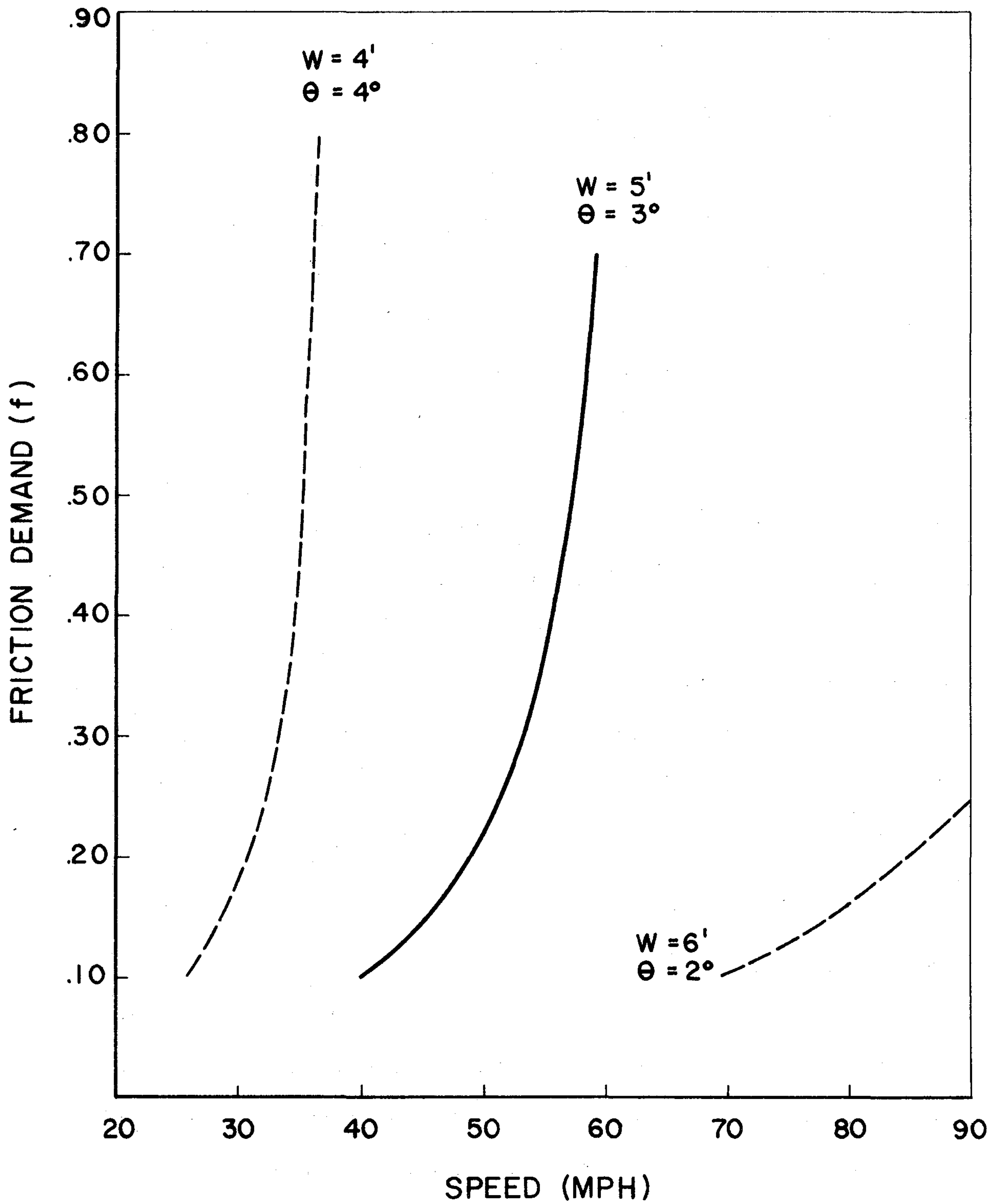


Figure 11 - Frictional Requirement for Emergency Path Correction on a Highway with no Paved Shoulders

DETERMINATION FRAMEWORK

Apparent from the previous discussion, the determination of wet weather speed limits requires consideration of various frictional requirements for traffic. Therefore, a composite determination basis is called for; one that considers number of lanes, shoulder width, horizontal curvature, and minimum stopping sight distance. Using the previously developed frictional requirements, this section presents a composite determination framework.

Obviously there is some desirable lower limit for wet weather speed limits. Surely, a wet weather speed limit of, say, 35 mph could not be placed on a primary multi-lane rural highway. The higher this minimum limit is set, the more likely the chance of having sections of highway that cannot satisfy the frictional requirements of traffic. For these highway sections something else must be done. Therefore, this section also discusses the aspects of a skidding accident prevention program that integrates wet weather speed limits with skid surface improvements and geometric design improvements.

