Development of a Pavement Management System

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The objective of this paper is to describe an investigation by the Washington State Department of Highways to determine the feasibility of developing a pavement management system. A pavement management system, as envisioned by this investigation, should provide systematic and reasonably objective information regarding the optimum economic maintenance strategy on a project-by-project basis. The system is concerned primarily with the development of a performance prediction model and a cost model, both to be based on the data bank of information that has been collected by Washington during the past 6 to 8 years. This paper describes two approaches to the performance model: a regression equation and a probability transition matrix. Efforts to develop a prediction model by regression techniques were unsuccessful. The transition matrix appears promising and relatively simple. General procedures for development and use of this model are given in the paper. A cost model is developed that includes considerations of routine maintenance costs, construction costs, interest, inflation, and excess user costs. The pavement management system framework as developed provides an objective procedure for comparing the performance and cost models of several maintenance strategies and selecting the strategy that will be the most economical for any designated time period.

The investigation described here was implemented in an effort to determine the feasibility of developing a pavement management system for the Washington State Department of Highways. The basic objective of a pavement management system is to develop a systematic procedure that would predict the most economical maintenance strategy for a particular pavement within Washington's network of highways. In effect, the system should provide information on what maintenance to perform and when such maintenance should be started. Thus the system would maximize the effective use of money to be programmed for maintenance on any specific project. In analyzing maintenance strategies, the management system was expected to give specific consideration to the economic advantages of preventive maintenance (generally applied before pavement deteriorates to some unsatisfactory state) over corrective maintenance (generally applied after pavement has deteriorated to an unsatisfactory state).

Publication of this paper sponsored by Committee on Theory of Pavement Design.

RESEARCH OBJECTIVES

The pavement management system considered by this investigation contains four basic features: (a) ability to predict performance; (b) ability to compute costs for various maintenance strategies; (c) ability to be adaptive (dynamic), that is ability to respond to uncertainties associated with actual performance as compared to predicted performance; and (d) ability to make internal changes (system updating) with regard to features a, b, and c.

Performance Model

The purpose of the performance model is to predict the future condition of a given roadway (pavement). Such a prediction is necessary to estimate when major maintenance would be required, predict performance after major maintenance is completed, and relate user costs to pavement performance.

Two specific performance models were studied—the regression model and the Markov chain model. The latter was selected as the most reasonable procedure at this time. The details of the Markov chain model will be given.

Cost Model

The cost items included in the model are:

1. Routine maintenance,
2. Cost of preparation associated with major maintenance,
3. Cost of major maintenance,
4. Cost of shoulder improvements,
5. Interest and inflation,
6. Salvage value,
7. Excess user costs associated with major maintenance, and
8. Excess user costs associated with traffic slowdown due to pavement deterioration.

In determining economic cost of a maintenance strategy, we discounted all the future costs to their present worth at a specified time by using an appropriate interest rate.

Adaptive Characteristics

The management system is based on the ability to predict future performance of pavements on a kilometer-by-kilometer basis. The prediction model provides an estimate of the expected performance value of the pavement at some future time. It has been recognized that specific kilometer-by-kilometer sections may not perform as predicted. Parts of this variation can be attributed to errors in field evaluation; unusual circumstances (severe climate, construction variations, or change in traffic pattern); and unexplained factors that influence performance. Thus the management system must be adaptive or responsive to deviations from predicted values.

System Updating

One of the requirements of the management system is the need for it to be updated, which allows for changes in the performance model associated with factors such as new construction methods, new design practices, or new legal load limits. In general, the scheme adopted for system updating would result in the accumulation of field data for approximately 6 years in the data bank. As more information is obtained from the field, the older data would be eliminated in determining parameters of the performance model.

