Models for Predicting Pavement Deterioration

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The measurement and prediction of pavement performance is a critical element of any pavement management system (PMS). Pavement condition rating (PCR), a composite statistic derived from functional and structural conditions, is used as a measure of serviceability. After a review of the various types of prediction models, the authors concluded that an empirical-mechanistic model is best suited, with a systematic database that includes the structural information, traffic volume, and condition data for each "homogeneous" section of the road. Pavements with an asphalt concrete surface are grouped into three categories (pavements with no overlay, pavements with overlay, and composite pavements), and prediction equations are developed for each of them. The equations are validated by comparing them with several existing models, both empirically and mechanistically based. In all three prediction models, age is by far the most significant predictor of serviceability. The traffic volume and weight expressed in terms of equivalent single-axle loads (*ESALs*) and the structural makeup of the pavement described by the composite structural number play only a secondary role in forecasting performance of pavements.

Over the past two decades considerable emphasis has been directed toward rationalizing planning in the area of pavement maintenance and rehabilitation. Planning at the project level deals with issues relating to the design of proper treatments for particular deficiencies and the impacts of traffic and environmental factors on pavement structures. Network-level planning, the backbone of a pavement management system (PMS), addresses the need for trade-offs in project selection, including viewing the benefits and costs of each in relation to all other potentially competing projects.

Modeling pavement performance is an essential activity of a pavement management system. The models play a crucial role in several aspects of the PMS, including financial planning and budgeting as well as pavement design and life-cycle economic analysis. First, models are used in PMSs to predict when maintenance will be required for individual road sections and how to prioritize competing maintenance requirements. Second, by virtue of its prediction capability, the model enables the owner agency to estimate long-range funding requirements for pavement preservation and to analyze the consequences of different budgets on the condition of the pavement network. Third, because the models attempt to relate the influence of pavement exposure variables to pavement distresses or to a combined performance index, they can be used for design as well as the life-cycle economic evaluation.

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Several approaches employed for their development include regression analysis using field performance data, mechanistic modeling based on pavement response parameters, and models that combine both field data and response parameters, which are aptly called mechanistic-empirical models. An excellent summary and comparison of several models of the first type appear in Hajek et al. (*1*). Although these models currently serve a crucial role in expediting pavement management decisions, future endeavors should be directed toward developing physically based deterioration mechanisms.

The research reported in this paper is part of a program to develop a pavement management system for 2,000 lane-miles of roads in northern Mississippi. Employing the condition data of the road system, the authors developed performance equations for three categories of pavements: flexible pavements with no overlay, flexible pavements with overlay, and composite pavements (asphalt concrete surface over a rigid base). Several equation forms are attempted. As a basic principle, the form of the equation is selected on the basis of whether it adheres to the boundary conditions or other physical principles that govern the deterioration of the pavement family. With the equation form chosen, multiple regression analysis, using the SAS program, is employed for developing pavement deterioration equations.

REVIEW OF PERFORMANCE PREDICTION MODELS

Performance is a broad, general term describing how pavement conditions change or how pavements serve their intended function with accumulating use. What should be included in a performance evaluation depends to a large measure on whether one's interest lies in project-level or network-level activities. Various approaches have been used in quantifying the performance measure. The pavement serviceability index (PSI), coined in connection with the AASHO Road Test (*2*), pavement condition index (0–100 scale), and pavement quality index (0–10 scale), are but a few of many existing measures. The performance indicator developed by the authors is designated a pavement condition rating (*PCR*, 0–100 scale), which is a composite index derived from monitoring data—pavement roughness or roughness rating (*RR*) and distress rating (*DR*)—in accordance with the following relation:

$$PCR = RR^{0.6}\, DR^{0.4} \tag{1}$$

The equipment and procedure that determine pavement roughness employing the AASHO concept of slope variance (in turn, present serviceability rating) and that quantify the

density and severity of distresses facilitating the calculation of distress rating are described elsewhere (*3*).

