Development of a Procedure for Correcting Skid-Resistance Measurements to a Standard End-of-Season Value

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ABSTRACT

The wet skid resistance of a pavement can vary significantly from one day to another and from one season to another. A general decay in skid resistance occurs from the spring to the fall with day-to-day perturbations superimposed over the general decay. The seasonal decay and the day-to-day perturbations may individually be as many as 10 to 15 skid numbers. These variations are of concern when skid resistance measurements are made for survey purposes. A general statistical model developed by others was used as a prediction equation to adjust skid measurements made on any given day to an end-of-season value. In the prediction equation, day-to-day variations are accounted for by the recent rainfall history (0 to 7 days) and the air temperature at the time of test. The general decay in skid resistance that occurs over the season is accounted for by the Julian calendar day and the average daily traffic. Adjusted end-of-season values for the data obtained in New York, Pennsylvania, and Virginia were such that 90 percent of the adjusted end-of-season values were within approximately +3.6 to -3.6 skid numbers of the measured end-of-season value. Additional research is needed to develop a fundamental understanding of the mechanisms that cause changes in skid resistance. This is necessary so that a more rational model can be developed to account for the site specificity of the changes in skid resistance that were observed.

The wet skid resistance of a pavement can vary significantly over time. Temporal changes in wet skid resistance occur over the life of a pavement, from one season to another and from one day to another (1). The mechanisms that cause these changes are not well understood; however, there is empirical knowledge of the factors that cause these changes.

The skid resistance of bituminous pavements increases in the first 1 or 2 years as the bitumen at the surface is worn away. After this conditioning period, the skid resistance tends to decrease over the years depending on factors such as traffic, mixture design, aggregate properties, and the environment. In the northern climates of the United States, seasonal changes are superimposed on the long-term skid resistance changes. During the fall and winter seasons skid resistance increases, followed by a loss of skid resistance over the late spring and summer months. Traffic polishes the pavement surface in the summer while alternate freezing and thawing of the aggregate and the use of antiskid materials and studded tires cause roughening of the surface (2).

Superimposed on the seasonal changes of skid resistance are day-to-day changes that have been attributed to short-term weather changes, principally rainfall and temperature. On bituminous surfaces, extended dry periods and periods of increasing temperature tend to decrease skid resistance. A typical sample of a plot of skid resistance versus time for a single season is shown in Figure 1. The short-term variations range as high as 10 to 15 skid numbers with a similar decrease in skid number during a single testing season.

The changes that occur in the skid resistance of portland cement concrete pavements are not as pronounced: there is no appreciable conditioning period during the first few years, and the seasonal and day-to-day variations tend to be smaller. However, the skid resistance of portland cement concrete can change dramatically as the pavement wears through the surface finish, the sand matrix, and into the coarse aggregate.

FHWA requires state agencies to make periodic measurements of skid resistance for inventory purposes. Because skid resistance can vary over a testing season by as many as 10 to 15 skid numbers, it would simplify inventorying procedures if skid numbers obtained on any given day could be corrected to some reference condition, such as the end-of-season minimum skid number. The objective of this study was to develop a procedure for correcting skid numbers made on any arbitrary day to an end-of-season minimum skid number. Because the procedure was designed for pavement management purposes, only those measurements that can be readily obtained in survey tests at 40 mph were included in the procedure. Such a procedure should also be useful for reconstructing the skid resistance on some given day from measurements taken on a later day as, for example, in reconstructing the conditions that existed at the time of a traffic accident.

Two predictor models were used in this study as algorithms for making short- and long-term corrections in measured skid resistance values. These predictor models, referred to as the mechanistic and statistical models, were developed by Henry et al. (3). In order to validate these models and to determine the most practical set of variables for use with the models, a sensitivity analysis was performed with an extensive 1979-1980 data set obtained previously by the Pennsylvania Transportation Institute. Final validation was done with a new data set obtained in New York, Pennsylvania, and Virginia in the summer of 1983. A single model was developed that contains only variables that can be readily measured by a survey crew making skid tests at 40 mph or obtained from highway agency records or weather stations. This

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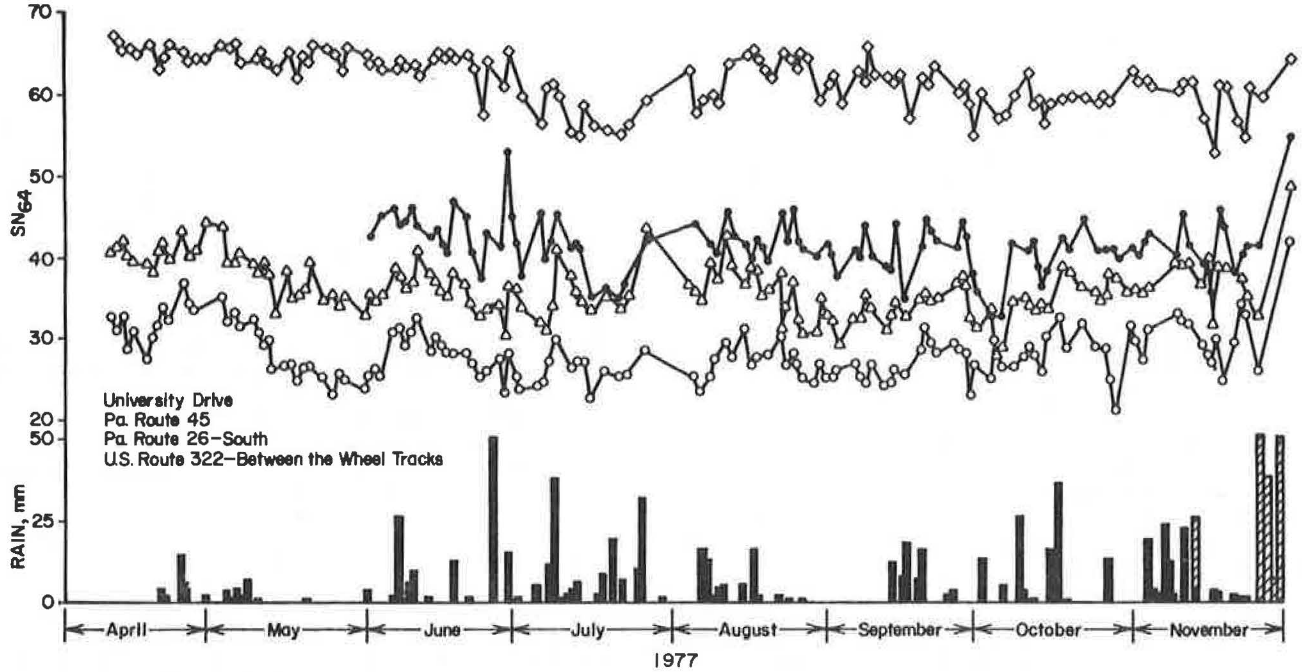

