Integration of Maintenance, Repair, and Replacement Decisions in Bridge Management Based on Reliability, Optimization, and Life-Cycle Cost

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ABSTRACT

Over the past several decades, the concepts of structural reliability, optimization, and life-cycle cost analysis and design have developed rapidly and become widely accepted among researchers and increasingly acknowledged among practicing engineers. The United States has a national inventory of almost 600,000 highway bridges, many of which have deteriorated substantially and will require large expenditures to repair. A reliability-based approach to optimizing the maintenance, repair and replacement of these bridges will provide a more efficient use of limited financial resources by ensuring an acceptable level of safety at a minimum expected life-cycle cost. The application of the minimum expected life-cycle cost criterion to optimize the management of highway bridges in the United States was recommended in 1991 by the Intermodal Surface Transportation Efficiency Act of Congress. Also, the 1996 National Science Foundation Workshop on Incorporation of Structural Reliability in Bridge Engineering recommended that a methodology for realistic life-cycle cost estimation of highway bridges has to be developed and used to produce optimal expenditures for new and existing bridges under reliability constraints. These optimal expenditures have to take into account all expected costs from the design stage to the end of the bridge's life span. Such a methodology could be incorporated into modern bridge management systems. This paper presents such a methodology by integrating maintenance, repair and replacement decisions in bridge management based on reliability, optimization, and life-cycle cost. After providing the framework of this methodology, the approach is illustrated for both new and existing highway bridges. Applying this methodology on a network-level by using life-cycle activity profiles requires considerable research support. Increased data expected in the future will permit the rational evolution of bridge management systems based on reliability, optimization, and life-cycle cost considerations.

INTRODUCTION

The need for the application of life-cycle cost analysis methods to bridge maintenance planning decisions is well established (*1*, *2*). In fact, at least two federal mandates require project planners to consider the costs of a proposed project over the entire life span of the structure (*3*). To predict all costs associated with a bridge over its lifetime, future maintenance requirements must be forecasted based on the expected resistance deterioration and increased load demand. This requires a quantitative predictive model of the condition of the bridge.

Condition assessment of bridges is an ongoing task for State Transportation Departments. The Federal Government created a comprehensive bridge inspection program (*2*), and biennial inspection of bridges is now required. Several bridge management systems (BMS) have been developed during the past decade to assist in the significant task of acquiring and interpreting inspection data from the nation's bridges, such as BRIDGIT (*4*) and Pontis (*5*). These BMS are used to assist in the prioritization of allocation of maintenance funds to the existing bridge stock. However, all of the data that currently feed into these BMS are based on visual inspection and subjective condition assessment (*6*).

Although the current BMS are useful in identifying the bridges which have the most visible signs of deterioration, they do not provide the quantitative information necessary for reliability-based bridge evaluation. Using the current systems, bridges are repaired based on a visual indication of deterioration rather than on the reliability of the bridge with respect to serviceability and ultimate limit states. Maintenance needs for bridges should be based on safety and serviceability rather than on the visible condition state of the structure (*7*).

When the total cost of a bridge is expressed in life-cycle terms, minimum cost maintenance strategies can be identified using optimization techniques. Optimal maintenance strategies have been identified for critical bridge elements such as decks (*8, 9*). But these models rely on deterministic damage data, and the failure criteria are not reliability based. To capture the full benefit of optimization based on life-cycle cost analysis, reliability-based methods have to be used in conjunction with quantitative condition assessment and prediction. Maintenance strategies which rely solely on deterministic condition assessment and bridge design code load ratings can be overconservative, which can lead to an overestimation of the need for bridge rehabilitation. For example, Enevoldsen (*10*) recently reported that the use of probabilistic methods in the assessment of the Vislund Bridge (Denmark) saved over US$3.3 million in rehabilitation costs compared to the deterministic approach. Also, when a reliability analysis is performed, the level of rehabilitation applied can be matched to the acceptable risk of failure.

In this study, reliability-based life-cycle cost is formulated based on quantitative condition assessment, including costs of inspection, maintenance, and failure. Several examples are presented based on recent studies at the University of Colorado (*11–15*), which illustrate reliability-based life-cycle cost optimization for new and existing bridges.

RELIABILITY-BASED BRIDGE ASSESSMENT

In the United States, bridge repair/maintenance decisions are often based on load ratings from deterministic strength assessments. Since the load and resistance factors found in the bridge design code (*16*) were developed to maintain a target reliability level for a wide range of bridge types and configurations under the maximum expected live load over a 75-year period (*17*), they may be overconservative for the assessment of existing bridges, particularly when site-specific load and resistance values are known.

Maintenance planning decisions based on these overconservative estimates can lead to wasteful intervention actions. Since the overall objective in bridge management is to ensure bridge safety and serviceability at minimum cost, a more rational approach is to evaluate both reliability and total life-cycle cost over the life span of a bridge. Maintenance actions can be based on an acceptable level of risk, which can be quantified using structural reliability methods. Optimum maintenance strategies can be identified which provide safety and serviceability at minimum expected life-cycle cost.