Performance prediction models may be categorized into two kinds: deterministic and probabilistic. Deterministic models include primary response, structural performance, functional performance, and damage models. All of the preceding models may be either empirical, implying they are developed from regression analysis, or mechanistic-empirical correlations. For the latter type, a combination of mechanistic and empirical parameters enter the prediction model. In the damage models, damage—an abstract number (0–1 scale)—is being predicted; a typical example is the pioneering equation of the AASHO Road Test (*2*).

Probabilistic models include Markov chain (MC) models and survivor curves (*4,5*). Knowing the "before" condition or state of pavement in probabilistic form, one can employ the Markov process to predict the "after" state, again in probabilistic forms, for as many time steps as are desired. The evolution is governed by a characteristic transition rule, otherwise known as transition probability matrix in MC theory. Survivor curves describe pavement deterioration in the form of a cumulative distribution, which subsequently can be employed to develop a transition probability matrix. The principal advantage of probabilistic predictions lies in their ability to recognize and accommodate uncertainties in design/analysis leading to reliability-based designs.

DEVELOPMENT OF A PAVEMENT DETERIORATION MODEL

Pavements are complex physical structures responding in a complex way to the influences of numerous environmental and load-related variables and their interactions. A prediction model, therefore, should consider the evolution of various distresses and how they may be affected by both routine and planned maintenance. Such an approach is so highly complex that a compromise procedure combining a strong empirical base and a mechanistic approach is adopted to achieve a reliable model. The empirical base includes time-series pavement condition data compiled on pavements exposed to different environmental and loading conditions. With regard to mechanistic principles, interactions between traffic loading and pavement strength parameters, between loading and pavement deflections, and so on are carefully observed and included when significant. These considerations dictated the model form and provided guidance in the selection of independent variables (parameters) for inclusion in the prediction model.

Model Variables

The empirical-mechanistic model alluded to earlier requires a variety of data on factors that affect the rate of deterioration; these include traffic loads, pavement layer thicknesses, materials, subgrade strength, environmental factors, and construction technique, to name a few. The historical component of the PMS database provided this segment of information; the condition data (*PCR*) were compiled from the 1986 and 1988 pavement condition surveys.

The task of predicting the responses of pavements to a battery of interrelated variables is a complex problem that can be accomplished only by resorting to a number of assumptions and simplifications. A brief discussion of these simplifications and a listing of the independent variables (factors) follow.

Ideally, data collection would consist of complete histories, or sample functions, of *PCR* versus time for roads belonging to a particular family of pavements. It would also be convenient for data to be collected from roads put into use at the same time, so that their ages would be identical. The pavement survey data available in this study do not conform to this pattern, since the roads included in the survey were placed into service at different times whereas the survey data were collected at a single point in time (Figure 1a). The transformation into *PCR* versus age data is shown in Figure 1b.

A preliminary analysis of the data confirmed the contention that the rate of deterioration varies from pavement to pavement, and possibly the best strategy would be to attempt to determine a single relationship for a family of pavements having similar characteristics. The data dictated that five categories of pavements be recognized in the analysis: flexible pavements with no overlay, flexible pavements with one or more overlays, composite pavements, jointed concrete pavements, and continuously reinforced concrete pavements. Only the first three categories are included in this study.

The selection of independent variables for the prediction equations is based on experience suggesting that the predic-