WET WEATHER SPEED LIMITS

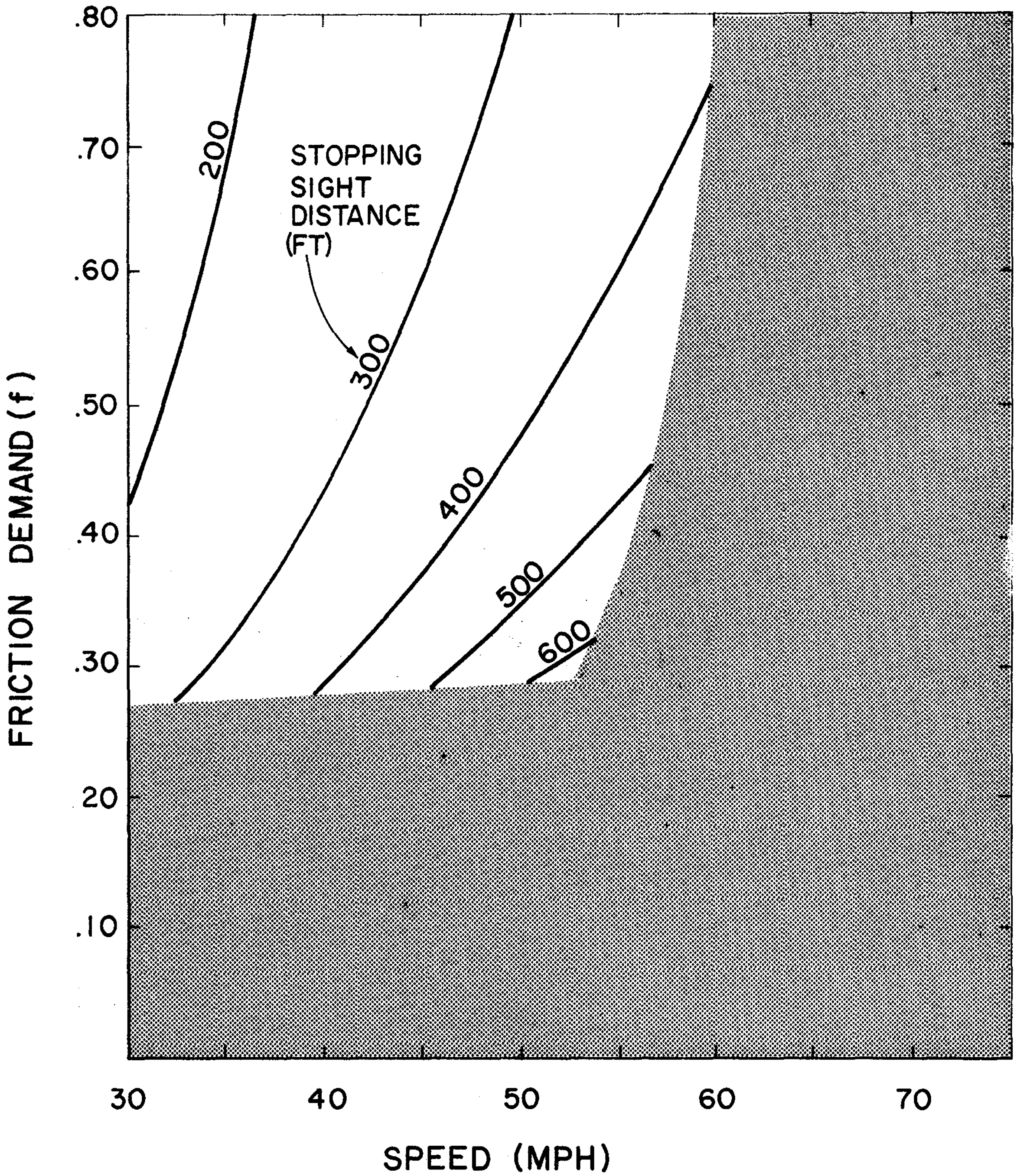
Because the potential for skidding on wet pavements is so sensitive to vehicle speed, wet weather speed limits represent a logical method for reducing wet weather skidding accidents. Although the effectiveness of wet weather speed limits in reducing traffic speeds has not been documented, it is believed that drivers would tend to comply with limits rationally set for prevailing conditions. Wet weather speed limits represent operational criteria that have previously been left to the driver's judgement.

Using the frictional requirement relationships for stopping, tracking, and passing (two-lane only), composite determination charts can be drawn as shown in Figures 12 through 15. Figure 12 is for 2-lane highways with no shoulders, Figure 13 is for 2-lane highways with 6-10 foot shoulders, Figure 14 is for multi-lane highways with no shoulders, and Figure 15 is for multi-lane highways with 6-10 foot shoulders. These charts each have a determination envelope defined by the shaded area. Wet weather speed limits are determined within the non-shaded area.

