Pavement Maintenance Effectiveness

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Maintenance and rehabilitation (M&R) activities upgrade pavement condition and foster a new life cycle. Precise prediction of the effectiveness of these activities and how they retard the progression of distresses are key issues in setting priorities in a pavement management system. The extent to which the timing and level of M&R activities influence pavement condition is explored. Employing time series pavement performance data, mechanistic empirical models have been developed to predict the immediate jump in pavement condition, and, following the treatment, the rate of deterioration. Pavement condition rating, an aggregate statistic of both roughness and distress, is used as a measure of serviceability. Parametric studies were undertaken to estimate the timing and to select the most effective level of treatment. The results indicate that the immediate effect of an M&R activity depends on the condition of the underlying structure. The life-cycle analysis of three treatments (surface treatment and thin and thick overlays) applied at various condition levels indicates that if repairs are performed while the pavement is still in the "slow rate of deterioration" phase, life cycles are greatly increased. Similarly, timely maintenance treatment will reduce the equivalent uniform annual cost of the facility.

In recent years the emphasis of highway construction has gradually shifted from new design and construction to maintenance and rehabilitation (M&R) of the existing network. Historically, overlays have been the most common rehabilitation technique. They have often been performed without regard to cost-effectiveness. In many cases it may have been more cost-effective to perform other types of rehabilitation or to do routine maintenance. Maintenance is generally defined as work undertaken to extend the service life of the roadway. Rehabilitation includes placement of additional surface material or other work necessary to return an existing roadway to a condition of structural or functional adequacy. The restoration program could include complete removal and replacement of the pavement structure.

It is easy to visualize the effects of major maintenance, rehabilitation, or renovation on the condition of the pavement. These activities produce a substantial, immediately identifiable correction of deficiencies, represented by abrupt improvements in the condition curve, as shown in Figure 1. The effects of routine maintenance, on the other hand, are harder to detect. It may be that the improvements in pavement condition are so small as to escape measurement, or the maintenance activity may not correct existing damage but rather may prevent future damage or may slow the rate of deterioration.

The effects of M&R must be quantified to make life-cycle cost analyses of alternatives. Several approaches have been used in the past, three of which are described here. The first approach, typical of the EAROMAR-2 (*1*), simulates the mechanism by which routine maintenance purportedly reduces the rate of deterioration. The primary mechanism studied in this way is the reduction in water infiltration due to sealing or patching of joints and cracks. A secondary effect considered is the reduction in roughness, rutting, or spalling due to patching. The second approach, typified by an Austin Research Engineers study (*2*), treats maintenance effectiveness more as a statistical correction to pavement condition or deterioration instead of modeling the specific mechanism involved. A third approach addresses the effect of routine maintenance on the present serviceability index (PSI) (*3*). The effect of routine maintenance on pavement performance is visualized as a shift in the PSI-ESAL loss curve. Not only do the maintenance policy and its effect on pavement performance vary, but so do the annual maintenance expenditures needed to accomplish the maintenance work.

A highway agency can adopt a variety of M&R strategies; each strategy provides a measurable benefit to the system. To provide decision makers with a more definite method for selecting M&R activities, highway agencies are resorting to structured maintenance management principles. Pavement management systems (PMSs) are being instituted to identify and define M&R needs to achieve desired levels of pavement service. These systems compare alternative M&R strategies; the objective is to identify the strategy that will minimize pavement life-cycle costs.

The timing of M&R can be an important factor in maintaining pavements economically. Typical pavement deterioration curves depict pavement life cycles as consisting of two phases (*4*). During the first stage, denoted as "slow deterioration phase," a 40 percent deterioration of pavement condition gradually occurs during 75 percent of the life of the pavement. A sharp decrease in condition occurs during the second phase. An equivalent 40 percent drop in condition takes place during 12 percent of the life of the pavement. Pavement M&R costs at this point are four to six times as high as those at the end of the first phase. If pavement repairs are taken up while the pavement is in the first phase instead of deferring them until the decline to a poor condition, life cycles can be greatly increased.