RESEARCH APPROACH

The procedure for implementation of this investigation was as follows:

1. Determine the desired goals for a management system by discussion with the personnel of the Washington Department of Highways;
2. Discuss with department personnel current operating procedures for materials, design, construction, and maintenance;
3. Review with department personnel specific data potentially available for use in management system;
4. Combine information from items 1, 2, and 3 into a hypothetical system and illustrate the operational characteristics with hypothetical data;
5. By using sample information provided by the department, generate performance and cost models; and
6. Develop computer programs to (a) determine the maintenance strategy that will result in the minimum total expected cost, (b) predict the expected value of pavement condition and standard error of the performance prediction, and (c) calculate the budget requirements for each 2-year period for the selected maintenance strategy.

SCOPE

Because of space limitations, implementation of all the steps presented in the research approach cannot be described in this paper. Details on all aspects of the investigation are available elsewhere (1).

This paper emphasizes a summary of the completed investigation. Details of the performance model and the cost model are given, and the operational logic of the search method employed in determining optimum maintenance strategy for a given pavement section is discussed. The adaptive characteristics of the system, the scheme of updating information, and details of the computer programs are not discussed.

PERFORMANCE MODEL

Two specific performance models were studied—the multiple regression model and Markov chain model. In both models, the pavement condition was described by a pavement rating number R_R between 0 and 100. The R_R used by the Washington Department of Highways combines objective measurement of pavement roughness G_R and the subjective measurement of physical distress G_D into a single number. Pavement condition surveys are made every 2 years over the entire state system, and data are currently available on most pavements since 1968. Details regarding computation of R_R can be found elsewhere (2).

Multiple Regression Model

The multiple regression approach has the potential of individualizing pavement performance on a kilometer-by-kilometer basis depending on those physical factors known to engineers to influence significantly the performance of a pavement. The pertinent factors for regression analysis, chosen in consultation with the department personnel, are given in Table 1.

The results of the regression analysis were considered to be unacceptable for use as a prediction model. The multiple correlation coefficients were 0.718 for rigid pavements and 0.846 for flexible pavements. The standard error of estimate for R_R was approximately 7 for rigid pavements and 11 for flexible pavements. An analysis of variance indicated that time was the only factor that affected average R_R significantly. For rigid pavements, the partial regression coefficient for time was 2.9 with a standard error of ± 0.4. Thus, annual change in R_R could be estimated to range between 1.7 and 4.1 ($\pm$ three times the standard error) with the expected value being 2.9. For flexible pavements, the partial regression coefficient was 4.6 with a standard error of ± 0.7. The annual change in R_R for these pavements could range from 2.5 to 6.7. These average rates of change in R_R were significantly higher than those currently being estimated by the department.

Markov Chain Model

The Markov chain model uses a one-step probability transition matrix in predicting future pavement conditions. The theoretical background of this approach can be found in probability textbooks (3, 4).

The essential requirement needed to develop a prediction model is the probability transition matrix such as that shown in Figure 1 for maintenance alternative 1 for asphalt pavement. For this matrix, reducing the pavement rating from discrete values to condition states as defined by intervals of R_R was found to be convenient. The interval selected was 10 points on the R_R scale. This interval was selected based on the general confidence interval believed to be associated with the field determination of the pavement rating. Thus in Figure 1 a condition state of 7 indicates an R_R value between 70 and 79.

The tabulation summarizes the field data for any 2-year period for which field observations were made on a series of roadway sections. For example, for a particular section, the condition of a particular roadway has changed from a condition state of 6 to a condition state of 5. By combining data from all pavement sections within a particular district, one can obtain a distribution of the probable transitions or a probability transition matrix for that type of pavement in that district.

Again, in Figure 1, the numerical values indicate the probability associated with each transition. For example, the data used to develop this matrix have indicated that, when a pavement is in condition state 7, there is a 5

Table 1. Factors included in regression analysis to predict pavement conditions.

