Simplified Pavement Performance Models

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There is a great need for simplified pavement performance models that can be used for forecasting pavement condition on the basis of a minimal amount of available data. The development of predictive models is summarized for five conventional pavement types: asphalt concrete (flexible), composite, jointed plain concrete, jointed reinforced concrete, and continuously reinforced concrete. These models predict the present serviceability rating (PSR) using only knowledge of the pavement's age, cumulative equivalent single-axle loads, and a pavement structural parameter (structural number for flexible, overlay thickness for composite, and slab thickness for concrete pavements). The models were developed from data from several reliable and readily available data bases in Illinois. A unique calibration technique was introduced and incorporated into the proposed models so that they can be used to predict the performance of existing and new pavements. The models were then extended through the development of adjustment factors to various functional groups and climatic zones using data from the actual multiyear nationwide Highway Performance Monitoring System (HPMS) data bases. The accuracy of PSR prediction was tested for several thousand HPMS sections throughout the United States using a user-friendly computer program (SIMPERF). The results appeared to be very reasonable in a large proportion of cases analyzed. However, the models are empirical and definitely not suitable for use in pavement design or for comparison of the performance of different pavement types.

Many pavement management activities require the prediction of pavement performance in a network. One example is the determination of future pavement rehabilitation needs for a state highway network from which a multiyear plan for rehabilitation is formed. In fact, every agency that owns or is responsible for pavements and wishes to manage those facilities in a rational manner needs to be able to predict the performance of their pavements.

However, collecting reliable inventory and monitoring data to develop predictive models for a large pavement network system is a formidable and very costly task. Many agencies do not have comprehensive data bases that can provide a lot of data about each section in the network. Although this inadequacy is improving through the development of pavement management systems, most agencies can provide only the current condition (in various forms), the current average daily traffic (ADT) and percentage trucks, type of pavement, and perhaps some design and rehabilitation history for their pavement sections. Thus, there is a great need for simplified pavement prediction models that require only a minimal amount of data likely to be available in the pavement management data base.

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FHWA must report to the Congress on a regular basis the long-term needs of the nation's highway system, and pavements are the system's largest component. This paper summarizes the development of predictive models and mean adjustment factors to be used in the Highway Performance Monitoring System (HPMS) pavement performance simulation process (*1*).

IDENTIFICATION OF PAVEMENT GROUPS

Item 28 of the HPMS data elements (pavement attributes) includes 15 pavement types, which cover nearly all combinations of original construction and rehabilitation types. However, they are separated into only two main groups—flexible and rigid pavements—in the HPMS pavement performance simulation process. The AASHTO flexible and rigid pavement equations are then used for pavement performance simulation. This procedure has some obvious deficiencies.

To more adequately represent a wide variety of different pavement attributes in the HPMS, the following five major conventional pavement types were considered:

- Asphalt concrete (flexible, or FLEX),
- Composite (AC/portland cement concrete, or COMP),
- Jointed plain concrete pavement (JPCP),
- Jointed reinforced concrete pavement (JRCP), and
- Continuously reinforced concrete pavement (CRCP).

Some pavement types—including unimproved road, graded and drained, soil, grave, or stone, bricked, blocked, and other combinations—in the HPMS were not considered in this study.

Nine climatic zones (Item 68) based on Thornthwaite potential evapotranspiration and moisture index and their interaction (*1,2*) were also considered in the "group" identification. This provides a fairly adequate consideration of the diverse climates and geographic areas that exist across the United States, including any combination of wet, intermediate, and dry climates in freeze, freeze-thaw, and no-freeze regions.

Item 9 of the data elements contains 12 functional systems. After analysis and discussion with FHWA, they were condensed into two major functional groups (FGROUP). Interstate highways and principal arterials were treated as one group, and minor arterials and all collectors were treated as the other. This grouping was done to reflect expected differences in cross sections, drainage, and pavement performance.

The HPMS data base was then divided into similar performance groups, which were expected to have similar deterioration mechanisms and performance relationships. A given pavement group was defined having the same general pavement type, functional group, and climatic zone as previously described. It is assumed that pavements within the same group more or less follow the same performance pattern. Thus, predictive models need only be developed for a few groups of conditions, as opposed to many different types of pavement design, functional system, climatic region, and rehabilitation type.

