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DEVELOPMENT OF THE GENERALIZED PREDICTOR MODEL FOR SEASONAL VARIATIONS IN SKID RESISTANCE OF PAVEMENT SURFACE

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This paper describes the findings of research program to develop and validate a model for predicting seasonal variations in skid resistance. The model was developed by obtaining frequent skid-resistance measurements in several geographical areas in the United States and from purely statistical consideration. To apply the model, the user should select the set of coefficient values that pertains to the pavement type and geographical area of interest. The model was applied for predicting the skid resistance on a particular day and for predicting the level of skid resistance at the end of the year. Based on these results, it is concluded that the developed generalized model is effective predictor model for predicting seasonally adjusted values of skid resistance.

Keywords : skid resistance, variation, model, pavement surface, regression analysis

1. INTRODUCTION

It was discovered in 1931 that the skid test results for wet surfaces showed a marked seasonal effect1). For each surface tested, higher values of friction were found in winter than in summer. Giles and Sabey2) reported that under British conditions, seasonal changes in skid resistance averaged from 10 to 15 skid numbers had been measured. They also presented data that showed a strong relationship between seasonal variations in skid resistance and personal injury accidents. Other investigators3),4) stressed the importance of such seasonal changes and then need for further evaluation, but little attention has been paid to model these variations.

Skid-resistance measurements made on public highways in Pennsylvania and other States5)~7) in accordance with ASTM E 274 Method of Test8) exhibit seasonal and short-term variations. Seasonal cycles have been observed, at least in the northern states, where the skid resistance tends to be higher in winter through spring than in summer through fall (Fig. 1). Superimposed on these annual cycles are short-term variations, seemingly the result of rainfall and other local weather conditions. Several other states have reported to Federal Highway Administration (FHWA) their observations on seasonal skid-resistance variations were summarized by Rice9). Analyzing these variations, which occur rather systematically, Hegmon10) concluded that there are real changes in skid resistance that are related to changing conditions.

These variations in skid resistance make it impossible to determine the friction performance of a pavement from a single measurement. Not only it is difficult to specify minimum skid resistance value, much

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less enforce their maintenance, but it is also difficult to compare the skid-resistance histories of different types of pavement. Transportation departments require the identification of friction levels on their road systems in order to take corrective measures where needed and to evaluate surfacing materials and practices. The minimum friction level for a given pavement is normally the critical level to be determined, but it is obviously impossible to survey all or most pavements during the short period of time when the friction level is expected to be a minimum. Thus, some analytical procedures are needed which provide a correction to the measured skid resistance for seasonal and short-term variations in skid resistance.

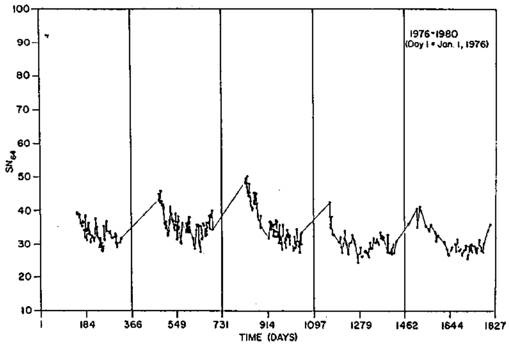


Fig. 1 Five-year History of Skid-Resistance Variations with Time for Pennsylvania Site 16 (Asphalt).

2. OBJECTIVES OF THE STUDY

The FHWA recognized the need for analytical means of interpreting skid-resistance data subjected to seasonal and short-term variations. In 1979, FHWA initiated a three-year research program with the Pennsylvania State University to collect frequent skid-resistance measurements of pavements in various geographical areas of the United States and to develop predictor models to describe seasonal variations in skid resistance of pavement surfaces.

The research program had three main objectives :

(1) To develop and validate a generalized model for predicting minimum pavement skid resistance values from measurements taken at any time during the test season.

(2) To provide predictor equations for various geographical areas in the United States for which adequate data can be supplied.

(3) To identify and measure the physical, chemical, and other changes that contribute to seasonal skid-resistance variations, and to develop a basic mechanistic model to predict those changes as a fuction of environmental and traffic contditions.

It is the primary objective of this paper to summarize a generalized model developed to describe seasonal and short-term variations in skid resistance. The model was developed by obtaining frequent skid-resistance measurements during a season in several geographical areas and by performing a large-scale multiple regression. The model may be utilized to adjust the skid-resistance measurement made at any time during the season to the end-of-season level. These estimates may be utilized usefully to establish a rational maintenance program in which skid resistance is one of the important factors. In this paper, the modeling approach used in the development of the generalized model and its some applications are described. The mechanistic model developed in this research program was already presented[11]. The complete results of the research program were reported in detail to FHWA[12].

