Mays meter results gave a correlation coefficient of 0.99. Both systems therefore have almost identical characteristics over a wide range of operating conditions except that the PSARM shows better resolution and automatically reduces and stores the data. In the test configuration, the resolution of the axle displacement measurement was approximately 100 times better with the PSARM system than with the Mays meter.

CONCLUSIONS

A microprocessor-based data acquisition system is the basis of the PSARM, which has been developed as a replacement for the Mays ride meter currently used by many state highway departments. The system offers substantial improvements in resolution, cost-effectiveness, and ease of use and requires a minimum of operator training. It provides all of the functions currently found on the Mays meter and adds several important features:

1. Strip-chart output, which is expensive to reduce, has been eliminated in favor of reduced data storage on digital cassette tape. Information can now be fed directly into a road inventory data base. Summary data are provided in hard copy as the test proceeds.
2. The event identification and recording procedure has been streamlined, and more information is obtained. The type, location, and duration of any event are stored directly onto tape with a minimum of user input.

ACKNOWLEDGMENT

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Mechanistic Model for Predicting Seasonal Variations in Skid Resistance

KAZUO SAITO AND J. J. HENRY

Some of the findings of a 3-year research program to develop a basic mechanistic model for predicting seasonal and short-term variations in skid resistance as a function of environmental and traffic conditions are described. The model treats seasonal and short-term variations separately. Data from 21 test surfaces in State College, Pennsylvania, and 10 surfaces in Tennessee and North Carolina were analyzed. For the seasonal trend, an exponential curve was fitted to the skid number data for the asphalt pavements whereas a linear relationship best fit the data for portland cement concrete surfaces. The coefficients of the resulting seasonal variation curves were related to pavement and traffic parameters to provide predictors for long-term effects. Significant predictors were found to be British pendulum number (BPN) and average daily traffic. Other predictors for pavement polishing are suggested in place of BPN to predict the rate of decrease in skid resistance over an annual cycle. After the data for seasonal variations were adjusted, the remaining short-term variations were regressed against rainfall, temperature, and macrotexture parameters. The short-term variations can be predicted by dry spell factor and pavement temperature, but the introduction of the measured percentage normalized gradient was found to improve the regressions. Although good agreement was observed for the test data from the two locations, it is suggested that similar investigations be conducted in other geographic areas.

It is generally recognized that the skid resistance of pavement surfaces changes with time. Two decades ago, Giles and Sabey (1) reported that investigations on some British pavements revealed the existence of significant differences between summer and winter skid resistance. They also presented data that showed a strong relationship between seasonal variation in skid resistance and personal-injury accidents.

Skid-resistance measurements made on public highways in Pennsylvania and other states in accordance with ASTM E274 (2) exhibit seasonal and short-term variations (3-5). Seasonal cycles have been observed in the northern states, where skid resistance tends to be higher in winter through spring than in summer through fall. Superimposed on these annual cycles are short-term variations that appear to result from rainfall and other local weather conditions. These variations make it difficult to establish a rational maintenance program in which skid resistance is one of the important factors.

During the past two decades, several transportation departments and other agencies in the United States have conducted extensive skid-resistance surveys, but until the past few years little attention was paid to seasonal variations in these measurements. Until recently, the most comprehensively documented studies involving both seasonal and short-term skid-resistance variations were the ones undertaken by the Pennsylvania Department of Transportation (4,5). The skid-resistance measurements made in the first of these studies showed that, when the pavement surfaces had stabilized after being exposed to weather and traffic for 1 or 2 years, they exhibited cyclic skid-resistance variations. Several other states have reported to FHWA their observations on seasonal skid-resistance variations. Extreme seasonal variations as high as 30 skid numbers have been observed as well as more typical variations in the range of 5 to 15. These observations were summarized in 1977 by Rice (6). Analyzing these large changes, which occur rather systematically, Hegmon (7) concluded that there are real changes in skid resistance that are related to changing conditions.

Observed seasonal and short-term variations in skid resistance make it difficult for a state transportation agency to determine the minimum skid-resistance value for a given road surface. It is obviously impossible for the states to conduct their entire inventory program in the short period in which pavement skid resistance is expected to be at its lowest value. Some states conduct skid tests during most of the year, except for periods of freezing weather. Where the testing season is short, it may require several years to conduct a complete inventory of a state highway system. Thus, there is a need to establish analytic procedures that provide corrections to measured skid resistance for seasonal and short-term variations in test conditions.

The observed skid-resistance variations reported by various agencies are helpful in providing qualitative information on the trends and magnitude of seasonal and short-term variations in skid resistance. However, the measurements have not been taken frequently enough to provide the information needed to develop a model that could be used to predict the lowest skid number expected during the year on a given pavement.

FHWA recognized the need for analytic means of interpreting skid-resistance data subjected to seasonal and short-term variations. In 1978 FHWA initiated a 3-year research program with the Pennsylvania Transportation Institute of Pennsylvania State University to collect frequent skid-resistance measurements of pavements in various geographic areas of the United States and to develop predictor models for describing seasonal variation in skid resistance.

In this paper, the findings of a portion of this research program are described--i.e., the development of a basic mechanistic model for predicting seasonal and short-term variations in skid resistance as a function of environmental and traffic conditions. The model is based on 21 pavements in Pennsylvania and 10 pavements in Tennessee and North Carolina. Complete results of the project are reported elsewhere (8).

DATA BASE

The data base consisted of skid-resistance measurements taken at various speeds, pavement-related data, and weather data recorded at weather stations located near the test sites.

Test Sites

Skid testing was performed on 21 test pavements in Pennsylvania between January and December 1980. The 21 sites represented a variety of aggregates and mix designs and included 16 asphalt pavements and 5 portland cement concrete (PCC) pavements, which were subjected to a wide range of average daily traffic (ADT). During the same period, data were collected for 10 sites in Tennessee and North Carolina. The pavement and traffic parameters for each site are given in Table 1. The construction materials and locations of the test sites have been fully described by Henry and Dahir (9).

