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Skid-Resistance Measurements with Blank and Ribbed Test Tires and Their Relationship to Pavement Texture

J.J. HENRY AND KAZUO SAITO

A prediction model for the ratio of skid numbers obtained with the ribbed ASTM E501 test tire to those obtained with the blank ASTM E524 test tire at any speed has been developed by 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). 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 a test speed of 64 km/hr was also developed. Values calculated from both models show good agreement with each other as well as with the actual data. An effort was also made 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, by performing a pavement skid-resistance survey with both the blank E524 and the ribbed E501 test tires, the levels of macrotexture and microtexture can readily be estimated. Seasonal and short-term variations in data with the two tires were also compared. Short-term variations do not pose as great a problem in the blank-tire data as in the ribbed-tire data.

Adequate tire-pavement friction on wet pavement is important for maintaining safe vehicle operation. The wet-pavement friction of the primary highway systems of most states is monitored in annual surveys by using the test procedure specified in ASTM test method E274-79 (1). This method is used to determine the skid resistance of the wet pavement with a ribbed test tire specified by ASTM E501-76 (1) under fully specified test conditions. The E501 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. The specification requires that the tire be discarded when the minimum depth of the grooves reaches 4 mm.

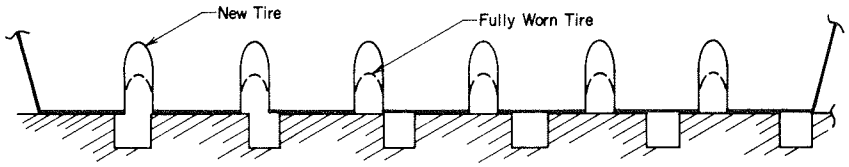
Recently, the use of the E501 test tire for evaluating wet-pavement safety has been questioned (2,3). Pavement grooving is widely accepted as an effective means of reducing skidding accidents on wet pavement. However, the skid number measured with the ribbed tire is not significantly improved by grooving (4,5). In a Michigan study (6), skid-resistance measurements were made with both ribbed and blank tires, both before and after longitudinal grooving, at a site that had a high rate of wet-pavement accidents. 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 measured with the blank tire.

Figure 1 shows a conceptualized profile of a ribbed test tire superimposed on a typical pavement grooving pattern. Because 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) pavement would not predict the low friction potential that such a pavement might have for a car with worn tires if the pavement were covered with a thick water film (7).

Several state agencies are investigating the use of the blank tire specified by ASTM E524-76 (1). A Connecticut study suggested that tests with the blank tire correlate well with frequency of wet-pavement accidents, especially hydroplaning accidents, regardless of pavement type (8). A study of 31 test sites in Virginia, including both bituminous and portland cement concrete (PCC) 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 FHWA was initiated at Penn-

Figure 1. Geometry of interface of a ribbed tire and typical grooved pavement (0.65- x 0.65-mm grooves on 25-mm spacing).



sylvania State University to obtain additional data in Pennsylvania and to compare the results with those of the state projects. The preliminary results indicate that the E501 tire is a poor discriminator of macrotexture. Although the safety of pavements can be adequately ranked with a narrow range of macrotexture by using the E501 tire, it is not possible to correctly compare, for example, dense-graded (DG) and open-graded (OG) asphalt pavements or grooved and ungrooved PCC pavements (2). Based on these results, it has been concluded that the ribbed E501 test tire provides a good evaluation of microtexture but is not sensitive to macrotexture, which is a significant factor in wet-pavement safety.

Ideally, a pavement skid-resistance survey should be performed with both the ribbed E501 and the blank E524 tires. By comparing the skid-resistance values obtained from both tires, the levels of microtexture and macrotexture can be readily estimated and thus the cause of poor skid resistance and the choice and likelihood of success of corrective measures can be assessed.

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

DATA BASE

Data are available from tests with both blank and ribbed test tires on the 22 pavement test sites of the skid-test program conducted by Pennsylvania State University. The pavements at these sites represent a variety of aggregates and mix designs and include both asphalt and PCC. 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 ASTM E274 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 E303 (1) and mean texture depth (MTD) by the sand-patch test according to the American Concrete Paving Association method (11).

ROLE OF PAVEMENT TEXTURE IN SKID RESISTANCE

When skid testing is performed with a particular test tire, pavement surface properties are the main factors that affect the measurement. The pavement surface characteristics that affect skid resistance can be divided into two groups: microtexture and macrotexture. Microtexture, with a space-frequency content greater than 2,000 cycles/m, is a function of the asperities and surface roughness of individual aggregate particles. Macrotexture, with a space-frequency range from 25 to 2,000 cycles/m, is a function of aggregate gradation (12). Microtexture penetrates the water film to provide direct contact with the tire; macrotexture provides channels for water to escape from the tire-pavement interface and thus plays an important role in the prevention of wet-pavement accidents.