3. DATA BASE

The four geographical data sets were used in the development of the generalized model and the associated predictor equations. These data pertains to sites in Pennsylvania, North Carolina and Tennessee, Massachusetts, and Florida. The data sets consisted of skid-resistance measurements taken at various speed, pavement-related data, weather-related data recorded at weather stations located near the test sites and average daily traffic (ADT) count for each site. The skid-resistance measurement was made by the locked-wheel method which provides a coefficient of friction as a skid number $SN_V = 100(F/N)$; where F is friction force ; N is normal (vertical) load on the test tire ; and V is test speed. The skid number at

64 km/h (40 mph), SN_{64}, is usually utilized to evaluate the pavement friction in the United States.

The Pennsylvania data base used for modeling consisted of daily and monthly non-winter data associated with six highway sites for each 5 years (1976–1980) and data from 16 additional sites for each of 2 years (1979–1980). The daily data consisted of information collected during skid-resistance testing of the site surfaces and weather-related information assembled from weather records. The data derived from the daily skid-resistance testing included : date; various skid-test data such as SN_{64}, SN_{48}, SN_{32} which are the skid numbers measured at 64, 48, 32 km/h respectively; and also air, tire, and pavement temperatures recorded at the time of the test. Texture measurements were made monthly at each site and included British Pendulum Number (BPN) according to ASTM E 303[8] and mean texture depth (MTD) as determined by the sand-patch technique[13]. General characteristics for each site were also available : type of pavement surface; pavement mix design and source of pavement aggregate; petrographic description; and ADT.

The data base of other three geographical areas included the same information as was recorded for the Pennsylvania sites except the number of site and the data span. The North Carolina/Tennessee data base consisted of data associated with 11 sites for a 16-month period (1979–1980). The Massachusetts data base consisted of data from 3 sites which covered a 3 years period (1978–1980) and the Florida data base consisted of 6 sites for an 8-month period (1979–1980). All the measurements performed in the course of research are listed in Table 1.

4. DEVELOPMENT OF THE GENERALIZED MODEL

(1) Statistical modeling approaches

An overview is given of the modeling philosophy followed and the various approaches tried. The primary goal of the modeling was to produce an equation, or model, that reliably predicts pavement skid resistance. The predictive worth of such model can be evaluated in a rigorous manner, but the construction of candidate model is based on analytical judgement. The development of the generalized model was guided by the following modeling principles :

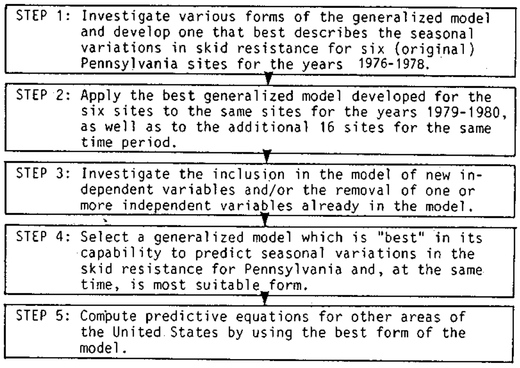
(1) The model should be as simple as possible in mathematical form.

(2) Ideally, the model should be amenable to standard statistical procedure, e.g., multiple regression analysis.

(3) The model should be compatible with, or at least not imcompatible with, known physical characteristics of the systems.

Table 1 Measurements Made During the Course of the Research.

1. Frequent tests on pavements
    A. Skid-resistance measurements (ASTM E 274)
        1. SN_{64}
        2. SN_{48}, SN_{80} (or SN_0, PNG)
        3. SN_{48}^B, SN_{80}^B (or SN_0^B, PNG^B)--blank tire tests
    B. Temperature observations
        1. Pavement temperature (T_p)
        2. Air temperature (T_a)
        3. Water temperature (T_w)
        4. Tire temperature (T_t)
2. Weather station data
    A. Maximum and minimum daily temperature (NOAA Station)
    B. Temperature at 8:00 a.m. standard time (NOAA Station)
    C. Relative humidity (NOAA Station)
    D. Cloud cover (NOAA Station)
    E. Wind direction and speed (NOAA Station)
    F. Precipitation (total per day) (NOAA Station)
    G. Rainfall rate during test season (tilting bucket at local site)
3. Pavement data
    A. Pavement type
    B. Aggregate source
    C. Mix design
    D. Construction date
    E. Average daily traffic (including traffic classification)
4. Texture measurements (monthly)
    A. BPN (ASTM E 303)
    B. Sand-patch mean texture depth (ACPA Method)
    C. Microtexture profiles
    D. Macrotexture profiles
    E. Stereo photographs (ASTM E 559)
    F. BPN after polishing with the reciprocating pavement polisher



STEP 1: Investigate various forms of the generalized model and develop one that best describes the seasonal variations in skid resistance for six (original) Pennsylvania sites for the years 1976-1978.