To use these charts for a specific section of highway requires the following information:

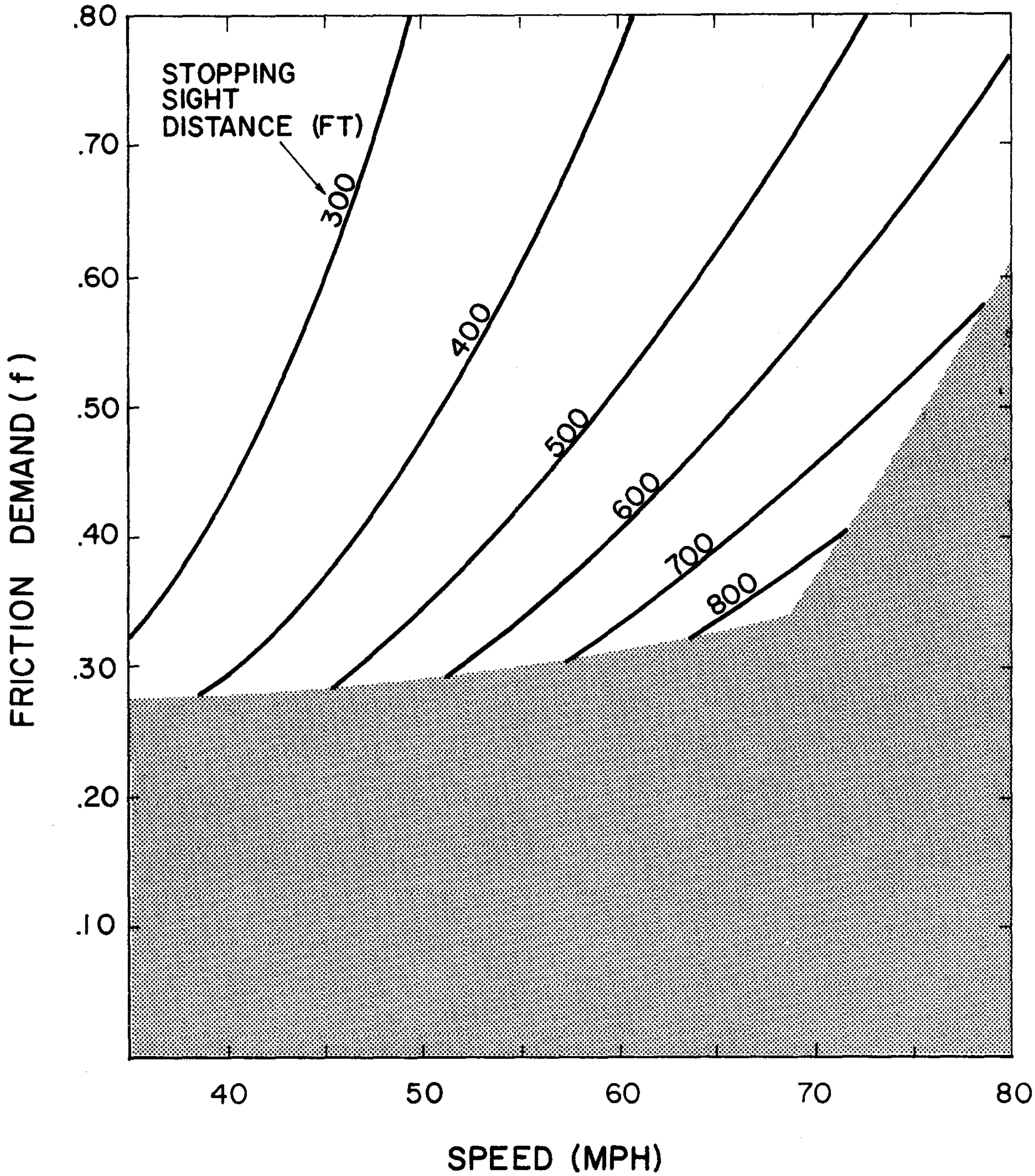
1. Number of lanes
2. Shoulder width
3. Minimum stopping sight distance
4. Skid resistance versus speed relationship

By plotting, on the appropriate chart, the skid resistance versus speed relationship for the highway section, the wet speed limit can be determined. The wet speed limit is the lower of the two speeds where the skid resistance curve intersects the appropriate sight distance curve and the envelope curve. For example, using the 50th percentile pavement of Figure 3, the appropriate wet weather speed limits on a two-lane highway with no shoulders would be: 30 mph for 200-foot sight distance, 40 mph for 300-foot sight distance, 45 mph for 400-foot sight distance, 50 mph for 500-foot sight distance, and 55 mph for 600-foot sight distance or greater. If the same highway section was the 20th percentile pavement of Figure 3, the wet weather speed limits would be: 35 mph for 300-foot sight distance,



