

Effect of Short-term and Long-term Weather on Pavement Surface Friction

M. Alauddin Ahammed¹⁺ and Susan L. Tighe²

Abstract: Pavement surface friction plays an important role on highway safety, especially during the wet weather. The available surface friction may vary significantly due to weather related changes in pavement surface condition. Several past studies have examined the short-term or seasonal skid resistance variation but mostly ended with unreasonable results. The effect of long-term weather on skid resistance variation is not yet studied well. The surface friction, in terms of British Pendulum Number (*BPN*), of both Portland cement concrete (PCC) and asphalt concrete (AC) pavements were measured bi-weekly or monthly from February to October to determine the effect of short-term weather changes on skid resistance variation. Long Term Pavement Performance (LTPP) program data for both PCC and AC pavements were used to determine the effect of long-term weather on surface friction variation. Analysis has shown that available friction fluctuates at 0.35*BPN* per 1°C change in prevailing ambient or pavement surface temperature with an overall eight *BPN* seasonal fluctuation. Prior short-term rainfall, dry-spell, and temperature were shown to be insignificant for changes in skid resistance. Similarly, prior long-term weather was shown to be insignificant for changes in skid resistance of both AC and PCC pavements.

Key words: *Asphalt concrete pavement; Long-term weather; Pavement surface friction; Portland cement concrete pavement; Short-term weather.*

Introduction

In Canada, 2,889 people have died and another 199,337 have been injured from 147,360 traffic crashes in 2006 [1]. In the U.S., 37,261 people were killed and 2.35 million were injured from 5.8 million traffic crashes in 2008 [2]. Several factors including driver skill and behavior, roadway and vehicle conditions, and vehicle speed contribute to highway crashes. However, inadequate surface friction has been found to contribute to a substantial portion of highway crashes, especially during the wet weather. A study in the U.S. found that skidding could contribute to up to 35% of wet weather accidents [3]. Another study in the U.K. found that an improvement of average friction coefficient by 0.1 could reduce the wet-accident by 13% [4]. In fact, 70% of the wet weather crashes are preventable with improved friction on pavement surfaces [5].

Increased temperature and moisture can significantly reduce the available surface friction. These leave pavements at increased risk of skid related accidents. A study has shown that pavement surface friction reduces at about 1.2*SN* for an increase in temperature by 10°C [6]. The average difference in measured surface friction in winter and summer was six *SN* [7]. Pavement surface friction also changes over time due to environmental and traffic related polishing/wear. A study in Maryland has shown that pavement

surface friction decreases at 0.22*SN* per year on rural roads and 0.26*SN* per year on urban roads [8]. Analysis of the Long Term Pavement Performance (LTPP) program data has shown that surface friction reduces at 0.7*SN* and 1.2*SN* per year for Portland cement concrete (PCC) and asphalt concrete (AC) pavements, respectively [9]. These indicate that the variation of surface friction due to traffic and environmental factors should be taken into consideration during the selection of pavement surfaces.

A number of research were devoted to study the effect of short-term weather on skid resistance variation but mostly ended with inadequate and/or inappropriate results/conclusions and models. Lack of understanding of the actual phenomena of skid resistance variation, no or improper interpretation of the developed models or inconsistency in testing may be factors that caused such findings/results (refer to literature review). The effect of long-term weather on pavement surface friction has not yet been adequately studied. This study was devoted to evaluate the effect of short-term (prevailing to seven days prior) and long-term (over several years) weather on pavement surface friction including the overall seasonal variation within a year. The findings are expected to aid the highway agencies in taking an appropriate measure e.g., action to improve the skid resistance.

Literature Review

The Concept of Skid Resistance Variation

Published literature indicates that pavement surface friction can vary seasonally or in short-term due to several factors including changes in temperature, moisture (rainfall), surface contamination, and microtexture [10, 11]. Skid resistance can also be reduced over long-term due to inadequate construction or polishing/wear of the surface by traffic and/or environmental effects [10]. However, the

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fundamental process that governs the variation in skid resistance seasonally has not been clearly understood. The general hypothesis is that fine particles accumulate on the pavement surface during prolonged dry period in summer making the surface smooth. This causes microtexture and macrotexture loss, and thereby a reduction in surface friction. Contamination due to oil or grease drip/spillage causes further reduction in available surface friction. Alternatively, de-icing salts, applied during winter, causes wear of pavement surface or aggregates. The surface texture is thus rejuvenated with exposure of new particles or regeneration of microtexture. Heavy rainfall flushes out fine grit and clears drainage channels between aggregate particles during the early spring. This results in an increased macrotexture from coarse aggregate and increased skid resistance in spring [7, 12].

