Pavement Performance Prediction Model Using the Markov Process

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A good pavement-management system requires an accurate and efficient pavement performance and prediction model. A pavement performance and prediction model based on the Pavement Condition Index and the age of the pavement has been developed. The Pavement Condition Index ranging from 0 to 100 has been divided into ten equal condition states. A combination of homogeneous and nonhomogeneous Markov chains has been used in the development of the model. The life span of the pavement is divided into zones, with each zone representing a period of 6 years. The transition matrix of each zone is determined using nonlinear programming. If the state of any given pavement section is known, its future condition can be predicted efficiently from the corresponding transition matrices. The model presented in this paper will play an integral part in the decision-making procedure for determining optimal maintenance and repair strategies. A comparison between the Markov model and the constrained least-squares model is presented.

The performance of existing pavements and the prediction of their future conditions is a matter of great concern to pavement engineers. In recent years there has been a rapid growth in the technology of pavement evaluation and rehabilitation. A corresponding growth has occurred in the development of Pavement Management Systems (PMS), which are based on the performance of the existing pavements. These developments necessitate more reliable pavement performance and prediction models. Knowledge about the future condition of the pavement is required for inspection scheduling, life cycle costing, benefit analysis, and budget optimization. A pavement performance and prediction model based on Pavement Condition Index (PCI) and age has been developed. The PCI ranging from 0 to 100 has been divided into ten equal states and a combination of homogeneous and nonhomogeneous Markov chains has been used. This prediction model has the potential to be an integral part in the decision-making procedure for determining optimal maintenance and repair strategy.

CURRENT PREDICTION MODELS

The prediction models currently in use vary in complexity from simple straight-line extrapolation *(1)* to probability-based models *(2)*. Straight-line extrapolation is used to predict the condition of a pavement section. When sufficient data are available, it is found that the shape of the deterioration curve is generally curvilinear rather than the straight line that results from straight-line extrapolation.

In other attempts the regression techniques have been used to model the pavement condition deterioration over time *(3–5)*. These regression techniques are valid only if the predictive variables can be found that are related to pavement condition deterioration. The regression techniques are applicable only to specific climatic conditions, materials, construction techniques, and others.

Recently, researchers at U.S. Army Construction Engineering Research Laboratory (USA-CERL) have investigated two other mathematical techniques for curve fitting *(6)*: the constrained least-squares and the *B*-spline. The constrained least-squares model fits a polynomial curve to the data that minimizes the squared distance between the predicted and the actual data points. At the same time the technique applies a constraint that ensures a monotonically decreasing slope of the predicted condition versus age curve.

The *B*-spline method is based on the original mechanical splines used in drafting and it assumes that the curve takes on a shape that minimizes its potential energy. A *B*-spline of degree k is a continuous function having its first k-1 derivatives continuous. Because of the complex nature of selecting the number and the position of interior knots and the possibility of the occurrence of a positive slope in the function, the *B*-spline technique is not deemed suitable as a pavement condition prediction-modeling technique. The constrained least-squares curves, unlike *B*-spline curves, never exhibit a positive slope; i.e., the PCI values are not allowed to increase with age.

From this initial evaluation, the constrained least-squares estimation approach was selected to model the relationship between PCI and age. Figure 1 shows the curve-fitting results with constrained least-squares estimation and *B*-spline approximation. The *B*-spline curve shows a positive slope, whereas the constrained least-squares curve more accurately predicts the normal pavement deterioration behavior.

The probability-based Markov model was first developed for the Arizona PMS *(2)* to describe pavement condition changes. Intuitively, the behavior of pavements is not deterministic but is probabilistic. Consequently, the selection of an appropriate repair strategy is also an uncertain procedure. Because of the probabilistic nature of pavements, it was decided to develop a probability-based prediction model, as outlined in the next section.