Skid-Resistance Tests

For the Pennsylvania sites, the daily skid-resistance tests were made in the transient slip mode (10). These tests provided SN_{64} data according to ASTM E274 and also brake slip numbers at 16, 48 km/h (10, 20, and 30 mph), which can be use approximate SN_{16}, SN_{32}, and SN_{48} (10). For the Tennessee and North Carolina sites, locked-wheel skid-resistance measurements were conducted primarily at 64 km/h (40 mph), although some tests were made at 48 and 80 km/h (30 and 50 mph). Air, tire, and pavement temperatures were recorded at the time of each test.

Texture Measurements

Monthly texture measurements made at each site included British pendulum number (BPN) according to ASTM E303 (2) and mean texture depth (MTD) according to the sand-patch method described by the American Concrete Paving Association (11).

Weather-Related Data

The weather data available in the daily data base for Pennsylvania sites were obtained from weather records provided by the Pennsylvania State University weather station at University Park. For North Carolina and Tennessee sites, information was obtained from weather stations at Ashville, North Carolina, and Knoxville, Tennessee.

Pavement Polishing Data

During July 1980 the Penn State reciprocating pavement polisher (12) was used in a series of tests carried out on the Pennsylvania sites. The device uses a loaded rubber pad (100 by 150 mm) through which a slurry containing abrasive is introduced. Each pavement was subjected to 2,000 cycles of polishing with a 0.05-mm silica abrasive; measurements were taken initially (BPN_0), after 500 cycles (BPN_{500}), and after 2,000 cycles (BPN_{2000}). The polishing was performed on unpolished portions of the pavement (out of wheel tracks). The results are given in Table 2. In many cases the BPN values were higher after 500 cycles of polishing than initially; this is thought to be a result of the removal of the surface glaze.

DEVELOPMENT OF MECHANISTIC MODEL

In the course of evaluating the data collected in the research program, some cyclic patterns were observed. Measurements showed that the seasonal variations from spring to fall were similar for all of the bituminous pavements: the skid number was low in the fall and was brought to approximately its original level as skid resistance was rejuvenated over the winter season (see Figure 1). Superimposed on this seasonal cycle were short-term variations that resulted in low skid numbers after a dry period and high (rejuvenated) skid numbers after a rainy period (see Figure 2) (3,13,14). These trends indicated that it might be possible to develop an equation or a model to predict the low skid numbers that occur in the fall from a skid-resistance measurement taken at any time during the year.

Based on these observations, a mechanistic model that treats seasonal and short-term variations separately has been developed (15-17). In this model it is hypothesized that seasonal variation is due to a reduction in the microtexture and the macrotexture as a result of polishing and wear of the aggregate. Polishing causes a reduction of microtexture, and wear results in a reduction of macrotexture. The short-term effects are attributed to contaminants that accumulate on the pavement (18) and, in some cases, to chemical reactions such as those that might occur between limestone aggregate and acid rain. The short-term effects, therefore, have been

Table 1. Pavement and traffic parameters.

State	Site	Type of Pavement	Year of Construction	Type of Aggregate: Coarse	Type of Aggregate: Fine	Percentage Normalized Gradient (h/km)	British Pendulum No.[a]	Mean Texture Depth[a] (mm)	ADT (no. of vehicles)
Pennsylvania	1	DG	1970	Limestone	NA	0.83	58.5	0.368	6,630
	2	PCC	1960	Limestone	Natural sand	0.32	53.0	0.394	7,700
	3	PCC	1973	Limestone	Natural sand	0.71	70.0	0.330	3,640
	4	DG	1972	Limestone	NA	0.84	62.5	0.330	3,640
	8	DG	1972	Limestone	Silica sand	0.61	55.0	0.864	1,820
	9	DG	1972	Limestone	Silica sand	0.69	69.5	0.645	1,710
	10	PCC	1973	Limestone	Silica sand	0.77	72.0	0.292	1,710
	11	DG	1963	Limestone	NA	0.79	56.0	0.432	4,490
	12	DG	1970	Limestone	NA	0.63	60.0	0.648	4,490
	13	OG	1969	Limestone	NA	0.53	90.5	0.978	7,920
	14	PCC	1967	Limestone	NA	0.83	62.0	0.368	8,770
	15	OG	1969	Limestone	NA	0.53	86.5	1.194	7,920
	16	DG	1966	Limestone	Limestone	0.88	50.0	0.394	6,500
	17	DG	1961	Limestone	Limestone	0.67	53.5	0.745	800
	18	PCC	1973	Limestone	NA	0.66	77.0	0.470	1,200
	19	DG	1968	Limestone	Silica sand	0.81	54.0	0.508	7,000
	20	DG	1968	Limestone	Silica sand	0.82	65.0	0.508	7,000
	21	OG	1969	Limestone	Silica sand	0.68	64.0	1.029	2,500
	22	OG	1969	Gravel	Silica sand	0.58	84.5	1.384	2,500
	24	DG	1963	Limestone	NA	0.83	54.0	0.432	4,490
	25	DG	1963	Gravel	NA	0.68	81.0	0.521	7,920
Tennessee and North Carolina	1	DG	1976	Gravel	Natural sand	0.49	73.3	0.945	2,377
	2	DG	1968	Gravel	Natural sand	0.41	86.3	1.600	2,107
	3	PCC	1967	Limestone	Natural sand	0.81	56.8	0.785	11,347
	4	DG	1976	Gravel	Natural sand	0.44	68.2	1.186	4,610
	5	DG	1962	Limestone	Natural sand	0.43	54.0	1.389	1,773
	6	BST	1967	Limestone	Natural sand	0.38	57.2	1.344	640
	7	DG	1970	Granite	Granite	0.50	71.0	0.856	3,973
	8	PCC	1971	Gravestone	Gravestone	0.60	58.2	1.524	6,475
	9	BST	1972	Gravestone	NA	0.41	75.2	1.636	2,310
	11	DG	NA	Slag	NA	0.70	12.0	1.034	4,354

Note: DG = dense graded, OG = open graded, and BST = bituminous surface treatment.
[a]Average value of tests made in April and May.