However, studies in different jurisdictions have produced mixed results with some indicating that prior weather has no effect while some other indicating that it has significant effect on skid resistance variation. In fact, the severity of contamination and the removal of dirt/contaminants are highly dependent on road/pavement location and use as well as type of dirt/contaminants. There is no salt or sand application for deicing where there is no snow (e.g., Texas, Florida). Furthermore, there may be no or little rainfall in some areas to wash out the contaminants or dirt particles. Alternatively, pavement surface friction may vary from time to time without any change in the contamination level or without having any contaminant. Therefore, it may not be appropriate to associate the short-term or seasonal skid resistance variation only with contamination or deicing salt/sand application.

A Synopsis of Relevant Past Studies

In Arizona, PCC pavement surface friction was shown to be 33SN in September, 52SN in January, and then down to 32SN in May. Rainfall and temperature data did not explain the variation. In Connecticut, AC surface friction was shown to vary by 15SN between July/August and late fall/early spring which was explained to be associated with surface contamination. Illinois experienced a 5SN to 10SN variation between fall and spring for AC pavements. Kansas reported a seasonal variation of 30SN for AC and 14SN for PCC pavements. Kentucky observed a seasonal variation of 10SN for sand-asphalts. Louisiana did not find any seasonal variation between cold, mild, and hot weather. Missouri found a variation in friction coefficient between fall and spring of 0.10 for PCC and 0.17 for AC surfaces. Texas reported a variation of 10SN between summer and winter that was considered associated with polishing and rainfall. West Virginia observed a reduction of 14SN from March to October and an increase of 10SN from December to May. In the U.K., the seasonal variation of AC pavements surface friction coefficient was shown to be 0.10 to 0.15 [12]. The reported variations and presumed causes are inconsistent and seem to be unreasonably high in some cases.

The effect of contaminants (dust mass) on the variation of low speed SN was examined and several models were developed [13]. The best correlation (Eq. (1)) was found for dust mass up to 0.007gm/m^2 in 7.0 to $50.0\mu\text{m}$ size range. The developed model predicts SN_0 of 64.21 for no dust (clean/washed surface) and SN_0 of 51.18 for 0.007gm/m^2 of dust i.e., a reduction by 13SN. Skid testing

at 27km/hr (low speed) on the test surface before and after three times scrubbing (with stiff broom) and rinsing, and a heavy rainfall showed an increase in SN of 2.8. The validity of the developed model may therefore be questioned.

$$SN_0 = 64.21 - 1862.0M_1 \quad R^2 = 0.82 \quad (1)$$

Where, SN_0 = Low speed Skid Number (intercept of Pennsylvania model), R^2 = Coefficient of determination, and M_1 = Mass of dust particles, 7.0 - $50.0\mu\text{m}$ size and not exceeding 0.007gm/m^2 .

The short-term, weather related, variation of skid resistance was examined and several models were developed using data collected in Pennsylvania (e.g., Eqs. (2, 3)), and North Carolina/Tennessee (e.g., Eq. (4)). The year round skid data showed a reduction of 1.7SN for a seven-day period without rain (dry-spell) and a reduction of 1.2SN for an increase in temperature by 10°C [6]. Eqs. (2-4) show 0.014, 0.232, and 0.15SN reductions, respectively, for each 1°C increase in pavement temperature. Furthermore, for the same DSF of 2.08 (at $t_R = 7$ days) and T_p of 30°C , the Pennsylvania Model (Eq. (2)) estimates a SN_{OR} of 0.94 i.e., a 0.94SN increase whereas, in contrast, the North Carolina/Tennessee model (Eq. (4)) estimates SN_{OR} of - 4.22 i.e., a 4.22SN reduction.

$$SN_{OR} = 3.79 - 1.17DSF - 0.014T_p \quad R^2 = 0.12 \quad (r = 0.35) \quad (2)$$

$$SN_{OR} = 5.09 - 0.232T_p \quad R^2 = 0.25 \quad (r = 0.50) \quad (3)$$

$$SN_{OR} = 1.88 - 0.77DSF - 0.15T_p \quad R^2 = 0.32 \quad (r = 0.57) \quad (4)$$

Where, SN_{OR} = Short-term variation of skid resistance, DSF = Dry-Spell Factor = $\ln(t_R + 1)$, T_p = Pavements temperature ($^\circ\text{C}$), r = Correlation coefficient, and t_R = Number of days (maximum seven) since last rainfall of 2.5mm (0.1in) or more.

