Limitations of Using Skid Number in Accident Analysis and Pavement Management

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Pavement frictional characteristics are commonly determined by conducting skid tests in accordance with ASTM Standard E274. The results of these tests [skid number (SN)] are used in ranking roads to establish construction priorities and to estimate tire-pavement friction in accident analysis. The role of SN in these two applications is addressed. There are serious limitations constraining the use of SN in accident analysis as well as in pavement management. Use of SN-based estimates of coefficient of friction may lead to large errors in estimating the braking distance or initial speed of a vehicle involved in an accident. In pavement management, SN is an important factor in evaluating traffic safety; however, other factors must also be considered, such as accident history data, driving difficulty, road geometry, and traffic characteristics. A wet pavement index, incorporating all factors relevant for traffic safety under wet weather conditions, should be developed to provide a basis for pavement management decisions related to highway safety.

The role of skid resistance and its use in wet accident analysis is addressed. Highway traffic accidents are a major concern of all state highway and transportation departments. One of the many causes of highway accidents is wet slippery pavements. Because all of the forces needed to control a vehicle come from the interaction between the tires and pavement, the frictional demand, which varies with road, tire, weather, and traffic conditions, must be met under all driving conditions. The ability of a tire-pavement interaction to provide adequate traction on wet roads is directly related to the safe operation of vehicles. The importance of wet-pavement traction to safety was emphasized by the findings of the National Transportation Safety Board, which reported that while the pavements are exposed to precipitation less than 3.5 percent of the time, wet-pavement accidents account for 13.5 percent of all fatal accidents (*1*). Also, the National Safety Council's 1988 summary reports more than 49,000 people killed and over 1.8 million injured and a total estimated cost of vehicle accidents of approximately $70 billion (*2*). This means that motor vehicle accidents account for almost 50 percent of all fatalities in the United States and about 50 percent of the cost, or that wet-weather accidents account for about 7 percent of all fatalities and their cost.

Research on pavement skid resistance is an active ongoing effort at both the federal and state level. The standardization of skid resistance measurement in the United States and the routine calibration of test equipment has greatly enhanced the reliability of these measurements (ASTM E274). Even so, there has only been moderate success in establishing a clear relationship between skidding accidents and pavement condition (*3–7*).

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First what a skid resistance is and how it is varied are reviewed. Then the drag factor (DF), a quantity used by accident investigators, and how it relates to accident reconstruction, are reviewed. Conditions under which skid number (SN) and DF are and are not related are discussed. Finally, factors other than skid resistance that affect wet pavement safety are reviewed.

ESTIMATING FRICTION IN ACCIDENT ANALYSIS

One of the most critical tasks in accident analysis is to find the speed of a vehicle involved in an accident at the time or just before the time when the accident occurred. In order to determine that speed, an estimate of the coefficient of tire-pavement friction is required. In four-wheel braking, the vehicle speed can be calculated from the following equation:

$$mV\frac{dV}{dx} + \frac{C_D A_f \rho}{2}(V + v)^2 + mgf + mg(G + R) = 0 \qquad (1)$$

where

- m = mass of the vehicle;
- V = vehicle velocity;
- v = component of wind velocity in direction opposite to vehicle motion;
- x = distance in forward direction of vehicle measured from onset of braking;
- g = gravitational acceleration;
- f = coefficient of tire-pavement friction;
- C_D = coefficient of air resistance;
- A_f = vehicle frontal area;
- ρ = density of ambient air;
- G = grade, positive in upward direction; and
- R = coefficient of rolling resistance.

Equation 1 is difficult to solve analytically, especially when f is considered to be a function of speed, which it is under wet conditions. However, the equation can be solved numerically using a simple computer program. A copy of such a program can be obtained from the Pennsylvania Transportation Institute (PTI) and is referenced in the new FHWA Skid Resistance Manual (*8*).

In order to ensure that the results obtained by solving Equation 1 are meaningful and accurate for specific braking conditions, all parameters in this equation must be carefully estimated because they are seldom known accurately. The most difficult parameter to estimate is the coefficient of friction between the tires of the vehicle involved in the accident and the pavement surface on which the accident occurred. The tire-pavement friction is affected by the type and condition of the vehicle tires, vehicle suspension, vehicle load and load distribution, water film thickness, and pavement surface characteristics, to name just the most important factors (*9,10*). In general, tire-pavement friction has been estimated either by DF or by SN with no knowledge of how good or bad these estimates are. Even worse, if DF or SN is not available, a handbook value of the coefficient of friction is used.

