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DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE AND PAVEMENT SURFACE TEXTURE

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DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE AND PAVEMENT SURFACE TEXTURE

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Abstract

The Pennsylvania Transportation Institute at the Pennsylvania State University has conducted a comprehensive study on the development of some empirical relationships between skid resistance and pavement surface texture. This paper describes a part of the findings of this study. The most conceptually satisfying model, the Penn State Model for skid resistance-speed behavior, was developed and has shown that the model coefficients correlate well with texture parameters. Skid resistance at any speed can be predicted from one microtexture and one macrotexture by using this model.

Another attempt was made to develop the prediction model of skid number with ribbed and blank test tires from surface texture parameters and vice versa. Linear regression equations were used to relate each of the two tire test results to a measure of microtexture defined by British Pendulum Number (BPN) measurements, and to a measure of macrotexture defined by mean texture depth (MTD) determined from sand-patch tests. The concept of using both types of skid test data shows promise as a candidate indirect texture parameter measurement method.

1. Introduction

Adequate skid resistance of pavement surface is important for maintaining safe vehicle operation. A number of studies have shown that the wet-pavement accident rate is related to the skid resistance of the pavement. A Kentucky study showed that a 25 percent reduction in the friction level could increase the proportion of wet-pavement accidents by more than 50 percent¹⁾, and also showed that the existence of a threshold or minimum friction level²⁾ (Fig. 1). If pavement friction falls below this value, the effect on accident would be felt, and there would be a sharp rise in accidents with further friction reduction. It is, therefore, important to maintain skid resistance at levels sufficient to prevent high wet-pavement accident rate.

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The wet-pavement skid resistance of the primary highway systems of nearly all states in the United States is monitored in annual surveys by using test procedure specified by ASTM E 274 method of test³. This method is used to determine the skid resistance of wet-pavement with a ribbed test tire specified by ASTM E 501³ under fully specified conditions. The measurement are usually performed at one speed only, typically at 64 km/h (40 mph). The E 501 test tire has seven smooth, longitudinal ribs separated by six grooves, which provide for drainage of water from the tire-pavement interface as the tire slides over the wet-pavement during the test. A trailer with test tire is towed at constant speed, water is supplied at constant rate through standard nozzle to the tire-pavement interface, test tire is locked and friction force (F_f) and normal load (F_n) are measured. The skid number at test speed V (SN_v) is then calculated as

$$SN_v = 100F_f/F_n \tag{1}$$

This method has been widely accepted because it is relatively straightforward and has an obvious connection with the problem it was designed to combat, i. e., the skidding of automobiles on slippery road. It does, however, have a number of drawbacks, among which are: (1) continuous measurement of skid resistance is not possible; (2) initial and operating costs of the test equipment are high; (3) tests are conducted only at one speed so that speed dependence of skid resistance cannot be determined without repeated measurements on same section of road; and (4) skid resistance can not be measured on nontangent of roadway the desired test speed is higher than the attainable test vehicle speed, either because of risk of an accident or because of dynamic effects on the measurements⁴. All of these drawbacks require some alternative methods for determining the skid resistance of the pavement surfaces.

It is now generally agreed that the skid resistance of a pavement is fundamentally controlled by the surface texture characteristics. Therefore, by measuring the relevant texture describing parameters, or by measuring a physical process dependent on texture, regression techniques can be used to relate skid resistance to the chosen texture parameter or measured process. Two scales of texture are of particular importance: microtexture (small-scale asperities) and macrotexture (large-

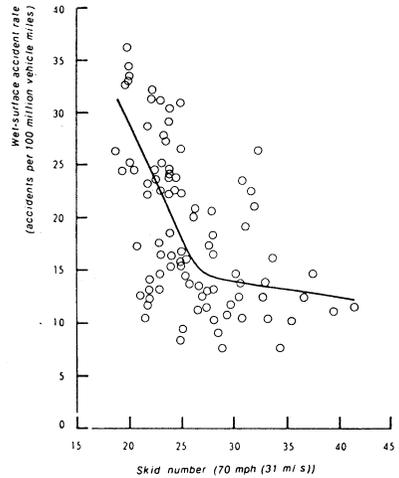


Fig. 1 Five Point Moving Averages for Wet-Surface Accident Rate for Summer-Fall Period Versus Skid Number

DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
AND PAVEMENT SURFACE TEXTURE

scale asperities). Therefore, it is possible to develop an analytical procedure or model for determining the relation between skid resistance and pavement surface texture by using these two scales of texture, and thus for predicting skid resistance indirectly and inexpensively.

