MACROSCOPIC OPTIMUM SYSTEM FOR MANAGEMENT OF PAVEMENT REHABILITATION

By Khaled A. Abaza,[1] Suleiman A. Ashur,[2] Member, ASCE, Sameer A. Abu-Eisheh,[3] Member, ASCE, and Amer Rabay'a[4]

ABSTRACT: A macroscopic pavement management system has been designed to yield optimum pavement conditions under constrained budgets. The system can predict future pavement conditions from performance curves generated using the serviceability concept developed by the American Association of State Highways and Transportation Officials (AASHTO). The pavement performance curves are generated using an incremental analysis of the AASHTO basic design equation. The system then applies an effective optimum decision policy that aims toward maximizing the annual average network present serviceability index according to the expected outcomes of predefined major rehabilitation actions and subject to budget constraints. In contrast to the microscopic approach that considers ''short'' pavement sections, the macroscopic approach to pavement management uses ''long'' pavement sections, i.e., projects. Each project is constructed of the same pavement structural section and possesses a unique performance curve. Pavement projects with similar performance trends are grouped into six classes with each class treated as a single entity. The system is particularly beneficial in establishing long-term pavement rehabilitation policies in terms of planning, scheduling, and budgeting.

INTRODUCTION

The development of both an effective performance prediction model and a sound optimum decision policy is the key to the successful implementation of any pavement management system. Pavement performance has long been recognized as being probabilistic since local conditions may vary from one pavement section to another. Several stochastic pavement prediction models have been investigated by researchers [e.g., Pedigo et al. (1982), Way et al. (1982), Butt et al. (1987), Shahin et al. (1987), and Abaza and Ashur (2000)].

The prediction model used by the macroscopic pavement management system developed in this research uses an incremental solution of the AASHTO basic design equation to produce AASHTO performance curves. The performance curve is a plot of the present serviceability index (PSI) versus time or accumulated 80 kN equivalent single axle load (ESAL) applications. The AASHTO basic design equation is based on statistical regression analysis of pavement condition indicators measured during the AASHTO road test.

The estimation of a future PSI value from a related performance curve is considered to represent the overall average condition of a pavement project constructed from the same pavement structural section. Therefore, the estimated value would be adequate for use in solving the pavement management problem, especially on the macroscopic level since the entire pavement project is considered as one section.

Several optimum models (Wang et al. 1993; Butt et al. 1995; Chua et al. 1993; Li et al. 1997; Abaza and Ashur 1999) have been developed for solving the pavement management problem to optimality, considering the microscopic level. The major obstacle has always been that of formulations where the identity of individual projects is preserved (Pilson et al. 1999).

[1]Asst. Prof., Birzeit Univ., Dept. of Civ. Engrg., P.O. Box 14, Birzeit, West Bank, Palestine. E-mail: kabaza@birzeit.edu

[2]Asst. Prof., Univ. of Texas at El Paso, Dept. of Civ. Engrg., El Paso, TX 79968. E-mail: ashur@utep.edu

[3]Assoc. Prof., An-Najah Nat. Univ., Dept. of Civ. Engrg., P.O. Box 7, Nablus, West Bank, Palestine. E-mail: sameeraa@najah.edu

[4]Civ. Engr. (Software Programmer), Birzeit Univ., Dept. of Civ. Engrg., P.O. Box 14, Birzeit, West Bank, Palestine. E-mail: engamer@yahoo.com

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The complexity of the pavement management problem increases exponentially with the size of the problem. For example, on the project level (one section), if A is the number of rehabilitation actions to be considered over m years (or time periods) within a study period, the number of possible combinatorial solutions is A^m. The number of solutions would become $(A^m)^N$, where N is the number of pavement sections making up a network. Clearly, the optimization of the pavement management problem suffers from the curse of combinatorial explosion and is labeled as ''np-hard'' by the operations research community (Pilson et al. 1999). Therefore, it is quite impossible to solve the microscopic pavement management problem to optimality even for moderate size networks using the fastest supercomputers and the most efficient optimization techniques.

This research simplified the combinatorial problem by substituting pavement classes for pavement projects. There are six pavement classes and only four classes are considered in the optimization process, namely those requiring major rehabilitation. Also, the number of rehabilitation actions A is limited to four with the number of time periods m limited to five. Even with these limitations, the resulting combinatorial solutions would still be very large.

The optimization process to this stated problem has been attempted in a modified approach. The pavement network consists of a number of pavement projects, each constructed of a unique structural section, with each having its own performance curve. The pavement projects are then grouped into six classes based on their current conditions as defined by the corresponding PSI values. The optimization process takes place with respect to four variables representing the amount of rehabilitation work that should be done on each pavement class as a percentage of its total length during each time period of the budget cycle.

The optimization technique used is the simultaneous uniform search (exhaustive search) that divides each variable range [0, 1.0] into search values that increase by 0.05 increments. The optimization process is handled separately for each year in the study period with the outcome of any preceding year considered valid in the optimization of the following year. The objective of the optimization is maximizing the annual average network PSI for a given pavement network. There are budget constraints to be verified prior to the selection of any feasible solution. The details of the optimization procedure are provided in the Methodology section.

METHODOLOGY

There are three key modules to be presented in this section that are considered essential components of any effective pavement management system. They are namely (1) a performance prediction module; (2) a rehabilitation strategies module; and (3) an optimum decision policy module. Each one will be presented in detail in a subsequent subsection.