Skid Resistance

ASTM Committee E17 has the following definition of skid resistance under consideration: "The retarding force generated by the interaction between a pavement and a tire under locked, nonrotating wheel conditions." Measurements of skid resistance conducted in accordance with ASTM Standard E274 are reported as SN values. SN values are measured at 40 mph and are equal to the force required to slide the locked test tire divided by the effective wheel load and multiplied by 100. If the skid test is performed at another speed, then the velocity (V) must be reported, i.e., SN_V. Pavement SN and its many surrogates are accepted worldwide as a measure of pavement frictional characteristics; as SN increases, the pavement frictional characteristics improve. Results of skid resistance measurements provide the basis for pavement management safety decisions.

One of the primary objectives of pavement management systems is to provide motorists with highway surfaces that allow them to drive safely under wet pavement conditions. An important part of this process is the identification of sections of roads that do not provide adequate friction under wet pavement conditions for vehicles performing braking, cornering, lane changing, and other maneuvers. Skid resistance plays the key role in ranking roads according to their safety under wet conditions. A number of studies have been conducted to determine the correlation between SN and wet-pavement accident rate (*7,11–13*).

SN represents one of the most important factors for establishing wet-pavement safety. However, other factors must also be considered when making pavement management decisions: road geometrics, driving conflicts, visibility, traffic characteristics (including percent of trucks), and average wet time (average period of time during a year when the road is wet). Several studies have recently been completed or are currently underway to develop an integrated approach to the problem of evaluating the safety of wet pavements both abroad and in the United States (*14–17*).

Transportation departments are able to provide pavements with good skid resistance, and the ASTM locked-wheel skid tester is a reliable tool to rank pavements. However, improvement is needed in applying this ranking, because SN only ranks the pavement skid resistance, not the vehicle demand for it nor the actual friction of a particular vehicle tire–pavement interaction.

Drag Factor

In the field of accident reconstruction, DF is used rather than a coefficient of friction. This factor is obtained by conducting a vehicle braking test with locked wheels. A correct test takes place at the accident site and involves a similar vehicle, similar tires, and similar weather conditions to those of the accident. In order to be correct, the test should also be conducted at the estimated speed of the vehicle or vehicles involved in the accident. DF then becomes a function of many variables, including friction, air resistance, grade, vehicle weight distribution, and weather. DF is calculated from the following equation:

$$\mathrm{DF} = \frac{V^2}{30D} \qquad (2)$$

where

V = vehicle velocity before braking, mph; and
D = distance traveled after braking, ft.

Thus, using Equation 2 in the form

$$V = (30 \times D \times \mathrm{DF})^{1/2} \qquad (3)$$

yields the initial velocity for known stopping distance, D, and known DF values, or

$$D = \frac{V^2}{30} \times \mathrm{DF} \qquad (4)$$

yields the stopping distance for known initial velocity, V, and DF values. Equations 2–4 are then used in place of Equation 1 and include all of the effects of Equation 1.

Skid Number

If SN is used, SN/100 becomes an estimate of the coefficient of friction in Equation 1. SN divided by 100 can also be used as an estimate of the relationship for friction versus speed in the following equation (*18*):

$$f(V) = \frac{\mathrm{SN}(V)}{100} = \left(\frac{\mathrm{SN}_0 e^{\frac{-\mathrm{PNG}}{100} V}}{100}\right) \qquad (5)$$

where SN_0 (zero-velocity intercept) and PNG (percent normalized gradient) are the model parameters. The values of SN_0 and PNG can be estimated from locked-wheel SN values obtained with ribbed or blank tires or by conducting several skid tests at three or more different speeds and doing a log regression to Equation 3 (*19*).

For measurements of SN in accordance with ASTM E274, a standard ASTM E501 ribbed tire is used. This standard tire does not represent any specific type of vehicle tire and in fact is a belted tire, whereas presently, most passenger car tires are radial tires. Therefore, SN can only be considered an estimate of friction between an actual vehicle tire and road surface, and by itself neglects all the other parameters in Equation 1. Unfortunately, circumstances often do not allow for such tests to be performed, and then an SN or an SN-based estimate of tire-pavement friction is used. For passenger cars, an estimate of the mean effective coefficient of friction was proposed (*20*):

$$\bar{f}_{V_i} = \frac{SN_0\,(PNG/100)^2V_i^2}{200} \times \left[1 - e^{\frac{PNG}{100}V_i}\left(1 - \frac{PNG}{100}V_i\right)\right]^{-1} \quad (6)$$

where V_i is the initial velocity of a vehicle. This estimate was developed for new and slightly worn passenger car tires of a similar size and construction as the ASTM ribbed tire. It tends to overestimate friction for moderately worn tires and for all tires when the water film thickness is more than 0.05 in.