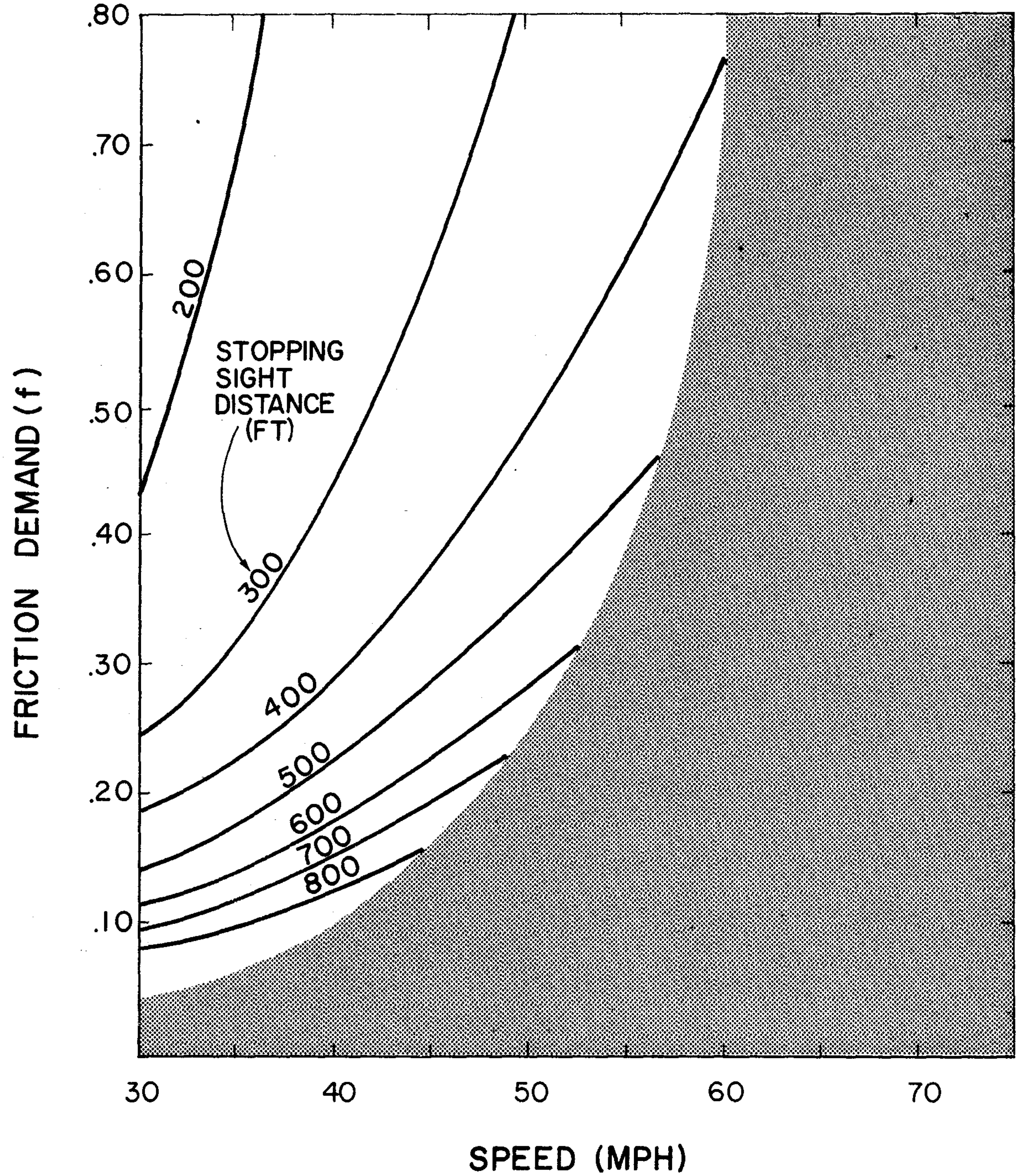
Note: The wet weather speed limit is determined within the non-shaded area. The skid resistance versus speed relationship for the highway section is plotted. The wet speed limit is the lower of the two speeds where the skid resistance curve intersects the appropriate sight distance curve and the envelope curve.