DEVELOPMENT OF PERFORMANCE PREDICTION MODELS

After considerable review of different regression techniques, it was decided that nonlinear regression should not be used to develop predictive models for the HPMS because of the high possibility of having many errors in the data base. Several trials using nonlinear regression produced unacceptable models largely due to including some bad data points in the analysis. Therefore, the following steps were adopted to develop predictive models:

1. A feasible general present serviceability rating (PSR) loss model form was assumed including variables based on engineering knowledge and available data bases.
2. Least-median-squares, or "robust," regression was performed to identify the potential outliers by using this assumed model form (*3,4*).
3. After screening out possible outliers, traditional least-squares regression was then used to obtain the regression coefficients and summary statistics.

Because it cannot be guaranteed a priori that the assumed functional form is valid, the analysis must proceed iteratively so that a more meaningful and reliable model can be developed. An alternating conditional expectations algorithm (*5*) was also applied to find other possible transformations of each explanatory variable to maximize the squared multiple correlation coefficient (R^2) for the next trial.

A new statistical package named S-PLUS, which has been widely used by statisticians for data analysis (*6–8*), was selected because of the availability of these techniques. S-PLUS is very strong in its graphics, data exploration tools, and flexibility but weak in data base management as compared with the most well-known and widely used statistical package, SAS (*9*). As a result, SAS was used primarily for data retrieval and data summary whereas S-PLUS was used for most of the modeling processes.

Attempts To Develop Models Directly from HPMS Data Base

Five sets of the HPMS data base in 1982, 1984, 1986, 1988, and 1989 were first retrieved from magnetic tapes (*1*) and downloaded to a personal computer (PC) for further analysis. To obtain the needed history of the HPMS pavement performance, the data were merged by their unique identification number, that is, sample number (Item 24) and sample subdivision (Item 25).

Initially, major research efforts were focused on developing predictive models directly from the HPMS data base using data from 1984 to 1989. Several feasible model forms were used to develop the performance prediction models. Robust regression successfully identified portions of the data base as potential outliers, which after deletion improved the regression dramatically. However, the regression models were still not adequate for implementation. This attempt was unsuccessful because of problems with the HPMS data base, such as missing data, highly variable performance histories, and apparent errors in many important data elements.

Alternative Data Bases for Model Development

Owing to the difficulties in developing prediction models directly from the HPMS data base, other accessible data bases were considered for developing PSR prediction models for each of the five major pavement types. They include the pavement management data base from the Illinois Department of Transportation, the Illinois portions of the NCHRP Project 1-19 data base (*10*), the original AASHO Road Test data (DS 7322) (*11*), and some additional data from the extended road test (1962–1974) (*12,13*).

The Illinois pavement management data base contains detailed information about pavement inventories, materials, distress surveys, condition rating surveys, maintenance and rehabilitation records, and traffic data. The most recent data (March 1991)—which contain six condition rating surveys, in 1981, 1982, 1984, 1986, 1988, and 1990—were obtained to construct data bases for CRCP and composite pavements.

The NCHRP Project 1-19 data base, which contains some existing Illinois Interstate JRCP pavements and sections from the original and the extended AASHO Road Test for JRCP, was used to construct a JRCP data base. The JPCP data base was constructed from the original and the extended AASHO Road Tests. The serviceability records of flexible pavements of the original AASHO Road Test at 22-week (or 11-index-day) intervals were obtained to create the data base for flexible pavement.

Proposed Predictive Model Form

After considerable evaluations of different model forms including linear, logarithm, and other simplified forms, the following functional form was chosen to develop the proposed HPMS predictive models for all five major pavement types:

$$PSR = PSR_I - a * STR^b * AGE^c * CESAL^d \qquad (1)$$

where

PSR_I = initial value of PSR at construction (4.5 used in analysis);
STR = existing pavement structure: structural number for flexible pavement, total AC overlay thickness for composite pavements (in.), and slab thickness for concrete pavements (in.) (1 in. = 25.4 mm);
AGE = age of pavement since construction or major rehabilitation (overlay) (years); and
CESAL = cumulative 18-kip equivalent single-axle loads (ESALs) applied to pavement in the heaviest traffic lane (millions).

