PAVEMENT SKID-RESISTANCE REQUIREMENTS

Duane F. Dunlap, Paul S. Fancher, Jr., Robert E. Scott, Charles C. MacAdam, and Leonard Segel, Highway Safety Research Institute, University of Michigan, Ann Arbor

Requirements for pavement skid resistance are determined in relation to roadway design elements, tire-tread depth, and rainfall experience. Turnpike accident data are analyzed to show that certain low-curvature curves have higher than average accident involvement histories, and excessive water build-up and, hence, poor pavement drainage is determined to be a responsible factor. Tire traction is shown to be substantially degraded at water depths well below those needed for hydroplaning, and water depth on the road surface is shown to be primarily influenced by road width, superelevation, and rainfall rate and to be essentially independent of grade. We used computer simulation analyses involving parametric variations of vehicles, tires, road surfaces, curvature, superelevation, grade, and maneuvers to define specific limiting velocity boundaries for vehicle-handling performance and then used the accident, traction, drainage, and vehicle performance analyses to develop an equation for required pavement skid number. An example is used to illustrate applications of the equation.

•A SKID number of 37 was recommended by Kummer and Meyer (1) as the minimum requirement for main rural highways in 1967. This recommendation was based on the normal skid-resistance needs of traffic as derived from driver behavior studies. In this paper, the development of skid-resistance requirements is taken a step further, and such requirements are related directly to roadway design elements, tire characteristics, and precipitation experience. The work reported on is an outgrowth of studies conducted for the National Cooperative Highway Research Program concerning the influence of combined highway grade and horizontal curvature on skidding accidents (2). The studies involved the analysis of accident data, vehicle loss-of-control mechanisms, pavement drainage, and tire-pavement friction.

ACCIDENT DATA ANALYSIS

Accident data for the Ohio and Pennsylvania Turnpikes were analyzed to determine the relationship between roadway design elements and accident rates. Neither set of data was found to markedly depend on grade, although the accident rates for downgrades were higher than for upgrades. Accident rates did increase as curvature increased. Figure 1 shows that 1-deg curves on the Ohio Turnpike were found to have a high accident rate; this was particularly true during wet weather. On one specific 1-deg curve on a 3-deg downgrade, almost 70 percent of the accidents occurred during wet weather. Heavily worn tires were associated with many of these accidents; however, no evidence of effects that could be attributed to combinations of curvature and grade was found.

TIRE-PAVEMENT TRACTION AND WATER DEPTH

Water depth has a critical influence on the friction available at the tire-pavement interface. Tire hydroplaning is commonly considered to be the primary adverse effect resulting from excess water on the pavement. Actually, however, most wet-weather skidding accidents undoubtedly occur as a result of water depths well below those needed for hydroplaning (3).

Equations for predicting pavement water depth as a function of rainfall rate and pavement surface geometry have been independently developed through research at the Texas Transportation Institute, the U.K. Transport and Road Research Laboratory, and the Goodyear Tire and Rubber Company. These equations show that rainfall rate, pavement width, and superelevation are the primary factors influencing water depth. Roadway grade and pavement texture are secondary factors. [A physical explanation of why superelevation is an important factor and grade is not can be found elsewhere (2).] The most conservative of these equations (4) (i.e., for predicting the greatest depths of water) can be written as follows:

$$d = (5.9 \times 10^{-3}) \left(\frac{LI}{e}\right)^{0.47} (e^2 + G^2)^{0.135} \quad (1)$$

where

d = water depth above the pavement texture in inches (millimeters),
L = pavement width in feet (meters),
e = pavement superelevation in feet/foot (meters/meter),
G = percentage of pavement grade, and
I = rainfall intensity in inches/hour (millimeters/hour).

SKID-RESISTANCE REQUIREMENTS

Computer simulation was used to examine parametric variations of road (surface, curvature, grade, and superelevation) and tire factors in three types of vehicle maneuvers. These results were then generalized to yield pavement skid-resistance requirements.

