Methodology for Analyzing Texture and Skid Resistance Data for Use in Pavement Management Systems

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Results of recent research in skid resistance have been incorporated into a methodology for use in pavement maintenance management programs by transportation agencies. The methodology, which is part of a computer program developed for the Federal Highway Administration (MAPCON), can perform the data processing to reduce and analyze the raw measurement data from various types of texture and skid resistance measurements. This paper discusses the capability and structure of the methodology. It covers aspects of skid resistance, adjustments for seasonal and weather-related variations, side force coefficients, and the hydroplaning potential. The use of the computer program is also discussed.

Skid resistance is a measure of the friction between the tires of a moving vehicle and the wet pavement. Pavement friction determines the amount of control available to the driver of the vehicle and is important for safety. In recent years research has improved the understanding and prediction of the skid resistance of pavements. Incorporation of recent research findings (1-5) to form a methodology for analysis of skid resistance will provide a compact tool for pavement management by transportation agencies. Similar methodologies can be applied to other pavement management inputs such as road roughness, pavement distress, and ride quality. An overall methodology, which uses the computer program methodology for analyzing pavement condition (MAPCON), has been developed by the Pennsylvania Transportation Institute to provide inputs by reducing and analyzing the raw measurement data into some significant quantities for use in management systems. This paper discusses the aspects of the program related to the skid resistance of the pavement.

METHODOLOGY

The methodology for the analysis of skid resistance has been developed from in-depth investigations of all the measurement methods, analyses, and research findings currently available. The structure of the analysis is illustrated in the block diagram in Figure 1, where the computation is performed by using inputs shown on the left side of the diagram to produce the outputs shown on the right side. The program can operate on such data as British pendulum numbers (BPNs), sand-patch data, or texture profiles to perform specified analyses and provide meaningful results.

The skid-resistance analysis describes the friction between vehicles and wet pavements currently quantified as skid number (SN), the friction force divided by the vertical load on a skidding tire. SN depends not only on pavement properties but also on the relative sliding velocity of the tire in the form (1):

$$SN = SN_0\, e^{-(PNG/100)V} \quad (1)$$

where

SN_0 = skid number intercept,
PNG = percentage of normalized gradient = $-(100/SN)(d/dV)(SN)$, and
V = sliding velocity.

Usually, SN at 64 km/h (SN_{64}) is used as a common index in evaluating pavement performance. The side force coefficient (SFC), the side force times 100 divided by the normal force on a cornering tire, is sometimes used for evaluating pavement safety because it is a measure of steering capability. In fact, Henry (1) shows that SFC is also a function of SN_0 and PNG, as follows:

$$SFC = SN_0[3(\rho^2 - \rho^3) + e^{-(PNG/100)(V/2)\tan\alpha}(1 - 3\rho^2 + 2\rho^3)] \quad (2)$$

where

$\rho = 1 - [\tan\alpha/3(SN_0)][d(SFC)/d\alpha] \quad \alpha \to 0$,
α = yaw angle, and
$d(SFC)/d\alpha$ = 1980 rad^{-1} for ASTM E 501 tire (6) and 1500 rad^{-1} for ASTM E 524 tire (6).

SN_0 and PNG are important parameters for skid-resistance analysis. They are used to predict and evaluate the pavement friction performance (SN and SFC) as a function of speed. However, SN_0 and PNG are parameters closely related to the pavement texture, with SN_0 related to the microtexture of the pavement and PNG related to its macrotexture. Thus, they can be estimated from texture measurements or computed directly from pavement friction tester data. There are four ways to provide estimates of SN_0 and PNG, which are described below as Pennsylvania State University (PSU) models I, II, III, and IV.

PSU Model I

PSU model I uses skid-trailer tester results and performs a log-linear regression from skid number-sliding velocity pairs (SN_i, V_i) to estimate the best values for SN_0 and PNG in Equation 1. The regression in this form provides excellent correlation with the experimental data (1).

PSU Model II

PSU model II uses one skid number at a known sliding velocity and one texture descriptor. The texture descriptor can be either a macrotexture or a microtexture parameter. Depending on whether the texture data are macro or micro, SN_0 or PNG is determined. Then Equation 3,

$$SN_0 = SN_V\, e^{(PNG/100)V} \quad (3)$$

is used with known PNG, or Equation 4,

$$PNG = (100/V)\ln(SN_0/SN) \quad (4)$$

is used with known SN_0.