The Pennsylvania Transportation Institute (PTI) at the Pennsylvania State University has recognized these needs and has conducted a comprehensive study on the development of some empirical relationships between skid resistance and pavement surface texture. This paper describes a summary of the findings.

2. Role of Pavement Texture in Skid Resistance

The measurement of the texture of highway pavements is of interest to highway engineers because it has a direct influence on the level of tire-pavement interaction, particularly under wet conditions. Pavement texture also influences other safety aspects, such as splash and spray from wet-pavements, and glare and light condition.

The skid resistance of a pavement is determined by its surface texture which can be divided into two scales, microtexture and macrotexture, which are specified by ASTM E 867³⁾ as

Texture, pavement-micro-- the deviations of pavement surface from a true planar surface with the characteristic dimensions of wavelength and amplitude less than 0.5 mm

Texture, pavement-macro-- the deviations of pavement surface from a true planar surface with the characteristic dimensions of wavelength and amplitude from 0.5 mm up to those that no longer affect tire-pavement interaction

Kummer and Meyer⁵⁾ reported the combined effects of microtexture and macrotexture. Microtexture, the fine scale surface texture of the pavement aggregate, determines the skid resistance at low speeds. Macrotexture, on the scale of the gradation of the aggregate, influences the wet skid resistance by determining the rate at which water can escape from the tire footprint, and therefore is responsible for the rate at which skid resistance decreases as speed increases. Thus, it should be possible to predict the skid resistance-speed curve from suitable microtexture and macrotexture parameters. The first part of this paper refers to the development of a model for characterizing the skid resistance-speed behavior of pavements and to relate this model to suitable measures of pavement surface texture.

In an attempt to better define the skid resistance values of pavements, researchers have begun to investigate comparisons of skid resistance data using the ASTM E 274 locked wheel of test with ribbed E 501 and blank E 524³⁾ test tires. The E 501 test tire has seven smooth longitudinal ribs, separated by six grooves, which are sufficiently deep so that as the tire wears over its allow-

able useful life the test results are not significantly affected. As a consequence, tests with this tire are insensitive to the rate of water application over a fairly wide range⁶⁾ (Fig. 2). Recently, the use of the ribbed test tire for evaluating wet pavement safety has been questioned⁷⁾⁸⁾. Several states agencies, including Connecticut, Florida, Illinois, have been investigating the use of the blank tire, specified by ASTM E 524 "Standard specification for smooth-tread tire for specific-purpose pavement skid resistance tests". Results from these studies have shown that the ribbed tire skid resistance values provide a good evaluation

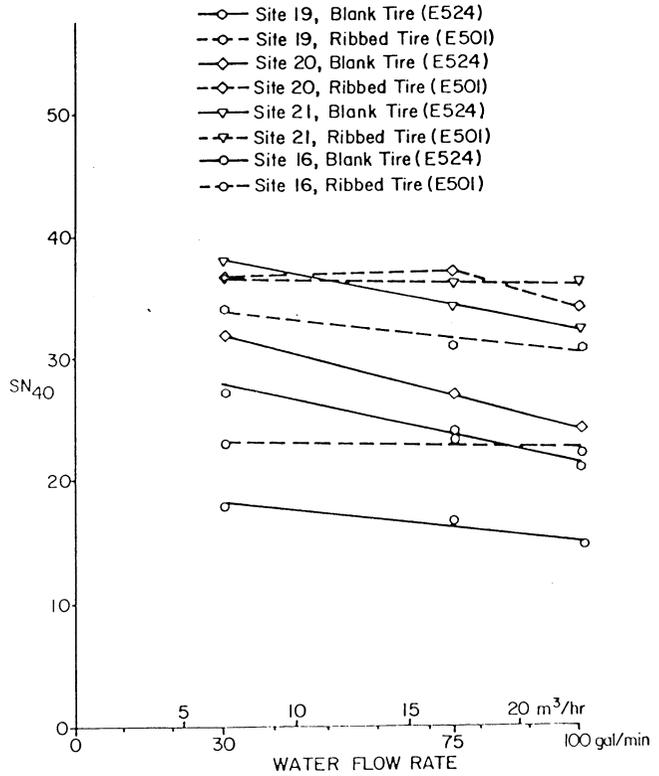


Fig. 2 Effects of Water Flow Rate on Skid Resistance Measurements (Penn State Nozzle)

of microtexture, but is not sensitive to macrotexture, which is an important factor in wet-pavement safety. The apparent insensitivity of the ribbed tire to macrotexture is felt to be a result of the deep, continuous grooves on the tire which, without the aid of the pavement macrotexture, artificially provide water drainage from the footprint area. On the other hand, tests with the blank E 524 test tire have produced skid resistance data which are sensitive to both microtexture and macrotexture.

