Sensitivity of Design Parameters on Optimal Pavement Maintenance Decisions at the Project Level

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Sensitivity analyses are important parts of both studying complex systems and measuring the variation in input parameters on the response. They are useful to decision makers for understanding the robustness of the optimal solution that they are to adapt to variations of the parameters of the problem. The sensitivity of the optimal solution of a project-level pavement management problem is analyzed, and the robustness of the optimal solution to the interventions and the timing, cost, and benefit are investigated. The input parameters, which affect the optimal maintenance solution, are identified as the structural and functional condition parameters (defined in terms of deflection and roughness, respectively, at the beginning of the analysis period), traffic volume, growth rate, and discount rate. The problem of computing the optimal treatment and timing for a given budget level is modeled as a mixed integer nonlinear optimization problem and solved by using a computationally efficient network-optimization technique. The benefits are evaluated by considering the pavement performance and are quantified as the area between the performance curve and the threshold values. The optimal budget required for pavements in different structural and functional conditions as well as traffic levels is presented. The effect of initial pavement condition on the optimal maintenance actions as well as their timings is studied. The result of the sensitivity analysis showed that the cumulative standard axle loads and traffic growth rate have a significant effect on the selection and timing of rehabilitation and preventive maintenance actions. The effect of the discount rate on the maintenance management decisions is also presented.

In recent years, investments in the infrastructure, especially in the road sector, have increased significantly. It has been well recognized that a well-developed network of highways contributes to savings in vehicle operation cost; reduced fuel consumption; safer, faster, and more comfortable travel; and reduced maintenance costs. Preservation of existing road assets is more important than the creation of new assets. However, the funds required for maintenance are far less than the actual requirements. The preservation of the road infrastructure assets needs a better maintenance management information support system. The maintenance management system will help in better road maintenance investment planning and help in making appropriate budgeting decisions. A pavement management system empowered with optimization techniques is a rigorous tool that is capable of giving better investment decisions, thus assisting the decision-making process and identifying solutions toward better pavement management practices.

In the present study, the evaluation of optimum maintenance and rehabilitation (M&R) treatments and their timing are formulated as a mixed integer nonlinear optimization problem. The functional characteristics of the pavement directly affect the ride quality and vehicle operating cost. The structural condition of the pavement determines the remaining structural life of the pavement. Therefore, it is desirable that the condition of the pavement is evaluated by considering both structural and functional performance.

Sensitivity analysis of an optimal solution for a project-level pavement management problem consists of computing the ranges within which input parameters may vary without altering the optimal solution at hand. The objective of sensitivity analysis is to analyze the behavior of the response of the system and to evaluate the sensitivities of the system response to variations in the system input parameters around their nominal values. This paper analyzes the sensitivity of the design input parameters to quantify their impact on the optimal sequence of M&R actions and on the performance of the pavement at the project level.

The overall objectives of the study are

1. To find the optimum budget required for project-level maintenance management of a highway pavement by duly considering the structural and functional conditions of the pavement at varying traffic-volume levels and
2. To study the sensitivity of the various design parameters on optimal M&R actions and timings.

SCOPE

The present study considers rebound deflection of the pavement as the structural condition parameter and roughness as the functional condition parameter. The evaluation of the optimum M&R actions at the project level is limited to flexible pavements, and the design input parameters considered are deflection, roughness, traffic volume, discount rate, and traffic growth rate.

BACKGROUND

Various approaches for project-level management and resource allocation have been developed to determine appropriate rehabilitation or maintenance alternatives. Life-cycle cost analysis (LCCA) is based on the principles of economic analysis to evaluate the overall

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long-term economic efficiency among competing alternative investment options. LCCAs based on deterministic (*1, 2*) performance prediction models have been developed by several researchers. Probabilistic models have been applied in flexible pavement design, the generation of preservation strategies, and in the evaluation of the life-cycle costs considering the inherent uncertainty in the input parameters (*3*). There are several limitations in the implementation of many existing LCCA models. One limitation is that all maintenance-related factors are to be transformed into equivalent monetary values. It is difficult to measure all the relevant impacts in terms of money. Therefore, in such cases where multiple constraints are to be considered, a priority-ranking method based on economic evaluation may not be effective.

Operation research and system methods provide a scientific basis for decision makers to allocate resources to maximize the benefit or minimize the cost, which ensures optimum solutions. While a number of different optimization techniques could be applied, the sequential nature of the problem (repeated applications of M&R actions over different periods) renders dynamic programming (*4, 5*) as one of the preferred approaches. Heuristic optimization techniques such as genetic algorithm (*6*) and policy improvement algorithm (*7*) are also used for optimizing M&R actions at the project level.