A Texas study showed a variation of 10 to 12SN for AC pavements in a bi-weekly period. A model (Eq. (5)) for seasonal skid resistance variation was developed [7]. The number of dry days prior to skid measurement was not statistically significant. No justification or clarification of the variables $[\sin(2\pi/365)]$ and I_1 through I_5 was presented. It is completely illogical that surface friction of a pavement type will vary with the difference in surface friction with other pavement types. Furthermore, pavement surface friction on a particular day of the year can only be estimated if the surface condition (e.g., texture, temperature, contamination) on that day is known in advance.

$$SN_{64} = 32.28 - 0.14(TEMP_5) + 0.031(RF_5) - 0.66\sin\left(\frac{2\pi}{365}JD\right) + 13.53I_1 - 3.12I_2 - 2.78I_3 - 9.52I_4 + 7.43I_5, R^2 = 0.917 \quad (5)$$

Where, SN_{64} = Skid Number at 64km/hr , $TEMP_5$ = Average of daily temperature for five days prior to skid measurement, RF_5 = Cumulative rainfall over the 5-day period preceding the skid measurement, JD = Julian calendar day corresponding to the day of skid measurement, and I_1 through I_5 = Indicator variables that account for the differences in the mean SN from one test pavement to other pavements.

An Australian study did not find any effect of rainfall pattern on the long-term average of skid resistance [14]. A Virginia study [15]

examined the effect of temperature on skid resistance variation for AC pavements surfaces and developed several models (e.g., Eqs. (6, 7) for a mix containing 9.5mm maximum size aggregate and PG 70-22 binder). For a particular speed, Eq. (6) (smooth tire) predicts an increase in skid resistance with an increase in temperature while Eq. (7) (ribbed tire) predicts the reverse i.e., a decrease in SN with an increase in temperature contrasting Model 6.

$$SN_S(T) = (159 - 1.14T) * e^{\frac{-(2.27 - 0.02T)*V}{100}} \quad (6)$$

$$SN_R(T) = (118 - 0.73T) * e^{\frac{-(1.00 - 0.01T)*V}{100}} \quad (7)$$

Where, $SN_S(T)$ = Smooth tire skid number at temperature T , $SN_R(T)$ = Ribbed tire skid number at temperature T , V = Vehicle speed in km/hr , and T = Temperature, $^{\circ}C$

A laboratory study [16] found that temperature has no significant effect for unpolished AC surface skid resistance but has a significant effect after some degree of polishing. The reason was not clear. AC surface friction was shown to decrease by 0.232BPN for $1^{\circ}K$ increase in temperature. A Maryland study [8] of AC surfaces has shown a 1.26SN increase for every 2.54mm (0.1in) increase in rainfall and a 1.0SN decrease for every $0.56^{\circ}C$ ($1^{\circ}F$) increase in average daily temperature. With this trend, surface friction will drop from 50 to 0SN (no friction) for temperature increase from 5 to $33^{\circ}C$ ($28^{\circ}C$ or $50^{\circ}F$ change). Such trend seems to be an overestimate of skid resistance variation, as compared to the findings in other similar studies, due to temperature change.

Using the data from 35 sections in different States, a regression model (Eq. (8)) was developed for the longevity of diamond ground PCC pavements surface texture [17]. The developed model shows that region with freezing weather will cause a higher reduction in pavement surface texture.

$$MTD = 0.887 - 0.152 (1 + 0.233FREEZE) \ln(AGE) \quad R^2 = 0.83 \quad (8)$$

Where, MTD = Mean Texture Depth (mm), $FREEZE$ = A dummy variable (wet non-freeze or dry non-freeze = 0 and wet-freeze or dry-freeze = 1), and AGE = Age since grinding (year).

Objective and Scope

Literature review presented above indicates that most studies of the effect of short-term weather or contamination on skid resistance led to illogical or controversial results while the effect of long-term weather is not yet adequately studied. The objectives of this paper are: (1) to examine the effect of short-term weather (e.g., dry-spell, prior rainfall, prevailing and prior temperatures) on skid resistance including the overall seasonal variation, and (2) to examine the effect of long-term weather (e.g., climatic regions, annual wet days, and annual average temperature) on skid resistance.

The effect of short-term weather on six PCC and five AC pavement surfaces was examined. The PCC surfaces include smooth surface, burlap, broom and astroturf dragged surfaces, exposed aggregate texture, and longitudinal tined surface. The PCC specimens were prepared in the Centre for Pavement and Transportation Technology (CPATT) laboratory at the University of

Waterloo, Ontario from standard 30MPa ready mix concrete used for PCC pavements in Ontario. Each surface texture configuration consists of three specimens i.e., total eighteen PCC specimens were used. The AC surfaces include conventional hot laid (HL3) dense mix (two sections), Superpave (SP), Stone Mastic Asphalt (SMA), and Polymer Modified Asphalt (PMA) on CPATT test track at Waterloo landfill site. Fifteen specimens were obtained by coring from midline (between two wheel paths) of these five sections. All these AC mixes contain aggregates from the same locality (similar microtexture). All these sections were also constructed using one contractor in one season (i.e., same age pavements). All the surfaces were free of cracks and other visible surface distresses including flushing/bleeding.