Leu and Henry (13) have shown that skid number data decrease exponentially with speed according to the Penn State model:

$$SN_V = SN_0 \exp[-(PNG/100)\,V] \quad (1)$$

where

SN_V = skid number at velocity V (km/h);
SN_0 = skid number/speed intercept; and
PNG = percentage normalized gradient (h/km), defined as $-(100/SN) \cdot [d(SN)/dV]$.

Leu and Henry (13) also found that, for the ribbed-tire test data, SN_0 is highly correlated with such microtexture parameters as height of the microtexture profiles 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 MTD. A significant advantage of this model is that it separates the effects of macrotexture and microtexture. Good skid resistance at traffic speeds such as 64 km/h requires high levels of both macrotexture and microtexture.

MODEL FOR PREDICTION OF SKID NUMBER WITH BLANK TIRE

Relationship Between Skid Number and Speed for Blank and Ribbed Tires

The relationship between skid number and speed for blank and ribbed tires can be developed by using the Penn State model, given as Equation 1. The model for ribbed-tire data can be expressed as

$$SN_V^R = SN_0^R \exp[-(PNG^R/100)\,V] \quad (2)$$

The model for blank-tire data is

$$SN_V^B = SN_0^B \exp[-(PNG^B/100)V] \quad (3)$$

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 = PNG for the ribbed tire, and
PNG^B = PNG for the blank tire.

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

$$SN_V^B/SN_V^R = (SN_0^B/SN_0^R) \exp[(PNG^R - PNG^B)V/100] \quad (4)$$

or

$$SN_V^B = SN_V^R C_0 \exp(\Delta PNG/100) V \quad (5)$$

where $C_0 = SN_0^B/SN_0^R$ and $\Delta PNG = PNG^R - PNG^B$.

If it is possible to correlate C_0 and ΔPNG with pavement texture, Equation 4 or 5 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 and that the differences are larger at low macrotexture than at high macrotexture. Therefore, it is assumed that both C_0 and ΔPNG are the function of macrotexture.

C_0 Versus Macrotexture

To test the hypothesis that a macrotexture parameter can be used to predict C_0, an attempt was made to correlate C_0 with MTD for the data obtained in the fall of 1979 (see Table 1). A high degree of correlation was found, as shown in Figure 2. A least-squares regression analysis yields

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

Here and in subsequent equations, MTD is expressed in millimeters.

ΔPNG Versus Macrotexture

Next, a correlation between ΔPNG and MTD was attempted as a means of testing the hypothesis that ΔPNG can be predicted by macrotexture data. In Figure 3, ΔPNG is plotted versus MTD for the 20 test sites. The resulting relationship is

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

The results show that the difference between the ribbed-tire and blank-tire values for PNG decreases sharply as macrotexture increases and approaches zero at high macrotexture.

Prediction of Skid Numbers for Blank Tire from Ribbed-Tire Measurements and Macrotexture

By combining Equations 5 through 7, a relationship among skid number with a blank tire (SN_V^B), skid number with a ribbed tire (SN_V^R), sand-patch MTD, and speed (V) can be obtained:

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

Skid number values at 32 km/h (SN_{32}^B) and 64 km/h (SN_{64}^B), calculated from the ribbed-tire data at the corresponding speed and macrotexture by using Equation 8, are compared with the measured skid numbers in Figures 4 and 5. Both figures show excellent agreement between measured skid numbers and predicted ones.

Figure 2. C_0 versus MTD: fall 1979.

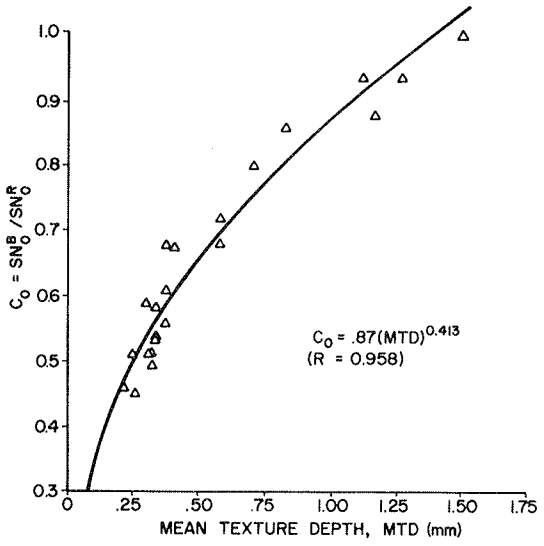


Table 1. Skid-resistance and texture data.