Performance Prediction Module

The AASHTO method of flexible pavement design is probably the most widely used design method, not only in the United States but also worldwide. The AASHTO Guide for Design of Flexible Pavements (AASHTO 1993) is mainly based on performance trends. The two main factors defining performance are the PSI and 80 kN ESAL load applications. These two factors are also related to several other factors such as materials properties, drainage and environmental conditions, and performance reliability. The design approach applies all these factors to obtain a measure of the required structural strength through an index known as the structural number (SN). The structural number is then converted to pavement layer thicknesses according to layer coefficients representing relative strength of the layer materials. The basic design equation used for flexible pavement (AASHTO 1993) is as follows:

$$\log W_{80} = Z_R S_0 + 9.36 \log(\mathrm{SN} + 1) + \frac{\log\left[\dfrac{\Delta \mathrm{PSI}}{4.2 - 1.5}\right]}{0.40 + \dfrac{1{,}094}{(\mathrm{SN} + 1)^{5.19}}} + 2.32 \log(M_R) - 8.27 \quad (1)$$

where W_{80} = number of 80 kN equivalent single axle load applications estimated for a selected design period and design lane; Z_R = standard normal deviate; S_0 = combined standard error of the traffic prediction and performance prediction; ΔPSI = difference between the initial or present serviceability index (P_0) and the terminal serviceability index (P_t); SN = design structural number indicative of the total required pavement thickness; and M_R = subgrade resilient modulus and must be in newtons per square meter (pounds per square inch).

In the design mode and after all related parameters are estimated, (1) is solved for the design SN by trial and error or using the design chart found in AASHTO (1993). The approach used to define a pavement performance curve as a function of the present serviceability index and 80 kN load applications or service time is based on the direct use of (1). The incremental 80 kN load applications $(W_{80})_i$ is calculated by specifying varying values of the incremental change in the present serviceability index ($\Delta \mathrm{PSI}_i$). The incremental change in the present serviceability index is defined as the difference between the initial serviceability index (P_0) and the incremental present serviceability index (PSI_i). The incremental present serviceability index is varied between its initial value of about 4.5 and the AASHTO lowest allowed PSI value of 1.5. Fig. 1 illustrates the basic concept by which the difference between two successive data points can be used to construct the pavement performance curve. The estimated incremental change in load applications ($\Delta W_{i,i+1}$) can then be converted into an equivalent incremental service time interval ($\Delta T_{i,i+1}$). A computer system has been designed using visual basic programming language with one of its main functions being solving the mathematical algorithm presented below. The assumption made in establishing (2) is that the 80 kN ESAL load applications increase linearly with time

$$\Delta T_{i,i+1} = \frac{\Delta W_{i,i+1}}{W_T} T \quad (2)$$

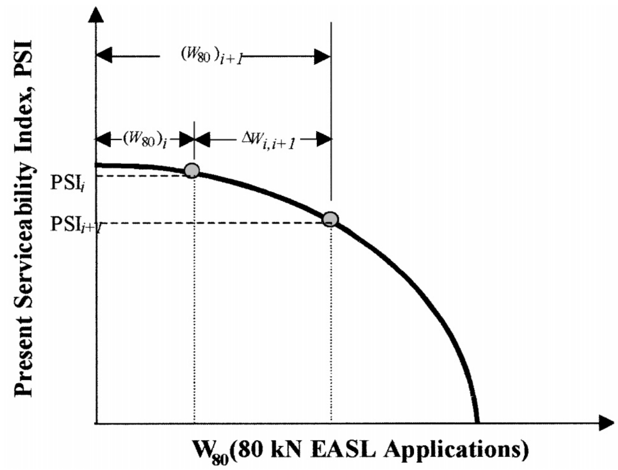

FIG. 1. Basic Pavement Performance Curve

where $\Delta W_{i,i+1} = (W_{80})_{i+1} - (W_{80})_i$, where $i = 1, 2, \ldots, n$; $(W_{80})_i = F(\Delta \mathrm{PSI}_i, \mathrm{SN}, M_R, Z_R, S_0)$ calculated from (1); $(W_{80})_{i+1} = F(\Delta \mathrm{PSI}_{i+1}, \mathrm{SN}, M_R, Z_R, S_0)$ calculated from (1); and $W_T = \sum_{i=1}^{n} \Delta W_{i,i+1}$.

Note that W_T is also the total number of 80 kN ESAL load applications estimated over a design life of T years, where $\mathrm{SN} = F(W_T, \Delta \mathrm{PSI}, Z_R, S_0, M_R)$ calculated from (1), $T = \sum_{i=1}^{n} \Delta T_{i,i+1}$, and $N_{T_{i+1}} = \sum_i \Delta W_{i,i+1} = (W_{80})_{i+1}$, $N_{T_1} = 0.0$, where $N_{T_{i+1}}$ is the cumulative number of 80 kN ESAL load applications estimated over a service life of T_{i+1} years. Also, $T_{i+1} = \sum_i \Delta T_{i,i+1}$, $T_1 = 0.0$, where T_{i+1} is the cumulative service time in years associated with the cumulative 80 kN ESAL load applications ($N_{T_{i+1}}$). In addition, $\Delta \mathrm{PSI}_i = P_0 - \mathrm{PSI}_i$, $\mathrm{PSI}_i = P_0 - (i - 1)\Delta P$, where $i = 1, 2, \ldots, n + 1$, $n = \Delta \mathrm{PSI}/\Delta P$, and $\Delta \mathrm{PSI} = P_0 - P_t$, where ΔP is the specified incremental change in the PSI value used to generate $(n + 1)$ data points to be used in the construction of a particular pavement performance curve. It must be specified either as a tenth or hundredth of a point to ensure that n will be an integer. In the computer program, one hundredth of a point has been specified with the corresponding computer time being very small. A performance curve is then constructed by plotting the incremental present serviceability index (PSI_i) versus the cumulative aging time (T_{i+1}).

The performance curve can be used to estimate the present serviceability index—an indication of future pavement condition—at any specified time. The computer system performs this step graphically as it enters the curve with a specified time and reads the corresponding PSI value. The computer system is also programmed to generate a pavement performance matrix indicating the PSI value at each year of the pavement service life. The performance matrix is generated for each pavement structural section within the network. Performance matrices are stored in the system database for efficient retrieval during the search for an optimum decision policy.

