Relationships Between Skid-Resistance Measurements with the Ribbed and Blank Test Tires, and Pavement Texture

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Kazuo SAITO* and John J. HENRY**

Abstract

The prediction model for the ratio of skid numbers obtained with the ribbed E 501 test tire to those obtained with the blank E 524 test tire at any speed has been developed using data from 22 pavement test sites in Pennsylvania. The prediction is based on the Penn State Model for skid resistance-speed behavior. The model was developed as a function of a macrotexture parameter defined by sand-patch mean texture depth (*MTD*). An application of this model permits the prediction of the blank-tire skid number at any speed from a measured ribbed-tire skid number and a macrotexture measurement. A simplified model for the blank-tire skid number at 64 km/h (40 mph) test speed was also developed. Values calculated from both models show good agreement with each other as well as with the actual data.

Another effort in this study was to relate skid resistance measured with both types of test tires to pavement texture. The results show a strong relationship between skid numbers with both test tires and pavement macrotexture and microtexture. Therefore, if a pavement skid-resistance survey is performed with both the blank E 524 and the ribbed E 501 test tires, the levels of macrotexture and microtexture can readily be estimated.

The seasonal and short-term variations in data with the two tires also were compared. It was found that the short-term variations in the blank tire data do not pose at great a problem as those in the ribbed tire data.

1. INTRODUCTION

Adequate tire-pavement friction on wet pavement surfaces is important for maintaining safe vehicle operation. The wet-pavement friction of the primary highway systems of most states in monitored in annual surveys according to the test procedure specified by ASTM Method of Test E 274-79, "Skid Resistance of Paved Surfaces Using a Full-Scale Tire".[1] This method provedes the skid resistance of the wet pavement with a ribbed test tire specified by ASTM Standard E 501-76, "Standard Tire for Pavement Skid-Resistance

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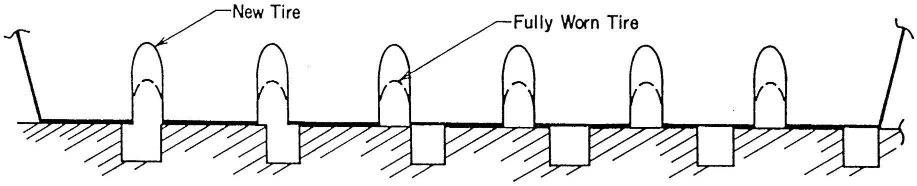

Figure. 1 Comparison of the geometry of the interface of a ribbed tire and a typical grooved pavement

Tests",[1] under fully specified test conditions. The E 501 test tire has seven smooth longitudinal ribs separated by six grooves which provide for drainage of water from the tire-pavement surfaces as the tire slides over the wetted pavement during the test. The specification requires that the tire be discarded when the minimum depth of the grooves reaches 4 mm.

Recently the use of the E 501 test tire for evaluating wet-pavement safety has been questioned.[2),3] Pavement grooving is widely accepted as an effective means of reducing wet skidding accidents. It has been noted, however, that the skid number measured with the ribbed tire is not significantly improved by grooving.[4),5] In a Michigan study, skid resistance measurements with both ribbed and blank tires were made at a site with a high rate of wet-pavement accidents, before and after longitudinal grooving.[6] Wet-pavement accidents decreased dramatically in the grooved areas, which showed only a slight increase in skid resistance when measured with the ribbed tire, but a large increase when the blank tire was used. Figure 1 shows a conceptualized ribbed test tire profile superimposed on a typical grooving pattern. Since the presence or absence of the grooves does not affect the skid number, it is apparent that sufficient drainage is provided by the tire grooves. Therefore, if the skid number measured with the ribbed test tire were a true measure of safety, pavement grooving could not be justified. Because of its adequate drainage, the ribbed test tire is not sensitive to the drainage capability provided by the pavement macrotexture. The skid resistance measured with the ribbed test tire on dense-graded (fine textured) pavements would not predict the low friction potential that such a pavement might have for a car with worn tires on a pavement with a thick water film.[7]