Of even more concern is the case of using the standard SN value at a speed of 40 mph as the estimate of the coefficient of friction. Here the SN is not known as a function of velocity so that not only is the tire type incorrect, but there is no estimate of the mean effective friction. The use of SN, which is measured in a locked-wheel test, has even more error if the car is equipped with an antilock brake system (ABS) and could result in errors of 100 percent or more on low-friction surfaces where braking is near the peak coefficient rather than at locked wheel.

Estimation of tire-pavement friction is more complicated for trucks and buses. Data on the coefficient of friction for various types of truck tires were reported in several studies (*21,22*). Truck and bus tires are designed primarily for high-wear resistance and usually have lower friction coefficients than passenger car tires. It is generally estimated that the locked-wheel coefficient of friction of truck tires is about 70 percent of that for passenger car tires. A procedure for predicting the braking distances of trucks operating on poor, wet roads was developed by Olson et al. (*23*). The peak locked-wheel friction (f_p) of a new truck tire is estimated by

$$f_p(V) = 1.45 f_s(V) \quad (7)$$

where f_s is a sliding coefficient of friction. Truck drivers modulate brakes during braking to avoid wheel lock and maintain directional control. This results in the effective truck tire friction coefficient being higher than the sliding coefficient of friction, f_s, but still lower than the peak coefficient of friction, f_p. Moreover, on the basis of experimental data, truck drivers attained approximately 62 percent of the performance capabilities of the road-tire-vehicle system represented by the peak coefficient of friction (*23*). The effective truck tire friction can be estimated by SN, using the following equation (*8,23*):

$$f(V) = 0.62 \times 1.45 \times 0.0084\,SN(V) \quad (8)$$

or, equivalently

$$f(V) = 0.00755\,SN(V) \quad (9)$$

As in the case of passenger car tires, SN dependence on speed must be known to calculate the coefficient of friction as a function of speed, using Equation 9.

Remember that SN only provides an estimate of the coefficient of friction between an actual vehicle and the road surface. It is generally accepted that vehicle tire-pavement friction improves as SN increases. Quantitatively, however, there may be a considerable difference between SN and the tire-pavement coefficient of friction for two reasons.

First, as mentioned earlier, the properties of the standard ASTM tire used in skid tests are different from the properties of actual automobile tires, and they are bias instead of radial. With the variety of car and truck tires currently in use, it is difficult to predict how their coefficients of friction will compare with those of the ASTM tire. Previous research has shown that the ASTM E501 ribbed tire produces friction levels lower than those produced by a comparable, new, and slightly worn passenger car tire of similar size and construction, as shown in Figure 1 (*20*). However, when water film thickness is increased, the passenger car tire produces lower levels of friction than the ASTM tire, as shown in Figure 2. How the ASTM test tire and actual vehicle tires compare depends also on the type of pavement surface (*24*). On polished, wet surfaces, the skid resistance of the ASTM tire was considerably lower than that of conventional tires used on motor vehicles. The trend is reversed on higher-friction surfaces having SN greater than 20.

Second, tire operating conditions including load, inflation pressure, speed, percent slip, water film thickness, and vehicle suspension characteristics during a skid test are different from those of a vehicle tire.

Current knowledge of the relationship between the pavement skid resistance and vehicle tire-pavement coefficient of friction does not provide a method for calculating the error involved in approximating the tire-pavement coefficient of friction by SN. The following examples describing actual cases illustrate the consequences of using an SN-based estimate for tire-pavement friction.

Example 1

The results of a braking test performed with a Pontiac Sunbird on a wet section of bituminous pavement were as follows:

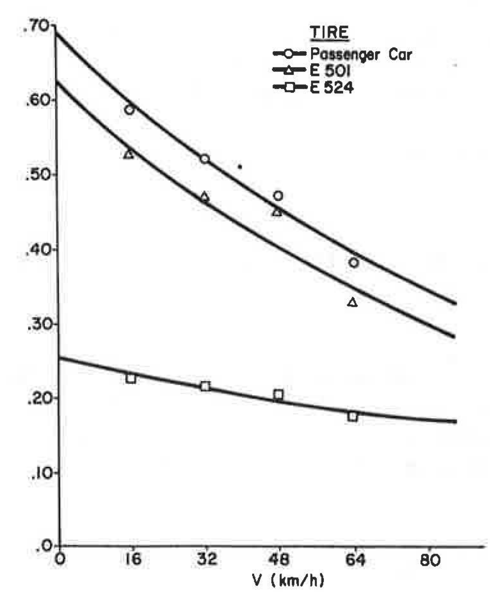

FIGURE 1 Coefficient of friction versus speed for the ASTM tires and the passenger car tire when new—Site 1, 1980 (1 km = 0.6 mi) (*21*).

