# FACTORS AFFECTING VEHICLE SKIDS: A BASIS FOR WET WEATHER SPEED ZONING

REPORT NO. 135-2F

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Research Study No. 1-8-70-135

Definition of Relative Importance of Factors
Affecting Vehicle Skids

Sponsored by

The Texas Highway Department
in Cooperation With
The U. S. Department of Transportation
Federal Highway Administration

February 1973

TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY
COLLEGE STATION, TEXAS

# ACKNOWLEDGMENTS

This study represents one phase of Research Study No. 1-8-70-135, "Factors Influencing Vehicle Skids," a continuing study in the cooperative research program of the Texas Transportation Institute and the Texas Highway Department in cooperation with the Federal Highway Administration.

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# ABSTRACT

It is recognized that speed is a vital contributing factor in many wet weather skidding accidents. Since the potential for skidding is so speed-sensitive, establishment of wet weather speed limits represents one approach to relieving the immediate problem in priority locations.

This report includes an assimilation of findings from various related skid research efforts to form a basis for equating the available friction at a site (pavement skid resistance) to the expected friction demand for selected maneuvers.

Friction normally decreases with increased speed. Since the speeds in question are usually in excess of 40 mph, the speed at which skid numbers are normally determined, the change in available friction with respect to speed must be considered. Nomographs and curves are presented in the report to accomplish this. The report presents curves to determine the critical speed for hydroplaning, stopping maneuvers, cornering maneuvers, passing maneuvers, emergency path-correction maneuvers, and combined maneuvers.

A process is recommended by which wet weather speed zoning may be implemented at selected sites. A design process to establish the wet weather speed limit is discussed and examples are presented to illustrate the use of the curves in the report.

Key Words: Speed Zoning, Wet Weather Speed, Vehicle Maneuvers,
Skid Resistance, Friction Demand

# FOREWORD

The Texas Law governing the speed of vehicles gives the State Highway Commission the power and authority to alter the general speed limits on highways under its jurisdiction subject to a finding of need by an engineering and traffic investigation. Altering the general state-wide speed limits to fit existing traffic and physical conditions of the highway constitutes the basic principle of speed zoning.

It is recognized that speed is a vital contributing factor in many wet weather skidding accidents. Since the potential for skidding is so speed-sensitive, establishment of wet weather speed limits represents one approach toward attacking the wet weather skidding problem. Other corrective measures such as geometric improvements and intensive driver education are obviously warranted in many cases. However, these measures represent long-term objectives in the total skid reduction program, whereas wet weather speed zoning offers the possibility of relieving the immediate problem in priority locations.

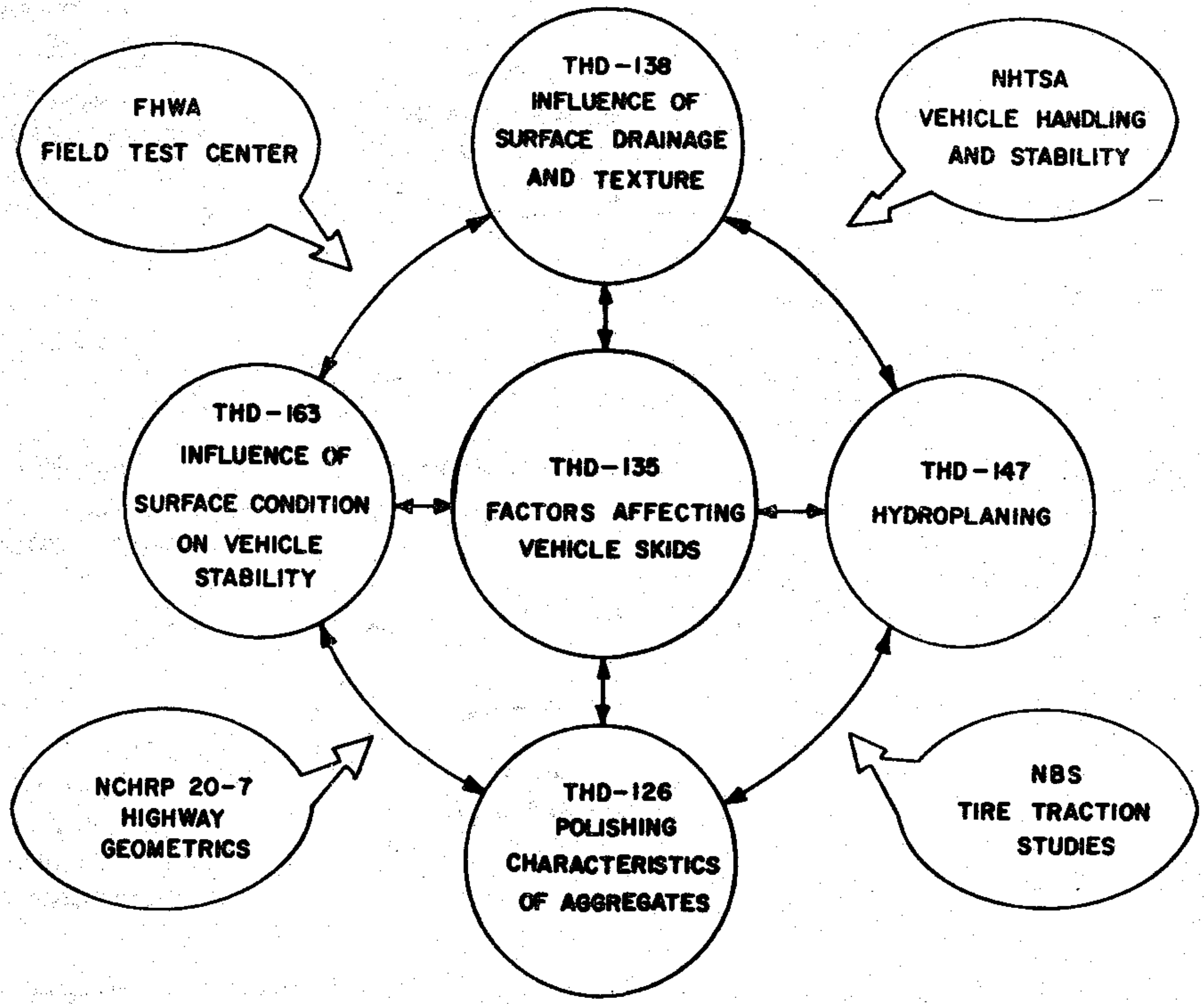
The enactment of Texas Senate Bill No. 183, Section 167 has placed upon the State Highway Commission the authority and responsibility to establish reasonable and safe speed limits when conditions caused by wet or inclement weather require such action. This report presents a method, based on the assimilation of available information from various skid-related research, by which wet weather speed zoning may be implemented in Texas.

# SUMMARY

Reducing the human and economic losses due to wet-weather skidding accidents is a high priority goal of the Texas Highway Department and the Federal Highway Administration. Although the highway surface is only one part of the problem, pavement slipperiness seems to be the only factor receiving attention in some sectors. In order to apply the available information appropriately, the various influencing factors must be kept in proper perspective. This is the goal of Study 1-8-70-135, the coordinating study in the program shown by Figure S-1. As a specific task within Study 135, the "Wet Weather Speed Zoning" report has made use of information from the individual studies in this comprehensive program to form a basis for implementing wet weather speed zoning at selected sites in Texas in response to Senate Bill 183, Section 167.

Speed is a significant factor in many wet weather accidents. Practically every driver realizes that he must reduce his speed when the roadway is wet if he is to maintain vehicle control comparable to dry pavement conditions. Unfortunately, the degree of speed reduction necessary for safe operation may not be readily apparent.

Since the potential for skidding is so speed-sensitive, establishment of wet weather speed limits represents one approach toward attacking the wet weather skidding problem. Other corrective measures such as geometric and surface improvements and intensive driver education are obviously warranted in many cases. However,



Vehicle-Roadway Interaction Program in Texas

Figure S-1

these measures represent long-term objectives in the total skid reduction program, whereas wet weather speed zoning offers the possibility of relieving the immediate problem in priority locations.

## FRICTION AVAILABILITY VS. FRICTION DEMAND

The performance of desired maneuvers is dependent upon the existence of tire/road friction. It is well known that the friction required (demand) by a vehicle to perform a given maneuver increases with speed. On the other hand, the friction available to the vehicle (skid resistance) at the tire-pavement interface normally decreases with increased speed. Loss of control usually occurs when the friction demand exceeds the friction available. The friction at the point where availability and demand are equal is defined as *"critical friction,"* and the speed at which this occurs is termed the *"critical speed."* The critical friction concept is used throughout this report as a basis for evaluating the individual factors that influence friction demand.

## AVAILABLE FRICTION

The skid number (SN) determined by the locked wheel skid trailer at 40 mph is a widely accepted measure of pavement friction. Friction measurement by this method, however, is usually obtained at the one speed, 40 mph, and as mentioned previously, friction decreases as vehicle speed increases. Since the speeds in question here are usually in excess of 40 mph, the change in available friction with respect to speed must be considered. Nomographs and curves are presented in the report to accomplish this.

## DEMAND FRICTION

Having determined the relationship of available friction with speed, the other part of the problem involves equating the demand friction for traffic maneuvers to this from which the critical speed may be determined.

Demand friction relationships are provided for the following maneuvers:

Stopping Maneuvers (page 17)
Cornering Maneuvers (page 19)
Passing Maneuvers (page 24)
Emergency Path Correction Maneuvers (page 29)
Hydroplaning (page 30)
Combined Maneuvers (page 39)

## WET WEATHER SPEED ZONING DESIGN PROCESS

The design process involves equating the available friction at the selected site to the friction demand for traffic operational maneuvers expected at that site. To do this, certain engineering characteristics of the site must be known from which the available friction may be determined. Similarly, certain traffic operating characteristics must be determined. Engineering and traffic characteristics necessary for site evaluation are discussed in Section III.

A critical speed is determined for each expected maneuver. The wet weather speed limit will be governed by the expected maneuver producing the lowest critical speed. Examples are presented in Section III to illustrate the design procedure for selecting the wet weather speed limit.

# IMPLEMENTATION

The wet weather speed design process developed in this study represents one method of attacking the skidding accident problem at selected sites. Much of the research on which the friction demand curves are based has been substantiated by full-scale controlled vehicle tests or by measurement of vehicle characteristics under actual highway operating conditions. Some of the concepts, such as the emergency path-correction friction demand curves are based on engineering judgment without the benefit of field verification.

A survey of high-frequency skidding accident sites throughout the state is being conducted as this study continues. Based on this survey, several sites will be recommended that are suitable for wet weather speed zoning. The procedures outlined in this report provide a basis for selecting sites and setting appropriate wet weather speed limits. The procedures will be evaluated from data obtained during the field studies of the selected sites.

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# I. INTRODUCTION

The proportionally greater number of skidding accidents occurring under wet weather conditions compared to those during dry weather has been well documented. From this, it is recognized that speed is a vital contributing factor in many wet weather accidents. Practically every driver realizes that he must reduce his speed when the roadway is wet if he is to maintain vehicle control comparable to dry pavement conditions. Unfortunately, the degree of speed reduction may not be readily apparent.

Since the potential for skidding is so speed-sensitive, establishment of wet weather speed limits represents one procedure with which to attack the wet weather skidding problem. Other corrective measures such as geometric improvements and intensive driver education are obviously warranted in many cases. However, these measures represent long-term objectives in the total skid reduction program, whereas wet weather speed zoning offers the possibility of relieving the immediate problem in priority locations.

Broadly stated, skidding accidents result from the dynamic interaction of four basic elements: the vehicle, the roadway, the driver, and the environment. Although simply stated, the problems posed by skidding accidents are complex. Many individual factors affect skid potential, thus the problem is compounded greatly by the combined factors acting as a total system or sequence of events.

Considerable research has been conducted on isolated factors to determine the influence of each on skid potential. Friction or skid resistance characteristics of pavements have been investigated both in the field and under controlled conditions. Projects have been completed recently to investigate the relationship of highway geometrics to vehicle skidding (1, 2, 3). The hydroplaning phenomenon has received considerable attention by NASA and other agencies, and research is being conducted currently to study its relation to the vehicle skidding problem (4).

The effects of vehicle tire condition, speed, pavement texture, and pavement skid numbers have been studied at accident sites. Extensive tests have been conducted to investigate the combined influence of water depth, tire condition, skid number, pavement texture, and speed (5). Vehicle suspension and steering characteristics are a relatively new target for researchers in an attempt to further define the interaction of vehicles and pavements. Recent studies by the HSRI (6) have shown significant differences in handling and stability of contemporary passenger vehicles. A most comprehensive study of the influence of the tire on skidding was conducted for the National Bureau of Standards (7) and further work is continuing. The studies mentioned here represent only a few of the many interrelated projects that comprise the state-of-the-art and knowledge concerning vehicle skidding. Although the solution to the problem cannot be considered complete, much information exists, and a significant portion of it is implementable at this time.

As a preliminary step toward reducing the toll of skidding accidents, the Texas Legislature has placed upon the State Highway Commission the authority and responsibility to establish reasonable and safe speed limits when conditions caused by wet or inclement weather require such action. This was accomplished through the enactment of S. B. No. 183, Section 167, pertinent statements of which are presented below:

> Section 167. (a) Whenever the State Highway Commission shall determine upon the basis of an engineering and traffic investigation that any prima facie maximum speed limit hereinbefore set forth is greater or less than is reasonable or safe under the conditions found to exist at any intersection or other place or upon any part of the highway system, taking into consideration the width and condition of the pavement and other circumstances on such portion of said highway as well as the usual traffic thereon, said State Highway Commission may determine and declare a reasonable and safe prima facie maximum speed limit thereat or thereon, and another reasonable and safe speed when conditions caused by wet or inclement weather require it, by proper order of the Commission entered on its minutes, which limits, when appropriate signs giving notice thereof are erected, shall be effective at such intersection or other place or part of the highway system at all times or during hours of daylight or darkness, or at such other times as may be determined; provided, however, that said State Highway Commission shall not have the authority to modify or alter the rules established in Paragraph (b) of Section 166, nor to establish a speed limit higher than seventy (70) miles per hour; and provided further that the speed limits for vehicles described in Paragraphs a, b, and c of Subdivision 5 of Subsection (a) of Section 166 shall not be increased.

By wet or inclement weather is meant conditions of the pavement or roadway caused by precipitation, water, ice or snow which make driving thereon unsafe and hazardous.