This nonlinear model form is also an implicit linear model since after transformation it becomes

$$\log_{10}(PSR_I - PSR) = \log_{10}a + b * \log_{10}STR + c * \log_{10}AGE + d * \log_{10}CESAL \quad (2)$$

This nonlinear model form permits a realistic consideration of age, traffic, and pavement structure on the prediction of PSR. Subsequent model development has shown that this equation form fits all of the pavement types reasonably well.

Note that the structural number is reported as an indicator of pavement structure for both flexible and composite pavements in the HPMS data base so that the AASHTO FLEX equation could be used to predict performance. However, composite pavements perform dramatically different from flexible pavements due to different failure modes. It is believed that the AC overlay thickness rather than the structural number or the underlying concrete slab thickness is the dominating factor in the performance of composite pavements. Thus, overlay thickness was used in the model development. The questionable determination of structural number for composite pavements is no longer needed in the HPMS data base since no adequate guidelines are available.

Summary of Proposed Predictive Models

The regression coefficients and summary statistics of each predictive model for all five major pavement types are summarized in Table 1. The standard error of estimates (*SEE*) as provided in the table is also a very good indicator of the accuracy of the prediction of the loss of PSR (ΔPSR). The number of potential outliers identified and then excluded from the model are also indicated by parentheses in the table. For example, 31 out of 553 data points were deleted from the FLEX model.

The statistics of the CRCP model are not very good as expected, since both D-cracked and non-D-cracked pavements from the Illinois Interstate highways were all included in the data base to develop this model. This model can be improved after more D-cracking information is collected in the HPMS data base.

To check the adequacy of each proposed model, the predicted ΔPSR values were plotted against the actual values as shown in Figures 1 through 5. Several sensitivity analyses of the variables included in each model were also performed and found to be very reasonable (*14*). In general, the PSR curves of FLEX, COMP, and CRCP are in a concave shape or have more rapid loss of PSR early. The PSR curves of JPCP and JRCP are in a convex shape or have more rapid loss of PSR later.

APPLICATION OF PROPOSED MODELS TO HPMS

Calibration of Models to Existing Pavement Conditions

On the basis of the proposed predictive models, a fixed family of curves could be developed for different pavement structures. Unfortunately, both age and cumulative ESALs are not available in the HPMS data base. Therefore, it is necessary to obtain the best estimates of pavement age and cumulative ESALs through knowledge of only the current annual ESALs and the current year condition of an existing pavement structure in the HPMS data base.

Assume that there is a direct relationship between pavement age and cumulative ESALs:

$$CESAL = AGE * ESALPYR \quad (3)$$

where ESALPYR is current yearly ESALs in millions.

TABLE 1 Summary of Proposed Predictive Models

	Model				
	FLEX	COMP	JPCP	JRCP	CRCP
$\log_{10}a$	1.1550	-0.4185	0.5104	1.7241	0.7900
b	-1.8720	-0.1458	-1.7701	-2.7359	-1.3121
c	0.3499	0.5732	1.0713	0.3800	0.1849
d	0.3385	0.1431	0.2493	0.6212	0.2634
R^2	0.52	0.58	0.79	0.57	0.37
SEE	0.45	0.38	0.26	0.40	0.31
N	522 (31)	509 (0)	117 (3)	254 (21)	1204 (65)

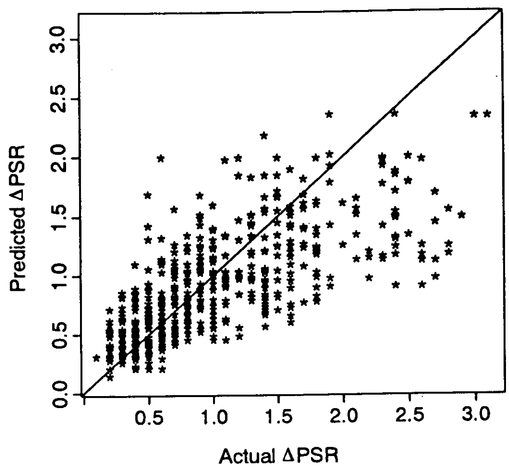

FIGURE 1 FLEX model: predicted versus actual ΔPSR.

