WET-WEATHER SPEED ZONING

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Speed is a significant factor in many wet-weather skidding accidents. Establishing wet-weather speed limits at certain locations, therefore, may be one way to reduce these accidents. This paper assimilates findings from various 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 as speed increases. Because the speeds in question are usually higher than 40 mph, the standard speed at which the skid number is determined, the change in available friction with respect to speed must be considered. Methods to accomplish this are discussed. The paper presents curves to determine, for various pavement frictions, the critical speed for hydroplaning, stopping maneuvers, cornering maneuvers, passing maneuvers, emergency path-correction maneuvers, and combined maneuvers. A design process to establish the wet-weather speed limit is discussed, and examples are presented to illustrate the use of the curves.

•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. Unfortunately, the degree of speed reduction may not be readily apparent.

Because the potential for skidding is so speed-sensitive, establishing 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 4 basic elements: vehicle, roadway, driver, and 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 recently completed investigated the relation 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 rel-

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atively new research targets. Although the solution to the problem cannot be considered complete, much information exists, and a significant portion of it can be implemented at this time.

As a preliminary step toward reducing the toll of skidding accidents, the Texas legislature placed on 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. According to the legislation, the establishment of wet-weather speed limits should be based on "an engineering and traffic investigation." A study (6) was recently completed by the Texas Transportation Institute having as its primary objective the assimilation of 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.

This paper presents the significant findings of that study. A basis is given for equating the available friction at a site (pavement skid resistance) to the expected friction demand for selected traffic maneuvers including hydroplaning, stopping maneuvers, cornering maneuvers, and passing maneuvers. Also discussed is a design process to establish the wet-weather speed limit.

FACTORS AFFECTING VEHICLE SKIDS

Relation of Friction Availability and Demand

The performance of desired maneuvers is dependent on the existence of tire-road surface friction. 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 relation between friction demand and friction availability is shown schematically in Figure 1 (7). 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.

Available Friction

A widely accepted measure of pavement friction is the skid number (SN) determined by the locked-wheel skid trailer traveling at 40 mph and using an internal watering system (ASTM E 274-70). In this report, SN (including the effect of speed) is assumed to be equivalent to available friction. Other studies (3, 7, 8) 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 4 wheels on a vehicle. Consequently, the SN is assumed to provide a reasonable approximation of the average friction available to the vehicle.

Friction measurement by this method, however, is obtained at only one speed, 40 mph. To reiterate, friction decreases with increased speed. Because the speeds in question here are usually higher than 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 3 methods:

1. By conducting standard skid-trailer measurements at 20, 40, and 60 mph and determining the speed and SN relation graphically;
2. By conducting the 20-, 40-, and 60-mph skid measurement with an external watering system (3); and
3. By conducting standard 40-mph skid measurements and determining the applicable SN at other speeds by using curves similar to those shown in Figure 2.

Using the input factors of pavement surface texture, water depth, vehicle speed, and tire tread depth from Gallaway's studies (5, 12), the Texas Highway Department developed an equation to predict the available friction on wet pavement (6). Also, Gallaway (5) developed an equation to determine water depth on the pavement as a function of texture, drainage length, rainfall intensity, and cross slope. Nomographs have been developed to solve these 2 complex equations for various parameters. So that the determination of available friction can be simplified for operational purposes, representative values have been selected for tire tread depth, pavement texture, water depth, and rainfall intensity. For a texture of 0.050 in. (measured by the putty method), tire tread depth of $^2/_{32}$ in., and average 85th percentile rainfall intensity of 0.14 in./hour, the speed-SN relations developed by the Texas Highway Department are shown in Figure 2 (6). Similar curves may be developed from the basic equations for any particular values of the individual factors.

The available friction curves shown in Figure 2 were developed from skid data obtained under an external watering system (rain machine) rather than under the standard ASTM internal watering system. These curves more clearly reflect pavement characteristics under actual wet-weather conditions. The available friction curves are superimposed on the friction demand curves in the remainder of this paper to permit determination of critical speed.

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 (9) that the minimum acceptable design will provide at least sufficient sight distance to allow a driver to safely stop his vehicle before he hits an obstacle in his path.

Rearranging the basic stopping distance equation and substituting a 2.5-sec perception-reaction time gives the following demand friction in stopping a vehicle within the available sight distance (7):

$$FN_s = \frac{V^2}{0.3\,(d - 3.67V)} \quad (1)$$

where

FN_s = demand friction number for stopping;
d = available sight distance, ft; and
V = vehicle speed, mph.