## OBJECTIVES

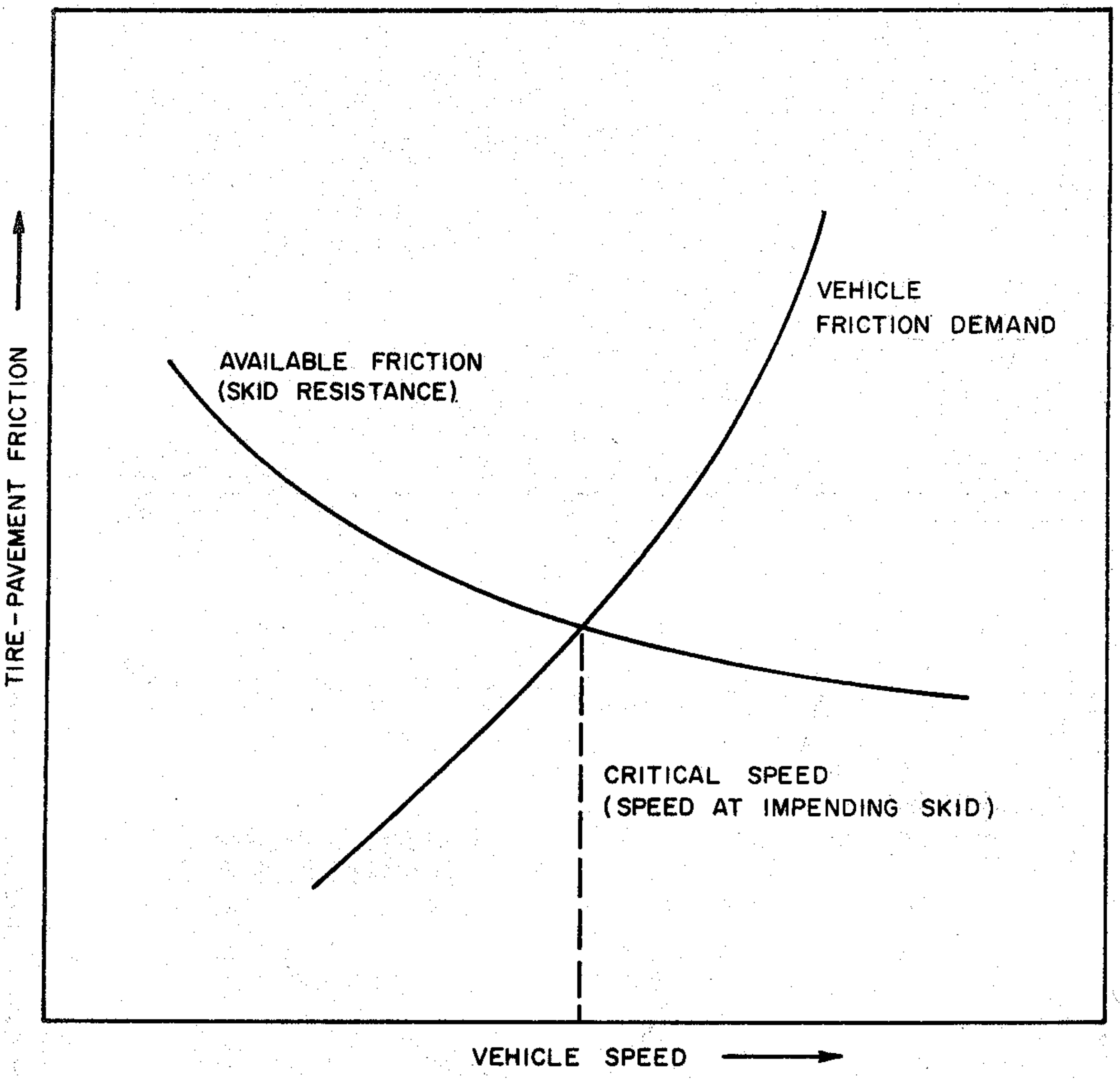
The establishment of wet weather speed limits is based on "...an engineering and traffic investigation." The primary objective of this study was to assimilate pertinent findings from various skid-related research efforts to provide an objective basis on which potential wet weather accident sites can be analyzed and hence, safe wet weather speed limits may be determined.

# II. FACTORS AFFECTING VEHICLE SKIDS

## RELATIONSHIP OF FRICTION AVAILABILITY AND DEMAND

The performance of desired maneuvers is dependent upon the existence of tire-road surface friction. It is well known that the friction required (demand) by a vehicle to perform a given maneuver increases with speed. On the other hand, the friction available to the vehicle (skid resistance) at the tire-pavement interface normally decreases with increased speed. The relationship between friction demand and friction availability is shown schematically in Figure 1. Loss of control usually occurs when the friction demand exceeds the friction available. The friction at the point where availability and demand are equal is defined in this report as *"critical friction."* It should be noted that the critical friction *for a given maneuver* occurs at a *critical speed*. For speeds less than the critical speed, sufficient friction exists to perform the maneuver.

The critical friction concept is used throughout this report as a basis for evaluating the individual factors that influence friction availability and the vehicle maneuvers that affect the friction demand. Relationships between speed and measured skid number (an indication of available friction), and between speed and friction demand for several maneuvers have been developed in related research studies. These relationships form the basis for equating the available friction at a site to the expected friction demand.



**Relationship Between Friction Demand and Pavement Skid Resistance (8)**

**Figure 1**

## AVAILABLE FRICTION

A widely accepted measure of pavement friction is the skid number (SN) determined by the locked-wheel skid trailer at 40 mph using an internal trailer watering system (ASTM E 274-70). In this report, SN (including the effect of speed) is assumed equivalent to available friction. Other studies (3, 8, 9) have shown this assumption to be reasonably valid for relatively steady state cornering and stopping. Although it is well documented that individual tires can develop significantly higher friction forces in a braking or side-slipping condition, these maximum values can rarely be realized simultaneously by all four wheels on a vehicle. Consequently, the SN is assumed to provide a reasonable approximation of the *average* friction available to the vehicle.

In the past, friction measurement by this method has usually been obtained at only one speed, 40 mph. To reiterate, friction decreases with increased speed. Since the speeds in question here are usually in excess of 40 mph, the change in available friction with respect to speed must be considered. The available friction, including the effects of speed may be approximated by three methods described below:

(1) The speed variation of SN may be determined by conducting standard skid trailer measurements at 20, 40 and 60 mph. The relationship of speed to SN can then be determined graphically.

(2) The 20, 40, and 60-mph measurements may be obtained with a skid-trailer test but using an external trailer watering system. (3) Although this may impose a considerable traffic control problem, it allows observation of such factors as puddling, rutting, and drainage.

(3) The pavement friction as indicated by SN may be measured at 40-mph and then the applicable SN at other speeds may be determined from Figure 5. The development of Figure 5 is discussed below.

Using the input factors of pavement surface texture, water depth, vehicle speed, and tire tread depth from Gallaway's (5, 14) studies, the Texas Highway Department (15) developed the following equation to predict the available friction on wet pavement.

$$F = 0.7483\ (FM)^{1.03081} \left(\frac{40}{Vel}\right)^{0.34903} \quad \text{-----(Eqn 1)}$$

when

$$FM = [(1.1907 - 0.0089775\ Vel)(SN_{40})] + [(29) - (1{,}416 + 60\ Vel)(Text)][WD]$$

Vel = vehicle speed, mph

$SN_{40}$ = basic friction value, skid number obtained in a standard test with internal watering system

Tread = tire tread depth, inches (use value 1.0 for a smooth tire or 2.0 for a tire with full tread depth)

Text = pavement surface texture, cu. in. per sq. in. (putty impression method)

WD = water depth on pavement surface, inches above texture asperities

The data used in developing the above equation were obtained from ASTM skid trailer measurements on 5 skid pads with water depth being a variable test condition. The correlation coefficient was 92 with a standard error of estimate of 1.2 skid numbers indicating that the predicted available friction could vary from the measured available friction by ±2.4 skid numbers with a 95 percent confidence level.

Figure 2 is a graphical solution of Equation 1 and represents the general case for determination of available friction at some speed other than 40 mph given a particular speed, pavement texture, water depth and the $SN_{40}$ value. An example solution is shown in Figure 2 to illustrate its use (smooth tire, 2/32 inch or less tread).

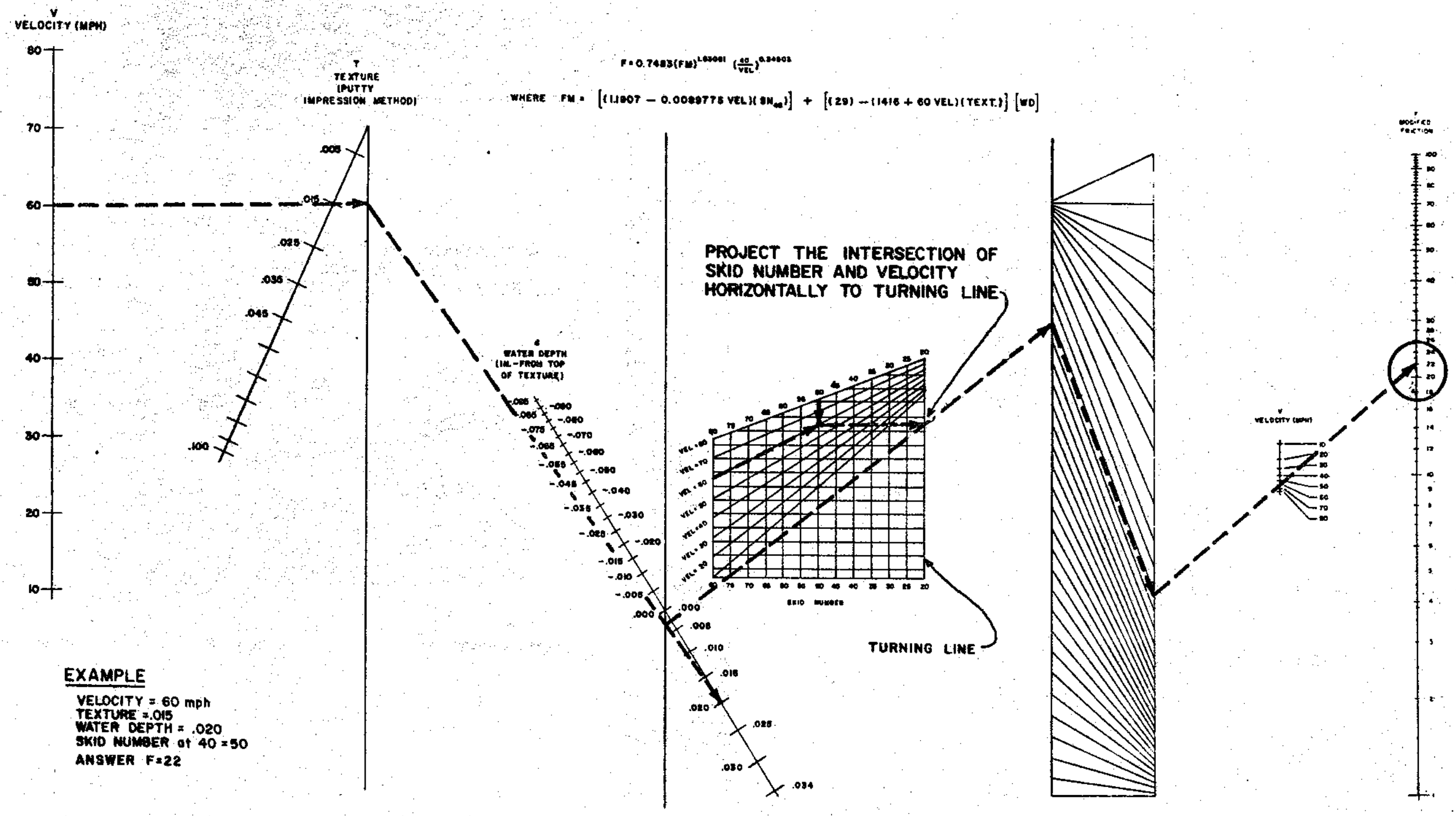
Gallaway (5) developed an equation to determine water depth on the pavement as a function of texture, drainage length, rai fall intensity, and cross-slope:

$$d = [3.38 \times 10^{-3} (\frac{1}{T})^{-0.11} (L)^{0.43} (I)^{0.59} (\frac{1}{S})^{0.42}] - T \quad \text{-----(Eqn 2)}$$

where:

d = water depth above top of texture (in.)

T = average texture depth (in.) (putty impression method)



**EXAMPLE**

VELOCITY = 60 mph
TEXTURE =.015
WATER DEPTH = .020
SKID NUMBER at 40 =50
ANSWER F=22

The Determination of Available Friction
(General Nomograph)

Figure 2

L = drainage path length (ft)

I = rainfall intensity (in./hr)

S = cross-slope (ft/ft)

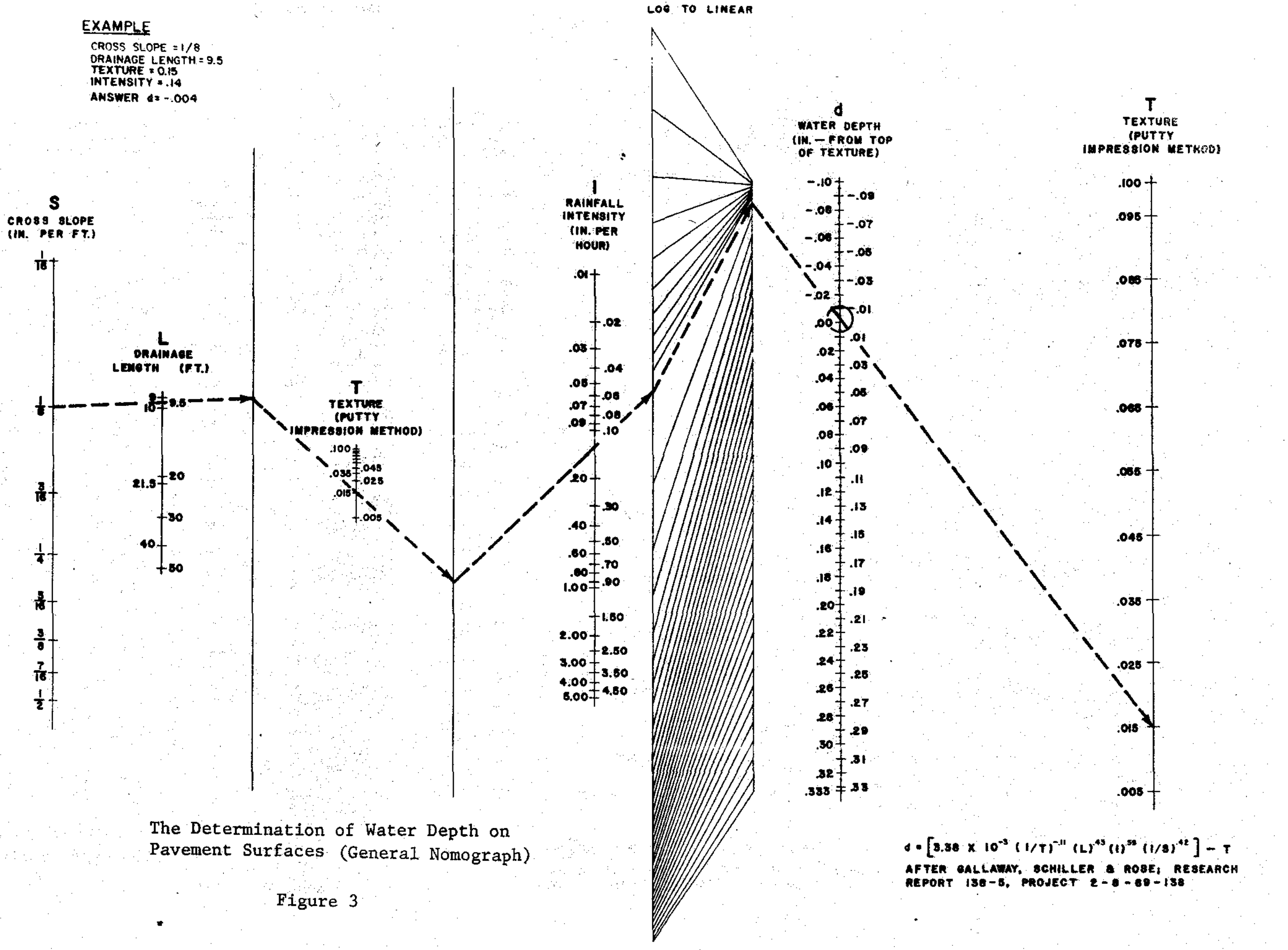
Equation 2 may be solved graphically through use of the nomograph in Figure 3 using as input, measured values of cross-slope, drainage length, texture, and rainfall intensity. An example solution to determine water depth is shown in Figure 3 to illustrate its use. Figure 3 represents a general solution for water depth determination for various rainfall intensities and pavement characteristics.