Most agencies formulate a project-level optimization problem that includes a minimum serviceability level so as to keep the pavement condition above this minimum level. It is apparent that this is not equivalent to pavement performance consideration, as many strategies with different overall pavement performance can be formulated to satisfy this requirement. Therefore there is a need for pavement performance consideration in the LCCA (*8*) from the point of view of both the highway agencies and road users. Available project-level optimization models consider either structural condition or functional condition in terms of their objective function to represent pavement condition, but not both simultaneously. Traditionally, highway maintenance and improvement programs have developed as two distinct programs with separate sets of objectives (*2, 4*). When a pavement section deteriorates beyond maintenance capacity, a rehabilitation action is applied. Much research has been conducted in the area of decision analysis on choice among pavement M&R activities (*9–12*). In most of the optimization models cited above, the deterioration of the pavement is modeled as a state-based model making use of Markov property. But this approach suffers from serious limitations. It does not explicitly capture the effect of various explanatory variables (*13*). The deterioration of the pavement depends not only on the current condition but also the maintenance history of the pavement.

In this paper a new approach to compute the optimal timing and type of M&R actions at the project level is developed to address many of the limitations of the existing models. The problem features and constraints are modeled through a suitably specified directed network and solved by using a constrained shortest-path algorithm. The important features of the proposed optimization problem are given below:

1. This model considers pavement performance in assessing the merits of M&R actions;
2. The dynamic nature of the performance of the pavement under assorted time-varying variables and sequence of maintenance treatments are also captured;
3. In the finite horizon optimization problem, the remaining life of the pavement is considered so as to take into account the extended life of the pavement due to the sequence of M&R actions;
4. Rehabilitation and preventive maintenance actions are integrated and optimized; and
5. All feasible combinations of strategies are considered that are generated endogenously in the model so that the solution is global optimum.

This methodology addresses several limitations of many pavement management models in practice. A sensitivity analysis was performed for various levels of input variables to study the effect of these variables on optimum cost, treatment, and timing of M&R actions obtained from this optimization problem.

PROBLEM FORMULATION

Project-level management of M&R actions is a multistage decision-making problem. The entire analysis period can be divided into a number of stages (a 1-year duration is considered in the present study). At the beginning of each stage, a decision must be made regarding which M&R action is to be undertaken. The goal of the multistage decision-making problem is to select the optimum policy that results in maximum benefit for a given cost while ensuring predetermined performance standards during the analysis period.

The benefit is taken as the area between the realistic performance curves and the threshold values of the performance indicators over time. Since the strategies are not exogenously specified, the benefits are calculated for each stage following the sequence of actions, and the summation of these benefits over all the stages is the benefit due to a given strategy. Thus, the objective function is formulated to capture the dynamics of the problem as follows:

objective function

$$\text{maximize} \sum_{n=1}^{N} \sum_{i=1}^{I_n} \sum_{k=1}^{K} \mathrm{PVB}_n(i,k) X_{ink} \tag{1}$$

where

$\mathrm{PVB}_n(i, k)$ = the present value of benefit during the nth period corresponding to M&R action k, applied to the pavement in condition state i,
i = 1, . . . , I_n, i denotes the indicator for possible condition states in each stage n,
n = 1, 2, . . . , N, n denotes the number of stages of decision making, and
k = 1, . . . , K, k corresponds to a prespecified M&R action.

The decision variables X_{ink} in the objective function are integer valued and correspond to M&R actions applied at the beginning of each period. $X_{ink} = 1$, if action k is applied at the nth period when the pavement is in the ith state; $X_{ink} = 0$ otherwise.

The constraints are the budget constraint (discounted budget); the total cost of the chosen strategy should not exceed the budget available.

$$\sum_{n=1}^{N} \sum_{i=1}^{I_n} \sum_{k=1}^{K} \mathrm{PVC}_n(i,k) X_{ink} \le C \tag{2}$$

where $\mathrm{PVC}_n(i, k)$ = present value of the (discounted) cost of M&R action k applied at the nth period to the pavement in the ith state, and C = total budget available in the analysis period.