In identifying cost-effective maintenance strategy, the engineer has to consider the level, type, and timing of M&R action. Life-cycle cost analysis has often been performed to facilitate this procedure. Two performance models are required as a part of life-cycle cost analysis: first, a model to quantify the jump in performance arising from the application of each treatment, and second, a model to detail the rate of deterioration following the treatment. The objective of this paper is to develop the two performance models and to conduct a parametric study elaborating how timing and level of maintenance action affect deterioration rate, pavement life cycle, and, in turn, life-cycle costs of three M&R treatments.

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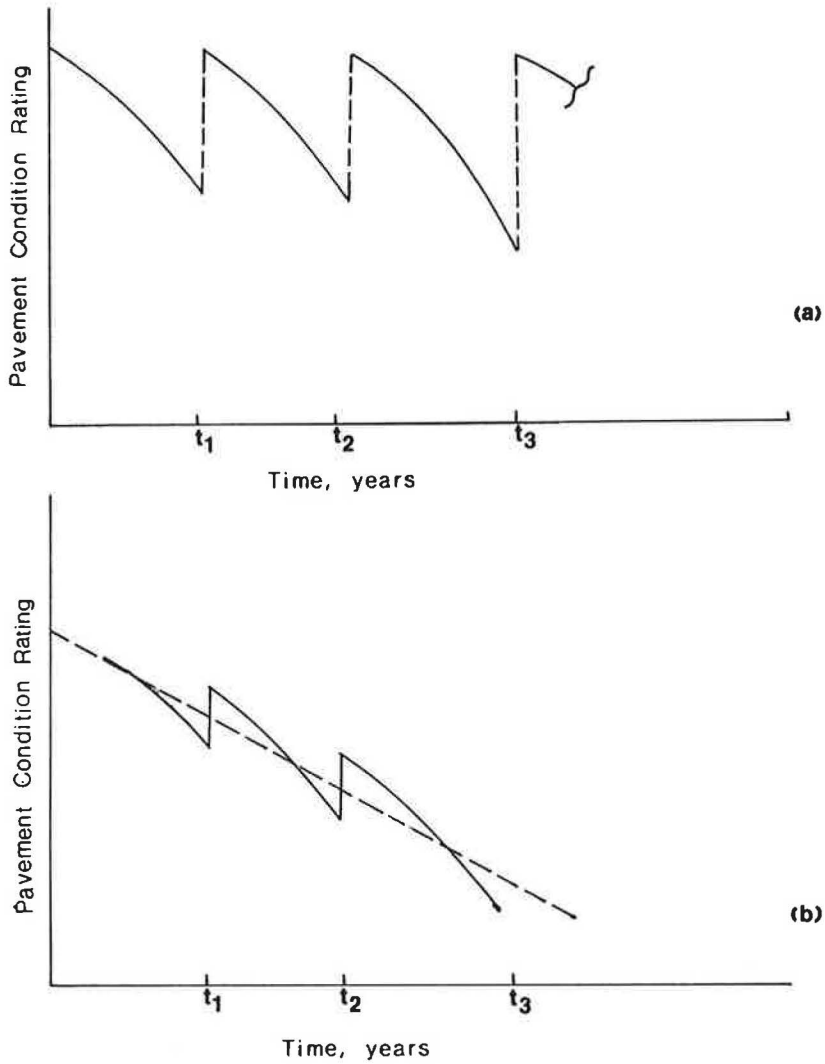


FIGURE 1 Schematic representation of effects of (*a*) rehabilitation and (*b*) routine maintenance.

BACKGROUND

The study includes performance models of flexible pavements with different levels of maintenance treatments. Only three M&R treatments are investigated: (*a*) surface treatment, equivalent thickness of ½ in. of hot mix asphalt concrete (HMAC), (*b*) thin overlay of 1½ in. HMAC, and (*c*) thick overlay of 3½ in. HMAC.

The historical and monitoring data used to derive the models were obtained from a PMS data base of a 2,000 lane-mi road network in north Mississippi. The performance indicator is a pavement condition rating (PCR), which can range from 0 to 100. PCR is an aggregate index derived from monitoring data—pavement roughness rating (RR) and distress rating (DR)—in accordance with the following equation:

$$PCR = RR^{0.6}\, DR^{0.4} \quad (1)$$

As indicated previously, two models will be developed. The first, which captures the immediate improvement, is based on the PCRs of those sections (30 in all) that received maintenance between 1986 and 1989. The second, a pavement deterioration model, uses the performance history of 600 mi of flexible pavements with overlays. The two models together will be used to compare alternative maintenance actions.