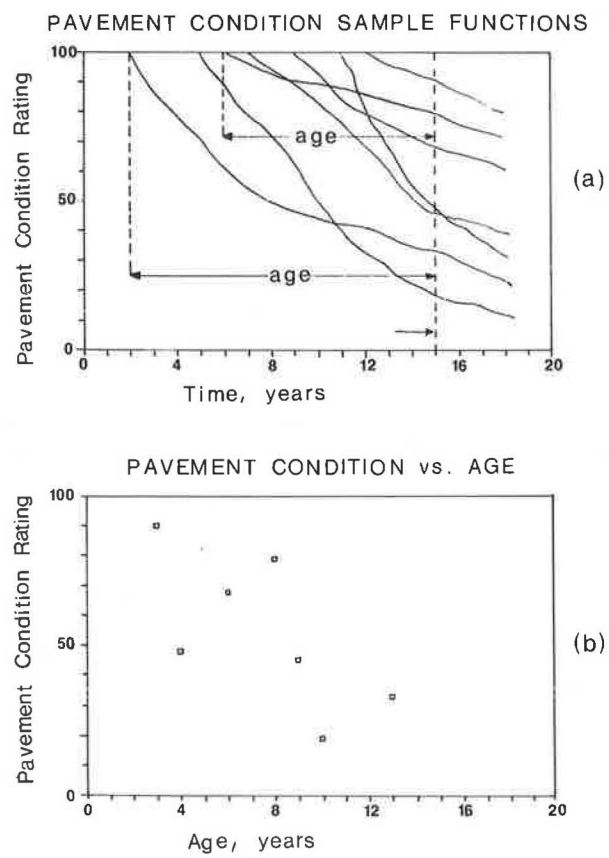

FIGURE 1 Transformation of one-time pavement survey data to *PCR* versus age (adaptation *4*).

tion of pavement condition depends on the following factors:

1. Period during which the pavement has been in service, age of the pavement (Age, years);
2. Traffic volume and weight, which are expressed in terms of yearly equivalent single-axle loads (*ESAL*s);
3. Thickness of last overlay, *T*, in inches;
4. Strength and condition of pavement structure represented by modified structural number (*SNC*). The American Association of State Highway Officials (AASHO) structural number, modified to account for subgrade support, is designated as modified structural number (*6*):

$$SNC = \Sigma a_i h_i + SN_g \quad (2)$$

where

a_i = material layer coefficients,

h_i = layer thicknesses (in.),

SN_g = subgrade contribution, and

$$= 3.51 \log CBR - 0.85 (\log CBR)^2 - 1.43 \quad (3)$$

in which CBR = in situ California bearing ratio of subgrade (percent).

5. Surface deflection/Benkelman beam deflection under 18-kip axle load DEF, mm. The empirical equations employed for deflection calculation are due to Paterson (*6*):

For granular base pavements,

$$DEF = 6.5\ SNC^{-1.6} \quad (4)$$

For cement-treated base pavements,

$$DEF = 3.5\ SNC^{-1.6} \quad (5)$$

6. Construction quality (*CQ*). For want of quantitative data, this factor could not be included in the analysis.

The performance equation of each pavement category has been derived from a statistical analysis of road condition trends observed at two discrete times on in-service highways in Mississippi. The data included 54, 193, and 135 observations, respectively, for flexible pavements with no overlay, flexible pavements with overlay, and composite pavements. The ranges of variables of the database are given in Table 1. The causative factors, such as traffic volume, surface deflection, and modified structural number, are obtained directly from the PMS database or are calculated employing the structural data relating to each pavement section.

Data Analysis

After the factors affecting pavement deterioration have been identified, one wishes to derive a regression equation (i.e., a statistical transform) that can be used to make future predictions of pavement condition. SAS version 5 is capable of handling three types of regression analysis: regular, nonlinear, and stepwise. The latter method was employed initially, without much success. Nonlinear analysis, however, resulted in physically based equations reported in this paper.

Several different models were constructed and evaluated. The evaluation was based on rational formulation and behavior of the model and on its statistical parameters. Primarily owing to the large scatter of data points, several equation forms appear to fit the data with more or less the same correlation coefficient. Exponential and power functions of both concave and convex shapes, including an S-shape (sigmoidal), were explored. The criterion that dictated the selection of a particular model for a pavement family was its ability to satisfy the initial and possibly the end-of-life boundary conditions, in addition to yielding a reasonably low standard error of estimate.

The best-fit model for the performance prediction of flexible pavement with no overlay is presented in Equation 6.

$$PCR(t) = 90 - a\,[\exp(\mathrm{Age}^b) - 1] \log\left[\frac{ESAL}{SNC^c}\right] \quad (6)$$

with $a = 0.6349$; $b = 0.4203$; and $c = 2.7062$.

$$R^2 = 1 - \frac{\Sigma(y - \hat{y})^2}{\Sigma(y - \bar{y})^2} = 0.75$$

where $PCR(t)$ = pavement condition rating at time t.