For determining the effect of long-term weather, data of LTPP program Release 21 [18] were obtained for both PCC and AC pavements incorporating all geographic/climatic regions of Canada and the U.S. The PCC pavements include all sections under GPS-3, GPS-4, GPS-5, and GPS-9 while AC pavements include all sections under GPS-1, GPS-2, GPS-6, and GPS-7.

Data Collection

All the PCC and AC specimens were exposed to outside natural environment and surface friction was measured bi-weekly or monthly from February to October (2007) using the British Pendulum. The equipment was set at the roadside on a frame that firmly holds the specimens during the testing. For few months, BPN was measured directly on the AC road surfaces at midlane. The test site is located at landfill and was mostly closed for traffic during the testing period. The surface texture was measured (sand patch method) time to time for determining possible changes in surface macrotexture level. Daily low and high temperatures and rainfall data were obtained from the University of Waterloo weather station located just six kilometers away from the test site. The 7-, 5-, 3-, and 1-day mean temperatures, total precipitation, and the number of dry days prior to skid testing day were calculated. Pavement surface and ambient temperatures during the testing were also recorded. This enabled to determine the true effect of environment/weather on the variation of skid resistance.

The obtained data for each LTPP section include friction (skid) number, surface age, annual wet days, annual average temperature, climatic region, and speed and temperature during the skid testing. The obtained data for PCC pavements consist of 1,692 skid measurements while AC pavements data consists of 2,742 skid measurements.

Data Processing

The bi-weekly or monthly skid data were routinely checked during the actual testing for accuracy and consistency relative to preceding measurements. Measurements were repeated if any doubtful situation occurred. It should be noted that surface friction measurement were taken on wet surface after removal of dust and other debris for determining effect of rainfall, temperature, and dry-spell without associating them with surface contamination. As the effect of contamination will vary depending on the type of contaminant and the degree of contamination, this study did not

Table 1. Descriptive Statistics of the Bi-weekly/Monthly Skid Data.

Month	MTD (mm)	Amb. Temp. (°C)	Surf. Temp. (°C)	BPN	Corrected BPN
<u>AC Pavements</u>					
February	1.04	4.2	4.9	71.3	66.3
March-9	1.04	3	9.7	75.8	72.8
March-23	1.04	9.3	3.6	73.4	68.4
April	1.04	32.4	35.1	65.5	68.5
May	1.02	23.6	24.2	71	72
June	1.02	34.8	34.6	62.5	65.5
July	1.02	20	22.4	66.7	66.7
August	1.11	28.9	25.2	63.7	64.7
September	1.11	21.9	21	67.6	67.6
October	1.11	10.5	10.9	73.9	70.9
Minimum	1.02	3	3.6	62.5	64.7
Maximum	1.11	34.8	35.1	75.8	72.8
Average	1.05	18.8	19.2	69.2	68.4
Std. Dev.	0.04	11.5	11.4	4.6	2.8
<u>PCC Pavements</u>					
February	1.38	4.7	5.1	71.1	66.1
March-9	1.38	5.8	8.6	72	69
March-23	1.38	5.7	3.8	71.2	66.2
April	1.38	31.6	27.6	62.9	63.9
May	1.38	27.8	29	63	65
June	1.38	25.3	21.8	65.3	65.3
July	1.38	27.7	21.5	65.3	65.3
August	1.37	33.4	30.2	62.4	64.4
September	1.37	18.3	17.2	72.4	71.4
October	1.37	15.6	12.7	71.9	69.9
Minimum	1.37	4.7	3.8	62.4	63.9
Maximum	1.38	33.4	30.2	72.4	71.4
Average	1.38	19.6	17.7	67.8	66.7
Std. Dev.	0.01	11.2	9.9	4.3	2.5

consider contamination as short-term effect on skid resistance. To determine the effect of prior weather, the measured surface friction was normalized to BPN at 20°C using the temperature-BPN correlation chart supplied by the manufacturer of British Pendulum.

The trends of short-term or seasonal variation of skid resistance for different AC (HL3, PMA, SP, and SMA) mixes were not different from one another. Similarly, the trends of skid resistance variation for different PCC surface (smooth, dragged, tined, exposed aggregate) textures were not different from one another. That is, neither AC mix types nor PCC texture types were statistically different, at 5% significance level, with respect to seasonal and short-term variation in wet surface friction. Moreover, the variation in macrotexture that resulted in friction variation from one surface to the other did not show any effect on seasonal skid resistance variation. Therefore, average skid resistance of all AC pavements and all PCC surfaces were used for subsequent analysis. Table 1 shows the summary statistics of bi-weekly/monthly average BPN for AC and PCC surfaces.

The surface friction data in LTPP database consists of measurements taken by several types of friction tester. Therefore, friction measurements taken using only the locked wheel skid trailer

Table 2. Descriptive Statistics of the LTPP Data.