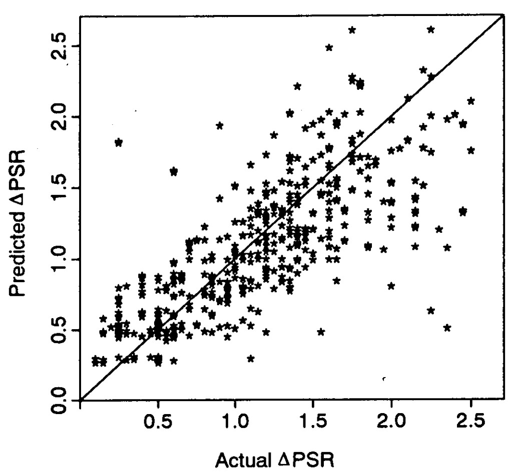

FIGURE 2 COMP model: predicted versus actual ΔPSR.

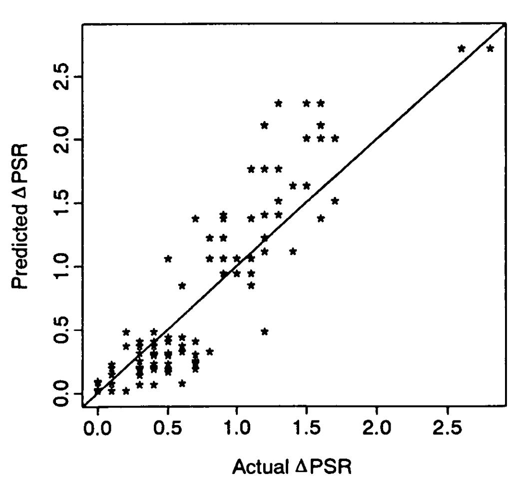

FIGURE 3 JPCP model: predicted versus actual ΔPSR.

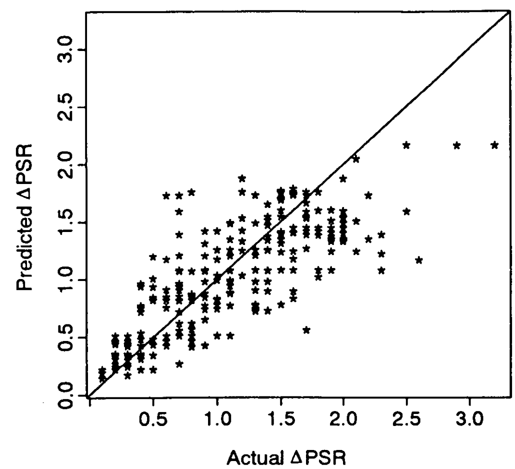

FIGURE 4 JRCP model: predicted versus actual ΔPSR.

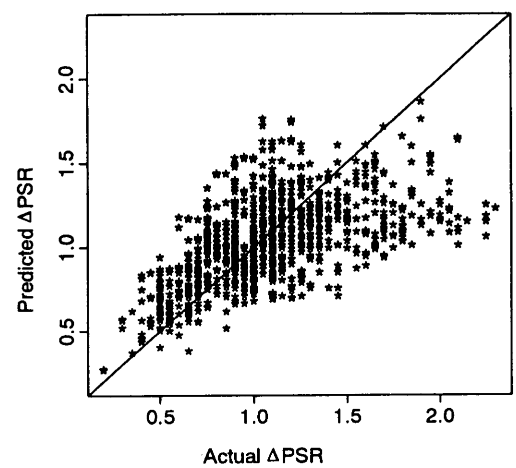

FIGURE 5 CRCP model: predicted versus actual ΔPSR.

To locate the current year condition in a unique performance curve, the following calibration constants (C_1 and C_2) could be treated as the best estimates of pavement age and cumulative ESALs, respectively:

$$C_1 = \text{AGE} = \left[\frac{\text{PSR}_I - \text{PSR}_1}{a * \text{STR}^b * \text{ESALPYR}^d}\right]^{\frac{1}{c+d}} \quad (4)$$

$$C_2 = \text{CESAL} = C_1 * \text{ESALPYR} \quad (5)$$

where PSR_1 is the current year pavement condition. Thus, the proposed models can be reformulated to the following form, which is a function of the current year condition, a pavement structure parameter, and the current annual ESALs of an existing pavement in the HPMS data base:

$$\text{PSR} = \text{PSR}_I - a * \text{STR}^b * (C_1 + \Delta\text{YEAR})^c * (C_2 + \Delta\text{ESAL})^d \quad (6)$$

where ΔYEAR is the change in age of pavement in years, and ΔESAL is the change in cumulative ESALs in millions.