There are two pavement performance constraints: the structural condition of the pavement is represented by rebound deflection values, and the functional condition is represented by the roughness values. For a strategy to be feasible, the maximum allowable values of deflection and roughness should not be exceeded in any year *n*.

$$\sum_{k=1}^{K} \text{DEF}_n(i,k) X_{ink} \leq \text{TV}_{\text{DEF}} \qquad \forall n, \forall i \tag{3}$$

$$\sum_{k=1}^{K} R_n(i,k) X_{ink} \leq \text{TV}_R \qquad \forall n, \forall i \tag{4}$$

where $\text{DEF}_n(i, k)$, $R_n(i, k)$ = pavement condition states for deflection and roughness, respectively, and TV_{DEF}, TV_R = maximum allowable (upper threshold) values for the above measures.

METHODOLOGY

The overall conceptual methodology is shown in Figure 1. The methodology consists of five key modules as follows:

1. Traffic module,
2. Performance module,
3. Benefit and cost computation module,
4. Network construction module, and
5. Optimization module.

These modules are briefly explained below.

Traffic Module

In the traffic prediction module, the commercial traffic volume in the base year is considered (when the age of the pavement is zero) and predicted for the design period with a uniform traffic growth rate. The cumulative standard axle load repetitions are computed to predict the performance of the pavement during the design life.

Performance Module

The performance of the pavement depends on time-varying variables, namely, condition of the pavement, cumulative standard axle loads, age, and sequence of M&R actions. The deflection and roughness deterioration equations are evaluated for each action, and the condition of the pavement is computed every year. The long-term performance of flexible pavements can be determined by the magnitude of the transient deflection measured by using a Benkelman beam under a slow-moving load. To evaluate the structural condition D_t at time t of the pavement, the following deflection prediction model (*14*) is used:

$$D_t = \text{idef} + \alpha\left(N_t \times \text{age}\right)^{\text{idef}} \tag{5}$$

where

idef = initial rebound deflection, mm;
age = age of pavement at *t*th year;
α = constant affecting deterioration (α may vary across different levels of initial deflection); and
N_t = cumulative standard axle load repetitions, in millions, up to *t*th year.

The following generic progression equation, which has both linear and exponential terms of initial international roughness index (ETIRI), is used (*15*) to predict the functional condition:

$$\text{IRI}_t = 0.8484 \times \text{IRIbase} + 0.2022 \times \text{ETIRI} + 0.033 \times N_t \tag{6}$$

where

IRI_t = international roughness index (IRI) at time *t*,
IRIbase = initial roughness, that is, IRI in the base year when the age of the pavement is zero, and
ETIRI = IRIbase($e^{0.0151 \times \text{age}}$).

Benefit and Cost Computation Module

The benefit for each condition indicator (deflection, roughness) for a given period is computed by determining the area between the corresponding performance curve and its upper threshold value during that stage. This is obtained by integrating the ordinate difference between the performance measure and its upper threshold over the stage of interest. The areas above the deflection and roughness progression curve and below the upper threshold curve are computed during every stage, normalized, and added to get the overall yearly benefit. To the yearly benefit at the last stage, the salvage value is added by considering the extended life of the pavement due to the maintenance interventions. The present worth of future expenditure and benefit is computed by discounting the cost of M&R actions and the yearly overall benefits to the present year.

Network Construction

In the network construction module, the problem is represented by using a directed network G that consists of a set of nodes and arcs. Each node in the network represents an initial condition state at a particular stage and corresponds to a unique history of prior maintenance actions. The arcs represent the possible M&R actions from each node. The discounted overall yearly benefit is considered as the arc length.

Optimization Module

In the optimization module, the longest path from source node (initial condition state) to sink node (final condition state) is found by using a reaching algorithm. The maximum weighted path gives the optimal maintenance strategy (actions and their timing) that maximizes the discounted benefit. This constrained problem is converted into an unconstrained problem by using the Lagrangian relaxation method.

Implementation

Figure 1 shows the connection between these modules. Forward star representation is used to represent the directed network. The first node, which represents the condition of the pavement at the beginning of the analysis period, is taken as the source node. From the nodes, arcs are generated that correspond to each M&R action. The information computed for each arc includes connectivity details, namely, head node, tail node, forward star, and backward star. In addition, empirical values that predict the performance of the pavement, such as initial traffic, age of the pavement, current action, year, initial deflection, and initial roughness (corresponding to tail node) are stored, and M&R actions are the inputs to predict the performance. If the deflection or roughness threshold value is exceeded, that node is dropped. For each arc, the benefits are calculated as explained in the benefit