Statistics	Count	Min.	Max.	Mean	Stand. Dev.
<u>Rigid Pavements</u>					
SN	743	22.0	65.5	46.6	6.86
Age, years	743	0	15.95	2.85	3.22
Speed, km/hr	743	41.8	88.5	65.3	4.64
Annual Avg. Temperature, °C	743	2.8	22.9	13.4	4.25
Annual Avg. Wet Days, %	743	9.2	51.8	34.6	8.16
<u>Flexible Pavements</u>					
SN	1,229	23.0	68.5	44.8	8.01
Age, years	1,229	0	12.05	2.12	2.26
Speed, km/hr	1,229	57.9	88.5	67.5	7.86
Annual Avg. Temperature, °C	1,079	2.7	25.1	12.7	4.23
Annual Avg. Wet Days, %	1,079	6.5	56.6	35.0	9.59

(ASTM E 274) mounted with ribbed tire, that has the maximum number of data points, were selected for analysis to avoid equipment/method related bias. The friction data from each section were then individually checked for practicality/consistency and all doubtful data (such as unusual increase or decrease) were filtered out. Finally, the friction data with decreasing trends after an early life increase of surface friction were selected for all analysis in this paper. The selected data include 238 PCC pavements in 38 States/Provinces and 256 AC pavements in 33 States/Provinces (U.S. and Canada).

Average SN of multiple measurements on each section was calculated and used as the available surface friction of each section at each season/year. All the relevant data were converted to metric units. Mean annual wet days (as percentage of number of days in each year) and annual average mean temperatures were calculated from weather data of year 1986 to 2005 (twenty years). Table 2 shows the summary statistics of the LTPP data that was used in the analysis. The data covers four climatic regions: dry freeze, wet freeze, dry no freeze, and wet no freeze.

Results and Discussion

Effect of Short-term Weather on Pavement Surface Friction

Seasonal Skid Resistance Variation

The month to month fluctuation of corrected (normalized to 20°C) wet surface friction for both AC and PCC pavement surfaces were shown to be almost identical given the limitation of reproducibility of test results and variation in temperature during the testing (Table 1). That is, the type of pavements (AC versus PCC) did not show any statistically significant difference in seasonal skid resistance variation. The trends for the variation in surface friction due to temperature (surface and air) variation were also shown to be identical for AC and PCC pavement surfaces. These probably indicate that the seasonal variation of skid resistance is associated with something other than pavement surface condition given that pavement surface is not soft (due to soft binder or high binder content), contaminated or bled with binder. For example, the variation in surface friction may be more sensitive to temperature

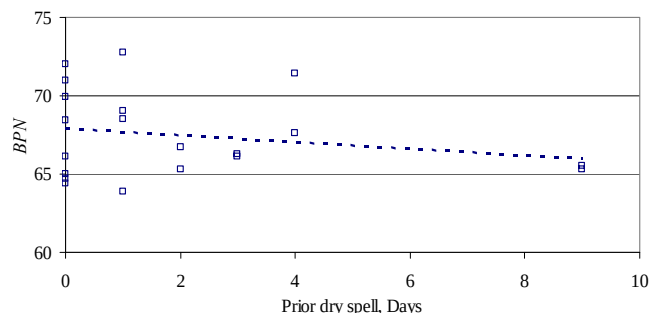


Fig. 1. Effect of Short-term Dry-spell on Surface Friction Variation.

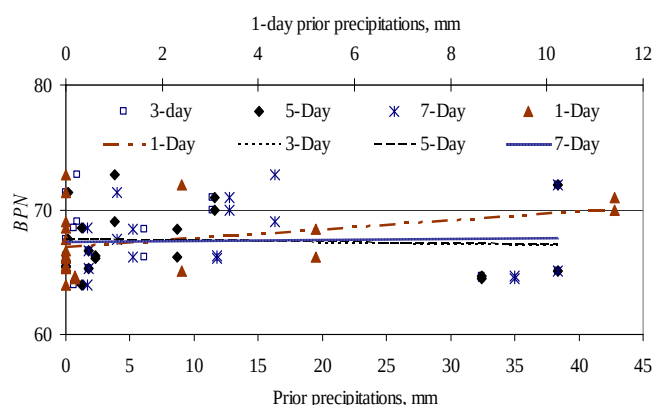


Fig. 2. Effect of Short-term Prior Precipitations on Surface Friction.

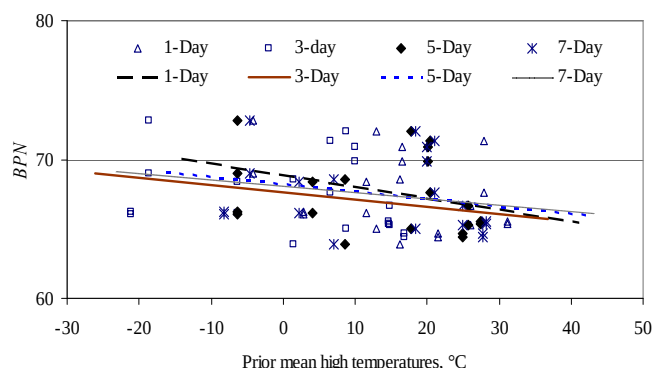


Fig. 3. Effect of Short-term Prior Temperatures on Surface Friction Variation.

related change in tire hardness than a change in pavement stiffness.