RELIABILITY-BASED OPTIMUM LIFE-CYCLE COST FRAMEWORK

The total cost of a bridge over its life-cycle consists of initial, maintenance (including preventative maintenance), inspection, repair, and failure costs. To perform life-cycle cost analysis, the time value of money must also be considered. For *new* bridges, the total life-cycle cost can be expressed as (*14*):

$$C_{E,L} = C_I + C_{PM,L} + C_{INS,L} + C_{REP,L} + C_{FAIL,L} \quad (1)$$

where $C_{E,L}$ = total expected cost over the bridge life span (i.e., design life), C_I = initial cost, $C_{PM,L}$ = preventative maintenance cost over the bridge life span, $C_{INS,L}$ = inspection cost over the bridge life span, $C_{REP,L}$ = repair cost over the bridge life span, and $C_{FAIL,L}$ = $C_F\, P_{F,L}$ = bridge failure cost, where C_F = costs associated with failure and $P_{F,L}$ = probability of failure over the bridge life span.

The optimization problem consists of minimizing total expected cost under reliability constraints as follows:

$$\min C_{E,L} \quad (2)$$

subject to

$$\beta_L \geq \beta_L^* \quad (3)$$

where β_L = bridge lifetime reliability index, and β_L^* = bridge lifetime target reliability index.

For *existing* bridges, the total life-cycle cost can be expressed as (*14*):

$$C_{E,RL} = C_{PM,RL} + C_{INS,RL} + C_{REP,RL} + C_{FAIL,RL} \quad (4)$$

where $C_{E,RL}$ = total expected cost over the remaining bridge life span, $C_{PM,RL}$ = preventative maintenance cost over the remaining bridge life span, $C_{INS,RL}$ = inspection cost over the remaining bridge life span, $C_{REP,RL}$ = repair cost over the remaining bridge life span, and $C_{FAIL,RL}$ = bridge failure cost over the remaining bridge life span.

The optimization problem for existing bridges consists of minimizing total expected cost under reliability constraints as follows:

$$\min C_{E,RL} \quad (5)$$

subject to

$$\beta_{RL} \geq \beta^*_{RL} \tag{6}$$

where β_{RL} and β^*_{RL} are the bridge lifetime reliability index and bridge lifetime target reliability index associated with the remaining life of the bridge, respectively.

APPLICATION TO NEW BRIDGES

Reliability-based optimization technology can be applied to bridge design. In this context, Lin (*11*) showed that for a given environment, the dimensions of bridge elements based on AASHTO requirements (*18*) can be modified to increase the time between repairs and reduce the total number of repairs over the life span of the bridge. The dimensions of bridge elements are identified using optimization techniques, and a reliability-based optimal maintenance strategy is identified which minimizes total life-cycle cost. In addition to prescribed values for all costs, values for the strength degradation rate, the discount rate, and deterioration must also be specified to identify the minimum cost solution.

A brief example is shown in Figures 1 and 2 for a new reinforced concrete T-beam bridge (*11, 19*) under corrosion attack. The life span of the bridge is 75 years. The rate of corrosion is $\nu = 0.0035$ in./year and the nondestructive inspection has a specified probability of damage detection $\eta_{0.5} = 0.10$ [see (*19*) for details]. In Figure 1, the costs specified in Eq. (1) are shown versus the number of lifetime inspections. It can be observed that as the number of inspections increases, the inspection and repair costs increase, whereas the failure cost decreases. For the optimal lifetime maintenance strategy, the number of inspections *m* which minimizes total life-cycle cost is six. In Figure 2, the influence of the inspection strategy on the reliability of the bridge is shown versus time. It can be observed that although there is a total of six inspections (i.e., $m = 6$), only four repair actions are performed (i.e., $n = 4$, where *n* is the number of repairs). This is due to the low probability of repair associated with inspections performed early in the life of the bridge [see (*19*) for details]. This approach can be used to compare several bridge design solutions for a variety of configurations and materials based on the total expected life-cycle cost criterion.

APPLICATION TO EXISTING HIGHWAY BRIDGES

An example of reliability-based life-cycle cost optimization of existing bridges is shown in Figures 3 to 6 (*12, 14, 20*). A system reliability-based approach is used to identify a minimum cost maintenance strategy for an existing bridge. The bridge, Colorado E-17-EH (Figures 3 and 4), is a three-span, four lane steel girder structure located near Denver, Colorado. It has an overall length of 42 m, and each of the three simply supported spans consists of nine girders.

The bridge is subjected to corrosion-based strength degradation. The overall bridge system is modeled using sixteen failure modes. Several repair strategies are

