Network Level Optimization/Prioritization of Pavement Rehabilitation

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A procedure has been developed to optimize pavement rehabilitation strategies for the highway network in Mississippi. The methodology is developed in two stages: project level and network level. First, at the project level, a set of feasible double-action strategies and the corresponding times of implementation of each alternative of every strategy are determined. The optimum rehabilitative strategies are selected by maximizing pavement performance for a 12-yr analysis period. A univariant search technique is employed to solve for the nonlinear optimization problem. The second part of the analysis deals with network level optimization. Selection of the set of projects is done by maximizing pavements performance weighted with respect to traffic. The projects for rehabilitation for the next 12 years are selected using a 0-1 integer linear program, which, for computational convenience, is transformed into a dynamic program. The final results of the two-stage analysis are the selection and timing of major rehabilitative activities. An example problem involving 39 sections (250 two-lane miles) of Interstate highways in north Mississippi is solved, and salient results are presented in the report.

A major objective of a pavement management system (PMS) is to assist highway engineers in making consistent and cost-effective decisions related to the maintenance and rehabilitation of pavements. Realizing the importance of PMS, the Mississippi State Highway Department (MSHD) initiated a research project to develop a pavement management information system (PMIS) in April 1986. An integral part of a PMIS is a decision model that can be used to determine the optimum type and timing of preservation actions for different pavement segments. An optimization model, with provision to prioritize rehabilitation actions for maximum benefit, is described in this paper.

The PMIS, as envisioned, comprises four distinct but interrelated components: data base, pavement rating system, prediction model, and ranking method for the selection of annual maintenance and rehabilitation (M and R) program. A brief description of these items is included in the following sections.

The pavement data compiled for the PMIS include both historical data (geometric information, original construction data, overlay information, junction details, and traffic data) and inventory or condition data (road roughness and distress information). The dBase III Plus in conjunction with a second package, Symphony, compose the data base.

The inventory data, collected annually for the time being, need standardization, for which a rating scale, zero to 100, is adopted. The pavement rating, designated pavement condition rating (PCR), includes two component elements: road roughness (RR), measured in terms of present serviceability rating (PSR) on a zero to five scale, and the distress data determined by a subjective field survey but reduced to distress rating (DR) employing deduct values and weighting factors. A complete description of the data reduction and subsequent PCR calculation procedure by combining RR and DR can be seen elsewhere (1). The condition data is collected by RDM-5000 equipment supplied by Dynatest. The major components of RDM include HP-85 microcomputer, RDM-5000 electronic processor, ultra precision accelerometer, digital distance encoder, and an eight-push-button control box. The roughness measurement by RDM is fully automatic, whereas distress survey is subjective. A description of the equipment as well as the data collection procedure is given in the manufacturer's literature (2).

Not only the present condition of the network, but also the future condition of each pavement section is required for forecasting future needs. Site-specific prediction models are being investigated, and the details of these investigations can be found elsewhere (3). For the purpose of this paper, the deterioration of a road surface may be described by two basic relations: one equation that describes the evolution of road roughness and a second that describes the surface distress. Both equations are assumed to be linear, with a scale from zero to 100. A prediction model, designated as the performance curve, is depicted in figure 1. As the curve indicates, during the early life of the pavement, the roughness rating is generally lower than the distress rating, in which case the roughness rating governs the performance curve.

The fourth component of a PMS involves some form of ranking methodology or an optimization and/or prioritization system. The ranking methodology generally encompasses a ranking of the pavement sections for scheduling the annual rehabilitation program. Programming at the network level for a predetermined period in the future, designated as the analysis/programming period, would require complex optimization methodology that has the additional capability for shifting projects back and forth to result in maximum benefit to public road users. This paper presents the development of an optimization/prioritization model followed by an example problem that illustrates the salient features and typical results of the model.

OPTIMIZATION AND PRIORITIZATION

A comprehensive process of priority programming should enable one to answer the following three questions:

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• What projects (or sections) should be built? (selection of projects)
• How should they be built? (selection of alternative strategies within projects)
• When should they be built? (selection of project timings)

Models, however, that simultaneously deal with these three questions are complex. Consequently, most of the models used by highway agencies deal only with the first or first two questions. If the available funds are to be optimized, however, all three questions need to be considered; the present study addresses all three questions.