The difference between the corrected lowest and highest wet surface friction was shown to be eight *BPN* for both AC and PCC surfaces. This result agrees well with that indicated by Jayawickrama and Thomas [7] concerning the seasonal variation of six *SN* between winter and summer taking the *SN* value as 77% of the *BPN* as found in a Canadian study [19]. As the seasonal variation of skid resistance was shown to be identical for tested AC and PCC pavements, the available data for these two pavements was combined together for examining the effect of prior and prevailing temperatures, rainfall, and dry-spell.

Effect of Dry-spell on Surface Friction Variation

The effect of dry period i.e., number of days without any

precipitation (dry-spell) prior to skid measurement is shown in Fig. 1 (AC and PCC surfaces combined together). As shown in the figure, skid resistance decreases by 0.22*BPN* per dry day. However, the correlation (with a correlation coefficient, $r = 0.22$) was not shown to be statistically significant at 5 or 10% levels of significance. Furthermore, the trend is constant if the nine days data points are excluded from the analysis. These suggest that dry-spell has no significant effect on the variation of wet surface friction (negligible for all practical purposes) given that no surface contamination or bleeding is associated with the dry-spell.

Effect of Prior Precipitation on Surface Friction Variation

Fig. 2 shows the variation of surface friction with the variation of prior precipitation. The 1-day trend (with $r = 0.36$) indicates that surface friction will increase by 0.27*BPN* for each 1mm prior precipitation in a 1-day period. This is probably related to washing out of the minor dust particles and rejuvenation of surface microtexture. The trends for the total 3-, 5-, and 7-day prior precipitation have shown to be constant indicating that precipitation prior to the last 1-day has no effect on skid resistance variation. However, none of the correlations including the 1-day prior precipitation was shown to be statistically significant at the 5 or 10% levels of significance to explain the variation of wet surface friction over time. This means that the effect of prior precipitation is also not considerable for any practical purpose.

Effect of Prior Temperatures on Surface Friction Variation

Fig. 3 shows the effect of prior temperatures on the short-term/seasonal variation of wet surface friction. As shown in the figure, the trends for 1-, 3-, 5-, and 7-day mean high temperatures are almost identical with a slightly decreasing trend of surface friction with an increase in prior temperature. The trend for 1-day temperature (sharpest among the trends with $r = 0.33$) has shown a negligible variation of surface friction of 0.08*BPN* per 1°C increase in temperature. As for the cases of prior dry-spell and precipitation, none of the prior temperatures has explained the variation of wet surface friction at the 5 or 10% significance levels. This further indicates that temperature related change in tire rubber hardness, not the stiffness of conventional pavements, probably influence the seasonal or day-to-day variation in available surface friction.

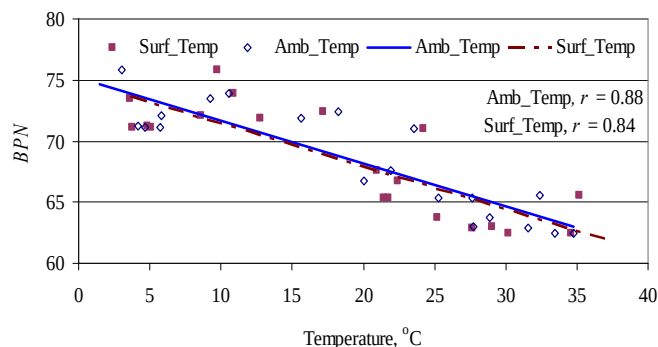


Fig. 4. Effect of Prevailing Temperatures on Surface Friction Variation.

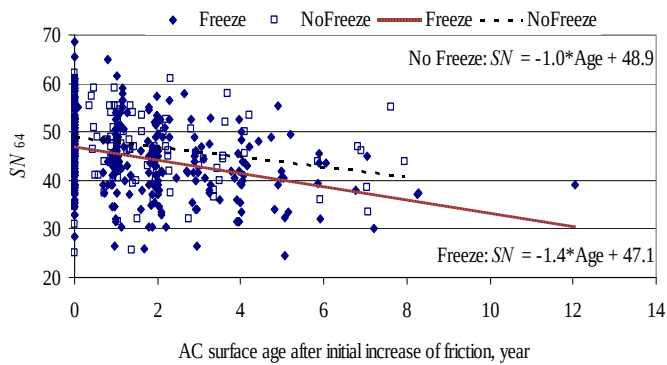


Fig. 5. Changes in AC Skid Resistance with Age after an Initial Increase.