TABLE 1 RANGES OF VALUES OF MAIN PARAMETERS IN EMPIRICAL DATA BASE

	Range of Each Parameter, Flexible Pavement		
Parameter	No Overlay	Overlay	Composite Pavement
Number of data points	54	193	135
Thickness of AC surface, inches (*T*)	NA	1.0–8.0	2.0–5.0
Modified structural number (*SNC*)	2.5–7.7	1.1–8.2	NA
Yearly equivalent single axle load (*ESAL*)	1,055–104,965	1,191–809,289	4,331–119,696
Age since construction or last overlay, years	1–16	1–10	1–10
Pavement condition rating (*PCR*)	59–89	62–89	52–89
Year of *PCR* survey	1986–1988	1986–1988	1986–1988

Similar equations are developed for flexible pavement with overlay and composite pavements. Respectively, those equations are:

$$PCR_{(t)} = 90 - a[\exp(\text{Age}^b) - 1] \log\left[\frac{ESAL}{SNC^{c*}\ T}\right] \quad (7)$$

with $a = 0.8122$, $b = 0.3390$, and $c = 0.8082$.

$$PCR_{(t)} = 90 - a\left[\exp\left(\frac{\text{Age}}{T}\right)^b - 1\right] \log[ESAL] \quad (8)$$

with $a = 1.7661$ and $b = 0.2826$. All other symbols are explained in the previous sections.

Model Evaluation

The prediction model of Equation 6 was statistically significant with an R^2 of 0.75. Models for the other two types, flexible pavements with overlay and composite pavements, exhibited R^2s of 0.76 and 0.70, respectively. Table 2 lists the regression constants and their standard errors of estimate in Equations 6, 7, and 8. The relatively small standard errors of the regression coefficients suggest that the relation is satisfactory and can be advantageously used for predicting pavement performance.

As a further verification of the model, a plot of measured versus calculated *PCR* is presented in Figure 2. The residuals, differences between the predicted and observed *PCR* values, were normally distributed.

Despite the fact that *PCR* is influenced by three factors (age, traffic, and *SNC*), the evolution of serviceability, with time suppressing the other two variables, would be of interest in the overall evaluation of a specific family of pavements. The scattergram of the 54 data points and the trend line, along with the 95 percent confidence levels for average values of traffic and *SNC* ($ADT = 3000$, $SNC = 3.0$), are presented in Figure 3. The trend line conforms to the traditional "concave down" shape subscribing to slow deterioration during the early life followed by a period in which the rate of deterioration surges significantly. Typically, one-half of pavement deterioration (and an even higher proportion of maintenance costs) is concentrated in the final third of the design life (approximately 15 years) of the pavement.

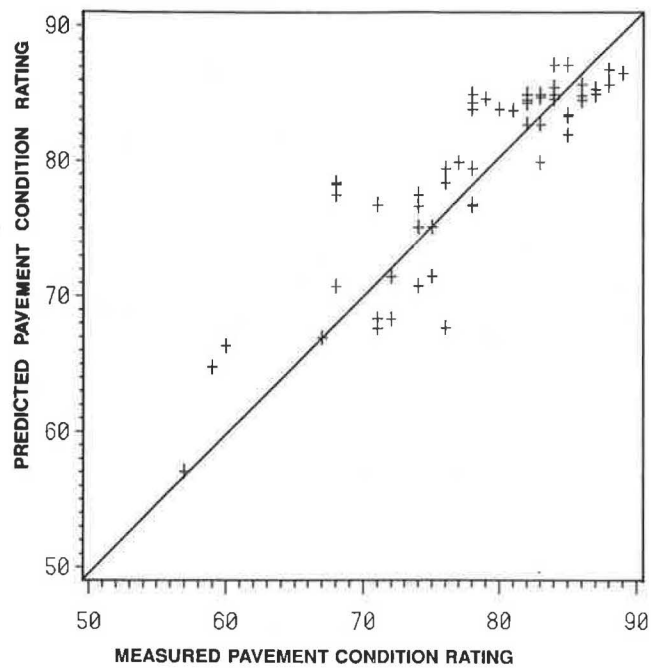

FIGURE 2 Measured versus prediction (Equation 6) pavement condition rating (*PCR*). Flexible pavement with no overlay.

