Prediction of Skid Resistance as a Function of Speed From Pavement Texture Measurements

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A model that can be used to describe the variation of skid resistance with vehicle speed is presented. The model contains two constants: One is a measure of low-speed skid resistance, and the other accounts for the decrease in skid resistance as vehicle speed increases. It is demonstrated that the constants can be predicted from measurements of pavement microtexture and macrotexture. A significant feature of the model is that it clearly separates the effects of the two texture types. It can also be used to determine skid resistance-speed characteristics from a single speed measurement and a macrotexture measurement.

It is current practice in the United States to evaluate the skid resistance of highways by taking annual measurements of the locked-wheel skid number of the primary road system (1). These measurements are usually performed at one speed only—typically 64 km/h (40 mph)—but sometimes at the "prevailing traffic speed." Such measurements only partially characterize pavement safety in that they do not indicate the degree to which skid resistance changes with speed. The measurement of the relation between skid resistance and speed requires testing at two speeds or more, which would require three times the effort of conducting an annual survey.

The skid resistance of a pavement is determined by its surface texture. Kummer and Meyer (2) have reported the combined effects of microtexture and macrotexture. Microtexture, the fine-scale surface texture of the pavement aggregate, determines skid resistance at low vehicle speeds. Macrotexture, on the scale of the gradation of the aggregate, influences wet-pavement skid resistance by determining the rate at which water can escape from the tire footprint and therefore the rate at which skid resistance decreases as speed increases. Thus, it should be possible to predict the skid resistance-speed curve from suitable parameters for macrotexture and microtexture. An alternative method for determining the relation between skid resistance and speed for a pavement would be to perform a measurement at any convenient vehicle speed and combine the result with a macrotexture measurement to predict skid resistance at other speeds.

The objective of this research was to develop a model for characterizing the skid resistance-speed behavior of pavements and to relate this model to measures of pavement texture. Considerations are limited to measurements of skid resistance made according to the E 279-77 test method of the American Society for Testing and Materials (ASTM) (1). The effects of commercial tires, water-film thickness, and other test conditions are not considered here. Seasonal effects and variations in skid resistance caused by rain are also excluded from consideration because all data were obtained at the same time.

MODEL FOR THE RELATION BETWEEN SKID NUMBER AND SPEED

Three forms of the relation between skid number (SN) and speed (V) are considered; eventually, one is selected on the basis of how well it fits the experimental data and relates to the texture parameters.

A second-order relation is most frequently used to fit SN data (3):

$$SN = a_0 + a_1 V + a_2 V^2 \quad (1)$$

In this model, a_0 represents low-speed skid resistance and would therefore be expected to be related to some measure of microtexture. The skid number-speed gradient (SNG) for this model is

$$SNG \equiv -[d(SN)/dV] = -(a_1 + 2a_2 V) \quad (2)$$

and the percentage SNG (PSNG) is

$$PSNG \equiv (SNG/SN) \times 100 = [-(a_1 + 2a_2 V)100/a_0 + a_1 V + a_2 V^2] \quad (3)$$

The results of other investigations (4,5) have shown that PSNG is a function of macrotexture alone. The model in Equation 1 contradicts this observation because Equation 3 contains a parameter (a_0) that must be highly dependent on microtexture. Another deficiency of this model is that it often results in curve shapes that are concave downward (negative second derivative) or curves that indicate an increase of SN with speed at high vehicle speeds.

Majcherczyk (6) has plotted skid number versus speed data on log-log paper and obtained a linear fit, implying the following model:

$$SN = b_0 V^{b_1} \quad (4)$$

The gradient and percentage gradient for the model are as follows:

$$SNG = -b_0 b_1 V_1 \exp(b_1 - 1) \quad (5)$$

$$PSNG = (-b_1/V)100 \quad (6)$$

Majcherczyk found a correlation between b_1 and macrotexture that is consistent with earlier findings that PSNG at a given speed is a function of macrotexture alone. The deficiency of this model lies in its low-speed skid number behavior. The curve is so steep at low speeds that it predicts consistently high skid numbers at low speeds. The b_0 parameter, therefore, cannot be correlated with microtexture.

