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Short-Term, Weather-Related Skid Resistance Variations

BARRY J. HILL AND JOHN J. HENRY

A three-year research program was initiated in 1978 at the Pennsylvania Transportation Institute by the U.S. Department of Transportation to investigate possible causes for seasonal and short-term skid resistance variations. The primary objective is to determine the parameters that can be used to predict the influence of seasonal and short-term effects. Results concerning short-term, weather-related skid resistance variations are presented and discussed. Twenty-one test surfaces in State College, Pennsylvania, were selected for testing. The testing program includes daily skid measurements according to ASTM test method E274 and the collection of daily weather data. After the data are adjusted for long-term variations, the short-term residuals are regressed against rainfall and temperature parameters. The number of days since the last significant rainfall and the test pavement temperature are both found to be significant causes of short-term skid resistance variations. Further unexplained variations are attributable to measurement errors, particularly the lateral placement of the skid test trailer. The Pennsylvania results are supported by data collected in a similar study of 10 sites located in North Carolina and Tennessee (Federal Highway Administration Region 15).

Skid resistance measurements made according to ASTM test method E274 (1) exhibit both long-term seasonal and short-term variations on public highways in Pennsylvania and other states (2,3). These variations make the establishment of a maintenance program in which skid resistance is one of the important factors a difficult task. Variations from day to day, seemingly due to rainfall pattern and local weather conditions, are superimposed on an annual cycle. At least in the northern states, this annual cycle tends to be higher in winter through spring than summer through fall. Frequent tests during the summer period indicate that pavement skid resistance may vary by as much as 25 percent during a single week. In analyzing these large changes, which occur rather systematically, Hegmon (4) concluded that they are real skid resistance changes related to changing conditions.

During the past two decades, several state highway 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 and short-term variations. Until recently, the most comprehensive documented studies involving seasonal and short-term skid resistance variations were the ones undertaken by the Pennsylvania Department of Transportation (2,5). In the course of evaluating skid resistance measurements, some cyclic patterns were observed. Measurements showed that, once a pavement surface had stabilized after being exposed to traffic and weather for one to two years, the surface had cyclic skid resistance variations. The skid number gen-

Figure 1. Skid-number history for limestone surface completed on June 8, 1969.

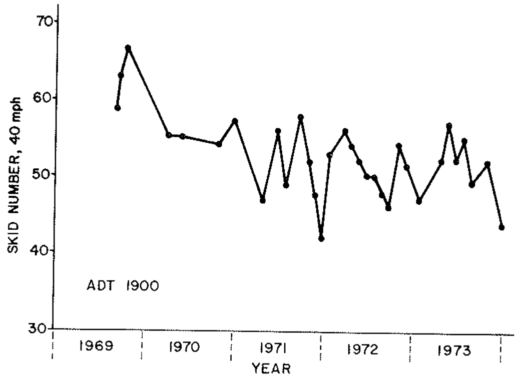
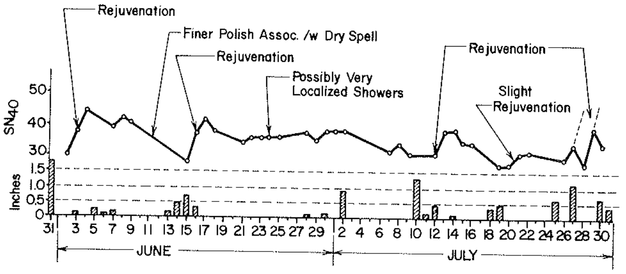


Figure 2. Influence of precipitation on skid resistance.



Note: 1 in = 25.4 mm

erally decreased to a minimum over the summer months and was rejuvenated to about its original level over the winter season (see Figure 1) (2,5). Superimposed on this seasonal cycle were short-term variations that resulted in low skid numbers after a dry period and in high (rejuvenated) skid numbers after a rainy period (see Figure 2) (5).