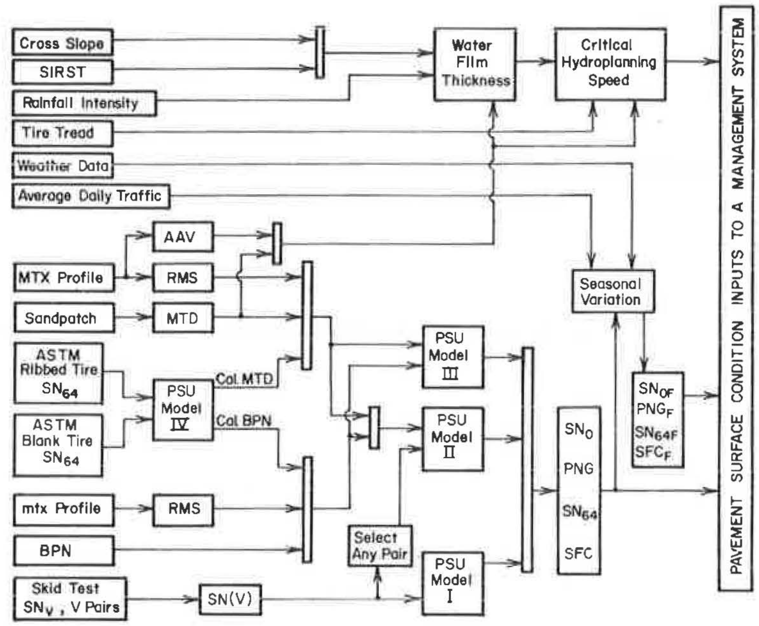
PSU Model III

PSU model III uses texture data to estimate SN_0 and PNG.

Macrotexture Data for Estimating PNG

The macrotexture profile can be measured by using a texture profile tracer, either a mechanical instrument with a contacting stylus or a noncontact opti-

Figure 1. Functional block diagram for methodology in skid-resistance analysis.



cal instrument. The macrotexture profile contains wavelengths in excess of 0.5 mm [the choice of 0.5 mm for dividing macrotexture and microtexture is based on the study by Henry (1)] and is reduced to its root mean square height ($RMSH_{MA}$). PNG can be estimated by the relation (1)

$$PNG = b_1 RMSH_{MA}^{b_2} \quad (5)$$

Typical values for b_1 and b_2 and coefficients for subsequent equations are listed in Table 1. These are typical values that have been developed by using the data collected in Pennsylvania. As additional data that describe a wider range of pavement designs become available, these values may be refined.

Sand-patch mean texture depth (MTD) measured from the sand-patch method is related to PNG (1),

$$PNG = c_1 \cdot MTD^{c_2} \quad (6)$$

Microtexture Data for Estimating SN_0

Microtexture profile data can be measured by using a microtexture profile tracer. The microtexture profile, which contains wavelengths below 0.5 mm, can be obtained and reduced to its root mean square height ($RMSH_{MI}$). This quantity is used to estimate SN_0 by (1),

$$SN_0 = d_1 + d_2 \cdot RMSH_{MI} \quad (7)$$

BPN can be measured by using ASTM E 303 (6) and can be related to SN_0 by (1)

$$SN_0 = e_1 + e_2 \cdot BPN \quad (8)$$

PSU Model IV

It has been found (4) that skid numbers measured by using ASTM E 524 smooth tire (Equation 9) (SN_{64}^B) and the ASTM E 501 ribbed tire (SN_{64}^R) correlate very well with BPN and MTD numbers in the forms of

$$SN_{64}^B = f_{1B} + f_{2B} \cdot (BPN) + f_{3B} \cdot (MTD) \quad (9a)$$

$$SN_{64}^R = f_{1R} + f_{2R} \cdot (BPN) + f_{3R} \cdot (MTD) \quad (9b)$$

by solving these two equations simultaneously, equivalent data for BPN and MTD can be computed from SN_{64}^B and SN_{64}^R. Then, PGN and SN_0 can be estimated by using the formula of Equations 6 and 8.