FIGURE 1 Skid number (SN_{64}) and rainfall data for the 1977 test season.

approach obviates the use of variables such as the British Portable Number (BPN) or texture depth measures, which require that traffic be stopped.

SENSITIVITY ANALYSIS USING THE 1979-1980 DATA

Data that had been obtained in Pennsylvania during 1979 and 1980 from 25 asphalt and portland cement concrete pavement sites (3) were used in the preliminary analyses. Two proposed prediction models were considered. The first, referred to as mechanistic model (3), is based on the assumed dependency of skid resistance on microtexture and macrotexture:

$$SN_{64} = SN_0 e^{-0.64PNG} \quad (1)$$

where

SN_{64} = skid resistance measured at 64 km/h (40 mph);
SN_0 = skid number-speed intercept (i.e., skid resistance extrapolated to zero speed);
PNG = percent normalized skid-resistance gradient, defined as $-100/SN \cdot [d(SN)/dV]$; and
SN = skid resistance at any velocity V.

The SN_0 and the PNG terms are highly correlated with microtexture and macrotexture, respectively. Macrotextrue is defined as texture with asperities greater than 0.1 mm, whereas microtexture is defined as texture with asperities of 0.1 mm and smaller. The mechanistic model has been proposed as a predictor of both long- and short-term variations in skid resistance. In this model both SN_0 and PNG may be expressed as a function of time. Because it is a function of macrotexture, PNG can be expected to experience little change over a single testing season. However, in order to determine the end-of-season value for SN_0, it is necessary to have polishing and texture data that would typically have to be obtained from laboratory tests. Therefore, this model was considered inappropriate for the objectives of this study.

The sensitivity analyses were then focused on the generalized model

$$\ln SN_{64} = b_0 + b_1 DSF + b_2 TEMP + b_3 T30 + b_4 JDAY + b_5 AGE + b_6 ADT + b_7 SN_{64}F + \varepsilon \quad (2)$$

where

SN_{64} = a skid-resistance measurement made in accordance with ASTM E274 at 64 km/h (40 mph) using the ASTM Standard Test Tire E501;
DSF = dry spell factor, $\ln(t_r+1)$, where t_r is number of days since last daily rainfall of 0.1 in. (2.5 mm) or more, $t_r < 7$ and DSF < 2.08;
TEMP = average of daily maximum and minimum temperature on the day of test;
T30 = weighted temperature history defined as

$$1/30 \sum_{i=1}^{30} \left\{ [(29/30)^{i} T_{j-1}] \right\}$$

where T_{j-i} is the average of the maximum and minimum air temperatures on the Julian calendar day i days before the date of interest (3);

JDAY = Julian calendar day;
AGE = age of the pavement surface, years;
ADT = average daily traffic;
$SN_{64}F$ = the measured skid number at the end of the season;
$b_0, \ldots, b_i$ = regression coefficients; and
ε = random error term associated with regression.

In this model, the dry spell factor (DSF), median daily air temperature (TEMP), and the weighted average temperature (T30) account for the short-term weather effects, whereas the Julian calendar day (JDAY), pavement age (AGE), and end-of-season skid number ($SN_{64}F$) account for the seasonal effects. Thus the model describes changes in skid resistance that occur day-to-day and throughout the season.

Final end-of-season skid numbers were obtained from the data by plotting the data and observing trends. Linear regression was then used to calculate the coefficients, $b_0, \ldots, b_i$, in Equation 2. The following regression equation was obtained for the asphalt concrete sites that were measured in 1979 and 1980 (3):

$$\ell nSN_{64} = 3.12 - 0.0371\ DSF + 0.0\ TEMP - 0.0028\ T30 - 0.00047\ JDAY - 0.0041\ AGE + 0.0\ ADT + 0.0244\ SN_{64}F + error \quad (3)$$

Equation 3 was then used to calculate values of the natural logarithm of the skid resistance (ℓnSN_{64}), and these values were compared with the measured skid resistance values. This was done for each site and day of test in the data set. The differences between observed and predicted values, the residuals, were analyzed statistically for their magnitude and trends.

The significance of each of the terms in Equation 3 can be realized by multiplying the range of each of the variables by their respective model coefficient. This is given in Table 1 where both the absolute range (maximum value-minimum value) and the interquartile range (the range containing 50 percent of the observations) are used. The effect of each of these variables is small, less than four skid numbers, except for the variable $SN_{64}F$, which yields changes of 36 skid numbers. Although, except for $SN_{64}F$, the individual change attributable to any one of the variables is small, in combination, the changes can be significant, as shown in Figure 1.

Typical examples of the residuals for the predicted values of SN_{64} are shown in Figures 2 through 4. The residuals are not randomly distributed about zero but show systematic changes throughout the year. Further, the trend of the residuals over the testing season is not consistent from one year to the next as shown by comparison of Figures 3 and 4 (1979 versus 1980). This implies that the model coefficients are both site and year specific. To test for site-specific trends, a dummy site-specific variable was added to Equation 2, and this variable was shown to be highly significant (3). Quite obviously, from the statistical analyses and Figures 2 through 4, there are site-specific trends in the 1979-1980 data that are not accounted for by the model of Equation 2.