Figure 3 shows the relation of available friction and friction demand for stopping maneuvers.

Cornering Maneuvers

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:

$$e + f = \frac{V^2}{15R} \quad (2)$$

where

e = superelevation rate, ft/ft;
f = coefficient of friction;
V = vehicle speed, mph; and
R = curve radius, ft.

Figure 1. Relation between friction demand and pavement skid resistance.

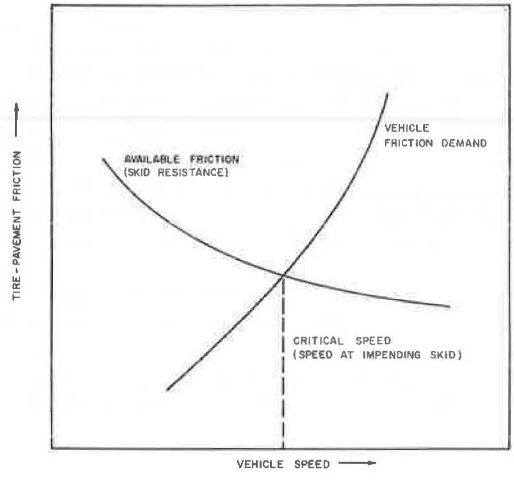


Figure 2. Available friction as predicted by skid number.

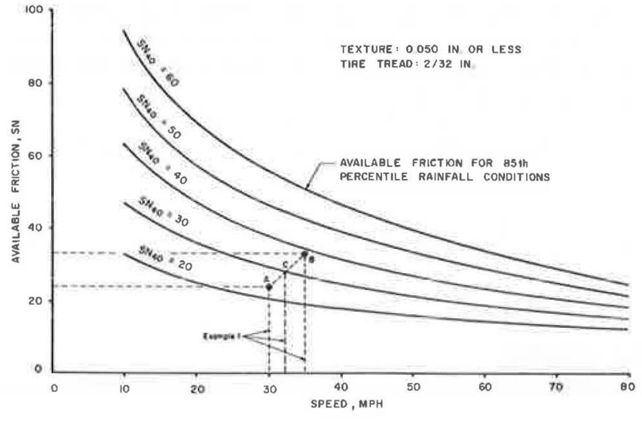
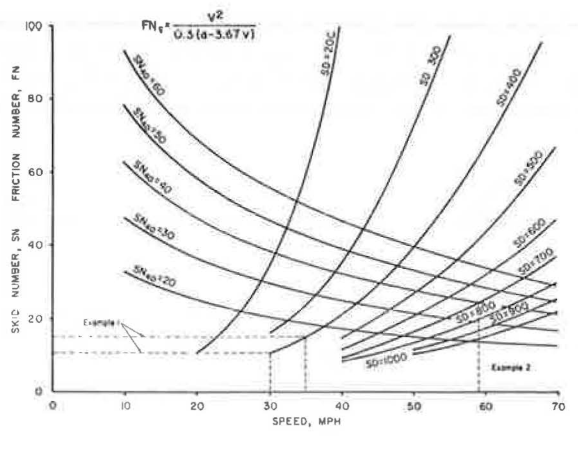


Figure 3. Critical speed for emergency stop imposed by sight distance and available friction.



There is the provision that friction, f, be approximated by skid number and considered to be speed dependent. The friction demand for cornering, FN_c, may then be described by

$$\frac{FN_c}{100} + e = \frac{V^2}{15R} \tag{3}$$

Figure 4 shows the lateral friction demand during traversal of nonsuperelevated highway curves for degrees of curvature from 0.5 to 20 deg (1). 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.

The curves shown in Figure 4 are developed on a 0-superelevation basis to which appropriate correction factors may be easily applied for a desired superelevation rate. To include the effect of superelevation, the given demand curve, FN_c, is translated vertically by the amount of the superelevation expressed in percent. For example, if a 15-deg curve contained 0.05 positive superelevation, the 15-deg curve would be lowered 5 units of FN as shown by the dashed curve in Figure 4. Similarly, the curve would be translated upward an equal amount if the superelevation were negative.

The critical speeds determined from curves shown in Figure 4 represent allowable speeds provided the vehicle smoothly traverses the path of the highway curve. Therefore, Figure 4 should be used for spiraled transitions or at locations within a curve.