Table 2. Results of polishing tests with Penn State reciprocating pavement polisher for Pennsylvania sites: 1980.

Site	BPN: Initial (BPN_0)	BPN: After 500 Cycles (BPN_{500})	BPN: After 2000 Cycles (BPN_{2000})	$\frac{BPN_{500} - BPN_{2000}}{BPN_{500}}$ (%)
1	59	60	59	1.67
2	68	75	64	16.00
3	74	79	70	11.39
4	58	68	64	5.88
7	68	70	71	-1.43
8	56	51	50	1.96
9	71	66	69	-4.55
10	70	72	75	-4.17
11	67	68	66	2.94
12	87	82	73	10.98
13	89	85	87	-2.35
14	73	68	66	-4.17
15	87	85	81	4.71
16	70	62	56	9.68
17[a]	–	–	–	–
18	74	73	67	-1.61
19	65	62	63	8.22
20	65	62	63	-1.61
21	67	74	68	8.11
22	81	76	78	-2.63
24	50	59	56	5.08
25	79	77	71	7.79

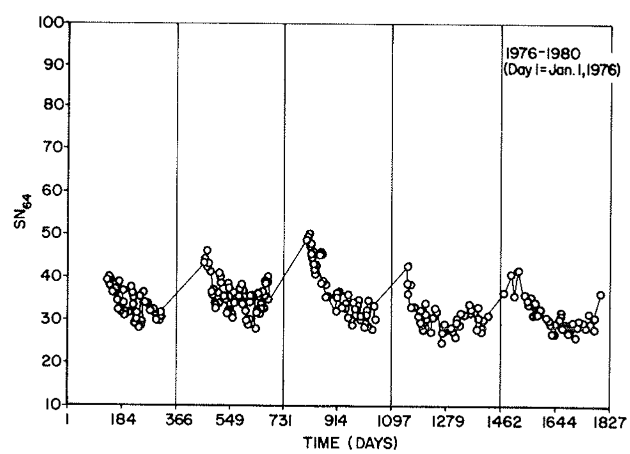
[a]Site has been resurfaced.

modeled as causing short-term modifications to the microtexture.

The model uses the Penn State model (19), in which SN_0 is related to microtexture and PNG is related to macrotexture:

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

Figure 1. Five-year history of skid-resistance variations with time for Pennsylvania site 16 (dense-graded asphalt).



where

SN_V = skid number at velocity V (km/h);
SN_0 = skid number/speed intercept, which correlates well with microtexture; and
PNG = percentage normalized gradient (h/km).

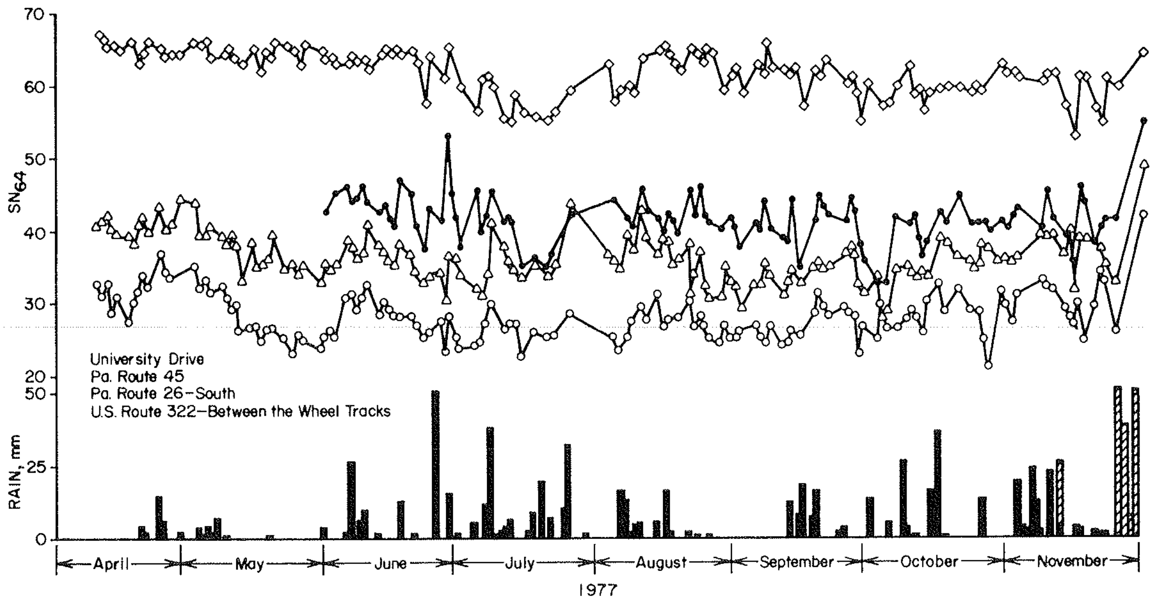
PNG, defined as $-(100/SN) \cdot [d(SN)/dV]$, correlates well with macrotexture.

For skid resistance at 64 km/h (40 mph),

$$SN_{64} = SN_0 \exp(-0.64PNG) \quad (2)$$

The term SN_0 (microtexture) has both seasonal and short-term components (SN_{0L} and SN_{0R}), where Sn_{0R} is the residuals after curve-fitting a sea-

Figure 2. Skid number (SN_{64}) and rainfall data for Pennsylvania sites: 1977 test season.



sonal trend SN_{0L}. Thus, the value of SN_0 at any time can be expressed as

$$SN_0 = SN_{0L} + SN_{0R} \quad (3)$$

The values of SN_0 deduced from data collected throughout the year typically exhibit seasonal variations, as shown in Figures 3 and 4. Figure 3 shows the results for dense-graded asphalt cement surfaces. The seasonal trend for this case can be considered to be exponential in nature, whereas the trend in the data for PCC surfaces (Figure 4) is linear.