SELECTION OF TEST VARIABLES FOR 1983 TEST SEASON

The analysis of the 1979-1980 data showed that the dry spell factor (DSF), median air temperature on the day of test (TMEAN), 30-day weighted average air temperature (T30), pavement age (AGE), Julian calendar day on the day of test (JCD), and end-of-season skid number ($SN_{64}F$) are all statistically significant variables in the predictor model. Therefore, the 1983 validation testing program was developed to accommodate as wide a range as possible in these variables. Pavement and air temperature at the time of test were included because the skid tester that was used was equipped to collect this information.

Although the average daily traffic variable was not significant in the model with the 1979-1980 data set, engineering judgment dictates that it should be. It was reasoned that it was not significant because the 1979-1980 data did not have a sufficient range in ADT. Therefore, it was decided to retain ADT as a variable and to seek a wider range in ADT for the 1983 validation testing.

During the sensitivity analysis, other temperature variables were tried as a substitute for T30 because of the large amount of data required to calculate T30. The single 5-day average of the maximum and minimum temperature was found to be just as effective as T30, and data were collected to calculate this variable.

Because the preliminary model (Equation 2) did not completely account for temporal site-specific variations in skid resistance, blank tire (ASTM E524) skid resistance measurements were included in the 1983 test program. This decision was based on the hypothesis (4) that a comparison of blank and ribbed skid-resistance measurements would provide insight into the texture of the pavement surface at each site. Ribbed and blank tire measurements were made by testing each of the sites with one tire, changing tires, and then repeating the tests. Combined blank and ribbed tire data would be relatively easy to obtain with a two-wheel skid trailer, whereas site-specific texture measurements would be complex and costly with existing test equipment. It should be noted, however, that the use of the two-wheeled trailer to simultaneously measure blank and ribbed skid numbers was done at the peril of measuring two different pavement populations. Research by others has shown that the skid resistance can be significantly different in the two tire tracks (4). A more acceptable procedure would be to modify existing equipment to allow the blank and ribbed tire to be used in areas on the same tester.

1983 TEST PROGRAM

Skid-resistance testing was conducted in New York, Pennsylvania, and Virginia in the summer of 1983, providing a range of climates and surface types. Because both short-term and long-term variations in skid resistance were to be modeled, data were gathered on a daily basis during four different weeks in each of the three states. Testing was conducted

TABLE 1 Changes in Predicted Skid Resistance Due to Changes in the Independent Variables

Independent Variable	Model Coefficient, b_i	Range R	$\Delta \tilde{SN}_{64}$ Due to Range[a]	Interquartile Range (Q3-Q1)	$\Delta \tilde{SN}_{64}$ Due to Interquartile Range[a]
DSF, days	-.0371	2.08	-2.79	1.26	-1.70
T30, °F	-.0028	24.4	-2.46	10.8	-1.09
TEMP, °F	0	49.5	0	18.0	0
JDAY, day	-.00047	210.0	-3.59	106.0	-1.81
AGE, years	-.0041	11.0	-1.63	4.0	-.58
ADT, vehicles/day	0	3,650.0	0	23.5	0
$SN_{64}F$	.0244	39.2	36.1	18.0	16.1

[a] $\Delta \tilde{SN}_{64}$ is the change in the predicted value of SN_{64} due to a change in the independent variable equal to the range or interquartile range.

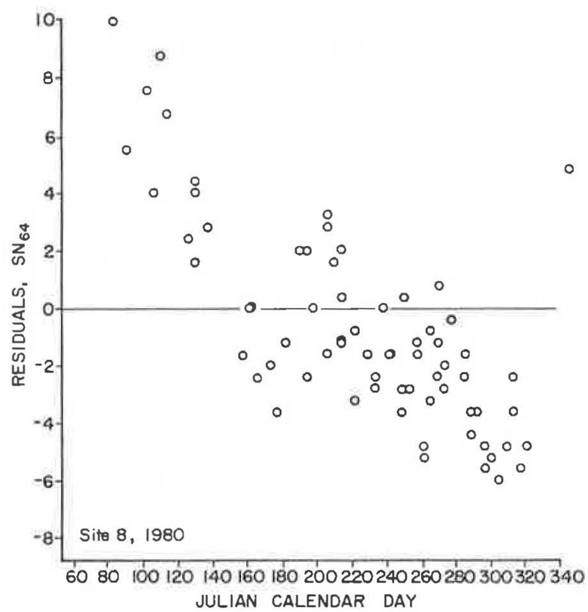

FIGURE 2 Residuals for Pennsylvania Site 8, 1980.

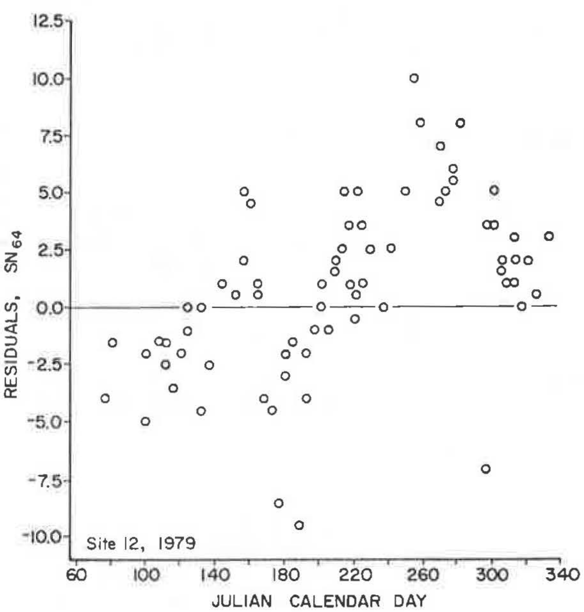

FIGURE 3 Residuals for Pennsylvania Site 12, 1979.