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. Results of these studies indicated that the radius of path followed could be expressed by

$$R_v = 0.524R + 268 \tag{4}$$

where

R_v = vehicle path radius, ft; and
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. Because the friction demand at these locations is more stringent, critical speed should be determined on the basis of this minimum radius. When R_v is substituted in Eq. 3, the friction demand for cornering, FN_c, becomes

$$FN_c = \frac{V^2}{0.786R + 40.3} - 100e \tag{5}$$

Figure 5 shows speed-friction relations for various degrees of curvature (1). It is suggested that these curves be used for determination of critical speeds on curves having abrupt transition regions at either end (nonspiraled curves and at ends of curves).

Passing Maneuvers

The passing maneuver may be one of the most critical nonemergency maneuvers performed on a 2-lane highway. Several characteristics combine during the passing maneuver to influence the demand friction: The maneuver is performed at relatively high speeds; the passing vehicle executes both pullout and return maneuvers against negative superelevation due to normal crown; and the maneuver involves combinations of forward and lateral acceleration.

From studies of actual passing maneuvers on 2-lane highways (10), Glennon (2) determined frictional requirements for the critical portion of the passing maneuver based on maximum lateral friction demand. Assuming an e value of -0.02 to represent the adverse pavement cross slope, Glennon developed the following relation for lateral friction demand during the passing (pullout) maneuver:

$$FN_p = \frac{V^2}{220} + 2 \qquad (6)$$

where

FN_p = friction demand number for passing, and
V = vehicle speed, mph.

Based on Kummer and Meyer's (11) relation between forward friction demand and speed for full-throttle acceleration of an American standard automobile, Glennon developed a demand friction-speed relation by using the vector sum of forward and lateral acceleration demand. The demand curve, shown in Figure 6, is based on Glennon's results but does not include his safety margin (2).

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 (7) 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 roadway. Assuming a -0.02 cross slope, Glennon developed the following friction demand for path correction (Fig. 7):

$$f = \frac{V^2 (1 - \cos \theta)}{15 (W - 1.47V \sin \theta)} + 0.02 \qquad (7)$$

where

V = vehicle speed, mph; and
θ = encroachment angle, deg.

Hydroplaning

Numerous factors influence the hydroplaning potential; the more significant are pavement texture, speed, water depth, tire inflation pressure and tread depth, and wheel load. Martinez, Lewis, and Stocker (4) considered these influencing factors on a portland cement concrete and a bituminous pavement.

Although no single critical speed is appropriate for the range of pavement, tire pressure, and tire parameters investigated, it is obvious that partial hydroplaning and thus some loss of vehicle control results at speeds significantly below the speed limit on most major rural highways. No critical speeds lower than 40 mph were found. The approximate median value for all parameters investigated resulted in a 50-mph critical speed, and this speed could be increased by providing a high surface macrotexture. It is suggested that critical wet-weather speed for hydroplaning be determined from curves shown in Figure 8.

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. The maneuver involves combined braking and cornering such as might be experienced at an exit ramp to a stop-controlled service road.

Engineering studies revealed the following site characteristics:

1. Available friction, FN, 30;
2. Available stopping sight distance, SD, 400 ft; and

Figure 4. Critical speed for smooth transition on nonsuperelevated horizontal curves.

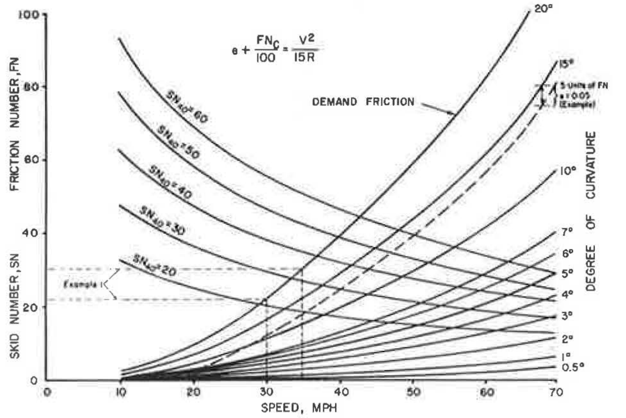


Figure 5. Critical speed for abrupt transition on nonsuperelevated horizontal curves.

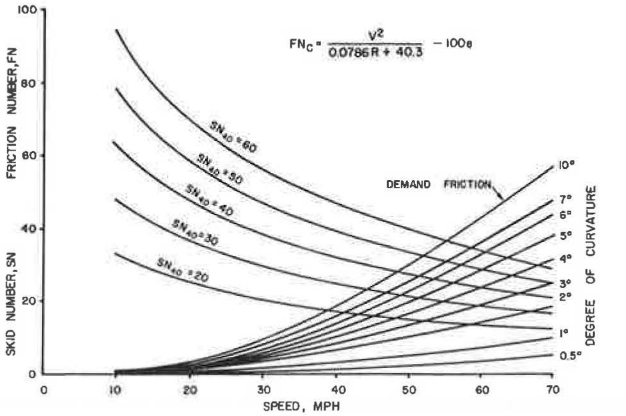


Figure 6. Critical speed for passing maneuvers.