Adjustment Factors for Different Pavement Groups

In addition, adjustment factors similar to the regional factor adopted in the 1972 *AASHO Interim Guide* (*15*) were introduced to adjust the rate of deterioration of PSR of the proposed models for different pavement groups in the HPMS data base. The adjustment factor is defined as the ratio of the average rate of deterioration in a particular climatic zone and functional group to that determined by the proposed models:

$$AF_j = \frac{\Delta PSR_j}{\Delta PSR} = \frac{PSR_I - PSR_j}{PSR_I - PSR} \quad (7)$$

where

AF_j = adjustment factor in pavement group j;
ΔPSR_j, PSR_j = actual ΔPSR and PSR values of existing pavements in group j, respectively; and
ΔPSR, PSR = predicted ΔPSR and PSR values of existing pavements determined by proposed models, respectively.

An adjustment factor greater than 1.0 indicates that the actual rate of PSR loss is greater in that pavement group than the rate predicted by the model based on Illinois conditions, and vice versa. For example, the effects of adjustment factors of a flexible pavement with a structural number of 6 and traffic load of 0.5 million ESALs per year are illustrated in Figure 6.

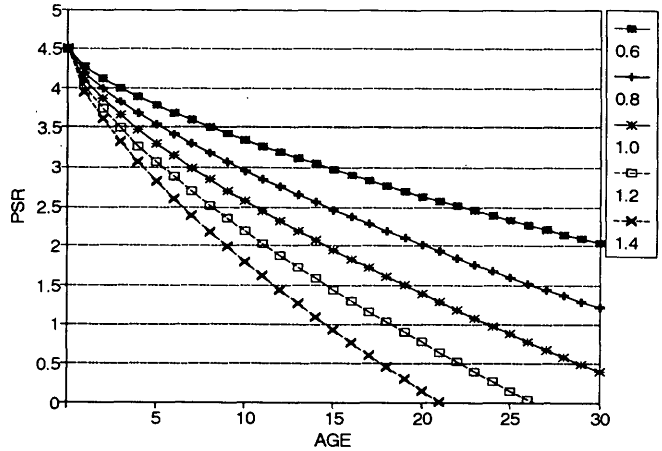

FIGURE 6 Effects of adjustment factors on pavement performance.

Determination of Mean Adjustment Factors

Five sets of the HPMS data base in 1982, 1984, 1986, 1988, and 1989 were received from FHWA. However, it was decided not to use the 1982 data base for determining adjustment factors after discussion with FHWA personnel. Any PSR value that increases more than 0.5 or decreases more than 0.75 a year was deleted to avoid retrieving sections that have been rehabilitated or had apparently deteriorated too fast to be believable. In addition, only the 3-, 4-, and 5-year PSR drops were retrieved because the PSR records may not be updated during a very short reporting cycle (1 or 2 years).

A total of 85,533 data points were obtained from all five major pavement types, nine climatic zones, and two functional groups. Note that a few very large or very small adjustment factor values (1.7 percent of the data), which were outside the range of −10 to 10, were excluded from further consideration. The mean adjustment factors determined on the basis of a different number of sections ranging from several thousand down to only one in a few cases are summarized in Table 2 (*14*). Mean values based on fewer than 25 data points and marked with an asterisk in Table 2 should not be strongly considered.

The mean values vary widely across pavement type, climatic zone, and functional group, especially when they were determined on the basis of only a few data points. In general, pavements in the South (fewer freeze-thaw and cold temperatures) showed a lower deterioration rate than those in northern climates. And pavements in the western United States (drier climate) showed a lower rate of deterioration than those in wetter climates in the East.

In addition, higher variation of the adjustment factors was observed for pavements in minor arterials and collectors. This may also be explained by the fact that the most important indicator of pavement structure (structural number or slab thickness) is not recorded in the HPMS data base. Thus, default values for these pavement sections rated as heavy, medium, and light (Item 31) (*1*) were assigned to determine the adjustment factors.