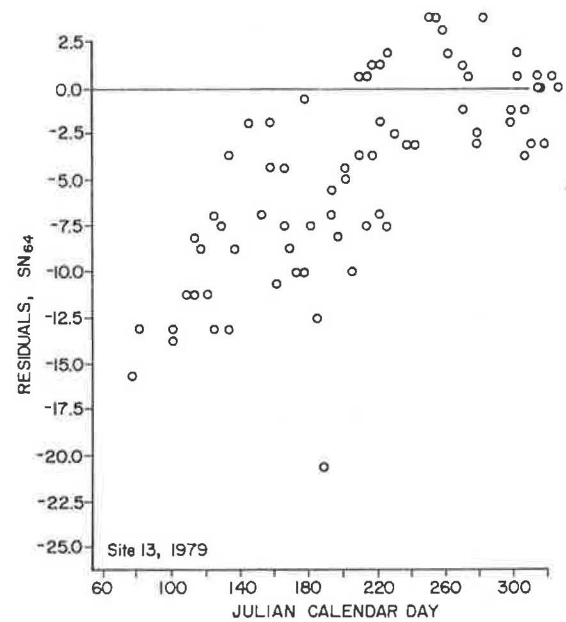

FIGURE 4 Residuals for Pennsylvania Site 13, 1979.

throughout the day on the second, third, and fourth days of the week in order to evaluate within-day variations in skid resistance. Water, pavement, and air temperatures were recorded at the time of each test. Each test consisted of five lock-ups averaged as required by ASTM E274, and measurements were taken with both a ribbed and a blank tire (ASTM Standard Pavement Test Tires E501 and E524, respectively). Summaries of the ribbed tire, skid-resistance measurements for New York, Pennsylvania, and Virginia are given in Tables 2 through 4. Details of the testing program can be found elsewhere (5).

Typical plots of skid resistance versus time are shown in Figure 5 for two Pennsylvania sites. In this figure the skid numbers decrease during the months of June, July, and August but show an increase by September or October. This trend is typical of the data from each state. Average standard deviations for the five lock-ups that constitute a single measurement and the average standard deviations for the multiple measurements taken on any given day are given in Table 5. The standard deviations are approximately two skid numbers with some tendency to decrease during the testing season. Given these standard deviations for testing error, a model should not be expected to predict skid numbers with an accuracy better than plus or minus 2 to 3 skid numbers.

The short-term weather corrections are too small to account individually for the typical variations measured in the field (Figure 1). The authors believe that much of the "noise" in the data is due to measurement error as well as to transverse and longitudinal variations in skid resistance on the surface of the pavement. Average within-run (among the five lockups) standard deviation for SN_{64} is 1.7, whereas the within-day standard deviation among repeat runs is only 2.0 skid numbers (Table 5). These values are of the same order of magnitude as the adjustments as a result of temperature and rainfall.

In order to develop a prediction model, it was necessary to estimate the end-of-season minimum skid number. This was done in three different ways: by examining the trend of the plot of skid resistance plotted versus Julian calendar day for each site, by averaging the skid numbers obtained on the first week of testing, and by using a statistical model that assumes an exponential decay in skid resistance from spring to fall (3). The first technique was unsatisfactory because the noise in the data made it difficult to estimate trends over the season. The nonlinear statistical mode

$$SN_{64}\tilde{F} = \ell SN_{64} e^{-(JDAY-300)/t} \qquad (4)$$

where

$SN_{64}\tilde{F}$ = predicted skid resistance on day 300;
SN_{64} = skid resistance measured on any arbitrary day, JDAY; and
t = regression coefficient.

did not provide reliable estimates because the seasonal changes in skid resistance often varied sinusoidally or linearly rather than exponentially with time.

The end-of-season skid numbers that were used in

TABLE 2 Mean Skid Numbers (SN_{64}) and Standard Deviation for Each Week of Testing in New York in 1983—Ribbed Tire (E501)

	New York								
	June 13-17		July 11-15		Aug. 29- Sept. 2		Oct. 17- 21		
Site No.	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$SN_{64}F$
1	43	3.3							40
2	42	4.1							40
3	45	0.9	41	1.5	42	1.7	40	4.0	39
4	40	1.5	37	1.6	39	1.3	38	3.9	43
5	35	1.1	36	0.9	35	1.2	32	2.5	28
6	27	1.6	24	3.3	27	1.2	28	3.3	27
7	34	1.4	32	1.5	30	1.1	29	3.7	26
8	48	2.1	46	1.6	47	1.5	42	4.2	40
9	37	1.6	36	1.3	35	1.0	31	2.8	29
10	28	1.4	29	3.2	26	1.3	24	2.5	25
11	34	1.1	35	3.1	31	1.7	30	4.5	33
12	48	1.5	45	2.3	46	1.0	38	2.4	25
13	23	1.1	22	1.0					42
14	50	3.2	48	1.3	47	1.4	42	2.9	33
15	40	1.5	39	1.0	39	1.4	34	2.4	27
16	35	3.4	35	1.1	34	1.2	31	2.9	27
17	43	2.8	42	1.4	43	1.4	38	2.8	27
18	48	2.8	47	1.0	48	2.6	40	2.9	28
19	40	0.9	40	1.4	40	2.4	34	2.3	33
20	30	1.3	31	4.0	30	1.4	28	3.1	26
Avg		1.9		1.8		1.5		3.2	

Note: N = number of tests, each test consisting of five lockups; $\bar{X}$ = mean of the tests for given week; s = standard deviation of tests for given week; and $SN_{64}F$ = arithmetic average of the skid-resistance measurements for last week of testing; corrected for short-term weather changes before being averaged.