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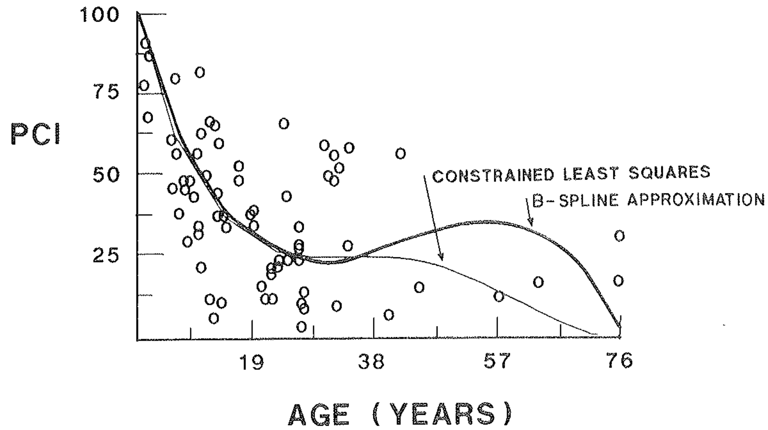

FIGURE 1 Constrained least squares versus *B*-spline approximation.

ADVANTAGES OF PROBABILITY-BASED PREDICTION MODELS

Kulkarni *(7)* outlined several advantages in using a Markov probability decision process in pavement management. These include the following:

1. Future decisions on preservation actions are not fixed but depend on how the pavements actually perform.
2. Actions to be taken now can be identified; also, likely actions to be taken in the next few years can be identified with a high degree of probability.
3. It is possible to compare the expected proportions in given condition states with the actual proportions observed in the field, and in this way possible defects in construction, materials, quality control, and so on, can be identified.
4. A dynamic decision model has the potential for significant cost savings by selecting less conservative rehabilitation actions that will still satisfy the prescribed performance standards.

Straight-line extrapolation techniques are deterministic and do not attempt to explain the variability among the data points; they merely fit a best line to the data. Regression techniques are powerful tools, but in many cases the models are chosen for the best fit without regard to the suitability or intrinsic relevance of the variables selected. Polynomials of different degrees and mathematical functions can be manipulated to fit the data; but when these functions are projected beyond the bounds of the data the results can be totally misleading.

It is known that the rate of deterioration is uncertain. Therefore, the predictive model should portray this rate of deterioration as uncertain, rather than using the erroneous assumption of deterministic behavior. The Markov process imposes a rational structure on the deterioration model. This form of predictive model has the further advantage of ensuring that projections beyond the limits of the data will continue to have the classic pattern of worsening condition with age, something that the regression models cannot guarantee.

Another advantage of probability-based models is the ease with which they can be integrated into optimization processes. The Markov process is a natural tool to use in alliance with dynamic programming to produce optimal solutions. It is believed that the application of the Markov process in conjunction with dynamic programming will produce optimal maintenance and rehabilitation (M&R) strategies for selected pavement sections quickly and efficiently.

CONCEPTS UTILIZED

Pavement Condition Index

The procedure used to measure the performance of the existing pavements is the PCI, developed by USA-CERL *(8)*. PCI is a composite index of the pavement's structural integrity and operating condition. The PCI of a pavement is determined from a detailed survey that measures distress type, severity, and quantity to produce a numerical index ranging from 0 to 100, with 100 being excellent.

Pavement Family Classification

The PAVER data base was used for the development of the prediction model *(1)*. Every pavement section stored in the PAVER data base is identified by the location, the pavement type, the pavement use, and the pavement rank or functional classification. The family concept of grouping similar pavement sections, as shown in Figure 2, is used to account for the variety of factors affecting the pavement performance. A pavement family is defined as the group of pavement sections with the same pavement type, the pavement use, and the pavement rank.

The desired (ideal) form of data for determining the rate of deterioration is shown in Figure 3. In this form, all the pavement sections are put into use at the same time. Unfortunately, there are very few pavement sections for which complete pavement condition history data are available. Therefore, the approach taken was to survey all pavement sections of various ages of a family at the same time, as shown in Figure 4*a*.

An assumption was made that these sections represent the condition of a pavement section at the various ages as shown in Figure 4*b*. Of course, when sufficient information is available over time for each pavement section, there will be more confidence in the predicted curves.