The adjustment factors as given in Table 2 obviously have very strong effects on the pavement performance prediction. They were also evaluated for several thousand HPMS sections using a user-friendly PC program (SIMPERF). The overall results showed that using either very high or very low adjustment factors produced unreasonable future service lives of HPMS pavement sections. A recommended adjustment factor ranging from approximately 0.4 to 1.5 is believed to provide reasonable PSR predictions. Many of the mean values that fall outside this range are the result of a small sample size and would thus be expected to be highly variable.

Table 3 provides the recommended mean adjustment factors for use as defaults in the HPMS analytical process. The mean values were recommended, unless the value fell outside this range. For those lower than 0.4 or higher than 1.5, the value was assigned to that cell. The only exception to these rules was for CRCP in minor arterials and collectors, where a value of 1.0 was assigned for wet and intermediate zones and a value of 0.5 was for dry zones.

Currently, the recommended adjustment factors along with the proposed predictive models are implemented in the SIMPERF program for pavement performance and subsequent rehabilitation simulations. Users can modify the recommended adjustment factors, which can be easily adjusted to more accurately reflect the performance of any given pavement type.

TABLE 2 Mean Adjustment Factors Directly Generated from SAS Program

	PTYPE									
	FLEX		COMP		JPCP		JRCP		CRCP	
	FGROUP		FGROUP		FGROUP		FGROUP		FGROUP	
	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL
	AF	AF	AF	AF	AF	AF	AF	AF	AF	AF
	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN
ZONE										
1. Wet; Freeze	0.59	0.81	1.04	1.11	0.56	0.99	0.87	2.27	0.57	-0.18*
2. Wet; Freeze-Thaw	0.37	0.85	1.13	1.07	0.33	0.64	1.25	1.46	0.39	2.12*
3. Wet; No Freeze	0.44	0.69	0.78	0.31	0.60	0.55	0.57	0.97	1.08	1.74*
4. Intermediate; Freeze	0.27	0.49	0.55	1.15	0.46	0.52	0.23	0.12*	0.94	0.00*
5. Intermediate; Freeze-Thaw	0.52	0.71	0.26	0.64*	0.66	1.61*	2.09	1.00*	1.10*	1.56*
6. Intermediate; No Freeze	0.43	0.65	0.71	0.87	0.27	1.34	1.71	2.61	2.02	.
7. Dry; Freeze	0.22	0.43	0.76*	2.53*	0.79	0.79	0.22	0.00*	0.17	.
8. Dry; Freeze-Thaw	0.32	0.39	-0.44*	0.00*	1.80	.	0.49*	0.00*	-0.13	.
9. Dry; No Freeze	0.38	0.79	0.26	.	0.22	0.66*	-0.30*	2.10*	0.45*	.

Note:
INT/OPA = Interstate highways and other principal arterials, FGROUP=1
MA/COL = minor arterials and collectors, FGROUP=2
* = mean AFs based on 25 data points or less
. = data unavailable

TABLE 3 Recommended Mean Adjustment Factors for Different Pavement Groups

	PTYPE									
	FLEX		COMP		JPCP		JRCP		CRCP	
	FGROUP		FGROUP		FGROUP		FGROUP		FGROUP	
	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL	INT/-OPA	MA/C-OL
	AF	AF	AF	AF	AF	AF	AF	AF	AF	AF
	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN	MEAN
ZONE										
1. Wet; Freeze	0.59	0.81	1.04	1.11	0.56	0.99	0.87	1.50	0.57	1.00
2. Wet; Freeze-Thaw	0.40	0.85	1.13	1.07	0.40	0.64	1.25	1.46	0.40	1.00
3. Wet; No Freeze	0.44	0.69	0.78	0.40	0.60	0.55	0.57	0.97	1.08	1.00
4. Intermediate; Freeze	0.40	0.49	0.55	1.15	0.46	0.52	0.40	0.40	0.94	1.00
5. Intermediate; Freeze-Thaw	0.52	0.71	0.40	0.64	0.66	1.50	1.50	1.00	1.10	1.00
6. Intermediate; No Freeze	0.43	0.65	0.71	0.87	0.40	1.34	1.50	1.50	1.50	1.00
7. Dry; Freeze	0.40	0.43	0.76	1.50	0.79	0.79	0.40	0.40	0.40	0.50
8. Dry; Freeze-Thaw	0.40	0.40	0.40	0.40	1.50	0.40	0.49	0.40	0.40	0.50
9. Dry; No Freeze	0.40	0.79	0.40	0.40	0.40	0.66	0.40	1.50	0.45	0.50

Further Discussion

An adjustment factor represents the ratio of the PSR loss of a section of highway to the PSR loss predicted by the model for that section. Many reasons for differences in performance are not climate-related, including different subgrades, materials, construction quality, design (such as joint design), and maintenance. The adjustment factors should be compared only within a pavement type since each predictive PSR model was based on a different data base. Comparisons between different pavement types are not meaningful.