Figure 12 - Wet Weather Speed Limit Determination Chart for Two-Lane Highways with No Paved Shoulders



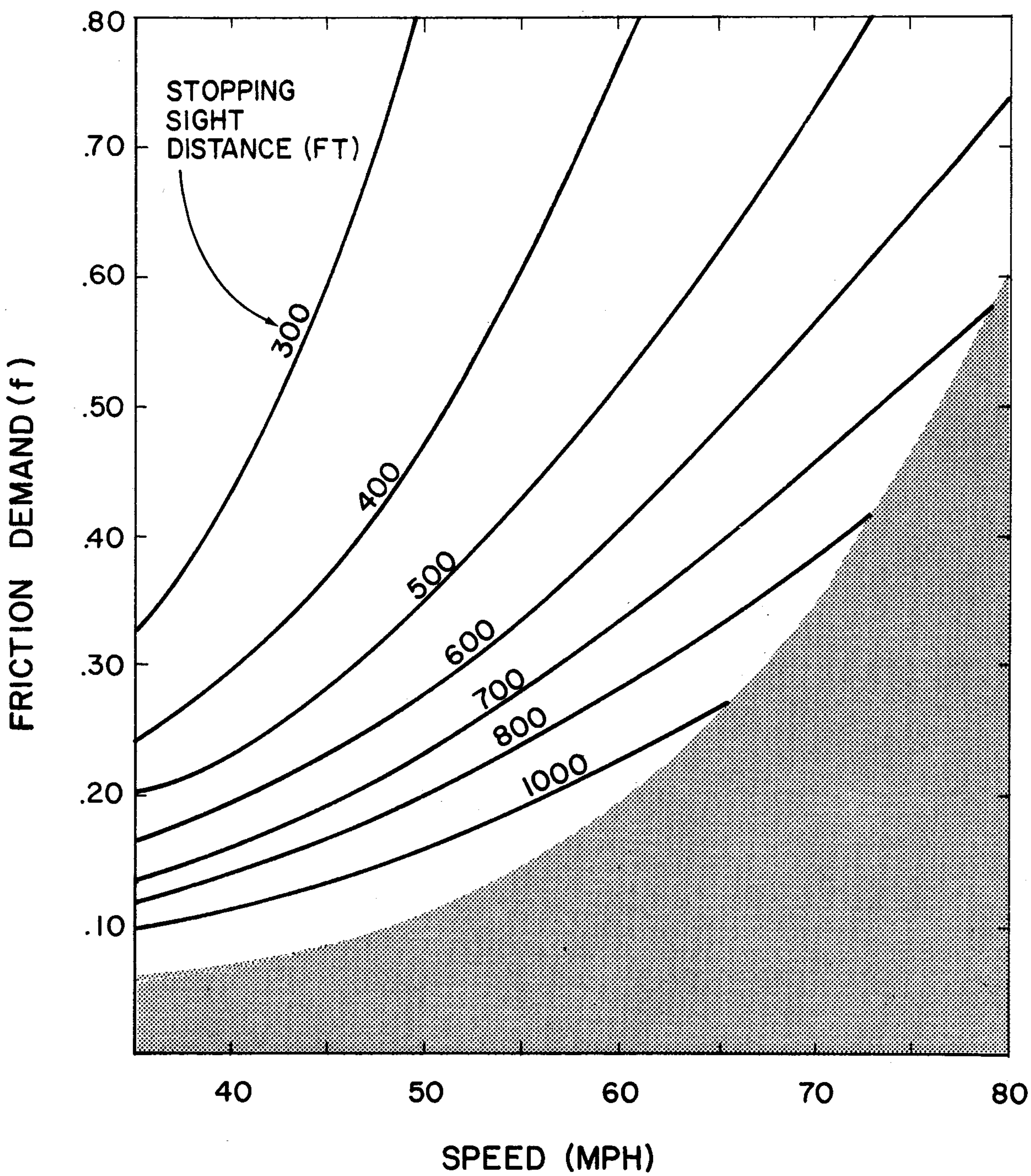
Note: The wet weather speed limit is determined within the non-shaded area. The skid resistance versus speed relationship for the highway section is plotted. The wet speed limit is the lower of the two speeds where the skid resistance curve intersects the appropriate sight distance curve and the envelope curve.

Figure 13 - Wet Weather Speed Limit Determination Chart for Two-Lane Highways with 6-10 foot Paved Shoulders



Note: The wet weather speed limit is determined within the non-shaded area. The skid resistance versus speed relationship for the highway section is plotted. The wet speed limit is the lower of the two speeds where the skid resistance curve intersects the appropriate sight distance curve and the envelope curve.

Figure 14 - Wet Weather Speed Limit Determination Chart for Multi-lane Highways with No Paved Shoulders



Note: The wet weather speed limit is determined within the non-shaded area. The skid resistance versus speed relationship for the highway section is plotted. The wet speed limit is the lower of the two speeds where the skid resistance curve intersects the appropriate sight distance curve and the envelope curve.