The determination of available friction may be greatly simplified if certain assumptions are made for values of tread depth, texture, and rainfall intensity. Assuming the 85th percentile rainfall intensity in Texas, water depth on the pavement may be determined from Figure 4 for various cross-slopes, drainage lengths, and pavement texture. Figure 4, therefore, represents a graphical solution of Equation 2 with the rainfall intensity term, I, being the average 85th percentile value for Texas as discussed below.

Table 1 presents hourly rainfall intensity data collected for 18 cities in Texas for a period of one year. The 85th percentile intensity was selected for study. The average 85th percentile rainfall intensity was 0.14 inches per hour. There appeared to be no relationship between rainfall intensity and total annual rainfall, however, variation in intensity appeared to be related to the number of individual rains. Therefore, a sufficient sample is required to determine the distribution of rainfall intensity for a particular location.

**EXAMPLE**

CROSS SLOPE = 1/8
DRAINAGE LENGTH = 9.5
TEXTURE = 0.15
INTENSITY = .14
ANSWER d = -.004



$$d = \left[3.38 \times 10^{-3} (1/T)^{-.11} (L)^{.43} (I)^{.59} (1/S)^{.42}\right] - T$$

AFTER GALLAWAY, SCHILLER & ROSE; RESEARCH REPORT 138-5, PROJECT 2-8-69-138

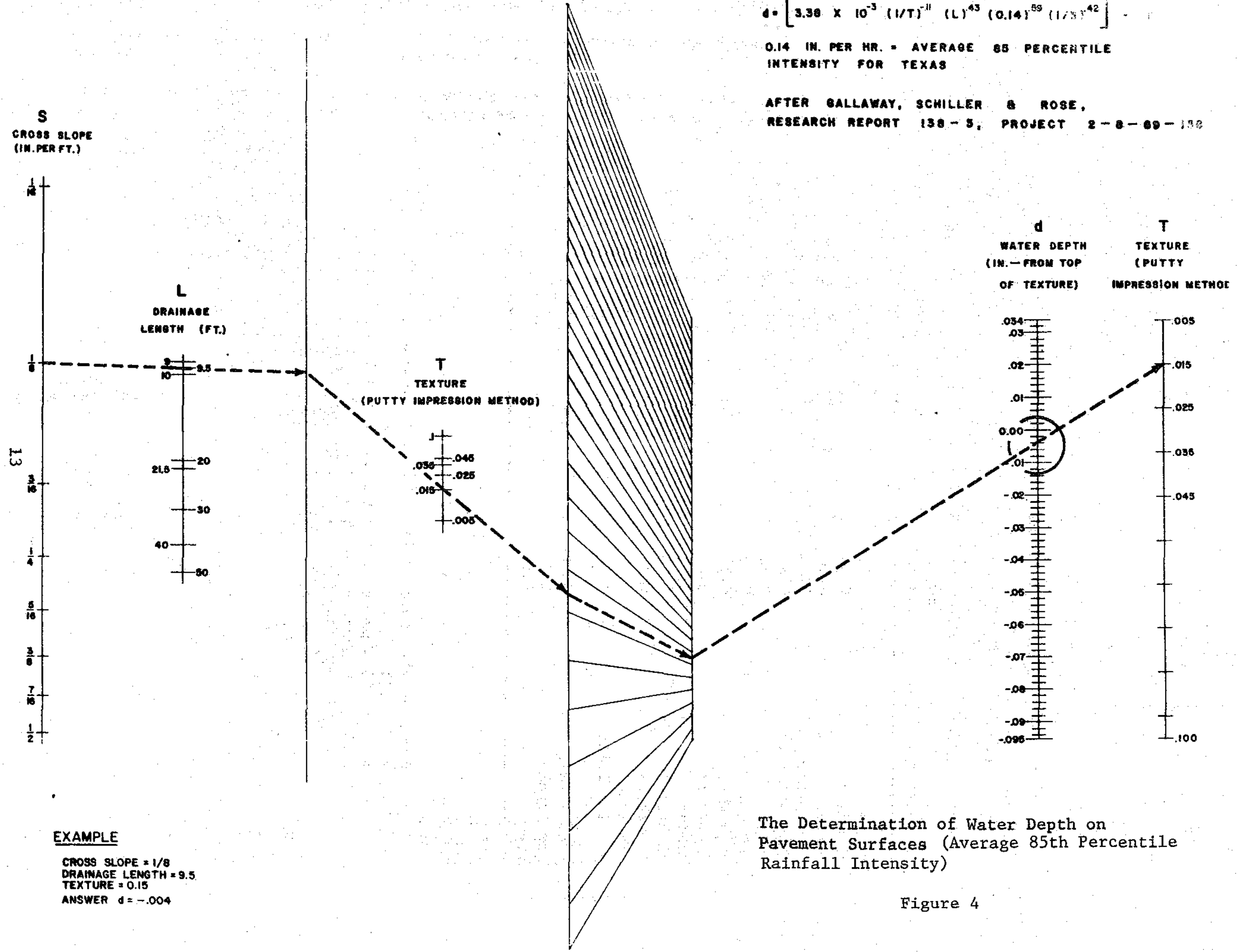
The Determination of Water Depth on Pavement Surfaces (General Nomograph)

Figure 3

$$d = \left[3.38 \times 10^{-3} \, (1/T)^{.11} \, (L)^{.43} \, (0.14)^{.59} \, (1/S)^{.42}\right] - T$$

0.14 IN. PER HR. = AVERAGE 85 PERCENTILE INTENSITY FOR TEXAS

AFTER GALLAWAY, SCHILLER & ROSE, RESEARCH REPORT 138 - 5, PROJECT 2 - 8 - 69 - 138



EXAMPLE

CROSS SLOPE = 1/8
DRAINAGE LENGTH = 9.5
TEXTURE = 0.15
ANSWER d = -.004

The Determination of Water Depth on Pavement Surfaces (Average 85th Percentile Rainfall Intensity)

Figure 4

## TABLE 1

## 85th PERCENTILE RAINFALL INTENSITY FOR 18 LOCATIONS IN TEXAS

| Location | 85th Percentile Intensity (in./hr) | Annual Rainfall (in.) |
|---|---|---|
| Abilene | 0.15 | 36.84 |
| Amarillo | 0.13 | 22.55 |
| Austin | 0.20 | 33.59 |
| Brownsville | 0.13 | 27.35 |
| Corpus Christi | 0.11 | 23.57 |
| Dallas | 0.13 | 38.55 |
| Del Rio | 0.13 | 33.22 |
| Fort Worth | 0.13 | 35.69 |
| Galveston | 0.17 | 41.79 |
| Lubbock | 0.15 | 29.19 |
| Midland | 0.10 | 16.94 |
| Texarkana | 0.15 | 43.87 |
| Victoria | 0.18 | 44.64 |
| Wichita Falls | 0.13 | 31.61 |
| El Paso | 0.05 | 4.34 |
| Port Arthur | 0.16 | 48.44 |
| San Angelo | 0.13 | 30.04 |
| Waco | 0.13 | 31.50 |

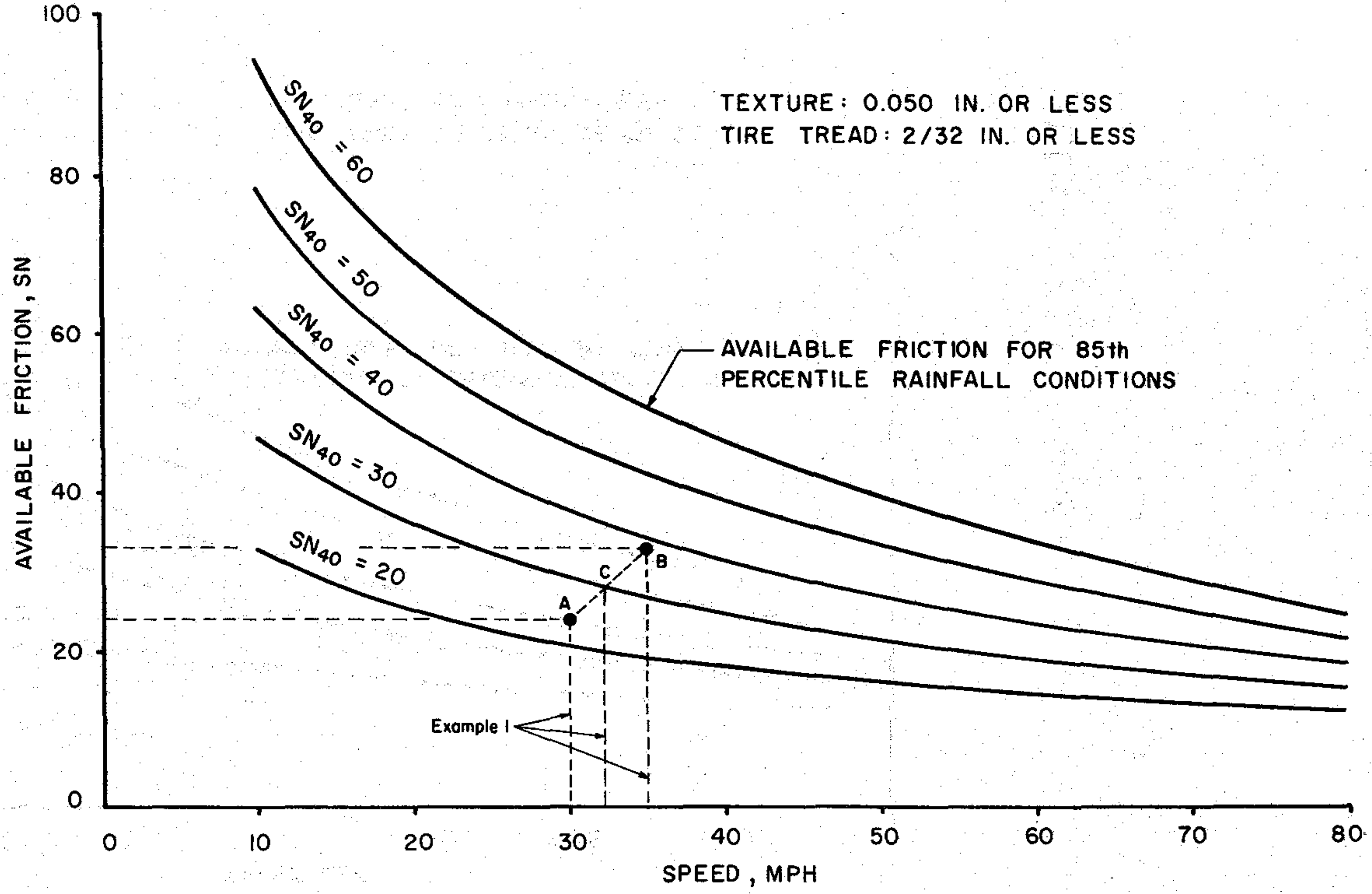
Notes:

(1) Range of 85th percentile rainfall intensities: 0.05 to 0.20 in./hr
(2) Average 85th percentile rainfall intensity: 0.137 in./hr
(3) Source: Weather Bureau hourly records, Jan. 1, 1969 to December 31, 1969

The determination of available friction by Equation 1 may be further simplified by selecting representative values for tire tread depth and pavement texture. In a sampling (10) of passenger vehicle tire tread depths, it was found that 85 percent of the tire tread depths measured were 2/32 inch or more. It was also found that up to 50 percent of certain skidding accidents occurred when tire tread depth was 2/32 inch or less. The minimum allowable tread depth for annual vehicle safety inspection approval in Texas is 2/32 inch. A legally conservative assumption for tire tread depth for use in Equation 1 is 2/32 inch.

The friction generated by a 2/32-inch tread depth or less is influenced significantly by speed and $SN_{40}$ values, but not significantly by water depth and texture if the surface texture is 0.050 inches or less and not inundated. Using the assumptions discussed, water depths developed at the 0.14-inch-per-hour rainfall intensity are very small and rarely inundate the surface texture peaks. It has been estimated (10) that 87 percent of the surface textures on Texas Highways are 0.050 in. or less.

The determination of available friction is greatly simplified if variations in water depth and texture are considered insignificant. Therefore, it is suggested that only $SN_{40}$ values and vehicle speed be considered in the determination of available friction. Under these conditions, and assuming a texture of 0.050 inches, a tire tread depth of 2/32 inch, and the 85th percentile rainfall intensity of 0.14 inches/hour, the available friction at various speeds may be estimated from standard $SN_{40}$ measurements using Figure 5.



Available Friction As Predicted by Skid Number (15)

Figure 5

It should be noted that in Figure 5, the intersection of a vertical line at 40 mph with the $SN_{40}$ = 40 mph curve does not yield a skid number of 40 when projected horizontally to the available friction ordinate. Although this, at first, may appear questionable, the reason lies in the fact that the curves were developed from skid data obtained under external watering conditions (rain machine) rather than the standard ASTM internal trailer watering system. The curves in Figure 5 more closely reflect pavement characteristics under actual wet weather conditions.

## STOPPING MANEUVERS

The ability to see the roadway ahead is vital to the safe and efficient operation of a vehicle. Although it is desirable to provide ample sight distance for practically unlimited passing opportunity, compromises must be made and the roadway must be designed to less than this optimum. General practice has been (11) that the minimum acceptable design will provide at least sufficient sight distance to allow a driver to safely stop his vehicle before hitting an obstacle in his path.

Minimum stopping sight distance is the sum of two distances: the distance traveled from the instant the driver sights an object for which a stop is necessary, to the instant the brakes are applied; and the distance required to brake the vehicle to stop. (11) The former is primarily a function of speed and reaction time, the latter a function of speed and frictional resistance between the pavement surface and tires. The total distance may be approximated by the equation: (11)

$$d = \frac{V^2}{30f} + 1.47\ Vt \qquad \text{-----Eqn. 3}$$

where:

d = minimum stopping sight distance, ft

V = vehicle speed, mph

f = coefficient of friction between tires and roadway

t = perception-reaction time, sec.