The predictive models were developed on the basis of field data from regular in-service pavement sections, which included maintenance (except the AASHO Road Test pavements). Heavy maintenance could prevent pavements from deteriorating to very low serviceability levels. All of the proposed models show that the rate of deterioration decreases as PSR decreases, which reflects the impact of maintenance when the pavement conditions get worse.

The FLEX model was based on the original AASHO Road Test data only. The mean adjustment factor for wet-freeze zone is 0.59 based on 5,685 data points for Interstate highways and principal arterials. This indicates that the pavements in the HPMS data base in the same climatic zone have performed better than the pavements of the AASHO Road Test. In general, the mean values decrease from wet to dry climatic zones, which means that flexible pavements in drier climates show a lower rate of PSR loss. The Interstate highways and principal arterials have lower adjustment factors and thus perform better than the minor arterials and collectors.

In addition, the adjustment factors for the FLEX model were computed for two major functional groups and for levels of ADT greater and less than 6,000 vehicles. Even when similar traffic levels were considered, the Interstate highways and principal arterials still exhibited lower adjustment factors than the other group. Also, within the same functional group, the ADT level did not appear to cause a consistent difference in the adjustment factors. These results may indicate that some physical difference, such as improved drainage or construction quality for the Interstate highways and primary arterials, results in a lower rate of deterioration for the same traffic level.

The COMP model was based on the in-service Illinois Interstate highway pavements. In the wet-freeze climate, the mean adjustment factor is close to 1.0, indicating that on average other pavements in this zone are performing similarly. As with flexible pavements, the adjustment factor decreases with a drier climate and increases with the lower functional group.

The JPCP model was based on the AASHO Road Test data plus a few sections that were left in-service on I-80 for 14 years. The mean adjustment factor for wet-freeze zone is 0.56 based on 946 data points for Interstate highways and principal arterials. This indicates that the pavements in the HPMS data base in this climate zone have performed better than the JPCP at the AASHO Road Test. The mean values generally show a decrease going from wet to dry climatic zones, which means that JPCP in drier climates shows a lower rate of loss of PSR. A previous study showed that JPCP in a dry-nonfreeze climate performed much better than that in a wet-freeze climate (*10*).

The JRCP model was based on the AASHO Road Test data plus many sections from regular Illinois Interstate highways. The mean adjustment factor for the wet-freeze zone is 0.87 based on 2,149 data points for Interstate highways and principal arterials. This indicates that the pavements in the HPMS data base in this climate zone have performed about the same as the combined AASHO Road Test and Illinois Interstate highways. The mean values show a wide range of results over different climatic zones. However, the number of data points from many of the JRCP sections is very limited, which has caused some wide-ranging results.

The CRCP model was based on many sections from regular Illinois Interstate highways. The mean adjustment factor for the wet-freeze zone is 0.57 based on 462 data points for Interstate highways and principal arterials. This indicates that the pavements in the HPMS data base throughout this climate zone have performed better than the Illinois Interstate highways. This may be due to the large amount of D-cracking in the Illinois CRCP pavements. The values show a wide range of results over different climatic zones, but, as in the JRCP sections, the number of data points from many of the CRCP sections is very limited and results in wide-ranging results.

Summary of Proposed HPMS Performance Prediction

The proposed HPMS performance prediction equations for both existing and new pavements in pavement group j based on only knowledge of a given pavement structure, current year condition, and current yearly ESALs are summarized as follows:

$$\mathrm{PSR}_j = \mathrm{PSR}_I - \mathrm{AF}_j * [a * \mathrm{STR}^b * (C_{1j} + \Delta\mathrm{YEAR})^c * (C_{2j} + \Delta\mathrm{ESAL})^d] \tag{8}$$

$$C_{1j} = \mathrm{AGE}_j = \left[\frac{\mathrm{PSR}_I - \mathrm{PSR}_1}{\mathrm{AF}_j * (a * \mathrm{STR}^b * \mathrm{ESALPYR}^d)}\right] \tag{9}$$

$$C_{2j} = \mathrm{CESAL}_j = C_{1j} * \mathrm{ESALPYR} \tag{10}$$

The calibration constants (C_{1j} and C_{2j}) can be treated as the best estimates of current pavement age (AGE_j) and current cumulative ESALs (CESAL_j) for any existing pavement in Group j.