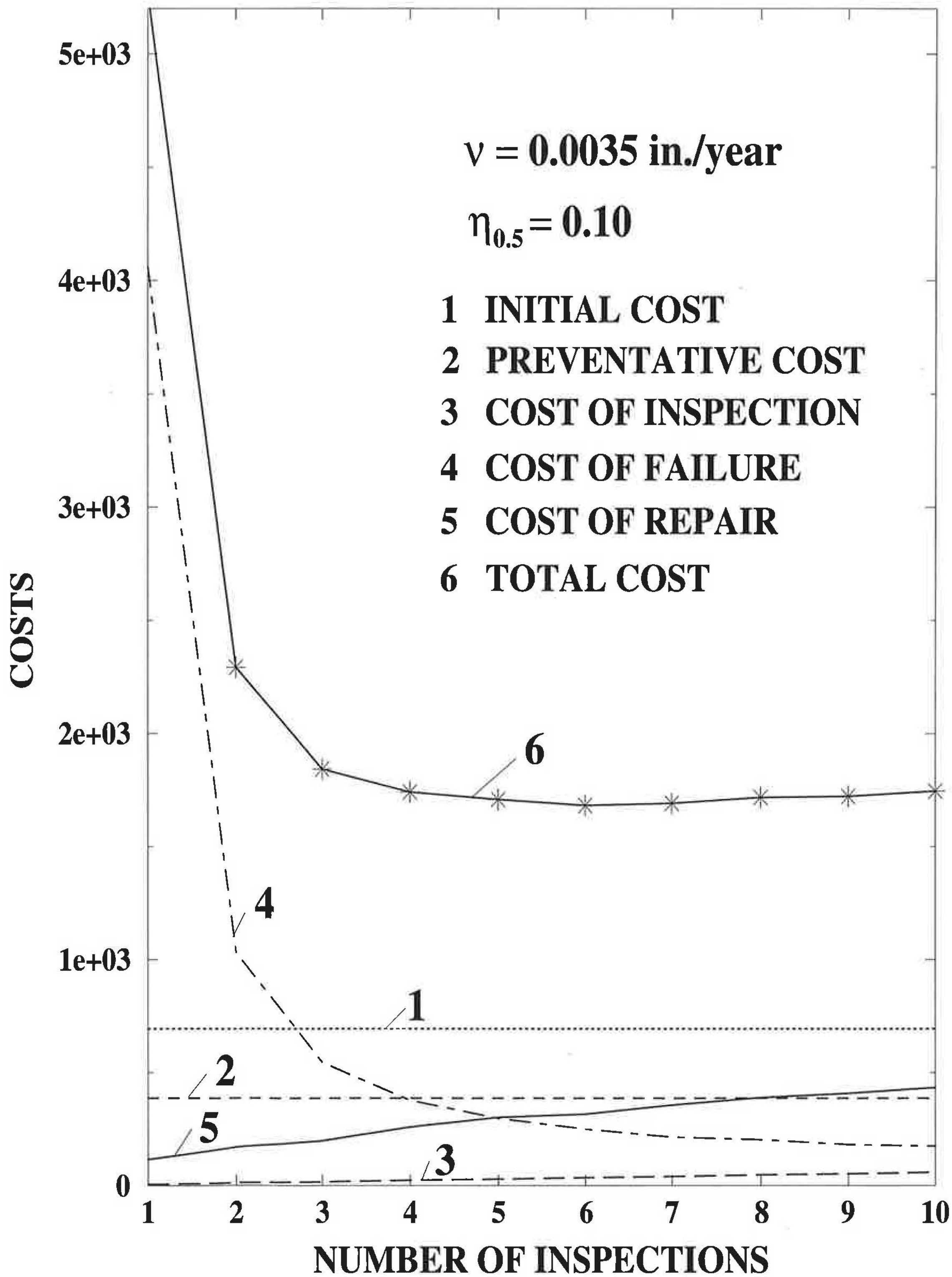

Figure 1: Costs versus number of lifetime inspections for a new bridge.