Because of their interdependence the three questions cannot be answered independently; the two main programs developed in this paper, however, address them collectively. Each program covers the two phases of an optimization methodology: project level and network level. The project-level optimization, employing the performance equations in conjunction with cost-benefit ratio and maximizing user benefit, solves for project timings and economically feasible strategies for each project. For a given set of annual budgets, the network-level analysis produces an optimum (again, maximizing user benefit) priority program of pavement improvements for a programming period of up to 12 years at the network level.

Project Level Optimization

The subsystem theoretically allows the engineer to analyze as many different types of alternatives as he desires for each road section analyzed. It is not unusual, however, for the engineer to select subjectively a few (three to five) alternatives from the list of all possible alternatives (see Table 1). The selection of alternatives for a network depends primarily on the severity and extent of distresses on the road surface.

The selection of a single alternative or a combination of alternatives, hereafter referred to as a strategy, depends on the minimum life constraint. In other words, performance equations must be defined for each alternative in order to establish the most cost-effective rehabilitation strategy for each project. Analytical or empirical methods have been employed in the past for predicting pavement condition as a function of age and traffic (4). Judging from the previous studies, several years' inventory data would be required to derive reliable performance relationships. The lack of adequate data has mandated that linear performance models, based primarily on projected life of rehabilitation, be adopted in this study. That is, the course of deterioration is dictated by the expected life of each alternative, as listed in Table 1.

The distress rating increase to 100 after a rehabilitation treatment; whereas the roughness rating, dictated by the treatment and also by the condition rating before the treatment, increases to a value not more than 84. A roughness rating of 84 corresponds to a PSR value of 4.2, the maximum attainable in a new or overlaid pavement (5). Following rehabilitation treatment, the condition rating continues to decrease linearly with time.

A word of caution concerning the linearity assumed in the above two models is appropriate. It is generally believed that the performance curves show an increasing rate of deterioration with time (5). Some recent studies (6), however, show the relationship to be neither linear nor exponential as generally assumed, it assumes a sigmoidal shape. For lack of a better relationship, and because of the (prediction) model description is not crucial for purposes of this study, the researchers decided to employ linear relationships as shown in figure 1. Note that the linearity assumption does not alter the basic problem; its use, however, may affect $t_1$ and $t_2$ —times at which the first and second rehabilitation actions are to be undertaken.

Using the performance prediction models described in figure 1, one must define a threshold region within which a rehabilitation alternative should be considered. As a pavement ages, its condition gradually deteriorates to a point where
TABLE 1 FIVE REHABILITATION ALTERNATIVES SELECTED FOR INTERSTATE HIGHWAYS

<table>
<thead>
<tr>
<th>No</th>
<th>Description of Rehabilitation</th>
<th>Expected Life, years</th>
<th>Cost of Rehabilitation, $/sq. yd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1 1/2 inch HMAC overlay</td>
<td>3.75</td>
<td>4.65</td>
</tr>
<tr>
<td>2.</td>
<td>1 1/2 inch HMAC overlay with stress relieving layer</td>
<td>4.25</td>
<td>5.85</td>
</tr>
<tr>
<td>3.</td>
<td>3 inch HMAC overlay</td>
<td>6.00</td>
<td>7.20</td>
</tr>
<tr>
<td>4.</td>
<td>1 1/2 inch Milling and 3 inch HMAC overlay</td>
<td>7.50</td>
<td>9.00</td>
</tr>
<tr>
<td>5.</td>
<td>1 1/2 inch HMAC with stress relieving layer</td>
<td>10.00</td>
<td>11.00</td>
</tr>
</tbody>
</table>

FIGURE 2 Performance trend when rehabilitated. Moment of the shaded area (bounded by line segments ABCDEFGHI) about the zero PCR level provides benefit.

some type of rehabilitation should be applied. At this state of deterioration distress is showing but might not yet be severe enough to call for immediate remedial action. Unfortunately, this point is all too often passed and the pavement continues to deteriorate until something must be done to rehabilitate it. These two points on the performance curve, aptly named the upper and lower margins (figure 2), define a probable rehabilitation period. This concept is slightly different from a single trigger rating, as shown in figure 1.