For asphalt surfaces, the seasonal component is well-described by an exponential relationship at any time t when a measurement is made:

$$SN_{0L} = SN_{0F} + \Delta SN_0 \exp(-t/\tau) \quad (4)$$

For PCC surfaces, however, a linear relationship better fits the observations:

$$SN_{0L} = SN_{0F} + (\Delta SN_0/\tau)(\tau - t) \quad (5)$$

where

SN_{0F} = level of SN_0 after the pavement is fully polished (SN_{0F} is independent of both seasonal and short-term variations);
ΔSN_0 = polish susceptibility of the aggregate (an aggregate property); and
τ = polishing rate of the aggregate, a combination of aggregate property and ADT.

At any time t when a measurement of SN_{64} is made, Equations 2 through 4 combine for asphalt pavement surfaces to yield

$$SN_{64} = [SN_{0R} + SN_{0F} + \Delta SN_0 \exp(-t/\tau)] \exp(-0.64PNG) \quad (6)$$

The level of skid resistance at the end of the season (SN_{64F}) can be written as follows (note that the mean of the residuals SN_{0R} is zero):

$$SN_{64F} = SN_{0F} \exp(-0.64PNG) \quad (7)$$

Figure 3. SN_0 versus time for dense-graded Pennsylvania site 8: 1980.

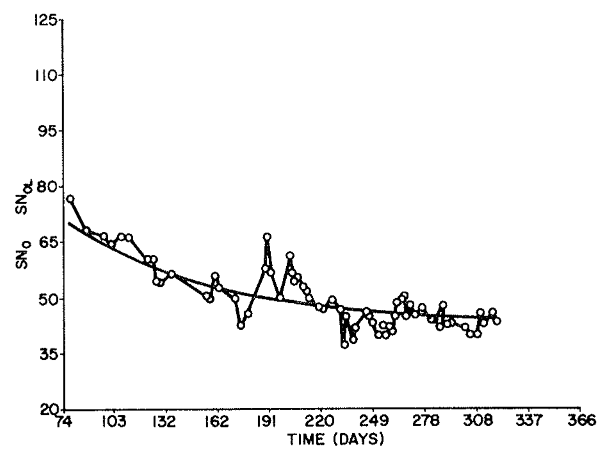
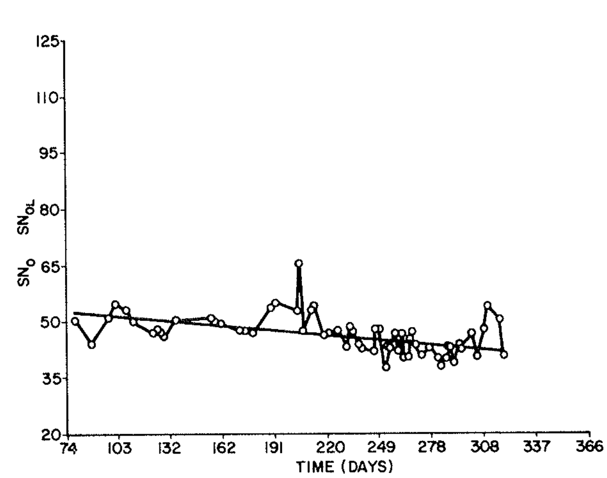


Figure 4. SN_0 versus time for PCC Pennsylvania site 2: 1980.



Substituting Equation 7 into Equation 6 to eliminate SN_{0F} and rearranging produces a relationship that can be used to predict the level of skid resistance at the end of the year (SN_{64F}) from a measurement taken at any other time during the season (SN_{64}):

$$SN_{64F} = SN_{64} - [SN_{0R} + \Delta SN_0 \exp(-t/\tau)] \exp(-0.64PNG) \quad (8)$$

For PCC surfaces,

$$SN_{64F} = SN_{64} - [SN_{0R} + (\Delta SN_0/\tau)(\tau - t)] \exp(-0.64PNG) \quad (9)$$

The short-term component SN_{0R} in Equation 3 can be described by variables related to weather and texture in the form of the following linear model:

$$SN_{0R} = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \quad (10)$$

where a_i is a coefficient determined by multiple regression and x_i denotes variables related to weather and texture.

FITTING OF SEASONAL RELATIONSHIP

The reduction in the skid resistance of asphalt pavements that occurs over the testing season appears to be exponential. Simple regression techniques cannot be used to fit an exponential relationship to the sequence of all data points in the form of Equation 4. There are three variables for which values are to be found: SN_{0F} (the magnitude of SN_0 at $t \to \infty$), ΔSN_0 (the difference between the intercept at $t = 0$ and SN_{0F}), and τ (time constant for the exponential decrease).

To overcome this problem and to fit the data systematically, for each site data were first averaged for each month, and these average values of SN_0 were assigned at the middle of each month. Next, the seasonal variations of monthly averages of SN_0 were fit according to the shifted model instead of Equation 4 because the highest recorded values of SN_0 at each site were observed at the beginning of the season, in mid-March (t = 74 days):

$$SN_{0L} = SN_{0F} + \Delta SN_0 \exp[-(t - 74)/\tau] \quad (11)$$

Figure 5 shows the basic concept of this model, and Figures 6 and 7 show the procedure used to obtain the best fit of the monthly averaged data to Equation 11. The value τ is treated as an independent variable, and the data are regressed for a fixed value of τ. To fit the data, τ is varied and the data are regressed to provide values of SN_{0F} and ΔSN_0 for each value of τ. When there is sufficient traffic and the pavement has enough polish susceptibility to reduce the value of SN_{0F} to its terminal value (Figure 6), the regression that provides the highest correlation is selected (see Figure 8). When the terminal value of SN_{0F} is not reached within the season (Figure 7), a maximum correlation coefficient does not occur for τ less than 290 days. In this case the criterion is to select a data set that corresponds to an improvement of the correlation coefficient (R^2) of less than 0.001 for a 10-day increment of τ (see Figure 9). The results for all asphalt concrete surfaces from the Pennsylvania, Tennessee, and North Carolina sites are summarized in Table 3.