The model that was developed in the course of this research is

$$SN = c_0 \exp(c_1 V) \quad (7)$$

where c_0 is the zero speed intercept and the gradient and the percentage gradient are

$$SNG = -c_0 c_1 \exp(c_1 V) \quad (8)$$

and

$$PSNG = -100\, c_1 \quad (9)$$

As in Equation 1, low-speed skid resistance is indicated by the zero speed intercept of the curve fitting the data. It would therefore be anticipated that c_0 would be strongly correlated with parameters of microtexture. The c_1 parameter is proportional to the PSNG and should therefore be related to macrotexture parameters. It is interesting to note that the PSNG for this model is a constant that is independent of speed. In fact, the model in Equation 7 was suggested as a result of the observation that the PSNG of actual data did not vary significantly with speed. The model can be derived from the following definition of PSNG:

$$PSNG \equiv (-100/SN)\,[d(SN)/dV] \tag{10}$$

which can be rearranged to obtain

$$[d(SN)/SN] = (-PSNG/100)\,dV \tag{11}$$

Integrating from zero to any speed and assuming the PSNG is independent of speed,

$$\ln(SN_V/SN_{V=0}) = -(PSNG/100)\,V \tag{12}$$

which yields the Pennsylvania State University (PSU) model for skid resistance-speed behavior:

$$SN = SN_0 \exp[-(PSNG/100)\,V] \tag{13}$$

where

SN_0 = zero speed intercept (related to microtexture) and
PSNG = percentage skid number-speed gradient (related to macrotexture).

A significant advantage of this model is that it separates the effects of macrotexture and microtexture.

Figure 1 shows the results of a least squares fit of the three models to three sets of skid resistance-speed data. Although the three models fit the data equally well, only the PSU model (Equation 13) consistently provides the expected shape and low-speed behavior. Further evidence of the superior ability of this model to fit skid resistance-speed data may be found in the treatment of data for six pavements where the vehicle speed ranged from 16 to 80 km/h (10 to 50 mph) (7).

The speed gradient from Equation 13 is

$$SNG = SN_0\,(PSNG/100)\exp[-(PSNG/100)\,V] \tag{14}$$

If it is assumed that SN_0 is a function of microtexture and PSNG is a function of macrotexture, then SNG is a function of both macrotexture and microtexture. For two surfaces with the same macrotexture, the one with a better microtexture will have a steeper gradient.

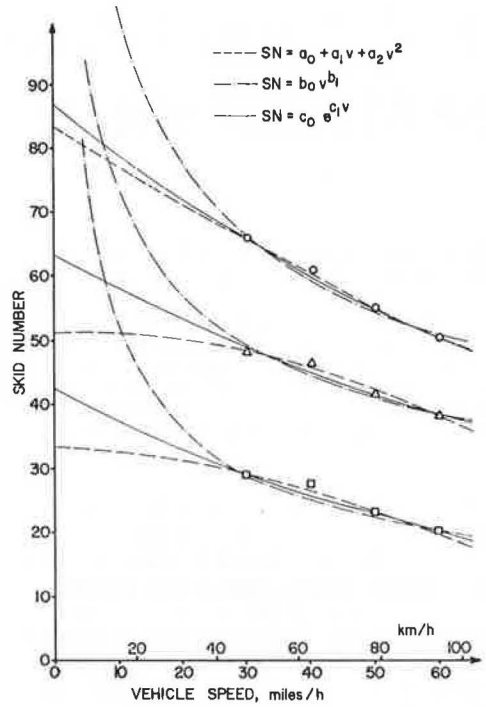
Findings in earlier research appear to be consistent with the PSU model. Sabey (8) and Gallaway and Rose (9) both found a higher correlation between macrotexture and PSNG than between macrotexture and SNG. Schulze (10), using model surfaces, concluded that surfaces with high microtexture produce high skid numbers at low speeds and a steeper SNG than do surfaces with low microtexture. Mahone (11), in research on actual pavements, found that surfaces that originally had a steep gradient would have an intermediate gradient after polishing (wearing away of the microtexture).