The initial boundary condition is satisfied in that the trend lines pass through the 90-*PCR* point, signifying that a new pavement would start with a *PCR* of 90. The authors believe that the increasing rate of deterioration, beyond approximately 10 years of service, is reasonable provided the pavement in question does not undergo heavy maintenance or rehabilitation activities. The "more-than-normal" *PCR* drop during the first year can be attributed to the "breaking in" of the pavement structure by the traffic and environmental loads.

To evaluate the authors' model, the performance histories predicted by five other models (*1*) are compared with the one

TABLE 2 STATISTICAL PARAMETERS OF *PCR* PREDICTION MODELS

Type of Pavement	Regression Coefficient	Standard Error of estimate, %	R^2
Flexible Original	a = 0.6349	17.1	0.75
	b = 0.4203	5.6	
	c = 2.7062	21.4	
Flexible Overlay	a = 0.8122	7.4	0.76
	b = 0.3390	3.2	
	c = 0.8082	38.8	
Composite	a = 1.7661	3.0	0.69
	b = 0.2826	6.0	

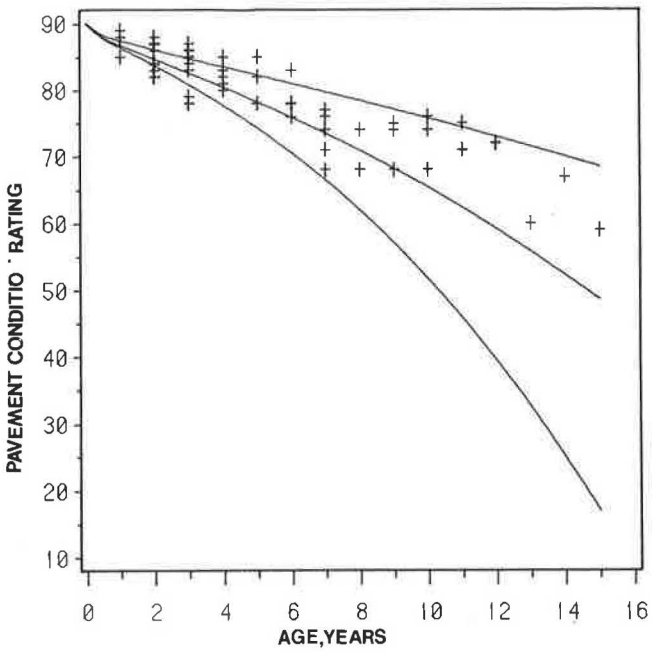

FIGURE 3 Scattergram of pavement condition data with age. Predicted *PCR* (*ADT* = 3000, and *SNC* = 3.0) using Equation 6 and corresponding 95 percent confidence limits.

developed herein (Equation 6), as shown in Figure 4. The performance history observed by Hajek et al. (*1*) is also plotted in the figure. It is gratifying to note that the proposed model is in good agreement, especially with the observed points, despite some difference in regard to curvature of the models elsewhere (*1*).

Significance of Causal Factors

The prediction equation recognizes three causal factors in defining pavement performance. They are age (years since original construction or last overlay), yearly traffic (*ESAL*), and composite structural number, with age being the most significant factor. That the yearly *ESAL* and structural number are of only minor importance can clearly be seen from Figures 5 and 6, where each of these factors is varied over a moderate range and the corresponding *PCR* changes are investigated. The changes in *PCR* after 15 years of service, owing to variations of *ESAL* and *SNC*, amount to only 9 and 8 points, respectively.

The question now arises of why age is so significant in predicting pavement deterioration. In fact, the data suggest that age alone can account for a substantial portion of the decline in serviceability. Age is significant because it is a common factor in the estimation of both cumulative traffic loads and environmental loads over the life-cycle period. For example, cumulative traffic is the product of yearly *ESAL* and age of pavement. Between the two, *ESAL* would be the weakest link in the cumulative traffic computation because several questionable input parameters (for example, the sample traffic count, the growth factor, the truck factor) enter the daily (or yearly) *ESAL* estimation. In contrast, age can be determined precisely for any pavement and, by virtue of its accuracy, would be expected to be a better predictor. The same argument also holds well for environmental loads. The environmental loads include thermal effects, subgrade movements in expansive clays if applicable, freeze-thaw effects, and bitumen aging, which are difficult to quantify. Age, however, can be a surrogate for the cumulative effect of these detrimental factors. Simply put, age plays a pivotal role in predicting pavement deterioration.