PERFORMANCE MODELS—A REVIEW

Pavement management activities must consider performance of the pavement and the factors that influence costs throughout its service life. Models to predict pavement condition, deterioration, and M&R are included in life-cycle economic analysis for two reasons. First, to estimate the requirements for and the cost of M&R, one must be able to predict the deterioration in pavement condition and when it will occur. Second, the condition of the highway surface affects pavement serviceability and may affect vehicle operating costs and, in turn, user costs.

Most of the current performance or distress prediction models, however, do not consider the influence of preventive,

TABLE 1 FLEXIBLE PAVEMENT DETERIORATION MODELS

Deterministic Models						
	Distress Prediction Models					
Performance Prediction Models	Roughness	Fatigue Crack	Transverse Rutting	Thermal Crack	Raveling	Probabilistic Models
AASHTO, VESYS, Texas FPDS, Mississippi PCR, Washington State, PAVER, Fernando Equation, PARS, PQI, PENNDOT	Arizona, Fwa and Sinha	VESYS, Asphalt Institute, Shell, ARE, World Bank	VESYS, Shell, WATMODE, Ohio State, World Bank	Shahin McCollough	World Bank	Markov chain, survivor curves

corrective, or emergency pavement maintenance activities on the performance of the pavement. This is a serious deficiency, because most highway organizations are faced with a shortage of resources and are being forced to delay pavement maintenance or select among M&R strategies, or both. With appropriate prediction models, the effects as well as the costs of alternative investment policies can be computed.

In making alternative maintenance policy decisions or evaluating maintenance effectiveness, two classes of models are required: pavement performance models and cost models. The current performance models will be briefly reviewed here. The models describe mathematically how pavement condition changes with time and traffic.

Performance in its broadest sense is predicted by deterministic and probabilistic models. The deterministic models include those for predicting structural and functional performance and damage in pavements. The probabilistic models include survivor curves and Markov and semi-Markov transition processes. Damage models are particularly important because they affect M&R activities. Alternatively, pavement performance can be predicted in terms of a single attribute (for example, alligator cracking or roughness) or a combined attribute (for example, AASHO present serviceability rating, which accounts for both roughness and distresses). Table 1 gives some of those models, categorized in accordance with the preceding discussion.

The distress or performance (combined-attribute) models predict the rate of change of condition of new or rehabilitated pavements. To describe the condition after a maintenance activity, however, another model that quantifies the immediate improvements in condition is required. In lieu of this model, a tacit assumption made in several existing PMSs is that the pavement is restored to its original condition—that is, the road becomes smooth and the distresses disappear regardless of the timing of treatment. This assumption might be valid when pavements are rehabilitated with thick overlays.

A maintenance treatment provided to retard distress development (a preventive maintenance program) adds a new dimension because the pavement is not restored to its as-constructed condition. Overlooking this aspect could substantially affect the prediction of the life of the maintenance activity. Accordingly, several recent studies have attempted to model the immediate improvement brought about by a variety of maintenance activities. A life-cycle cost evaluation study (*5*) defined and used a maintenance effectiveness index, which is the ratio of the pavement condition index (PCI) with maintenance and the PCI without maintenance in any given year. The Program Analysis of Rehabilitation Strategies model (*6*) presented a table of immediate jump in PCR as compiled from historical records in Ontario. A 20-section field study in Arizona (*7*) related the roughness improvement to the roughness before treatment. On the basis of roughness data for the Interstate system in Indiana, Colucci-Rios and Sinha (*8*) developed a model for reduction of roughness as follows:

$$RED = 61.35 * T^{0.26} \quad (2)$$

where RED is the percentage reduction in roughness and T is the overlay thickness in inches.

In summary, a cost-effective M&R program must analyze the effect of each activity on pavement performance as well as on life-cycle costs. A study of the effect of maintenance on performance must include models to evaluate the immediate improvement of performance and the rate of change of deterioration after the treatment.