Several state agencies are investigating the use of the blank tire specified by ASTM Standard E 524-76, "Smooth-Tread Standard Tire for Special-Purpose Pavement Skid-Resistance Test".[1] A study in Connecticut suggested that tests with the blank tire correlate with wet-pavement accident frequency, especially hydroplaning accidents, regardless of pavement type.[8] A study in Virginia on 31 test sites, both bituminous and portland cement concrete pavements, compared the skid numbers measured with both blank and ribbed tires by grouping the pavements by texture depth.[9] On some pavements with high macrotexture the blank and ribbed skid numbers were almost identical, whereas on the pavements with low levels of macrotexture they differed significantly. A study sponsored by the Federal Highway Administration was initiated at the Pennsylvania State University to obtain additional data in Pennsylvania and to compare the results indicate that the E 501 tire is a poor discriminator of macrotexture. Although its use may adequately rank the safety of pavements with a narrow range of macrotexture, it cannot compare, for example, dense-graded asphalt pavements with open-graded ones, or grooved portland cement concrete pavements with ungrooved ones. Based on these results, it has been concluded that the ribbed E 501 test tire provides a good evaluation of microtexture, but is not sensitive to macrotexpure, which is a significant factor in wet-pavement safety.

Ideally, a pavement skid-resistance survey should be performed with both the ribbed E 501 and the blank E 524 tires. By comparing the skid-resistance values from both tires, one can readily estimate the levels of microtexture and macrotexture and thus assess the cause of poor skid resistance and the choice and likelihood of success of corrective measures.

In this paper, a prediction model is developed which can be used to estimate the skid-resistance level with a blank tire from the actual measurements made with the ribbed tire and from the pavement macrotexture. An attempt is made also to develop the relationship between pavement texture and skid resistance with both tires.

2. DATA BASE

Data are avaiable from tests with both the blank and the ribbed test tires on the 22 pavement test sites of the skid-resistance program conducted by the Pennsylvania State University. These sites represent a variety of aggregates and mix designs, and include both asphalt and portland cement concrete. The pavements are subject to a wide range of average daily traffic. The skid tests were made in the transient slip mode[10] which not only provides SN_{64} data according to the ASTM Method of Test E 274, but also yields brake slip numbers at 16, 32, and 48 km/h, which can be used to approximate SN_{16}, SN_{32}, and SN_{48} for both blank and ribbed test tires. Texture measurements made at each site included British pendulum number (*BPN*) according to ASTM Method of Test E 303[1], and mean texture depth (*MTD*) by the sand-patch test according to the PCA method.[11]

3. ROLE OF PAVEMENT TEXTURE IN SKID RESISTANCE

When skid testing is performed with a particular test tire, the pavement surface properties are the main factors that influence the measurement. The pavement surface characteristics that influence skid resistance can be divided into two scales : microtexture and macrotexture. Microtexture, with a space frequency content greater than 2000 cycles per meter, is a function of the asperities and surface roughness of individual aggregate particles. Macrotexture, with a space frequency range from 25 to 2000 cycles per meter, is a function of aggregate gradition.[12] Microtexture penetrates the water film to provide direct contact with the tire, while macrotexture provides channels for water to escape from the tire-pavement interface. Macrotexture thus plays an important role in the prevention of wet-pavement accidemts.

Leu and Henry[13] have shown that skid number data decrease exponentially with speed according to the Penn State Model :

$$SN_V = SN_0 \ e^{-\frac{PNG}{100} V} \quad (1)$$

SN_V=skid number at velocity V (km/h)

SN_0=skid number-speed intercept

PNG=percent normalized gradient defined as : $-\frac{100dSN}{SN \ dV}$ and has units of km/h.

They also have found that, for the ribbed tire test data, SN_0 is highly correlated with such microtexture parameters as height of the microtexture profile and *BPN*, and that the rate at which the skid number decreases with speed, described by *PNG*, is correlated with macrotexture parameters such as the height of macrotexture profiles and sand-patch mean texture depth.[13] A significant advantage of this model is that it separates the effects macrotexture and microtexture. Good skid resistance at traffic speeds such as 64 km/h requires high levels of both macrotexture and microtexture.

4. THE BLANK TEST TIRE

The blank test tire is, except for the absense of the grooves, the same as the E 501 ribbed tire. Clearly, its contribution to the tire-pavement interface drainage capability is zero and one would therefore expect it to produce data with a strong dependence upon macrotexture for measurements at 64 km/h. The blank tire is an extreme case, with actual tires ranking between it and the ribbed tire in drainage capability. However, an intermediate test tire, for example, one with shallower grooves, would be impractical as it would have a very limited useful life. That is, either the grooves must be sufficiently deep that their depth does not affect the test, or they must be absent.