Rearranging Equation 3, the demand friction in stopping a vehicle within restricted sight distance becomes:

$$f = \frac{V^2}{30(d-1.47Vt)} \qquad \text{------Eqn. 4}$$

Using a 2.5 second perception-reaction time currently recommended (11), the demand friction for stopping maneuvers may be related to speed by:

$$FN_s = \frac{V^2}{0.3(d-3.67V)} \qquad \text{-----Eqn. 5}$$

where:

$FN_d$ = friction demand number for stopping within available sight distance

V = vehicle speed, mph

d = available sight distance, ft

Figure 6 illustrates the relationship of available friction and friction demand for stopping maneuvers under sight distances ranging from 200 to 1000 feet. The friction demand curves in Figure 6 are computed from Equation 5 for selected sight distances and speed. The available friction curves superimposed were developed as previously discussed for Figure 5.

## CORNERING MANEUVERS

Lateral friction during a cornering maneuver must be sufficient to generate the lateral forces necessary to traverse a given curve. Findings in a recently completed research study (3) showed that the skid number predicted by an ASTM locked-wheel trailer approximated the average lateral friction available during a cornering maneuver provided that the skid number was considered a function of vehicle speed. Thus, a reliable estimate of critical speed may be obtained from the standard centripetal force equation,

$$e + f = \frac{V^2}{15R} \qquad \text{-----Eqn. 6}$$

where:

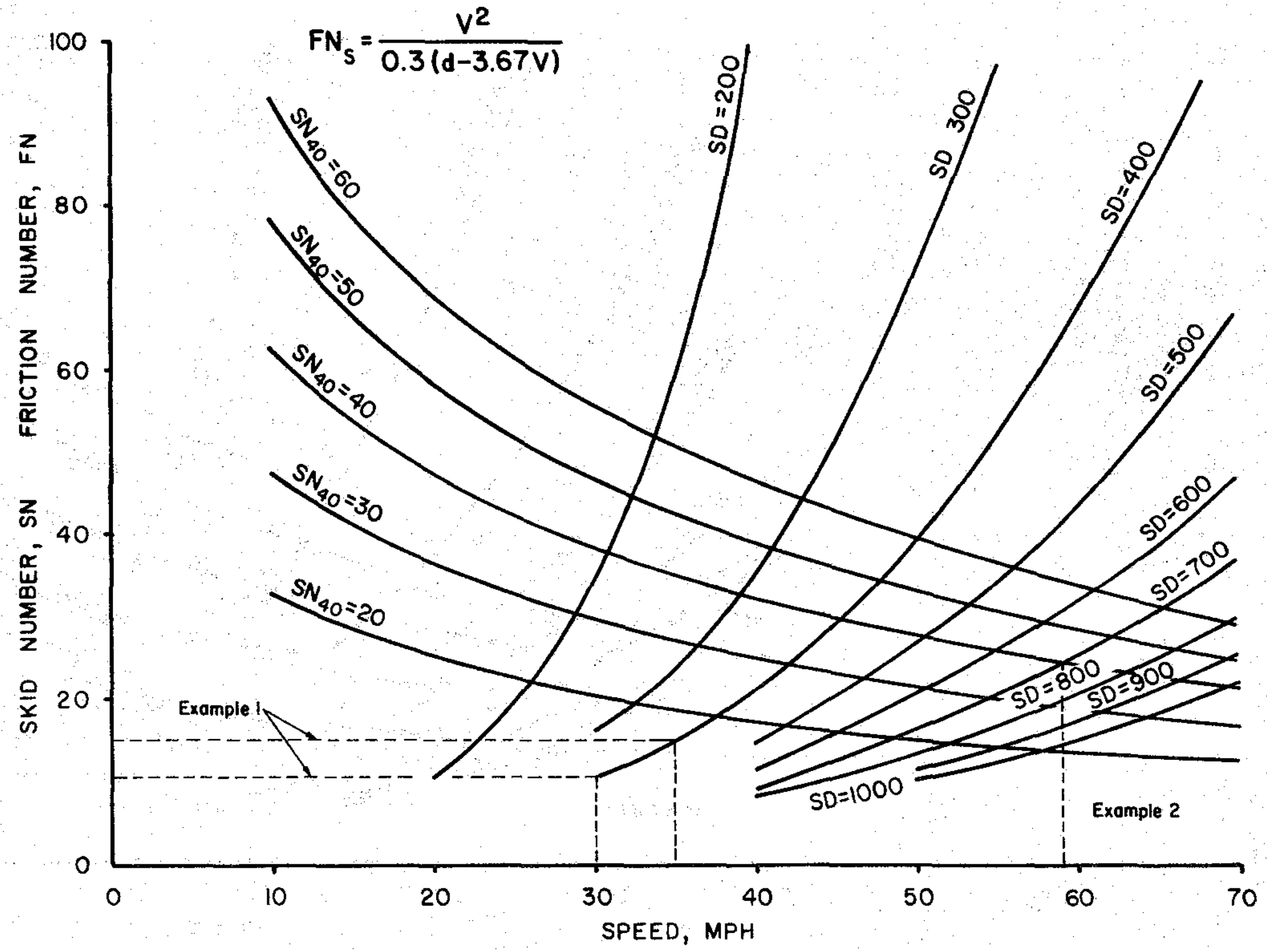
$e$ = superelevation rate, ft per ft

$f$ = coefficient of friction

$V$ = vehicle speed, mph

$R$ = curve radius, ft

provided friction, f, is approximated by skid number and considered speed dependent. The friction demand for cornering, $FN_c$, may then be described by:



Critical Speed for Emergency Stop Imposed by Sight Distance and Available Friction (8)

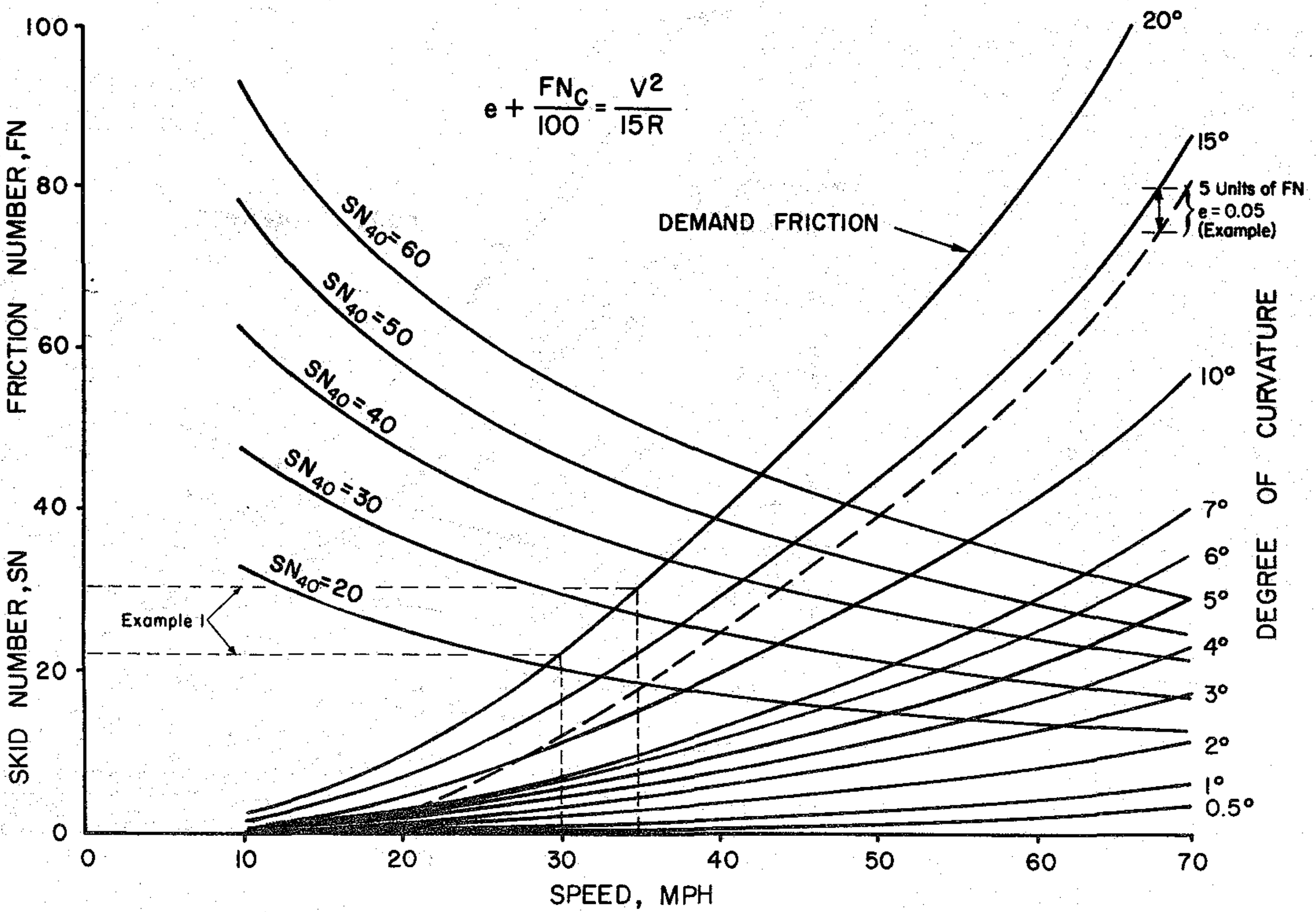
Figure 6

$$\frac{FN_c}{100} + e = \frac{V^2}{15R} \qquad \text{-----Eqn. 7}$$

Figure 7 shows the lateral friction demand during traversal of non-superelevated highway curves for degrees of curvature from 0.5 to 20 degrees. The variation of SN with speed is superimposed. The critical speed is established by the intersection of the applicable SN-curve and the degree of curvature curve. For example, the critical speed under conditions of a non-superelevated 15-degree curve and $SN_{40}$ of 40 would be 42 mph as shown.

Rather than developing a series of curves for selected degrees of superelevation, the curves in Figure 7 are developed on a zero-superelevation basis to which appropriate correction factors may be easily applied for a desired superelevation rate. The effect of superelevation is linear as shown by Equation 7. To include the effect of superelevation, the given demand curve, $FN_c$, is translated vertically by the amount of the superelevation expressed in percent. As an example, if a 15-degree curve contained 0.05 positive superelevation, the 15-degree curve would be lowered 5 units of FN as shown by the dashed curve in Figure 7. Similarly, the curve would be translated upward an equal amount if the superelevation were negative.

It should be noted that the critical speeds determined from Figure 7 represent allowable speeds provided the vehicle smoothly traverses the highway curve. Therefore, Figure 7 should be used for spiraled transitions or at locations within a curve.



Critical Speed on Horizontal Curves (Smooth Transition, Zero Superelevation) (1)

Figure 7

Photographic studies of vehicle maneuvers on highway curves (1) indicated that most vehicle paths, regardless of speed, exceed the degree of highway curve at some point throughout the curve. For example, on a 3-degree curve, 10 percent of the vehicles can be expected to exceed 4.3 degrees. Randomly selected vehicles were photographed throughout unspiraled highway curves ranging from 2 to 7 degrees. Lateral placement and speed were determined at 20-ft. intervals by analyzing the movie film from which an instantaneous radius at each point was estimated by calculating the radius of the circular curve through three successive points.

To determine the critical friction requirement, the 10th percentile path radius, $R_v$, was selected and substituted in the centripetal force equation. The 10th percentile relationship (only 10 percent of the vehicles would travel along a lower path radius at any particular speed) is: (8)

$$R_v = 0.524R + 268.0 \qquad \text{-----Eqn. 8}$$

where:

$R_v$ = vehicle path radius, ft

$R$ = highway curve radius, ft

A large percentage of the observed vehicles negotiated the minimum path radius at the ends of the curve near the transition between tangent and curve. Since the friction demand at these locations appears to be more stringent, critical speed should be determined on the basis of this minimum radius. Similarly, superelevation should be determined at this critical point on the curve. Often, superelevation at this point is less than maximum due to superelevation runoff.

When $R_v$ is substituted in Equation 6, the following equation results:

$$e + f = \frac{V^2}{7.86R+4020} \qquad \text{-----Eqn. 9}$$

From this, the friction demand, $FN_c$, becomes:

$$FN_c = \frac{V^2}{0.0786R+40.2} - 100e \qquad \text{----Eqn. 10}$$

Figure 8 presents speed-friction relationships for various degrees of curvature. These curves contain no margin of safety, but they are developed on the basis of Glennon and Weaver's research (1) and, therefore, consider the effects of the more severe radius traveled. It is suggested that these curves be used for determination of critical speeds on curves having abrupt transition regions at either end (situations normally found when spiral or compound curve transitions are not provided).

## PASSING MANEUVERS

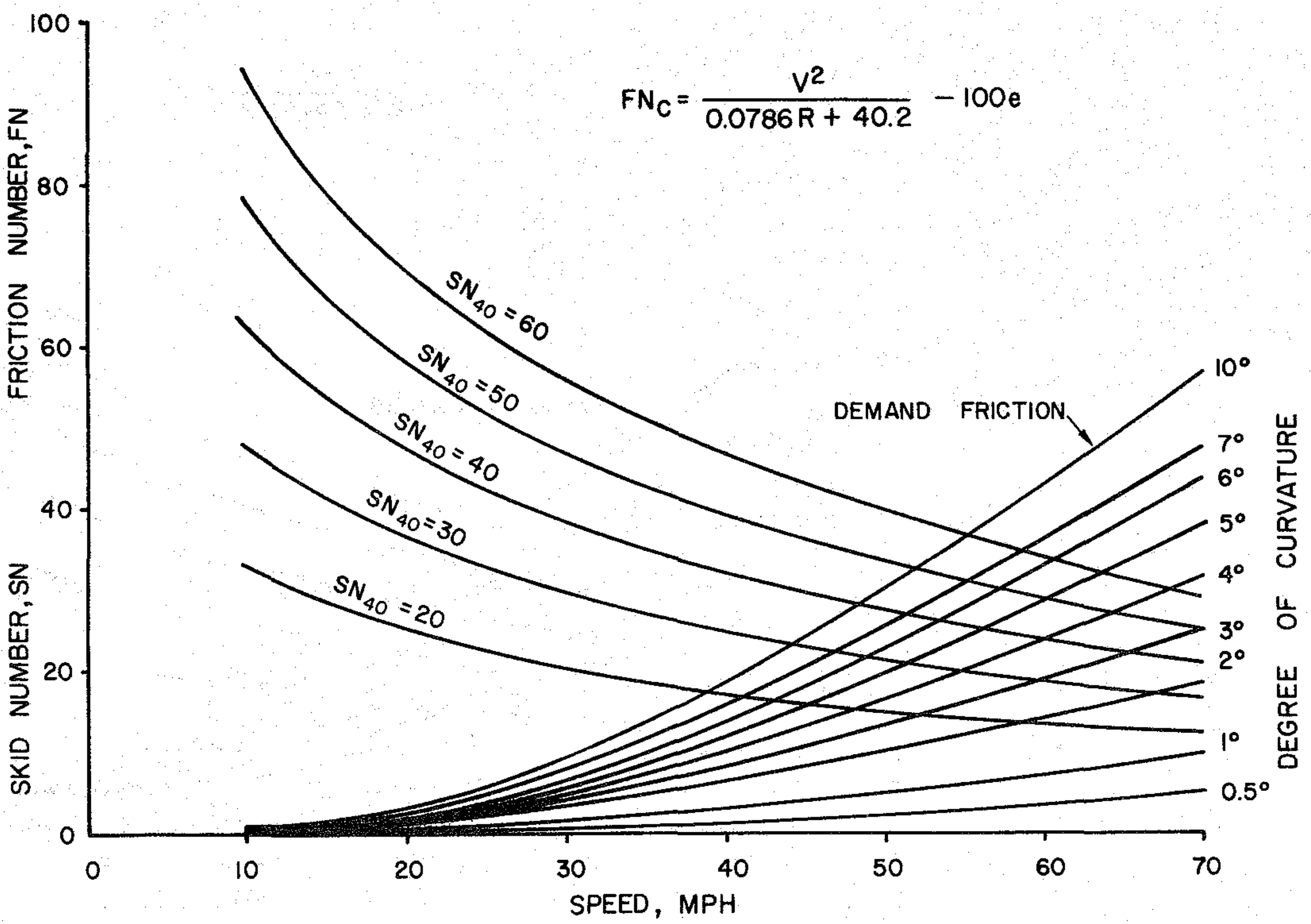
The passing maneuvers may be one of the most critical non-emergency maneuvers performed on a two-lane highway. Several characteristics combine during the passing maneuver to influence the demand for friction: the maneuver is performed at relatively high speeds; the passing vehicle executes both pull-out and return maneuvers against negative superelevation due to normal crown; and finally, the maneuver involves combinations of forward and lateral acceleration.