SEASONAL VARIATIONS

SN_0 and PNG can be estimated from PSU models I, II, or III. However, skid-resistance measurements on two hypothetically identical pavements will produce different skid numbers if the measurements are made at different times in the season or under different weather conditions. We must correct for these effects in order to compare pavements on a common basis. The object of this analysis is to determine a seasonally adjusted value for SN from measurements taken at any time during the season and also to account for the weather conditions that prevailed when the measurement was made. The seasonally adjusted value ($SN_{64}F$) is known when corresponding values of SN_{0F} and PNG_F are determined.

From a measurement of SN_0, the value of SN_{0F} can be determined:

$$SN_{0F} = SN_0 - SN_{0R} - SN_{0L} \quad (10)$$

where SN_{0R} is the short-term variation residual and SN_{0L} is the long-term variation residual. Equation 10 describes the changes that SN_{0F} undergoes as a result of long-term (annual) and short-term (weather-related) variations.

The short-term and long-term variations of SN_0 (SN_{0R} and SN_{0L}) can be estimated by using (3)

$$SN_{0R} = g_1 - g_2 DSF - g_3 TP \quad (11a)$$

$$SN_{0L} = SN_{0F} + \Delta SN_0 e^{(-t_1/h_4 - h_5 ADT)} \quad (11b)$$

and

$$\Delta SN_0 = h_1 - h_2 ADT - h_3 BPN \quad (11c)$$

where

ADT = average daily traffic,
DSF = dry spell factor,
TP = pavement temperature, and

Table 1. Typical values for coefficients.

Coefficient	Value	Equation	Remarks	Reference
b_1	0.35	$PNG = b_1 \cdot RMSH_{MA}^{b2}$	$RMSH_{MA}$ in mm	1
b_2	-0.52		PNG in h/km	
c_1	0.45	$PNG = C_1 \cdot MTD^{C2}$	MTD in mm	1
c_2	-0.47		PNG in h/km	
d_1	-44.4	$SN_0 = d_1 + d_2 \cdot RMSH_{MI}$	$RMSH_{MI}$ in mm	1
d_2	9.44			
e_1	-34.9	$SN_0 = e_1 + e_2 \cdot BPN$		1
e_2	1.32			
f_{1B}	-16.87	$SN_{64}^{B} = f_{1B} + f_{2B}(BPN) + f_{3B}(MTD)$	MTD in mm	5
f_{2B}	0.54			
f_{3B}	0.50			
f_{1R}	-9.19	$SN_{64}^{R} = f_{1R} + f_{2R}(BPN) + f_{3R}(MTD)$	Spring 1979 test	5
f_{2R}	0.74			
f_{3R}	0.15			
g_1	3.8	$SN_{0R} = g_1 - g_2 \cdot DSF - g_3 \cdot TP$	TP in °C	3
g_2	1.15			
g_3	0.10			
h_1	28.5	$\Delta SN_0 = h_1 - h_2 \cdot ADT - h_3 \cdot BPN$		2
h_2	0.002 3			
h_3	0.09			
h_4	67.67	$SN_{0L} = \Delta SN_0 \cdot e^{[-T_1/(h_4 - h_5 \cdot ADT)]}$	T_1 in days	2
h_5	0.003 7			
j_1	0.005 979	$WT = j_1(MTD^{j2}\, RAIN^{j3}\, CSLP^{j4}) - MTD$	MTD in mm	6
j_2	0.11		RAIN in mm/h	
j_3	0.59		CSLP in m/m	
j_4	-0.42		WT in mm	
			For runoff length 11 m	
k_1	8.454 8	$V_c = k_1[(TD/25.4) + 1]^{k2}\, MTD^{k3}[WT^{(k4/k5)} + 1]$	V_c in km/h	6
k_2	0.05		TD in mm	
k_3	0.01		Based on 10 percent spin down	
k_4	1.879 8		165 kPa tire pressure	
k_5	0.01			

t_1 = number of days between the day for which ΔSN_0 is estimated and the date when the measurement was made.

$$DSF = \log(1 + TR) \tag{12}$$

where TR is the number of days since the last rainfall of 2.5 mm or more with an upper limit of seven days.