It has been suggested that a disadvantage of the blank tire is that it also is sensitive to the amount of water on the pavement. *ASTM* Method of Test E 274[1] specifies water flow rates which would

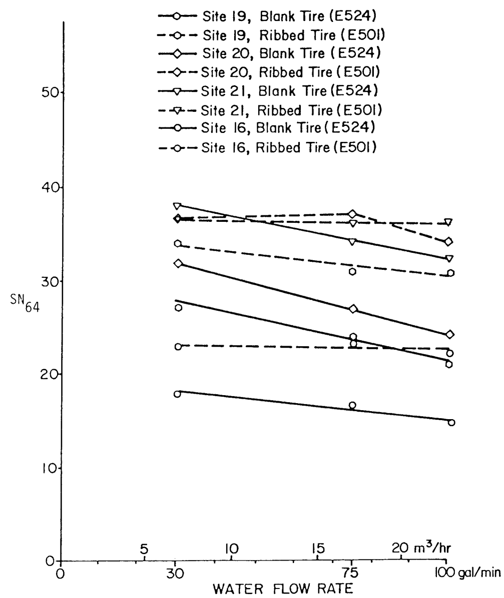

Figure. 2 Effects of water flow rate on skid resistance measurements(Penn state nozzle)

produce a water film thichness of 0.5 mm (0.02 in.) if all the water were to lie uniformly on the pavement in the tire path. Actual film thicknesses are undoutedly somewhat less. The ribbed tire with its terminal mean effective tread depth of 0.97 mm (0.038 in.) can easily permit the escape of this amount of water or more without a noticeable decrease in friction. Tests were run with both tires over four pavements with water flow from 6.8 to 22.7 m^3/h (30 to 100 gal/min) and the results are shown in Figure 2. Although the effect of the rate of water delivery to the test tire is pronounced for the blank tire, there is no severe problem if reasonable calibration of the water flow rate is maintained. At 64 km/h the ribbed tire can accept as much as three times the normal water flow rate without affecting the data by more than three skid numbers.[2] The fact that it is insensitive to water flow rate casts doubt on the validity of the ribbed tires as a means of evaluating pavements for wet weather safety.

5. PREDICTION MODEL OF SKID NUMBER WITH BLANK TIRE

(1) Skid Number-Speed Relationship for Blank and Ribbed Tires

The skid number-speed relationship for blank and ribbed tires can be developed using the Penn State Model, given as equation (1). A model for ribbed tire data can be expressed in the from :

$$SN_V^R = SN_0^R \ e^{-\frac{PNG^R}{100}V} \tag{2}$$

and for blank tire data :

$$SN_V^B = SN_0^B \ e^{-\frac{PNG^B}{100}V} \tag{3}$$

where SN_V^R = skid number with the ribbed tire at velocity V (km/h)
SN_V^B = skid number with the blank tire at velocity V (km/h)
SN_0^R = skid number-speed intercept for the ribbed tire
SN_0^B = skid number-speed intercept for the blank tire
PNG^R = percent normalized gradient for the ribbed tire
PNG^B = percent normalized gradient for the blank tire

The ratio of SN_V^B to SN_V^R is then formed :

$$\frac{SN_V^B}{SN_V^R} = \frac{SN_V^B}{SN_V^R} \ e^{(PNG^R - PNG^B)V/100} \tag{4}$$

or $$SN_V^B = SN_V^R \ C_0 \ e^{\frac{\Delta PNG}{100}V} \tag{5}$$

where

$$C_0 = SN_0^B / SN_0^R \qquad \Delta PNG = PNG^R - PNG^B$$

If it is possible to correlate C_0 and $\triangle PNG$ with pavement texture, equation (4) or (5)