STEP 2: Apply the best generalized model developed for the six sites to the same sites for the years 1979-1980, as well as to the additional 16 sites for the same time period.

STEP 3: Investigate the inclusion in the model of new independent variables and/or the removal of one or more independent variables already in the model.

STEP 4: Select a generalized model which is "best" in its capability to predict seasonal variations in the skid resistance for Pennsylvania and, at the same time, is most suitable form.

STEP 5: Compute predictive equations for other areas of the United States by using the best form of the model.

Fig. 2 The Steps of Statistical Modeling Approach.

(4) The application of the model should be readily explainable to predicting engineers.

(5) Subject to all these "simplicity" requirements, the model should nevertheless be quantitatively accurate enough to be of value.

Based on these modeling principles, the statistical modeling approach can be summarized as the steps shown in Fig. 2.

(2) Preliminary modeling approach

Various responces were analyzed in the initial modeling efforts. The most extensive effort in both initial and subsequent stages was spent on modeling the seasonal variations in SN_{64} because of the general interest in this variable. Thus, the discussion that follows concentrates on SN_{64}.

In the course of evaluating the data collected in the research program, it was observed that the variations of SN_{64} values has both seasonal cycle and short-term variations. The skid resistance appears to be highest in early spring, and decreases gradually to a stable level in the late of fall. Superimposed on this annual cycle is short-term variations. This trend imply that it may be possible to develop a model to describe the variations of SN_{64} by treating seasonal cycle and short-term variations separately. Therefore, the preliminary step was taken to obtain a general seasonal cycle in a mathematical form. After the curve-fitting for this general seasonal cycle, the examination of residuals from curve fit allowed decisions to be made about the daily variables as potential predictors which can describe the short-term variations.

At this point, it is necessary to choose a general statistical method for the subsequent modeling effort. The statistical procedure chosen is multiple regression analysis, a technique available in standard statistical packages. For a multiple regression analysis to be appropriate, however, the data must be compatible with several assumptions. If SN_{64} is used, these assumptions have the following consequences. First, the mathematical form of the generalized model must be linear in the parameters. Second, the residual error or method error in SN_{64} must be uniform in size. Third, the residuals (deviations between model predictions and observed values) must be approximately independent.

The observed seasonal cycles over a year for the six original Pennsylvania sites (Fig. 1) can be considered to be parabolic in nature. The first modeling approach consisted simply of passing parabolas in Julian calendar time t_j via regression analysis. The parabolic fits, especially the logarithmic form, reasonably described the seasonal cycle of SN_{64}. The analysis also showed, generally speaking, that the quadratic term and higher-order polynomials of the logarithmic form did not improve the fit of model. Under the considerations of above assumptions and the results of this analysis, it was decided that the following mathematical form, in which t_j is Julian calendar time in days,

$$\ln SN_{64} = a_0 + a_1 t_j \quad \cdots\cdots (1)$$

could be used to describe the general seasonal patterns observed for each site year. In the next step, this form served empirically to remove the general seasonal patterns so that the importance of other factors could be examined.

All of the variables of temperature observations and weather station data listed in Table 1 were examined in a stepwise fashion, using each individual site-year data set. Visual examination of the residual plots and other consideration resulted in the creation of derived variables. There were of three types: (1) a daily midrange ambient air temperature (the average of the daily maximum and minimum temperatures); (2) various "lagged" (in time) ambient air temperatures; (3) different rainfall fuction. The residual plots indicated that SN_{64} follows the daily ambient air temperature, for example, at a lag of about one month or more. Various lagged ambient air temperature functions were therefore investigated as candidate predictors.

A large number of regression analyses were examined in the development of a preliminary generalized model. The model that best described the seasonal variations in skid resistance for the six original Pennsylvania sites had the following form:

$$\ln SN_{64} = f(RF, T, T_{30}, T_{90}, t_j) \quad \cdots\cdots (2)$$

or

$$\ln SN_{64}=a_0+a_1RF+a_2T+a_3T_{30}+a_4T_{90}+a_5t_j \cdots\cdots \quad (3)$$

where RF : rainfall function exponentially smoothes rainfall amounts restropectively and is computed in the following manner for the M_i (rainfall in mm) for the i-th day.

$$RF=1/4\,M_i+1/8\,M_{i-1}+1/16\,M_{i-2}+1/32\,M_{i-3}+\cdots\cdots \quad (4)$$

T : midrange of the daily maximum (T_U) and minimun (T_L) ambient air temperature for the i-th day; $T=(T_U+T_L)/2$.