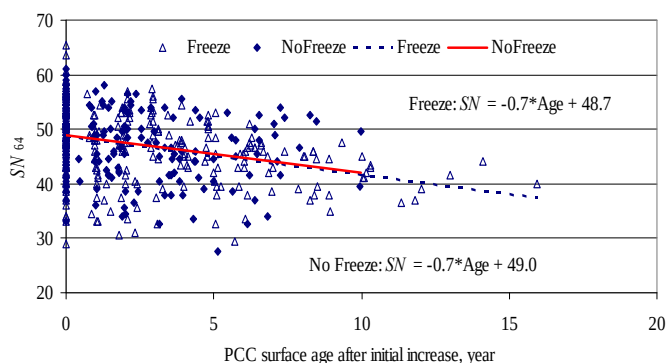


Fig. 6. Changes in PCC Skid Resistance with Age after an Initial Increase.

Effect of Prevailing Temperatures on Surface Friction Variation

As described above, none of the prior temperatures, precipitation, and dry-spells was shown to be statistically significant to explain the seasonal or short-term variation of skid resistance. The interactions of temperatures and precipitations, temperatures and dry-spells, and precipitations and dry-spells were also statistically insignificant. Therefore, an attempt was made to examine the trend of raw (uncorrected) surface friction with the variation of prevailing pavement surface and ambient temperatures. Fig. 4 shows that trends for air and pavement surface temperatures are identical and overlapping each other with good correlation coefficients of 0.84 and 0.88. The correlations are statistically significant at the 5% significance level. This indicates that the day-to-day variation in surface friction is mainly explained by the variation in pavement surface or ambient temperature during the testing (driving) which is mainly related to changes in tire rubber hardness. This also suggests that the seasonal variation of available surface friction may roughly be estimated from the variation in either of the prevailing surface or of ambient air temperatures, given that the pavement surface is not contaminated, soft or bled with bituminous binder.

The trend of surface friction with the variation of prevailing ambient temperature showed that for a 1°C increase in temperature the wet surface friction will decrease by 0.35BPN . This translates to 0.27SN using the earlier mentioned correlation between BPN and

SN [19] i.e., the skid resistance will decrease by 0.27SN for each 1°C increase in temperature. This estimate agrees closely with the finding by Hill and Henry [6] in regards to the temperature effect. Such a variation may not be important when the available surface friction is high but may be a factor when the available friction is low or marginal. Highway agencies or tire manufacturers should consider the rate of change or overall change in available surface friction, not the maximum value for the tested surfaces.

Effect of Long-term Weather on Pavement Surface Friction

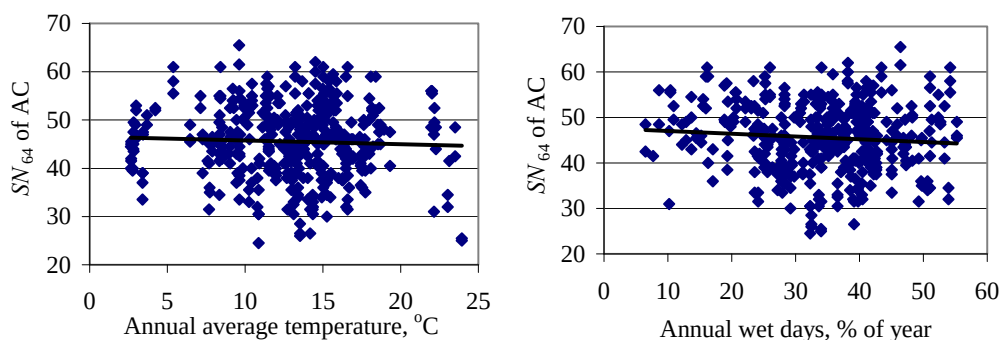
Variation with Pavement Age and Climatic Regions

The trend for change in AC pavement surface friction, measured at 64km/hr , after an early life increase, is shown in Fig. 5. The trends in the figure show that AC surface friction is expected to reduce at an average 1.0 and 1.4SN per year for no freeze (dry no freeze and wet no freeze) and freeze (dry freeze and wet freeze) climatic regions, respectively. Fig. 6 shows the trends for PCC surface friction loss over time after a period of initial increase for two dominant climatic regions. Both trends are overlapping with identical rate of friction loss (0.7SN per year) indicating that PCC surface friction loss is less susceptible to predominant weather condition. Less susceptibility of PCC pavements to surface distress, variation of weather and expeditious rejuvenation of microtexture, especially from sand, probably justifies such variation.