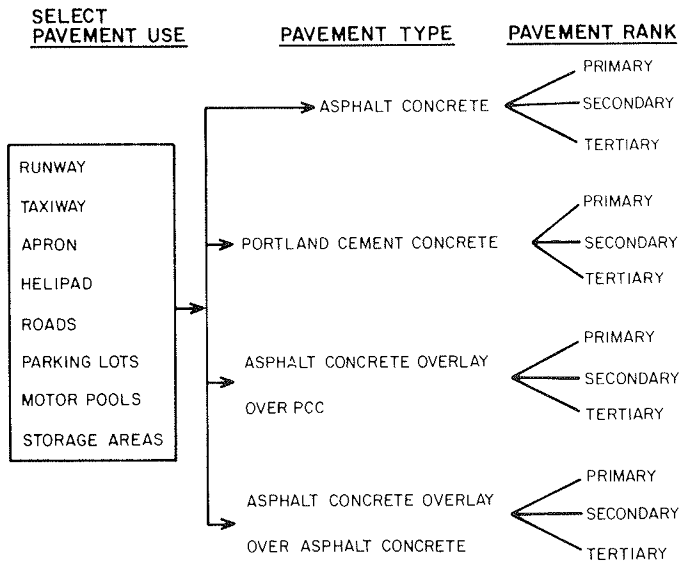

FIGURE 2 Family definition from PAVER data base.

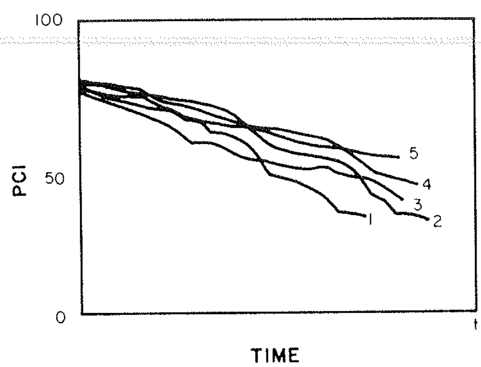

FIGURE 3 Desired (ideal) form of data.

Data Errors Screening (Filtering)

There are errors in the family data retrieved from the PAVER data base. These errors might have originated during data collection, coding, or entering the data into the data base. A computerized filtering program, developed at USA-CERL, is used to identify obviously erroneous data such as duplicate records, same age and different PCI for a given section, PCI greater than 100, and unrealistic PCI values. The user has the option of examining the erroneous data file and making adjustments to the filter boundaries.

Outliers Identification

An outlier analysis program developed at USA-CERL *(6)* is used to remove the extreme observations. The extreme data points have substantial impact on modeling the family behavior. The outlier program fits a constrained least-squares curve to the filtered family data file and sets confidence limits for the residuals of given observations; e.g., 95 percent, to be established by the user for removal of extreme cases.

MODELING APPROACH

The model development process is made up of the following steps:

- Data retrieval by pavement family
- Data errors screening (filtering)
- Outliers identification
- Development of Markov model

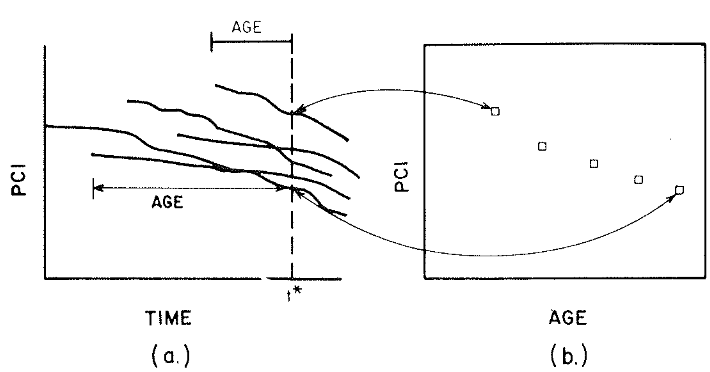

FIGURE 4 Relationship between PCI and age of all pavement sections of a family surveyed at the same time.