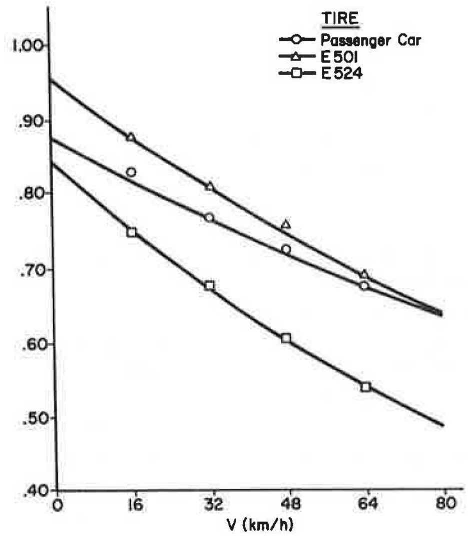

FIGURE 2 Coefficient of friction versus speed for the three tires on the braking distance site, 1981 (1 km = 0.6 mi).

- Initial speed, V_i = 30 mph; and
- Braking distance, d = 34.0 ft.

The results of the skid tests conducted on the same pavement and under the same weather conditions were as follows:

- Ribbed tire SN at 40 mph, SN_{40} = 39.8; and
- Ribbed tire SN at 30 mph, SN_{30} = 50.3.

Case A: Coefficient of Friction Estimated by $SN_{40}/100$ This situation is likely to occur in real life. The vehicle speed is unknown; therefore, a standard ASTM E274 test at 40 mph is used to estimate tire-pavement friction, $f = SN_{40}/100 = 0.398$. Because the braking distance d is known, the estimate of the initial speed is then calculated as follows:

$$V_i = 5.5(d \times f)^{1/2}$$
$$= 5.5(34 \times 0.398)^{1/2} = 20.2 \text{ mph} \quad (10)$$

The actual initial speed is 30 mph; therefore, the speed prediction error is −9.8 mph, or −32.7 percent.

Case B: Coefficient of Friction Estimated by $SN_{30}/100$ In this case, SN measured at the actual vehicle speed is used, which is not likely to happen in real life. The predicted initial speed, assuming that the braking distance is known, is

$$V_i = 5.5(d \times f)^{1/2}$$
$$= 5.5(34 \times 0.503)^{1/2} = 22.7 \text{ mph} \quad (11)$$

which gives the speed prediction error of −7.3 mph, or −24.3 percent.

Case C: Coefficient of Friction Estimated Using Equation 6 First, the parameters SN_0 and PNG, describing the skid resistance dependence on speed, must be determined. Because ribbed tire SN values at two different speeds are known, SN_0 and PNG can be calculated directly to be SN_0 = 101.1 and PNG = 2.27. In order to calculate the average coefficient of friction from Equation 6, an initial speed of the vehicle must be assumed. For an assumed speed of 40 mph, the average coefficient of friction is then calculated as follows:

$$f = \frac{101.1 \times 0.227^2 \times 40^2}{200} \times \left[1 - e^{0.0227 \times 40}\left(1 - 0.0227 \times 40\right)\right]^{-1}$$
$$= 0.54 \quad (12)$$

Hence, the predicted initial speed is

$$V_i = 5.5(d \times f)^{1/2}$$
$$= 5.5(34 \times 0.54)^{1/2} = 23.6 \text{ mph} \quad (13)$$

This value is different from the assumed value of 40 mph. In order to improve accuracy, the process of calculating V_i is repeated, until the assumed and predicted values of V_i are the same. Repeating the calculation of f and V_i yields f = 0.67 and V_i = 26.3. The prediction error is −3.7 mph or −12.3 percent. The results of predicting initial speed based on the different estimates of the tire-pavement coefficient of friction obtained in this example are presented in Table 1.