The maximum velocities at which these maneuvers could be performed without loss of control were used as measures to quantify the results. These velocities and maneuvers are defined as follows:

V_{CR} = limiting velocity (i.e., without loss of control) for traversing a curve; drive thrust is applied to maintain constant velocity.
V_{LC} = limiting velocity for traversing a curve while, at the same time, a 9 to 12-ft (2.7 to 3.7-m) lane-change (obstacle-avoidance) maneuver is performed; drive thrust is applied to maintain constant velocity.
V_{LOC} = maximum initial velocity from which a combined lane-change and abrupt-stop maneuver can be performed while a curve is traversed.

The simulation results showed that executing a lane change on a curve (i.e., toward the inside of the curve) generally requires that more lateral force be generated in the tire-road friction couple than a similar maneuver on a tangent section requires. In normalized units, the additional force margin can be denoted as follows:

$$\bar{f} = \frac{V^2 D}{85{,}944} - e \quad (2)$$

where

V = maximum velocity at which the lane change can be executed in miles (kilometers) per hour, and
D = curvature of the curve in degrees.

It is evident, then, that an extra margin of maneuvering safety should be built into curved sections of the roadway. It is reasonable to provide this margin by increasing the skid number (SN) on a curve over that needed on a tangent section by an amount proportional to $\bar{f}$.

Similarly, considering that downgrades tend to correlate with an increase in the accident rate (physically a vehicle's weight shifts forward on a downgrade; this results in an increased potential for rear-wheel lockup during braking and, hence, in a tendency for directional instability or spinout), it seems reasonable to allow an independent SN margin for downgrade sites proportional to the magnitude of the downgrade. At curve-grade sites, then, the requirements for skid resistance can be combined additively to obtain the following expression for required SN:

$$SN_{CG} = SN_T + 100(\bar{f} + G') \tag{3}$$

where

SN_T = required SN for safe travel on a tangent section,
G' = magnitude of the grade for downgrades, and
G' = 0 for upgrades.

Equation 3 can be modified to account for deficiencies in pavement drainage and for the influence of tire characteristics different from that of the ASTM standard tire. (The ASTM standard tire is used as a reference because it is the standard tire used in pavement skid-resistance measurements.) This modification is as follows:

$$SN_{CG} = \frac{SN_T + 100(\bar{f} + G')}{T_F} + SN_D \tag{4}$$

where

SN_D = SN increment needed to overcome drainage deficiencies, and
T_F = factor to relate operational tire characteristics to the ASTM standard tire.

Equation 4 can be further modified to yield an expression for the required SN, measured at 40 mph (64 km/h), for safe travel at velocity V. The result is as follows:

$$SN_{(40/V)CG} = \frac{SN_{(40/V)T} + 100(\bar{f} + G')}{T_F} + SN_D \tag{5}$$

where V is a characteristic velocity that is near the maximum velocity that vehicles travel on the given highway section. Examples of this velocity are the speed limit, the highway design speed, or the 90th percentile of the speed distribution.

Values of $SN_{(40/V)T}$ can be determined from the V_{LOC} curves in Figure 2. Through a process of normalizing the data on Figure 2 for curvature, grade, tire-tread depth, and SN gradient, it can be shown that

$$SN_{(40/V)CG} = \frac{SN_{(40/40)T} + 100(\bar{f} + G') + (0.2 - SN_{grad})(V - 40)}{T_F} + SN_D \tag{6}$$

where

$SN_{(40/40)T}$ = SN_{40} value needed on a tangent section for safe travel on ASTM equivalent tires at 40 mph (64 km/h) (this value is about 4 in equation 6), and
SN_{grad} = SN gradient, SN/mph (SN/km/h) (SN_{grad} is almost always negative).

Equation 6 is the desired relationship for SN requirements and is applicable only to main rural highways where the selected characteristic velocity is at least 50 mph (80 km/h).

APPLICATION

A careful examination of equation 1 shows that pavement water depth can be essentially expressed in terms of the rainfall rate I and the single drainage design parameter K(L/e), where K is a correction factor for overall slope. This parameter is plotted versus rainfall rate as shown in Figure 3. Figure 3 is divided into four parts by curves for design water depths of 0.02, 0.04, and 0.06 in. (0.51, 1.02, and 1.52 mm). A maximum design water depth of 0.02 in. (0.51 mm) is desirable because this is the standard depth used in pavement skid testing. In the acceptable region (Figure 3), where the design water depth is 0.02 in. (0.51 mm) or less, an increase in SN is not needed [0.02 in. (0.51 mm) is the standard water depth used in pavement skid testing]. Compensating increases recommended for other parts of Figure 3 are given below (1 in. = 25.4 mm):

Region in Figure 3	Design Water Depth (in.)	Skid Resistance Increment (SN)
Acceptable	0 to 0.2	0
Region I	0.02 to 0.04	7
Region II	0.02 to 0.06	13
Unacceptable	>0.06	Not recommended

Note that design water depths greater than 0.06 in. (1.52 mm) are not recommended since hydroplaning may occur at these depths.