Several other states have reported to the Federal Highway Administration (FHWA) their observations relative to seasonal skid resistance variations. The observations were summarized in 1977 by Rice (3). Although these and other observations from various agencies are helpful in providing qualitative information relative to trends and magnitudes of seasonal and short-term variations in skid resistance, the measurements are spaced too far apart in time to offer sufficient information to develop a model for predicting the low skid number expected to occur during the year on a given pavement.

To establish further means of interpreting skid resistance data subject to seasonal and short-term variations, the U.S. Department of Transportation initiated in 1978 a three-year research program at the Pennsylvania Transportation Institute. This paper describes the findings regarding short-term skid resistance variations on 21 pavements in Pennsylvania and compares them with short-term variations experienced on 10 pavements in Tennessee and North Carolina (FHWA Region 15). The results of studies on long-term seasonal variations are reported elsewhere (6).

TEST SITES

The selection criteria for the test pavements include the requirements that they should be at least three years old, so that their surface characteristics would have stabilized, that they should contain a variety of aggregates and mix designs and include portland cement concrete (PCC) pavements, and that they should have as wide a range of average daily traffic (ADT) as possible. A full description of the test-site construction materials and locations is given elsewhere (7).

The number of test pavements of each type at the Pennsylvania and FHWA Region 15 sites is as follows:

Area	Pavement Type	Number
Pennsylvania	Dense-graded asphalt	10
	Open-graded asphalt	5
	PCC	6
Total		21
FHWA Region 15	Dense-graded asphalt	4
	Open-graded asphalt	2
	Bituminous surface treatment	2
	PCC	2
Total		10

DATA COLLECTION

Skid Resistance Tests

Pennsylvania

In 1979, skid testing was performed between 31 March and 28 November. A total of between 64 and 72 tests were made on each test section. All tests were made in the transient slip mode (8), which, while providing SN_{64} skid number data at a speed of 64 km/h (40 mph) according to ASTM E274, also provides brake slip numbers at 16, 32, and 48 km/h (10, 20, and 30 mph), which can be used to approximate SN_{16}, SN_{32}, SN_{48} (8).

FHWA Region 15

During the 12-month period starting on July 6, 1979, skid tests were performed at approximately weekly intervals according to ASTM E274. These tests were done at 64 km/h (40 mph) and also at 48 and 80 km/h (30 and 50 mph) to permit the relation between skid resistance and speed to be developed in terms of the percentage normalized gradient (8) and the zero-speed skid number intercept (SN_0) by using the relation in Equation 1. The temperature of the test tire and the test pavement and the ambient temperature were recorded in each case.

Weather Data

Weather data for the Pennsylvania sites were obtained from records provided by the Pennsylvania State University Weather Station at University Park and for FHWA Region 15 sites from weather stations located at Asheville, North Carolina, and Knoxville, Tennessee.

MECHANISTIC MODEL

The Penn State Model relates skid resistance to speed and texture (8) according to the exponential relation

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

where

SN_V = skid number at velocity V,
SN_0 = zero-speed skid number intercept (a function of pavement microtexture), and
PNG = percentage normalized gradient (a function

of pavement macrotexture) = $-(100/SN)/[d(SN)/dV]$ (h/km).

The SN_0 deduced from data collected throughout the year typically exhibits long-term variations (6), as shown in Figures 3, 4, and 5. Figures 3 and 4 show the results for a dense-graded and open-graded asphalt surface, and Figure 5 shows the results for a PCC surface. It has been found that long-term variations in skid resistance for asphalt surfaces can be considered to be an exponential relation whereas the PCC surfaces exhibit a linear increase in skid resistance with time. Hence, the value of SN_0 at any time t can be expressed as

$$SN_0 = SN_{0R} + SN_{0L} + SN_{0F} \quad (2)$$

where SN_{0R} is the short-term residual and SN_{0F} is a measure of SN_0, which is independent of short- and long-term variations.

For asphalt surfaces,

$$SN_{0L} = \Delta SN_0 \exp(-t/\tau) \quad (3)$$

whereas, for PCC surfaces,

$$SN_{0L} = (\Delta SN_0/\Delta t)t \quad (4)$$

where

ΔSN_0 = change in SN_0 over testing season, a function of aggregate polish susceptibility;
τ = rate at which polishing takes place, a function of ADT; and
Δt = length of the testing season (days).