This example demonstrates that the use of SN as an estimate of tire-pavement friction may lead to large errors in predicting vehicle speed. The magnitude of the error is likely to be particularly high when the coefficient of friction is estimated by SN/100.

Example 2

The results of several braking tests on both wet and dry surfaces of a section of the bituminous skid pad at the PTI test track are presented in Table 2.

The results obtained with an ASTM skid trailer on the same surfaces are presented in Table 3.

On the basis of a regression of the wet E501 (ribbed) tire tests, the following values were calculated:

- SN_0 = 80.17,
- SN_0 (peak) = 107.7,

TABLE 1 RESULTS OF PREDICTING INITIAL SPEED FOR EXAMPLE 1

	$Sn_{40}/100$	$Sn_{30}/100$	f, eq. 6
Predicted Speed, mi/h	20.2	22.7	26.3
Absolute Error, mi/h	-9.8	-7.3	-3.7
Relative Error, %	-32.7	-24.3	-12.3

TABLE 2 RESULTS OF BRAKING TESTS CONSIDERED IN EXAMPLE 2

Vehicle	Wet/Dry	V_i, mi/h	d, feet	DF
Pontiac Sunbird	Dry	30	34.8	.86
Pontiac Sunbird	Wet	30	44.5	.67
Transit Bus	Dry	26	42.5	.53
Transit Bus	Dry	42	112.7	.52
Lincoln	Dry	31	40.0	.80
Cadillac (with ABS)	Dry	46	99.0	.81
Dump Truck	Dry	30	37.6	.79

TABLE 3 RESULTS OF SKID RESISTANCE TESTS FOR EXAMPLE 2

Tire	Condition	Speed	SN	Peak
E501 (ribbed)	Wet	29.8	51.7	97.1
E501 (ribbed)	Wet	40.7	40.1	95.6
E501 (ribbed)	Wet	50.1	37.8	90.8
E524 (blank)	Wet	39.9	38.1	92.7
E501 (ribbed)	Dry	39.6	56.4	107.0

- PNG = 1.563, and
- PNG (peak) = 0.325.

Using these values, the calculations of Cases A, B, and C in Example 1 were repeated to obtain the results presented in Tables 4–6.

OTHER FACTORS AFFECTING WET-PAVEMENT SAFETY

The examples presented in the previous section demonstrated that using SN or SN-based estimates of tire-pavement friction can lead to very large errors in calculations of speed and stopping distance in accident analysis. SN alone is not a good measure of wet pavement safety either. Figure 3 shows considerable scatter of data in the ratio of wet to dry accidents versus the SN plot obtained by Havens in 1979 (*24*). That nothing has changed in respect to the relationship between number of wet accidents and SN is demonstrated by Figure 4, obtained from the validation data set collected for the 1990 study (*17*).

Although the process of identification of sections that do not provide adequate traction under wet-pavement conditions is an important part of pavement management, it is but one factor needed in providing motorists with highway surfaces that allow them to drive safely. Many other factors affect safety under wet-pavement conditions, and it is only when these conditions demand a particular level of traction that SN then becomes important.

TABLE 4 RESULTS OF PREDICTING INITIAL SPEED FOR EXAMPLE 2, CASE A ($SN_{40}/100$ IS USED AS f)

Vehicle	Condition	f	V_i Calculated mi/h	V_i Actual mi/h	Percent Error
Pontiac Sunbird	Dry	.564	24.3	30	-19
Pontiac Sunbird	Wet	.378	22.6	30	-25
Transit Bus	Dry	.564	26.9	26	+ 3
Transit Bus	Dry	.564	43.8	42	+ 4
Lincoln	Dry	.564	26.1	31	-16
Cadillac (ABS)	Dry	.564	41.1	46	-11
Cadillac (ABS)	Dry	.564	24.5	30	-18
Dump Truck	Wet	.378	20.7	30	-31

TABLE 5 RESULTS OF PREDICTING INITIAL SPEED FOR EXAMPLE 2, CASE B [SN(v) NEAREST TEST SPEED IS USED]

Vehicle	Condition	f	V_i Calculated mi/h	V_i Actual mi/h	Percent Error
Pontiac Sunbird	Wet	.517	26.4	30	-12
Transit Bus	Dry	.564	43.8	42	+ 4
Cadillac (ABS)	Dry	.564	41.1	46	-11
Dump Truck	Wet	.517	24.3	30	-19

TABLE 6 RESULTS OF PREDICTING INITIAL SPEED FOR EXAMPLE 2, CASE C [SN(v) IS CALCULATED]