The apparent sensitivities of the two types of tires suggest that the ribbed versus blank tire skid test comparison is a promising indirect method of measuring both microtexture and macrotexture. Conversely, if both microtexture and macrotexture measurements are made, this concept gives promise as a candidate indirect method for predicting the level of skid resistance.

The second part of this paper refers to the development of a prediction models which can be used to estimate the skid-resistance level with both ribbed and a blank-test tire from the actual

DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
AND PAVEMENT SURFACE TEXTURE

measurements of pavement surface texture parameters. An attempt is made also to develop the relationship between pavement texture and skid resistance with both tires.

3. Development of a Model for Skid Number-Texture-Speed Relationship

The objective of this part is to develop a model to predict the skid number at any speed, SN_v, and appropriate skid number speed gradient parameters. The development of this model will employ both conceptual mechanisms of the influence of texture on skid resistance and empirical techniques such as regression analysis to establish coefficient values of the model. The model is consistent, conceptually, with the known influences of texture on skid resistance, i.e., the model must exhibit the same characteristics as the experimental data, and has empirically determined coefficients. The need for both empirically and conceptually valid models is illustrated by the following discussion.

3 - 1. Conceptual Model for the Skid Number-Speed Relationship

Three forms of the skid number (SN) versus speed (V) relationships are considered here, leading to the selection of one based on its ability to fit experimental data and to relate to texture parameters.

A second order relationship is most frequently used to fit SN data:

$$SN_v = a_0 + a_1V + a_2V^2 \quad (2)$$

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

$$SNG = - \frac{d(SN)}{dV} = - (a_1 + a_2V) \quad (3)$$

and the percent normalized skid number speed gradient (PNG) is:

$$PNG = \frac{SNG}{SN} \times 100 = \frac{-(a_1 + 2a_2V) \times 100}{a_0 + a_1V + a_2V^2} \quad (4)$$

The results of other investigations have shown that SNG is a function of macrotexture alone⁹⁾¹⁰⁾. The above model (2) is in contradiction with this observation since expression (4) contains a parameter a_0 which 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 speeds.

Majcherczyk¹¹⁾ developed a log-log model of the form:

$$SN_v = b_0 V^{(b_1 - 1)} \quad (5)$$

The gradient and percent normalized gradient for this model are:

$$SNG = -b_0 b_1 V^{(b_1 - 1)} \quad (6)$$

$$PNG = \frac{-b_1}{V} \times 100 \quad (7)$$

Majcherczyk found a correlation between b_1 and macrotexture which is consistent with earlier that SNG at a given speed is a function of macrotexture alone. This model has a conceptual weakness in its prediction of the low speed skid number behavior. The shape of the resulting curve is so steep at low speeds that it predicts consistently high skid number at low speeds. The parameter b_0 therefor cannot be correlated with microtexture.

The most conceptually satisfying model was developed in this study¹²⁾. The model has the form:

$$SN_v = c_0 e^{c_1 V} \quad (8)$$

with the gradient and percent normalized gradient given by

$$SNG = -c_0 c_1 e^{c_1 V} \quad (9)$$

$$PNG = -100 c_1 \quad (10)$$

The model can be derived from the definition of PNG:

$$PNG = -\frac{100}{SN} \frac{d(SN)}{dV} \quad (11)$$

which can be rearranged to obtain

$$\frac{d(SN)}{SN} = -\frac{PNG}{100} V \quad (12)$$

Integrating from zero to any speed, assuming the PNG is independent of speed:

$$\int_{SN_0}^{SN_v} \frac{d(SN)}{SN} = -\frac{PNG}{100} \int_0^v dV \quad (13)$$

which yields the "Penn State Model" for skid resistance-speed behavior (Fig. 3):

$$SN_v = SN_0 e^{-\frac{PNG}{100} V} \quad (14)$$

DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
AND PAVEMENT SURFACE TEXTURE

where: SN_0 = the zero speed intercept

PNG = percent normalized skid number-speed gradient

This model is consistent with the known skid number texture-gradient relationships in that c_0 (the low-speed number, SN_0) can be correlated with microtexture alone, and c_1 (which is proportional to PNG) can be correlated with macrotexture alone. It is interesting to note that the PNG for this model is a constant, independent of speed. This is consistent with the observation that the PNG for experimental data does not vary significantly with speed.