The determination of the parameters for long-term seasonal variation is described in detail elsewhere (6), and the results are given in Table 1.

Initially, SN_0 and PNG values were obtained from the skid test data for each day, and variations in PNG with time similar to those found for six Pennsylvania sites in 1977 and 1978 (5) were noticed for all of the sites considered here. The variations in PNG appear to be random measurement errors and are of sufficiently small magnitude to allow an average value to be used for each site without altering significantly the SN_0 values subsequently obtained. Figure 6 shows a plot of PNG versus time for site 22, and Figure 7 shows the originally calculated SN_0 values compared with SN_{0P}, the values calculated by using the average PNG. Similar relations were found for all the sites. Equation 2 can now be written

$$SN_{0P} = SN_{0R} + SN_{0L} + SN_{0F} \quad (5)$$

The skid number at 64 km/h (40 mph) will contain

Figure 3. SN_0 versus time for dense-graded Pennsylvania site 17.

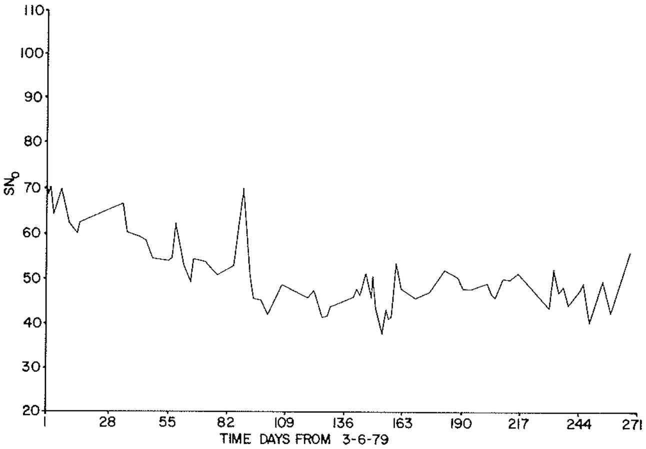


Figure 4. SN_0 versus time for open-graded Pennsylvania site 22.

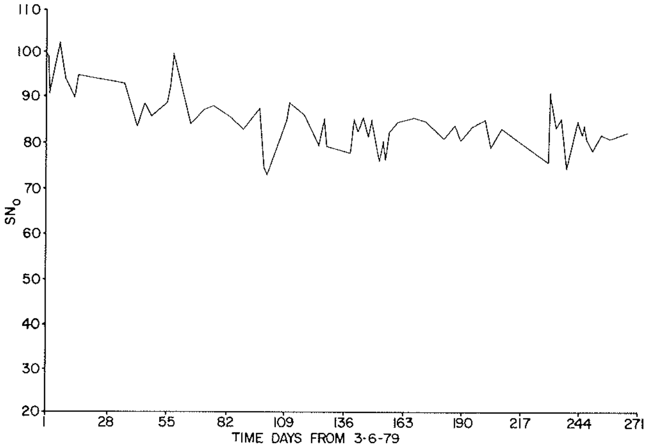


Figure 5. SN_0 versus time for PCC Pennsylvania site 10.

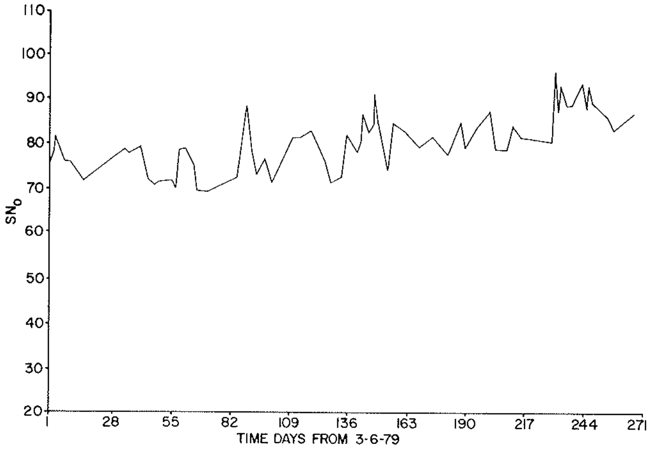


Table 1. Parameters for seasonal variations at Pennsylvania sites.