T_{30} : 30-day exponentially lagged temperature function. At any day i, T_{30i} is calculated iteratively as follows :

$$T_{30i}=\alpha T_i+\alpha(1-\alpha)T_{i-1}+\alpha(1-\alpha)^2T_{i-2}+\cdots\cdots \quad (5)$$

where T_i is the midrange temperature at day i and the constant α equals to $1/30$.

t_j : Julian calendar time (short-term calendar time) in days.

The preliminary generalized model in Eq. (2) was subsequently applied to two additional years of data (1979-1980) as they became available for the six sites as well as for the 16 additional Pennsylvania sites. In this analysis, three new variables, t, DSF, and T_p were added to six variables included in the model in Eq. (2) to investigate the efficacy of including in the preliminary generalized model new independent variables and/or the removal of one or more independent variables already in the model. t is considered to account for long-term variation of SN_{64} when the model is applied to data covering a period of more than one year. T_p is the pavement surface temperature at the time of skid test, and DSF is a dry spell factor. DSF is an exponentially increasing function dependent upon the number of days, up to 7 days since the last significant rainfall, defined as

$$DSF=\ln(t_R+1) \cdots\cdots \quad (6)$$

where, for each day, t_R is the number of days since the last rainfall of 2.5 mm or more with an upper limit of 7 days. Hence, $0\leqq t_R\leqq 7$ and $0\leqq \text{DSF}\leqq 2.079$. Both DSF and T_p were included in the modeling because these factors were found to be more important in the mechanistic model.

A large-scale multiple regression analysis was performed using the data from 22 Pennsylvania sites for the 2-year period 1979-1980. Regression coefficients for each combination of variable and their associated R^2 value were calculated and compared. Here R^2 is a measure of the variability in the data explained or accounted for by the respective regression model. This quantity can be interpreted as a measure of the efficacy of the model in explaining the variations of SN_{64}. The results of the individual regression analysis for nine combinations of variable and the respective R^2 values showed that the adequacy of the model varies considerably between asphalt and concrete sites. The two types of pavement were then considered separately, and averaged R^2 values were determined separately for the 7 portland cement concrete (PCC) sites and for the 15 asphalt sites. The model applied to the PCC sites yielded an average R^2 value of only 0.179, while an average R^2 value of 0.431 was obtained for the asphalt sites. This finding led to the conclusion that only the results obtained from the asphalt sites should be considered in the selection of the "best" model. Table 2 shows the average R^2 values for the nine combinations of variable for asphalt sites, in decending order. The followings can be drawn from Table 2 that :

(1) On the average, substituting the rainfall function for a dry spell factor had a negligible effect on the regression results.

(2) The improvement obtained when the T_{90} term (90-day exponentially lagged midrange air temperature factor) is included is of little importance compared with the amount of additional weather information necessary to compute this factor.

Table 2 The Average R^2 Values for Nine Models (Asphalt, 15 Sites).

Model	Average R^2
$\ln SN_{64}=f(RF, T, T_{30}, T_{90}, t_j, t)$	0.460
$\ln SN_{64}=f(RF, T, T_{30}, T_{90}, t_j, t)$	0.457
$\ln SN_{64}=f(RF, T, T_{30}, t_j, t)$	0.450
$\ln SN_{64}=f(DSF, T, T_{30}, t_j, t)$	0.445
$\ln SN_{64}=f(RF, T_p, T_{30}, T_{90}, t_j, t)$	0.434
$\ln SN_{64}=f(DSF, T_p, T_{30}, T_{90}, t_j, t)$	0.431
$\ln SN_{64}=f(DSF, T_p, T_{30}, t_j, t)$	0.432
$\ln SN_{64}=f(DSF, T, t_j, t)$	0.406
$\ln SN_{64}=f(DSF, T_p, t_j, t)$	0.378

(3) The substitution of the pavement temperature at the time of test, T_p, for the daily midrange temperature, T, resulted in lower average R^2 values for the 15 asphalt sites. Also, a daily midrange air temperature appears to be a more appropriate measure than the one-point measure of the temperature at the time of the test. T_p is a function of the time at which the skid test is performed and is therefore subject to hourly fluctuations, whereas T is not.

In addition to these results, two other criteria for the "best" model were considered :

(1) Simplicity of the model, i. e., a model with the fewest variables and therefore easiest to apply, but nevertheless accurate.

(2) Comparability with the mechanistic model which is already developed in terms of the variables used.

After the consideration of all these conditions, the following model

$$\ln SN_{64}=f(DSF, T, T_{30}, t_j, t) \cdots\cdots (7)$$

involving a dry spell factor, a midrange air temperature, a 30-day exponentially lagged temperature, a Julian calendar time, and a long-term calendar time, was chosen as the best preliminary predictive model to describe the seasonal variation of SN_{64} for the Pennsylvania sites.