DATA BASE

The skid resistance data used in this study were obtained by the West Virginia Department of Highways on 20 test sections in West Virginia in July 1976. The tests were conducted in accordance with ASTM E 274-77 at speeds of 48, 64, 80, and 96 km/h (30, 40, 50, and 60 mph). Twelve tests were made at each speed, and the average values were used in the study. A least squares fit of the data to the PSU model (4) was performed to provide values of SN_0 and PSNG for each pavement.

At the time the skid resistance measurements were made, two core samples were taken from each section and sand-patch measurements (8) were performed by personnel of the West Virginia Department of Highways. During the same week, PSU personnel recorded macrotexture and microtexture profiles. PSU personnel subsequently analyzed the profile data to obtain root mean square values for the heights of the macrotexture and microtexture profiles ($RMSH_{MA}$ and $RMSH_{MI}$ respectively) (7) and obtained British portable numbers from the core samples.

Figure 1. Test of three models for relation between skid number and vehicle speed.



PAVEMENT MACROTEXTURE AND PSNG

To test the hypothesis that macrotexture parameters can be used to predict PSNG, two parameters were considered: root mean square height ($RMSH_{MA}$) from profile analysis and sand-patch mean texture depth (MD). A high degree of correlation was found between these two parameters (Figure 2). Therefore, either of the two can be selected with similar results.

Figure 3 shows the correlation of PSNG with MD. The relation

$$PSNG = 4.1(MD)^{-0.47} \tag{15}$$

is seen to fit the data well. Similar results were obtained when $RMSH_{MA}$ and other profile-derived parameters were used (7).

Although the sand-patch method is relatively simple, it has two disadvantages as a method for measuring macrotexture: (a) It is somewhat lacking in precision, and (b) it requires closing the pavement to traffic. Noncontacting methods that can be used at traffic speeds are under development (5) and should be considered as substitutes for sand-patch or profiling techniques.

PAVEMENT MICROTEXTURE AND SN_0

Two microtexture parameters, root mean square height ($RMSH_{MI}$) from profiles and British portable number (BPN) from core samples, are available to test the hypothesis that SN_0 can be predicted from microtexture data. The values of $RMSH_{MI}$ depend on the definition of the size range of microtexture. Values for $RMSH_{MI}$ were computed as a function of the largest wavelength considered. The cutoff wavelengths ranged from 0.05 to 2.54 mm (0.002 to 0.10 in). A correlation between the resulting values of $RMSH_{MI}$ and SN_0 was then attempted for each cutoff wavelength. The highest correlations, with correlation coefficients of 0.69 and 0.87 for two data sets, were obtained for the cutoff wavelength of 0.5 mm (0.02 in) (7). Microtexture is therefore defined here as consisting of asperities whose width is less than 0.5 mm.

The correlation between the $RMSH_{MI}$ of asperities less than 0.5 mm (0.02 in) wide and the BPN from the core samples is shown in Figure 4. The fact that only two core samples were obtained at each test section could account for some of the scatter.

In Figure 5, SN_0 is plotted versus BPN for 20 test sites. A least squares regression analysis yields the following:

$$SN_0 = -31 + 1.38\ BPN \tag{16}$$

with a correlation coefficient of 0.75. Other data obtained at six sites in Pennsylvania, for which BPN measurements were taken at five rather than two locations at each site, are given by Leu (7). For these data, the regression equation was

$$SN_0 = -35 + 1.32\ BPN \tag{17}$$

with a correlation coefficient of 0.95.