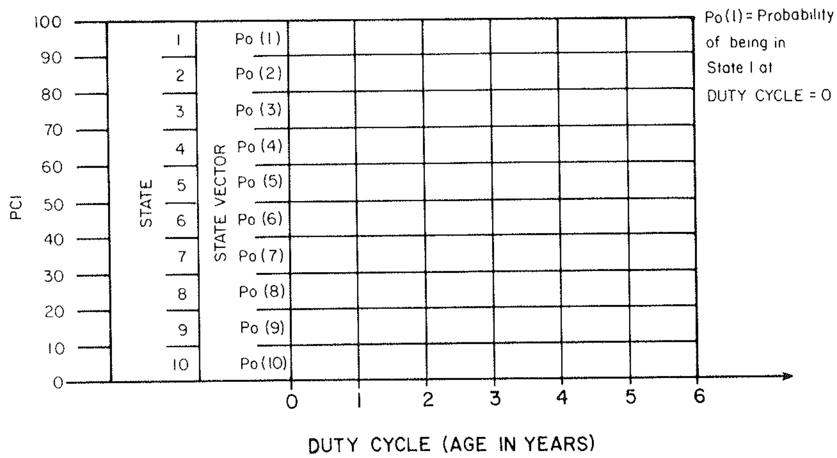

FIGURE 5 Schematic representation of state, state vector, and duty cycle.

DEVELOPMENT OF MARKOV MODEL

A pavement begins its life in nearly perfect condition and is then subjected to a sequence of duty cycles that cause the pavement condition to deteriorate. In this study the state of a pavement is defined in terms of PCI rating. The PCI ranging from 0 to 100 has been divided into ten equal states, each state being 10 PCI points wide. A duty cycle for a pavement is defined as one year's duration of weather and traffic. A state vector indicates the probability of a pavement section being in each of the ten states in any given year. Figure 5 is the schematic representation of state, state vector, and duty cycle.

After filtering and outlier analysis, all the surveyed pavement sections of a family are categorized into one of the ten states at any age. It is assumed that all the pavement sections are in State 1 (PCI of 90 to 100) at an age of 0 yr. Thus, the state vector in duty cycle 0 (age = 0) is given by (1, 0, 0, 0, 0, 0, 0, 0, 0, 0), as it is known (with probability of 1.0) that the pavement sections must lie in State 1 at an age of 0 yr.

To model the way in which the pavement deteriorates with time, it is necessary to identify the Markov probability transition matrix. In the present case, the assumption is made that the pavement condition will not drop by more than one state (10 PCI points) in a single year. Thus, the pavement will either stay in its current state or transit to the next lower state in one year. Consequently, the probability transition matrix has the form:

$$P = \begin{matrix} p(1) & q(1) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p(2) & q(2) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p(9) & q(9) \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{matrix}$$

where $p(j)$ is the probability of a road staying in state j during one duty cycle, and $q(j) = 1 - p(j)$ is the probability of a road transiting down to the next state $(j + 1)$ during one duty cycle.

The entry of 1 in the last row of the transition matrix corresponding to State 10 (PCI of 0 to 10) indicates a holding or trapping state. The pavement condition cannot transit from this state unless repair action is performed.

The state vector for any duty cycle, t, is obtained by multiplying the initial state vector $\bar{p}(0)$ by the transition matrix P raised to the power of t. Thus,

$$\bar{p}(1) = \bar{p}(0) \times P$$
$$\bar{p}(2) = \bar{p}(1) \times P = \bar{p}(0) \times P^2$$
$$\vdots$$
$$\bar{p}(t) = \bar{p}(t-1) \times P = \bar{p}(0) \times P^t$$

With this procedure, if the transition matrix probabilities can be estimated, the future state of the road at any duty cycle, t, can be predicted.

To estimate the transition matrix probabilities, the Fletcher-Powell algorithm *(9)*, a nonlinear programming approach, is used. The objective of the search is to determine values of the nine parameters, $p(1)$ through $p(9)$, that would minimize the absolute distance between the actual PCI versus age data points, and the expected (predicted) pavement condition for the corresponding age generated by the Markov chain using these nine parameters.

The objective function has the following form:

$$\text{MIN} = \sum_{t=1}^{N} \sum_{j=1}^{M(t)} \left| Y(t, j) - E[X(t, p)] \right|$$

where

N = total number of duty cycles (age) for which PCI versus age data are available within each family;
$M(t)$ = total number of data points recorded at a duty cycle (age) t;
$Y(t, j)$ = PCI rating for each sample taken at a duty cycle (age) t; and
$E[X(t, p)]$ = expected value in PCI at a duty cycle (age) t, as predicted by the current Markov values.