A recent study (12) investigated the passing characteristics under high-speed operation on two-lane highways. Approximately 300 complete passing maneuvers at speeds from 50 to 65 mph were photographed and analyzed. From this analysis vehicle acceleration, lateral placement, speed and distance traveled were determined. Frictional requirements (2) were determined for the critical portion of the maneuver based on maximum lateral friction demand.

The point where vehicle speed and radius produced maximum lateral friction $(\frac{V^2}{15R} - e)$ was determined for each pull-out and return maneuver. These points, for most samples, coincided with either the point of minimum path radius or the point of maximum speed, or both.

To determine the critical side friction requirement, the 10th percentile path radius was selected; that is, only 10 percent of the vehicles would have a shorter path radius during pull-out or return. Under this criteria, the critical vehicle path radii were 1470 feet for the pull-out maneuver and 1640 feet for the return maneuver. Assuming an e-value of -0.02 to represent the adverse pavement cross-slope and substituting in the centripetal force equation, yields the following relationship for lateral friction demand during the passing maneuver (pull-out maneuver): (8)

$$f = \frac{V^2}{22050} - 0.02 \qquad \text{----Eqn. 11}$$



Critical Speed on Horizontal Curves (Abrupt Transition, Zero Superelevation) (1)

Figure 8

or,
$$FN_p = \frac{V^2}{220} + 2 \qquad \text{----Eqn. 12}$$

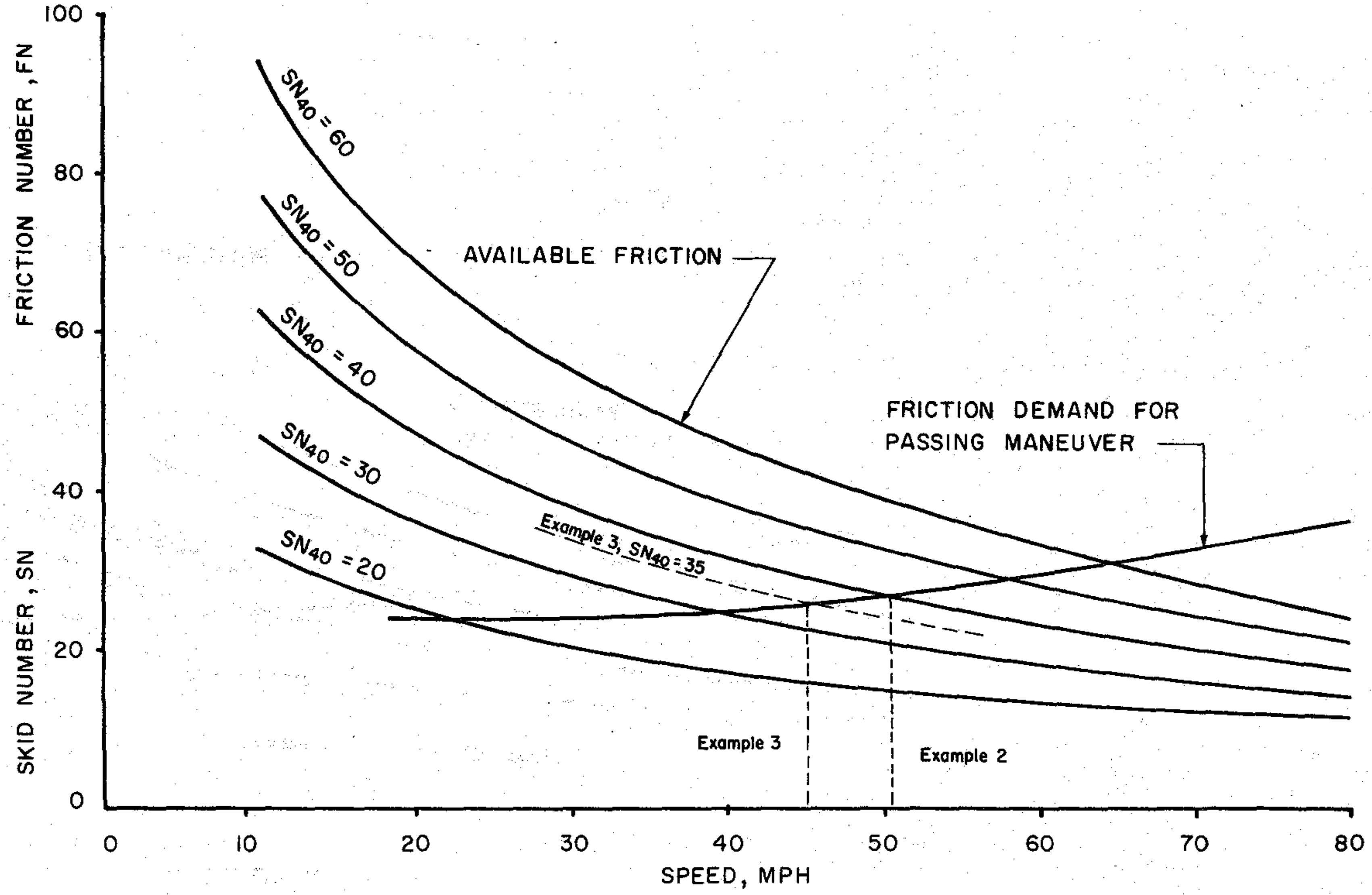
where:

$FN_p$ = friction demand number for passing

$V$ = vehicle speed, mph

The total friction demand can be expressed as the vector sum of the forward and lateral accelerations. Based on Kummer and Meyer's (13) relationship between forward friction demand and speed for full-throttle acceleration of an American "Standard" automobile, Glennon (2) assumed the instantaneous forward acceleration of the passing vehicle to vary linearly from 40 to 60 percent full-throttle at 40 and 80 mph respectively. This corresponds to 6.4 ft/sec$^2$ and 5.0 ft/sec$^2$ acceleration at 40 and 80 mph respectively for a 4000-pound vehicle. Glennon then developed a critical demand friction-speed relationship using the vector sum of forward and lateral acceleration demand. This relationship is shown in Figure 9 with superimposed SN curves. The demand curve in Figure 9 does not include a safety margin.

The critical speed is determined by the intersection of the applicable SN-curve and the demand curve. The examples (discussed later in this report) shown in Figure 9 depict a critical speed of 51 mph for a passing maneuver performed on a pavement having an $SN_{40}$ of 40, and 45 mph for a skid number of 35.



Critical Speed for Passing Maneuvers (2)

Figure 9

## EMERGENCY PATH-CORRECTION MANEUVERS

Drivers are occasionally required to perform corrective maneuvers to avoid leaving the roadway. Although it is not feasible to satisfy the more severe frictional requirements such as might be imposed in attempts to regain control after a violent swerve, the demand friction to correct minor encroachment paths should be considered, particularly on tangent sections.

Glennon (8) calculated frictional requirements for emergency path-corrections under several conditions. He concluded that the friction demand was highly sensitive to the encroachment angle and the initial distance from the edge of the paved roadway. Assuming a -0.02 cross-slope, Glennon developed the following friction demand for path-correction:

$$f = \frac{V^2\ (1-\cos\ \theta)}{15\ (W-1.47V\sin\ \theta)} + 0.02 \qquad \text{----Eqn. 13}$$

where:

$V$ = vehicle speed, mph

$\theta$ = encroachment angle, degrees

$W$ = distance from edge of paved roadway to vehicle right front corner at the point where the correction is perceived, feet

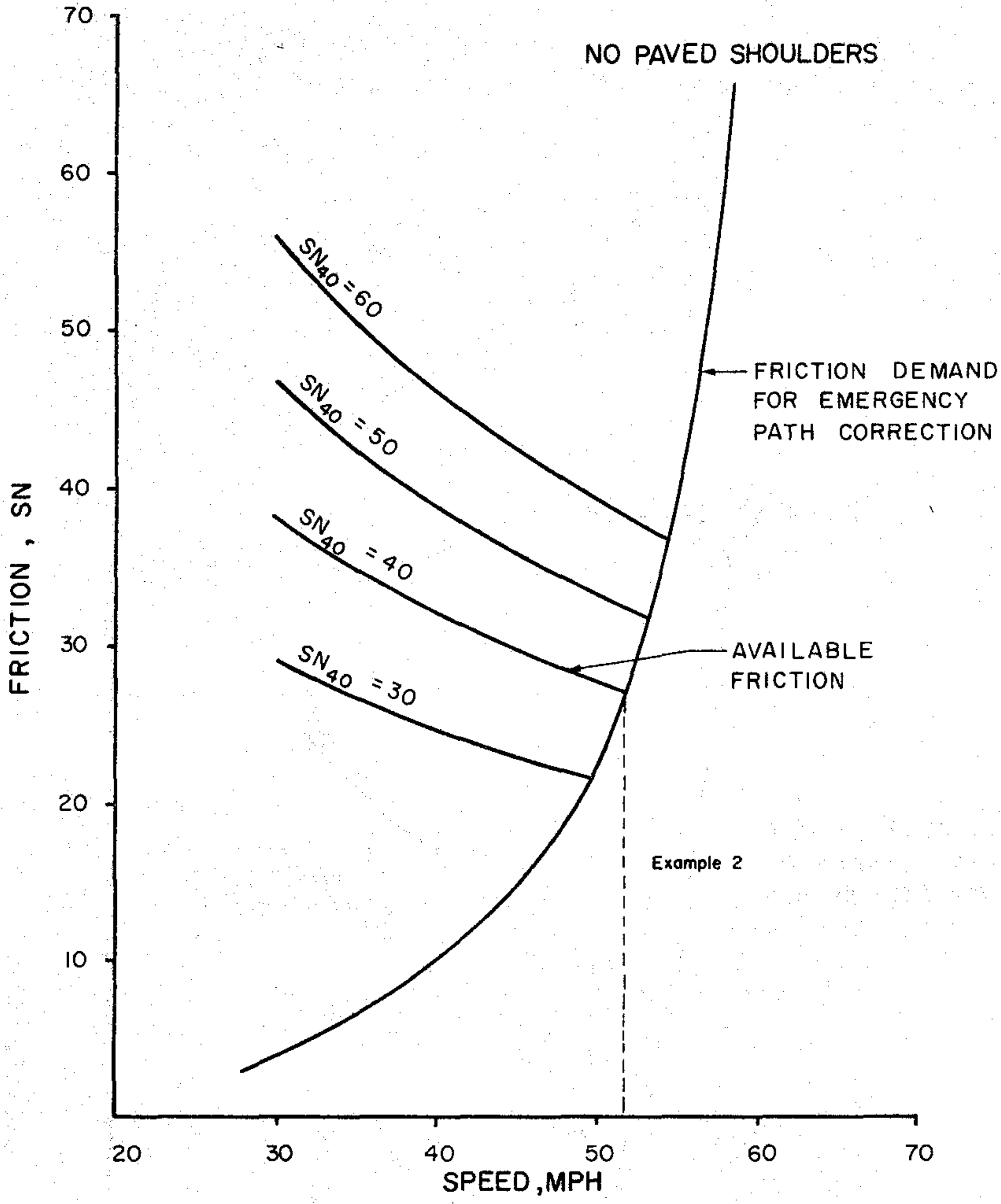
The distance W is a function of the paved shoulder width. Glennon examined frictional requirements for three shoulder widths: zero, six, and ten feet. Considering that vehicle placement was closer to the roadway centerline for narrower shoulders, the respective distances, W, for these conditions were 5, 10, and 13 feet respectively. Encroachment angles assumed for the respective shoulder widths were 3, 4, and 5 degrees.

Figures 10, 11, and 12 show the relationship between speed and friction demand for path-correction maneuvers on two-lane highways with several widths of shoulder. The curves are developed from Equation 13 with the above assumptions for vehicle placement and encroachment angle.