Pavement Rehabilitation Strategies Module

Pavement rehabilitation is a major maintenance action undertaken for the purpose of extending the service life of an existing pavement structure. The appropriate rehabilitation strategy is selected based on the present pavement structural condition. The most widely used rehabilitation actions are plain resurfacing (overlay), resurfacing combined with cold planning (milling), or a skin patch, and partial or complete reconstruction. Corrections to localized failures in the pavement structural section and subgrade are usually performed prior to the application of any rehabilitation treatment. These rehabilitation actions can be applied with cold or hot recycling treatment options as seen appropriate.

Pavement structural sections (projects) are grouped into six classes depending upon their present conditions as indicated by the corresponding present serviceability index values obtained from the performance matrices. Each pavement class is defined by placing upper and lower limits on the selected pavement condition indicator. Classes 1 and 2 are defined to contain ‘‘very good’’ and ‘‘good’’ pavements, respectively, and do not require any rehabilitation treatment. Classes 3, 4, 5, and 6 are defined to contain pavements rated as ‘‘fair,’’ ‘‘poor,’’ ‘‘very poor,’’ and ‘‘bad,’’ respectively, and do require rehabilitation treatment. Therefore, four major rehabilitation actions are needed so that they can be applied to the four pavement classes (3, 4, 5, and 6) as appropriate. Table 1 provides suggested guidelines for defining the various pavement classes using the PSI as the pavement condition indicator. The user can redefine the various classes by changing the limits as desired. The four applicable rehabilitation actions have been designated as rehabilitation action 1 (RA_1), rehabilitation action 2 (RA_2), rehabilitation action 3 (RA_3), and rehabilitation action 4 (RA_4) applied to Classes 3, 4, 5, and 6, respectively.

In this macroscopic pavement management system, the four major rehabilitation actions have been considered with their broad definitions. The system does not specify, nor require, the detailed descriptions of these major actions, but instead, they must be applied and performed as required by the system structure. The system is flexible in the sense that it does not specify exactly what these actions should be made of as long as the concerned highway agency is confident that they would perform as required.

In the system structure, it is assumed that major rehabilitation would result in improving a pavement structural section (project) from its present class to Class 1 or 2 depending on the confidence level the highway agency has in its specified rehabilitation actions and local construction practices. The confidence level is defined through the use of a probabilistic indicator termed as the reliability index α_i. The reliability index indicates that a pavement section currently in Class i will improve to Class 1 with α_i probability or to Class 2 with $(1 - \alpha_i)$ probability. The reliability index may range from 80% to 99% for complete reconstruction and from 50% to 80% for a plain overlay. The reason for lower reliability in the case of overlay can be attributed to aging and distressing of underlying pavement layers. Assigning appropriate values of the required reliability indices is to be determined through the design process according to the highway agency guidelines and policies. Fig. 2 shows a schematic presentation of the various pavement classes along with the applicable rehabilitation actions and their anticipated performance outcomes.

TABLE 1. Suggested Example of Pavement Class Definitions

Pavement class	PSI range	Condition rating	Applicable rehabilitation action
1	$4.5 \geq PSI \geq 4.0$	Very good	None
2	$4.0 > PSI \geq 3.5$	Good	None
3	$3.5 > PSI \geq 3.0$	Fair	RA_1
4	$3.0 > PSI \geq 2.5$	Poor	RA_2
5	$2.5 > PSI \geq 2.0$	Very poor	RA_3
6	$2.0 > PSI \geq 1.5$	Bad	RA_4

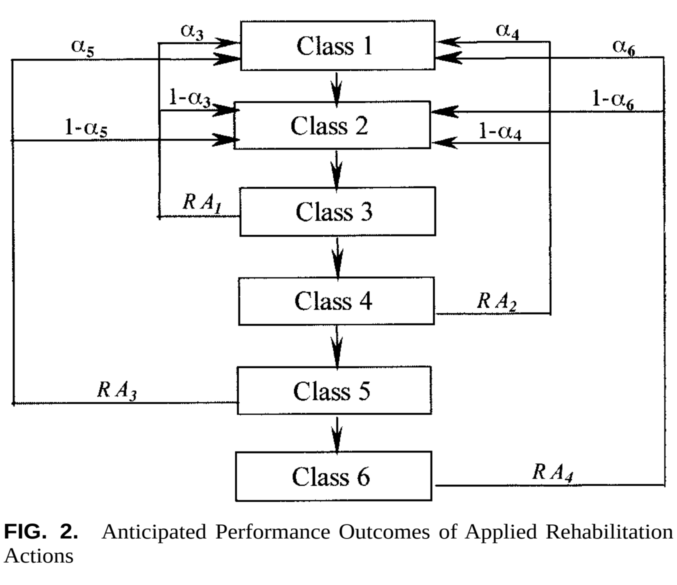

FIG. 2. Anticipated Performance Outcomes of Applied Rehabilitation Actions

Optimum Decision Policy Module

The optimum decision policy deployed by the macroscopic pavement management system is based on maximizing the annual average network PSI value. The average network PSI value is calculated for the various pavement structural sections (projects) in a network similar to a weighted average. The weights are represented by the lengths of various pavement projects in any given network. The optimization process takes place with respect to four variables representing the amount of rehabilitation work to be carried out annually on each pavement project in the four pavement classes qualifying for rehabilitation, namely Classes 3, 4, 5, and 6. The amount of rehabilitation work is defined as a percentage of the total length of all projects in a pavement class during any given year. The objective function of the optimization model is presented in (3).