TABLE 3 Mean Skid Numbers (SN_{64}) and Standard Deviation for Each Week of Testing in Pennsylvania in 1983—Ribbed Tire (E501)

	Pennsylvania								
	May 24-28		June 21-25		Sept. 6-10		Oct. 10-14		
Site No.	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$SN_{64}F$
1	30	1.5	27	1.7	24	3.4	23	1.2	23
2	47	2.2	47	1.3	37	4.8	41	3.0	40
3	44	3.2	43	0.8	39	1.4	39	2.1	38
4	27	2.3	27	1.6	22	0.7	25	1.6	24
5	43	5.5	45	2.3	38	1.2	40	1.6	38
6	34	0.8	34	1.9	28	1.5	34	2.1	33
7	30	0.9	29	1.4	24	0.8	28	2.4	27
8	36	1.3	35	1.0	32	1.0	33	1.9	33
9	33	0.6	33	1.9	31	2.1	32	1.4	32
10	47	2.6	49	2.1	46	1.5	46	2.5	45
11	32	1.3	30	1.4	27	1.4	31	3.4	29
12	36	1.1	34	2.0	32	1.1	32	1.6	31
13	37	3.0	37	1.0	36	0.8	35	4.4	34
14	34	1.9	35	3.5	31	0.7	32	3.9	31
15	40	2.9	39	2.3	36	0.9	37	2.1	36
16	37	1.1	37	1.4	35	0.9	34	1.3	33
17	44	1.7	43	2.2	40	1.8	39	1.9	37
18	44	1.6	43	1.6	40	1.3	39	1.3	37
19	51	2.2	49	1.6	47	1.7	45	2.5	45
20	30	1.0	29	1.2	27	2.8	27	1.2	26
21	27	2.0	26	1.6	22	1.7	24	2.1	24
22	53	1.4	52	3.6	46	2.1	47	1.7	46
23	45	1.4	42	1.9	38	1.4	37	2.3	35
Avg		1.9		1.8		1.6		2.2	

Note: N = number of tests, each test consisting of five lockups; $\bar{X}$ = mean of the tests for given week; s = standard deviation of tests for given week; and $SN_{64}F$ = arithmetic average of th skid-resistance measurements for last week of testing; corrected for short-term weather changes before being averaged.

the development of the model were estimated from the blank skid-resistance measurements collected during the last week of testing. These measurements were first adjusted for short-term changes to a set of reference conditions and then averaged. The adjustments were made with the following regression equation (5):

$$SN_{64} = \exp[\ell nSN_{64} - b_1(DSF-DSF_0) + b_2(AIRT-AIRT_0)] + b_3(TMEAN5-TMEAN5_0) \quad (5)$$

TABLE 4 Mean Skid Numbers (SN_{64}) and Standard Deviation for Each Week of Testing in Virginia in 1983—Ribbed Tire (E501)

	Virginia								
	May 9-14		June 27- July 2		Sept. 12-16		Oct. 24-28		
Site No.	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$\bar{X}$	s	$SN_{64}F$
1	59	1.9	56	1.9	52	1.2	51	3.1	50
2	57	5.3	55	1.3	52	1.4	51	3.4	50
3	43	1.1	41	0.8	39	1.8	36	2.1	35
4	42	1.5	39	1.3	38	2.1	35	3.0	35
5	44	1.3	41	1.6	40	1.4	38	2.1	37
6	47	2.5	41	1.2	40	1.6	37	2.8	35
7	47	2.1	43	1.1	40	1.0	36	2.6	32
8	43	1.9			36	1.5	33	2.1	32
9	42	2.7	37	1.5	37	1.9	34	3.0	33
10	49	2.5	44	1.6	43	1.8	40	2.7	39
11	42	1.4	41	0.7	39	2.0	37	2.8	35
12	46	2.0	46	1.3	43	2.6	42	2.4	40
13	38	1.4	35	1.7	35	1.9	34	2.0	33
14	45	1.0	36	2.4	37	2.6	37	2.4	36
15	43	1.8	40	1.0	37	2.6	35	2.2	34
16	40	1.8	35	0.8	33	1.9	32	3.1	31
17	49	1.5	45	1.1	42	1.7	39	2.8	38
18	49	1.1	45	0.8	44	2.0	40	2.6	39
19	42	1.6	40	0.6	37	2.6	34	2.8	33
20	42	1.4			33	3.1	34	2.7	33
21	49	4.5	4.5	1.0	43	1.8	39	2.9	38
Avg.		2.0		1.2		1.9		2.6	

Note: N = number of tests, each test consiting of five lockups; $\bar{X}$ = mean of the tests for given week; s = standard deviation of tests for given week; $SN_{64}F$ = arithmetic average of the skid-resistance measurements for last week of testing; corrected for short-term weather changes before being averaged.

where the subscript 0 refers to the reference conditions

AIRT = air temperature at time of test, and
TMEAN5 = average of median temperature for the 5 days before the day of test and standard conditions are as follows:
DSF_0 = 2.08, and
$AIRT_0$ = $TMEAN5_0$ = 68 F (20 C).

The coefficients for Equation 5 were calculated on a site-specific basis using the following equation:

$$\ell nSN_{64} = b_{0j} + b_1\ DSF + b_2\ AIRT + b_3\ TMEAN5 + b_4\ ADT + b_5 JDAY + e \quad (6)$$

were b_{0j} indicates the jth site.

Rainfall data were obtained from the nearest weather station and from rain gages installed at selected test sites. All rainfall data were corrected to a 24-hr observation period ending at 8:00 a.m. Temperature data were also obtained from local weather stations and from measurements taken at the time of test. Traffic data were obtained from the respective state departments of transportation and from spot traffic counts by the skid-testing crew. Traffic on the test sites ranged from less than 100 vehicles per day to nearly 20,000 vehicles per day.

REFINEMENT OF THE MODEL

The 1983 skid-resistance data were examined critically for normality before any statistical work was done to refine the prediction model. No serious exceptions were found except for the presence of several obvious outliers that were removed from the data base. A full discussion of the extensive statistical analyses that were conducted with the data is given elsewhere (5).