## HYDROPLANING

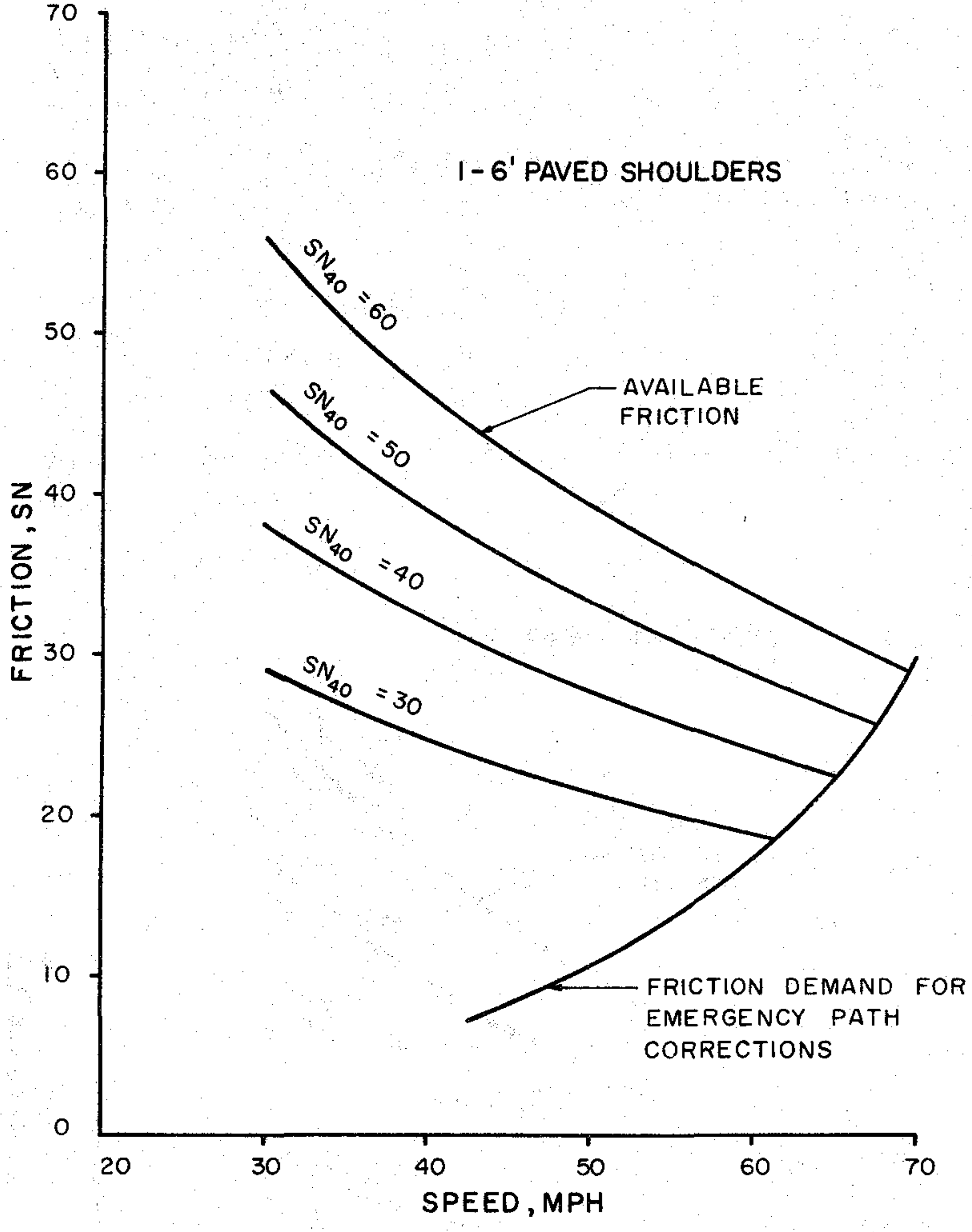
When operating on wet pavements, vehicle steering and braking capabilities are definitely impaired. As the depth of water on a pavement becomes sufficient that the vehicle wheel becomes physically separated from the pavement surface, the vehicle is said to be hydroplaning. The hydroplaning phenomenon is an extremely complex one. Although it becomes significant only when an appreciable depth of water is present on the pavement surface, this condition can be encountered during an exceptionally high-intensity rain or on pavements with poor drainage characteristics. Shallow depressions or wheel ruts in the surface contribute to puddling, and hence provide the potential for hydroplaning.

Wheel spin-down (reduction in wheel speed) is widely used as an indication of hydroplaning. Spin-down indicates a reduction of tire-pavement friction and is caused when the



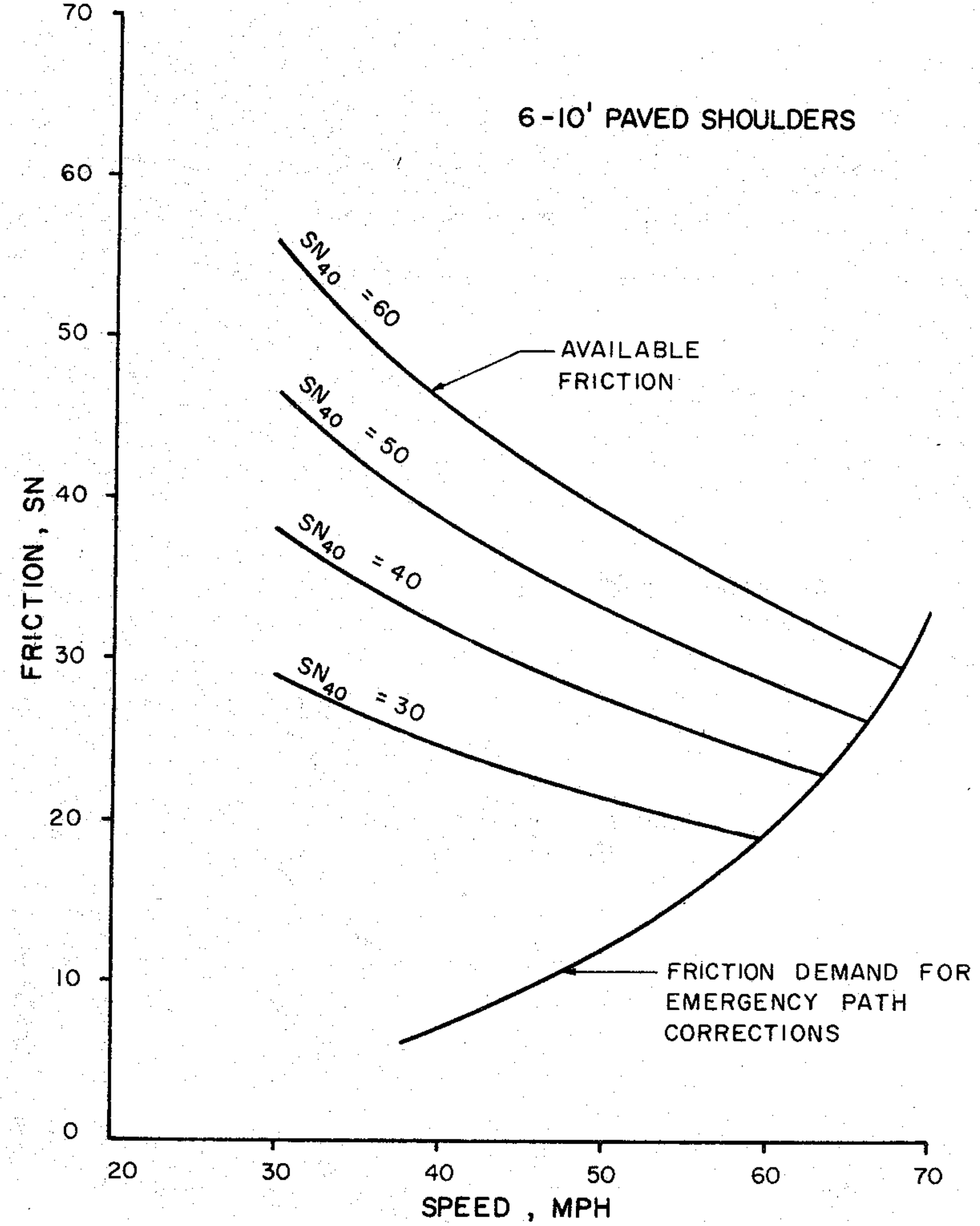
Critical Speed for Emergency Path Corrections (8)
(Two-Lane Highways, No Shoulders)

Figure 10



Critical Speed for Emergency Path Corrections (8)
(Two-Lane Highways, 1-6 ft. Shoulders)

Figure 11



Critical Speed for Emergency Path Corrections (8)
(Two-Lane Highways, 6-10 ft. Shoulders)

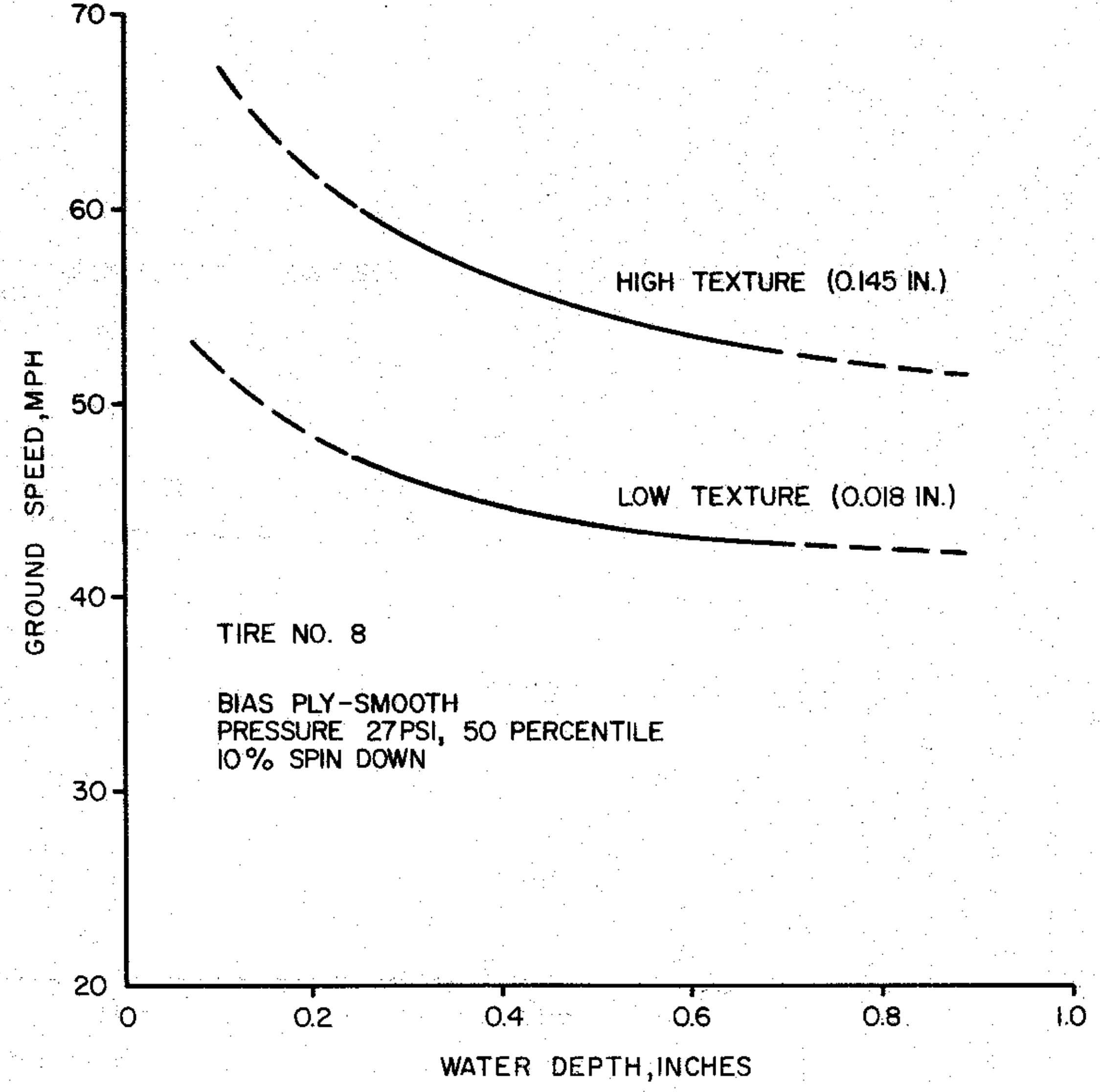
Figure 12

hydrodynamic lift effects combine to create a moment which opposes the normal rolling action of the tire caused by the drag forces (4).

The critical or "total" hydroplaning speed is the speed at which the force caused by hydrodynamic pressure is in equilibrium with the load carried by the tire. However, this speed is not necessarily the speed at which wheel spin-down is initiated--wheel spin-down can initiate at ground speeds considerably less than the critical hydroplaning speed (4). Thus, spin-down should be regarded as a manifestation of hydroplaning, and not as the only criterion to determine the critical hydroplaning speed (4).

Numerous factors influence the hydroplaning potential, the more significant being pavement texture, speed, water depth, tire inflation pressure and tread depth, and wheel load. Martinez et al. (4) considered these influencing factors on a portland cement concrete and a bituminous pavement. The significant findings are summarized here.

Pavement texture significantly influences partial hydroplaning speed (as indicated by 10 percent spin-down) as shown in Figure 13. Martinez found that a high macrotexture (bituminous surface treatment with rounded river gravel) pavement required a considerably higher ground speed to cause spin-down than a low macrotexture pavement (concrete, burlap drag). A 13-mph increase in critical speed was indicated using a smooth bias-ply tire at a water depth of 0.25 inches when the macrotexture was increased from 0.018 to 0.145 inch (silicone putty texture determination). This difference apparently decreases as water depth increases, according to Martinez.



Effect of Pavement Texture on Hydroplaning (4)

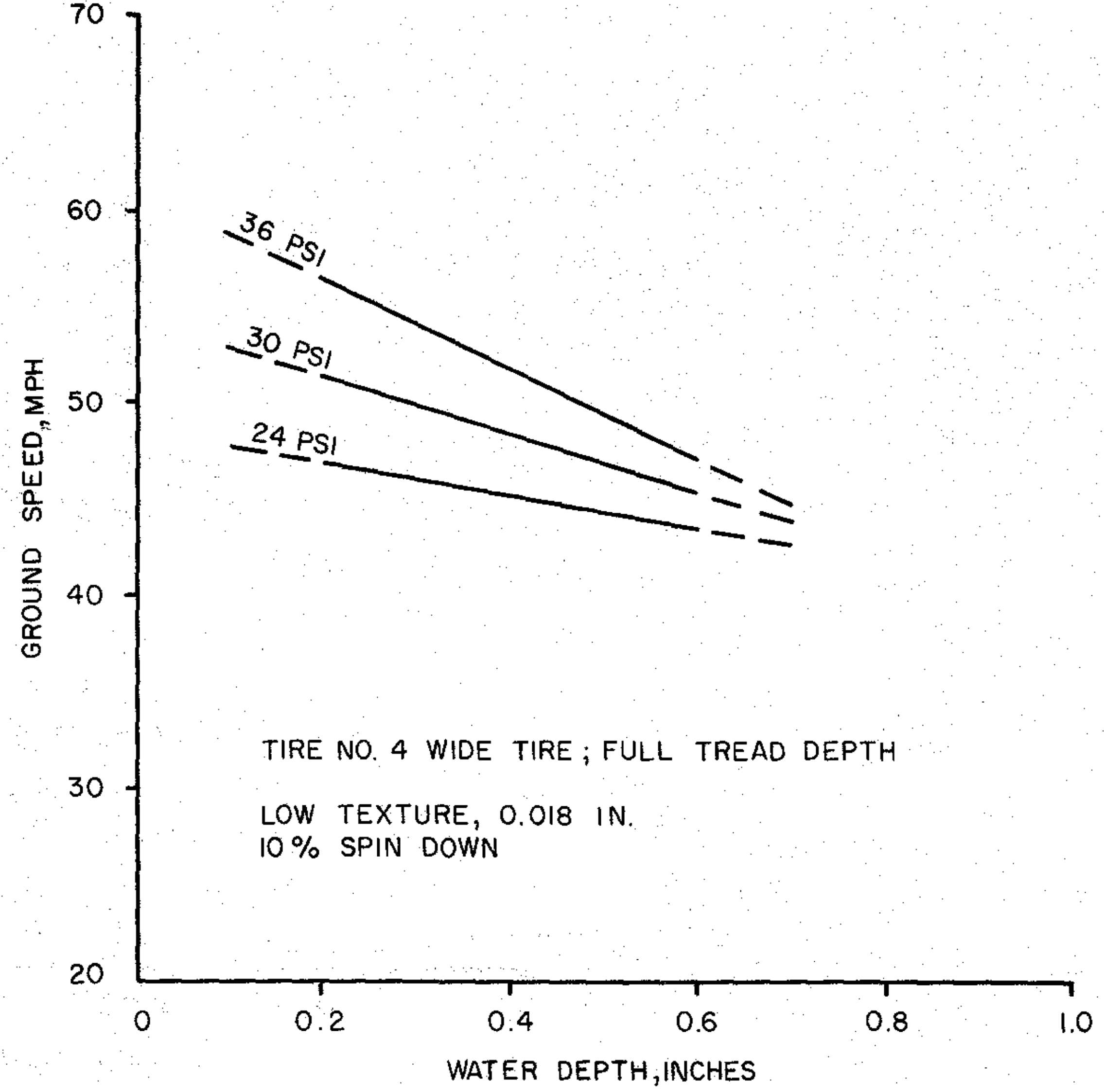
Figure 13

The effect of tire pressure on hydroplaning speed is illustrated by Figure 14. The range of tire pressures from 24 to 36 psi comprise approximately 70 percent of the range observed in a study of over 500 wet pavement accidents in Texas. (10) Figure 14 reveals that the change in critical speed is decreased as water depth increases above about 0.2 inch, and that tire pressure exerts less influence on the hydroplaning speed as the water depth increases. Martinez (4) reported that decreasing the tire inflation pressure normally lowered the ground speed at which a certain amount of spin-down occurred. Figure 14 shows that at a water depth of 0.1 inch, the critical speed was decreased approximately 10 mph as the tire pressure was decreased from 36 to 24 psi. This difference becomes much smaller at greater water depths.