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

3 - 2. Empirical Relation Between Model Coefficients and Texture

The coefficients of the model were derived empirically, i. e., estimated through regression analysis from the data. In the analysis, separate regression relationships for microtexture and macrotexture were developed in the following forms:

$$SN_0 = k_1 + k_2 (mt) \quad (15)$$

$$PNG = k_3 (MT)^{k_4} \quad (16)$$

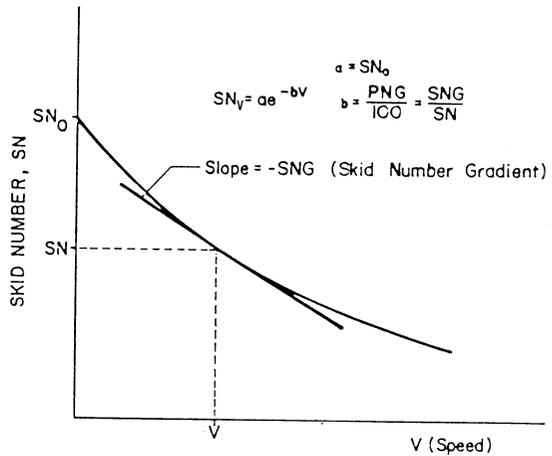


Fig. 3 Model for Skid Resistance-Speed Behavior

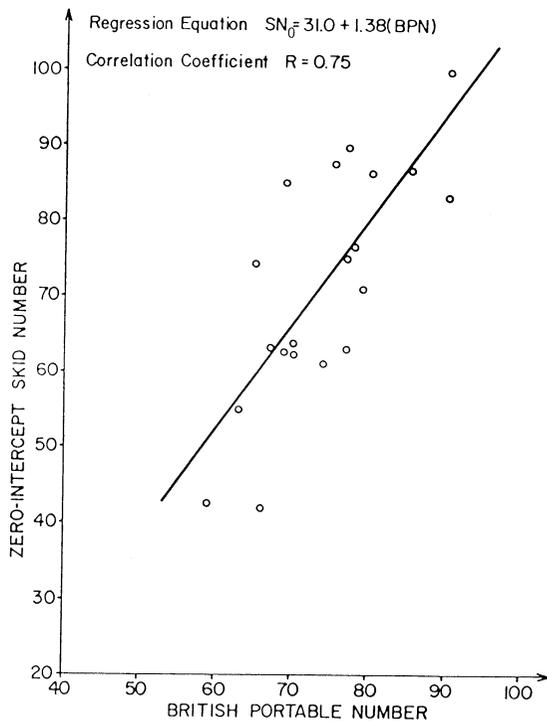


Fig. 4 Zero Speed-Intercept Skid Number (SN_0) Versus British Pendulum Number (BPN)

where mt = microtexture parameter

MT = macrotexture parameter

When substituted these two equations into the Penn State Model, this yields:

$$SN_v = [k_1 + k_2 (mt)] e^{-k_3 V (MT)^{k_4}} \tag{17}$$

The skid resistance data used in the analysis were obtained by the West Virginia Department of Highways on 20 test sections in West Virginia in 1976.

The test were conducted in accordance with ASTM E 274 method of test at speeds of 48,64,80, and 96 km/h (30, 40, 50, and 60 mph). A least squares fit of data to the Penn State Model was performed to provide values of SNo and PNG for each of the

pavement. At the time skid resistance measurements were made, two core samples were taken from each sections. The British pendulum number (BPN) in accordance with ASTM E 303³⁾ and sand-patch mean texture depth (MTD) in accordance with ASTM E 965³⁾ were obtained from the core samples. BPN is frequently used as a measure of microtexture parameter. BPN is, in fact, a direct measure of low-speed sliding friction. MTD is a measure of macrotexture.