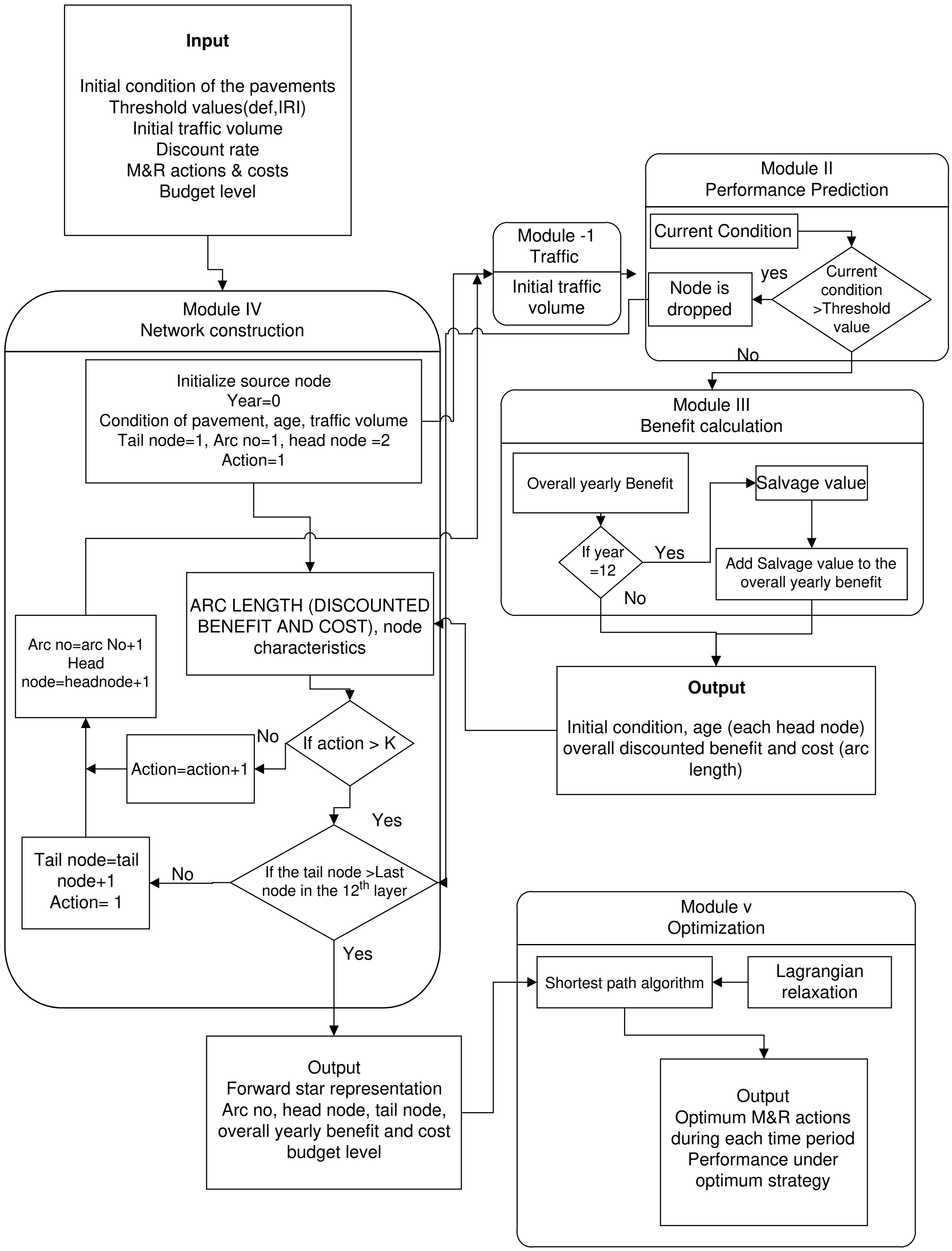

FIGURE 1 Overall conceptual methodology.

module, and the overall discounted and integrated benefit and discounted cost are calculated for each arc and stored in the arc list. Each path from source to sink in the network represents a unique sequence of M&R actions. Thus, the dynamic nature of this problem resulting from deterioration under time-varying variables and sequence of actions is captured.