Table 1. Skid Resistance and Texture Data

Site	Type of Pavement[a]	Summer 1979[b]		C_0	ΔPNG	Fall 1979[c]		
		C_{40}	*MTD* (mm)	(SN_0^B/SN_0^R)	(h/km)	C_{40}	*MTD* (mm)	*BPN*
1	*DG*	0.529	0.263	0.451	0.250	0.530	0.263	44.0
2	*PCC*	0.554	0.300	0.541	0.072	0.557	0.338	58.5
3	*PCC*	0.527	0.263	0.513	0.163	0.562	0.325	69.0
4	*DG*	0.642	0.225	0.589	0.078	0.611	0.200	56.5
7	*PCC*	0.551	0.225	0.512	0.191	0.575	0.250	69.0
8	*DG*	0.830	0.700	0.801	0.072	0.901	0.700	41.0
9	*DG*	0.724	0.588	0.722	0.109	0.766	0.575	47.5
10	*PCC*	0.430	0.225	0.456	0.445	0.527	0.213	65.5
11	*DG*	0.630	0.263	0.537	0.172	0.597	0.338	51.0
12	*DG*	0.741	0.438	0.681	0.200	0.769	0.375	57.5
13	*OG*	0.914	1.025	0.934	0.025	0.939	1.113	87.0
14	*PCC*	0.515	0.325	0.495	0.272	0.583	0.325	60.5
15	*OG*	0.996	1.388	0.936	0.034	0.973	1.263	78.0
16	*OG*	0.671	0.250	0.583	0.166	0.632	0.338	43.0
17	*DG*	0.878	0.925	0.862	0.044	0.842	0.825	52.5
18	*PCC*	0.667	0.463	0.674	0.100	0.696	0.400	68.5
19	*DG*	0.536	0.413	0.562	0.159	0.603	0.375	48.5
20	*DG*	0.657	0.413	0.610	0.141	0.646	0.375	58.0
21	*OG*	0.968	1.138	0.876	0.044	0.927	1.163	51.0
22	*OG*	0.969	1.250	1.001	0.001	0.985	1.488	81.0
24	*DG*	0.534	0.275	0.508	0.125	0.547	0.313	51.0
25	*OG*	0.717	0.765	0.681	0.097	0.742	0.575	75.5

[a] *PCC* = portland cement concrete: *DG* = dense graded asphalt cocrete; *OG* = open graded asphalt concrete.
[b] Values are averaged for July and August, 1979.
[c] Values are averaged for September and October, 1979.

can be used to predict blank-tire skid number from measured ribbed-tire skid number and pavement texture at any speed. It has been shown in studies in Illinois[14] and New York[15] that the difference between the ribbed-tire and blank-tire skid number is a function of macrotexture, with larger differences at low macrotexture than at high macrotexture. Therefore, it is assumed that both C_0 and $\triangle PNG$ are the function of macrotexture.

(2) C_0 **Versus Macrotexture**

To test the hypothesis that a macrotexture parameter can be used to predict C_0, and attempt was made to correlate C_0 with mean texture depth, MTD, for the data obtained in the fall of 1979 (see Table 1). A high degree of correlation was found, as shown in Figure 3. A least squares regression analysis yields :

$$C_0 = 0.87\ (MTD)^{0.413} \qquad (R = 0.958) \tag{6}$$

where MTD is expressed in mm here and in subsequent equations.

(3) $\triangle PNG$ **Versus Macrotexture**

Next, a correlation between $\triangle PNG$ and *MTD* was attempted as means of testing the

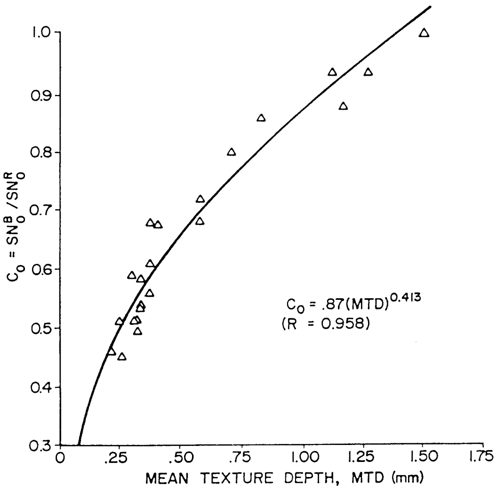

Figure. 3 Relationsip between C_0 and *MTD* (Pennsylvania sites, fall 1979)

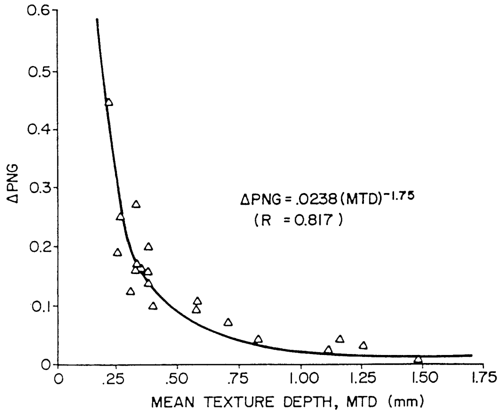

Figure. 4 Relationship between ΔPNG and *MTD* (Pennsylvania sites, fall 1979)