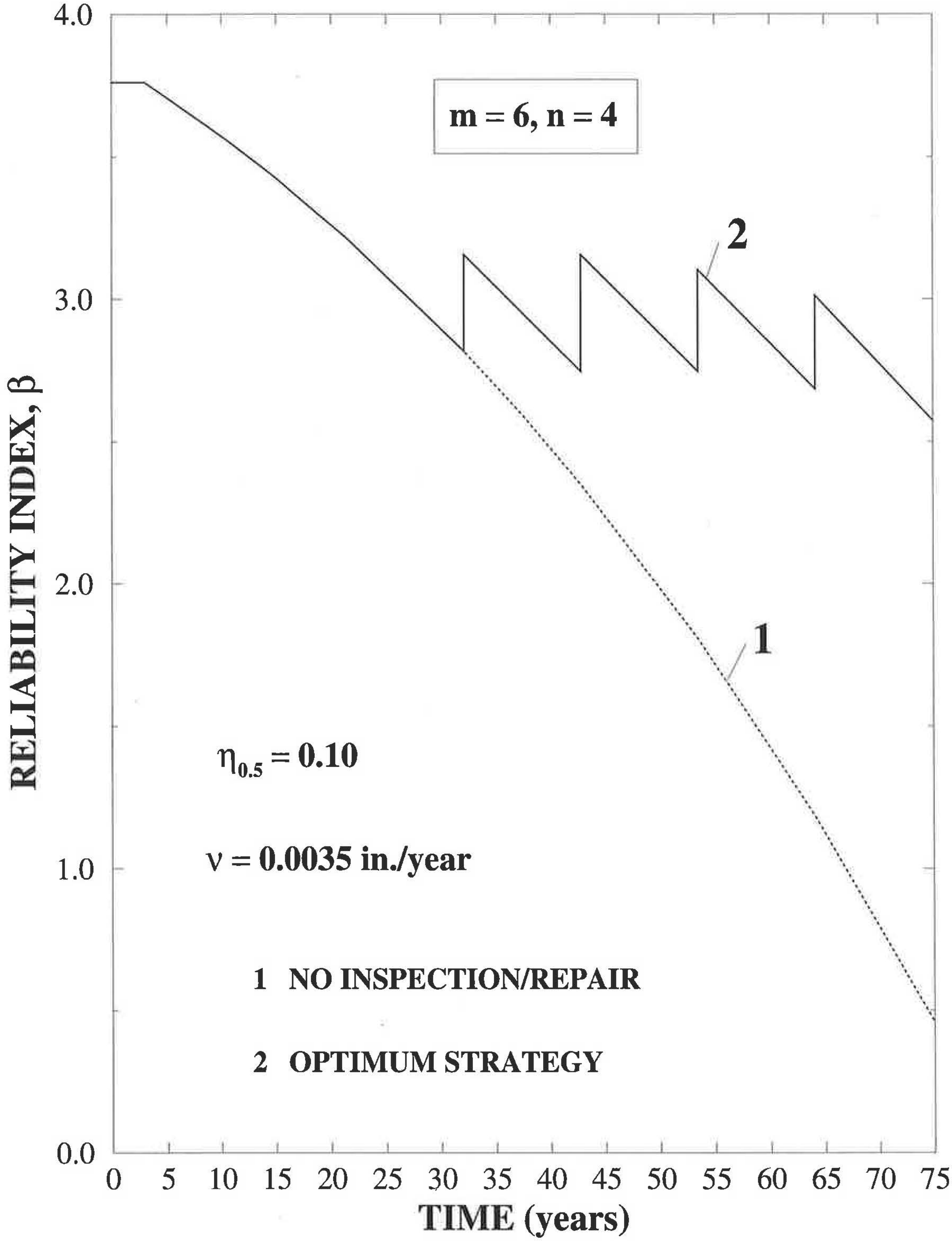

Figure 2: Optimum maintenance strategy for a new bridge.

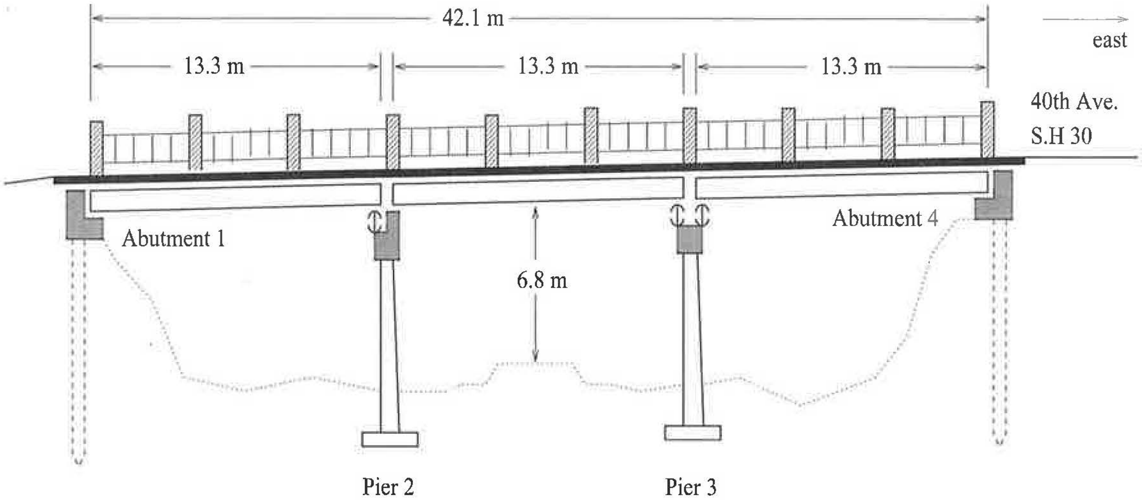

Figure 3: Elevation of Colorado Bridge E-17-AH.