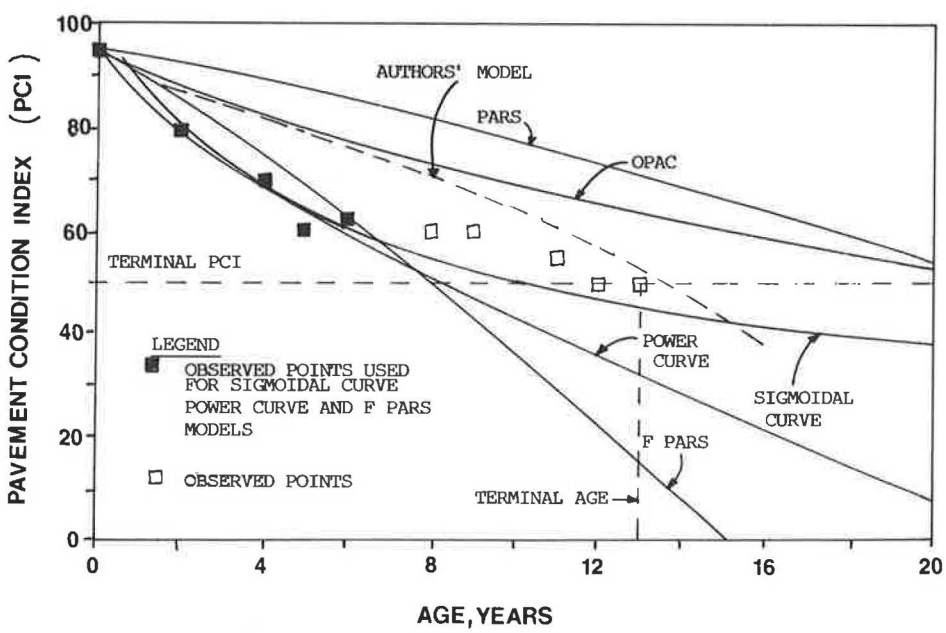

FIGURE 4 Model comparisons. Explanation: OPAC model (mechanistically derived), authors' model (Equation 6); PARS model (empirical, pavement classes); power curve (empirical-site-specific); sigmoidal curve (empirical, site-specific); factored PARS model (Bayesian approach, site-specific) (adaptation *1*).

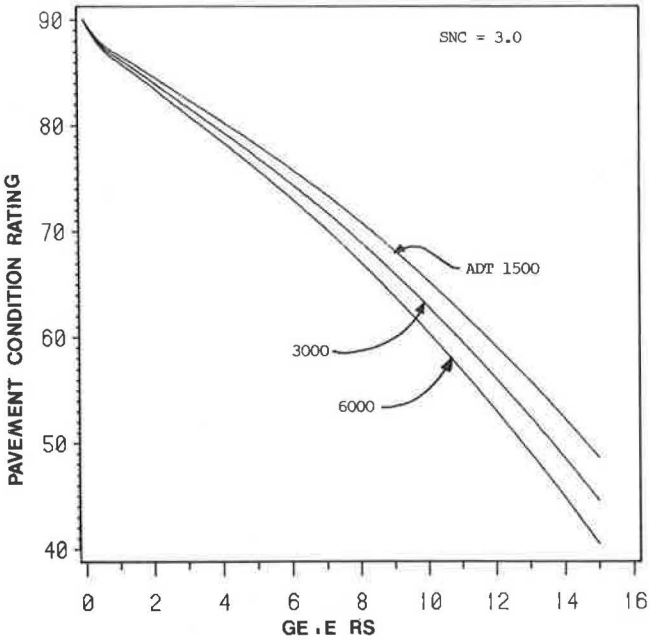

FIGURE 5 Effect of traffic on *PCR* as predicted by Equation 6. Flexible pavements with no overlay, structural number = 3.0.