PERFORMANCE MODELS FOR MAINTENANCE EFFECTIVENESS

Quantification of the impact of maintenance on damage rate requires the development and analysis of field performance records and deterioration models. The problem is to modify deterioration functions to reflect the effects of different kinds or levels of maintenance treatments. A pavement data base developed in connection with a PMS for the Mississippi State Highway Department provided the necessary data. The model was formulated in terms of PCR. What treatments and how many levels of each treatment need to be modeled will be discussed later.

The definition and interpretation of routine maintenance will be discussed first. A survey of working definitions of highway maintenance and the relationship between routine maintenance and more capital-intensive rehabilitation works is presented in Coikie and Markow (*9*). Markow et al. (*5*) have adopted an analytic perspective in that routine maintenance comprises activities that can be represented mathematically by corrections to the deterioration function as shown in Figure 1b. This approach provides a general and flexible structure within which different mixes and interpretations of maintenance activities can be simulated. It also distinguishes routine maintenance from rehabilitation by the degree of improvement in pavement condition.

Another issue concerns the classification and summarization of the approximately 20 maintenance activities applicable

to flexible pavements. A three-group classification is adopted in this study: (*a*) routine maintenance activities (for example, surface rejuvenation and fog seal) that bring about small changes in the deterioration curve but for modeling purposes cause a small immediate jump in performance soon after application, (*b*) minor rehabilitations (for example, resealing and surface treatment), and (*c*) major rehabilitations (thin overlay less than 2 in. and thick overlays equal to or greater than 2 in.) that result in noticeable improvement in pavement condition. By handling routine maintenance, minor rehabilitations, and major rehabilitations as different levels of a single treatment, their effectiveness can be captured by a single set of models (equations). In this study, the effectiveness of only minor and major rehabilitation treatments are investigated.

Modeling Performance

The research reported in this paper is a part of a program to develop a PMS for the Mississippi State Highway Department. By employing historical information and monitoring data over a 3-year period, mechanistic empirical predictive models are developed, the details of which can be seen elsewhere (*10,11*).

Nonlinear regression models are developed using SAS 5.0 with PCR as the dependent variable. The independent variables are age of the pavement (Age), cumulative equivalent single-axle loads (ESALC), composite structural number (SNC), life cycle before overlay (BEFL), and thickness in inches (T) of the proposed treatment. The best-fit model obtained for performance prediction of flexible pavement with overlays has the following form (the number of data points is 142):

$$\mathrm{PCR}(t) = 90 - a\{\exp(\mathrm{Age}/\mathrm{T})^b - 1\} \times \log(\mathrm{ESALC})(\mathrm{BEFL}/\mathrm{SNC})^c \qquad R^2 = 0.74 \qquad (3)$$

where

PCR(t) = pavement condition rating at time t,
a = 0.6632,
b = 0.3558, and
c = 0.1642.

Of the five causal factors recognized by the model in defining the performance of overlay pavements, a parametric study indicates that ESALC and SNC are of only minor importance. Thickness of the overlay and BEFL, in that order, contribute to overlay performance. Age, however, is the most significant predictor.

Condition Adjustment for M&R Action

Routine maintenance is considered to adjust the slope of the deterioration function, as illustrated conceptually in Figure 1b. Within the discrete simulation model proposed in this study, this effect is captured by small increments in current PCR that offset some of the accumulated pavement damage. Minor or major rehabilitations are assumed to repair or restore the pavement condition to some level substantially higher than the pretreatment level. In the extreme case a reconstruction will automatically restore the PCR of the pavement to its as-constructed value. The development of a model to depict the jump in PCR follows.

About 30 overlay projects completed during the 1986–1989 period were analyzed for this purpose. The PCR after the treatment (PCRAF) is the dependent variable, and the PCR before the treatment (PCRBF) and the thickness of the overlay (T) are the independent variables. A multiple regression analysis with SAS Version 5.0 was performed to derive the following functional relationship (the number of data points is 30):

$$\mathrm{PCRAF} = A*(\mathrm{PCRBF})^B*(\mathrm{T})^C \qquad R^2 = 0.56 \qquad (4)$$

where

A = 23.9984,
B = 0.2883, and
C = 0.0389.