Site	SN_{0F}	ΔSN_0	$\Delta SN_0/\Delta t$	τ(days)
1	50.5	8.28		55
2	49.4		0.036	
3	72.4		0.040	
4	55.4	9.60		45
7	69.8		0.058	
8	43.0	22.57		75
9	57.7	21.90		75
10	77.6		0.053	
11	44.6	12.87		50
12	59.8	6.89		27
13	89.9	2.61		58
14	63.6		0.034	
15	92.1	4.98		25
16	39.1	13.56		45
17	44.3	29.28		53
18	73.7		0.008	
19	49.2	12.56		30
21	45.2	17.35		65
22	80.5	14.04		65
24	44.4	3.57		27
25	80.5	3.36		63

Figure 6. Variation of PNG with time for Pennsylvania site 22.

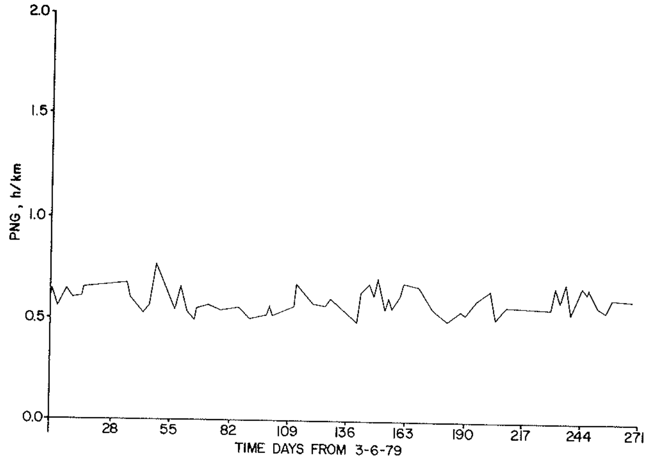


Figure 7. SN_0 and SN_{0P} versus time for Pennsylvania site 22.

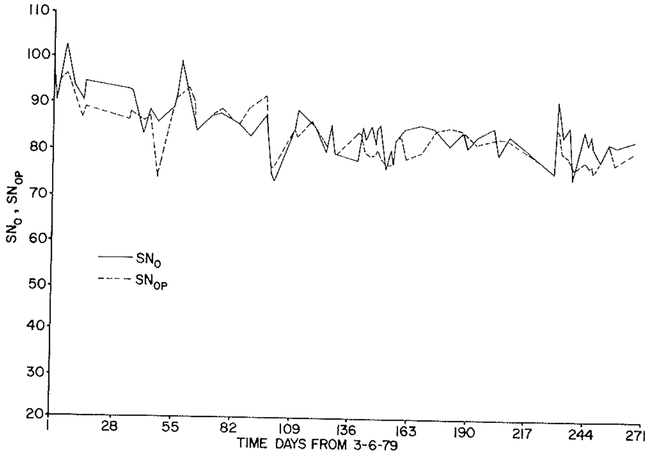


Table 2. Skid numbers versus WRF for selected sites.

Site	Year	Equation	r
16	1976	$SN_{64} = 32.8 + 0.089\ WRF$	0.133
1	1979	$SN_{0R} = -1.49 + 1.47\ WRF$	0.113
21	1979	$SN_{0R} = 0.12 + 0.112\ WRF$	0.077

similar long- and short-term effects according to Equation 1, and the value of SN_{64} after removal of these effects can be expressed as