When Figure 3 is used, rainfall rates between 0.25 and 0.50 in./hour (6.4 and 12.7 mm/hour) should be used for design purposes, depending on local precipitation experience. Rainfall rates greater than these values are relatively uncommon; they cause reduced visibility and, hence, a reduction in traffic speed. The slope factor K can be determined from Figure 4. T_F values (5) for use with Equation 6 are given below (1 in. = 25.4 mm):

Tread Depth (in.)	T_F
$^0/_{32}$, worn smooth	0.29
$^1/_{32}$	0.40
$^2/_{32}$	0.50
$^3/_{32}$	0.60
$^4/_{32}$	0.69
$^6/_{32}$, half worn	0.85
ASTM tire	1.00
$^{12}/_{32}$, new tire	1.20

Figure 1. Accident rate versus curvature for Ohio Turnpike, 1966 to 1970.

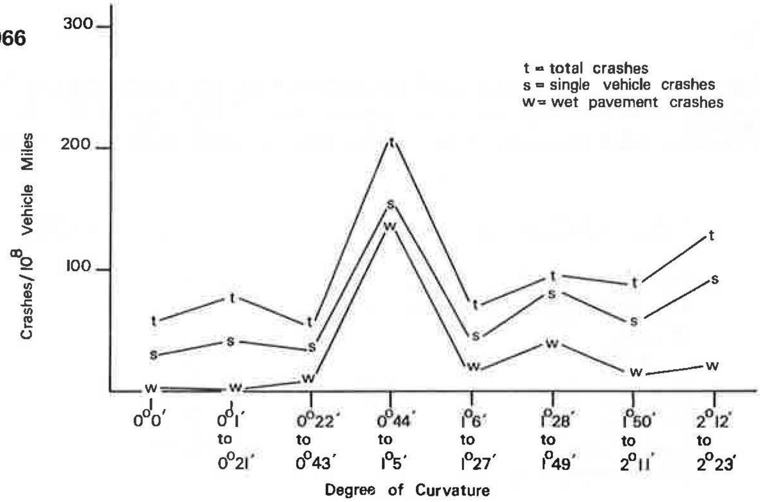


Figure 2. Effects of curvature and SN on V_{CR} and V_{LOC}.

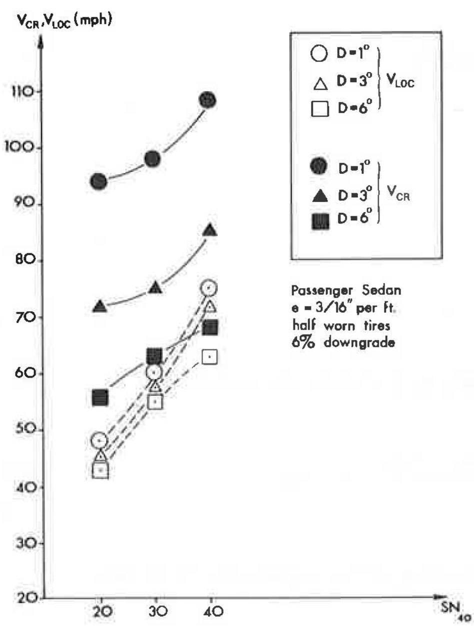


Figure 3. Drainage design parameter versus rainfall rate.