When rehabilitation treatment is eventually applied, the pavement rating increases abruptly, marking the beginning of a new cycle (see figure 2). Throughout the life of a pavement,
many restorative actions occur, demonstrating a new performance cycle each time rehabilitation is applied. Obviously, many different remedies are possible, and each one generates its own performance curve following application. Not only are many remedies possible, but a large number of different combinations are possible when the timing, sequence, or type of action are changed over an extended period. In this report, a rehabilitation strategy is defined as a combination of rehabilitation alternatives designated by type, sequence, and application time. Figure 2 illustrates pavement condition variation when two rehabilitation actions are applied at times \( t_1 \) and \( t_2 \), respectively.

### Economic and Benefit Analysis

Each rehabilitation strategy that meets the minimum life constraints is subject to an economic analysis, which involves calculation of the capital cost of all the strategies for a 12-yr period from the start of the priority programming period. The present worth of the total costs is calculated (accounting for interest rate and inflation) in determining the cost-effectiveness of the strategy.

The benefit or effectiveness as used in this study is nonmonetary and is a measure of the reliability with which a pavement segment will serve its expected life. The area under the performance curve (ABCDEFGH in figure 2), weighted with respect to user comfort, is judged to be an adequate measure to quantify the benefit accrued to the road user. Because a road section of higher condition level provides an improved ride and enhances user comfort, area elements closer to the performance curve (or farther away from the zero PCR level, figure 2) should be given a higher weighting factor than area elements closer to the zero PCR level. The weighting factor in benefit calculation is included by taking the first moment of the area about the zero PCR level (or time axis). The total benefit of each pavement section may be computed as the product of the above quantity with its length and with some function of the total traffic that it serves (AADT).

#### Project Level Optimization Program (PLOP)

Figure 3 is a flowchart demonstrating the operations and work flow in the optimizing program. The project level optimization is a systematic procedure to select all the optimal double-action strategies and the corresponding times of implementation for each project. (A double-action strategy comprises two alternatives.) Not 1 but 25 optimal double-action strategies are possible for each section. Five alternatives may result in more than 25 strategies (several hundreds) depending on the implementation times \( t_1 \) and \( t_2 \) selected from 0- to 12-yr analysis period. Out of all possible strategies, the search technique selects 25 optimal double-action strategies. The selection procedure is based on maximizing the user benefit.

First, the time of implementing all strategies is determined, followed by a benefit-cost analysis eliminating any unfeasible strategies for each project. The resulting ten to fifteen double-action strategies subsequently are subjected to incremental benefit-cost ratio (IBCR) analysis, as described later.

The decision variables of the first stage optimization include \( t_1 \) and \( t_2 \), the times of implementation of the double-action strategy, respectively. The objective function was to maximize the total benefit of each section, including the salvage value, for the analysis period of 12 years. Besides being lengthy, the objective function turned out to be nonlinear in \( t_1 \) and \( t_2 \), thus adding to the complexity of the solution procedure. Because conventional solution procedures (for example, Lagrangian multipliers, constraint variation, and penalty function, etc.) are time consuming for large problems such as that encountered in a PMS, a direct-search method (univariate search technique) is employed in this study. The univariate search is one-dimensional, with only one variable altered over its range at one time. Other details of the search technique and the software developed for this purpose can be seen elsewhere (7).

#### Selecting Feasible Strategies

The ten to fifteen double-action (optimal) strategies selected for each section are theoretically feasible for implementation because they satisfy the constraints of the Network Optimization/Prioritization System (NOPS).

The NOPS subsystem forms the priority or financial-planning analysis part of the PMS. Priority planning leads to a decision regarding which combination (based on highest benefit to the user), out of all the feasible combinations available in the PLOP program, will be used. The nonlinear optimization alluded to above results in five to eight alternatives that are technically and economically feasible. Which solution is selected depends on the condition of the rest of the network and the budget available. In order to select one alternative per section, one uses 0-1 integer programming to optimize the benefits accrued to the network system. The optimization provides the best solution that can be accommodated within budget limitations (figure 4).