$$SN_{64F} = SN_{0F} \exp(-0.64\ PNG) \tag{6}$$

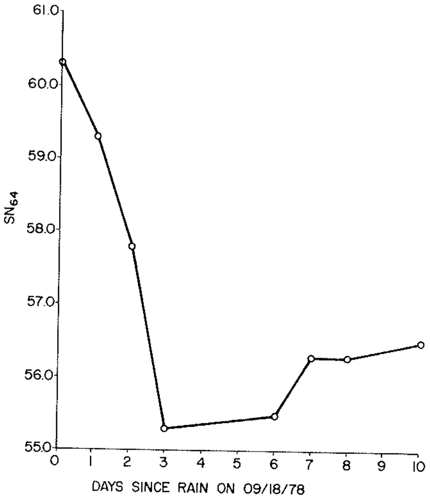
Combining Equations 1, 5, and 6 yields

$$SN_{64F} = SN_{64} - (SN_{0R} + SN_{0L}) \exp(-0.64\ PNG) \tag{7}$$

PREDICTION OF SHORT-TERM RESIDUALS

The long-term variations in skid resistance are assumed to be a function of pavement aggregate properties and traffic density, whereas the short-term residuals are a result of (a) rainfall effects, (b) temperature effects, and (c) errors in skid number measurements, the largest source of which is variation in the lateral placement of the test tire.

Figure 8. SN_{64} versus length of dry spell for Pennsylvania site 22.



Rainfall Effects

A number of studies (5,9,10) have recognized the influence of precipitation on skid resistance. In this study, as in others (5), it has been found that the skid resistance of a pavement decreases during dry periods and increases after heavy rain. A weighted rain function (WRF) has been suggested by Dahir, Henry, and Meyer (5) as a measure of the effect of rain on skid resistance, where

$$WRF = \sum_{i=1}^{5} (R_i/i) \tag{8}$$

where R_i is the rainfall on the ith day prior to the test.

By using data given by Dahir, Henry, and Meyer (5) and by Dry (10), the correlation between skid number and WRF was determined for a number of cases at Pennsylvania sites. The results are given in Table 2. The correlation coefficients (r) were found to be consistently low, and it is obvious that, if a correlation exists between precipitation and skid resistance, a parameter other than WRF must be used. Figure 8 shows SN_{64} measurements for a typical Pennsylvania site taken during a dry period and illustrates well the decrease in skid resistance with time when no rain has fallen. Relations similar to that shown in the figure were found for a number of cases. The decrease in skid number reaches a maximum after about seven days, and SN_{64} remains at a low level until the next significant rain. The following dry-spell factor (DSF) is proposed:

$$DSF = \ln (t_R + 1) \tag{9}$$

where t_R is the number of days since the last rainfall of 2.5 mm (0.1 in) or more (the upper limit is 7 days). Hence, $0 \leq t_R \leq 7$.

The correlations for the cases in Table 2 were repeated by using DSF as the rainfall parameter with a significant improvement in correlation coefficient r, as given in Table 3. As a final comparison, SN_{0R} values for all 21 Pennsylvania sites were regressed against both WRF and DSF with the following results:

$$SN_{0R} = 1.00 + 2.74\ WRF \quad r = 0.20 \tag{10}$$

$$SN_{0R} = 1.14 - 1.17\ DSF \quad r = 0.35 \tag{11}$$

Table 3. Skid numbers versus DSF for selected sites.

Site	Year	Equation	r
16	1976	$SN_{64} = 34.77 - 1.45$ DSF	0.463
1	1979	$SN_{0R} = 0.53 - 0.94$ DSF	0.161
21	1979	$SN_{0R} = 2.05 - 1.58$ DSF	0.318
18	1978	$SN_{64} = 52.17 - 1.89$ DSF	0.398
16	1978	$SN_{0R} = 2.23 - 2.05$ DSF	0.561

Figure 9. Comparison of SN_{64} and SN_{64F} for Pennsylvania site 17.