For PCC surfaces, the data exhibited a linearly decreasing trend in SN_0 with time over the testing season. The following linear model was applied to yield the average value of SN_{0F} and the rate of decrease ($\Delta SN_0/\tau$), where τ is fixed at 275 days (mid-December):

$$SN_{0L} = SN_{0F} + (\Delta SN_0/\tau)(\tau - t + 74) \quad (12)$$

These results for Pennsylvania sites are also given in Table 3.

Figure 5. Basic concept of mechanistic model.

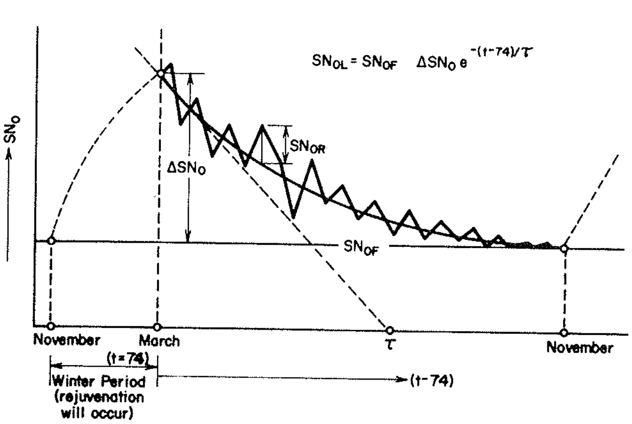


Figure 6. Annual variation of SN_{0L} for site whose terminal value is reached.

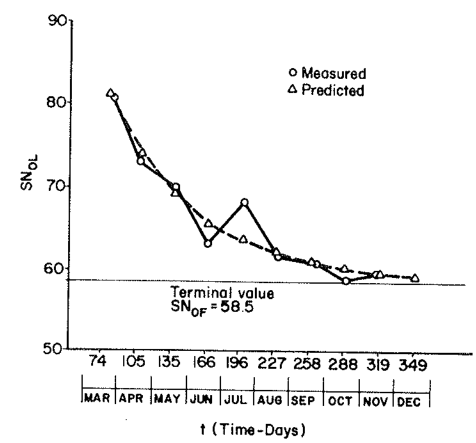


Figure 7. Annual variation of SN_{0L} for site whose terminal value is not reached because of insufficient polishing.

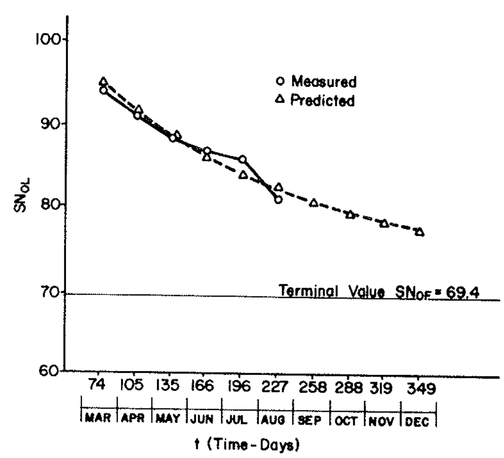


Table 3. Parameters of model for seasonal variations in skid resistance.

State	Type of Surface	Site	τ	ΔSN_0	SN_{0F}	R^2
Pennsylvania	Asphalt	1	190	22.8	44.2	0.765
		4	160	26.5	47.9	0.848
		8	80	28.6	43.1	0.919
		9	40	28.0	64.9	0.672
		11	110	19.4	44.2	0.787
		12	210	32.5	46.9	0.795
		13	160	26.6	78.4	0.926
		15	210	31.0	77.0	0.939
		16	170	14.8	34.3	0.656
		17	130	26.4	40.0	0.750
		19	140	19.9	44.2	0.844
		20	90	23.1	57.6	0.893
		21	150	26.2	40.4	0.767
		22	170	32.5	66.7	0.866
		24	190	20.4	39.6	0.720
		25	210	25.3	69.4	0.963
	PCC	2	275	12.4	40.5	0.544
		3	275	11.5	66.7	0.546
		10	275	8.2	77.8	0.512
		14	275	9.6	60.6	.0.597
		18	275	5.4	73.0	0.323
North Carolina and Tennessee	Asphalt	1	390	21.2	60.0	0.695
		2	500	23.5	50.3	0.545
		4	250	28.4	53.6	0.746
		5	190	7.8	38.1	0.411
		6	50	10.2	39.1	0.672
		7	20	20.9	70.4	0.508
		9	100	11.4	62.7	0.791
		11	210	23.9	47.3	0.803
	PCC	3	275	25.9	35.2	0.514
		8	275	3.2	52.2	0.046

PREDICTION OF SEASONAL PARAMETERS

After the values of SN_{0F}, ΔSN_0, and τ were obtained from measured data, methods of predicting them were tried. SN_{0F} is a measure of the microtexture of the pavement after removal of the seasonal and short-term effects. Thus, it seemed likely that a microtexture parameter could be used to predict SN_{0F}. Monthly measurements of BPN were available for each of the test pavements. A regression of SN_{0F} versus BPN (the average value of measurements in April and May) for asphalt pavement surfaces (see Figure 10) yields the following. For the Pennsylvania sites

$$SN_{0F} = -16.32 + 1.068BPN \quad R = 0.989 \tag{13}$$

For the Tennessee and North Carolina sites

$$SN_{0F} = -33.78 + 1.281BPN \quad R = 0.983 \tag{14}$$

A regression for PCC surfaces in Pennsylvania yields

$$SN_0 = -32.83 + 1.445BPN \quad R = 0.938 \tag{15}$$

The ΔSN_0 parameter is a measure of the rejuvenation of skid resistance (Figure 5) that occurs during the winter months as a result of the depolishing effects of winter conditions (5) and is also a measure of the polishing susceptibility of the aggregate by traffic. Therefore, BPN and ADT seemed likely parameters to be used as predictors. A linear regression of ΔSN_0 versus BPN and ADT for asphalt pavement surfaces (see Figure 11) yields the following. For Pennsylvania,

$$\Delta SN_0 = 6.69 + 0.324BPN - 0.000852ADT \quad R = 0.921 \tag{16}$$

For Tennessee and North Carolina,

$$\Delta SN_0 = -15.31 + 0.369BPN + 0.00348ADT \quad R = 0.944 \tag{17}$$

Figure 8. Procedure for determining best fit of data in Figure 6.