Figure 15 - Wet Weather Speed Limit Determination Chart for Multi-lane Highways with 6-10 foot Paved Shoulders

40 mph for 400-foot sight distance, and 45 mph for 500-foot sight distance or greater.

WET WEATHER SPEED LIMITS FOR HIGHWAY CURVES

The overall wet weather speed limit for a highway section is determined with Figures 12 through 15. Special speed limits for highway curves should be applied only when that limit is lower than the limit established for the highway section. Figure 16 shows the determination charts for highway curves.

INTEGRATED SKID PREVENTION PROGRAM

Wet weather speed limits, of course, are no panacea for wet weather skidding accidents. If Figure 3 is a representative distribution of skid resistance, some highway sections could require wet weather speed limits below 25 mph. Obviously, these low speed limits would be undesirable and probably ineffective on main rural highways. On the other hand, to set a minimum on wet weather speed limits at, say, 45 mph, would mean that several highway sections could not satisfy the frictional requirements of traffic.

To illustrate the above considerations, a wet weather speed limit program with speed limits ranging from 45 to 70 mph is used. This program is applied to a jurisdiction with the skid resistance distribution of Figure 3. For illustrative purposes, the distribution is assumed to apply uniformly for highway sections of varying characteristics. Table 1 lists the percentile distributions of wet weather speed limits