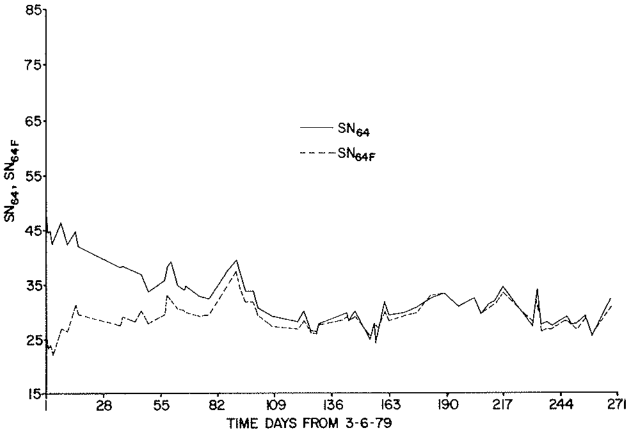


Figure 10. Comparison of SN_{64} and SN_{64F} for Pennsylvania site 22.

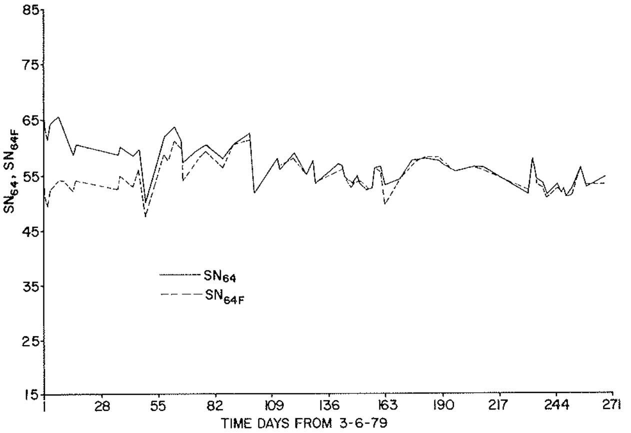
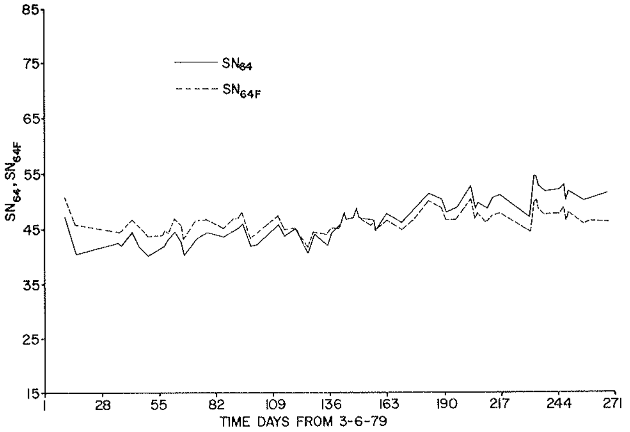


Figure 11. Comparison of SN_{64} and SN_{64F} for Pennsylvania site 10.



The conclusion is that, although r is still small, the length of time since the last significant rainfall is a better measure of the effect of rainfall on the skid resistance of pavements.

Temperature Effects

Some researchers (9,11) have found that an increase in temperature results in a corresponding decrease in skid resistance, whereas others (5) have not noticed this effect to be significant. A linear regression for Pennsylvania site 1 (1979) produces the following relation:

$$SN_{0R} = 5.09 - 0.232\,T_p \qquad r = 0.50 \tag{12}$$

where T_p is the pavement temperature (°C). This result, at least, indicates that pavement temperature is significant in its effect on skid resistance measurements and should not be eliminated as a parameter in further investigations.

Pavement temperature was chosen as the temperature parameter because (a) it is a more accurately defined measurement than ambient temperature and more easily measured than tire temperature and (b) good correlation exists among the three measures of temperature.

For the Pennsylvania data, the regression equations found to relate the three measures of temperature are as follows:

$$T_t = 8.54 + 0.810\,T_A \qquad r = 0.91 \tag{13}$$

$$T_t = 6.78 + 0.558\,T_p \qquad r = 0.87 \tag{14}$$

$$T_A = 0.87 + 0.573\,T_p \qquad r = 0.79 \tag{15}$$

where

T_t = tire temperature (°C),
T_p = pavement temperature (°C), and
T_A = ambient temperature (°C).