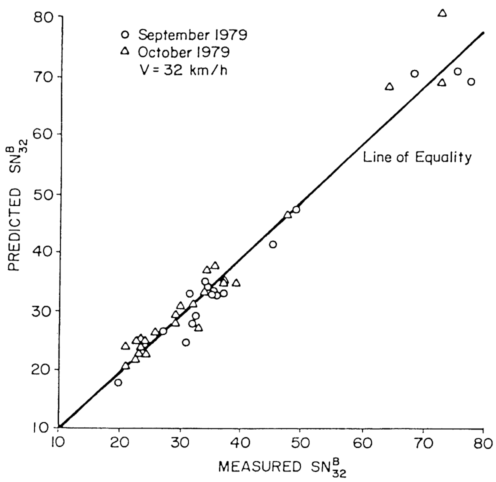

Figure. 5 Comparison of measured SN^B_{32} and estimated SN^B_{32}

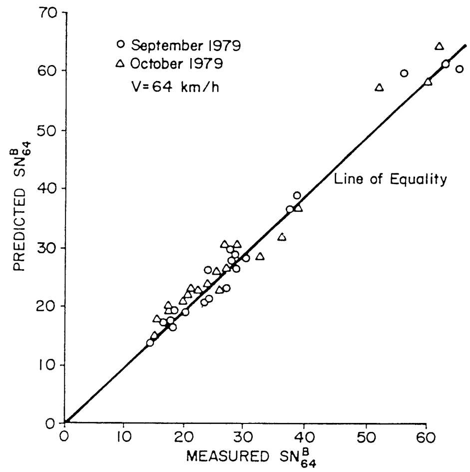

Figure. 6 Comparison of measured SN^B_{64} and estimated SN^B_{64}

hypothesis that $\triangle PNG$ can be predicted by macrotexture data. In Figure 4, $\triangle PNG$ is plotted against *MTD* for the 20 test sites. The resulting relationship is

$$\triangle PNG = 0.0238\ (MTD)^{-1.75} \qquad (R = 0.817) \qquad (7)$$

The result shows that the difference between the ribbed tire and blank tire values for *PNG* decrease sharply as macrotexture increases and approaches zero at high macrotexture.

(4) Prediction of Skid Numbers with the Blank Tire from Ribbed Tire Measurements and Macrotexture

By combining equations (5), (6), and (7), a relationship between skid number with the blank tire(SN_V^B), skid number with the ribbed tire(SN_V^R), sand-patch mean texture depth (MTD), and speed (V) can be obtained :

$$SN_V^B = 0.87\ SN_V^R(MTD)^{0.413}\quad e^{0.000238\ V(MTD)^{-1.75}} \tag{8}$$

Skid number values at 32 km/h (SN_{32}^B) and at 64 km/h (SN_{64}^B), calculated from the ribbed tire data at the corresponding speed and macrotexture using equation (8), are compared with measured skid numbers in Figures 5 and 6, respectively. Both figures show excellent agreement between measured skid numbers and predicted ones.

(5) Simplified Model for Testing Speed, 64 km/h (40 mph)

The skid test is usually performed at 64 km/h (40mph). The model in equation (8) can be used to predict the skid number with the blank tire at the test speed of 64 km/h, as shown in Figure 6, but this model is somewhat complicated. Therefore, a simplified model was developed.

The skid number measured with the blank tire at 64 km/h is designated as SN_{64}^B and with the ribbed tire as SN_{64}^R. The ratio of SN_{64}^B to SN_{64}^R, defined as $C_{64} = SN_{64}^B/SN_{64}^R$, is again correlated with macrotexture, MTD, for the data obtained from the 22 test sites in the summer and fall of 1979 (listed in Table 1). In Figure 7, C_{64} is plotted against MTD. A least squares regression analysis yields