The discounted benefit and cost are calculated for all nodes in the network. Thus, all feasible strategies that satisfy the constraints are endogenously generated. The constrained shortest-path algorithm solved by using the Lagrangian method is then used in optimization for a given budget level. The sequence of M&R actions corresponding to the longest path will be the optimum strategy. The

TABLE 1 Optimum Budget Level for Deflection 0.8 mm, IRI 3.4 m/km, and Traffic 3,000 cv/day

Budget Level, Rs. (million) (US$ million)	Optimal Maintenance and Rehabilitation Actions in Each Year												Benefit	Cost Rs. (million)	Incremental Benefit–Cost Ratio
	1	2	3	4	5	6	7	8	9	10	11	12			
7.5 (0.167)	6	1	1	1	1	4	1	1	1	1	5	6	22.39	7.13	0.43
6.5 (0.144)	6	1	1	1	1	4	1	1	1	1	4	6	22.02	6.28	3.52
5.5 (0.122)	6	1	1	3	1	1	2	1	4	1	1	5	18.32	5.23	3.15
4.5 (0.1)	6	1	1	1	4	1	1	1	3	1	1	4	15.44	4.31	

cv = commercial traffic volume.

other output is the optimal M&R actions with their time of application and performance of the pavement corresponding to this optimum strategy.

Sensitivity Analysis

A sensitivity analysis is performed to determine the effect of various input variables on the optimal timing and type of treatment and the resultant benefit. The analysis is performed considering the following deflection and roughness levels:

- Deflection value of 0.4 mm and roughness, in terms of IRI, of 2.16, 3.4, and 4.6 m/km;
- Deflection value of 0.8 mm and IRI of 2.16, 3.4, 4.6, and 5.7 m/km; and
- Deflection value of 1.2 mm and IRI of 3.4, 4.6, and 5.7 m/km.

For all these combinations of deflection and roughness levels the analysis is performed for three levels of traffic [2,000, 3,000, and 4,000 commercial traffic volume per day (cv/day)] and four budget levels [Rs. 4.5 million, Rs. 5.5 million, Rs. 6.5 million, and Rs. 8.5 million (US$1 = Rs. 45 in 2006)]. The analysis is also carried out for 4%, 6%, and 8% traffic growth rates. To study the effect of discount rates on the optimal strategy, the analysis is done for a 3%, 4%, and 5% discount rate.

In this analysis six M&R actions that include two rehabilitation actions and three preventive maintenance actions are considered. The maintenance options considered are do nothing (Action 1), crack sealing (Action 2), slurry seal (Action 3), surface dressing (Action 4), thin overlay (Action 5), and thick overlay (Action 6), for which the unit rate per 2 lane-km in million rupees are 0.05, 0.175, 0.245, 0.315, 1.6, and 3.2, respectively.

Optimum Budget Level

Considering four budget levels, Rs. 7.5 million, Rs. 6.5 million, Rs. 5.5 million, and Rs. 4.5 million, the optimum maintenance treatments and the timings and resultant benefits are computed. For an initial deflection value of 0.8 mm, IRI 3.4 m/km, and commercial vehicle volume of 3,000 cv/day, the incremental benefit-cost ratios are computed to arrive at the optimum budget required (Table 1). Both the discount rate and traffic growth rates are taken as 4%.

The incremental benefit–cost ratio is used to compare the strategies corresponding to different budget levels. For each strategy, the incremental benefit-cost ratio is computed by comparing the strategies with the next lower strategy as follows:

$$\text{bcratio}_i = \frac{\left(\text{benefit}_i - \text{benefit}_j\right)}{\left(\text{cost}_i - \text{cost}_j\right)} \quad (7)$$

where

bcratio_i = the incremental benefit–cost ratio for strategy *i,*
benefit_i = the benefit corresponding to strategy *i,*
benefit_j = the benefit corresponding to the immediate lower strategy *j,*
cost_i = the cost corresponding to strategy *i,* and
cost_j = the cost corresponding to strategy *j.*

When the budget level is increased from Rs. 4.5 million to Rs. 6.5 million, the benefit increases by 20%, but when it is further increased to Rs. 7.5 million the percentage increase in the benefit is only 1.7. The incremental benefit-cost ratio is maximum for budget level Rs. 6.5 million and is taken as the optimum budget level corresponding to the given pavement condition and traffic. For the optimum budget level, the allowable deflection and IRI values during the analysis period are 1 mm and 2.65 m/km, respectively.