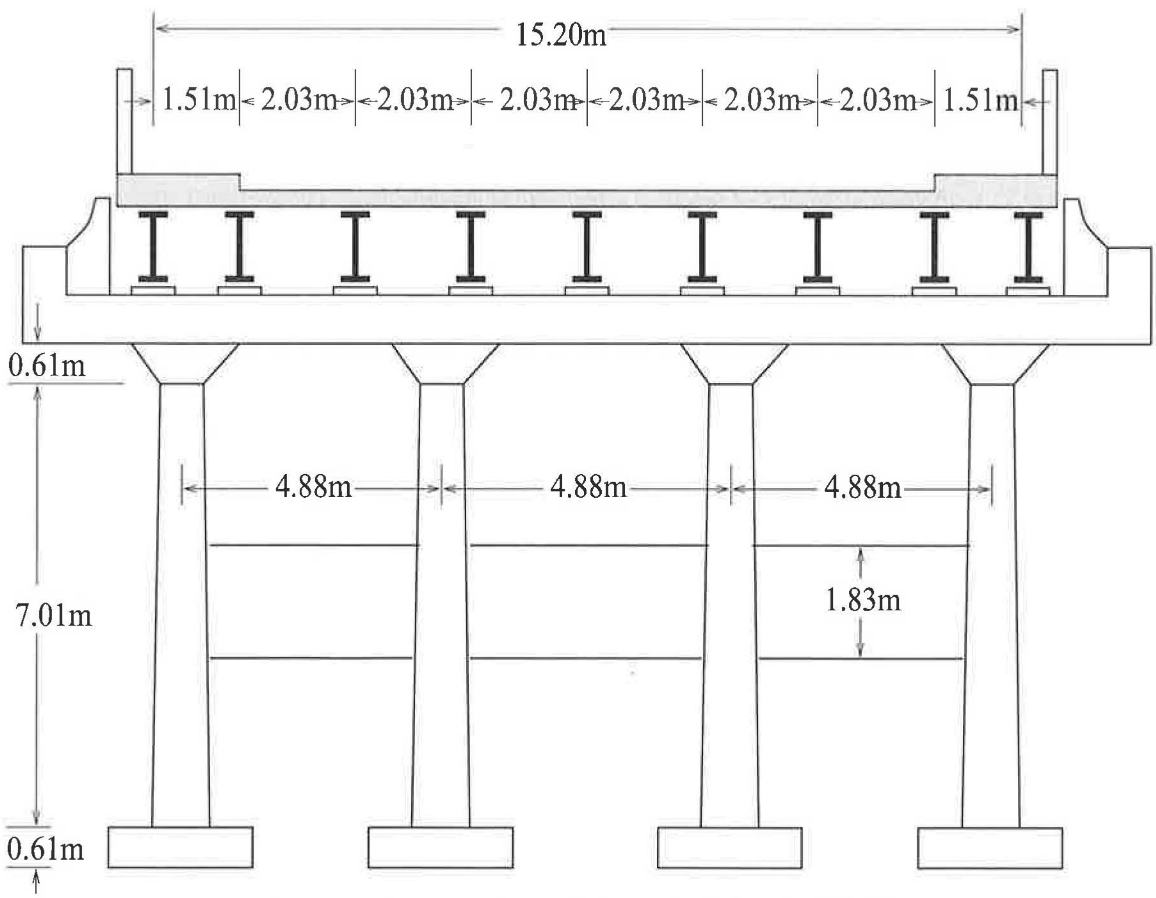

Figure 4: Cross section of Colorado Bridge E-17-AH.

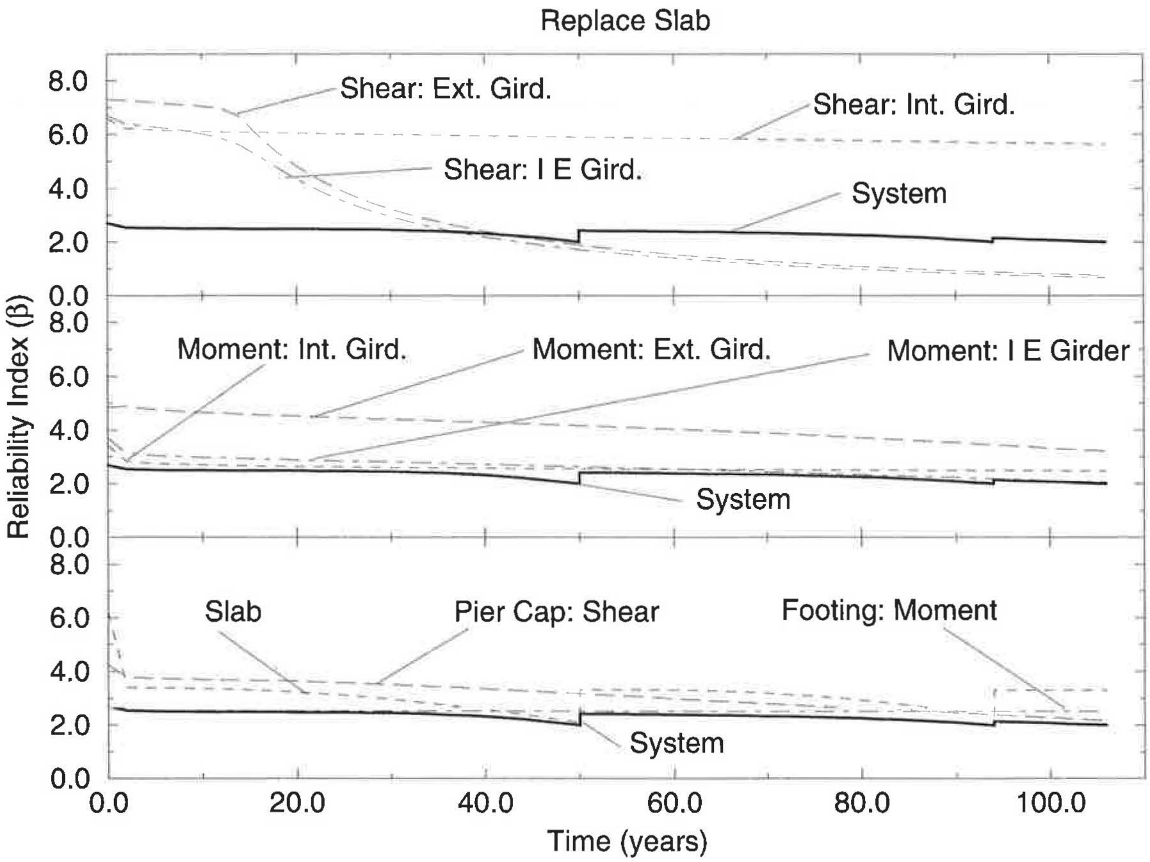

Figure 5: Colorado Bridge E-17-AH: Time-variant reliability of components and system, effect of bridge deck replacement at years 50 and 94.

considered for the bridge, such as replacement of the bridge deck (strategy 1), specified girders (strategy 2), specified girders and the deck (strategy 3), the entire superstructure (strategy 4), or the entire bridge (strategy 5). Member and system reliabilities associated with replacement of the bridge deck (i.e., strategy 1) at years 50 and 94 are shown in Figure 5. It can be observed that the reliabilities of some of the members are well below or above that of the bridge system.