The standard errors of estimate of A, B, and C are 23, 19, and 30 percent, respectively. In Equation 4, PCRAF is a function of thickness as well as the condition of the underlying pavement, a result that agrees with the findings of Colucci-Rios and Sinha (*8*).

Effectiveness of Maintenance

The gain in PCR owing to three levels of treatment (surface treatment, equivalent thickness of ½ in. HMAC; thin overlay of 1½ in. HMAC; and thick overlay of 3½ in. HMAC) is plotted in Figure 2. The thick overlay restores the PCR to just above 85 but falls short of the as-constructed level of 90. Why is the PCR not restored to 90 even with a thick overlay? It is likely that all of the distresses vanish as a result of an overlay emplacement, especially a thick one. By elimination, one may conclude that some roughness will still be present regardless of the overlay thickness. Colucci-Rios and Sinha (*8*) reported that even newly resurfaced pavements exhibit a certain level of roughness, somewhere between 300 and 500 counts/mi as measured by the Portland Cement Association road meter. Life-cycle cost studies at MIT (*5*) indicated similar results—the gain in pavement condition as a result of maintenance activities was 2 to 18 PCI (pavement condition index of PAVER) points, whereas the gain due to rehabilitation action ranged from 25 to 30 points.

Maintenance effectiveness is defined as the change in pavement condition after performing maintenance. The gain in pavement condition due to a 1½-in.-thick overlay ranges from 25 to 13 points for a deteriorated pavement (PCR = 50) to a fair-rated pavement (PCR = 70). The same general trend is observed for surface treatment and thick overlays. With routine maintenance treatments Markow et al. (*5*) obtained a different trend, in that maintenance effectiveness showed a mid-life peak. For patching treatment, Smith et al. (*12*) indicated that maximum maintenance effectiveness occurred early in the pavement's life. One explanation for the disagreement is that the three research studies have investigated different maintenance treatments—Markow et al. investigated routine maintenance, Smith et al. studied the effectiveness of patch-

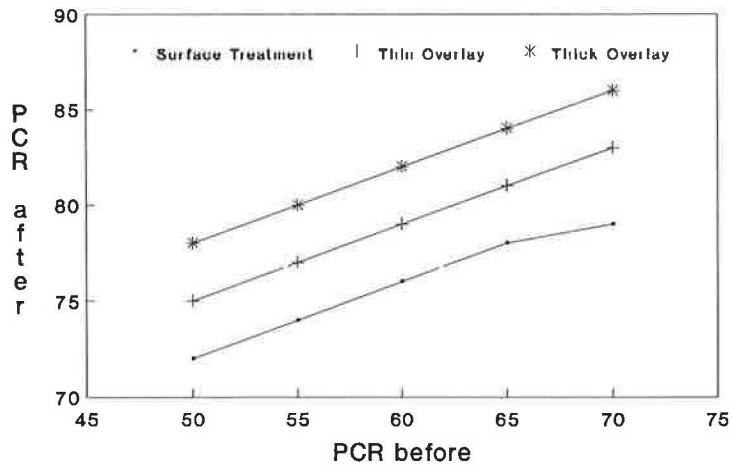


FIGURE 2 Pavement condition after treatment as a function of condition before treatment.

ing, and this research dealt with surface treatments and overlays. Apparently, the treatment level plays a major role in the gain in pavement condition, which, in turn, is affected by the condition before treatment. The three studies used different performance measures, which could be another reason for the contradictory results. Markow et al. and Smith et al. used PCI, which is distress based, whereas the authors used PCR, an aggregate measure of both roughness and distress.

Life Cycle of M&R Actions

Equation 3, with slight modifications, can be used for the life-cycle calculations of each treatment action. The modifications are required because the initial PCR of the road surface immediately after the treatment may not equal 90. Except perhaps for thick overlays, a rehabilitation action seldom restores the pavement condition to the as-constructed value of 90. To account for this difference, a four-step procedure is proposed for life-cycle computation of a specific treatment:

1. Compute the life cycle (L_1) of the maintenance treatment as if the initial PCR were 90 by using Equation 3 (see Path ABC in Figure 3, where the assumed threshold PCR is 50).
2. Locate Point D on Path ABC, where D represents the PCRAF derived from Equation 4.
3. Again using Equation 3, compute the life cycle for a threshold PCR = PCRAF. This life is denoted by L_2 in Figure 3.
4. Compute the life of the treatment as $L_1 - L_2$.