Type of Pavement	Factors for Regression Analysis
Rigid and flexible	R_R values for four condition surveys Average daily truck traffic Thickness of treated layers Thickness of untreated layers Resistance value of subgrade materials Time in years Number of days below 0°C
Rigid	Average modulus of rupture for PCC Range in modulus of rupture for PCC
Flexible	Average void content in asphalt concrete Range in void content in asphalt concrete

Note: 1°C = (1°F - 32)/1.8.

Figure 1. Probability transition matrix for alternative 1.

FROM CONDITION STATE \ TO CONDITION STATE	9 100-90	8 89-80	7 79-70	6 69-60	5 59-50	4 49-40	3 39-30	2 29-20	1 19-10
9 90-100	0 90	0 10							
8 80-89	0 05	0 65	0 30						
7 70-79		0 05	0 60	0 25	0 10				
6 60-69			0 05	0 45	0 25	0 20	0 05		
5 50-59				0 05	0 25	0 40	0 30		
4 40-49					0 05	0 20	0 75		
3 30-39						0 05	0 65	0 30	
2 20-29							0 10	0 80	0 10
1 10-19								0 05	0 95

Figure 2. Performance prediction obtained from probability transition matrix.

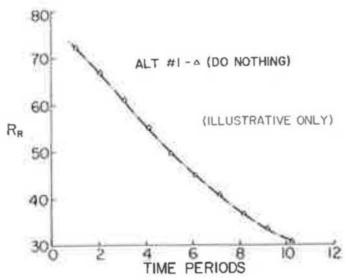


Figure 3. Performance trends for various maintenance alternatives.

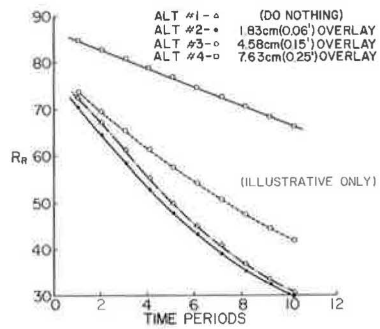


Figure 4. Constraint for mandatory action.

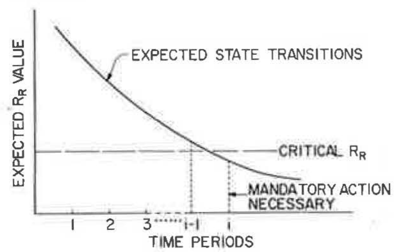
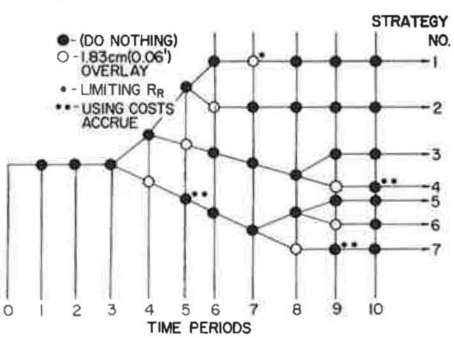


Figure 5. Subset of feasible maintenance strategies.



percent chance that it will be in condition state 8 after 2 years, a 60 percent chance that it will remain in state 7, a 25 percent chance that it will be in state 6, and a 10 percent chance that it will be in state 5. The matrix indicates there is no chance of being in those states for which no value is indicated.

From the probability transition matrix and initial condition of a pavement, one can find the expected R_R value of the pavement at any future time. The mathematics involved in this procedure can be found elsewhere (1). Figure 2 shows the expected performance trend for the information contained in Figure 1. This model is associated with the performance of the original construction aided only by routine maintenance. The continuation of routine maintenance is a valid maintenance strategy and is referred to here as the do nothing alternative.

From Figure 2 the performance trend line is observed to be curvilinear. The annual drop in R_R is approximately 3 points until the pavement reaches a value of 40 when the rate of change drops to 2 points/year. These rates are in keeping with the experience of department personnel.

For the pavement management system to function properly, three general types of transition matrices had to be developed for (a) performance after original construction, (b) condition immediately after major maintenance (initial state vector), and (c) performance after each alternative major maintenance.