Vehicle	Condition	f	V_i Calculated mi/h	V_i Actual mi/h	Percent Error
Pontiac Sunbird	Wet	.595	28.2	30	- 6
Dump Truck	Wet	.610	26.2	30	-13

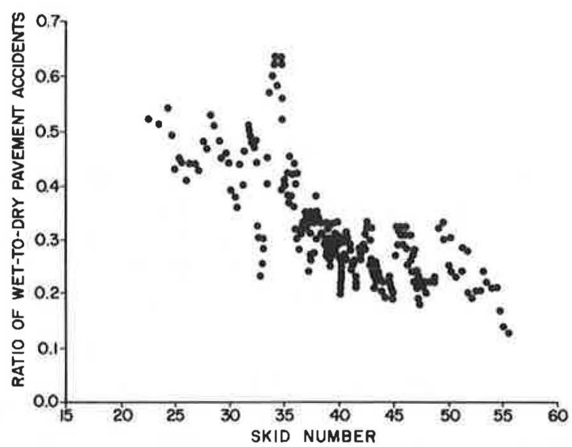

FIGURE 3 Ten-point moving averages of wet-to-dry pavement accidents for 120 test sections in Kentucky with ADT above 2,700 versus SN.

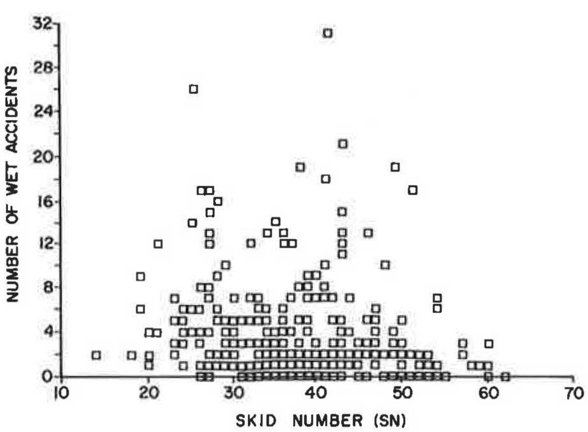

FIGURE 4 Number of wet accidents versus SN obtained from the validation data set.

All drivers in the traffic flow can maintain directional stability of their vehicles if the friction demand exerted by their vehicles does not exceed the available friction. The available friction depends on the pavement skid resistance. Friction demand is a function of vehicle speed, road geometry, traffic characteristics (including traffic density and percentage of trucks in the traffic flow), vehicle characteristics (including vehicle type and its understeer), and driver skills. SN, measured on a given section of road, represents the available friction at 40 mph. Whether or not this particular SN is sufficiently high to prevent wet accidents cannot be determined unless the demand for friction on the section of road under consideration is known. The effects of all important factors on friction demand must be considered in pavement management.

Vehicle Speed

Speed is a critical factor for the balance between friction demand and supply because it affects both. When speed increases, friction demand also increases. For instance, centrifugal forces generated during vehicle cornering, which must be counteracted by tire-pavement friction forces to prevent a vehicle from skidding off the road, are proportional to the square of vehicle speed. At the same time, the pavement skid resistance decreases with increasing speed in an approximately exponential manner (Equation 5).

Road Geometry

The amount of friction required for safe driving is strongly affected by road geometry. Friction demand on straight sections of road is low if the road is level, if vehicles travel at constant speed, and if there are no intersections. The demand for friction increases significantly if a grade or a curve must be negotiated (*12*). Page and Butas (*25*) concluded that pavement accident rates are significantly higher on curves than on any other type of geometric alignment. The effect of curvature on wet-accident rates was found to be particularly strong on pavements having SN values less than 25. When SN is less than 25, wet-pavement accident rates are significantly greater for both uphill and downhill slopes steeper than 3 percent than for flatter terrain.

Traffic Flow

Traffic volume, in general, does not have a significant influence on wet-accident rates (*26*). However, under special circumstances, namely, on undivided highways having SN values less than 25, wet-accident rates were found to increase significantly when the average daily traffic was greater than 15,000 vehicles per day (*25*). Traffic composition, in particular, the percentage of trucks in the traffic flow, has a significant effect on friction demand. This is because the stopping distances of trucks are 1.3 to 2.8 times longer than the stopping distances of passenger cars (*26*).

Driving difficulty is another important characteristic of traffic flow. The criteria determining driving difficulty include number of access points per segment of road, presence of turn lanes, type of surrounding land use, traffic signalization, and the roadway cross section.