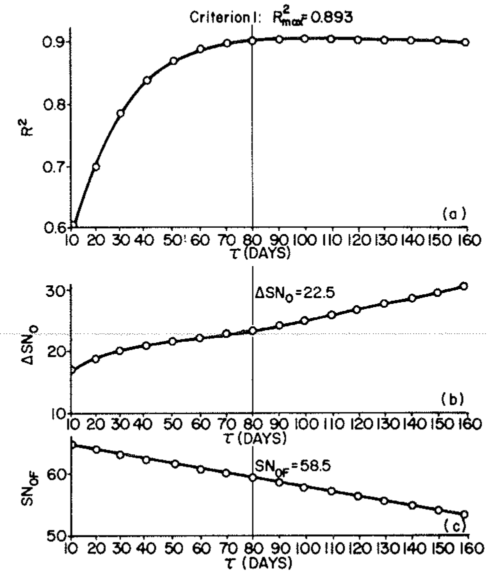
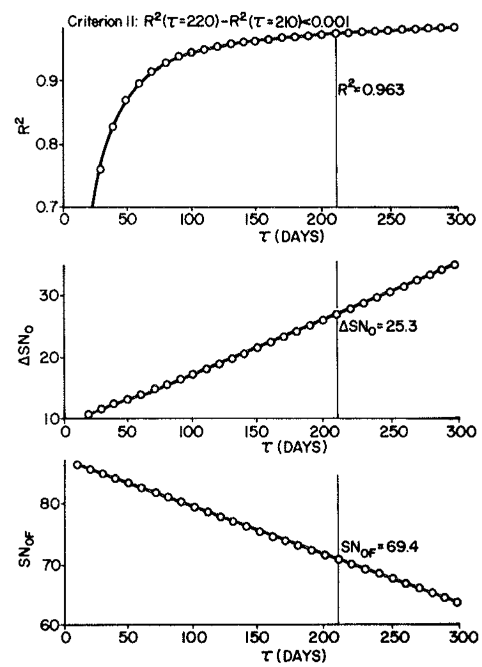


Figure 9. Procedure for determining best fit of data in Figure 7.



A regression for PCC surfaces in Pennsylvania yields

$$\Delta SN_0 = 29.51 - 0.289BPN - 0.000171ADT \quad R = 0.796 \tag{18}$$

The results for Pennsylvania sites indicate that the depolishing of the pavement that occurs as a result of the use of winter deicing chemicals is offset by the mechanical polishing that occurs with moderate traffic volumes. At the Tennessee and North Carolina sites, the effect of the depolishing of the pavement in winter is less apparent because the aggregate is polished further by the mechanical polishing that occurs with larger traffic volumes.

The mechanical aspects of pavement rejuvenation become important when the winter use of studded tires is considered. Data are available for five of the asphalt pavements in Pennsylvania for a period of three consecutive winters. In the winter of the second year (1978-1979), the use of studded tires was prohibited. The data given in Table 4 show that ΔSN_0 is consistently greater for the two winters during which studded tires were used. Specifically, ΔSN_0 is greatest for the first winter, during which studded tires were used by a large number of motorists, and for the third winter, during which studded tires were used by a relatively small number of motorists because it was uncertain until late November whether the use of studs would be permitted. These results appear to support the theory that a significant factor in winter rejuvenation of the surface texture is the mechanical interaction between tire and pavement.

Figure 10. SN_{0F} versus BPN for asphalt pavement surfaces.

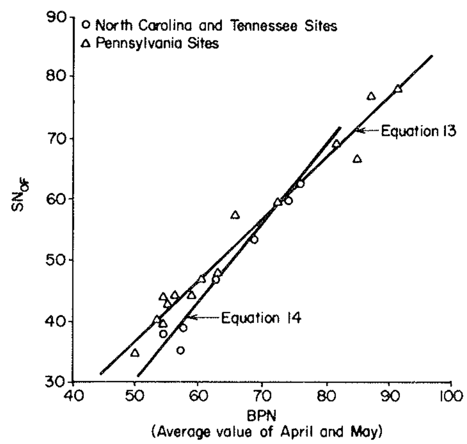


Figure 11. Prediction of ΔSN_0 from BPN and ADT for asphalt pavement surfaces.

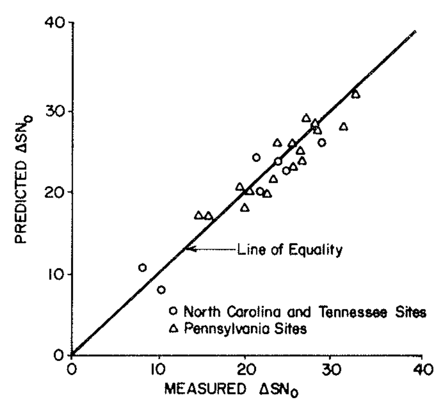


Table 4. Polish susceptibility of aggregate (ΔSN_0) for six Pennsylvania asphalt pavements over three consecutive winters.