The optimization model is subject to two sets of constraints. The first set is simply introduced to establish an upper feasible limit on each variable to minimize computer time. It requires that the annual cost of rehabilitation work associated with each variable, if solely considered, must not exceed the anticipated annual budget. The second set requires that the total annual cost of rehabilitation work associated with all four variables must not exceed the anticipated annual budget. The second set is verified for feasible solutions prior to the initiation of the optimization process and all other related calculations. This step would considerably help to cut down on computer time and speed up the convergence of the optimization search process. The two sets of constraints are mathematically described by (4) and (5)

$$\bar{P}_{(k)} = \frac{\sum_{j=1}^{j=N_{(k)}} P_{(j,t)} L_{(i,j,k)}}{\sum_{j=1}^{j=N_{(k)}} L_{(i,j,k)}}, \quad k = 1, 2, \ldots, m \qquad (3)$$

where $L_{(i,j,k)} = X_{(i,k)} \times L_{(i,j,k-1)}$, where $i = 1, 2, \ldots, 6$; and $t = A_{(j,k)} = a_{(j)} + k$

$$\text{Subject to} \quad 0.0 \leq X(i, k) \leq UL(i, k) \qquad (4)$$

where $UL_{(i,k)} = AB_{(k)}/(UC_{(i,k)} \times L_{(i,k-1)}) \leq 1.0$; and $L_{(i,k-1)} = \Sigma_j L_{(i,j,k-1)}$

$$\sum_{i=3}^{6} X(i, k) \times UC(i, k) \times L(i, k-1) \leq AB(k) \qquad (5)$$

where $\bar{P}_{(k)}$ = average network present serviceability index at the kth study year, which is a function of the rehabilitation variables $X_{(i,k)}$; $P_{(j,t)}$ = present serviceability index of the jth pavement project at t years of age as obtained from performance matrices; $A_{(j,k)}$ = age in years of the jth pavement project at the kth study year; $a_{(j)}$ = initial age of the jth pavement project in years ($k = 0.0$); $L_{(i,j,k)}$ = length of the jth pavement project at the kth year in the study period present in the ith class; $X_{(i,k)}$ = rehabilitation variables representing the amount of rehabilitation work to be applied to pavement projects in Class i during the kth year in the study period; $N_{(k)}$ = total number of pavement projects that exist at the end of the kth year in the network; m = number of years (or time periods) specified in the study period; $UL_{(i,k)}$ = upper limit placed on the variable $X_{(i,k)}$ due to budget limitation; $AB_{(K)}$ = annual budget available during the kth year in the study period; $UC_{(i,k)}$ = unit cost (dollars/lane-kilometer) associated with the rehabilitation action applicable to Class i pavements during the kth year; and $L_{(i,k-1)}$ = total length of pavement projects that are present in the ith class during the $(k - 1)$th year in the study period.

The individual identity of each pavement project is maintained throughout the entire optimization process despite the use of pavement classes. This is especially true for incorporating the projected future performance of each project, as obtained from its own performance curve or matrix, explicitly into the objective function. The use of pavement classes is merely for the purpose of specifying the same rehabilitation action and amount of rehabilitation work to all pavement projects in the same class. This seems reasonable as the intent is providing for pavement rehabilitation and the projects, all in the same class, are within a close range of pavement condition that would make them qualify for the same rehabilitation treatment.

In addition, the stated optimization model is solved independently for each year in the study period but with the optimum solution for a preceding year considered implemented prior to solving the problem for the following year. Therefore, a unique optimum rehabilitation policy can result for each year as defined by the four optimum rehabilitation variables, namely $X'_{(3,k)}$, $X'_{(4,k)}$, $X'_{(5,k)}$, $X'_{(6,k)}$. Also, a distinct optimum value of the objective function $P'_{(k)}$ is associated with each annual optimum rehabilitation policy.

The optimization procedure is initiated by the selection of a combinatorial solution of the four rehabilitation variables. The total number of combinatorial solutions depends on the incremental search value specified for generating these solutions. A 0.01 incremental search value results in 100 million solutions, whereas a 0.05 incremental search value results in only 160,000 solutions. The computer time required to solve a particular problem using the first incremental option is 625 times that required by the second option. Therefore, the second option has been recommended since it cuts down substantially on computer time and still provides adequate solutions. A refinement of a derived optimum solution can be efficiently sought in the neighborhood of that optimum if a more accurate solution is required.

A selected combinatorial solution is examined for feasibility by verifying that it meets the two sets of constraints. The feasible solution is then applied to the pavement projects in their respective classes. The length of each pavement project $L_{(i,j,k)}$ is multiplied by the selected feasible value of the applicable rehabilitation variable $X_{(i,k)}$ with their product representing the rehabilitated portion length. The rehabilitated portion length is then multiplied by the assigned value of the corresponding reliability index α_i to yield two new distinct pavement projects. The lengths of these two sections, L_1 and L_2, are simply calculated as indicated by

$$L_1 = X_{(i,k)}L_{(i,j,k)}\alpha_i; \quad L_2 = X_{(i,k)}L_{(i,j,k)}(1 - \alpha_i) \qquad (6a,b)$$

$$L_3 = L_{(i,j,k)}(1 - X_{(i,k)}) \qquad (6c)$$

These two new sections are labeled ''offspring'' and will usually have performance trends different from their ''parent'' project. A parent project is defined as a project that exists at the beginning of a time period. An offspring section is defined as a new project that is added at the end of a time period as a result of rehabilitation work. The first offspring (L_1) is assigned to Class 1 and the second offspring (L_2) to Class 2. Each offspring is assigned its own identification number and performance curve with its age set at zero. The unrehabilitated portion length L_3 will either remain in the same Class i or drop to the next worst one $(i + 1)$ at the end of one time period (year) depending on its present serviceability index value by the end of that time period. But, it continues to carry the same identification number and performance trend.