A tacit assumption is that the rate of decline in PCR is a function of the current PCR only.

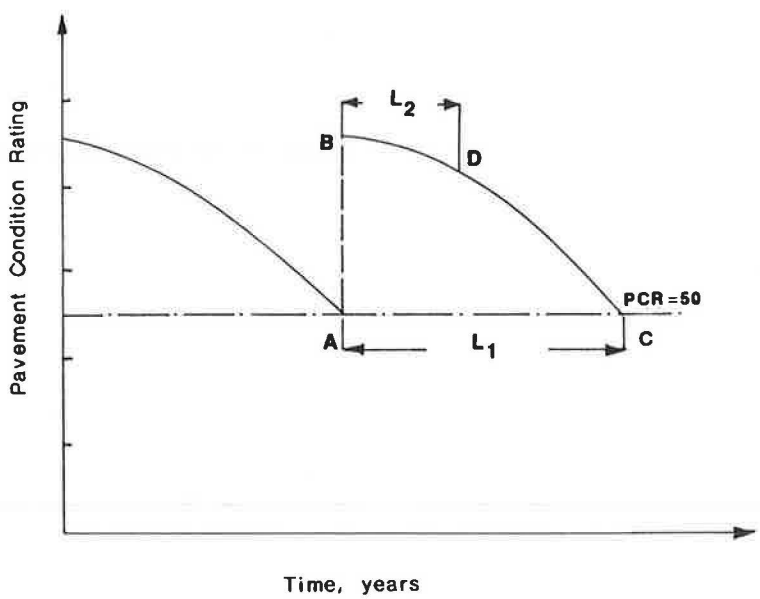


FIGURE 3 Conceptual performance curve for computing life cycle of rehabilitation treatment.

The life cycles of the three maintenance treatments are plotted as functions of PCRBF in Figure 4. As expected, the life cycle lengthens with increasing thickness of the overlay. In addition, the life cycles of all three treatments decrease when the timing is deferred until the PCR drops to the threshold value of 50. This result supports the conventional wisdom that if repairs are performed while the pavement is still in the first phase (defined previously) of deterioration, life cycles are greatly increased. Figure 5 shows two trend curves for each treatment. The first curve is based on the premise that soon after a treatment the condition is restored to the as-constructed value of 90; the second is based on the premise that the condition increases to a value as given by Equation 4. The former approach, which is currently adopted in several PMSs, would overpredict the life of surface treatments and thick overlays by 42 and 12 percent, respectively.

Life-Cycle Costs

The equivalent uniform annual cost (EUAC) of each treatment is calculated (see Figure 6) by using a discount rate of 8 percent and the life cycle as presented in Figure 4. The decrease in EUAC with increase in PCRBF is expected, because EUAC is strongly related to life cycle of the treatment. That is, as the life cycle increases, the EUAC must decrease, because the cost is distributed over a longer period. The benefit for the realistic evaluation of cost-effectiveness with respect to timing should also be included.

CONCLUDING REMARKS

M&R slows pavement deterioration and corrects distresses, prolonging pavement life. Two performance models were