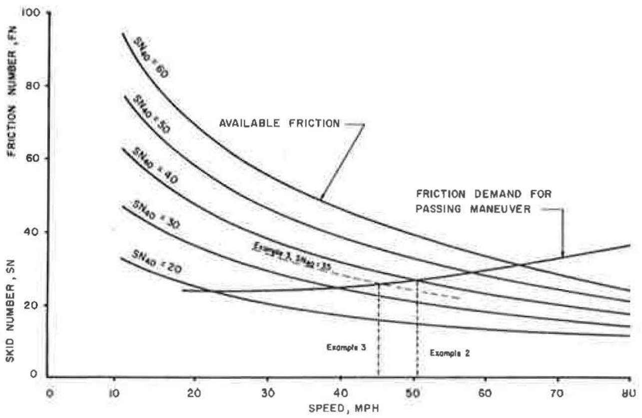


Figure 7. Critical speed for emergency path corrections on 2-lane highway.

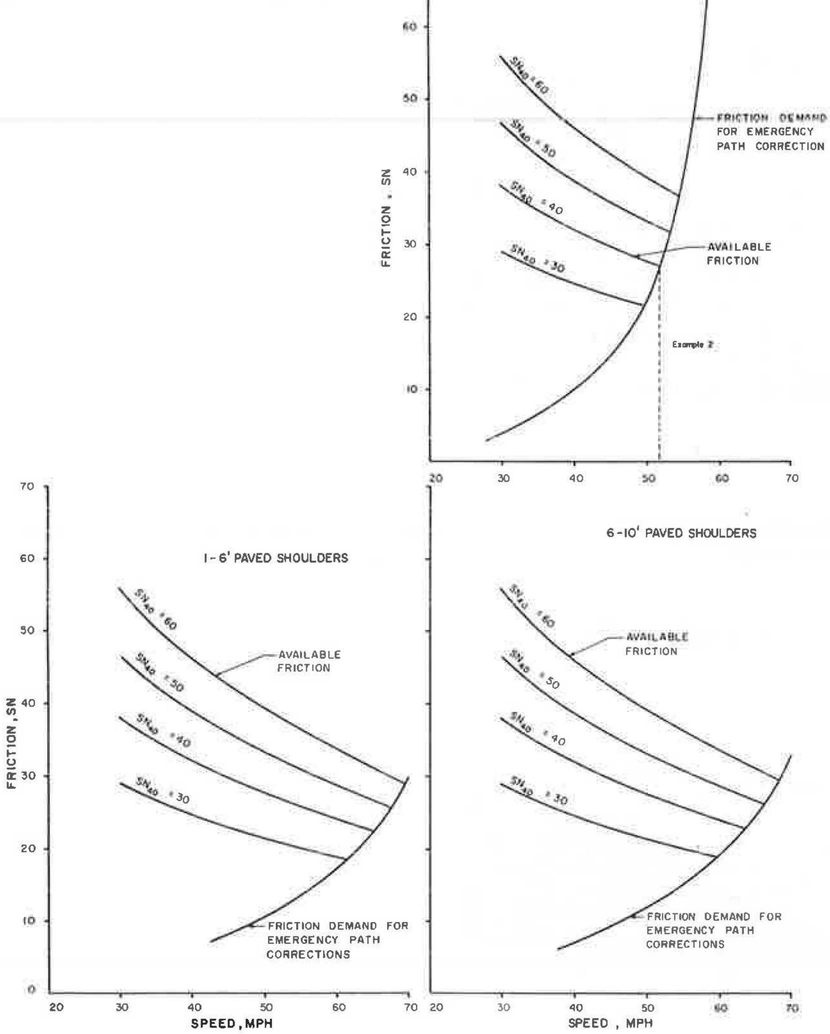
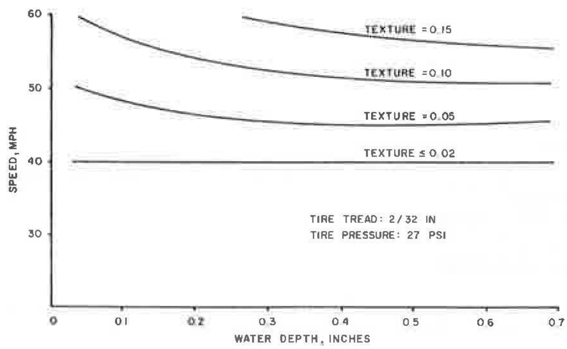


Figure 8. Critical hydroplaning speed imposed by water depth and pavement texture.