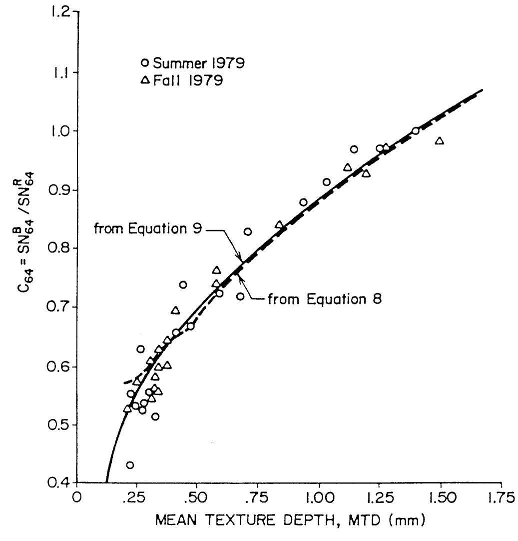

Figure. 7 Relationship between C_{64} and MTD (Pennsylvania Sites, summer and fall 1979)

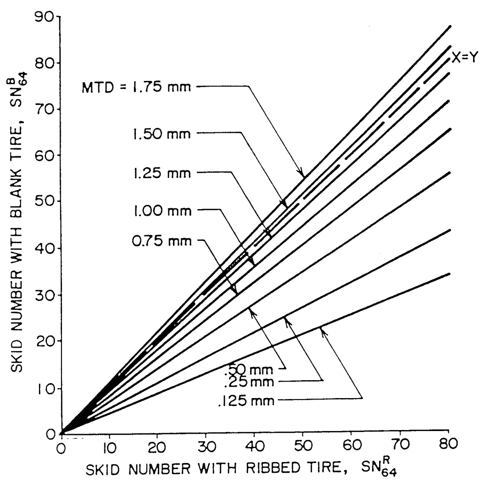

Figure. 8 Relationship between SN_{64}^R, SN_{64}^B, and MTD

$$C_{64} = 0.887\ (MTD)^{0.36} \qquad (R = 0.969) \tag{9}$$

or

$$SN_{64}^{B} = 0.887\ SN_{64}^{R}\ (MTD)^{0.36} \tag{10}$$

Similarly, an expression for C_{64} can be developed from equation (8) ; Figure 7 shows the results of both equations (8) and (9). Agreement is seen to be very good, but equation (8) must not be used for macrotexture levels below those used in the development of the model, i. e., below 0.25 mm.

The relationship between skid numbers with both the blank and ribbed tires at 64 km/h for various macrotexture levels is presented graphically in Figure 8. Conversely it could be shown that one can predict the mean texture depth by using this relationship when the skid resistance with both the ribbed and blank tires is known for the pavement.

6. RELATIONSHIP BETWEEN SKID RESISTANCE WITH BOTH TEST TIRES AND PAVEMENT TEXTURE

(1) Ribbed Versus Blank-Tire Skid Test Concept

In an attempt to better define the skid-resistance values of pavements, Henry[2] has compared the skid-resistance data measured with both the ribbed and blank test tires in the fall of 1978. The data are plotted in Figure 9 with *MTD* and BPN. Examination of Figure 9 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.

Linear regression equations were used to relate the test results for each tire to a measure of microtexture, defined by *BPN* measurements, and a mearure of macrotexture, defined by *MTD* as determined from sand-patch tests. The resulting regression equations have shown that the ribbed-tire skid number is highly sensitive to surface microtexture, while the blank-tire skid number is sensitive to both macrotexture and microtexture. The expression for *BPN* and *MTD* were preliminary at that time and needed further validation. However, the concept of using both types of skid test data shows promise as an indirect macrotexture and microtexture measurement method.

(2) Correlation of Skid Numbers with Texture Data

Data are available from skid tests which were conducted with both tires during April and October in 1979 and 1980 on 22 test sites in Pennsylvania. As in the previous study, linear regression equations were used to correlate the test results for each tire with *BPN* and *MTD*. The multiple regression analysis was performed on all data in the form :