Table 2 shows the optimum budget required for various levels of deflection, roughness, and traffic levels with a uniform traffic growth rate and a discount rate of 4%. The optimum budget levels are found to vary in the range of Rs. 3.5 million to Rs. 8.5 million when the deflection value ranges from 0.4 to 0.8 mm, the IRI value varies from 2.16 to 5.7 m/km, and traffic from 2,000 to 4,000 cv/day. When the initial deflection value is increased from 0.4 mm to 0.8 mm, keeping a constant roughness value of 3.42 m/km, the optimum budget is found to increase by 87%, 44%, and 54% when the initial commercial traffic volumes are 2,000, 3,000, and 4,000 cv/day, respectively. The optimum budget level is found to depend significantly on the structural condition of the pavement, namely, deflection and traffic rather than roughness. When traffic volume is less than 3,000 cv/day, the optimum budget is not found to vary significantly for a given condition of the pavement. When commercial traffic volume increases

TABLE 2 Optimum Budget Level for Various Input Levels

Deflection (mm)	IRI (m/km)	Optimum Cost in Rs. (million)		
		2,000 cv/day	3,000 cv/day	4,000 cv/day
0.4	2.16	3.5	4.5	5.5
0.4	3.42	3.5	4.5	5.5
0.4	4.62	5.5	5.5	6.5
0.8	2.16	6.5	6.5	8.5
0.8	3.42	6.5	6.5	8.5
0.8	4.62	6.5	6.5	8.5
0.8	5.78	6.5	6.5	8.5
1.2	3.42	6.5	8.5	8.5
1.2	4.62	8.5	8.5	8.5
1.2	5.78	8.5	8.5	8.5

TABLE 3 Optimal M&R Treatments and Timings for Various Deflection Levels (IRI, 3.42 m/km; traffic, 3,000 cv/day; and budget, Rs. 6.5 million)

Deflection (mm)	Optimal M&R Actions Each Year 1	2	3	4	5	6	7	8	9	10	11	12	Benefit	Cost Rs. (million)
0.4	4	4	1	1	4	1	4	1	6	1	4	6	22.58	6.20
0.8	6	1	1	1	1	4	1	1	1	4	1	6	19.05	6.28
1.2	5	6	1	4	1	1	4	3	1	4	1	4	14.71	6.18

from 3,000 to 4,000 cv/day, the optimum budget level is found to vary between 18% and 35%.

Optimal M&R Treatments and Timings for Various Levels of Input Variables

Tables 3 through 5 show the effect of variation in deflection, roughness, and traffic volume, respectively, on the optimal timing and treatments for a budget of Rs. 6.5 million. The traffic growth rate and discount rate are assumed to be 4%. The permissible limits or upper threshold values for deflection and roughness are assumed to be 1.5 mm and 4.6 m/km, respectively.

Optimal M&R Treatments and Timings for Various Deflection Levels

Table 3 shows the optimal timing and treatment for deflection values of 0.4, 0.8, and 1.2 mm with a roughness value of 3.24 m/km, traffic volume of 3,000 cv/day, and a budget of Rs. 6.5 million. For pavement with an initial deflection value of 0.4 mm, the optimum strategy requires two major rehabilitation actions in the 9th and 12th years and five preventive maintenance actions during an analysis period of 12 years. For a pavement with an initial deflection value of 0.8 mm, the optimum strategy requires two major rehabilitation actions in the 1st and 2nd years and two preventive maintenance actions in the 6th and 10th years. For a pavement with an initial deflection value of 1.2 mm, the optimum strategy requires two rehabilitation actions in the 1st and 2nd years and five preventive maintenance actions during the analysis period of 12 years (Table 3). For a particular budget of Rs. 6.5 million, the benefits are found to be less by 15% and 30% for pavements with initial deflection values of 0.8 and 1.2 mm, respectively, when compared with pavements with a deflection 0.4 mm. For pavements with higher values of deflection, more rehabilitation actions are needed during the analysis period. If the deflection value is low, then the rate of deterioration is also low. From the analysis, it can be inferred that the optimum benefit corresponding to optimum strategy is derived when the deflection and roughness values range between 1.04 mm to 1.2 mm and 2.43 m/km to 2.68 m/km, respectively.

Optimal M&R Treatments and Timings for Various Roughness Levels

For a pavement with a deflection value of 0.8 mm and traffic volume of 3,000 cv/day, the analysis was carried out at four IRI levels (2.16, 3.42, 4.62, and 5.78 m/km). The optimum M&R actions and timings are shown in Table 4. No significant variation in the benefits is found with the variation in roughness values. Corresponding to roughness values of 2.16 and 3.42 m/km, the optimum strategy requires two major rehabilitation actions in the 1st and 12th years. For pavements with roughness values of 4.62 and 5.78 m/km, rehabilitation actions are required in the 2nd and 12th years. Even though pavement rough-

TABLE 4 Optimal M&R Treatments and Timings for Various Roughness Levels (deflection, 0.8 mm; traffic, 3,000 cv/day; and budget, Rs. 6.5 million)