The generated offspring sections are treated as new pavement structural sections (projects) and added to Classes 1 and 2 by the end of each time period in the study period. Therefore, the total number of pavement projects from a qualifying class can triple by the end of each time period, but this is still not bad, as the initial total number of pavement structural sections (projects) would be much smaller than the total number of microscopic pavement sections in a given network. The total number of pavement projects resulting at the end of a time period (year) is calculated from

$$N_{(k)} = 3NR_{(k-1)} + (N_{(k-1)} - NR_{(k-1)}), \quad k = 1, 2, \ldots, m \qquad (7a)$$

$$N_{(k)} = 2NR_{(k-1)} + N_{(k-1)} \qquad (7b)$$

where $N_{(k)}$ = total number of pavement projects at the kth time period in a given network; and $NR_{(k-1)}$ = total number of pavement projects needing rehabilitation at the $(k - 1)$th time period. For example, if 10 pavement projects are initially present ($N_{(0)} = 10$) and among them are seven sections needing rehabilitation ($NR_{(0)} = 7$), the total number of projects that would be present at $k = 1$ is 24. The total number may not necessarily increase at the same rate in the following years as 14 sections out of 24 are just placed in Classes 1 and 2 and probably would not need rehabilitation for the next 5 years. Fig. 3 provides a flowchart depicting the basic tasks involved in the macroscopic system structure.

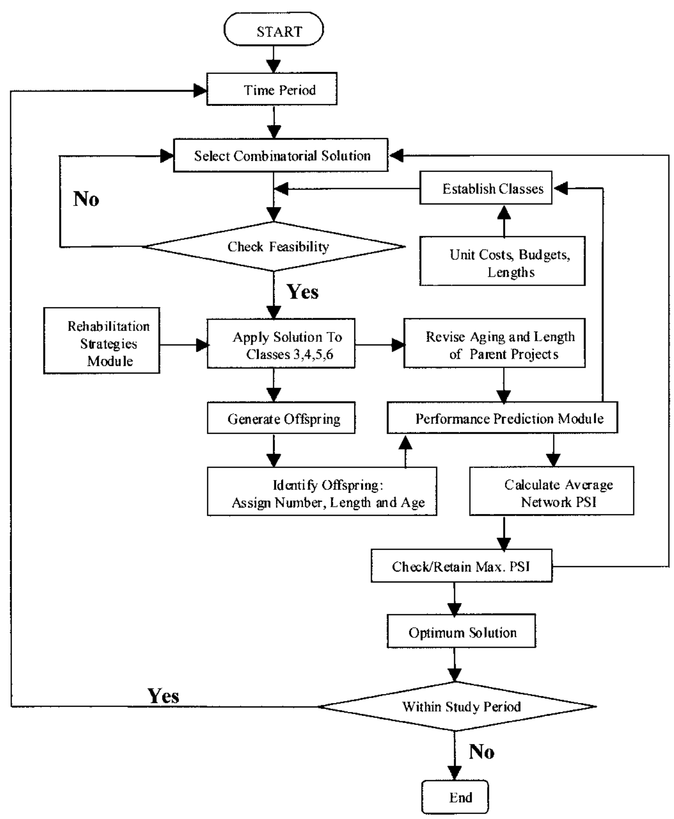

FIG. 3. Flowchart of Basic Tasks Used in Macroscopic System Structure

SYSTEM REQUIREMENTS AND SAMPLE RESULTS

The computer system requires certain data to be provided through screen-displayed specially formatted spreadsheets at various stages of the interactive session. The input data mainly consist of performance prediction data from the AASHTO module and data related to the development of the optimum decision policy module. The input data requirements will be outlined in detail through a sample problem.

Performance Prediction Input Data

The PSI has been chosen as the pavement condition indicator with pavement classes defined according to the suggested example provided in Table 1. For a network of 10 pavement projects, the design 80 kN ESAL applications (W_T) and resilient modulus (M_R) for each project are provided in Table 2. The initial and terminal serviceability indices (P_0 and P_t) are specified at 4.5 and 1.5 for new or completely deteriorated projects, respectively. The standard normal deviate (Z_R) is -1.645 for 95% confidence level. The combined standard error (S_0) is considered 0.35. The initial serviceability indices (P_{01} and P_{02}) for generated offspring sections are specified at 4.25 and 3.75 for first and second offspring, respectively. The design service life (T) is 20 years. The time period is specified as 1 year and the study period (m) is 5 years.

TABLE 2. Input Data for Sample Problem

Project number (J)	$W_T \times 10^6$	M_R	Age $a_{(j)}$ (years)	Length (lane-kilometers)
1	1.0	3,000	3	1.58
2	1.0	6,000	1	5.61
3	1.0	9,000	4	2.56
4	1.0	12,000	12	1.85
5	1.0	15,000	6	3.25
6	5.0	3,000	15	3.95
7	5.0	6,000	11	0.98
8	5.0	9,000	9	2.38
9	5.0	12,000	17	3.11
10	5.0	15,000	19	4.21

Optimum Decision Policy Input Data

1. The initial age in years $a_{(j)}$ and the length in lane-kilometer for each pavement project $L_{(j,k=0)}$ are provided in Table 2.
2. The annual budget $AB_{(k)}$ is assumed as \$160,000 and remains constant for a study period of 5 years. The system can accept a different budget for each year.
3. The unit costs $UC_{(i)}$ associated with the four rehabilitation actions are estimated based on local market prices at \$30,000, \$50,000, \$70,000, and \$90,000 per lane-kilometer for rehabilitation actions 1, 2, 3, and 4, respectively. The system also allows for an increase in prices by accepting an annual inflation rate.
4. The four reliability indices $\alpha_{(i)}$ are specified at 0.80, 0.85, 0.90, and 0.95 for rehabilitation actions 1, 2, 3, and 4, respectively.