$$SN_{64}^{R} = a_0 + a_1 MTD + a_2 BPN \tag{11}$$

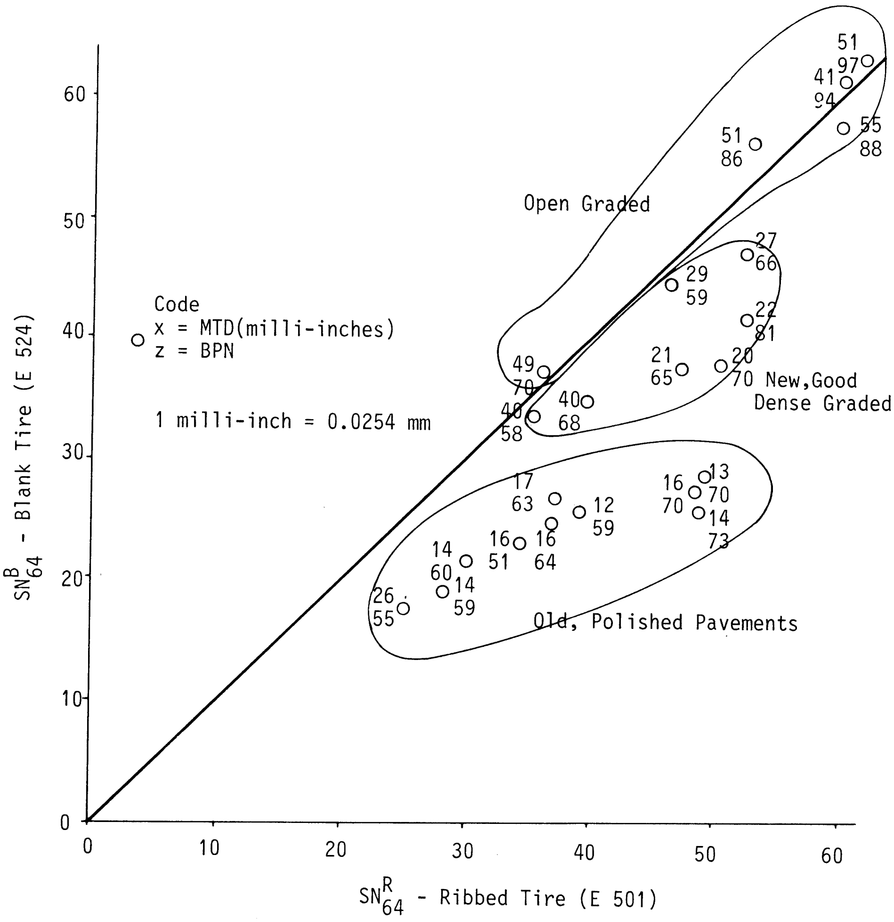

Figure. 9 Comparison of skid-resistance data measured with the ribbed and blank test tires (Pennsylvania sites, fall 1978)

$$SN_{64}^{B}=b_0+b_1 MTD+b_2 BPN \qquad (12)$$

where MTD is expressed in mm.

The resulting regression equations are

$$SN_{64}^{R}=-9.7+4.72\ MTD+0.766\ BPN \qquad (R=0.922) \qquad (13)$$

$$SN_{64}^{B}=-19.5+17.3\ MTD+0.628\ BPN \qquad (R=0.917) \qquad (14)$$

The coefficients are very similar to the early results, and they confirm the conclusion that skid measurements with the ribbed test tire are highly sensitive to pavement surface microtexture and relatively insensitive to macrotexture, while skid measurements with the blank test tire are sensitive to both macrotexture and microtexture.

(3) Correlation of Texture Data to Skid Numbers

Equations (13) and (14) could be solved for *BPN* and *MTD* in terms of both SN^{R}_{64} and SN^{B}_{64}. However, in order to examine the validity of the correlation, linear regression of the data was performed to relate *BPN* and *MTD* to skid numbers with both tires. The multiple regression analysis was performed on all data in the form :

$$BPN = c_0 + c_1\ SN^{R}_{64} + c_2\ SN^{B}_{64} \tag{15}$$

$$MTD = d_0 + d_1\ SN^{R}_{64} + d_2\ SN^{B}_{64} \tag{16}$$

where *MTD* has units of mm.

The resulting regression equations are

$$BPN = 20.0 + 0.405\ SN^{R}_{64} + 0.039\ SN^{B}_{64} \qquad (R = 0.905) \tag{17}$$

$$MTD = 0.49 - 0.0289 SN^{R}_{64} + 0.0426\ SN^{B}_{64} \qquad (R = 0.853) \tag{18}$$