Figure 15 illustrates the effect of three different tires on critical speed. The differences in critical speed between the tires increase as water depth increases. This is in contrast to the effects of tire pressure and pavement texture. It is notable that the full-tread wide tire curve lies between the bias-ply smooth and bias-ply full tread tire.

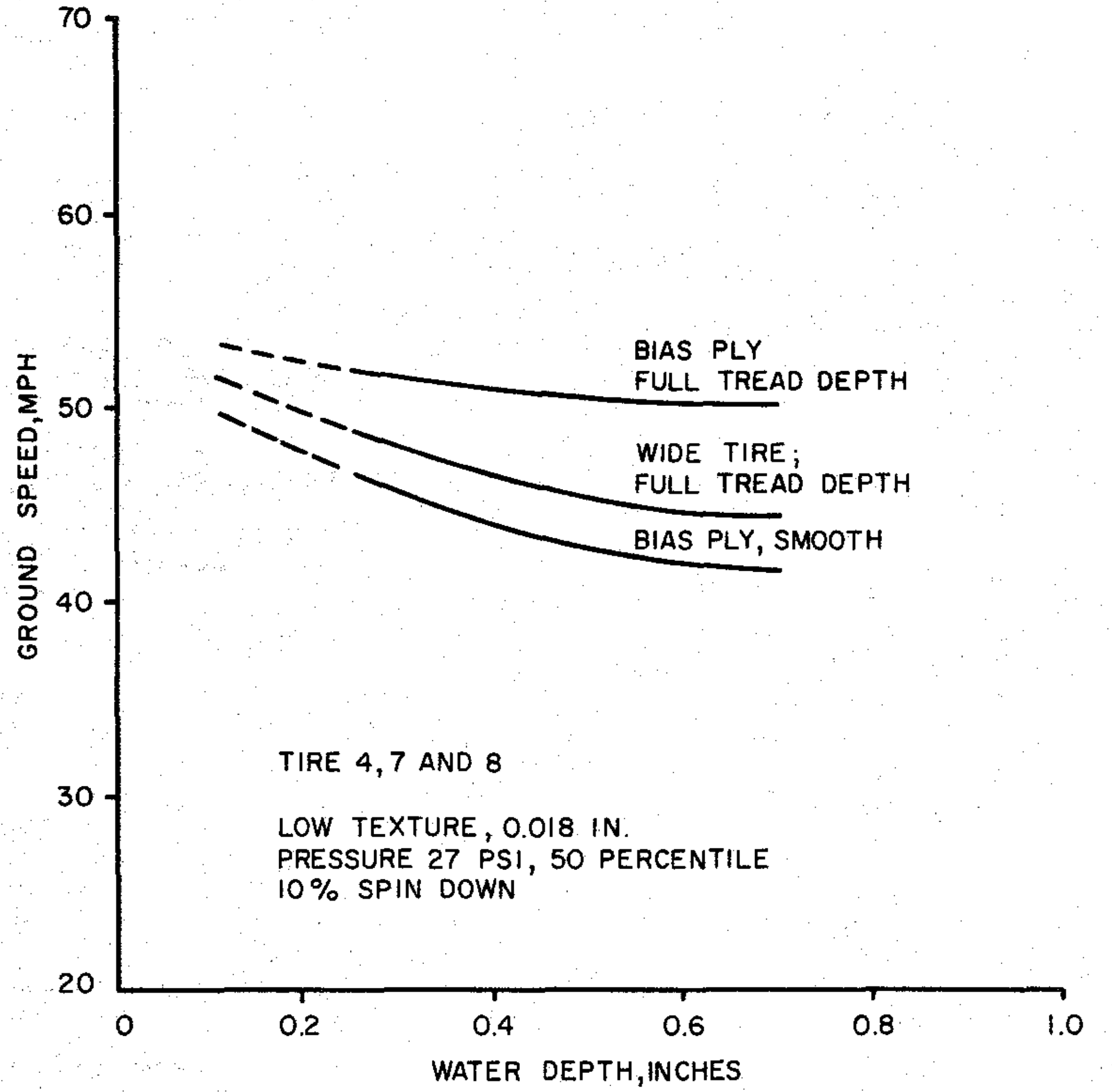
In regard to wheel load, Martinez concluded that the ground speed at which spin-down is initiated is raised by increasing the wheel load vehicle maintaining the same tire inflation pressure for a smooth tire. The reverse occurs for a full-tread depth tire.

Although no single critical speed is appropriate for the range of pavement, tire pressure, and tire parameters investigated,



Effect of Tire Inflation Pressure on Hydroplaning (4)

Figure 14



Effect of Tire Tread on Hydroplaning (4)

Figure 15

it is obvious that partial hydroplaning and thus some loss of vehicle control results at speeds significantly below the speed limit on Texas major rural highways. No critical speeds less than 40 mph were found. The approximate median value for all parameters investigated resulted in a 50-mph critical speed. This speed could be increased by providing a high surface macrotexture. It is suggested that critical wet weather speed be determined from Figure 16.

## COMBINED MANEUVERS

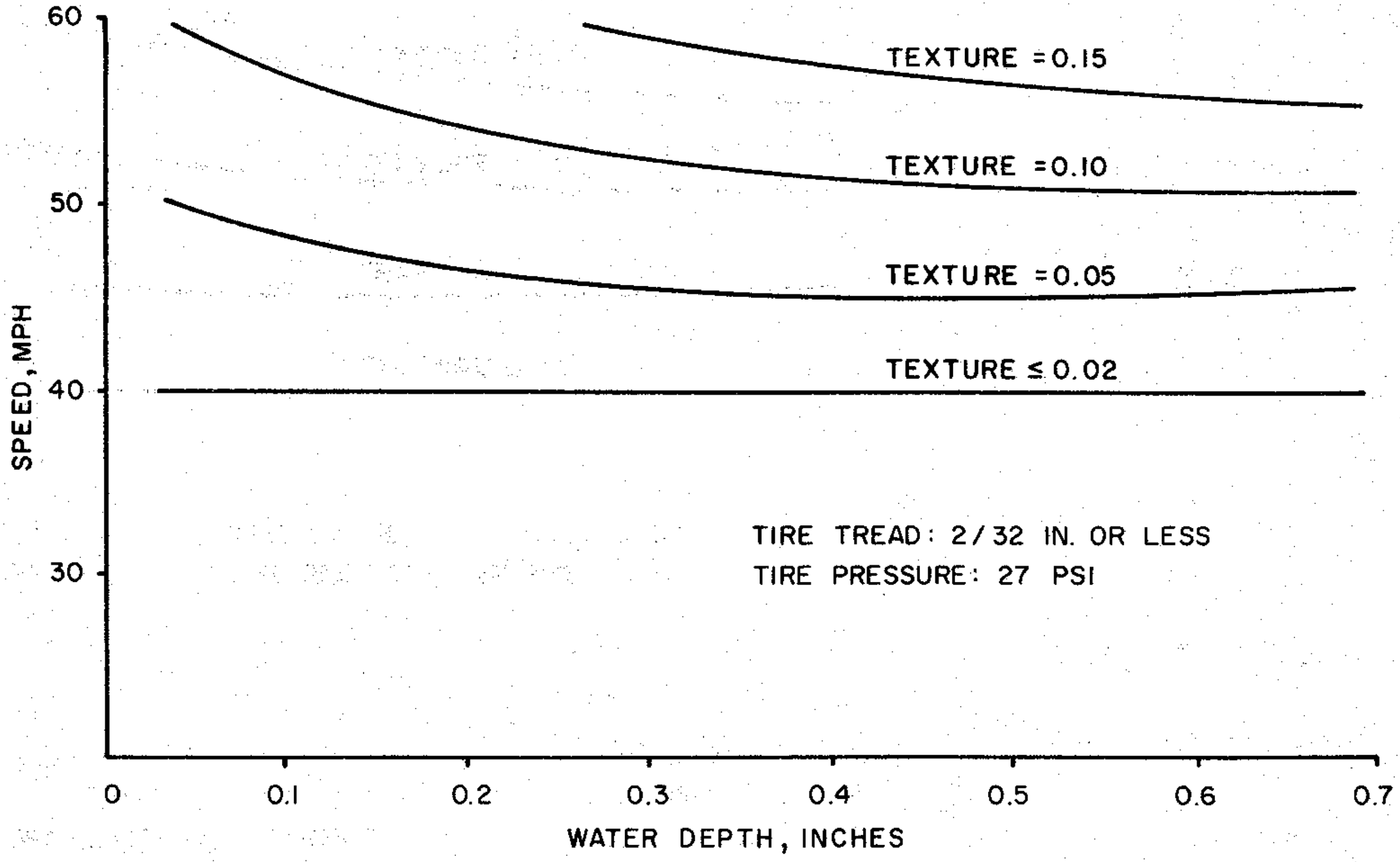
Many common maneuvers include some combination of acceleration, braking, and cornering. The total friction demand may be determined by vector summation of the friction demand for the individual maneuvers. The following example illustrates the manner in which the critical speed may be determined for a combination maneuver.

### Example 1: Critical Speed for Combined Maneuvers

This example illustrates the procedure to determine the critical speed for a maneuver involving combined braking and cornering such as might be experienced at an exit ramp to a stop-controlled service road.

Given: Engineering studies revealed the following site characteristics:

1. Available friction, FN = 30.
2. Available stopping sight distance, SD = 400 ft.
3. Ramp contains spiral transition curve to a 20-degree maximum curvature with no superelevation.



Critical Hydroplaning Speed Imposed by Water Depth and Pavement Texture (4)

Figure 16

Procedure:

1. Make an initial assumption of critical speed. $V_o = 30$ mph.
2. From Figure 7 (Use Figure 8 for an abrupt transition.) and the friction demand curves, determine the friction number demand for cornering, $FN_c$, using the assumed speed, $V_o$. As shown by the dashed line in Figure 7, $FN_c = 22$.
3. From Figure 6, determine the friction number demand for stopping, $FN_s$, using the assumed speed, $V_o$. As shown by the dashed line in Figure 6, $FN_s = 10$.
4. Compute the total friction number demand for the combined maneuver, $FN_t$. The total friction demand is the vector sum of the cornering demand, $FN_c$, and the stopping demand, $FN_s$.

$$FN_t = \sqrt{FN_c^{\,2} + FN_s^{\,2}}$$

$$= \sqrt{(22)^2 + (10)^2}$$

$$= 24.2$$

5. Since $FN_c$, $FN_s$, and hence, $FN_t$, are dependent on the assumed speed, the resultant interaction point (point having coordinates $V_o$, $FN_t$) must be located in Figure 5. If the point lies above the available friction curve applicable to the site (in this case, the $SN_{40} = 30$ curve), a lower initial speed, $V_o$, must be assumed, and the above process (Steps 1 through 4) repeated. Similarly, if the point lies below the applicable available friction curve, a higher speed, $V_o$, must be assumed, and the process repeated. The critical speed (the speed at which the point falls on the applicable SN-versus-speed curve) may be closely approximated in two or three trials.

6. Plotting the interaction point having coordinates $V_o = 30$ and $FN_t = 24.2$ on Figure 5 reveals that the point lies slightly below the applicable $SN_{40} = 30$ curve (Point A, Figure 5). Therefore, a higher speed, $V_o = 35$ mph was assumed, and the process repeated. For $V_o = 35$ mph, $FN_c = 30$ (Figure 7), $FN_s = 15$ (Figure 6), and $FN_t = 33.5$. The interaction point (coordinates 35, 33.5) is plotted as Point B in Figure 5 which lies slightly above the $SN_{40} = 30$ curve. A

straight line between Points A and B indicates a critical speed for the combination maneuver of approximately 32 mph (speed at Point C).

# III. WET WEATHER SPEED ZONING

In many instances, the safe wet weather speed must be less than the existing 70-mph state-wide posted speed where the available friction simply does not provide the capability of performing certain maneuvers at 70 mph. Thus, if speed reduction is the single criterion, the problem is one of establishing, at these points, a *reasonable* wet weather speed that is compatible with available friction.