The problem is formulated as follows:

\[
\text{Maximize } \sum_{j=1}^{m} \sum_{j=1}^{n} X_{ij} R_{ij} \\
\text{subject to:} \\
\sum_{j=1}^{m} X_{ij} C_{ij} \leq B_{ij} \\
\sum_{j=1}^{m} X_{ij} C_{ij} \leq B_{ij} \\
\sum_{j=1}^{m} X_{ij} = 1 \\
X_{ij} = 0 \text{ or } 1
\]

where:

- \( X_{ij} \) = \( j \)th double-action combination of the \( i \)th project (the decision variables),
- \( R_{ij} \) = benefit of \( i \)th project if the \( j \)th double-action combination is implemented,
- \( B_{ij} \) = total benefit of the total strategies.

In addition, the following constraints are also included:

\[
\sum_{i=1}^{n} X_{ij} \leq 1, \text{ for } j = 1, \ldots, m
\]

and

\[
\sum_{j=1}^{m} X_{ij} = 1, \text{ for } i = 1, 2, \ldots, l
\]
\( C_{ij} \) = cost of the \( j \)th double-action combination of \( i \)th project,
\( C_{ij} \) = cost of implementation of first or second action of the double-action combination \( j \) on \( i \)th project in year \( t \),
\( B_{xt} \) = overall analysis period budget, and
\( B_i \) = agency budget in year \( t \).

A detailed description of integer optimization formulation is given in references (7) and (8). The integer programming model is found to be appropriate for problems with comparatively few variables. With an increase in the number of variables the computation time becomes prohibitively excessive, and the probability of convergence to an optimum solution is questionable. Taking advantage of the sequential structure of the integer programming model transforms the problem into a dynamic programming model.

The sequential structure of the integer programming model, from the first road section to the last one in the network, constitutes an \( N \)-decision problem, where \( N \) represents the number of road sections in the network. Using the dynamic programming model transforms the \( N \)-decision problem into \( N \) one-decision problems. For example, if the decision process included three feasible strategies (ascertained from PLOP) and 10 sections the number of possible combinations of decisions would be \( 3^{10} \). Figure 5a depicts the complexity of the decision tree over just three decision levels.

When properly applied, dynamic programming reduces the
problem size and still guarantees an optimal or best solution within the bounds of the model used. In the cited example, the 3\textsuperscript{rd} possible combinations or decisions reduce to $3 \times 3 \times 9$ decisions for the same period.

The decision process of pavement rehabilitation at the project level is modeled as a series of staged decisions. At each decision level or stage, all the feasible strategies (only three in this study, signified by the three branches a, b, and c of the decision tree) are applied to each section. Only the strategy that gives each of the entering sections its maximum benefit or performance is retained and passed on to the next stage. The property of the dynamic programming algorithm permits reduction of the decision tree to a feasible size for computer solution. This is illustrated in figure 5b.

The overall budget for the 12-yr analysis period is satisfied in the dynamic problem algorithm, but the yearly (annual) budget may or may not have been satisfied. Should the funds required in any of the 12 years exceed the annual budget for the corresponding year, a benefit-cost ratio analysis is performed on all the rehabilitation strategies included in the optimum solutions, and the strategy with the lowest benefit-cost ratio is eliminated from the set of economically feasible (three in this study) strategies. The dynamic programming procedure is repeated with the revised set (one less than in the previous set) of feasible combinations to arrive at a possibly different optimum combination. This procedure is repeated until all the yearly budgets are satisfied.

Alternatively, a nearly optimum solution may be obtained by judiciously revising the yearly budgets, as dictated by the network condition. In the event that the road network is in uniform condition, the annual rehabilitation costs may fluctuate significantly from year to year. An indication of the yearly budget requirements is initially compiled from the first run of the dynamic optimization problem, this time employing a uniformly increasing yearly budget or any other appropriate combination. Based on the first stage, or exploratory, solution, the engineer may want to revise the yearly budgets reflecting the trend of the exploratory solution and simultaneously satisfying the financial constraints of the department.