At this point in the development of the generalized model, it was judged that t, the long-term calendar time, was not the most appropriate choice. A more site-specific time measure seemed more appropriate, and therefore, pavement age measured in year, t_a, was chosen to the model. For the 15 Pennsylvania asphalt sites (1979-1980 data), the R^2 improved from 0.075 to 0.188. For the 7 Pennsylvania PCC sites (1979-1980 data), the R^2 values improved from 0.036 to 0.753. In the remaining of the model development, t_a was used exclusively to describe the long-term time measure.

(3) Description of the generalized model

Mathematically, the seasonal variations of SN_{64} can be predicted by a product of six exponential terms :

$$SN_{64}= e^{a_0} e^{a_1 DSF} e^{a_2 T} e^{a_3 T_{30}} e^{a_4 t_j} e^{a_5 t_a} \cdots\cdots (8)$$

Alternatively, the natural logarithm of SN_{64} can be expressed as a linear combination of a constant plus five terms :

$$\ln SN_{64}=a_0+a_1 DSF+a_2 T+a_3 T_{30}+a_4 t_j+a_5 t_a \cdots\cdots (9)$$

where the a's are model coefficients; DSF, T, and T_{30}, are weather-related variables; t_j is a Julian calendar time; and t_a is the pavement age.

DSF is a dry spell factor defined in Eq. (6). The second term after a constant in Eq. (8) contains a measure of the ambient air temperature, T. The third term contains a 30-day exponentially lagged temperature function defined in Eq. (5). The term "lagged" temperature reflects the fact that the term T_{30} represents a historical temperature function with a turning point that lags approximately 30 days behind the current temperature. The third and fourth exponential terms, t_j and t_a, are time terms that represent the short-term and long-term decays in skid resistance. The short-term calendar time, t_j, is the Julian calendar time and is expressed in days. The long-term calendar time, t_a, has been set equal to the pavement age of each site and is expressed in years.

The numerical values for the a's were determined by stepwise multiple regression analysis using standard atatistical package (SAS). Eqs. (8) and (9) apply to a given site for several years, although different model parameter's values are necessary to characterize different sites. When the model is applied to a site for a single year, the long-term function of time, t_a, is omitted since it would be a constant for that year.

(4) Model results by site for Pennsylvania

The generalized model by Eqs. (8) and (9) was developed for six original Pennsylvania sites (1976-1978 data). It was then applied for the same six sites as well as for the 16 additional Pennsylvania sites (1979-1980 data). The adequacy of the model for each site-year combination was judged by the corresponding R^2 value. The goodness of fit of the predictive model varied from site to site for a given year and year to year for a given site. The predictive model was less powerful for the concrete site than the other original asphalt sites for all five years. The R^2 values of the model averaged over the five years 1976 to 1980 for six original sites are shown in Table 3.

Table 3 The R^2 Values of the Model Averaged Over the Years 1976-1980 for Six Original Sites.

Site	Type	$\bar{R}^2$
16	Asphalt	0.539
17	Asphalt	0.673
19	Asphalt	0.640
21	Asphalt	0.707
22	Asphalt	0.514
18	Concrete	0.179

The model produced very poor results when applied individually to the 1979 and 1980 data associated with concrete site. The contribution of the model to explain the variation observed in ln SN_{64} for these two years is not statistically significant. Such inadequacy of the model was not found for any of the site-year combination of the five original asphalt sites. Almost same inconsistency was found when the model was applied to the additional 16 Pennsylvania sites. In general, the model produced poorer results for the 16 additional sites when applied to the 1979 data than when applied to the 1980 data. This lack of fit was more evident for the asphalt sites than the concrete sites.

The following conclusions were drawn from these results :

(1) The model cannot be applied uniformely to combination of asphalt and concrete sites.

(2) The model does not account for site-to-site and year-to-year variations.

(3) The model needs to be applied to combined sites and years for a specific geographical areas in order to reduce the number of sets of models required for a given area.

(5) Need for Introducing Additional Site-Specific Terms in the Model

In general, the model coefficients developed for given site in a specific area of the United States would be applicable only to site with similar weather and site characteristics. Thus, to minimize the number of sets of model coefficients needed to describe sites within an area, it is necessary to pool data from many sites in an area. On the other hand, combining the data for all sites in an area and ignoring the "site effect" would result in a considerable loss of predictive power of the composite model. Therefore, model parameters that distinguish between pavements in the same environment, and classification by pavement type must be incorporated into the modeling. Thus, the following model was investigated :

$$\ln SN_{64} = a_0 + a_1 DSF + a_2 T + a_3 T_{30} + a_4 t_j + a_5 t_a + a_6 ADT + a_7 MTD + a_8 BPN \quad \cdots\cdots \quad (10)$$

or alternatively,

$$SN_{64} = e^{a_0} e^{a_1 DSF} e^{a_2 T} e^{a_3 T_{30}} e^{a_4 t_j} e^{a_5 t_a} e^{a_6 ADT} e^{a_7 MTD} e^{a_8 BPN} \quad \cdots\cdots \quad (11)$$

where the variables DSF, T, T_{30}, t_j, t_a are as defined in Eqs. (8) and (9).