To test the hypothesis that the zero speed skid number intercept (SNo) can be predicted by microtexture data, SNo is plotted against BPN for the 20 test sites as shown in Fig. 4. A least squares regression analysis yields:

$$SN_0 = 1.38 BPN - 31 \tag{18}$$

with a correlation coefficient of 0.75. Other data obtained on six sites in Pennsylvania¹³⁾, the re-

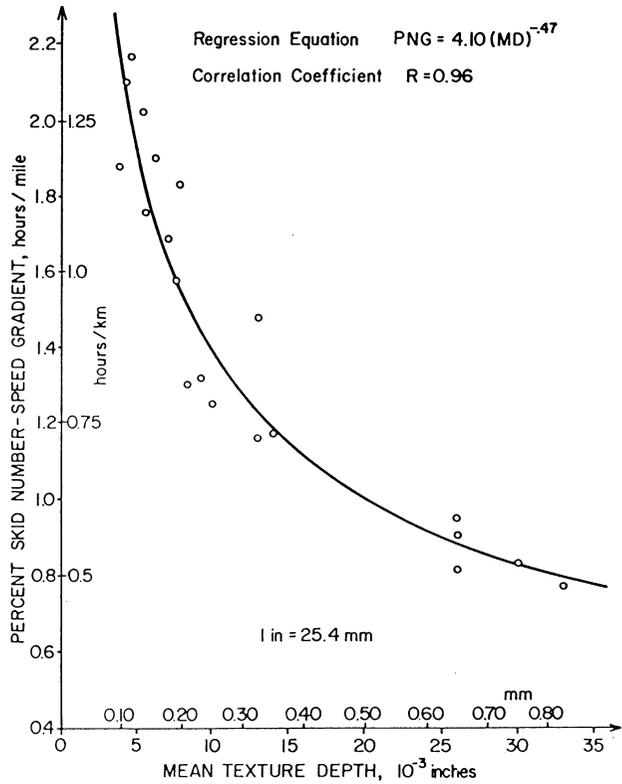


Fig. 5 Percent Normalized Skid Number-Speed Gradient (PNG) Versus Mean Texture Depth (MTD)

DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
AND PAVEMENT SURFACE TEXTURE

gression equation was:

$$SN_0 = 1.32 BPN - 35 \quad (19)$$

with a correlation of 0.95.

To test the hypothesis that macrotexture parameter can be used to predict the PNG, PNG is plotted against MTD data for the 20 test sections as shown in Fig. 5. The resulting relationship of the least squares regression analysis is :

$$PNG = 4.1 (MTD)^{-0.47} \quad (20)$$

with a correlation coefficient of 0.96. This relationship is seen to fit the data quite well.

By substituting Eqs. (18), (20) into Eq. (17), a relationship between skid number (SN), British pendulum number (BPN), and sand-patch mean texture depth (MTD), and speed (V) can be obtained:

$$SN_v = (1.38 BPN - 31) e^{-0.041 (MTD)^{-0.47}} \quad (21)$$

The relationship between skid number and speed for various microtexture and macrotexture is presented in Fig. 6. In designing pavements for good skid resistance at low speeds, it is important to provide high BPN levels, while for adequate skid resistance at high speeds it is necessary to have high values on MTD, macrotexture.

4. Development of Models for Skid Number-Surface Texture Relationship

The objective of this part is to develop the prediction model of skid number with ribbed and blank test tires from pavement surface texture parameters, and vice versa. In an attempt to better define the skid-resistance values of pavements, Henry⁽⁹⁾ has compared the skid-resistance data measured with both the ribbed and blank test tires. The data are plotted in Fig. 7 with BPN and