	ΔSN_0		
Site	1977-1978	1978-1979	1979-1980
16	28.0	14.0	14.8
17	31.7	24.9	26.4
19	36.3	23.2	19.9
20	27.3	22.4	23.1
21	30.3	21.5	26.2
22	37.8	15.3	32.5

The time constant τ is associated with the rate of decrease in skid resistance over an annual cycle and with the polishing rate of the aggregate. Again, BPN and ADT appear to be useful parameters for prediction. A linear regression of the data, however, yields a poor, though significant, correlation. The resulting relationship for asphalt pavement sites in Pennsylvania is

$$\tau = 56.3 + 0.972BPN + 0.00721ADT \quad R = 0.731 \tag{19}$$

The relationship for sites in Tennessee and North Carolina is

$$\tau = -370.1 + 9.008BPN - 0.0112ADT \quad R = 0.570 \tag{20}$$

The introduction of polishing parameter BPN_{2000} instead of BPN is found to improve the prediction of τ significantly. For Pennsylvania sites (see Figure 12),

$$\tau = -22.6 + 0.00933ADT + 2.120BPN_{2000} \quad R = 0.875 \tag{21}$$

where BPN_{2000} is the measure of the polish susceptibility of the aggregate, the value of BPN after 2,000 cycles of polishing with 0.05-mm silica abrasive and the Penn State reciprocating pavement polisher.

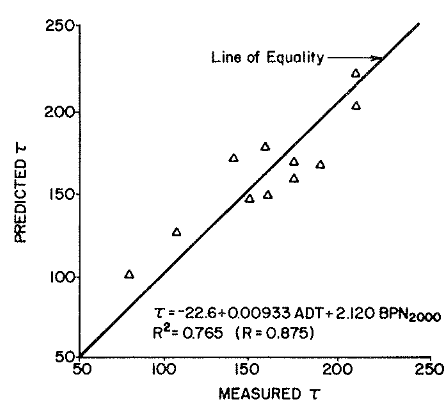
PREDICTION OF SHORT-TERM RESIDUALS

The seasonal variations in skid resistance are assumed to be a function of pavement aggregate properties and traffic density. The short-term residuals, however, are a result of rainfall effects, temperature effects, and errors in skid-resistance measurements. The largest source of measurement errors is the variation in the lateral placement of the test tire. Hill and Henry (17) discussed these three factors on the basis of 1979 data for 21 test pavements in Pennsylvania. A multiple regression of SN_{0R} versus dry spell factor (DSF) and pavement temperature (T_p) was performed. The resulting regression equation was

$$SN_{0R} = 3.79 - 1.17DSF - 0.104T_p \tag{22}$$

where DSF = ln $(t_R + 1)$, where t_R is the number of days since the last rainfall of 2.5 mm or more. The upper limit is 7 days; hence, $0 \leq t_R \leq 7$. T_p is the pavement temperature at the time of the test, measured continuously in the wheelpath not being tested. The correlation coefficient (R) of this regression was 0.35 (17). The result thus does not yield a good prediction of short-term residuals.

Figure 12. Prediction of τ from ADT and BPN_{2000} for asphalt pavement surfaces: Pennsylvania sites, 1980.



To improve the model, the parameter PNG, which can be deduced from skid-test data by using Equation 1 or predicted from a microtexture measurement (19), was introduced. A multiple regression was performed for the 1980 data. The results for each site are summarized in Table 5. The introduction of PNG was found to improve the prediction of SN_{0R} significantly.

For asphalt pavement surfaces, the regression equation for Pennsylvania (16 sites) is

$$SN_{0R} = -9.971 - 2.654DSF + 0.057T_p + 7.811PNG \quad R = 0.522 \quad (23)$$

The regression equation for Tennessee and North Carolina (8 sites) is

$$SN_{0R} = 3.584 - 0.669DSF - 0.016T_p + 10.022PNG \quad R = 0.539 \quad (24)$$

For PCC surfaces in Pennsylvania, the regression equation is

$$SN_{0R} = -11.464 - 1.049DSF + 0.0005T_p + 10.934PNG \quad R = 0.436 \quad (25)$$

PREDICTION OF ADJUSTED SKID RESISTANCE

Equations 23 and 25 can be used with Equations 8 and 9 to determine the value of SN_{64F} after adjustment for seasonal and short-term effects for the Pennsylvania sites. The models that can be used to predict the level of skid resistance at the end of the year (SN_{64F}) for a measurement taken at any other time during the season (SN_{64}) are as follows. For asphalt pavement surfaces in Pennsylvania,

$$SN_{64F} = SN_{64} - \{\Delta SN_0 \exp[-(t - 74)/\tau] - 9.971 - 2.654DSF + 0.057T_p + 7.811PNG\}\exp(-0.64PNG) \quad (26)$$

For PCC surfaces,

$$SN_{64F} = SN_{64} - [(\Delta SN_0/\tau)(\tau - t + 74) - 11.464 - 1.04DSF + 0.0005T_p + 10.934PNG]\exp(-0.64PNG) \quad (27)$$

Figures 13 and 14 show the adjusted SN_{64F} values compared with the original data for two Pennsylvania sites. The results for other sites are similar. Ideally, SN_{64F} should be constant with time after all of the seasonal and short-term effects are accounted for. The comparatively low correlation coefficients obviously limit the ability of regression Equations 23 and 25 to smooth the data for short-term variations.

Table 5. Short-term parameters for Pennsylvania sites: 1980.

Type of Surface	Site	a_1	a_2	a_3	a_4	R^2
Asphalt	1	-11.854	-3.587	0.039	9.807	0.431
	4	-27.665	-3.583	0.116	17.348	0.467
	8	-26.949	-1.171	0.026	24.026	0.665
	9	-24.638	-2.025	0.151	14.447	0.298
	11	-26.006	-2.556	0.084	18.416	0.490
	12	-20.614	-2.658	0.085	17.275	0.538
	13	-20.477	0.086	0.091	15.033	0.283
	15	-18.635	0.725	0.054	15.647	0.229
	16	-16.159	-2.419	-0.042	16.411	0.498
	17	-26.934	-5.594	-0.083	38.053	0.570
	19	-21.138	-2.124	-0.042	21.391	0.506
	20	-23.706	-2.251	-0.019	22.573	0.613
	21	-37.018	-2.785	0.069	32.793	0.877
	22	-43.415	-1.178	0.132	37.166	0.538
	24	-26.206	-2.786	0.013	22.295	0.563
	25	-12.345	-1.277	0.022	11.832	0.109
PCC	2	-29.867	-2.216	0.088	20.154	0.510
	3	-30.446	-0.760	0.124	19.876	0.430
	10	-20.154	-0.493	0.052	13.940	0.178
	14	-15.151	-1.938	0.005	10.821	0.171
	18	-19.174	-0.169	-0.005	23.071	0.567

Note: $SN_{0R} = a_1 + a_2DSF + a_3T_p + a_4PNG$.