Site	Type of Pavement	Summer 1979[a] C_{40}	Summer 1979[a] MTD (mm)	$C_0(SN_0^B/SN_0^R)$	ΔPNG (h/km)	Fall 1979[b] C_{40}	Fall 1979[b] 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] Averaged values for July and August. [b] Averaged values for September and October.

Figure 3. ΔPNG versus MTD: fall 1979.

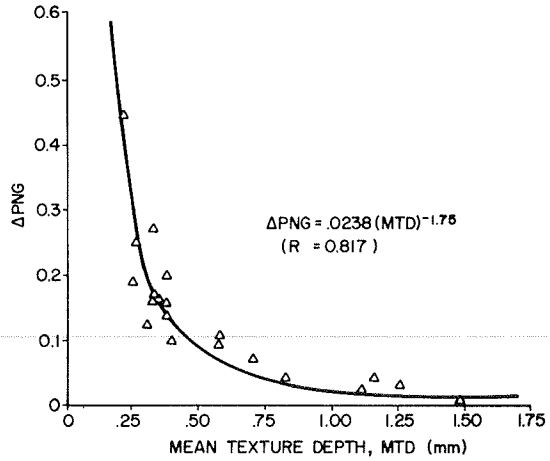
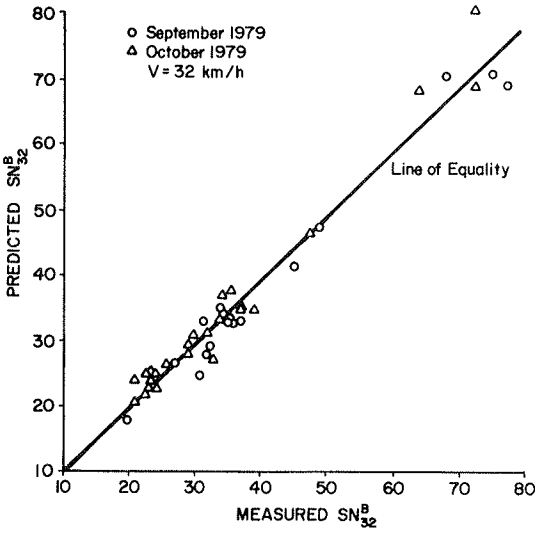


Figure 4. Measured versus predicted SN^B_{32}.



Simplified Model for Testing Speed

The skid test is usually performed at 64 km/h. 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 5. But, because this model is somewhat complicated, a simplified model was developed.

The skid number measured with the blank tire at 64 km/h is designated SN^B_{64}, and that measured with the ribbed tire is designated SN^R_{64}. The ratio of SN^B_{64} to SN^R_{64}, defined as $C_{64} = SN^B_{64}/SN^R_{64}$, is again correlated with macrotexture (MTD) for the data obtained from the 22 test sites in the summer and fall of 1979 (Table 1). In Figure 6, C_{64} is plotted versus MTD. A least-squares regression analysis yields

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

or

$$SN^B_{64} = 0.887 SN^R_{64}(MTD)^{0.36} \tag{10}$$

In the same way, an expression for C_{64} can be developed from Equation 8; Figure 6 shows the results of both Equations 8 and 9. Agreement is seen to be

Figure 5. Measured versus predicted SN^B_{64}.

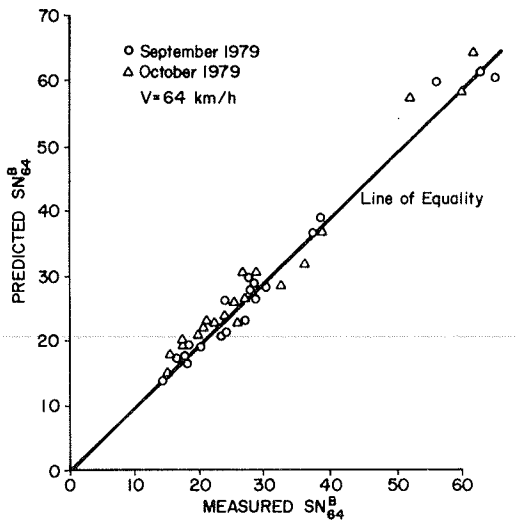
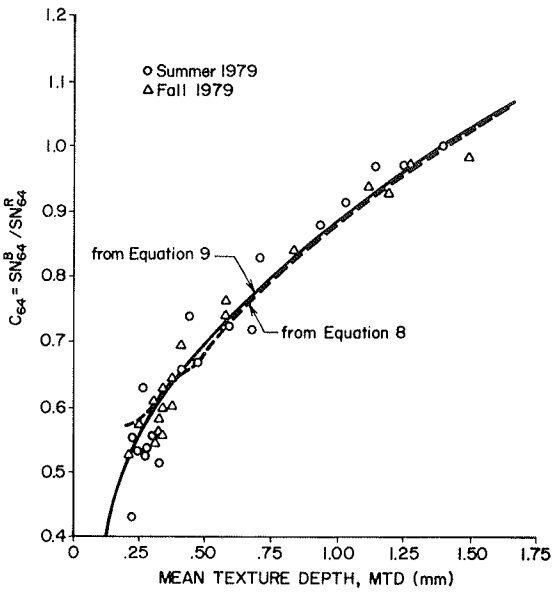