PREDICTION OF SNs FROM TEXTURE PARAMETERS

By combining Equations 13, 15, and 16, a relation can be obtained for SN, MD, BPN, and V:

$$SN = (-31 + 1.38\ BPN)\exp[-0.041\ V(MD)^{-0.47}] \tag{18}$$

Values of SN_{40} and SN_{60}, calculated from the texture data by using Equation 18, are compared with the mea-

Figure 2. Mean texture depth versus root mean square macrotexture height.

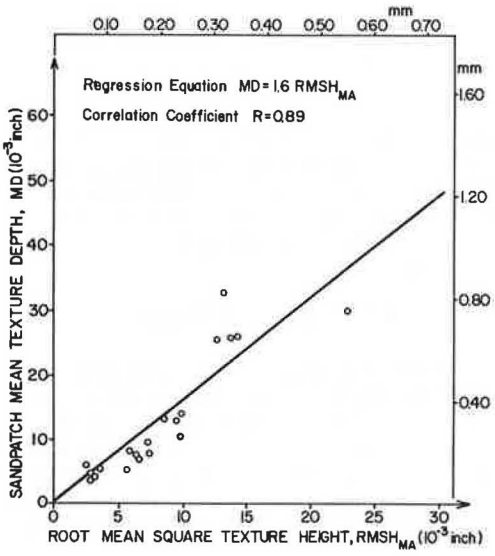


Figure 3. Percentage skid number-speed gradient versus mean texture depth.

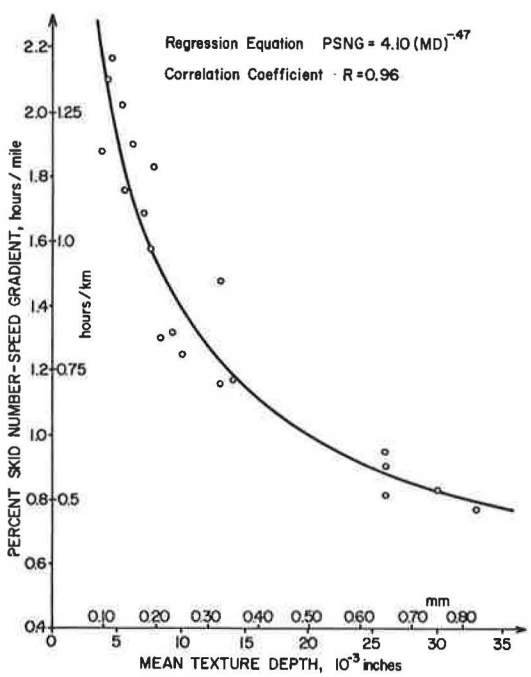


Figure 4. British portable number versus root mean square microtexture height.

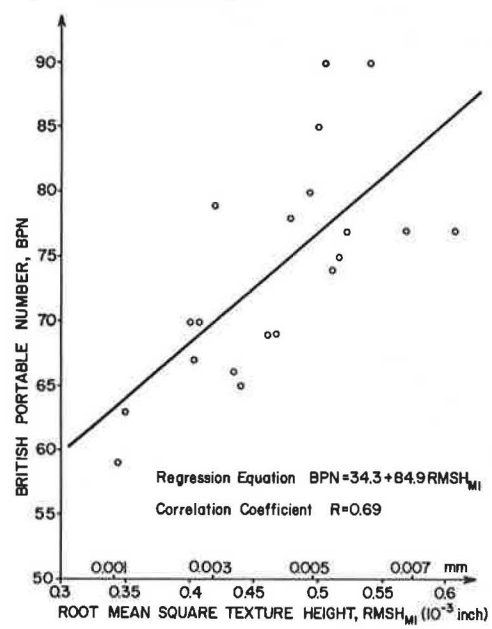
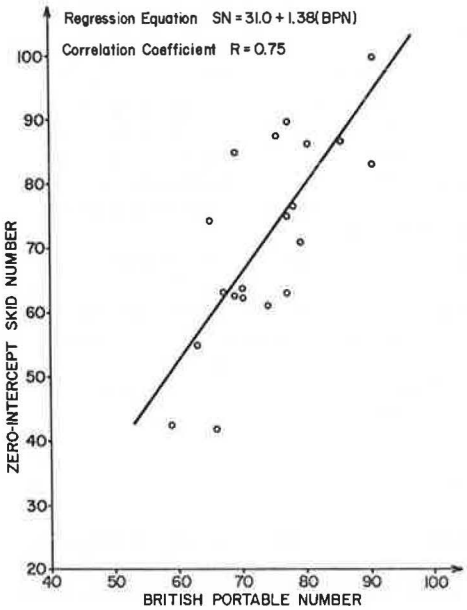