The magnitude of the effects of rainfall and temperature on the short-term variations in skid resistance can be determined by performing a multiple regression of SN_{0R} versus T_p and DSF for the data available. For the Pennsylvania sites, the regression equation is

$$SN_{0R} = 3.79 - 1.17\,\text{DSF} - 0.104\,T_p \tag{16}$$

with r = 0.35. For the FHWA Region 15 sites, the regression equation is

$$SN_{0R} = 1.88 - 0.77\,\text{DSF} - 0.15\,T_p \tag{17}$$

with r = 0.57.

Equations 16 and 17 can be used with Equation 7 to determine the value of SN_{64} after adjustment for seasonal and short-term effects. Figures 9, 10, and 11 show the adjusted SN_{64F} values compared with the original data for three Pennsylvania sites. All of the other sites show similar results. Ideally, SN_{64F} should be constant with time after all seasonal and short-term weather effects are accounted for. The low correlation coefficients obviously limit the ability of regression Equations 16 and 17 to "smooth" the data for short-term variations. The standard deviation of the "smoothed" SN_{64F} values is, however, between 2.04 and 2.54 skid numbers for the Pennsylvania sites and between 2.21 and 3.06 skid numbers for the FHWA Region 15 sites. These values must be compared with the possible variations in SN_{64} measurements due to measurement errors and other sources of error.

SIGNIFICANCE OF THE RESULTS

Meyer, Hegmon, and Gillespie (12) list a number of factors responsible for errors in locked-wheel pavement skid resistance tests and the average error band associated with each type of error. These include

Factor	Avg Error Band (SN)
Speed holding	±1.5
Pavement variability	
Lateral	±4
Longitudinal	±2
Dynamic wheel-load change	±1
Data evaluation by operator	±3

The magnitude of these average error bands can be reduced by taking adequate precautions, and it is unlikely that speed holding, longitudinal pavement variability, or evaluation of the data by the operator would, in the case of the data used in this study, be a significant contributor to the variations in SN_{64}. It is believed that variations due to small errors in lateral placement of the skid test tire are a major contributing factor. All skid test measurements are made in the wheel tracks on the pavement where contamination by foreign particles and polishing of the aggregate causes the measured skid resistance to be minimal (12). A deviation of only 125 mm (5 in) in lateral placement of the test tire relative to the wheel track can lead to variations in the measured SN_{64} of as much as ±2 SN. It would be unusual for an operator to place the skid test trailer consistently with such accuracy. The fluctuations in SN_{64F}, after the long- and short-term effects are eliminated, are less than the expected variations due to measurement errors, and further improvement in the correlation between the short-term residuals SN_{0R} and weather-related parameters would seem unlikely.

The data used to obtain Equations 16 and 17 were subjected to a Student's t-test of the hypothesis that the coefficients for DSF and T_p are zero. In each case, the t-values obtained had a probability of occurrence of 0.0001 if the hypothesis was true, which leads to a rejection of the hypothesis. Equations 16 and 17 are considered to be statistically significant.

CONCLUSIONS

The following conclusions can be made based on the results of this study:

1. Large variations in skid resistance measurements occur systematically over a short-term period (day to day or week to week).
2. The mechanisms that cause skid resistance variations appear to be complex. Rainfall and temperature appear to be the most significant causes of short-term variations. A seven-day period without rain can result in a decrease in skid resistance at 64 km/h of 1.7 SN. An increase in temperature of 10°C can result in a decrease in SN_{64} of about 1.2 SN.
3. A major cause of apparent skid resistance variations is measurement error, particularly lateral placement of the test tire, which can account for as much as ±4 SN at a speed of 64 km/h.
4. The standard deviation of skid resistance variations not explained by rainfall and temperature effects is about ±2.5 SN at a speed of 64 km/h.
5. The validity of the results is supported by the good agreement between the regression equation coefficients for the Pennsylvania sites and those for the FHWA Region 15 sites.
6. The weather conditions to which the Pennsylvania sites are subjected are different from those experienced by the FHWA Region 15 sites. However, the influence of weather on short-term skid resistance variations is similar for both data sets.

The results obtained are preliminary, and additional research in this area is continuing.

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