A second or third application of the dynamic program with those revised budgets would guarantee a nearly optimum solution for most problems.

In the unlikely event that the yearly budgets remain uniform, and when the trial procedure is repeated to the extent that only one feasible combination remains for every road section, there is no optimum solution for the problem subject to the proposed budget level and the specified upper and lower margins. One or more of these parameters must be altered toward a constraint relaxation condition. The dynamic optimization problem should then be repeated following changes in the parameter(s).

Example Network Analysis

To illustrate the use of the programs developed, the researchers analyzed the interstate system (250 miles of two-lane highway) of District No. 2 of the Mississippi Highway Department. The system includes thirty-nine sections with both flexible and rigid pavements. The input included the features of the sections, the distress ratings and roughness ratings, and corresponding performance prediction models. The five pavement rehabilitation alternatives listed in Table 1 were also input into the program. The output from the dynamic programming model is a listing of selected project plans giving the maximum objective function within the network funding limit.

The nonlinear optimization programming algorithm uses 20 processing seconds to solve for the feasible combinations for a network with 39 projects on an AMDHAL 470-V8 computer (for 39 projects, 5 alternatives or 25 double-action strategies for each project for a 12-yr analysis period). One run of the dynamic programming algorithm consumes 6 minutes to solve for the optimal double action combination for each project satisfying the overall 12-yr budget.

A partial output of the feasible alternatives for five typical sections is included in Table 2. The rehabilitation strategy selected (along with the two actions) by employing the dynamic programming algorithm again for the five typical sections, can
be seen in the table. Note that for section 5, despite that alternative 3 (3-in. HMAS overlay) would have lasted for six years, the dynamic programming solution stipulated that alternative 5 be implemented at the end of five years. Simply stated, it is beneficial to place alternative 5 (4½-in. HMAC with stress relieving layer) over alternative 3 (3-in. HMAS) sooner than six years—the expected life of the latter. The first stage analysis (dynamic program) started with a uniform annual budget of $4.5 \times 10^6; subsequently it was revised, however, as listed in column 2 of table 3. The funds that may be spent according to the optimization model are listed in column 3 of the table. Undertaking a plan of rehabilitation, as shown in column 4 of the table, would maintain the weighted average (weighted with respect to length) PCR of the 250-mi interstate system at approximately 72. Figure 6 depicts the general condition level of the system graphically during the 12-yr analysis period. The top graph (figure 6a) signifies how the average PCR of the system evolves with time. The writers are encouraged that the rehabilitation plan in accordance with the optimization program maintains the average PCR at approximately 72. The estimated percentage of projects with PCR less than 50 is represented by the graph labeled (b) in figure 6. The fact that the optimum plan costing $45.3 \times 10^6 dollars cannot preserve the entire system at the minimum level of PCR = 50 suggests that the rehabilitation budget should be increased in the future.

For comparison purposes, rehabilitation alternatives for the same 39-section network are selected on the worst-first strategy in conjunction with benefit-cost ratio analysis. The network condition signified by the average PCR, in accordance
TABLE 2  SUMMARY OF SAMPLE OUTPUT

<table>
<thead>
<tr>
<th>Section No.</th>
<th>Feasible Strategies Selected at Network</th>
<th>Strategy Chosen</th>
<th>Implementation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>First</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>S (1,1); S (1,2); S (2,2)</td>
<td>S (1, 1)</td>
<td>7.4</td>
</tr>
<tr>
<td>2</td>
<td>S (3,5), S (4,5)</td>
<td>S (3,5)</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>S (3,5), S (4,5)</td>
<td>S (3,5)</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>S (1,3), S (3,2)</td>
<td>S (1,3)</td>
<td>4.6</td>
</tr>
<tr>
<td>5</td>
<td>S (3,5), S (4,5)</td>
<td>S (3,5)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

*Note:* Strategy with alternative 1 (implemented at 7.4 years) followed by the same alternative (implemented at 11.1 years).