Figure 5. Zero speed intercept skid number versus British portable number.



sured skid numbers shown in Figure 6. Although the method provides good prediction of skid resistance, better results could be expected if more extensive BPN data were available.

The combination of an SN measurement and a macrotexture measurement can also be used to predict SNs at other speeds. For example, SN_{40} [64 km/h (40 mph)] and MD could be used by combining Equations 13 and 15 to yield

$$SN = SN_{40} \exp[-0.041(V - 40)(MD)^{-0.47}] \quad (19)$$

Figure 7 shows excellent agreement between measured SN_{60} [96 km/h (60 mph)] and the predictions from Equation 19. Noncontacting methods for measuring macrotexture at traffic speeds would provide a more convenient technique for use in an equation of the form of Equation 19; such methods are now being developed (5).

Figure 6. Measured skid number versus predicted skid number for British portable number and mean texture depth.

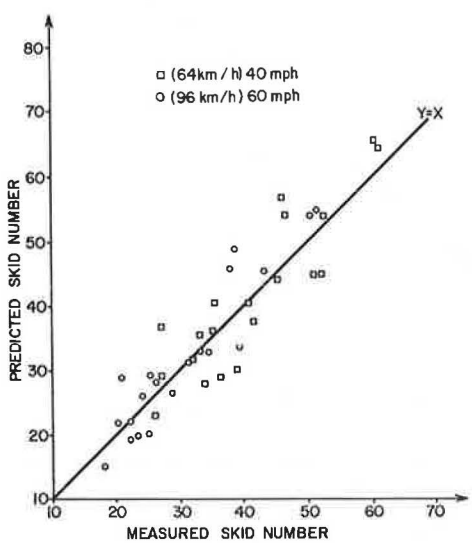
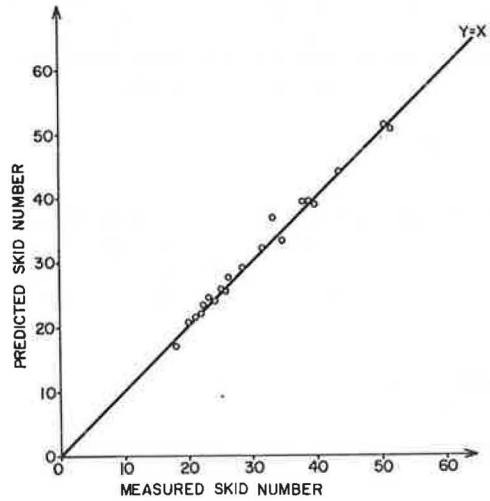


Figure 7. Skid number at 96 km/h (60 mph) as measured and predicted from skid number at 64 km/h (40 mph) and mean texture depth.