PNG is also subject to seasonal variation. Research is under way to determine the dependence of PNG and time. The proposed relation is

$$PNG_F = PNG - i_1 t_2 - i_2 ADT \tag{13}$$

where t_2 is the number of days since PNG was measured. For the current methodology, i_1 and i_2 are set at zero, and the variation of PNG is thus ignored.

By using Equations 11a and 11b, SN_{0F} can be obtained. The seasonally adjusted value can thus be given as:

$$SN_{64F} = SN_{0F}\, e^{-0.64 PNG_F} \tag{14}$$

Also, SFC_F can be estimated by substituting SN_{0F} and PNG_F for SN_0 and PNG in Equation 2.

HYDROPLANING POTENTIAL

SN and SFC are the quantities that describe the longitudinal and lateral friction available for controlling vehicle motion under ASTM E274 conditions with an effective water film thickness of 0.5 mm. However, if the rainfall is heavy, the vehicle may hydroplane. This is the condition when the tires are separated from the pavement by the water wedge, and the friction becomes so low that loss of vehicle control may occur. The hydroplaning potential is best described by a critical vehicle speed for specified rainfall. The critical speed, above which hydroplaning may occur, can be calculated from the following equation (5) if sufficient data are available:

$$WT = j_1(MTD^{j_2} RAIN^{j_3} CSLP^{j_4}) - MTD \tag{15}$$

$$V_c = K_1[(TD/25.4) + 1]^{k_2} MTD^{k_3}[(k_4/WT^{k_5}) + 1] \tag{15a}$$

where

WT = estimated water film thickness;
RAIN = rainfall intensity;
MTD = mean texture depth, which is obtained by using the sand-patch method or arithmetic average of the macrotexture profile;
CSLP = cross slope;
TD = tire tread depth; and
V_c = critical hydroplaning speed.

USE OF THE PROGRAM

MAPCON, which can perform the computation discussed previously, is written for batch processing computers. The user must prepare the input card deck or its equivalent to run the program. Among the several choices in the analysis, the user can specify which model (PSU model I, II, or III) is to be used for estimating SN_0 and PNG and can indicate whether the seasonal adjustment is to be made. A common choice is set as the default. The typical values of the coefficients of the regression equation can be changed by the user as better data become available. The user has only to specify keywords to the desired choice, the variable names, and values for the input quantities. The output will echo these choices and selected options and print the computed results in an organized fashion in both SI and U.S. conventional units. The results of the data processing will estimate the skid number-

Figure 2. Examples of skid-resistance analysis.

Example 1

Input

skid numbers	sliding velocities (km/hr)
60	20
56	30
50	40
46	50

model: PSU model I

seasonal adjustment: none

Output

SN_0 = 72.5 PNG = 0.91 hr/km

SFC = 50.3 at 7° yaw angle

SN_{64} = 71.59

for given velocity 27 km/hr SN = 56.70

for SN = 65. the corresponding velocity = 12 km/hr

Example 2

Input

model: PSU model II

one (SN,V) pair: SN = 35, and velocity = 30 km/hr

texture data: MTD = 15 mm

seasonal adjustment: none

Output

SN_0 = 36.3 PNG = 0.126 hr/km

SFC = 34.56 at 7° yaw angle

SN_{64} = 33.48

Example 3

Input

model: PSU model III

texture data: MTD = 15 mm BPN = 65.

seasonal adjustment: none

Output

SN_0 = 50.9 PNG = 0.126 hr/km

SFC = 48.39 at 7° yaw angle

for given velocity 60 km/hr SN = 47.19

for SN = 35. the corresponding velocity = 297.2 km/hr

for SN = 45. the corresponding velocity = [illegible]7.7 km/hr

sliding velocity relation, side force coefficients, and critical hydroplaning speed by using several possible combinations of inputs through various analyses. Figure 2 shows the output for three example runs.

CONCLUSION

A methodology is presented for skid-resistance analysis. It has been developed as part of the MAPCON computer program for the Federal Highway Administration for use by transportation agencies in the management of highway pavements. The program brings together recent research results. The equations and their coefficients are integrated into the computer program in such a manner that they may be modified to suit the user's needs or to accommodate improvements from future research.

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