To predict the performance of an existing pavement, proper coefficients based on major pavement type, climatic zone, and functional group are first selected, that is, AF_j, $\log_{10} a$, b, c, and d (Tables 1 and 3). C_{1j} and C_{2j} based on known STR, PSR_1, ESALPYR, and these coefficients are then determined. Thus, the future performance can be estimated for different future ΔESAL and ΔYEAR using Equation 8.

Numerical Example

Consider a high type-flexible pavement classified as a rural major collector and located in Climatic Zone 1. This pavement has a structural number of 5.0 and its current condition is 3.5 in 1991. The current yearly ESAL is 0.2 million with an average compounded future yearly ESAL growth rate of 6 percent.

The coefficients of the proposed model for flexible pavements (as given in Table 1) are $\log_{10} a = 1.1550$, $\log_{10} b =$

-1.8720, $\log_{10}c = 0.3449$, and $\log_{10}d = 0.3385$. The adjustment factor for pavements from rural major collectors in climatic zone 1 (as given in Table 3) is $AF_j = 0.81$. Thus, the best estimates of current pavement age (C_{1j}) and current cumulative ESALs (C_{2j}) using Equations 9 and 10 are $C_{1j} =$ 5.007 years and $C_{2j} = 5.007 * 0.2 = 1.001$ million ESALs.

Therefore, the following equation can be used to predict the future performance of this pavement:

$$\mathrm{PSR}_j = 4.5 - 0.81 * 10^{1.1550} * 5.0^{-1.8720} * (5.007 + \Delta\mathrm{YEAR})^{0.3499} * (1.001 + \Delta\mathrm{ESAL})^{0.3385} \quad (11)$$

ΔESAL based on a compound yearly ESAL growth rate (ESALGRW) can be calculated by

$$\Delta\mathrm{ESAL} = \frac{\mathrm{ESALPYR} * (1 + \mathrm{ESALGRW}) * [(1 + \mathrm{ESALGRW})^{\Delta\mathrm{YEAR}} - 1]}{\mathrm{ESALGRW}} \quad (12)$$

or, in this case,

$$\Delta\mathrm{ESAL} = \frac{0.2 * (1 + 0.06) * [(1 + 0.06)^{\Delta\mathrm{YEAR}} - 1]}{0.06} \quad (13)$$

CONCLUSIONS

The proposed models predict the PSR using only knowledge of the pavement's age since construction, cumulative ESALs, and a pavement structural parameter. The models were developed for five major pavement types based on data from the original and the extended AASHO Road Tests, the NCHRP Project 1-19 (COPES), and the Illinois pavement feedback system data bases.

A unique calibration technique was introduced and incorporated into the proposed models so that they can be used for performance prediction of both existing and new pavements. For an existing pavement, the predictive model is calibrated to its current condition and then projected into the future, which also greatly reduces the prediction error. Mean adjustment factors were also determined using the actual multiyear nationwide HPMS pavement performance data and engineering judgment to extend these models to other climatic zones and functional groups.

The reasonableness of PSR predictions was tested for several thousand HPMS sections throughout the United States according to researchers' past experience in pavement performance using the SIMPERF program. The results appeared to be reasonable in a large proportion of cases analyzed using the recommended adjustment factors. The mean adjustment factors can be easily adjusted by individual states or FHWA.

Many other factors also affect the performance of these pavements, although these factors are not reflected in the simplified models. Thus, the models should be used only to predict the performance of existing pavements. They are definitely not appropriate for use in pavement design or for comparison of the performance of different pavement types.

Within this context, it is believed that the predictive models and adjustment factors for other geographic and climatic areas and functional groups are approximate but reasonable for the purposes intended. There is no doubt that these models represent far more realistic predictions than what exists in the HPMS analytical process. The predictive models and adjustment factors can also be improved over time if additional data are added to the HPMS.

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