ADT : average daily traffic in the lane tested which is practically computed by taking the total amounts of annual daily traffic of highway and dividing it by the number of lane.

MTD : mean texture depth (macrotexture term) in mm, measured by sand-patch technique[13].

BPN : British Pendulum Number (microtexture term) which is measured according to ASTM E 303 Method of Test[8] and is annually averaged.

Each site was classified as either concrete or asphalt. A further subdivision of the asphalt pavement group as dense-graded and open-graded bituminous pavement was not carried out, because of the small size of the subgroups.

(6) Summary of model results by geographical area

The specific predictive equations for the generalized model in Eq. (10) were determined from the data for the 22 sites in Pennsylvania, the 6 sites in Florida, the 3 sites in Massachusetts, and the 11 sites in North Carolina/Tennessee. Both pavement types, asphalt and concrete, were considered separately and together, i.e., the generalized model was applied to total data set. Within each of three groups, three models were used to calculated the coefficient values and R^2 values : the model without BPN factor; the model without MTD factor ; and the model with both factors. The values of the model coefficients were accepted only if the contribution of the corresponding factor in explaining the variation observed in ln SN_{64}

Table 4 Model Coefficients for Various Geographical Areas.

Geographical Area	Pavement Type	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	R^2
Pennsylvania	Asphalt	2.933	-0.0397	0.0	-0.00033	-0.00034	-0.0143	-0.000034	*	0.0196	0.86
	Concrete	2.747	-0.0222	-0.0015	0.0011	0.0	-0.0159	-0.000008	*	0.018	0.80
Florida	Asphalt	4.106	-0.0125	-0.0007	0.0017	-0.00035	-0.0670	-0.000012	-0.226	*	0.79
	Concrete	------------------------ No Data Available ------------------------									
Massachusetts	Asphalt	------------- Generalized Model Investigated was Inadequate -------------									
	Concrete	------------------------ No Data Available ------------------------									
North Carolina/ Tennessee	Asphalt	3.065	-0.0097	0.0	0.0	-0.00043	-0.0151	0.000031	*	0.0138	0.91
	Concrete	1.728	-0.0288	0.0	-0.0028	-0.00018	0.0	0.0	0.0	*	0.69

* A blank indicates that term was excluded from the model.

**These R^2 values reflect the goodness of fit of the model for the ggraphical areas for which the model has been developed and are only as indicator of how well the model might work in future applications.

is significant at the 90 percent confidence level.

The model results for Pennsylvania sites showed that the model without the BPN factor gives rather poor R^2 value for the asphalt sites ($R^2=0.56$) and for all sites together ($R^2=0.47$) ; whereas for the concrete sites, the model yields a satisfactory R^2 value of 0.76. Including BPN in the model (without MTD) improved the fit of the model by such as 54 percent for the asphalt sites ($R^2=0.86$) and 77 percent for all sites together ($R^2=0.83$). For the concrete sites, R^2 value improved only from 0.76 to 0.80. Including both factors, MTD and BPN, in the model brought little or no improvement over the model with BPN only.

The best predictor model for explaining seasonal variations in skid resistance of Pennsylvaia asphalt sites is the one determined for the 15 sites (1,945 observations) for the 1979-1980 period as follows :

$$SN_{64}=e^{2.933}e^{-0.0397DSF}e^{-0.00033T_{30}}e^{-0.00034tj}e^{-0.0143ta}e^{-0.000034ADT}e^{0.0196BPN} \quad (R^2=0.86) \cdots\cdots \quad (12)$$

The best predictor model for concrete sites (926 observations) is the one determined for the 7 concrete sites for the 1979-1980 period as follows :

$$SN_{64}=e^{2.747}e^{-0.0222DSF}e^{-0.0015T}e^{0.0011T_{30}}e^{-0.0159ta}e^{-0.000008ADT}e^{0.018BPN} \quad (R^2=0.80) \cdots\cdots \quad (13)$$

Values for the predictive parameters of the model were computed for other three geographical areas in the same manner for the Pennsylvania sites. The best predictor models and associated coefficients for the various geographical areas are summarized in Table 4. The zero values in the tabulation denote that the contributions of the associated factors toward the variations observed in ln SN_{64} is not significant at the 90 percent confidence limit.