Vehicle Type

Figure 5 shows stopping distances of buses and various configurations of trucks versus the stopping distance for a typical passenger car from 60 mph (96 km/hr) on a dry road (*27*). The friction demand for buses and all types of trucks is higher than for passenger cars if equal stopping distance is required for all vehicles. The friction demand is also higher for vehicles with lower degrees of understeer (*20*).

Driver Skills

Few drivers can operate their vehicles at 100 percent efficiency, i.e., using 100 percent of the available friction. Olson

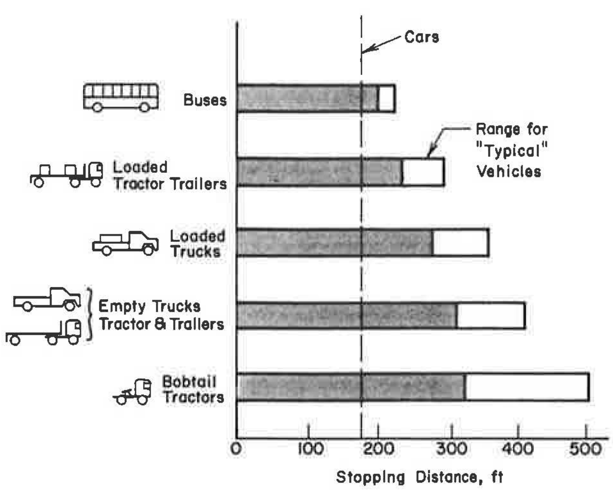

FIGURE 5 Stable stopping distance from 60 mph (96 km/hr) on dry road.

et al. (*23*) found that truck driver efficiencies range from 62 to 100 percent and that most drivers have little or no practice in emergency braking situations. The concern over driver braking skills will be alleviated when antilock brake systems become commonly used.

In order to fully evaluate the risk of a wet-pavement accident, all factors influencing the demand for friction and available friction must be considered. Several research studies are currently under way in which mathematical models of pavement safety index are being developed. These statistical models estimate the probability of wet pavement accidents as a function of the variables affecting the balance between friction demand and available friction.

CONCLUSION

In general, the use of SN_{40} as coefficient of tire-pavement friction would be expected to underestimate the speed or overestimate the stopping distance. In the case of a truck or bus, this was not true; however, if the 75.5 percent rule is used for truck tires, then the bus velocity would have also been underestimated. Using $SN(V)$ at the speed of the accident is an improvement, but it still underestimates the speed. Similarly, calculating a mean friction for $SN(V)$ over the speed of interest yields an even better estimate, but still underestimates the speed. This is to be expected because an ASTM tire was found to exhibit a lower SN than a regular tire.

In the case of pavement management, ranking roads on the basis of SN only is not wise. Certainly a long, straight road with an SN value of 30 and ADT of 1 is of no concern when there are so many roads with high ADT values, curves, intersections, etc., at the same or even higher SN values, which are thus more likely to have wet-weather accidents. Roads with good SN values are not problems with regard to skidding, but roads with low SN values (e.g., below 20) need to be addressed. For cases in between, the major problem area, it is recommended that an index that gives the probability of a wet-weather accident should be used in ranking which road should be repaired first on a safety basis.

REFERENCES

1. *Safety Effectiveness Evaluation: Selected State Highway Skid Resistance Programs*. Report NTSB-SEE-80-6. National Transportation Safety Board, Washington, D.C., Sept. 1980.
2. *Accident Facts*, National Safety Council, Washington, D.C., 1979.
3. R. R. Hegmon. Wet Weather Accidents and Pavement Skid Resistance. *Public Roads*, Sept. 1981, p. 68.
4. J. C. Wambold, J. J. Henry, and R. R. Hegmon. Skid Resistance of Wet Weather Accident Sites. *The Tire Pavement Interface*, STP 929. ASTM, Philadelphia, Pa., June 1985, pp. 47–60.
5. J. R. Hosking. *Relationship between Skidding Resistance and Accident Frequency: Estimates Based on Seasonal Variation*. Research Report 76. Transport and Road Research Laboratory, Crowthorne, Berkshire, U.K., 1986.
6. J. M. Zuieback et al. *Frictional Requirements Necessary to Reduce Skidding Accident Frequencies*. Report SAI-260-77-547-LA. FHWA, U.S. Department of Transportation, 1977.
7. R. R. Blackburn, D. W. Harwood, A. D. St. John, and M. C. Sharp. *Evaluation of Accident Rate–Skid Number Relationships, Effectiveness of Alternative Skid Reduction Measures*, Vol. 1. Report FHWA-RD-79-22. FHWA, U.S. Department of Transportation, Nov. 1978.
8. B. T. Kulakowski et al. *Skid Resistance Manual*. Pennsylvania Transportation Institute, University Park, Pa., July 1990.