For purposes of the feasibility study, matrices such as that shown in Figure 1 were developed in consultation with department personnel. Initial state vectors that specify pavement condition immediately after an overlay were also estimated. The performance trends for the various maintenance alternatives based on these matrices are shown in Figure 3. Alternative 1 in this figure represents the performance trend of the original construction with routine maintenance.

COST MODEL

A detailed economic analysis of road maintenance for use in the maintenance system can be found elsewhere (1). In this section, a brief summary of the elements of the analysis is provided.

Two kinds of costs are considered in the analysis: costs to the highway department and costs to the user. Costs to the highway department can be classified as direct and indirect. Direct costs (cash flow) would be those associated with the actual cost for personnel, materials, and equipment required to accomplish maintenance, including provision for inflation. Indirect costs would be those associated with interest. Excess user costs are those incurred by the user because of time delays resulting either from construction or from the condition of a particular roadway (5).

User costs have a significant effect on the selection of an optimum maintenance strategy. The only incentive for keeping pavements in smooth condition is the reduction in user costs. If these costs are neglected, the optimum maintenance strategy would almost always be to do nothing until the pavement reaches a totally unsatisfactory condition. Every effort should be made to obtain reasonable numbers for the user costs. In the initial implementation, the numbers suggested by Finn, Kulkarni, and Nair (1) may be used.

DETERMINATION OF OPTIMUM MAINTENANCE STRATEGY

The objective of the pavement management system is to provide information useful to the decision maker in the selection of the optimum maintenance strategy for a given pavement section. A maintenance strategy, as defined here, consists of two components: type of maintenance alternative to be adopted (such as type of overlay) and timing of that maintenance alternative.

The procedure used in determining the optimum maintenance strategy consists of the following steps:

1. Selection of a set of feasible maintenance strategies,
2. Prediction of pavement condition under each feasible maintenance strategy within the analysis period, and
3. Calculation of total expected cost of each feasible maintenance strategy.

Selection of a Set of Feasible Maintenance Strategies

To make the management system compatible with the current operating procedures of the state, the constraint of a mandatory action at a preselected critical R_R value is adopted. Thus, if at any time period the R_R value of a given pavement is expected to fall below the specified critical R_R value, it is assumed that one of the given maintenance alternatives will be adopted (Figure 4). Each time period in the analysis consists of 2 years.

Within the constraint of minimum R_R, a number of maintenance strategies can be obtained. In theory, one should consider all the given maintenance alternatives at each time period in the analysis. With only a few maintenance alternatives and a relatively short analysis period, the total possible maintenance strategies following this scheme become very large. Fortunately, from the optimization viewpoint, several of these possible strategies can be discarded as being very remote from the potential region of optimum solution. The set of the possible maintenance strategies can therefore be reduced to a much smaller set of feasible maintenance strategies.

The implementation of the search for feasible maintenance strategies can be best explained by an example. In the following discussion, K_1 denotes the time period since the start of the analysis at which the first overlay is scheduled and K_2 denotes the time period since K_1 at which a second overlay is scheduled.

Consider the following example in which, for the sake of illustration, only two maintenance alternatives are studied: (a) alternative 1, the do nothing alternative (normal rate of deterioration with routine maintenance), and (b) alternative 2, in which an overlay of 1.83 cm (0.06 ft) is used. In the example the following values apply:

Item	Value
Initial R_R value of the pavement	75
Critical R_R value (RCRI)	40
Level at which user costs start occurring (UCLEVEL)	50
Analysis period, time periods of 2 years each	10

Let the prediction of the expected R_R values of the pavement be as follows:

	Expected R_R Value			Expected R_R Value	
Time Period	Alternative 1	Alternative 2	Time Period	Alternative 1	Alternative 2
1	71	68	6	42	41
2	67	64	7	39	38
3	62	60	8	32	33
4	55	53	9	27	27
5	49	44	10	22	23

Three considerations are used in the selection of feasible maintenance strategies.