In Figure 6, the feasible repair options for the bridge and their associated costs (US$1996) are shown. The optimum repair strategy is dependent on the service life specified for the bridge. For example, if the specified service life is between 50 and 94 years, the optimum solution is to replace the slab once at a cost of $83,813. For a service life of 94 to 106 years, the optimum solution is to replace the bridge deck twice at a cost of $118,881. If the service life is between 106 and 108 years, the optimum solution is to replace the bridge deck during the first repair, and replace both the deck and the exterior girders during the second repair at a cost of $136,945. Finally, if the service life is greater than 108 years, the optimum solution is to replace the bridge deck during the first repair, and replace the entire bridge during the second repair at a cost of $186,393.

Another example of reliability-based life cycle cost optimization of existing bridges is shown in Figures 7 to 10 (*13*). The selection of the optimum repair time of a

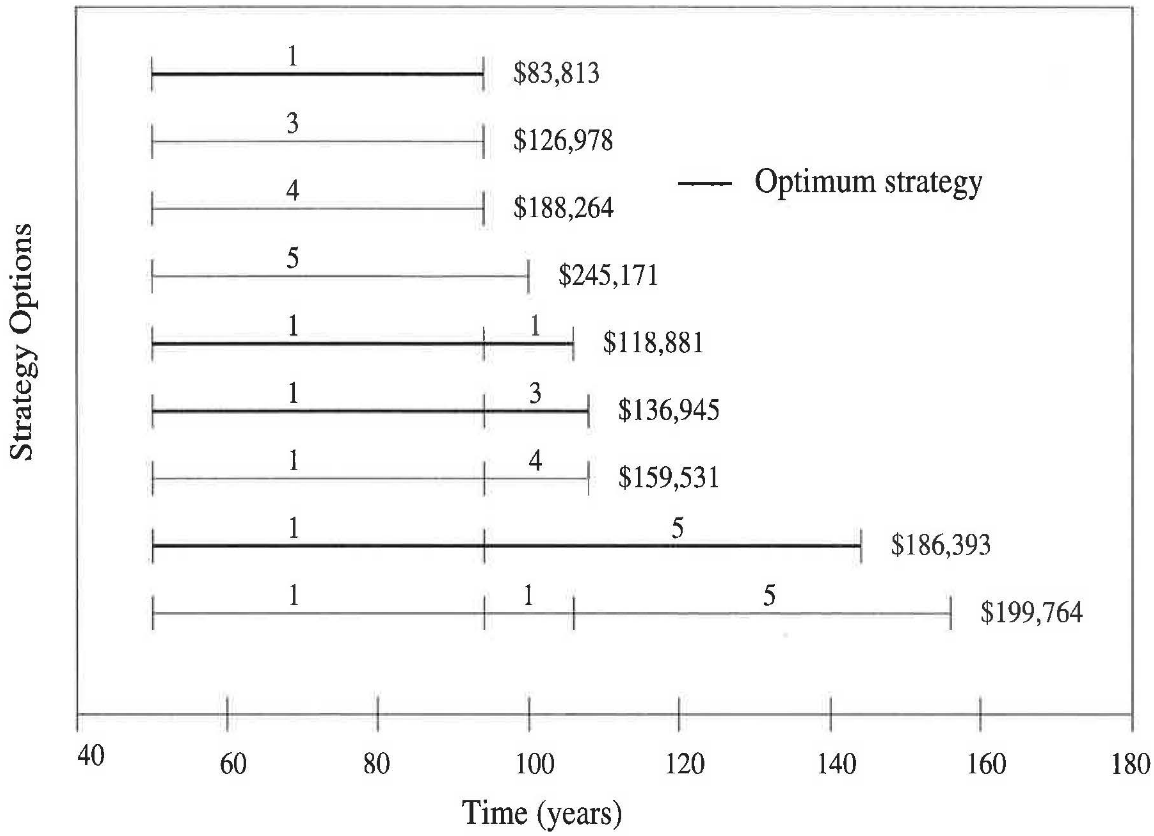

Figure 6: Colorado Bridge E-17-AH: Feasible repair options and optimum strategies.

typical reinforced T-beam highway bridge is considered using time-variant reliability-based life-cycle cost optimization. The bridge considered for the analysis, Colorado Highway Bridge L-18-BG, is shown in Figures 7 and 8. It consists of three 9.1 m simply supported spans (Figure 7). Each span has five girders equally spaced 2.6 m apart (Figure 8). The superstructure is modeled as a weakest link system subjected to strength