ORIGINAL MARKOV MODEL

The original Markov model for pavement deterioration was developed under a contract to USA-CERL by Keane and Keane *(10)*. In the initial investigation, the objective was to make the model as simple as possible. Therefore, the number of states

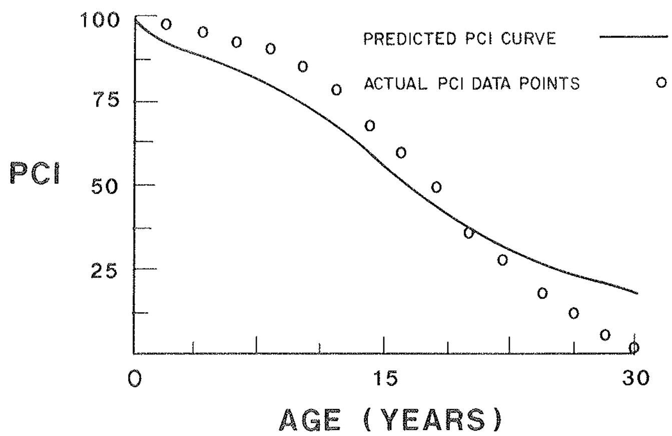

FIGURE 6 Pavement condition prediction curve using original Markov model.

was chosen to be eight and only one state transition was allowed during a duty cycle. Also, the Markov chain was assumed to be homogeneous or stationary; that is, the duty cycle was taken to be constant over time.

VALIDITY OF THE ORIGINAL MARKOV MODEL

The validity of the original Markov model was checked using a test data file representing actual PCI data points over a 30-year life of the pavement. The final results from the original model are shown in Figure 6. A significant difference between the predicted PCI values and the actual values is noticeable in this figure. It was concluded from this experiment that the original model was not capable of accurately matching the actual deterioration curve of the pavement.

This discrepancy in the original model is attributed to the incorrect assumption of a constant duty cycle over the life of the pavement. Traffic loads generally increase over time, which means that the duty cycle will have become successively more destructive each year. It should be noted here that the Markov prediction curves are developed for the family data files only. Therefore, the pavement type, traffic, and climate are already taken into account in family definition. The increase in the traffic loads, as already mentioned, is the gradual increase within a given traffic category; i.e., primary, secondary, or tertiary. In the development of the original model it was assumed that the pavement condition would not decrease more than 10 PCI points in a single year, and only one state transition was allowed. The additional assumption of eight states' division contradicts the assumption that the pavement condition would not decrease more than 10 PCI points in a single year because the last two states were made up of 20 PCI points each.

NEW MARKOV MODEL

In the new model a more refined definition of the states has been used. The number of states has been increased from eight to ten, each state covering 10 points on the PCI scale. To allow for changes in traffic loads and maintenance policies over the pavement life, different duty cycles have been introduced in the new model. An ideal approach for the model is to have a different duty cycle for each year. Because of the limited availability of yearly PCI data, this was not feasible. To achieve the result of having different duty cycles, a zoning scheme has been developed in which the life of the pavement has been divided into zones, each zone representing a period of 6 years. It is assumed that each zone has a constant rate of deterioration; hence a constant duty cycle has been assumed within each zone. The rate of deterioration is assumed to vary from one zone to another; therefore, different duty cycles have been assigned to different zones. The 6-year period of a zone is a realistic assumption as a PCI survey is performed every 3 years, on the average. This sequence provides two section-level PCI condition survey points within each zone.

As the duty cycle within a zone is assumed to be constant, a homogeneous Markov chain and a separate transition matrix have been developed for each zone. The duty cycle varies from one zone to another. Therefore, a nonhomogeneous Markov chain has been used for transition from one zone to another. Zone 1 is always assumed to start in State 1 with state vector (1, 0, 0, 0, 0, 0, 0, 0, 0, 0). Zone 2 takes the last state vector of Zone 1 as its starting state vector. This process continues for all the zones over the life of the pavement. This procedure ensures a continuous curve over the pavement life.