1. A mandatory action is necessary at time period 7 after the start of the analysis if alternative 1 is adopted throughout.
2. At time period 5, the expected R_R goes below 50, the level at which user costs start occurring; to avoid user costs, an overlay at time period 4 should be considered.
3. If an overlay of 1.83 cm (0.06 ft) is scheduled, mandatory maintenance becomes necessary again at time period 7 following the overlay.

With this information, values of 7, 6, 5, and 4 are successively chosen for K_1. Values higher than 7 cannot be considered because of the constraint of mandatory action; values lower than 4 are not considered because such values would only increase construction costs and not significantly reduce user costs.

Next, consider the selection of K_2 values for this example. Suppose that K_1 is 7; 3 time periods still remain within the analysis period of 10. The expected R_R values for these 3 time periods are 68, 64, and 60. Because the last value is greater than both RCRI and UCLEVEL, a second overlay is not scheduled and K_2 is set to zero. On the other hand, if K_1 is 4, the expected R_R values for the remaining 6 time periods are 68, 64, 60, 53, 44, and 41. Because the expected R_R goes below 50 at time period 5, a second overlay at time period 4 is considered and K_2 is set to 4.

All the feasible strategies selected for the illustrative example are shown in Figure 5. These can be enumerated as follows:

Maintenance Strategy	K_1 Value	K_2 Value	Maintenance Strategy	K_1 Value	K_2 Value
1	7	0	5	4	0
2	6	0	6	4	5
3	5	0	7	4	4
4	5	4			

Prediction of Pavement Conditions Under Each Feasible Strategy

The Markov chain model is employed to predict future conditions of a given pavement under each of the feasible maintenance strategies selected in the previous step. The Markov model requires the initial condition of a pavement immediately after the adoption of a given maintenance alternative and the one-step transition matrix for the alternative. From this information, the model finds the expected state of the pavement and its expected R_R value.

Calculation of Total Expected Cost of Feasible Maintenance Strategies

For each feasible maintenance strategy, routine maintenance costs, construction costs, preparation costs, traffic interruption costs during construction, excess user costs due to slower traffic, and salvage value at the end of the analysis period are calculated. The total expected cost is then found from the following

$$\text{Total expected cost} = \text{routine maintenance cost} + \text{construction cost} + \text{preparation cost} + \text{traffic interruption cost} + \text{excess user cost} - \text{salvage value} \quad (1)$$

All the costs are discounted to bring them to their present worth values. The discount factors are calculated from the following formula:

$$\beta(I) = 1/(1 + i_e)^{2I} \quad (2)$$

where

$\beta(I)$ = present value of $1 spent at the end of the Ith time period and
i_e = effective interest rate = interest rate - inflation rate

The salvage value is calculated as follows:

$$\text{Salvage value} = (\text{usable life left in last overlay} \div \text{total expected life of last overlay}) \times \text{construction cost of last overlay} \quad (3)$$

Preparation cost, excess user cost, and salvage value depend on pavement conditions; construction cost and traffic interruption cost depend on type of maintenance alternative and method of handling traffic during construction; and routine maintenance cost depends only on time periods since the last overlay.

CONCLUSIONS

The investigation described here indicates that a pavement management system is feasible and can be implemented by the Washington State Department of Highways. The major requirements for such a system can be satisfied within the constraints of existing operating procedures. The major benefits from the system will be in the optimum usage of funds. It must be noted that the implementation of the system may not reduce the funds required for maintenance of the total network. The management system will, however, provide a systematic and reasonably objective procedure for using maintenance funds in the most efficient way possible. This could result in a general upgrading of the network without an increase in the total budget requirements.

A limited parametric evaluation of the system indicates the crucial role of user costs in the selection of optimum maintenance. A major effort for the implementation of the system will be in developing realistic user costs.

Parts of the management system that may require improvement are treatment of uncertainties and consideration of time-dependent transition matrices in the Markov model.

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