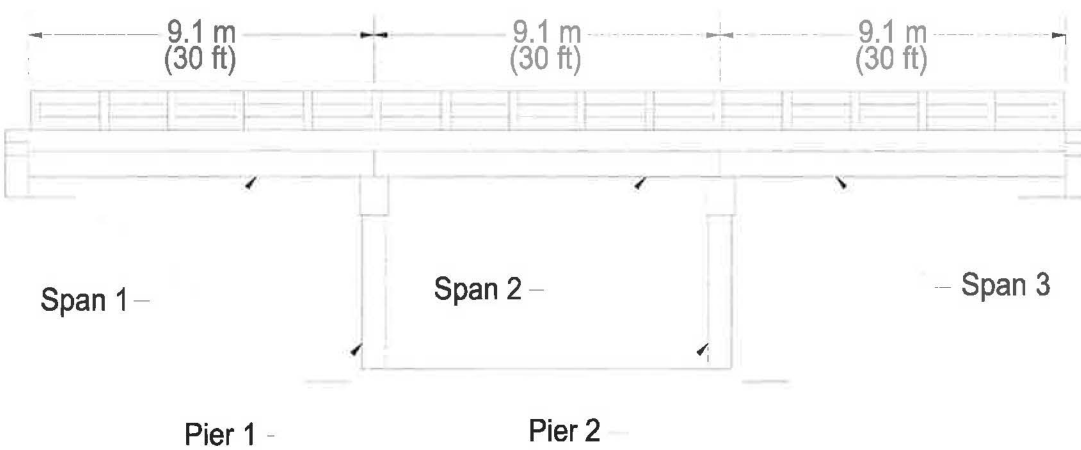

Figure 7: Elevation of Colorado Bridge L-18-BG.

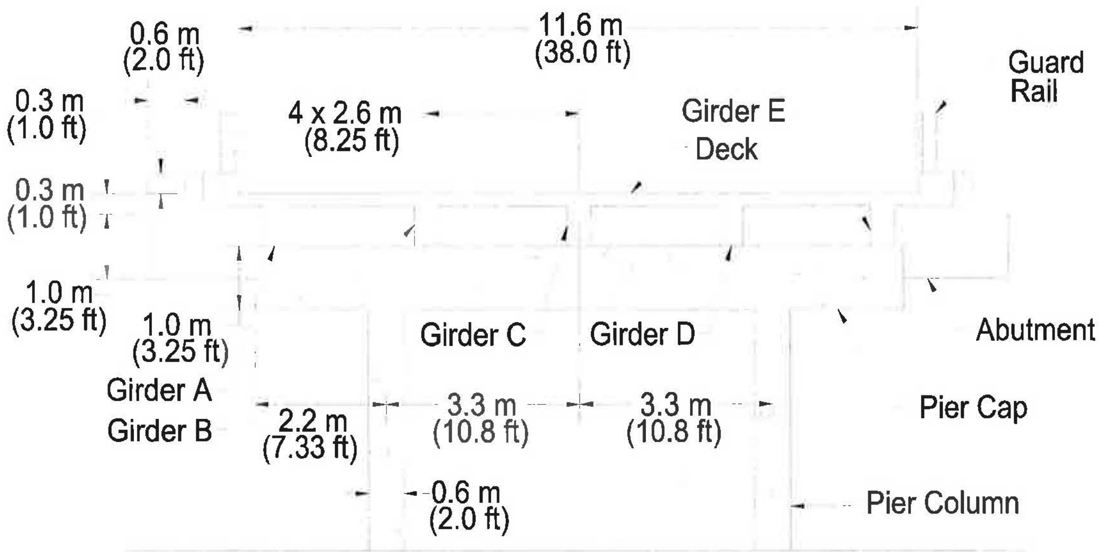

Figure 8: Cross section of Colorado Bridge L-18-BG.