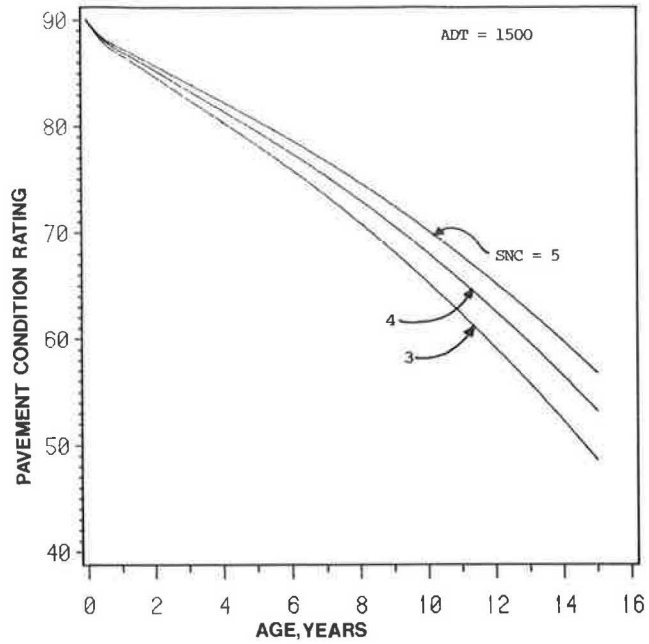

FIGURE 6 Effect of structural number on *PCR* as predicted by Equation 6. Flexible pavements with no overlay, *ADT* = 1500.

A question now arises of why traffic appears as a distinct entity in the equations (Equations 6, 7, and 8) whereas the environmental effects do not. The environmental factors of a specified region, north Mississippi, for example, can be assumed to be uniform, causing approximately the same ΔPCR in a wide range of pavement structures; age alone, therefore, can be a predictor of climate-related deterioration. Yearly traffic of the pavement network, however, ranges over two orders of magnitude (see Table 1), justifying the presence of traffic term in the equation.

Structural number, a mechanistic parameter in the equation, emerges, and rightly so, as a factor influencing the deterioration of flexible pavements without and with overlay. Composite and overlaid pavement equations include asphalt surface thickness as well. Besides their direct influence on the mechanistic parameters—for example, stress, strain, and deflection and, in turn, on performance—their computational accuracy could well be another reason for its significance in the performance model.

Had those pavements been proportioned in accordance with any one of the numerous design models, the structural number would be expected to increase with yearly *ESAL*. Only because of the collinearity between the loading and strength, the *ESAL*-structural number interaction term is coined as a ratio (see Equations 6–8), which accentuates the serviceability loss because the logarithm of this ratio always assumes values greater than 1.

Three Prediction Models Compared

The performance prediction equations for the three families of pavements are graphed with age, keeping traffic and *SNC* constant (see Figure 7). As can be noted, the flexible original pavement trend line conforms to the more traditional "concave down" shape, whereas the composite family follows a slightly "convex down" path, with the overlay family exhibiting hardly any curvature at all. The convex down shape or exponential decay of *PCR* with age has been reported by other researchers as well (see Figure 4 and Keddy [7]). A cursory examination of the distress data reveals that the composite pavements generally undergo premature (early) reflection cracking, with a concomitant abrupt *PCR* decrease setting the stage for exponential decay. Another noteworthy observation is that all the three families of pavements attain an assumed threshold (*PCR* = 55) in about 12 to 15 years. Similar life cycles have been reported by other researchers; for example, a survey of in-service flexible pavements in Ohio estimates them to last 14 years on the average. Hajek et al. (*1*) and Sharaf et al. (*8*) report that 3-in. overlays performed satisfactorily for 12 and 15 years, respectively. In summary, the authors believe that the serviceability trends, in accordance with Equations 6, 7, and 8, are reasonable and should serve well in predicting pavement condition at the project and/or network levels.