VERIFICATION OF NEW MARKOV MODEL

The validity of the new Markov model was verified using the same test data file that was used for the original model. The final results from the new model are shown in Figure 7. It is clear from this figure that the new Markov model predicts PCI values much closer to the actual PCI values than the original Markov model. The Markov model presented in this paper was tested using a large number of different data files. Examples of the results for two of these files are shown in Figures 8 and 9.

The Markov modeling procedure first sorts the actual PCI values by age and then groups them into zones. The state vector and transition matrix are determined separately for each zone. The expected PCI values for each year are determined from the state vector and the transition matrix of the given zone. The Markov model is very sensitive to initial starting values for the transition matrix probabilities. The rate of deterioration varies

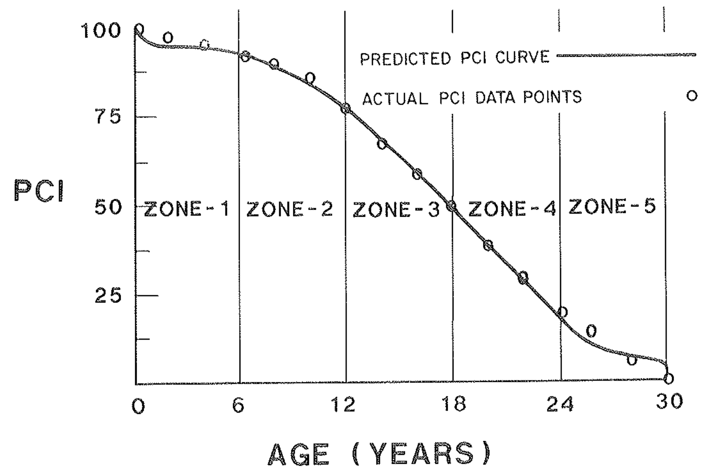

FIGURE 7 Pavement condition prediction curve using new Markov model.

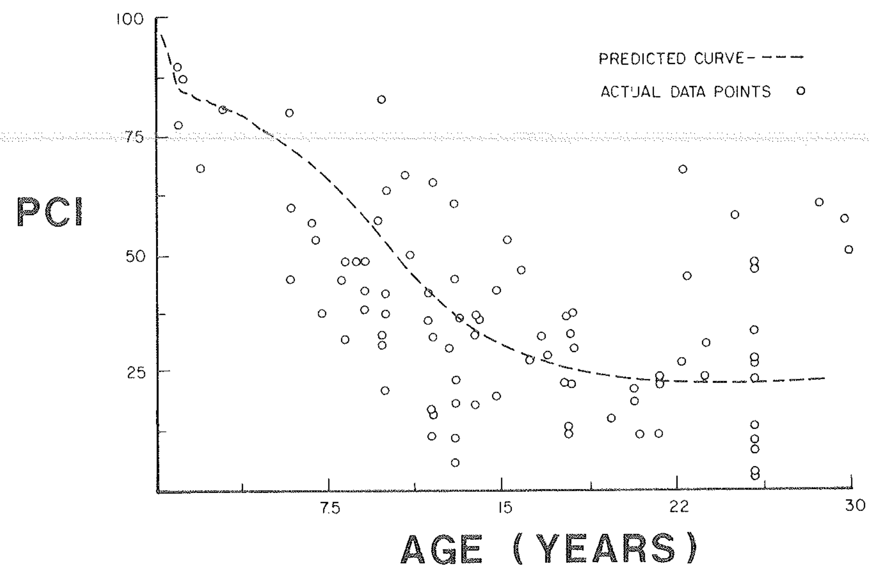

FIGURE 8 Example of pavement condition prediction curve using new Markov model.