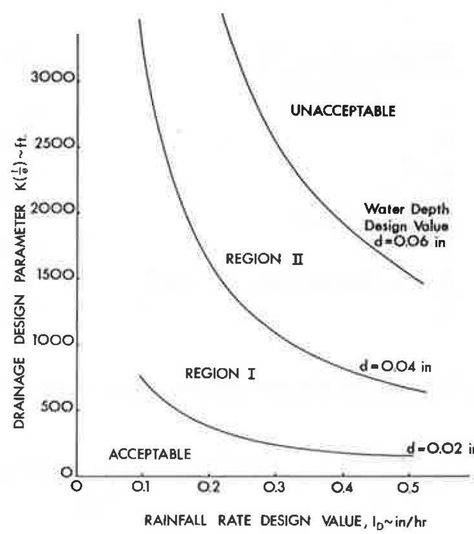
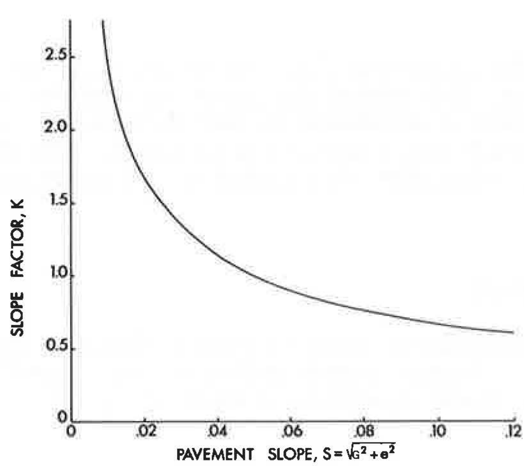


Figure 4. Slope factor versus pavement slope.



The site characteristics and measurements for an example of the use of equation 6 to specify skid resistance requirements are as follows (1 ft = 0.3 m, 1 in. = 25.4 mm, 1 in./ft = 83.3 mm/m, 1 mph = 1.6 km/h, 1 SN/mph = 0.6 SN/km/h):

Site Characteristic	Measurement
Roadway width, ft	24
Superelevated shoulder width, ft	10
D, deg	1
e, in./ft	$^3/_8$
G, percentage of downgrade	3
V, mph	80
I_D, in./hour	0.25
Tire-tread depth, in.	$^2/_{32}$

The derived quantities for an example of how equation 6 can be used are given below (1 ft = 0.3 m, 1 SN/mph = 0.6 SN/km/h):

Derived Quantity	Measurement
$S = \sqrt{e^2 + G'^2}$	0.0434
K	1.07
L, ft	30.5
K(L/e), ft	1,042
$\underline{SN}_D$ (region I)	7
$\bar{f}$	0.04
SN_{grad} (assumed), SN/mph	-0.5
T_F	0.50

Substituting the above derived quantities into equation 6 yields the following:

$$SN_{40/80} = \frac{4 + 100(0.04 + 0.03) + (0.2 + 0.5)(80 - 40)}{0.50} + 7 = 85 \qquad (7)$$

If the tires were new (T_F = 1.2), then the corresponding SN_{40} value would be 40.

CONCLUSION

Equation 6 provides a practical means for determining the SN requirements for a given section of roadway. It is evident that geometry, drainage, and tire use enter into pavement skid-resistance requirements and that these factors lead to different skid-resistance needs on different sections of pavement. Although the data supporting equation 6 are not exhaustive, the equation is fully representative of the best available information.

ACKNOWLEDGMENT

This paper was developed as part of a National Cooperative Highway Research Program project (2) on the influence of combined highway grade and horizontal alignment on skidding. The work was carried out at the Highway Safety Research Institute, University of Michigan. Harry A. Smith served as project engineer. The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the sponsoring agency.

REFERENCES

1. H. W. Kummer and W. E. Meyer. Tentative Skid Resistance Requirements for Main Rural Highways. NCHRP Rept. 37, 1967.
2. D. F. Dunlap, P. S. Fancher, R. F. Scott, C. C. MacAdam, and L. Segel. Influence of Combined Highway Grade and Horizontal Alignment on Skidding. Final Rept., NCHRP Project 1-14, Dec. 1973.
3. G. C. Staughton and T. Williams. Tyre Performance in Wet Surface Conditions. U.K. Transport and Road Research Laboratory, TRRL Rept. LR 355, 1970.
4. N. F. Ross and K. Russam. The Depth of Rain Water on Road Surfaces. U.K. Transport and Road Research Laboratory, TRRL Rept. LR 236, 1968.
5. P. S. Fancher, Jr., and L. Segel. Tire Traction Assessed by Shear Force and Vehicle Performance. Tire Science and Technology, Vol. 1, No. 4, Nov. 1973, pp. 363-381.