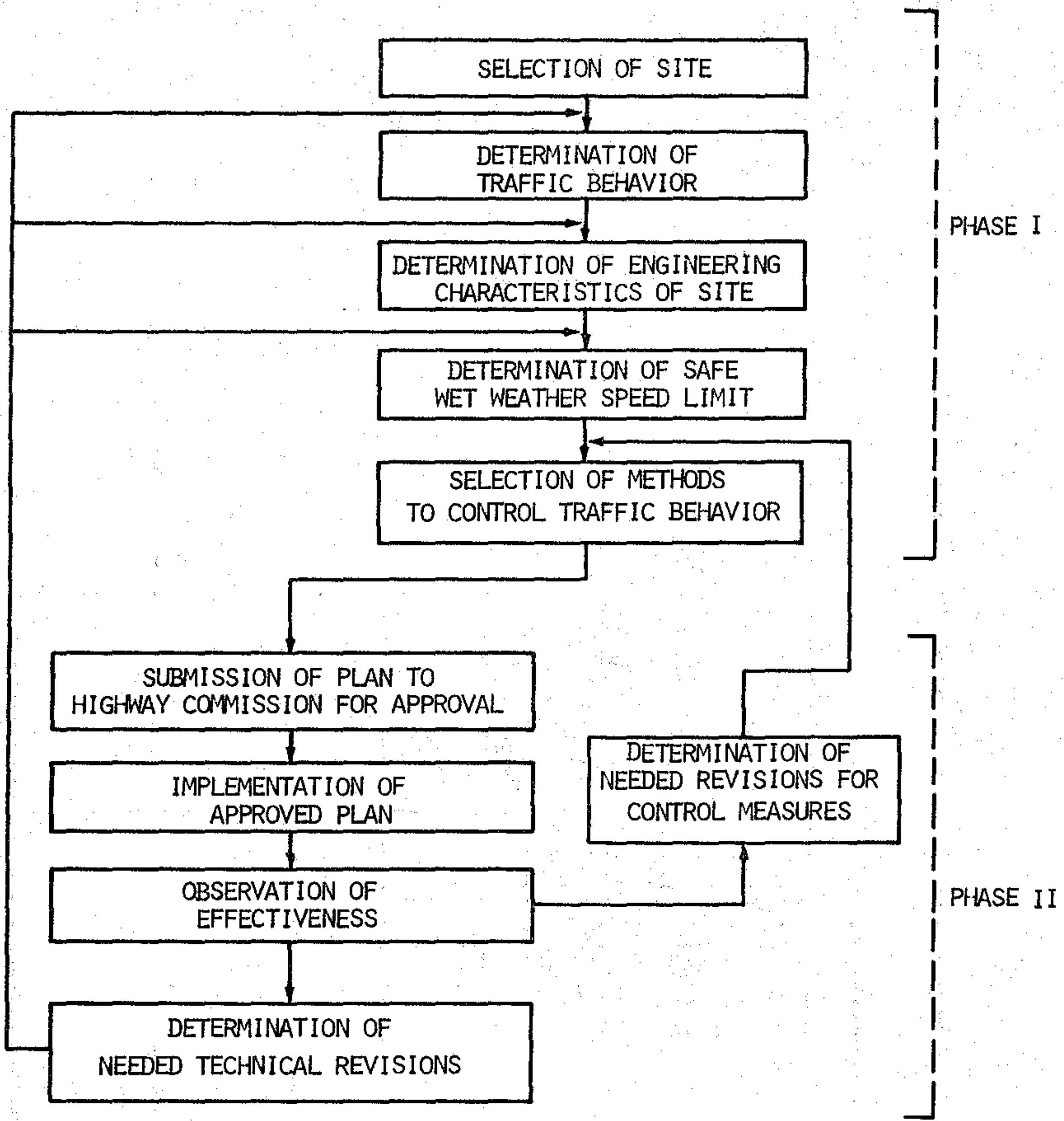
Wet weather speed limits may be implemented by two means: by introduction of a state-wide wet weather speed limit, or through speed zoning at selected sites. Although introduction of a state-wide wet weather speed limit would probably represent the most expedient attempt to reduce traffic operating speed during inclement weather, it offers one distinct disadvantage: the speed limit on all highways would be dictated by the safe wet weather speed on the lower quality highways. Thus, under blanket speed control, the level of service and vehicle speed would be reduced unnecessarily on many of the newer highways that provide surfaces and geometrics less susceptible to skidding.

The primary advantage of wet weather speed zoning at selected sites is that it offers a method to alleviate the most hazardous locations (those which exhibit a history of skid-related accidents) on a priority basis. Also, although allowable speeds can be predicted with some confidence for several individual situations, additional field experience must be obtained to permit confident estimates of safe wet weather speeds when all contributing factors act together. Use of wet weather speed zoning at selected sites on an "experimental" basis will permit evaluation of the designated safe speed and also the effect upon and acceptance by the driving public as well as an evaluation of the proposed method.

The Texas Law governing the speed of vehicles gives the State Highway Commission the power and authority to alter the general speed limits on highways under its jurisdiction. This power is granted subject to a finding of need by an engineering and traffic investigation. Altering the general state-wide speed limits to fit existing traffic and physical conditions of the highway constitutes the basic principle of speed zoning. In this respect, establishment of wet weather speed limits at selected sites would become a logical extension of the current speed zoning principles.

## IMPLEMENTATION PROCESS

Figure 17 outlines a sequence of events that is considered necessary to initiate wet weather speed zoning at selected sites in Texas. The events shown involve both pre-control and post-control investigations, but it is believed that this full-cycle effort is indicated for the first sites so controlled. The sequence is subdivided into two phases. Phase I includes the engineering aspects concerning site selection, determination of traffic and engineering characteristics, and hence, the safe wet weather speed limit. This report deals primarily with this phase. Phase II includes the administrative procedure by which the program may be implemented and



Process Schedule to Implement Wet Weather
Speed Zoning at Selected Sites

Figure 17

also evaluation of the effectiveness of the proposed method. It is anticipated that the program will be implemented through accepted speed zoning practices by the Texas Highway Department. Evaluation procedures will be established in cooperation with the Texas Highway Department. Phase II is not discussed in detail in this report.

The process outlined in this report for determination of the safe wet weather speed limit involves equating the available friction at the selected site to friction demand for traffic operational maneuvers expected at that site. Therefore, certain engineering characteristics of the site must be known from which the available friction may be determined. Similarly, certain traffic operating characteristics must be determined. A critical speed is determined for each expected maneuver. The speed limit will be governed by the expected maneuver producing the lowest critical speed.

## SITE SELECTION CRITERIA

The success of the initial phase of wet weather speed zoning, from the aspect of engineering evaluation, depends to a large degree on the particular sites selected. Texas is fortunate in that a continuing skid resistance evaluation program has been in progress for several years, resulting in an extensive history of pavement friction characteristics throughout the state. Potentially slick pavement sections have been observed and in most cases have received a deslicking treatment. In addition, extensive accident records are maintained. These factors will greatly assist site selection for wet weather speed zoning. With the current emphasis toward improving frictional capability, there is an increasing awareness of areas needing improvement throughout the districts. In many cases, sites are known but sufficient funds are not available. Signing should help in these areas:

The following criteria are suggested for site selection:

1. Any Control-Section exhibiting two or less wet weather accidents annually should not be considered.
2. All Control-Sections exhibiting 20 or more wet weather accidents annually should be considered.
3. For Control-Sections having 3 to 19 wet weather accidents annually, the Control-Section or sites within the Control-Section should be considered if:

   a. $\frac{\text{Daily Vehicle Miles}}{\text{No. of Wet Weather Accidents}} \leq 3{,}000$

   b. The Control-Section length is 0.30-mile or more.

The above criteria are based on studies of excessive <u>wet weather</u> accident rates, but the criteria are intended only as a guide. Locations exist where no single criteria is satisfied but where exceptional symptoms of skid-related problems exist. For example, a newly constructed facility or a recently modified section may exhibit an unusual number of skidding accidents, yet the changed conditions have not been in existence long enough to warrant installation of wet weather speed limits under the other criteria. Special locations, many having unreported accidents, can often be identified by Texas Highway Department and Department of Public Safety personnel who have a daily working knowledge of the highways in their District and are aware of proposed geometric improvements.

## ENGINEERING CHARACTERISTICS OF SITE

The engineering characteristics that are of primary importance to the selection of appropriate speeds for a given site are directly dependent on the maneuvers which vehicles may be expected to execute while traveling in the site locale, the basic maneuvers being acceleration, braking, and cornering. The performance of desired maneuvers is dependent upon the existence of tire-road surface friction. Therefore, the primary engineering characteristics that must be considered are those that determine the available friction and those that influence the demand for friction. The engineering characteristics and ways by which they may be determined are summarized in Table 2.

## TRAFFIC OPERATING CHARACTERISTICS

A knowledge of traffic behavior through the site locale is required under dry and wet conditions, and before and after the introduction of speed control or other corrective measures. The nature of the maneuvers and the speeds at which they are performed under the two environmental conditions dictate the friction demand

TABLE 2

ENGINEERING CHARACTERISTICS OF SITE

| CHARACTERISTIC | METHOD OF ATTAINMENT |
|---|---|
| A. Pavement Characteristics | |
| 1. Texture measurements | On-site determination<br>(a) sand patch method<br>(b) silicone putty method<br>(c) profilograph |
| 2. SN Values (including differential SN values between normal pavement surface and wheel paths, if any) | On-site determination<br>(a) skid trailer measurements at varied speeds and develop friction-speed relationships |
| 3. Presence of Rutting | On-site determination<br>(a) observation<br>(b) string-line measurement<br>(c) width and location of wheel path ruts should be determined |
| 4. Puddling | On-site determination<br>(a) flood pavement surface and observe<br>(b) observation during or immediately after rain<br>(c) observe pattern (isolated areas on pavement, repeated depressions along surface, etc.) |
| 5. Drainage Length (water drainage distance measured along drainage path between outer edges of pavement surface) | On-site determination |

TABLE 2 (CONTINUED)

ENGINEERING CHARACTERISTICS OF SITE

| CHARACTERISTIC | METHOD OF ATTAINMENT |
|---|---|
| B. Cross-Section Characteristics | |
| 1. Pavement Cross Slope | On-site investigation supplemented by construction plans |
| 2. Superelevation | On-site investigation supplemented by construction plans |
| 3. Number and Width of Traffic Lanes | On-site investigation supplemented by construction plans |
| 4. Shoulder Type and Width | On-site investigation supplemented by construction plans |
| C. Alignment and Sight Distance | |
| 1. Degree of Horizontal Curve | On-site investigation supplemented by construction plans |
| 2. Vertical Curve Geometry | On-site investigation supplemented by construction plans |
| 3. Transition of P.C. and and P.T. | On-site investigation supplemented by construction plans |
| 4. Available Sight Distance | On-site investigation |
| 5. Proximity of Intersections | On-site investigation supplemented by construction plans |

at the tire-pavement interface, and must be used as input in establishing the critical safe speed for the available friction. The effectiveness of the corrective action taken at the locale can be assessed only by evaluation of traffic behavior observed after installation.

Certain measures of traffic behavior are fundamental to evaluation of the vehicle-roadway needs. The measures required and methods by which they may be obtained are presented in Table 3.

## DESIGN PROCESS TO DETERMINE WET WEATHER SPEED LIMIT

The design process may be accomplished by the following procedure:

1. Determine engineering characteristics of the site (Reference Table 2).
2. Identify the expected traffic operating characteristics and expected maneuvers (Reference Table 3).
3. Determine the available friction at the site. The available friction, including the effects of speed, may be approximated by the methods listed:
    a. by conducting standard skid trailer measurements at 40 mph and determining the relationship of SN and speed from Figure 5.

TABLE 3

TRAFFIC OPERATING CHARACTERISTICS

| CHARACTERISTIC | METHOD OF ATTAINMENT |
|---|---|
| A. Dry Pavement Characteristics | |
| 1. Speed throughout site | Radar spot speed sampling |
| 2. Speed transition upstream from site | Radar spot speed sampling |
| 3. Speed transition downstream from site | Radar spot speed sampling |
| 4. Maneuvers performed | On-site observation |
| 5. Point at which braking or other maneuver occurs | On-site observation (brake light study) |
| B. Wet Pavement Characteristics | |
| Same characteristics as above. Changes in speed, point of maneuver initiation, transition points, etc., can be determined by comparison of dry and wet characteristics. | Same as above |

   b. by conducting tests with a skid trailer at 20, 40 and 60 mph using an external watering system such as a water truck and developing friction-speed relationships.

4. Determine the critical speed for the expected maneuvers from the applicable speed-friction relationships shown in Figures 5 through 16.
   a. stopping maneuvers (Figure 6)
   b. cornering maneuvers (Figure 7 or 8)
   c. passing maneuver (Figure 9)
   d. emergency path correction maneuvers (Figures 10 through 12)
   e. hydroplaning (Figure 16)
5. If combination maneuvers are expected at a site, determine the critical speed for the combined maneuver by the procedure discussed previously in this report.
6. Select the lowest critical speed determined from Steps 4 or 5. The wet weather speed limit is established as this value. The posted speed would be the wet weather speed rounded to the nearest 5-mph increment.

## EXAMPLES OF WET WEATHER SPEED DETERMINATION

Several examples are presented to illustrate the design process for establishing the wet weather speed limits at sites exhibiting different engineering and expected traffic operating characteristics.

### Example 2: Wet Weather Speed Limit on Tangent Section

The following site characteristics are assumed for illustrative purposes:

1. $SN_{40} = 40$.
2. Sight distance, SD = 700 ft.
3. Level tangent highway section having no paved shoulders.
4. Pavement texture = 0.05.
5. Pavement exhibits good drainage with no evidence of rutting or ponding.

Procedure:

1. Identify the traffic maneuvers that would be expected at the site. The expected maneuvers would include:
   a. stopping maneuvers
   b. passing maneuvers
   c. emergency correction maneuvers
2. Since the site is a level tangent section, cornering or combination maneuvers would not

be expected. Therefore, critical speeds for these maneuvers would not be applicable at this site. Similarly, since there is no evidence of rutting or ponding, and good drainage is provided, critical speed to produce hydroplaning is not applicable at this site.

3. From Figure 6, the critical speed for a stopping maneuver ($SN_{40}$ = 40, SD = 700 ft) is 59 mph.
4. From Figure 9, the critical speed for a passing maneuver ($SN_{40}$ = 40) is 51 mph.
5. From Figure 10, the critical speed for an emergency path correction ($SN_{40}$ = 40, no paved shoulders) is 52 mph.
6. The lowest critical speed from Steps 3 through 5 is 51 mph, governed by friction demand for a passing maneuver.
7. Rounding off to the nearest 5-mph increment, the wet weather speed limit would be 50 mph.

Example 3: Wet Weather Speed Limit on Horizontal Curve

The following site characteristics are assumed for illustrative purposes:

1. $SN_{40} = 35$.
2. Horizontal curvature = 3 degrees with an abrupt transition from tangent section to the circular curve (that is, no spiral was used at the transition).
3. Superelevation, e, = 0.05 percent.
4. Seal course pavement surface is slightly flushed in the wheel paths. The texture in the wheel paths is 0.020 as compared to 0.065 at other locations. The flushed wheel path is considerably wider throughout the curve than on the tangent approach.
5. The pavement grade is 0.4 percent.
6. The pavement surface is slightly rutted in transition area from normal crown to superelevated section. Based on stringline measurements of rut depth, observation of a flat area in the superelevation transition, and the differential texture between the wheel path and surrounding surface, expected water depth is approximately 0.160 inches.
7. Sight distance, SD, is in excess of 1000 ft.

Procedure:

1. Identify the traffic maneuvers that would be expected at the site. These would include:

   a. passing maneuvers
   b. cornering maneuvers
2. Since appreciable water depths are expected and rutting is evident, the critical speed for hydroplaning should be determined.
3. Since adequate sight distance is available, stopping maneuvers are not critical.
4. From Figure 8, the critical speed for cornering ($SN_{40}$ = 35, D = 3°, e = 0.05), is 68 mph.
5. From Figure 16, the critical speed for hydroplaning (texture = 0.02, water depth = 0.160 in.) is 40 mph.
6. From Figure 9, the critical speed for a passing maneuver ($SN_{40}$ = 35) is 45 mph.
7. The lowest critical speed determined in Steps 4 through 6 above is 40 mph, governed by hydroplaning.
8. The wet weather speed limit would be 40 mph.

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