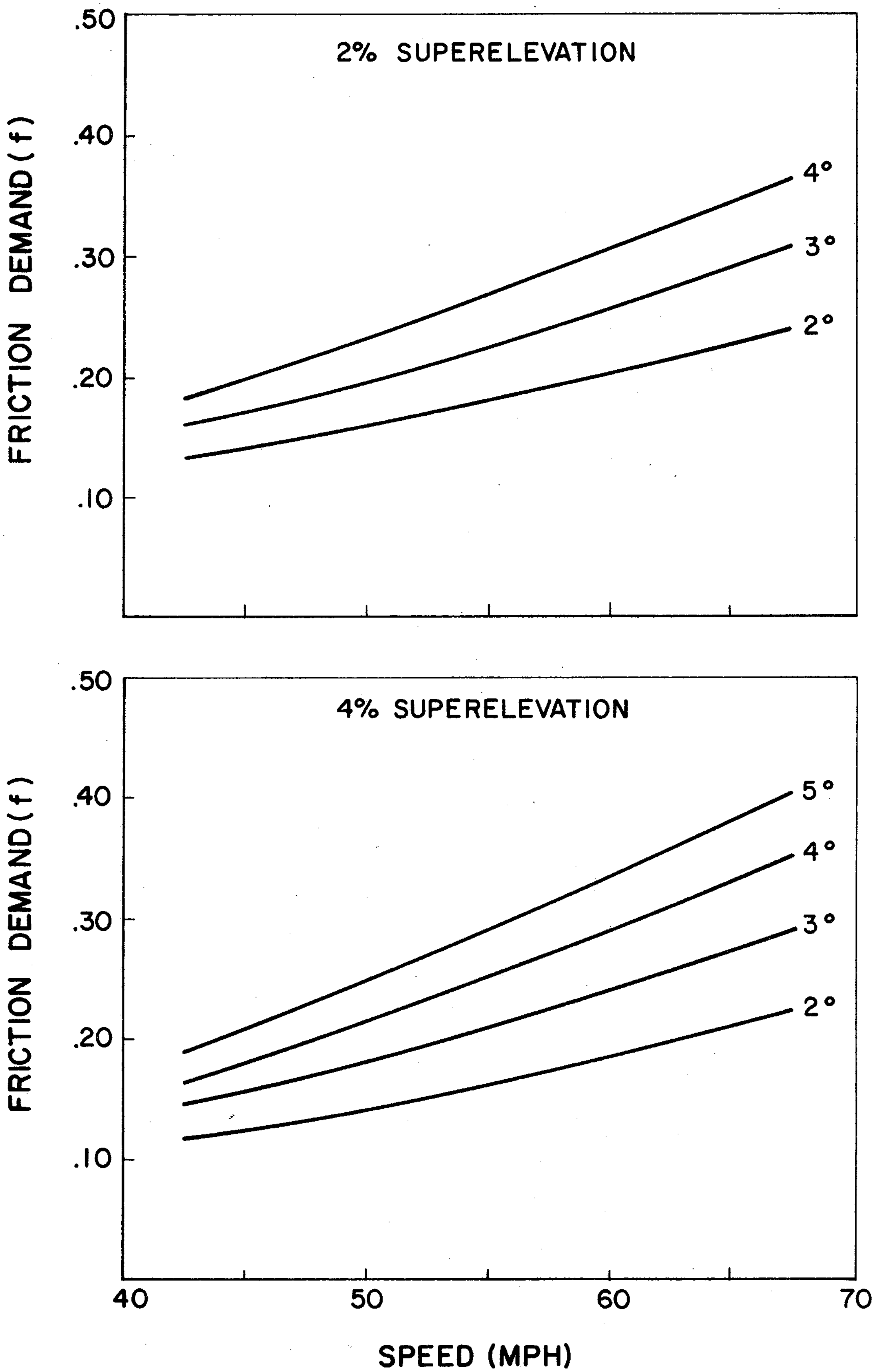
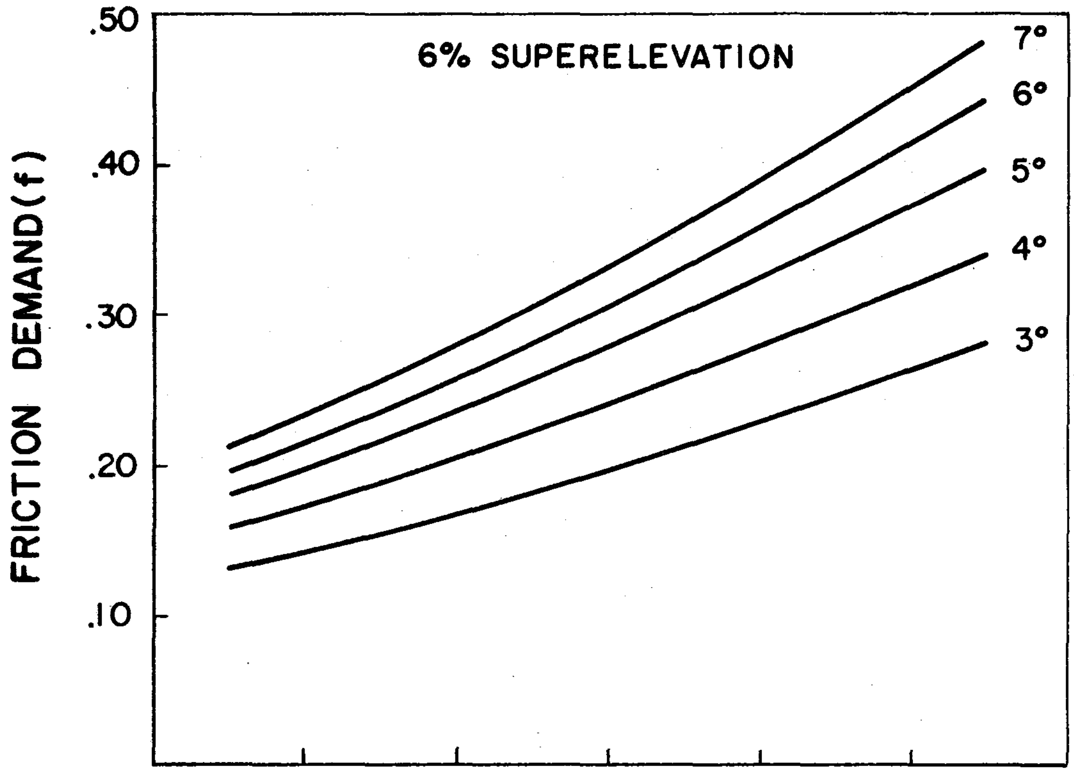