Performance Output Data

The output data from the system for the sample problem is of two types. The first type is the performance curves and matrices generated for each pavement parent project and its two offspring sections. Fig. 4 shows the three performance curves A, B, and C associated with a particular pavement project. Curve A represents the parent project, curve B represents the first offspring, and curve C represents the second offspring. In this case, the rehabilitation action is assumed to involve resurfacing; therefore, the performance of the offspring sections, as shown in Fig. 4, is inferior to that of the parent. This

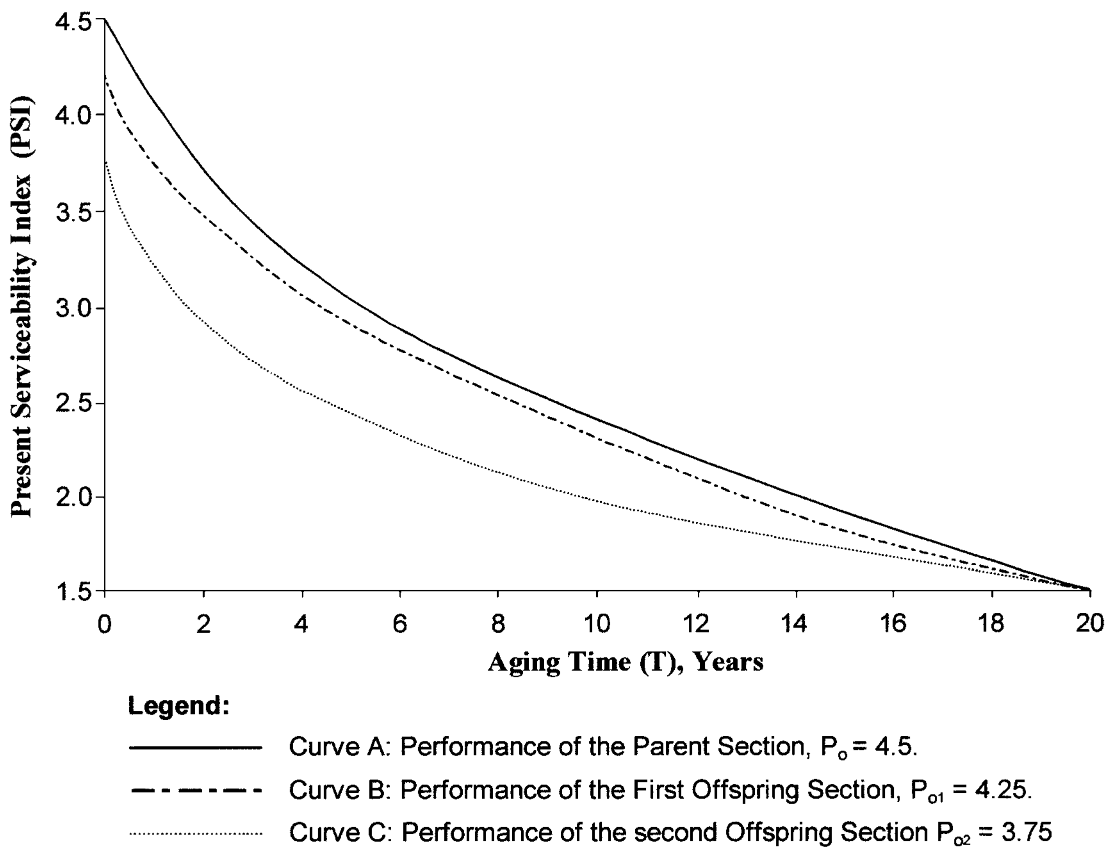

FIG. 4. Performance Curves for Parent Project and Its Two Offspring

TABLE 3. Performance Matrices for Parent Projects and Offspring Sections

Project number (J)	PREDICTED PSI VALUE AT kth TIME PERIOD (YEAR)																	
	Parent						First Offspring						Second Offspring					
	K = 0	1	2	3	4	5	K = 0	1	2	3	4	5	K = 0	1	2	3	4	5
1	3.55	3.37	3.21	3.06	2.92	2.78	3.35	3.19	3.04	2.9	2.77	2.65	2.97	2.83	2.71	2.6	2.5	2.4
2	4.29	4.11	3.95	3.79	3.63	3.48	4.04	3.88	3.72	3.57	3.42	3.28	3.55	3.4	3.26	3.14	3.02	2.9
3	4.08	3.95	3.81	3.67	3.52	3.37	3.84	3.72	3.59	3.46	3.32	3.19	3.38	3.27	3.16	3.05	2.94	2.83
4	3.16	2.98	2.79	2.59	2.38	2.17	3	2.83	2.66	2.48	2.29	2.1	2.68	2.55	2.41	2.27	2.12	1.97
5	4.22	4.12	4	3.87	3.73	3.57	3.98	3.88	3.78	3.66	3.52	3.38	3.5	3.42	3.33	3.23	3.12	3
6	1.89	1.81	1.73	1.65	1.57	1.5	1.85	1.78	1.91	1.64	1.57	1.5	1.78	1.72	1.66	1.61	1.55	1.5
7	2.41	2.3	2.19	2.09	1.98	1.88	2.32	2.22	2.12	2.02	1.93	1.84	2.14	2.06	1.98	1.91	1.83	1.76
8	2.85	2.71	2.58	2.45	2.32	2.2	2.71	2.59	2.47	2.35	2.24	2.13	2.44	2.34	2.25	2.16	2.07	1.98
9	1.9	1.77	1.63	1.5[a]	1.5[a]	1.5[a]	1.86	1.74	1.62	1.5[a]	1.5[a]	1.5[a]	1.78	1.68	1.59	1.5[a]	1.5[a]	1.5[a]
10	1.65	1.5[a]	1.5	1.5[a]	1.5[a]	1.5[a]	1.64	1.5[a]	1.5[a]	1.5[a]	1.5[a]	1.5[a]	1.61	1.5[a]	1.5[a]	1.5[a]	1.5[a]	1.5[a]

[a]Lowest PSI value as allowed by AASHTO model.

can be attributed to aging and distressing of the underlying layers of the resurfaced pavement.