SUMMARY

Employing historical information and monitoring data over a 2-year period on some 2,000 miles of roads, empirical-mechanistic predictive models have been developed. Preliminary investigation of the data (pavement with asphalt surfacing) suggested a three-group classification based on deterioration rate. The groups are flexible pavements with no overlay, flexible pavements with one or more overlay(s), and composite pavements. One model for each pavement family was developed. Of the three causal factors identified in each model, age (life cycle in years) indeed correlates strongly with serviceability decline. As formulated, age is a surrogate for

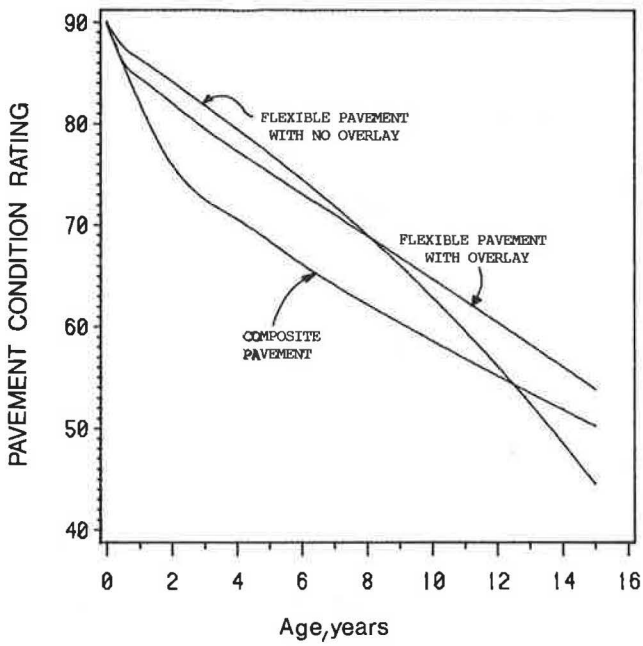

FIGURE 7 Pavement deterioration curves of three families of pavements. *ADT* = 3000; flexible pavement with no overlay, *SNC* = 3.0; flexible pavement with overlay, *SNC* = 3.0, *T* = 2 in.; composite pavement, *T* = 2 in.

both cumulative traffic and environmental loads. The composite structural number (the AASHO structural number modified to account for the subgrade support) shows a weak correlation to serviceability loss. The trends predicted by the respective models exhibit varied shapes: concave down for flexible pavements with no overlay, convex down for composite pavements, and neither concave nor convex curvature for overlaid pavements. Finally, the models are validated by comparing them with those developed (by other researchers) employing field performance data.

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REFERENCES

1. J. J. Hajek, W. A. Phang, A. Prakash, and G. A. Wrong. Performance Prediction for Pavement Management. *Proc., North American Pavement Management Conference*, Toronto, Ontario, Canada, Vol. 1, 1985.
2. *AASHO Road Test—Report 61E*. HRB, National Research Council, Washington, D.C., 1962.
3. *Pavement Distress Manual—PMIS Report No. 1*. Civil Engineering Department, University of Mississippi, University, Miss., 1986.
4. J. V. Carnahan, W. J. Davis, M. Y. Shahin, P. L. Keene, and M. I. Wu. Optimal Maintenance Decisions for Pavement Management. *Journal of Transportation Engineering*, ASCE, Vol. 113, No. 5, 1987, pp. 554–572.
5. R. L. Lytton. Concepts of Pavement Performance Prediction Modeling. *Proc., North American Conference on Managing Pavements*, Toronto, Canada, Vol. 2, 1987.
6. W. D. O. Paterson. Applicability of Structural Parameters to Prediction of Pavement Performance. The 1986 International Conference on Bearing Capacity of Roads and Airfields, Plymouth, England, 1986.
7. J. M. Keddy. Effective Pavement Management Through Good Inventory. *Proc., North American Pavement Management Conference*, Toronto, Ontario, Canada, Vol. 1, 1985.
8. E. A. Sharaf, E. Reichelt, M. Y. Shahin, and K. C. Sinha. Development of a Methodology to Estimate Pavement Maintenance and Repair Costs for Different Ranges of Pavement Condition Index. In *Transportation Research Record 1123*, TRB, National Research Council, Washington, D.C., 1987, pp. 30–39.

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