Figure 13. Comparison of measured and adjusted SN_{64} for asphalt pavement surface: Pennsylvania site 8, 1980.

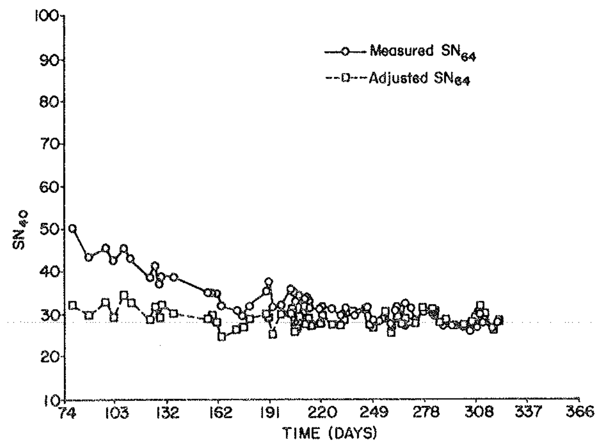
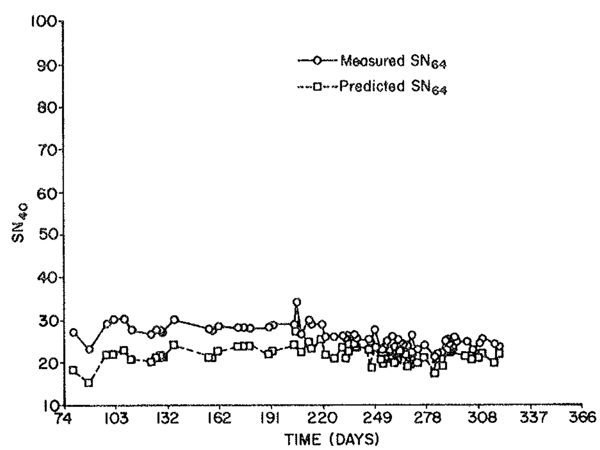


Figure 14. Comparison of measured and adjusted SN_{64} for PCC surface: Pennsylvania site 2, 1980.



The predicted values of SN_{64F} were calculated for each Pennsylvania site by applying Equations 26 and 27 on each day a measurement was made in 1980. The mean and standard deviation of the predictions for each site are compared in Table 6 with the observed values of SN_{64F} for the site. The mean predicted values agree well with the observed values: the standard deviation of the predicted values ranges from 1.68 to 3.70 skid numbers. These values are less than the variations in SN_{64} measurement expected to result from measurement error and other sources of error (20).

It should be noted that the derivation of Equations 26 and 27 requires the assumption that PNG (macrotexture) does not vary between the time of the test and the end of the season. This assumption is reasonable for pavements with relatively durable aggregates and moderate traffic volume, as in the case of the Pennsylvania data. The value of PNG does increase as macrotexture decreases with aggregate wear, which is a function of ADT, aggregate properties, and time.

CONCLUSIONS

The following conclusions can be drawn from the analysis of the mechanistic model:

1. In the course of evaluating the data collected, it was observed that large variations in

Table 6. Comparison of estimated and averaged SN_{64F} values for Pennsylvania sites: 1980.

Site	Observed Values of SN_{64F}	Mean and Standard Deviation of Prediction From All Observations	
		Mean	Standard Deviation
1	26.1	23.4	3.1
2	24.0	22.0	2.2
3	42.4	42.5	3.6
4	27.9	25.8	2.2
8	29.1	29.4	3.0
9	41.8	41.5	3.3
10	47.6	46.5	3.7
11	26.7	25.7	2.5
12	31.3	31.6	2.7
13	55.8	56.3	3.7
14	35.7	33.9	3.2
15	55.0	56.1	3.3
16	19.5	17.1	2.7
17	26.1	25.2	2.8
18	48.0	48.7	2.7
19	26.3	24.7	2.6
20	34.1	33.0	3.2
21	26.1	25.6	1.7
22	46.0	46.6	2.7
24	23.4	21.8	2.6
25	45.1	43.9	2.7

skid-resistance measurements occur systematically over a long period (from one season to another) and over a short period (day to day). The measurements showed that friction levels generally decline from a maximum in early spring to a minimum in late fall and then are rejuvenated to approximately their initial level during the winter. Superimposed on this seasonal cycle are significant short-term variations that result in low skid numbers after a dry period and high (rejuvenated) skid numbers after rainfall.

2. Based on these observations, an effective and simple mechanistic model that treats seasonal and short-term variations separately has been developed. In the model it is hypothesized that seasonal variations are caused by a reduction in the microtexture and the macrotexture as a result of polishing and wear of the aggregate. A procedure for systematically performing this model fitting has also been established.

3. It was found that the level of skid resistance at the beginning of spring is a function of surface microtexture as measured by BPN, average daily traffic volume, and mechanical effects such as the roughening of the surface by studded tires in the winter.

4. The level of SN_0 after removal of the seasonal and short-term effects (SN_{0F}) can be predicted by the average BPN obtained in April and May.

5. The rate of decrease in skid resistance attributable to polishing of the aggregate can be adequately predicted by ADT and by the BPN_{2000} value, which can be obtained by using the Penn State reciprocating pavement polisher.

6. The short-term variations can be predicted by dry spell factor and pavement temperature, but the introduction of PNG is found to improve the short-term prediction model significantly.

7. It has been shown that the mechanistic model developed here can be used to predict the level of skid resistance at the end of the season from a measurement taken at any time during the season.

8. Although fairly good agreement has been found between the results for the sites in Pennsylvania and those in Tennessee and North Carolina, similar investigations should be conducted in other geographic areas.

ACKNOWLEDGMENT

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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-