The effect of traffic on skid resistance variation has been analyzed by the authors [9], but is not presented here as this paper has focused only on weather effect. However, it should be noted that the variation in surface friction with pavement age accounts for the traffic because all pavements were open to traffic. The effect of weather, if any, is extra over age/traffic related wear/loss. Pavements located in freezing weather are generally subjected to de-icing salt or sand application and snow removal operation. AC pavements may lose microtexture or may experience an increased macrotexture (due to coarse aggregate raveling) to a level that reduces the net tire-pavement contact. In contrast, PCC pavements, for which fine aggregate or sand is primary contributor to the available surface friction may experience increased microtexture due to exposure of aggregates (polished surface becomes rough). It should also be noted that the effect of raveling might be favorable for available surface friction until the increased macrotexture does not result in a reduction in net tire-pavement contact. However, these aspects need to be further explored.

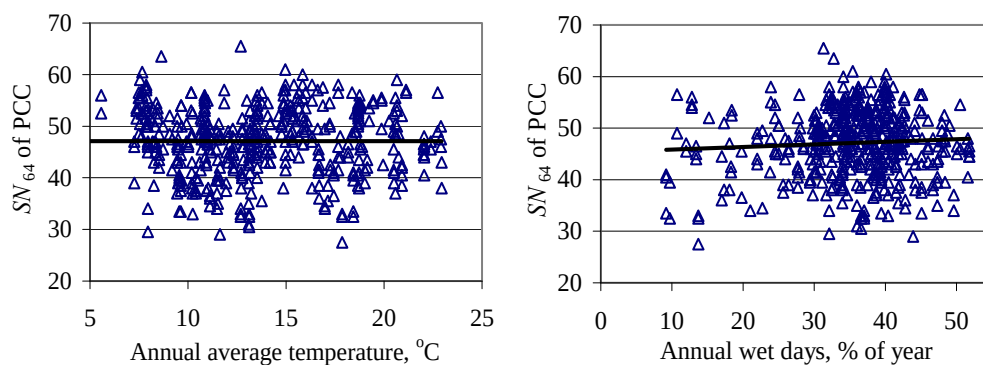
Effect of Long-term Weather

Fig. 7 shows the effect of the long-term weather on AC pavements skid resistance variation. The trend in Fig. 7(a) shows that prior temperature has no effect on the variation of AC pavements skid resistance over the long-term. The trend in Fig. 7(b) shows that skid resistance will decrease marginally over the long-term if the pavement is wet for a longer period. However, the trend was not shown to be strong enough (statistically significant) to draw any useful conclusion regarding the effect of precipitation on long-term skid resistance variation.



a) Effect of prior long term temperature

b) Effect of prior long term precipitation

Fig. 7. Effect of Long-term Weather on AC Skid Resistance (a) Prior Long-term Temperature and (b) Prior Long-term Precipitation.

a) Effect of prior long term temperature

b) Effect of prior long term precipitation

Fig. 8. Effect of Long-term Weather on PCC Skid Resistance (a) Prior Long-term Temperature and (b) Prior Long-term Precipitation.

The effect of the long-term weather on PCC pavements skid resistance variation is shown in Fig. 8. The trend in Fig. 8(a) is constant with no noticeable effect on the variation of PCC pavements skid resistance over time. Fig. 8(b) shows a slightly increasing trend of skid resistance with an increase in precipitation. However, the correlation is not strong to be statistically significant. All these indicate that the influence of neither prior temperature nor precipitation on the long-term variation in surface friction is considerable for practical applications.

Conclusions

This paper evaluated the effect of short-term and long-term weather on the variation of both AC and PCC pavements surface friction seasonally and over long run. The short-term variation was shown to depend mainly on the prevailing temperature with a maximum eight *BPN* (approximately six *SN*) variation from one season to another within a year. None of the short-term prior temperature, dry days without rain (dry-spell), and precipitations was shown to be statistically significant to explain the seasonal or short-term skid resistance variation for the tested pavements (not considerable for all practical purposes). Overall, the wet surface friction was shown to vary at 0.35*BPN* (approximately 0.27*SN*) for 1°C change in prevailing surface or ambient temperature. However, it should be noted that this short-term or seasonal variation does not account for the effect of surface contamination or bleeding.

Over long-term, AC surface friction was shown to reduce at an

average 1.0 and 1.4*SN* per year if the pavements are located in no freeze (dry no freeze and wet no freeze) and freeze (dry freeze and wet freeze) climatic regions, respectively. However, PCC surface long-term friction loss was shown to be similar for these two dominant climatic regions with 0.7*SN* loss per year indicating less susceptibility of PCC surface friction loss to climatic conditions (regions). Prior long-term temperature and rainfall were shown to have no statistically significant or logical effect on skid resistance variation of the AC and PCC pavements in the LTPP database.

Highway agencies should take into account, during the selection of pavement surface type for new construction or for rehabilitation of existing ones, the temperature and age/traffic related variation in available surface friction, depending on seasonal temperature variation and location as well as type of pavement in each jurisdiction.

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