Figure 6. C_{64} versus MTD: summer and fall 1979.



quite good, but Equation 8 must not be used for macrotexture levels below those used in the development of the model--i.e., <0.25 mm.

The relationship between skid numbers with both blank and ribbed tires at 64 km/h for various macrotexture levels is shown in Figure 7. Conversely, it could be shown that the MTD can be predicted by using this relationship when the skid resistance for the pavement with both types of test tires is known.

RELATIONSHIP BETWEEN SKID RESISTANCE WITH BOTH TYPES OF TEST TIRES AND PAVEMENT TEXTURE

Ribbed-Tire 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 and the spring of 1979. Linear regression equations were used to relate the test results for each tire to a

measure of microtexture, defined by BPN measurements, and a measure 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 and the blank-tire skid number is sensitive to both macrotexture and microtexture. The expressions for BPN and MTD were preliminary at that time and required further validation. However, the concept of using both types of skid-test data shows promise as an indirect method of macrotexture and microtexture measurement.

Correlation of Skid Numbers with Texture Data

Data are available from skid tests conducted with both types of 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 following form:

$$SN^R_{64} = a_0 + a_1 MTD + a_2 BPN \quad (11)$$

$$SN^B_{64} = b_0 + b_1 MTD + b_2 BPN \quad (12)$$

The resulting regression equations are

$$SN^R_{64} = -9.7 + 4.72MTD + 0.766BPN \quad R = 0.922 \quad (13)$$

$$SN^B_{64} = -19.5 + 17.3MTD + 0.628BPN \quad R = 0.917 \quad (14)$$

The coefficients are quite similar to the earlier results (2). They confirm the conclusion that skid measurements with the ribbed test tire are highly sensitive to pavement surface microtexture and relatively insensitive to macrotexture and that skid measurements with the blank test tire are sensitive to both macrotexture and microtexture.

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, to examine the validity of the correlation, a linear regression analysis 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 following form:

$$BPN = c_0 + c_1 SN^R_{64} + c_2 SN^R_{64} \quad (15)$$

$$MTD = d_0 + d_1 SN^R_{64} + d_2 SN^B_{64} \quad (16)$$

The resulting regression equations are

$$BPN = 20.0 + 0.405SN^R_{64} + 0.039SN^B_{64} \quad R = 0.905 \quad (17)$$

$$MTD = 0.490 - 0.0289SN^R_{64} + 0.0426SN^B_{64} \quad R = 0.853 \quad (18)$$

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^B_{64}. To test this hypothesis, an attempt was made to correlate BPN with SN^B_{64} for all available data. The least-squares analysis yields

$$BPN = 22.2 + 0.998SN^R_{64} \quad R = 0.894 \quad (19)$$

COMPARISON OF SEASONAL VARIATIONS IN SKID RESISTANCE WITH 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 along with more typical variations in the range of 5 to 15 (17). These variations make it difficult to establish a rational maintenance program in which skid resistance is an important factor.

Data are available from tests with the ribbed and blank tires for 1980. Figures 8 and 9 compare seasonal variations in skid number (SN_{64}) with the ribbed and blank tires for a dense-graded asphalt surface (site 1) and for a PCC surface (site 4). The 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.

As shown in the paper by Saito and Henry in this Record, the short-term variations in skid resistance with the ribbed tire show fairly large fluctuations resulting from rainfall, pavement temperature, and short-term changes of microtexture parameters and PNG. 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 PCC surface; the corresponding

Figure 7. Relationship of SN^R_{64}, SN^B_{64}, and MTD.