Three measures of air temperature were considered for use in the final model: the air temperature mea-

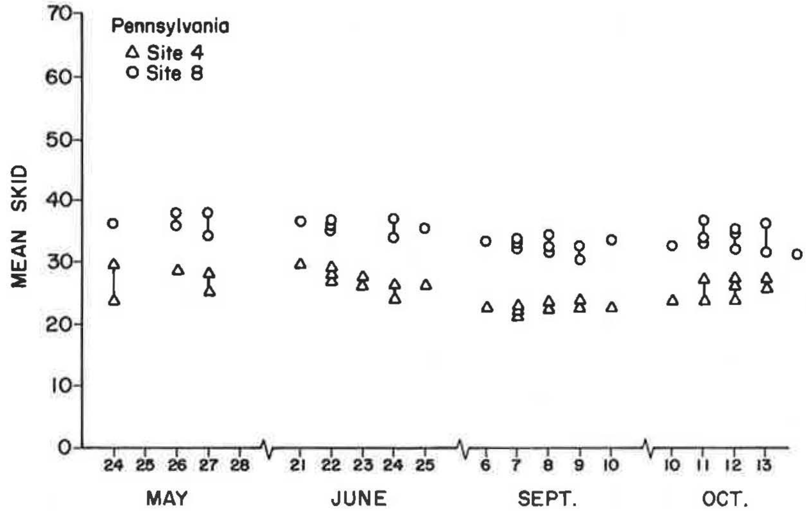

FIGURE 5 Mean SN_{64} versus calendar day of 1983 for Pennsylvania Sites 4 and 8.

TABLE 5 Standard Deviation of SN_{64} for Ribbed Tire (E501) on Bituminous Concrete

State	Week	Between-Run Standard Deviation	Within-Run Standard Deviation
New York	6	2.3	2.1
	10	2.0	1.9
	17	1.4	1.7
	24	3.4	1.6
Avg		2.3	1.8
Pennsylvania	3	2.4	2.6
	7	1.9	2.4
	18	1.6	1.9
	23	1.5	1.6
Avg		1.9	2.1
Virginia	2	2.4	2.0
	8	1.3	1.9
	19	2.0	1.6
	25	2.3	1.4
Avg		2.0	1.7

sured on the tester at the time of test (AIRT), the 5-day arithmetic average of the daily mid-range temperatures as recorded at the weather station nearest the site (TMEAN5), and an exponentially weighted 30-day average temperature (T30), also calculated from weather station data. The three temperature variables were highly correlated, and it was found that any one of the variables gave equally good prediction of $SN_{64}F$. Therefore, the air temperature at the time of test (AIRT) was chosen as the preferred variable because it is simple to measure and it does not require the acquisition of data from outside the user agency.

Julian calendar day crossed with average daily traffic was also considered a variable because it represents the cumulative traffic during the season. This variable was statistically significant but not to the extent that its inclusion in the model is warranted (R^2 increased from 0.862 to 0.864). More accurate ADT data, that is, actual counts taken during the season, and the development of techniques to properly account for the relative effects of automobile and truck traffic may make this a more significant variable.

The average daily traffic (ADT), Julian calendar day (JCD), dry spell factor (DSF), and air temperature (AIRT) at the time of test were found statistically significant and were retained in the final form of the model

$$\ell n SN_{64} = b_0 + b_1\, SN_{64}F + b_2\, ADT + b_3\, JDAY + b_4\, DSF + b_5\, AIRT + error \quad (7)$$

Site-specific changes in seasonal skid resistance had been observed in the 1979-1980 data, and similar trends were found in the 1983 data. Texture classifications, obtained visually at the time the sites were selected, and blank-ribbed tire data were used in various ways as variables in an attempt to explain site specificity (5). No further improvement in the correlation was obtained and therefore no further use of these data was made. However, it is believed that future research should include blank-ribbed tire measurements to further define site specificity. Alternate treatment of the data and more careful measurements might provide more worthwhile correlations. For example, the blank and ribbed tire measurements in this project were separated by 2 to 4 hr rather than being taken simultaneously. Also, the measurements with the two tires should be taken in the same wheel track, and care must be taken to obtain them at the same location.

PREDICTION PROCEDURE FOR END-OF-SEASON SKID NUMBER

The average skid numbers corrected for short-term weather effects from the last week of testing using the procedure described previously were used as the end-of-season minimum skid numbers for each site. These values were then used as predictors in the generalized model of Equation 7, which was fit separately for bituminous and portland cement concrete pavements. The estimated coefficients using the data from the three states (New York, Pennsylvania, and Virginia) are given in Table 6, along with the standard errors of estimate.

Calculation of the predicted end-of-season skid number, $SN_{64}\tilde{F}$, is accomplished by inverting Equation 7 such that $SN_{64}\tilde{F}$ is a function of measured SN_{64} and the other independent variables, ADT, JDAY, DSF, and AIRT

$$SN_{64}\tilde{F} = (\ell n SN_{64} - b_0 - b_2\, ADT - b_3\, JDAY - b_4\, DSF - b_5\, AIRT)/b_1 \quad (8)$$

In order for a highway agency to calculate adjusted end-of-season skid numbers, it would be first necessary to determine the regression coefficients in Equation 8. This would be done by selecting a set

TABLE 6 Estimated Coefficients of the Prediction Model for Individual States and All States Combined

Variable	Site-Specific Model Coefficients, $b_j \pm s(b_j)$[a] New York	Pennsylvania	Virginia	Combined
Bituminous Concrete				
Observations	461	832	623	1,916
Intercept	2.82 ± .0838	2.71 ± .0276	2.95 ± .0401	2.71 ± .022
$SN_{64}F$	.0353 ± .00097	.0338 ± .00044	.0295 ± .00097	.0346 ± .000385
ADT/1,000[b]	.0115 ± .0116	.0130 ± .0131	.0275 ± .0039	.0395 ± .00419
JDAY	−.00139 ± .000176	−.000918 ± .000053	−.00118 ± .000042	−.0011 ± .00004
DSF	−.027 ± .00679	−.0358 ± .00371	−.0176 ± .00345	−.026 ± .0023
AIRT	−.00044 ± .00053	−.000727 ± .000235	−.000799 ± .000238	−.00035 ± .00017
Portland Cement Concrete				
Observations	199	231	150	580
Intercept	3.55 ± .124	2.87 ± .0417	3.22 ± .228	2.84 ± .032
$SN_{64}F$	.023 ± .00108	.0273 ± .000616	.0204 ± .00434	.0275 ± .00037
ADT/1,000[b]	−.300 ± .0604	−.121 ± .0418	−.0176 ± .0398	.0435 ± .0052
JDAY	−.00149 ± .000198	−.00069 ± .0000688	−.000894 ± .000076	−.00088 ± .000058
DSF	−.00587 ± .000904	−.0194 ± .00407	−.00637 ± .00602	−.0052 ± .0035
AIRT	−.0019 ± .000587	−.000707 ± .000305	−.00077 ± .000416	−.00052 ± .00025