TABLE 3  ANNUAL REHABILITATION PROGRAM FOR 12-YEAR ANALYSIS PERIOD

<table>
<thead>
<tr>
<th>Year</th>
<th>Yearly Budget, $ x 10^3</th>
<th>Yearly Funds for Optimal Rehabilitation, $ x 10^3</th>
<th>Projects Selected for Rehabilitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>2600</td>
<td>2590</td>
<td>2,3,21,27,28</td>
</tr>
<tr>
<td>1989</td>
<td>5300</td>
<td>5274</td>
<td>7,8,16,17,18,22,24,26,28,36,38</td>
</tr>
<tr>
<td>1990</td>
<td>3100</td>
<td>3110</td>
<td>5,6,9,10,33,37,39</td>
</tr>
<tr>
<td>1991</td>
<td>4000</td>
<td>3857</td>
<td>13,15,29,31,35</td>
</tr>
<tr>
<td>1992</td>
<td>1850</td>
<td>1838</td>
<td>4,11,14</td>
</tr>
<tr>
<td>1993</td>
<td>6650</td>
<td>6797</td>
<td>19,23,24,3,9,18,21,27,28,39</td>
</tr>
<tr>
<td>1994</td>
<td>6650</td>
<td>6644</td>
<td>7,8,16,22,24,25,26,36,38</td>
</tr>
<tr>
<td>1995</td>
<td>7400</td>
<td>7587</td>
<td>1,12,20,30,31,32,5,6,11,14,29,34</td>
</tr>
<tr>
<td>1996</td>
<td>2100</td>
<td>2125</td>
<td>4,35</td>
</tr>
<tr>
<td>1997</td>
<td>2000</td>
<td>2020</td>
<td>13,15,17</td>
</tr>
<tr>
<td>1998</td>
<td>650</td>
<td>652</td>
<td>10,23,37</td>
</tr>
<tr>
<td>1999</td>
<td>3000</td>
<td>2870</td>
<td>1,12,19,20,30,31,32,33</td>
</tr>
</tbody>
</table>
with the ranking/benefit-cost ratio, is graphed in figure 7a. The effectiveness of optimal solution is substantial indeed, because with the same overall expenditure for a 12-yr period, the network remains at a higher average PCR level (~72) as opposed to a widely fluctuating PCR level, notably a PCR of below 72. The percentage of projects with PCR less than 50, employing ranking/benefit-cost ratio, is graphed in figure 7b and compared to figure 6b. The fact that fewer sections in figure 6b have their ratings fall below 50 attests to the premise that the optimization-prioritization procedure indeed strives to provide maximum benefit (effectiveness) at a specific funding level.

Although not discussed in this paper, if one employs the algorithms, it is a simple matter to justify for adjustments to annual budgets in order to maintain the system at a higher condition level. By repeating the calculation, one can arrive at an approximate optimum level of network funding for the analysis period. In summary, the plan represents the best group of long-range rehabilitation plans at selected yearly budget levels, and also strives to serve the user and pavement structure in the best way possible.

**SUMMARY AND CONCLUSIONS**

The programs and procedures developed in this study focus on the long-range planning of only major rehabilitative measures of a highway network. The approach provides pavement engineers with a tool with which to consider many different alternative plans and rationally select the series of major rehabilitations that maximize the user benefit. The benefit is measured in terms of the first moment of the area under the performance curve. Employing the optimization methodology, one can comprehensively consider the available options and can identify the unique plan that is best for each pavement project at a specific funding level. Reports generated by this procedure describe work to be done and when to schedule it for all the projects in the network. The report listings summarize the results of the long-range plan with respect to total network composite parameters of condition, cost, and performance. Furthermore, if desired, all this information is generated at each of the funding levels considered.

The practical utility of the optimization methodology is illustrated by devising a 12-yr rehabilitation strategy for the Interstate system of the second district of the Mississippi Highway Department. A comparison of the optimal selection procedure with the conventional ranking/benefit-cost ratio approach reveals that the optimal approach strives to provide maximum benefit (effectiveness) at a specific funding level.

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REFERENCES


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FIGURE 7 Ranking/benefit-cost method (a) weighted average PCR (end of year) during the analysis period (b) Percentage of projects with PCR less than 50.