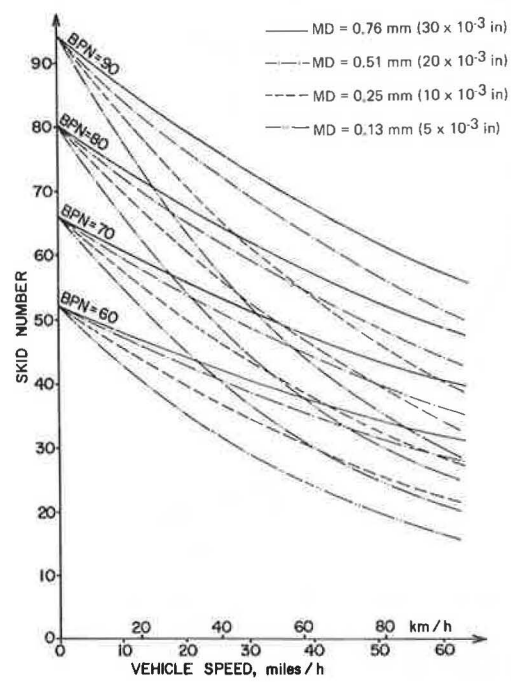


The relation between SN and V for various macrotextures and microtextures is shown graphically in Figure 8. In designing pavements for good skid resistance at low speeds, it is important to provide high BPN levels; for adequate skid resistance at high speeds, it is necessary to have high MD values.

CONCLUSIONS AND RECOMMENDATIONS

Skid resistance at any speed can be predicted from one microtexture and one macrotexture parameter by using the Pennsylvania State University model for skid resistance-speed behavior. An advantage of this model is that it clearly distinguishes the roles of macrotexture and microtexture. Another application of this model permits the prediction of skid resistance at any speed

Figure 8. Relation between skid number and vehicle speed for various conditions of pavement texture.



from a measured skid number at one speed and a macrotexture measurement.

Although British portable number and sand-patch texture depth are adequate measures of microtexture and macrotexture, they do require the interruption of traffic. It is unlikely that microtexture can be measured at high vehicle speeds. Progress is being made, however, in the development of noncontacting, high-speed methods for measuring macrotexture. The development of these methods should be encouraged so that a simultaneous macrotexture measurement and skid number measurement can be obtained that will make it possible to determine the skid resistance-speed characteristics of a pavement from a single test.

ACKNOWLEDGMENTS

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Discussion

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One of the mathematical models proposed by Leu and Henry allows prediction of a skid number at one vehicle speed from a combination of a skid number at another vehicle speed and a macrotexture measurement. Equation 19 is an expression of this model in which the constants were derived from tests on 20 bituminous pavements in West Virginia. For the West Virginia pavements, SN_{40} varied from 26 to 61 and mean sand-patch texture depth from 0.08 to 0.83 mm (0.003 to 0.032 in). It has recently been shown (12) that Equation 19 is also valid for 31 experimentally textured bituminous pavements in Texas (13) for which the range in SN_{40} is comparable to that in West Virginia but the range in texture depth is much greater [0.25 to 3.15 mm (0.01 to 0.12 in)]. The purpose of this discussion is to show that Equation 19 applies equally to a group of experimentally textured concrete pavements in New York State.

The New York data were collected at five different experimental sites, and each was textured by the same four methods—burlap drag, natural bristle paving broom, wire brush, and fluted float (14,15). Skid resistance at 64.5 and 88.5 km/h (40 and 55 mph) and sand-patch texture depths were measured immediately after construction and at various times over the next 4 years. SN_{40} in the New York data varied from 20 to 72 and sand-patch texture depth from 0.20 to 1.65 mm (0.008 to 0.064 in).

The New York data were first used to develop the relation between MD and PSNG (Figure 3). Fitting an exponential curve of the form of Equation 15 to these data resulted in the regression shown in Figure 9. Although the scatter of data points about this regression is greater than that found by Leu and Henry, the correlation coefficient (0.61) is significant at the 0.01 level and, more important, the constants in the regression equation are similar.

Because of this similarity, Equation 19 was used with the authors' constants (4.1 and 0.47) to estimate values of SN_{55} from measured values of SN_{40}. Comparison of the estimated and measured values of SN_{55} is shown in Figure 10 in which the 0.95 prediction limits for the regression and the line of equality are shown as broken lines. The regression itself is not plotted because of its close correspondence with the line of equality. The prediction limits correspond to a standard error of estimate of 2.6 skid numbers, a value only slightly larger than the measurement error associated with typical skid tests performed according to ASTM E 274 (16).