9. R. R. Hegmon. *Tire-Pavement Interaction*. Technical Paper 87024. SAE, Warrendale, Pa., 1987, pp. 197–204.
10. A. G. Veith. *Tire-Roads-Rainfall-Vehicles: The Traction Connection*. STP 793. ASTM, Philadelphia, Pa., 1983, pp. 3–40.
11. H. W. Kummer and W. E. Meyer. *NCHRP Report 37: Tentative Skid Resistance Requirements for Main Highways*. HRB, National Research Council, Washington, D.C., 1967.
12. E. Farber, M. S. Janoff, S. Cristinzio, J. G. Blubaugh, W. Reisener, and W. Dunning. *NCHRP Report 154: Determining Pavement Skid Resistance Requirements at Intersections and Braking Sites*. TRB, National Research Council, Washington, D.C., 1974.
13. A. B. Moore and J. B. Humphreys. High Speed Skid Resistance and the Effects of Surface Texture on the Accident Rate. In *Skid Resistance of Highway Pavements*, STP 530. ASTM, Philadelphia, Pa., 1973, pp. 91–100.
14. *OECD Road Safety Research: A Synthesis*. Organization for Economic Cooperation and Development Scientific Experts Group, Paris, France, 1986.
15. *Anti-Skid Tests in U.K.* International Road Federation, Paris, France, April 1988.
16. D. L. Ivey and L. I. Griffin III. *Development of a Wet Weather Safety Index*. Report FHWATX77-2211F. Texas State Department of Highways and Public Transportation, Austin, Nov. 1977.
17. B. T. Kulakowski et al. *Development of a Methodology to Identify and Correct Slippery Pavements*. Research Project 88-06. Pennsylvania Department of Transportation, University Park, Pa., Aug. 1990.
18. J. J. Henry, K. Saito, and R. Blackburn. *Predictor Model for Seasonal Variations in Skid Resistance: Comprehensive Final Report*, Report FHWA-RD-83/005. FHWA, U.S. Department of Transportation, 1983.
19. J. C. Wambold. Obtaining Skid Number at Any Speed from Test at Single Speed. In *Transportation Research Record 1196*, TRB, National Research Council, Washington, D.C., 1988.
20. J. J. Henry. *Comparison of the Friction Performance of a Passenger Car Tire and the ASTM Standard Test Tires*. Special Technical Publication 793, ASTM, Philadelphia, Pa., 1983, pp. 219–231.
21. P. S. Fancher, R. D. Ervin, C. B. Winkler, and T. D. Gillespie. *A Factbook of the Mechanical Properties of the Components of Single-Unit and Articulated Heavy Vehicles*. Report DOT HS 807-125. NHTSA, U.S. Department of Transportation, 1986.
22. I. Gusakov, R. Rice, S. Pugliese, and R. Galganski. *An Evaluation of Methods to Investigate Truck Tire Wet Traction*. Report DOT HS 806-577. NHTSA, U.S. Department of Transportation, 1984.
23. P. L. Olson, D. E. Cleveland, P. S. Fancher, L. P. Kostynick, and L. W. Schneiter. *NCHRP Report 270: Parameters Affecting Stopping Sight Distance*. TRB, National Research Council, Washington, D.C., June 1984.
24. W. Bergman. *Skid Resistance Properties of Tires and Their Influence on Vehicle Control*. In *Transportation Research Record 621*, TRB, National Research Council, Washington, D.C., 1977, pp. 8–18.
25. B. G. Page and L. F. Butas. *Evaluation of Friction Requirements for California State Highways in Terms of Highway Geometrics*. Report FHWA/CA/TL-86/01. FHWA, U.S. Department of Transportation, Jan. 1986.
26. D. C. Mahone and S. N. Runkle. *Pavement Friction Needs*. In *Highway Research Record 396*, HRB, National Research Council, Washington, D.C., 1972, pp. 1–11.
27. R. W. Rowlinski and S. F. Williams. *NHTSA Heavy Duty Vehicle Brake Research Program—Report No. 1: Stopping Capability of Air Braked Vehicles*. DOT HS806 738 and 739. NHTSA, U.S. Department of Transportation, April 1985.

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