Note: Model: $\ell n SN_{64} = b_0 + b_1 SN_{64}F + b_2 ADT/1{,}000 + b_3 JDAY + b_4 DSF + b_5 AIRT + \epsilon$.
[a] $b_j \pm s(b_j)$, where b_j is state-specific coefficient of variables in model and s is the standard deviation of associated coefficient.
[b] ADT/1,000 is used so that coefficient values are not intractably small.

of 12 to 16 pavement test sites with varying levels of traffic. Portland cement and bituminous pavements should be considered separately. Initially it may also be advantageous to consider different aggregate types separately, depending on the range in properties of the aggregates used in the state. Skid data would then be obtained at least four times throughout the testing season for each of the test sites. The coefficients in Equation 8 would then be determined by regressing the data with Equation 7. The coefficients should be verified in subsequent years to confirm that they do not vary excessively from year-to-year. Until a better understanding of the mechanisms that cause changes in skid resistance are understood, it will be necessary to determine the coefficients on a state or regional basis. Specific details regarding the use of this predictive technique are given in ASTM Test Method format in an associated report (6).

Assessment of the accuracy of the predicted final skid number, $SN_{64}\hat{F}$, was made by using Equation 8 to predict an end-of-season skid number from each measurement made during the first full 3 weeks of testing in New York, Pennsylvania, and Virginia. A summary of the deviations of the predicted final skid number from the observed values is given in Table 7.

TABLE 7 Summary of Resuduals Using State-Specific and Combined Regression Coefficients

State	N	s	Residuals[a] for Given Percentiles 5th	25th	75th	95th
Bituminous Concrete						
New York	461	2.53	−3.60	−1.53	1.24	4.69
Pennsylvania	832	2.19	−2.84	−1.46	1.16	3.58
Virginia	623	2.03	−3.30	−1.18	1.14	3.72
Three states combined	1,916	2.34	−3.51	−1.50	1.34	3.88
Portland Cement Concrete						
New York	199	3.00	−4.64	−1.78	1.76	4.66
Pennsylvania	231	1.82	−2.67	−1.19	.98	2.98
Virginia	150	1.51	−3.45	−1.28	1.24	3.71
Three states combined	580	2.30	−3.75	−1.33	1.27	3.54

Note: Number of observations and s = standard deviation of observation.
[a] A residual is the difference between the measured values and the predicted value.

According to the table, 90 percent of the predicted values are within −3.51 and +3.88 skid numbers of the measured values for the bituminous sites and within −3.75 and +3.54 skid numbers for the portland cement concrete sites. This is considered very good given that the standard deviation of the measurements is two skid numbers.

To illustrate the magnitude of the changes in SN_{64} afforded by the variables ADT, JDAY, DSF, and AIRT, Equation 7 was raised to the exponent e

$$SN_{64} = \exp(b_0 + b_1SN_{64}F + b_2ADT + b_3JDAY + b_4DSF + b_5AIRT) \quad (9)$$

The following reference values were inserted into Equation 9: ADT = 5,000 vehicles/day; JDAY = 200; DSF = 0; and AIRT = 68°F. Changes in skid number were then calculated by varying each of the variables, ADT, JDAY, DSF, and AIRT independently, creating Figures 6 through 9, respectively. A separate set of calculations was done for four levels of $SN_{64}F$, generating a separate curve for each set of calculations. The results of the calculations, which are presented in Figures 6 through 9, show that JDAY and $SN_{64}F$ are the most significant factors causing changes in skid resistance; air temperature has little effect, and the dry spell factor and average daily traffic have only minimal effect.

The use of paired skid measurements taken on two different days was considered an alternative method for predicting the end-of-season skid number, $SN_{64}F$. It was reasoned that this might bypass the problem of the site specificity of the model coefficients. To determine whether this was the case, 10 pairs of observations were randomly chosen from the first and third weeks of testing in New York. A simple linear extrapolation of the skid numbers was performed to day 300. Differences between the predicted end-of-season skid number and the measured end-of-season average were calculated for 10 pairs of measurements and 17 sites. The differences between the actual and predicted end-of-season skid number for each individual site were large and were inconsistent from site-to-site. This led to the conclusion that this approach is not promising and, consequently, was not pursued further.

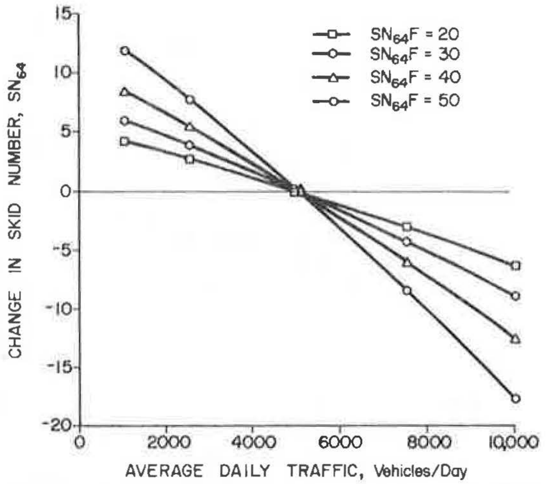

FIGURE 6 Corrections in SN_{64} due to change in ADT.