5. APPLICATION OF THE GENERALIZED MODEL

To apply the generalized model, the user should select the set of predictor coefficient values from Table 4 that pertains to the pavement type and geographical areas of interest. The other information required is the average daily traffic (ADT), rainfall history, ambient air temperature history in the vicinity of the site, and the date. The generalized model with an appropriate set of predictor coefficients can be used in several ways to furnish quantities of interest to the users.

(1) Prediction of SN_{64} on a particular day

As an example, consider the following data for Pennsylvania site 19 on June 11, 1980 ($t_j=193$ days) :

DSF=0.693, $T=48$ (°F), $T_{30}=40$ (°F), $t_j=163$ (days), $t_a=19$ (years), ADT=7 000 (vehicles per day), MTD=0.51 (mm), BPN=54

The generalized model predicts, for June 11 :

$$SN_{64}=e^{2.933}e^{.0397(.693)}e^{0(48)}e^{-.00033(40)}e^{-.00034(163)}e^{-.0143(19)}e^{-.000034(7000)}e^{0(.51)}e^{.0196(54)}=29.5$$

The skid number actually measured on June 11, 1980 was 30.2.

(2) Prediction of year-end level of skid resistance, SN_{64F}

Table 5 Observed SN_{64F} Values for 1979 and 1980 (Pennsylvania Sites).

Site No.	Type of* Pavement	Observed SN_{64F} 1979	1980
1	DG	21.3	26.1
2	PCC	31.9	24.0
3	PCC	49.7	42.4
4	DG	22.7	27.9
7	PCC	48.8	45.8
8	PCC	29.3	29.1
9	DG	36.7	41.8
10	PCC	52.3	47.6
11	DG	21.1	26.7
12	DG	34.3	31.3
13	OG	57.7	55.8
14	PCC	42.5	35.7
15	OG	53.9	55.0
16	DG	20.4	19.5
17	DG	27.5	26.1
18	PCC	40.8	48.0
19	DG	26.4	26.3
20	DG	32.5	34.1
21	OG	27.3	26.1
22	OG	54.1	46.0
24	DG	18.5	23.4
25	DG	42.9	45.1

*DG=dense-graded; OG=open-graded; PCC=portland cement concrete

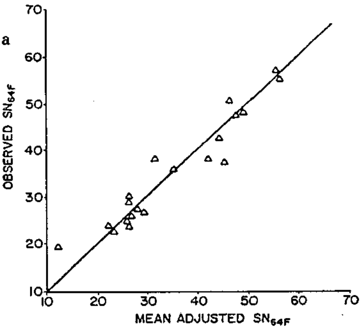


Fig. 3 Comparison of Observed SN_{64F} and Adjusted SN_{64} Obtained by Using the Generalized Model for Asphalt Pavement Surfaces (Pennsylvania Sites).

Table 7 Comparison of Measured SN_{64}, Adjusted SN_{64F} and Observed SN_{64F} for Asphalt Pavement Surfaces (Pennsylvania Sites, 1980).

Site No.	Measured SN_{64} Mean	S.D.	Adjusted SN_{64F} Mean	S.D.	Observed SN_{64F}
1	31.1	4.31	24.7	3.79	26.1
4	33.5	3.82	27.6	3.48	27.9
8	33.0	5.11	26.8	4.39	29.1
9	43.2	3.76	38.1	2.97	41.8
11	30.3	3.62	25.1	3.74	26.7
12	43.2	3.55	38.4	2.49	31.3
13	65.8	2.95	55.3	1.99	55.8
15	68.7	2.97	57.0	2.34	55.0
16	22.3	2.61	12.1	3.42	19.5
17	36.4	5.50	30.2	4.73	26.1
19	29.8	2.60	23.7	2.42	26.3
20	36.8	2.91	32.3	2.40	34.1
21	35.3	3.37	29.3	2.40	26.1
22	59.1	3.02	50.6	1.66	46.0
24	28.6	3.46	22.6	3.47	23.4
25	54.4	3.16	47.3	1.82	45.1

The generalized model can be used to adjust, for seasonal variations, the skid-resistance measurement taken at any time of the year. A method to predict the level of skid resistance at the end of the year (SN_{64F}) had been developed for the Pennsylvania sites from the generalized model. The generalized model recommended for the Pennsylvania sites contains only the annual average BPN as a site-specific variable and is expressed in the form :

$$SN_{64j}=e^{a_0}e^{a_1DSF}e^{a_2T}e^{a_3T_{30}}e^{a_4t_j}e^{a_5t_a}e^{a_6ADT}e^{a_8BPN}\cdots\cdots \quad (14\cdot a)$$