3. Spiral transition curve on ramp to a 20-deg maximum curvature with no superelevation.

The procedure is as follows:

1. Make an initial assumption of critical speed, say $V_o = 30$ mph.
2. From Figure 4 (or Figure 5 for abrupt transition) and the friction demand curves, determine the friction number demand for cornering, FN_c, by using the assumed speed, V_o. As shown by the dashed line in Figure 4, $FN_c = 22$.
3. From Figure 3, determine the friction number demand for stopping, FN_s, by using the assumed speed, V_o. As shown by the dashed line in Figure 3, $FN_s = 10$.
4. Compute the total friction demand number 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_2.

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

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

$$= 24.2$$

5. Because 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 2. 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 2 or 3 trials.
6. Plotting the interaction point having coordinates $V_o = 30$ and $FN_t = 24.2$ on Figure 2 reveals that the point lies slightly below the applicable $SN_{40} = 30$ curve (point A, Fig. 2). Therefore, a higher speed, $V_o = 35$ mph was assumed, and the process was repeated. For $V_o = 35$ mph, $FN_c = 30$ (Fig. 4), $FN_s = 15$ (Fig. 3), and $FN_t = 33.5$. The interaction point (coordinates 35, 33.5) is plotted as point B in Figure 2 and 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).

WET-WEATHER SPEED ZONING

In many instances, the safe wet-weather speed must be less than the existing 70-mph statewide 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.

The primary advantage of wet-weather speed zoning at selected sites is that it offers a method to alleviate the most hazardous locations (those that exhibit a history of skid-related accidents) on a priority basis. Although introduction of a statewide 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 lower quality highways. Thus, under blanket speed control, the speed would be reduced unnecessarily on many highways that provide surfaces and geometrics less susceptible to skidding.

The process outlined in the research (6) 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.

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.

Determining Wet-Weather Speed Limit on Tangent Section

The following site characteristics are assumed:

1. SN_{40} = 40;
2. Sight distance, SD = 700 ft;
3. Highway section is level tangent and has no paved shoulders;
4. Pavement texture = 0.05; and
5. Pavement exhibits good drainage with no evidence of rutting or ponding.

The procedure is as follows:

1. Identify the traffic maneuvers (stopping, passing, and emergency correction) that would be expected at the site. (Because 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, because there is no evidence of rutting or ponding and good drainage is provided, critical speed to produce hydroplaning is not applicable at this site.)

2. From Figure 3, the critical speed for a stopping maneuver (SN_{40} = 40, SD = 700 ft) is 59 mph.

3. From Figure 6, the critical speed for a passing maneuver (SN_{40} = 40) is 51 mph.

4. From Figure 7, the critical speed for an emergency path correction (SN_{40} = 40, no paved shoulders) is 52 mph.

5. The lowest critical speed from steps 2, 3, and 4 is 51 mph, governed by friction demand for a passing maneuver.

6. Rounding off to the nearest 5-mph increment, the wet-weather speed limit would be 50 mph.

Determining Wet-Weather Speed Limit on Horizontal Curve

The following site characteristics are assumed:

1. SN_{40} = 35.

2. Horizontal curvature = 3 deg 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 wheelpaths. The texture in the wheelpaths is 0.020 and 0.065 other than in the wheelpaths. The flushed wheelpath 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 string-line measurements of rut depth, observations of a flat area in the superelevation transition, and the differential texture between the wheelpath and surrounding surface, expected water depth is approximately 0.160 in.

7. Sight distance, SD, is more than 1,000 ft.

The procedure is as follows:

1. Identify the traffic maneuvers (passing and cornering) that would be expected at the site.

2. Because appreciable water depths are expected and rutting is evident, the critical speed for hydroplaning should be determined.

3. Because adequate sight distance is available, stopping maneuvers are not critical.

4. From Figure 5, the critical speed for cornering (SN_{40} = 35, D = 3 deg, e = 0.05) is more than 70 mph.

5. From Figure 10, the critical speed for hydroplaning (texture = 0.02, water depth = 0.160 in.) is 40 mph.

6. From Figure 6, the critical speed for a passing maneuver (SN_{40} = 35) is 45 mph.

7. The lowest critical speed determined in steps 4 through 6 is 40 mph, governed by hydroplaning.

8. The wet-weather speed limit would be 40 mph.

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