Thus, experience with bituminous pavements in Texas and concrete pavements in New York, which represent textures produced by a variety of methods, supports the authors' contention (based on experience in West Virginia) that skid resistance at one speed can be estimated with reasonable accuracy from a combination of skid resistance measured at another speed and a measurement of pavement macrotexture.

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Figure 9. Percentage skid number-speed gradient versus mean texture depth for experimental concrete textures in New York.

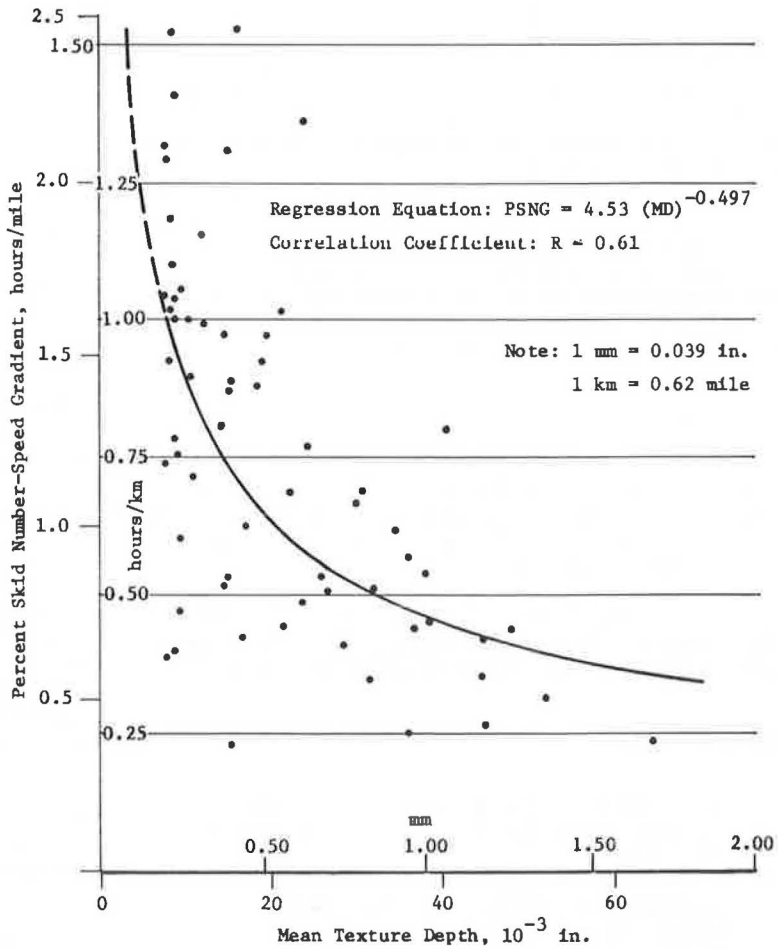
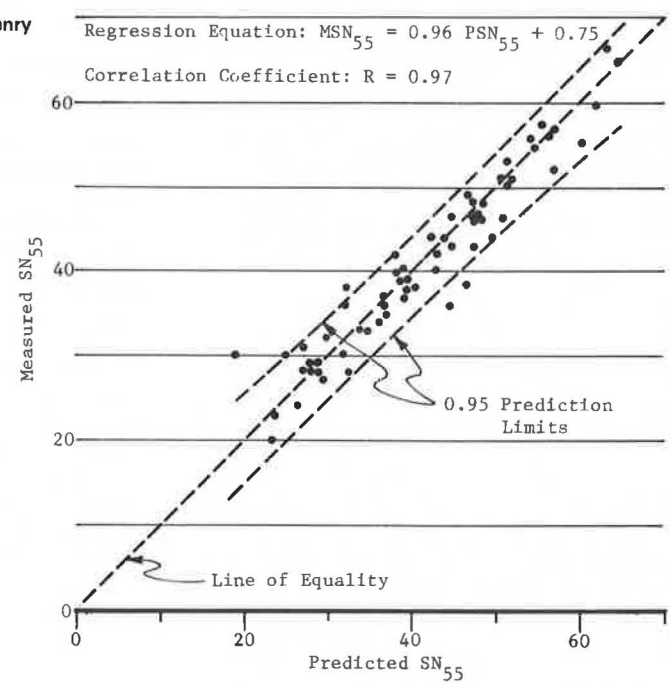