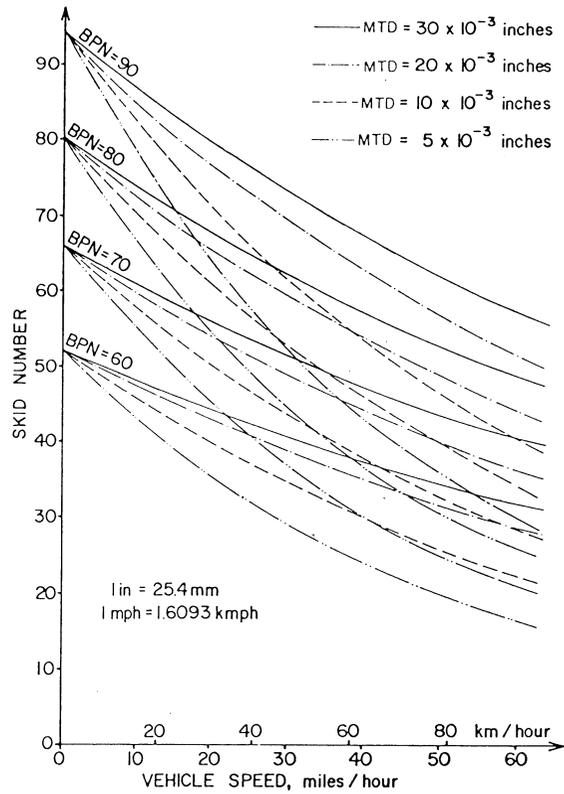


Fig. 6 The Skid Number-Speed Relationship for Different Pavement Texture Conditions

MTD. Examination of Fig. 7 shows that the ribbed tire ranks the pavements more strongly according to microtexture (BPN) than does the blank tire. The blank tire, however, ranks both according to microtexture (BPN) and macrotexture (MTD), while the ribbed tire is unable to distinguish differences in macrotexture. The apparent sensitivities of the types of test tires suggest that the ribbed, versus blank tire skid test comparison is a promising indirect method of measuring both microtexture and macrotexture. To test this hypothesis, two approaches have been tried as described by the following discussion.

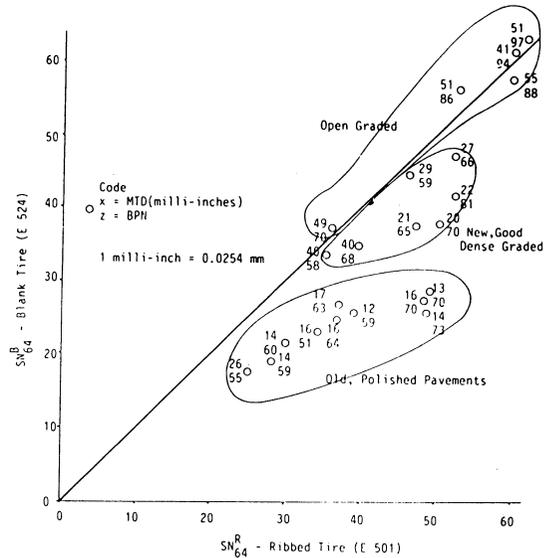


Fig. 7 Comparison of Skid-Resistance Data Measured with the Ribbed and Blank Test Tires (Pennsylvania Sites, 1978)

4 - 1. Prediction Model of Skid Number with Both Test Tires

The first approach was suggested by Philip Dierstein of the Illinois Department of Transportation ¹⁴⁾, who proposed the prediction of macrotexture using a macrotexture index defined as follows:

$$MTI = 1 + \frac{SN_{64}^R - SN_{64}^B}{SN_{64}^R + SN_{64}^B}$$

$$= \frac{2}{1 + SN_{64}^B / SN_{64}^R} \quad (22)$$

where SN_{64}^R = skid number with the ribbed test tire at speed 64km/h (40 mph)

Table 1. Macortexture Index (MTI) for Pennsylvania Sites

Site No.	SN_{64}^R	SN_{64}^B	Computed MTI	Texture Depth MTD (mm)	Pavement Type
June 1980					
2	28.0	14.8	1.31	0.33	PCC
3	46.0	28.9	1.23	0.30	PCC
9	40.7	32.3	1.12	0.79	ACC
12	42.3	32.5	1.13	0.69	ACC
13	65.0	60.7	1.03	1.02	PCC
14	36.6	22.5	1.24	0.33	PCC
15	68.4	61.3	1.05	1.19	ACC
16	19.9	11.3	1.25	0.28	FCC
17	31.7	26.0	1.10	1.04	ACC
19	29.0	18.1	1.23	0.38	ACC
21	32.7	28.5	1.07	1.17	ACC
22	58.2	55.3	1.03	1.42	ACC
24	27.6	15.2	1.29	0.38	ACC
June 1981					
1	34.3	16.3	1.36	0.28	ACC
2	26.1	13.3	1.33	0.30	PCC
3	40.3	22.5	1.28	0.33	PCC
7	41.4	23.3	1.30	0.30	PCC
9	42.6	34.5	1.10	0.81	ACC
10	45.5	18.7	1.42	0.28	PCC
16	23.9	13.6	1.27	0.46	ACC
19	33.6	21.0	1.23	0.41	ACC
23	62.3	46.3	1.15	0.43	ACC
27	38.3	26.2	1.19	0.61	ACC
29	34.0	21.3	1.23	0.48	ACC
30	29.7	17.2	1.27	0.41	ACC
31	24.2	11.3	1.36	0.25	ACC
32	38.0	28.0	1.15	0.52	ACC
33	26.7	15.3	1.27	0.38	ACC
31	56.3	52.5	1.04	1.35	ACC
35	39.0	34.7	1.06	0.61	ACC
36	29.0	13.3	1.37	0.28	ACC

DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
AND PAVEMENT SURFACE TEXTURE

SN_{64}^B = skid number with the
blank test tire at speed
64 km/h (40 mph)

MTI = macrotexture index

When applied to the Illinois data, a linear regression of the logarithms of the sand-patch mean texture depth (MTD) and the macrotexture index resulted in the following:

$$\ln MTD = 0.469 - 5.12 \ln MTI \quad (23)$$

where MTD is expressed in mm (1 mm = 0.039 in).

No correlation coefficient was reported for this regression.

The macrotexture index was applied to Pennsylvania data for June 1980 and June 1981, and is tabulated in Table 1. These data was plotted in Fig. 8, and a least squares regression in

the form conducted by Illinois was carried out with the following result¹⁵⁾:

$$\ln MTD = 0.397 - 5.73 \ln MTI \quad (24)$$

with a correlation coefficient of 0.95. The similarity of these two results is encouraging. In view of the excellent correlation found for the Pennsylvania sites, this procedure appears to be a promising method for indirectly determining macrotexture from skid number with both ribbed and blank test tires at speed of 64 km/h (40 mph).

4 - 2 . Prediction Model of Skid Numbers from Texture parameters

Henry and Saito^{8), 16)} have attempted to relate both microtexture and macrotexture with skid numbers measure by ribbed and blank test tires. Linear regressions were carried out to the form:

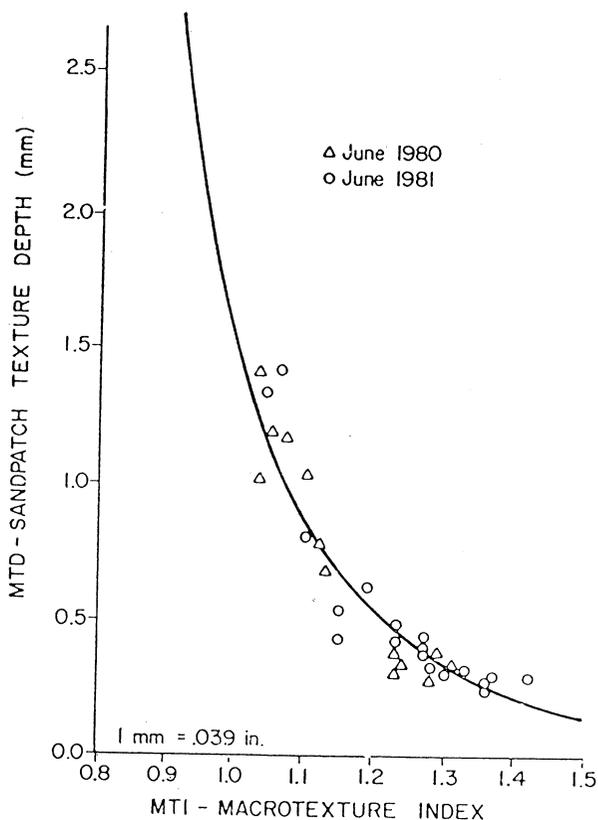


Fig. 8 Macrotexture Index (MTI) Versus Sand-Patch Mean Texture Depth (MTD) for Combined 1980-1981 Pennsylvania Data

$$\left. \begin{aligned} SN_{64}^R &= a_0 + a_1 BPN + a_2 MTD \\ SN_{64}^B &= b_0 + b_1 BPN + b_2 MTD \end{aligned} \right\} \quad (25)$$

The data were available from skid tests which were conducted with both ribbed and blank tires in 1979 and 1980 on 22 test sites in Pennsylvania. The test sites included 10 dense-graded, six open-graded, and six portland cement concrete surfaces. The multiple regression analysis produced the following results:

1979 data:

$$\left. \begin{aligned} SN_{64}^R &= 0.80 BPN - 4.72 MTD - 7.89 \quad (r = 0.86) \\ SN_{64}^B &= 0.64 BPN + 16.1 MTD - 19.68 \quad (r = 0.86) \end{aligned} \right\} \quad (26)$$

1980 data:

$$\left. \begin{aligned} SN_{64}^R &= 0.74 BPN + 5.91 MTD - 9.19 \quad (r = 0.96) \\ SN_{64}^B &= 0.54 BPN + 19.7 MTD - 16.87 \quad (r = 0.95) \end{aligned} \right\} \quad (27)$$

Subsequently, these data were combined, and a similar regression was performed, with the following results:

$$\left. \begin{aligned} SN_{64}^R &= 0.766 BPN + 4.72 MTD - 9.7 \quad (r = 0.92) \\ SN_{64}^B &= 0.628 BPN + 17.3 MTD - 19.5 \quad (r = 0.92) \end{aligned} \right\} \quad (28)$$

The results suggest that skid numbers with the ribbed test tire are highly sensitive to pavement surface microtexture and relatively insensitively to macrotexture, while skid numbers with the blank test tire are sensitive to both microtexture and macrotexture.

In addition, regressions were performed with the skid numbers as the dependent variables on combined 1979 and 1980 data in the following form:

$$\left. \begin{aligned} BPN &= c_0 + c_1 SN_{64}^R + c_2 SN_{64}^B \\ MTD &= d_0 + d_1 SN_{64}^R + d_2 SN_{64}^B \end{aligned} \right\} \quad (29)$$

with the following results:

DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
AND PAVEMENT SURFACE TEXTURE

$$\left. \begin{aligned} BPN &= 20 + 0.405 SN_{64}^R + 0.039 SN_{64}^B & (r = 0.91) \\ MTD &= 0.49 - 0.029 SN_{64}^R + 0.043 SN_{64}^B & (r = 0.86) \end{aligned} \right\} \quad (30)$$

The consistency of these data and the relatively high correlation coefficients obtained for the regressions indicate that skid number can be predicated from both microtexture parameter (BPN) and macrotexture (MTD) data by using an expression of the forms of equation (25). And they also suggest that both microtexture and macrotexture can be predicted from skid numbers data by using an expression of the form of equation (29). At this point, the coefficients given in equations (28) and (30) are recommended, but additional data should be obtained to verify the validity of the coefficients.

5. Conclusions and Recommendations

In this study, some attempts were made to relate the skid resistance to the pavement surface texture. The following conclusions and recommendations are drawn from the relationships developed in the study.

(1) The most conceptually satisfying model, the Penn State Model for skid resistance-speed behavior, was developed in the form of equation (8) and has shown that model coefficients correlate well with texture parameters.

(2) Skid resistance at any speed can be predicted from one microtexture and one macrotexture parameter, using the Penn State Model. To determine the speed dependence of skid resistance, measurements would have to be made at least at two different speeds, which increases the cost. Therefore, prediction of skid resistances would be very useful.

(3) The ribbed test tire provides a good evaluation of microtexture, but is not sensitive to macrotexture, which is an important factor in wet-pavement safety. The blank test tire is sensitive to both microtexture and macrotexture. Based on these differences in the dependency of skid resistance with ribbed and blank test tires on microtexture and macrotexture, the relationships between skid numbers with both test tires and pavement surface texture. As a result, it has shown that microtexture and macrotexture can be predicted from simultaneous measurements of ribbed and blank-tire skid resistance values at highway speeds (i.e., 64 km/h), and vice versa.

(4) The concept of using both types of skid test data shows promise as a candidate indirect microtexture and macrotexture measurement method. The fact that skid test trailers are extensively used by most states in the United States means that this indirect texture measurement concept could be implemented easily and with relatively little expense.

(5) The relationships developed in this study are based on microtexture measured by the sand-patch method and on the British pendulum number (BPN) as a surrogate for microtexture. Although they are adequate measures of microtexture and macrotexture, they do require the interruption of traffic. It is unlikely that a microtexture measurements can be made at high speeds. However, progress is being made in the development of noncontacting, high speed methods for measuring macrotexture. It remains to derive and verify a new set of model coefficients, based on more reliable texture measurements.

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DEVELOPMENT OF THE RELATIONSHIPS BETWEEN SKID RESISTANCE
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