As expected, the result for *BPN* shows that SN^{B}_{64} plays only a small role in the prediction of the level of *BPN*, and it may be possible to predict *BPN* solely from SN^{R}_{64}. To test this hypothesis, an attempt was made to correlate *BPN* with SN^{R}_{64} for all data avaiable. The least squares analysis yields

$$BPN = 22.2 + 0.998\ SN^{R}_{64} \qquad (R = 0.894) \tag{19}$$

7. COMPARISON OF SEASONAL VARIATIONS IN SKID RESISTANCE WITH THE RIBBED AND BLANK TIRES

Skid-resistance measurements with the ribbed tire on public highways in Pennsylvania and other states have exhibited seasonal and short-term variations,[16),17)] Extreme seasonal variations as high as 30 skid numbers have been observed, with more typical variations in the range of 5 to 15. These variations make it difficult to establish a rational maintenance

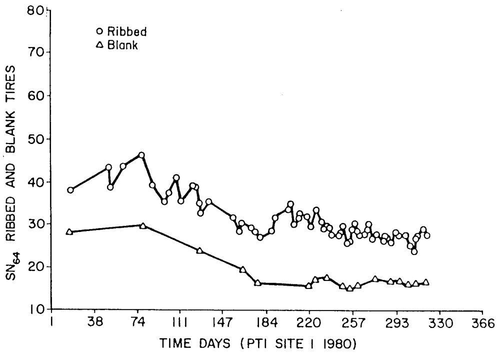

Figure. 10 Comparison of seasonal variations in SN_{64} with the ribbedand blank tires (*PCC* surface, 1980)

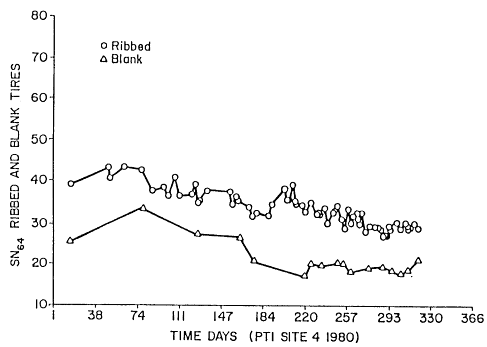

Figure. 11 Comparison of seasonal variations in SN_{64} with the ribbedand blank tires (Asphalt surface, 1980)

program in which skid resistance is an important factor.

Data are available form tests with the ribbed and blank tires for 1980. Figures 10 and 11 compare seasonal variations in skid number, SN_{64}, with the ribbed and blank tires for a dense-graded asphalt surface and for a portland cement concrete surface, respectively. These figures show clearly that long-term (seasonal) variations for both tires exhibit almost the same trend, whereas short-term (daily) variations for both tires are significantly different. The short-term variations in skid resistance with the ribbed tire show fairly large fluctuations which are the result of rainfall, pavement temperature, and short-term changes of microtexture parameters and *PNG*.[18] On the other hand, the short-term fluctuations with the blank tire are small and probably negligible. The standard deviations of the skid numbers with the ribbed tire are 1.83 for the asphalt surface and 2.05 for the portland cement concrete surface, while those with the blank tire are 0.65 and 0.91, respectively. It can be concluded from these results that the measurements with the blank test tire are not sensitive to the short-term variations and that the blank tire, therefore, is less of a problem with respect to shert-term variations in skid-resistance measurements.

8. CONCLUSIONS AND RECOMMENDATIONS

In this study, the prediction model for the ratio of skid resistance with the ribbed tire to that with the blank tire at any speed has been developed using the Penn State Model for skid resistance-speed behavior. The model was developed as a function only of a macrotexture parameter, described by the sand-patch mean texture depth (*MTD*). An application of this model permits the prediction of skid-resistance levels with the blank tire at any speed from a measured skid number with the ribbed tire at the same speed and a macrotexture measurement. For the user's convenience, a simplified model for the prediction of skid number with the blank tire at a test speed of 64 km/h (40 mph) has been developed. The values calculated from both models show good agreement.

This study also has shown that the ribbed E 501 tire provides a good evaluation of microtexture, but is not sensitive to macrotexture, which is an important factor in wet-pavement safety. The blank E 524 tire is sensitive to both macrotexture and microtexture. If both macrotexture and microtexture measurements are made, one can readily estimate the level of skid resistance. Conversely, if a pavement skid-resistance survey is performed with both the ribbed and blank tires, one can estimate the level of pavement microtexture and macrotexture. The fact that skid-test trailers are extensively used by most states means that this indirect texture measurement concept can be easily and relatively inexpensively implemented. If skid-resistance surveys are performed only with one tire, the blank E 524 tire appears to be the stronger candidate, especially since it is more sensitive to macrotexture and poses a lesser problem for short-term wariations in skid resistance.

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