For the case involving reconstruction, performance curves similar or even superior to that of the parents can be obtained depending on the design input parameters provided for the expected offspring sections. The predicted PSI provided in Table 3 is read from performance curves using the expected aging time at each year in the study period for each parent and its two offspring.

Optimum Decision Policy Output Data

The second type of output data is the optimum rehabilitation policy in terms of the four rehabilitation variables. There is a unique optimum solution for each year in the study period as shown in Table 4 along with the corresponding annual optimum values of the objective function. It can be seen that the optimum amount of rehabilitation work is variable over the 5-year period with the variables $X'_{(3,k)}$ and $X'_{(4,k)}$, representing rehabilitation actions 1 and 2, applied to Classes 3 and 4, dominating due to their relatively lower unit costs.

Table 5 provides optimum pavement class lengths and total annual costs associated with the optimum solutions presented in Table 4. Generally, there is no clear indication on how pavement class length varies with the corresponding optimum variables; while some lengths are rehabilitated, others deteriorate and exit their current classes. But, in this example, one can notice that the lengths of Class 1 fluctuated, those of Class 2 increased, and those of Classes 3–6 have generally decreased. The optimum costs are close to the annual budget of $160,000 assumed in the example problem. One can also observe from the values of the optimum objective function ($\bar{P}'_{(k)}$) shown in Table 4 that the allocated annual budget was helpful in providing a little improvement in the annual average network present serviceability index.

TABLE 4. Optimum Solutions for Sample Problem

Study year (k)	X'_3	X'_4	X'_5	X'_6	$\bar{P}'_{(k)}$
0	—	—	—	—	—
1	0.95	0.90	0.00	0.00	3.070
2	1.00	0.85	0.60	0.05	3.106
3	0.00	0.30	0.00	0.15	3.107
4	0.55	0.00	0.10	0.15	3.124
5	1.00	1.00	1.00	0.15	3.123

TABLE 5. Optimum Pavement Class Lengths for Sample Problem

Study year (k)	Optimum Pavement Class Length $L'(i, k)$, lane-kilometers (Pavement Class i)						Optimum cost ($)
	1	2	3	4	5	6	
0	11.42	1.580	1.850	2.380	0.980	11.27	—
1	12.09	3.233	1.672	0.238	0.980	11.27	159,826
2	7.230	10.79	0.321	0.036	0.392	10.71	159,774
3	3.362	15.86	0.736	0.000	0.417	9.100	159,944
4	4.329	16.48	0.552	0.004	0.022	8.088	159,666
5	4.520	5.630	12.46	0.000	0.000	6.875	155,038

SENSITIVITY ANALYSIS

Several analyses with variable input data have been made to study and analyze the impact of certain key parameters on the optimum solutions. Among the studied parameters are the reliability indices (α_i), the unit costs (UC_i), and the annual budgets (AB_k). Each one of those three parameters is analyzed independently using selected cases. Other input parameters have remained constant for the sample problem.

Case I: Studying Impact of Variable (α_3) as Example on Optimum Solutions

Examining the impact of variable (α_3) on the optimum solutions (X'_3, X'_4, X'_5, X'_6) as shown in Table 6, it can be noted that as α_3 decreases from 0.9 to 0.3, X'_3 becomes less dominant but with not much change in the 5-year average PSI values. This means that applying rehabilitation number 3 is still relatively better than doing other actions even though the reliability level is reduced. This is because its cost is still relatively

TABLE 6. Impact of Variable α_3 on Optimum Solutions

α_3	Year (k)	X'_3	X'_4	X'_5	X'_6	$\bar{P}'_{(k)}$	5-Year average PSI
0.9	1	0.95	0.90	0.00	0.00	3.073	
0.9	2	1.00	0.85	0.60	0.05	3.112	
0.9	3	0.05	0.05	0.00	0.15	3.113	3.110
0.9	4	0.90	0.00	0.00	0.15	3.131	
0.9	5	1.00	1.00	1.00	0.15	3.120	
	$\Sigma X'_i$	3.90	2.80	1.60	0.50	—	—
0.6	1	0.95	0.90	0.00	0.00	3.064	
0.6	2	0.05	0.90	0.55	0.10	3.096	
0.6	3	0.90	0.55	0.05	0.10	3.111	3.102
0.6	4	0.90	0.90	0.15	0.15	3.120	
0.6	5	0.65	0.35	0.70	0.15	3.118	
	$\Sigma X'_i$	3.45	3.60	1.45	0.50	—	—
0.3	1	0.95	0.90	0.00	0.00	3.055	
0.3	2	0.00	0.80	0.60	0.10	3.087	
0.3	3	0.00	0.95	0.05	0.15	3.099	3.094
0.3	4	0.85	0.95	0.35	0.10	3.119	
0.3	5	0.95	0.80	0.95	0.15	3.108	
	$\Sigma X'_i$	2.75	4.4	1.95	0.50	—	—

small and it gives a reasonable improvement from Class 3 to at least Class 2. But it can also be noted that no change has occurred in the values of X'_6, some overall decrease in X'_3, and consistent increase in the values of X'_4 as noted from summing the X'_i values for the 5-year study period. It is logical for X'_4 to make up for the decrease in X'_3 since it is associated with the lowest unit cost after X'_3.

Case II: Studying Impact of Variable (UC_3) as Example on Optimum Solutions

Examining the impact of variable (UC_3) on the optimum solutions (X'_3, X'_4, X'_5, X'_6) as shown in Table 7, it can be noted that as UC_3 increases, the values of the optimum variable X'_3 converge rapidly to zero. The variables X'_4 and X'_5 have increased to compensate for the decrease in X'_3 with X'_4 picking up most of the increase since X'_4 has the lowest unit cost among the remaining three variables. Of course, when X'_3 has a unit cost equal to that of X'_4, it would make sense to do more X'_4 than X'_3 as one gets improvement from Class 4 to 1 or 2 rather than from Class 3 to 1 or 2. Similarly, it would make sense to rehabilitate more of Class 5 than Class 3 when both have the same unit cost. The optimum PSI values have remained in the same range with the increase in the value of variable UC_3.