Roughness (IRI in m/km)	Optimal M&R Actions Each Year 1	2	3	4	5	6	7	8	9	10	11	12	Benefit	Cost Rs. (million)
2.16	1	6	1	1	1	4	1	1	2	1	4	6	19.03	6.24
3.42	6	1	1	1	1	4	1	1	1	4	1	6	18.96	6.28
4.62	2	6	1	1	1	1	4	1	1	1	4	6	17.92	6.27
5.78	4	6	1	1	1	1	4	1	1	1	4	6	17.92	6.43

TABLE 5 Optimal M&R Treatments and Timings for Various Traffic Levels (deflection, 0.8 mm; IRI, 3.42 m/km; and budget, Rs. 6.5 million)

Traffic Volume (cv/day)	Optimal M&R Actions Each Year 1	2	3	4	5	6	7	8	9	10	11	12	Benefit	Cost Rs. (million)
2,000	6	1	1	1	1	4	1	1	1	1	4	6	22.02	6.28
3,000	6	1	1	1	1	4	1	1	1	4	1	6	19.05	6.28
4,000	6	1	1	4	1	1	4	1	1	1	5	5	16.43	6.27

TABLE 6 Optimal M&R Treatments and Timings for Various Traffic Growth Rates (deflection, 0.8 mm; IRI, 3.42 m/km; traffic, 2,000 cv/day; and budget, Rs. 7.5 million)

Traffic Growth Rate	Optimal M&R Actions Each Year												Benefit
	1	2	3	4	5	6	7	8	9	10	11	12	
4%	6	1	1	1	1	4	1	1	1	1	5	6	22.39
6%	5	4	1	1	1	1	1	4	6	3	1	6	20.55
8%	5	1	1	1	1	4	1	1	6	4	1	6	16.01

ness has less influence on the optimum cost, roughness is found to influence the timing of both the rehabilitation actions and the type and timing of preventive maintenance actions. The allowable values of roughness during the analysis period are found to vary from 2.42 to 2.82 m/km.

Optimal M&R Treatments and Timings for Different Traffic Levels

The analysis was performed for traffic levels of 2,000, 3,000, and 4,000 cv/day with a pavement roughness value of 3.4m/km and deflection of 0.8 mm. The optimum M&R actions and timings are shown in Table 5. When traffic volume is increased from 2,000 to 3,000 cv/day, two major rehabilitation actions are needed in the 1st and 12th years. When the traffic level is 4,000 cv/day, more rehabilitation actions are required in the 1st, 11th, and 12th years, and two preventive maintenance actions are required in the 4th and 7th years. As the traffic volume increases, the time interval between the applications of rehabilitation actions decreases. The benefit decreases by 13% when the traffic volume increases from 2,000 to 3,000 cv/day and from 3,000 to 4,000 cv/day. Therefore, traffic volume has a significant role in treatment selection and timing, especially in the case of rehabilitation actions.

Effect of Traffic Growth Rate on Optimal M&R Actions and Timing

Table 6 shows the optimal M&R strategies and timings corresponding to traffic growth rates of 4%, 6%, and 8%. A pavement with deflection of 0.8 mm, IRI of 3.42 m/km, and traffic level of 2,000 cv/day is considered. The sensitivity analysis was performed for a budget level of Rs. 7.5 million. When the traffic growth rate is increased from 4% to 8%, three rehabilitation actions are required in the optimal strategy. In the case of higher traffic growth rates, many major rehabilitation actions are required to keep the pavement in the desired condition during the analysis period. From Table 6 it can be seen that at higher traffic growth rates, more M&R actions are required toward the end of the analysis period. The timing and treatment type significantly depends on the traffic and its growth rate.

Effect of Discount Rate on Optimal M&R Actions and Timing

Table 7 shows the effect of discount rates on the timing and selection of optimal strategies. The sensitivity analysis was performed with traffic growth rates of 3%, 4%, and 5%. The optimal strategy is computed with a deflection value of 1.2 mm, IRI at 3.42 m/km, and traffic at 3,000 cv/day with a budget level of Rs. 6.5 million. For a discount rate of 5%, a minor rehabilitation action is required in the 12th year when compared with other discount rates. A high discount rate makes it possible for more rehabilitation action at the end of the analysis period, as the discounted cost of the action is less. Even though the number of rehabilitation actions is more, the benefit is less as the discounted benefit will also be less due to high discount rates. Therefore, from Table 7 it can be inferred that the discounted benefit is maximum when the discount rate is 4%. Similarly, the discount rate influences the type of preventive maintenance treatments and timings. The optimal budget level is also influenced by the discount rate. When the discount rate is 3%, the optimum budget level required is Rs. 7.5 million, and for discount rates of 4% and 5%, the optimum budget level is Rs. 8.5 million.