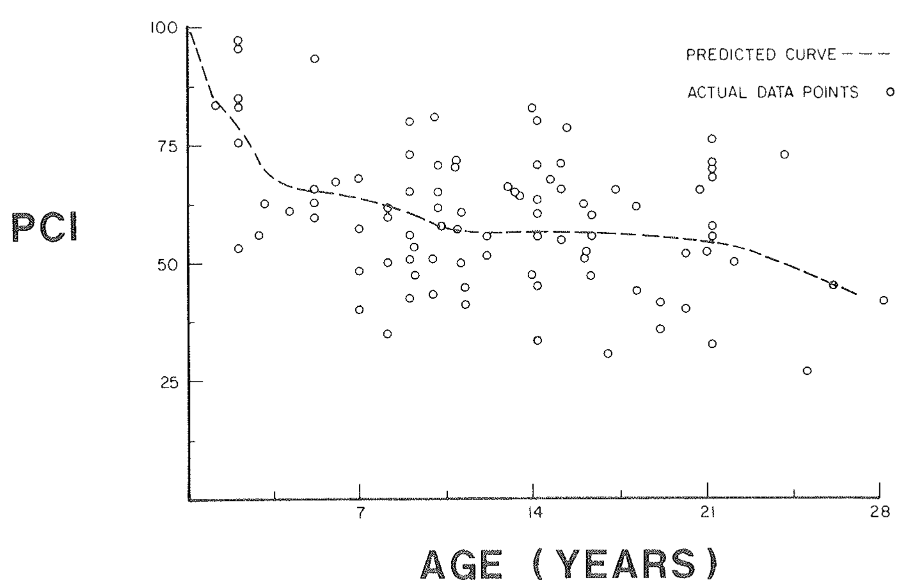

FIGURE 9 Example of pavement condition prediction curve using new Markov model.

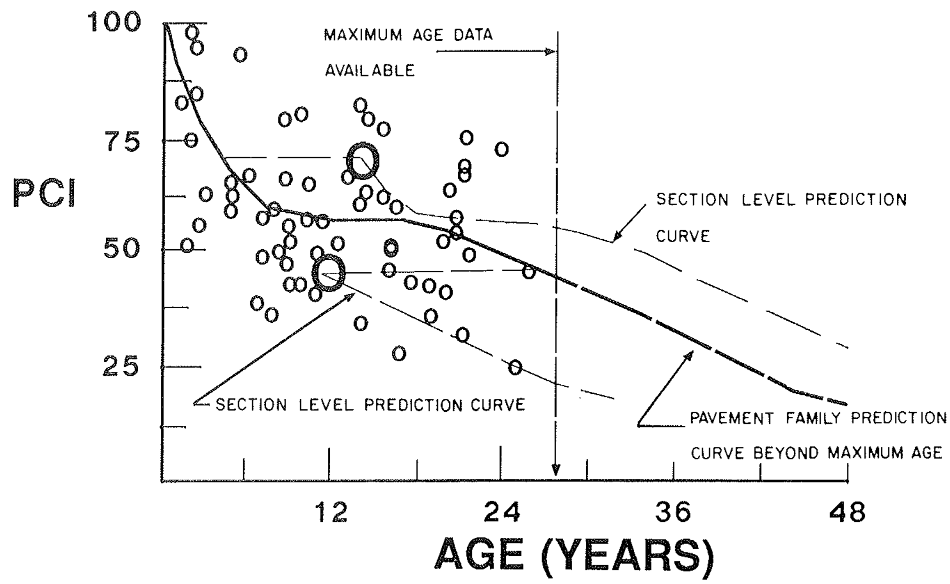

FIGURE 10 Pavement condition prediction curves using new Markov model.

from zone to zone, therefore different initial starting values for the transition matrix probabilities are used for different zones. The computer time and the number of iterations are reduced significantly by using different input starting values for different zones.

FUTURE PREDICTION USING NEW MARKOV MODEL

Information about the condition of the pavement in the future is needed for life-cycle cost analysis at the project level and for developing optimal M&R strategies at the network level. The capability of future prediction is required for pavement family curves and for each individual section. The Markov model is the only technique that is capable of predicting the condition of the pavement beyond the last available data point by using the transition matrix of the last zone. The section level prediction is carried out by first determining the present state of the section and then projecting the future condition by using the transition matrices of the respective zones. The pavement family prediction curve beyond the maximum age and the pavement section level prediction curves are shown in Figure 10.