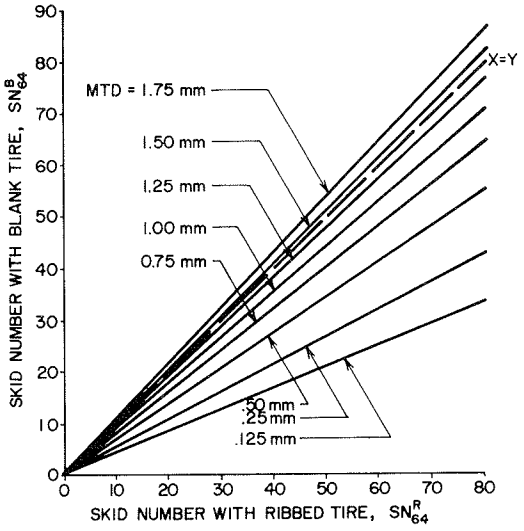


Figure 8. Comparison of seasonal variations in SN_{64} with ribbed and blank tires: PCC surface, 1980.

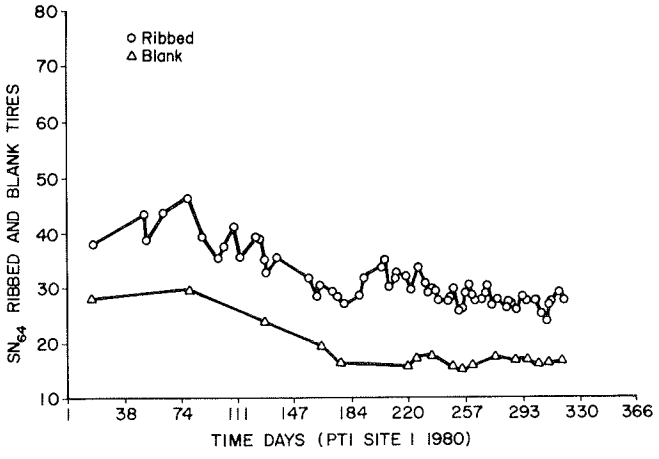
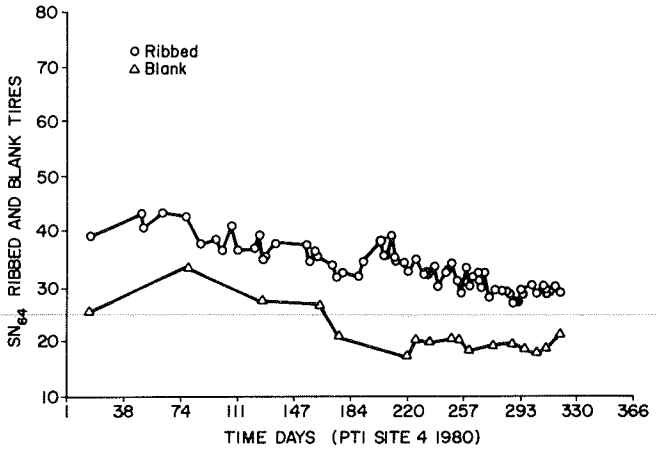


Figure 9. Comparison of seasonal variations in SN_{64} with ribbed and blank tires: asphalt surface, 1980.



standard deviations with the blank tire are 0.65 and 0.91.

It can be concluded from these results that the measurements with the blank test tire are not sensitive to short-term variations and therefore that the blank E524 tire is less of a problem with respect to short-term variations in skid-resistance measurements.

CONCLUSIONS AND RECOMMENDATIONS

In this study, the prediction model for the ratio of skid resistance with a ribbed tire to that with a blank tire at any speed has been developed by using the Penn State model for skid-resistance/speed behavior. The model was developed as a function only of a macrotexture parameter, described by sand-patch MTD. By using this model, skid-resistance levels can be predicted for the blank tire at any speed from a measured skid number obtained with the ribbed tire at the same speed and a macrotexture measurement. For the user's convenience, a simplified model has been developed to predict skid number with the blank tire at a test speed of 64 km/h. The values calculated from both models show good agreement.

The study results also show that the ribbed E501 tire provides a good evaluation of microtexture but is not sensitive to macrotexture, which is an important factor in wet-pavement safety. The blank E524 tire is sensitive to both macrotexture and microtexture. If both macrotexture and microtexture measurements are made, the level of skid resistance can readily be estimated. Conversely, by performing a pavement skid-resistance survey with both the ribbed and blank tires, the level of pavement microtexture and macrotexture can be estimated.

Because skid-test trailers are extensively used by most states, this concept of indirect texture measurement can be implemented easily and relatively inexpensively. If skid-resistance surveys are to be performed with only one type of tire, the blank E524 tire appears to be the stronger candidate, because it is more sensitive to macrotexture and poses less of a problem with respect to short-term variations in skid resistance.

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