TABLE 7. Impact of Variable UC_3 on Optimum Solutions

UC_3	Year (k)	X'_3	X'_4	X'_5	X'_6	$\bar{P}'_{(k)}$	5-Year average PSI
40,000	1	0.55	1.00	0.00	0.00	3.053	
40,000	2	0.00	0.00	0.00	0.15	3.079	
40,000	3	0.00	0.80	1.00	0.05	3.092	3.087
40,000	4	0.65	0.60	0.00	0.10	3.109	
40,000	5	0.25	0.30	0.95	0.15	3.104	
	$\Sigma X'_i$	1.45	2.70	1.95	0.45	—	—
50,000	1	0.05	0.85	0.05	0.05	3.051	
50,000	2	0.00	0.75	0.65	0.10	3.069	
50,000	3	0.00	1.00	0.40	0.05	3.075	3.080
50,000	4	0.00	1.00	1.00	0.15	3.101	
50,000	5	0.10	0.25	0.00	0.15	3.102	
	$\Sigma X'_i$	0.15	3.85	2.10	0.50	—	—
60,000	1	0.00	0.80	0.20	0.05	3.051	
60,000	2	0.00	0.85	0.65	0.10	3.068	
60,000	3	0.00	1.00	0.25	0.05	3.073	3.080
60,000	4	0.00	0.45	1.00	0.15	3.101	
60,000	5	0.00	0.30	0.00	0.15	3.102	
	$\Sigma X'_i$	0.00	3.40	2.10	0.50	—	—

TABLE 8. Impact of Variable Annual Budget AB_k on Optimum Solutions

Budget AB_k	Year (k)	X'_3	X'_4	X'_5	X'_6	$\bar{P}'_{(k)}$	5-Year average PSI
160,000	1	0.95	0.90	0.00	0.00	3.070	
160,000	2	1.00	0.85	0.60	0.05	3.106	
160,000	3	0.00	0.30	0.00	0.15	3.107	3.106
160,000	4	0.55	0.00	0.10	0.15	3.124	
160,000	5	1.00	1.00	1.00	0.15	3.123	
	$\Sigma X'_i$	3.50	3.05	1.70	0.50	—	—
190,000	1	1.00	0.70	0.00	0.05	3.099	
190,000	2	0.95	1.00	0.05	0.10	3.162	
190,000	3	0.95	0.00	0.50	0.15	3.190	3.180
190,000	4	1.00	1.00	1.00	0.15	3.225	
190,000	5	1.00	0.00	0.00	0.20	3.223	
	$\Sigma X'_i$	4.90	2.70	1.55	0.65	—	—
220,000	1	1.00	0.95	0.00	0.05	3.128	
220,000	2	0.95	1.00	0.20	0.15	3.231	
220,000	3	0.85	0.00	0.45	0.20	3.264	3.258
220,000	4	0.90	1.00	0.30	0.25	3.319	
220,000	5	1.00	1.00	0.00	0.30	3.350	
	$\Sigma X'_i$	4.70	3.95	0.95	0.95	—	—

Case III: Studying Impact of Variable Annual Budget (AB_k) on Optimum Solutions

Examining the impact of variable annual budget (AB_k) on the optimum solutions as shown in Table 8, one notices that as the allocated annual budget increases the optimum variables X'_3 and X'_4 remain dominant, with X'_3 being the heaviest since it is associated with the lowest unit cost. One also notices that as budget increased, most optimum variables have generally increased resulting in a consistent improvement in the 5-year average PSI values. This means that the additional funding has been effectively used to improve the overall condition of the pavement network. Generally, as more money is spent on rehabilitation work, the overall outcome is better pavements as indicated by the higher PSI values.

SUMMARY

It is believed that the presented macroscopic system provides an opportunity to solve the pavement management problem to optimality for the case involving major rehabilitation actions. This is made possible by replacing the traditional microscopic approach, which uses ''short'' pavement sections with pavement classes made of ''long'' pavement sections (projects). It requires that each pavement project be made up of the same pavement structural section. It is assumed that the entire project will possess one performance curve with any estimated future performance value representing the overall average pavement condition. Performance curves can be generated using the AASHTO serviceability concept or any other preferred model.

An optimum decision policy has been formulated with its main objective being maximizing the annual average network present serviceability index over a selected study period. Pavement projects are grouped into six classes with only four classes considered for major rehabilitation. Only four variables are used in the optimum model to represent the four rehabilitation actions applied as appropriate to the four pavement classes. The individuality of each pavement project is preserved throughout the entire optimization process but all pavement projects in the same class are subject to the same rehabilitation action and receive the same optimum rehabilitation policy in terms of the amount of rehabilitation work that should be done on them.

CONCLUSIONS AND RECOMMENDATIONS

The formulated decision policy has successfully yielded optimum pavement conditions under constrained budgets. The utilized optimization technique has effectively converged to optimal solutions with minimal computer time. The results of the research indicate that the optimum solutions are clearly sensitive to two main parameters, namely unit costs and reliability indices. Generally, the value of an optimum variable is inversely proportional to unit cost and directly proportional to reliability index.

It is recommended in the implementation of an optimum policy that a field review be conducted to identify and schedule segments—all in the same project or class—for rehabilitation based on their relative severity of pavement distress. It is recommended that whenever actual pavement performance data becomes available, it should replace the predicted PSI values from the AASHTO module. Any other appropriate pavement condition indicator such as PCI can easily be substituted. It is further recommended that the system be applied as often as necessary to obtain revised optimum rehabilitation policies that would incorporate the impact of any recent changes that might have taken place in the pavement network.

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