Figure 10. Prediction of SN_{55} by use of the Leu and Henry model.



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Authors' Closure

We would like to express our appreciation to Chamberlin for making available additional data in support of one aspect of our research. Chamberlin's regression coefficients of 4.53 and 0.497 are in good agreement with ours of 4.10 and 0.47 respectively, considering the precision of the correlated data (SN_{40} and mean depth measured by the sand-patch method). Research that will consider 20 sites in Pennsylvania is planned for 1979, so we would welcome similar data from others.

Equation 19 eliminates the parameter SN_0 from our model (Equation 13). We have found that this parameter is affected by both microtexture and short-term variations in weather. Weather-related effects are eliminated by conducting all skid measurements in one weather area at the same time. However, it is probably not possible to compare data sets taken at different locations at different times without correcting for weather-related factors such as rainfall history. The differences between Equations 16 and 17 can be attributed in part to these effects, and larger differences might be expected. Research into seasonal and short-term variations is under way and, if it is successful, we may be able to account for microtexture and weather in a generalized model.

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Determination of Skid Resistance-Speed Behavior and Side Force Coefficients of Pavements

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Pavement friction characteristics including skid resistance-speed dependence, side force coefficients, and brake slip numbers are seen to be derivable from data obtained in the transient slip test. The transient slip test is described, and it is noted that any friction tester with force-measuring transducers can be used for these measurements. The brake slip numbers are shown to be independent of the rate of wheel lockup, which leads to the observation that brake slip numbers obtained during a transient slip test are equivalent to locked-wheel skid numbers at the same sliding speed. Side force coefficients can be computed from transient slip data with the help of a model. The data and conclusions apply to the standard skid-test tire operating under fixed test conditions and normal load, water film thickness, and inflation pressure.

Highway safety in the United States is currently evaluated by using locked-wheel skid numbers (1). During the lifetime of a pavement wearing course, the skid number (SN) is measured at least once a year at a single vehicle speed—usually 65 km/h (40 mph)—although sometimes at the "prevailing traffic speed." Because vehicles are operated on highways at a variety of speeds and only rarely in the locked-wheel mode, the ranking of pavement safety by means of a locked-wheel test at a single speed can be questioned. Furthermore, vehicles require adequate lateral forces to maintain directional stability in cornering maneuvers. In a complete evaluation of pavement safety, it is necessary to measure the complete frictional characteristics of a pavement at various speeds, cornering angles, and wheel stop rates. It would clearly be impractical to do this for each pavement in the country on an annual basis.

Research was initiated at the Pennsylvania Transportation Institute (PTI), Pennsylvania State University, to determine the degree of interrelationship among slip, side force, and locked-wheel data (2,3). The objective of this research was to determine the most efficient means of evaluating the frictional capability of pavements. As a result of this research, a methodology was developed for processing data from a single measurement at one vehicle speed to obtain the speed dependence and side force frictional characteristics of a pavement.

EXPERIMENTAL PROCEDURE

The Penn State Mark III Road Friction Tester (4) was used in this study. The tester has a single wheel, a six-component force-torque measuring hub, and a hydraulic system that can steer the test wheel into angles of up to 12° in relation to the forward velocity of the towing vehicle. Two rotary variable differential transformers measure the angle of the test trailer and the angle of the free-trailing fifth wheel relative to the truck axis. In this way, the actual yaw angle of the test trailer—including the correction for any yaw it induces in the