COMPARISON OF NEW MARKOV MODEL WITH CONSTRAINED LEAST-SQUARES MODEL

Comparison of the curve-fitting results for the new Markov model and the constrained least-squares model is shown in Figure 11. The curves from the two different techniques show almost the identical trends of the pavement performance. Comparison of the extrapolation results from the two techniques is shown in Figure 12. The extrapolation curves from the two different techniques are significantly different. The extrapolation curve from the new Markov model is the most likely to represent the future condition of the pavement. The new Markov model is preferred to the constrained least-squares model because it is best for extrapolation. Also, the new

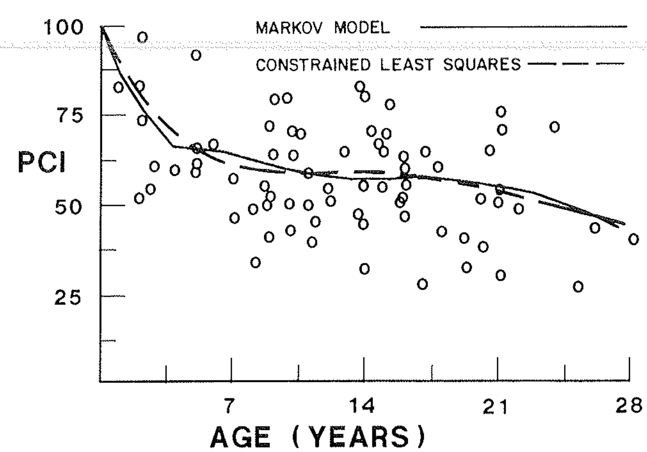

FIGURE 11 Pavement condition prediction curves using new Markov model and the constrained least squares.

Markov model can be used in dynamic programming to produce optimal M&R strategies for the selected pavement sections.

CONCLUSIONS

A pavement-performance and prediction model has been developed that is based on the Pavement Condition Index (PCI) and the age of the pavement. A combination of homogeneous and nonhomogeneous Markov chains has been used in the development of the model.

The Markov model introduces a rational structure to the pavement-deterioration modeling process and is the best for extrapolation. The Markov process will be used in conjunction with the dynamic programming to produce optimal M&R strategies for all the pavement sections in a network. To produce these optimal strategies, the future condition of the pavement is required. Accurate predictions are used for life-cycle cost analysis at the project level and establishing the feasible M&R strategies at the network level. The new Markov model has the

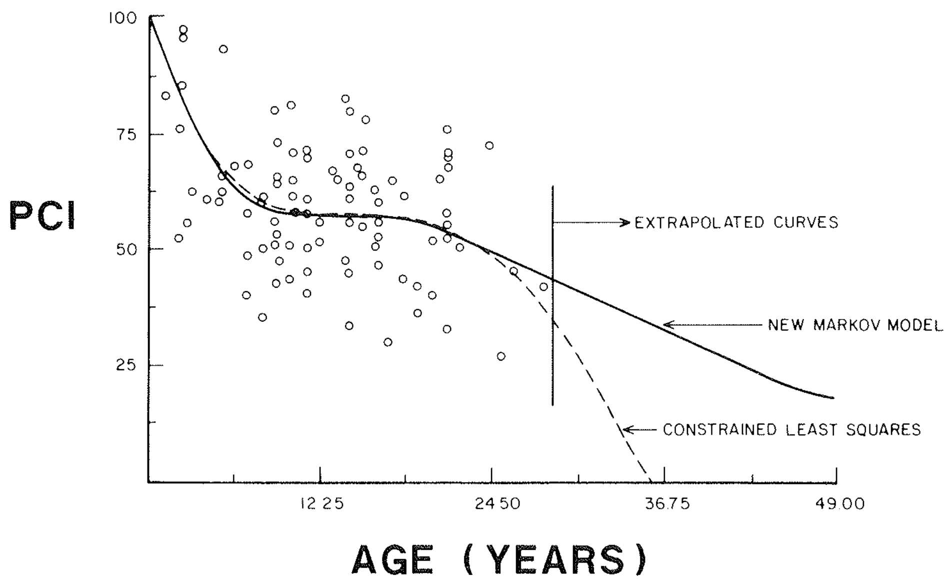

FIGURE 12 Pavement condition extrapolation using the new Markov model and the constrained least squares.

capability of providing this information with minimum effort on the part of the user and with better accuracy and reliability than other techniques that require unsupportable assumptions.

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