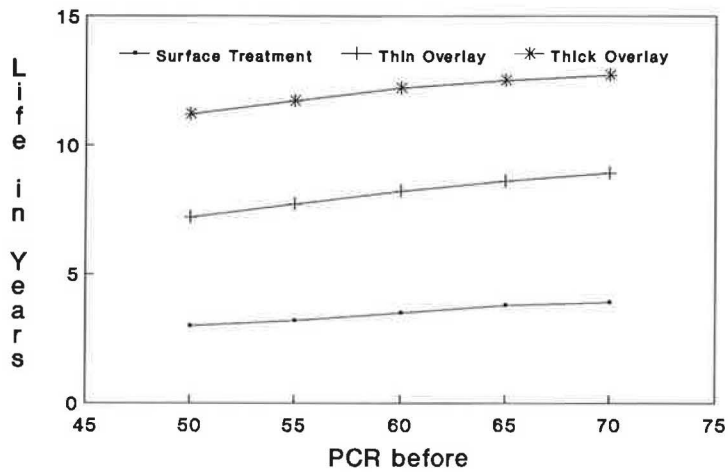
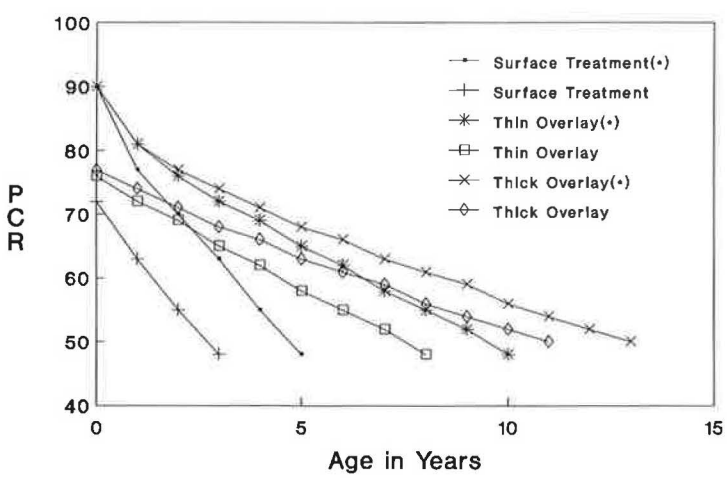


FIGURE 4 Life cycle of pavement as a function of timing of treatment.



(*) indicates PCR prediction with initial boundary constraint = 90

FIGURE 5 Pavement performance curves with and without initial boundary constraint.

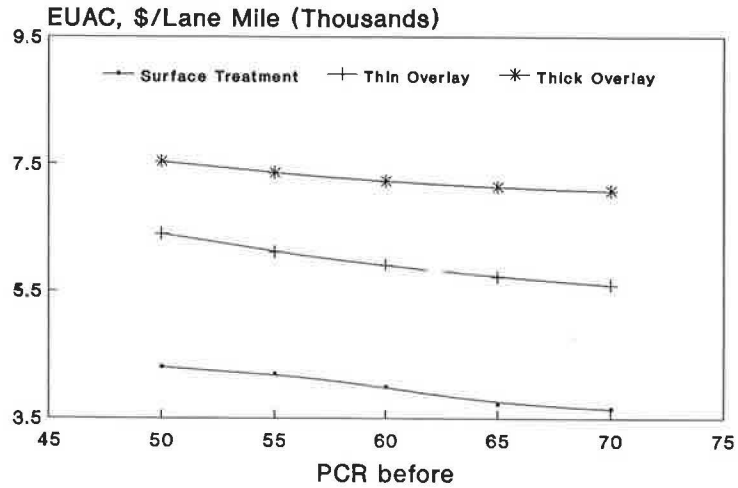


FIGURE 6 Effect of timing and level of action on EUAC.

developed to quantify these results—one to predict the immediate jump in performance and the other for the evolution of deterioration following the treatment. The pavement condition immediately after the treatment is a function of thickness as well as the condition of the underlying pavement. Of the five casual factors affecting deterioration of the rehabilitated pavement, age is the most significant predictor.

The effect of timing and level of maintenance treatment on overall pavement performance was investigated by using these models. The results suggest that pavement condition improves with overlay thickness, but the improvement approaches an asymptotic value that falls short of the as-constructed condition. The life-cycle analysis of treatments applied at various condition levels indicates that if repairs are performed while the pavement is still in the first phase of degradation (slow rate of deterioration), life cycles are greatly increased. By the same token, timely maintenance treatment will reduce the EUAC.

ACKNOWLEDGMENT

This report is a part of a study, *Pavement Management Information System*, conducted by the Department of Civil Engineering of the University of Mississippi in cooperation with the Mississippi State Highway Department and the Federal Highway Administration, U.S. Department of Transportation.

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