SUMMARY AND CONCLUSIONS

This paper presents the sensitivity of the optimal solution of project-level pavement management problems to the interventions and timing, cost, and benefit. The optimal solution identifies the sequence of preventive M&R actions and their timing, which maximize the total benefit subject to given budgetary and performance constraints. Since the benefit is considered as the area between the performance curve and the threshold values of the performance indicators, the benefit represents the condition of the pavement during the analysis

TABLE 7 Optimal M&R Treatments and Timings for Various Discount Rates (deflection, 1.2 mm; IRI, 3.4 m/km; traffic, 3,000 cv/day; and budget, Rs. 6.5 million)

Discount Rate	Optimal M&R Actions Each Year for Budget Level Rs. 6.5 Million												Benefit for Rs. 6.5 Million	Optimum Budget Level in Rs. (million)
	1	2	3	4	5	6	7	8	9	10	11	12		
3%	5	6	1	4	1	1	4	3	1	2	1	4	13.14	7.5
4%	5	6	1	4	1	1	4	3	1	4	1	4	14.71	8.5
5%	5	6	1	1	1	4	1	1	1	4	1	5	12.62	8.5

period. All the feasible strategies are considered while evolving the optimum strategy, and hence the solution is a global optimum. A sensitivity analysis was performed to evaluate the effect of various input parameters on the optimal timing and treatment of M&R actions. The findings of the sensitivity analysis are as follows:

1. When the initial deflection value is increased from 0.4 mm to 0.8 mm, keeping a constant roughness value of 3.42 m/km, the optimum budget is found to increase by 87%, 44%, and 54%, when the initial traffic is 2,000, 3,000, and 4,000 cv/day, respectively. An increase in budget is not consistent with variation in traffic levels for different initial conditions of the pavements, and this may be due to the change in the deflection performance curve for various initial conditions.
2. For a given traffic volume and deflection, roughness has less influence on optimal budget. This may be because cost-effective preventive maintenance treatments reduce the roughness significantly and improve the functional condition of the pavement.
3. From the sensitivity analysis it is found that for the optimum strategy, the maximum deflection value ranges from 1.04 mm to 1.2 mm during the analysis period for the range of traffic and roughness considered in the present analysis.
4. Even though influence of roughness on the optimum cost is not significant, roughness has significant influence on the timing of M&R actions. To derive maximum benefits, the allowable roughness values should range from 2.42 m/km to 2.82 m/km for traffic less than 3,000 cv/day.
5. When traffic is less than or equal to 3,000 cv/day the time interval between applications of rehabilitation action is 11 years. When traffic is 4,000 cv/day, the time interval between rehabilitation actions is 10 years for a traffic growth rate of 4%. As the traffic volume increases, the time interval between the applications of rehabilitation actions is found to decrease. The traffic volume a has significant role in the treatment selection and timing, especially in the case of rehabilitation actions.
6. When the traffic growth rate is 6%, rehabilitation action is required in the 1st, 7th, and 12th years for an initial traffic volume of 2,000 cv/day for a pavement with an initial deflection value of 0.8 mm and IRI of 3.42 m/km. For higher levels of traffic growth rate, many M&R actions are needed in the optimum strategy during the later period of the analysis. The timing and treatment type to a large extent depend on the traffic growth rate.
7. The discounted benefit is maximum for a discount rate of 4% within the range of discount rates considered in the analysis. The discount rate is found to influence the selection of the type of preventive maintenance treatments as well as the timings. The optimal budget level is also influenced by the discount rate. When the discount rate is 3%, the optimum budget level required is Rs. 7.5 million, and for 4% and 5% discount rates, the optimum budget level is Rs. 8.5 million for a pavement with a deflection value of 1.2 mm, IRI value of 3.42 m/km, and traffic volume of 3,000 cv/day.

Through investigation of the effect of these input variables, it can be inferred that the optimum budget level required is significantly influenced by the deflection values and the traffic volume. The optimal timing and type of preventive M&R actions are influenced by the condition of the pavement, traffic and its growth rate, and the discount rate. To derive the maximum benefit due to maintenance, the deflection value of the pavement should not exceed 1.2 mm for the range of input variables considered. A detailed analysis can be performed for a wide range of values, and a guideline can be evolved by considering the optimum intervention time.

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