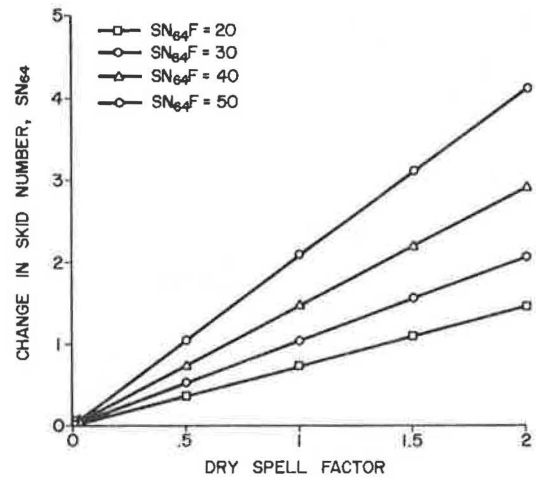

FIGURE 8 Corrections in SN_{64} due to changes in DSF.

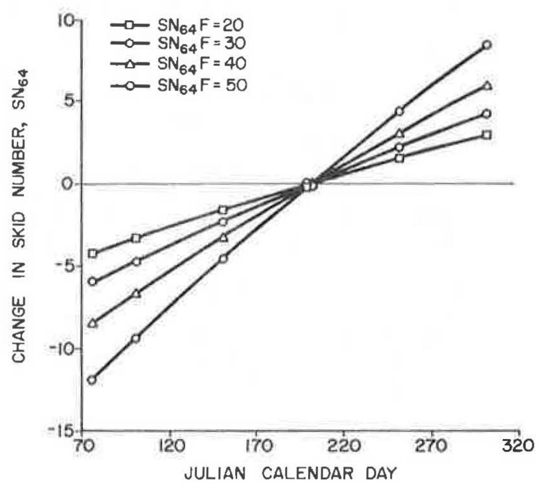

FIGURE 7 Corrections in SN_{64} due to changes in JDAY.

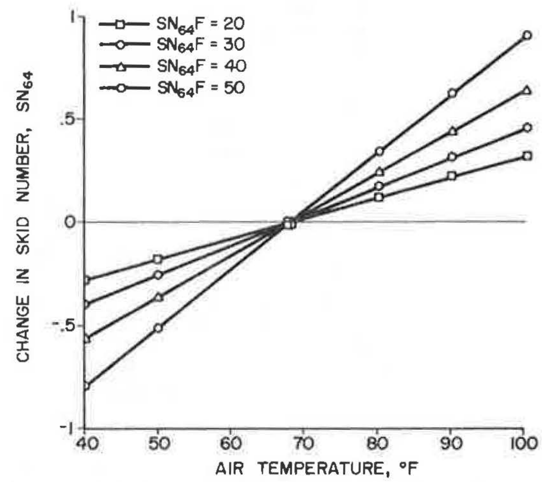

FIGURE 9 Corrections in SN_{64} due to changes in AIRT.

SUMMARY AND CONCLUSIONS

A procedure has been presented that can be used to predict the end-of-season skid number from a single measurement made at any time during the season. The procedure is empirical in that it is based on a prediction equation developed through the regression analysis of data obtained from field test sites. Variables included in the prediction equation are the dry spell factor, air temperature at the time of test, Julian calendar day, average daily traffic, and the skid number measured on any arbitrary day within the test season. The dry spell factor is based on the number of days since the last rainfall.

The end-of-season skid number was not predicted reliably with the exponential seasonal variation model. The skid resistance increases earlier in the season than accounted for by the exponential model.

In the prediction model, short-term (day-to-day) adjustments in skid number are accounted for by the dry spell factor and air temperature, whereas long-term adjustments (within season) are accounted for by Julian calendar day and average daily traffic. Only variables that can be readily obtained were included in the procedure so that it can be implemented by a typical highway agency.

Using the data obtained in this study, the procedure was used to adjust measurements made on any given day to the end-of-season values. As a result, 90 percent of the adjusted values were within approximately +3.6 to -3.6 skid numbers of the actual end-of-season value. This is considered very good given that the standard deviation of the skid numbers obtained from five consecutive lockups of the test tire on the same test site averaged 1.7 skid numbers and the standard deviation for multiple tests within a given day averaged 2.0 skid numbers.

The coefficients in the prediction equation were site-specific and varied from season-to-season. Blank and ribbed tire data and subjective descriptors of the site did not account for the site specificity. Additional research is needed to adequately understand the mechanisms that cause day-to-day and within-season variations in skid resistance so that more rational predictive models can be developed.

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NOMENCLATURE

ADT	Average daily traffic, vehicles/day/test lane,
AGE	Age of pavement surface, years.
AIRT	Air temperature at time of test, °F.
$b_0 \ldots b_i$	Regression coefficients.
DSF	Dry spell factor, $\ell n(t_r+1)$, where t_r is number of days since last rainfall of 0.1 in. or more, and DSF $\leq$ 2.08 $t_r \leq 7$.
e	Base of the natural logarithm.
JDAY	Julian calendar date.
PNG	Percent normalized skid-resistance gradient defined as -100/SN $\cdot$ [d(SN)/dV], where SN is the skid resistance at any velocity V.
Q1, Q3	First and third quartile, respectively.
R	Correlation coefficient or range in observations (maximum-minimum).
s	Standard deviation.
SN_0	Skid number extrapolated to zero speed.
SN_{64}	A skid-resistance measurement made in accordance with ASTM E274.
$SN_{64}F$	Average of skid-resistance measurements for last week of testing, first corrected for short-term weather changes before being averaged.
$SN_{64}\tilde{F}$	End-of-season skid resistance estimated from a predictor model.
t_r	Number of days since last rainfall, $t_r \leq 7$.
TEMP	Average of maximum and minimum temperatures on the day of test.
TMEAN5	Average of the daily mid-range temperatures for the 5 days before day of test.
T30	Weighted temperature history, °F defined as $1/30 \sum_{i=1}^{30} \left\{[(29/30)^i T_{j-1}]\right\}$, where T_{j-i} is the average of the maximum and minimum air temperatures on the Julian calendar date i days before the date of interest.

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