Figure 16 - Wet Weather Speed Limit Determination Charts for Highway Curves



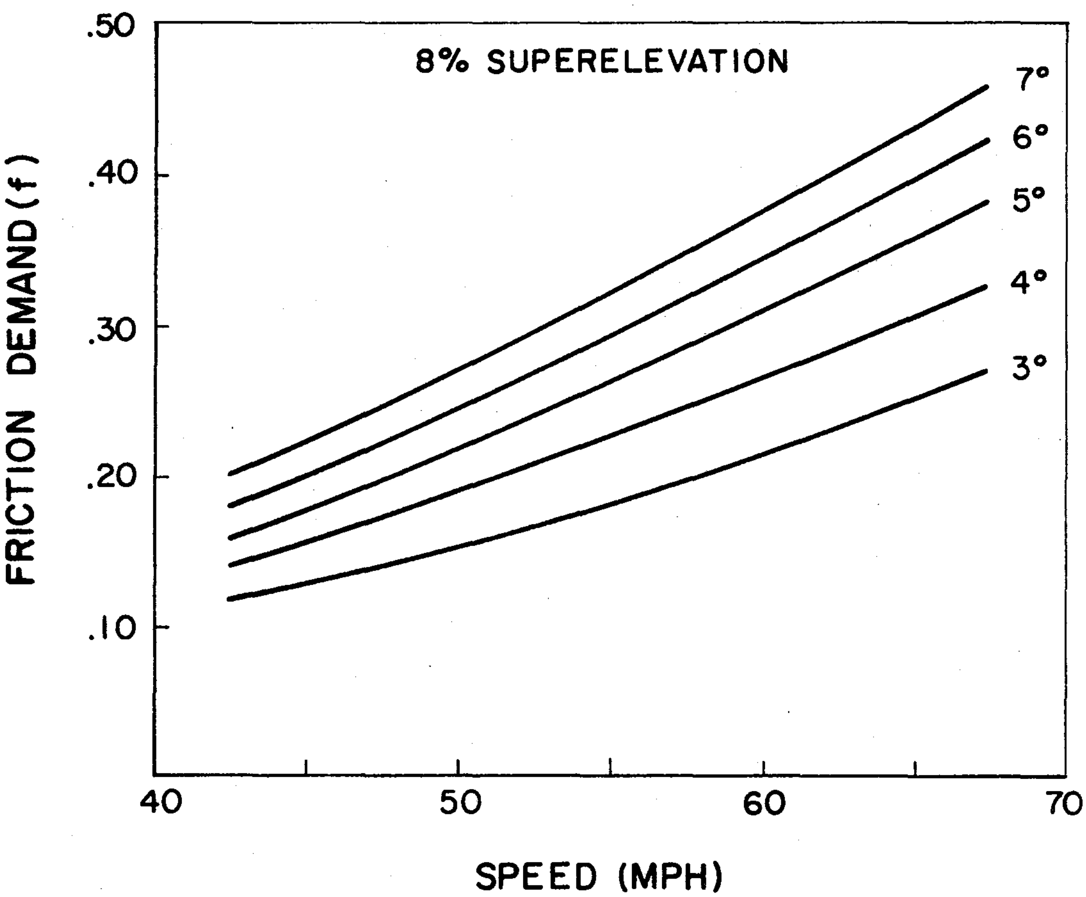


Figure 16 (Cont.) - Wet Weather Speed Limit Determination Charts for Highway Curves

TABLE 1

EXAMPLE DISTRIBUTION OF WET WEATHER SPEED LIMITS

Wet Weather Speed Limit	% of highway section within classification having designated wet weather speed limit							
	Minimum Stopping Sight Distance (ft)							
	200	300	400	500	600	700	800	1000
Two-Lane Highway, No Paved Shoulder								
60	0	0	5	10	10	10	10	10
55	0	0	5	30	60	60	60	60
50	0	5	25	25	5	5	5	5
45	0	10	30	15	5	5	5	5
<45	100	85	35	20	20	20	20	20
Two-Lane Highway, 6-10 foot Paved Shoulders								
70	0	0	0	5	10	20	50	50
65	0	0	0	5	10	20	10	10
60	0	0	5	5	20	25	5	5
55	0	0	5	25	25	5	5	5
50	0	5	25	25	10	5	5	5
45	0	10	30	15	5	5	5	5
<45	100	85	35	20	20	20	20	20
Multi-lane Highway, No Paved Shoulders								
60	0	0	5	10	10	10	10	10
55	0	0	5	25	55	55	55	55
50	0	5	25	30	20	25	25	25
45	0	10	30	20	5	5	5	5
<45	100	85	35	15	10	5	5	5
Multi-lane Highway, 6-10 foot Paved Shoulders								
70	0	0	0	5	10	20	50	65
65	0	0	0	5	10	20	10	15
60	0	0	5	5	20	25	20	10
55	0	0	5	25	25	15	10	5
50	0	5	25	25	15	10	5	5
45	0	10	30	20	10	5	5	0
<45	100	85	35	15	10	5	0	0

within each highway section classification, determined with Figures 12 through 15.

Although Table 1 is merely an illustration it indicates, if a 45 mph minimum is used for wet weather speed limits, that several highway sections may not satisfy the frictional requirements of traffic. A minimum skid resistance level program for skid surfacing is definitely needed to augment wet weather speed limits. Surface improvement, however, may not be enough for some sections with low minimum stopping sight distances. Therefore, the total program should also consider reconstruction to improve inadequate sight distance. In addition, if it is desirable to have more highway sections with the higher wet speed limits, addition of paved shoulders should be considered for those highways without paved shoulders.

In summary, a skidding accident prevention program should consider combinations of the following four alternatives:

1. Wet weather speed limits
2. Skid surfacing for pavements below some minimum skid resistance level
3. Reconstruction to improve inadequate stopping sight distance
4. Construction of paved shoulders

Cost-effectiveness considerations will determine the appropriate application of alternatives for any particular location.

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