For the application of the generalized model to the Pennsylvania sites, the BPN term in Eq. (14•a) was replaced by another sity-specific variable SN_{64F} (final skid-resistance level at the end-of-season), to yield the following form of the generalized model :

$$SN_{64j}=e^{a_0}e^{a_1DSF_j}e^{a_2T_j}e^{a_3T_{30j}}e^{a_4t_j}e^{a_5t_a}e^{a_6ADT}e^{a_9SN_{64F}}\cdots\cdots \quad (14\cdot b)$$

The values of the coefficient in Eq. (14•b) have been determined from the observed data, so that the adjusted skid number for seasonal variations (adjusetd SN_{64F}) can be predicted mathematically by a linear relationship produced by taking the natural logarithm of SN_{64j} in Eq. (14•b) and rearranging :

$$SN_{64F}=\frac{1}{(-a_9)}(a_0+a_1DSF_j+a_2T_j+a_3T_{30j}+a_4t_j+a_5t_a+a_6ADT-\ln SN_{64j})\cdots\cdots \quad (15)$$

In this analysis, the 1979 and 1980 data values of observed SN_{64F} (listed in **Table 5**)[11] were used. The coefficients that resulted are shown in **Table 6** for each pavement type. For this application, the adjusted level of skid resistance was produced for asphalt pavement from each observation during the 1980, test season. As an exemple, consider again Pennsylvania site 19. From the observed value of skid resistance on June 11, 1980, the model predicts the adjusted SN_{64F} using Eq. (15) with the data from the example in previous paragraph and with SN_{64j}=30.2 as follows :

$$SN_{64F}=\frac{1}{-.0244}[3.124-.0371(.693)+0(48)+.0028(40)-.00047(163)-.0041(19)+0(7000)$$
$$-\ln(30.2)]=23.6$$

Table 6 Values of Model Coefficients for Each Pavement Type (Pennsylvania Sites, 1979 and 1980).

Pavement Type	a_0	a_1 (DSF)	a_2 (T)	a_3 (T_{30})	a_4 (t_j)	a_5 (t_a)	a_6 (ADT)	a_9 (SN_{64F})	R^2
Asphalt	3.124	-0.0371	0.0	-0.0028	-0.00047	-0.0041	0.0	0.0244	0.85
Concrete	4.264	-0.0195	-0.0019	0.0013	0.0	-0.0440	0.0	-0.0028	0.73
All Sites	3.186	-0.0286	-0.0015	0.00063	-0.00056	-0.0045	-0.000020	0.0204	0.75

The value of the observed SN_{64F} for site 19 in 1980 was 26.3.

The results of applying the model in this way were shown in Table 7. In most cases, standard deviations were reduced by the application of the model. The average standard deviation of measured SN_{64} data is 3.55, which is reduced to a standard deviation of the adjusted SN_{64F} of 2.95. In Fig. 3, a good agreement is shown between the observed SN_{64F} and the average daily adjusted values of SN_{64}. When applied to the concrete sites, however, the model was not successful. The reason for this may be the different behavior noted in the skid-resistance histories for the concrete sites as well as the relatively small number of concrete sites (7) compared with the number of asphalt sites (15).

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from the development and applications of the generalized model :

(1) An effective and relatively simple generalized model for predicting SN_{64} of a site has been constructed. The use of the model requires a set of coefficient and knowledge of the age of the pavement; the average daily traffic count for the site; an annual estimate of the BPN value or MTD (mean texture depth) for the site as determined by the sand-patch technique; the rainfall and ambient air temperature histories in the vicinity of the site; and the date.

(2) The goodness of fit of the model for a regional set of highway sites was improved by adding ADT and a measure of surface texture (as determined by BPN and MTD) as factors to the model and by determining the predicition parameters separately for asphalt and concrete pavements. The improvement was greater when BPN was added than MTD was included.

(3) Relatively large differences between geographical areas can be seen in the model coefficients.

(4) Since it is a multiple regression, the generalized model can be used directly to establish future SN_{64} mean value for a given site.

(5) The equation to predict the level of skid resistance at the end of the year (SN_{64F}) from a measurement taken at any time during the season (SN_{64J}) have been developed for Pennsylvania sites in Eq. (15). The results of the application of the model to the 1980 data for Pennsylvania sites have shown in Table 7. Based on these results, it is concluded that the generalized model is an effective predictor model for estimating seasonally adjusted values of SN_{64}.

On the basis of these conclusions, the following recommendations can be made for further work : (1) It was not possible to generalize the model for geographical areas. At this time, it appears necessary to establish coefficients for each climate ragion, for the regression equation used in the generalized model; (2) Further data sets should be obtained and analyzed for the geographical areas in the world, using the procedures developed here, to determine whether similar coefficients are applicable to different geographical areas which have similar conditions.

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