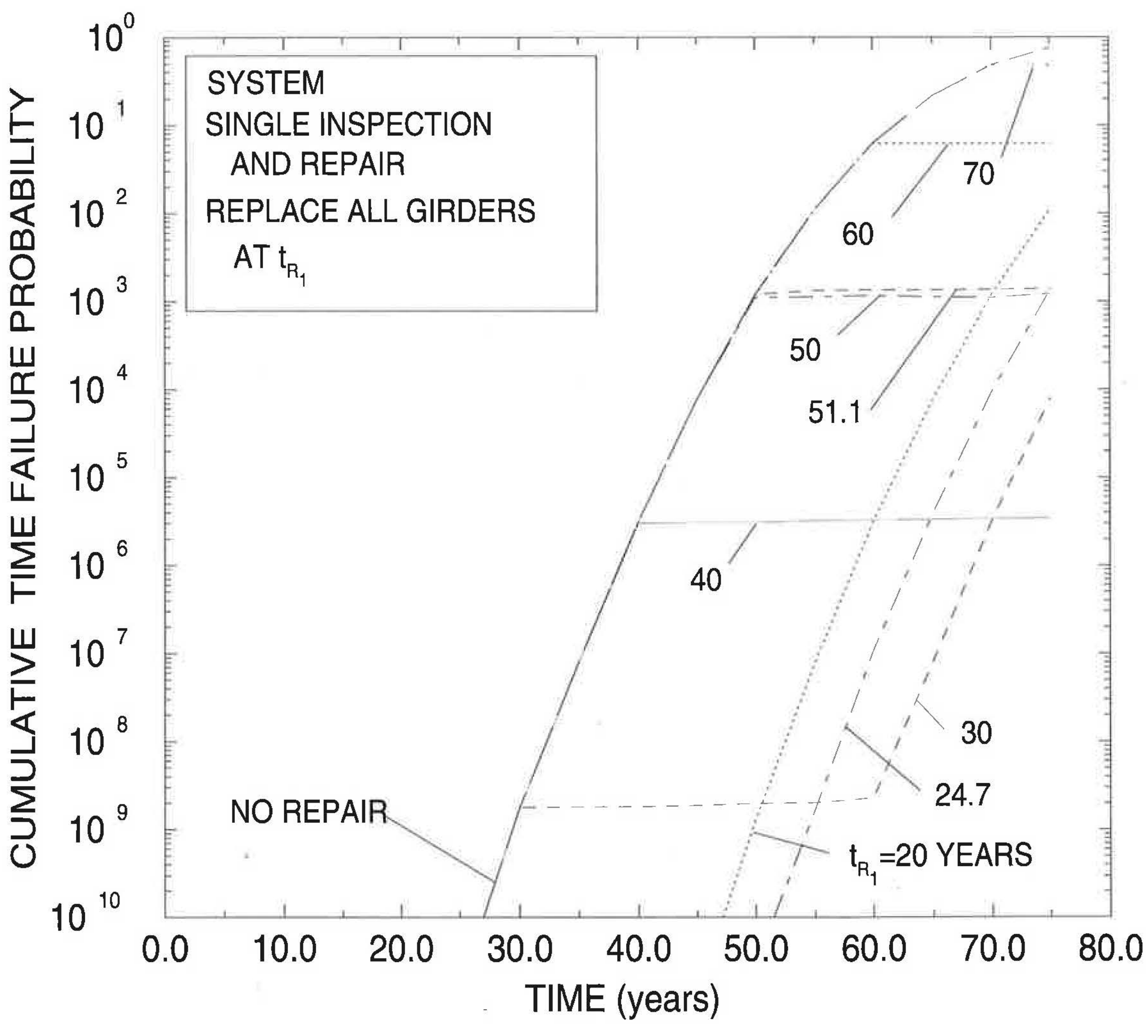

Figure 9: Influence of replacement of girders on cumulative-time failure probability of Colorado Bridge L-18-BG.

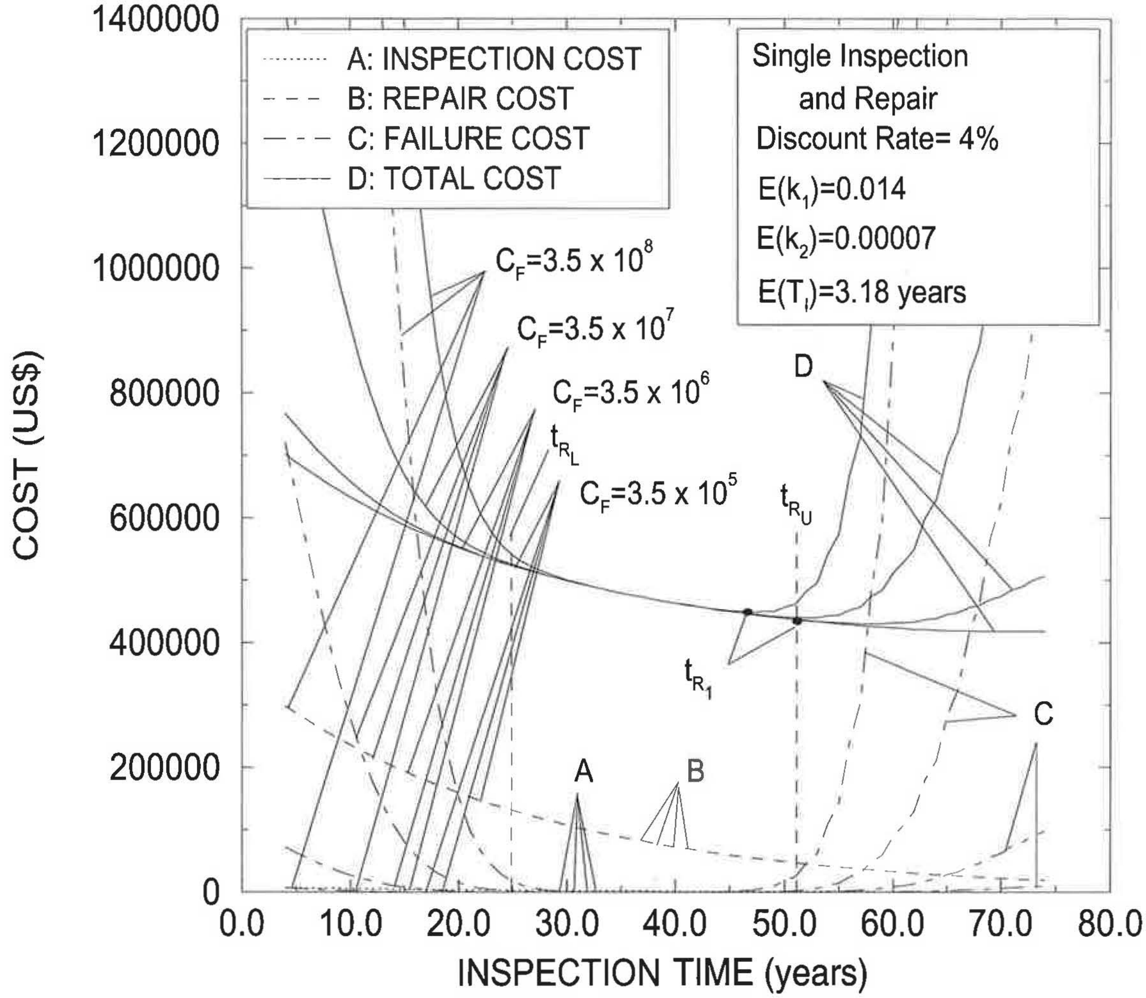

Figure 10: Costs versus time of inspection and minimum expected total cost solutions for Colorado Bridge L-18-BG.

degradation caused by corrosion of steel reinforcement, with target lifetime reliability index β^*_{RL}= 3.0 (i.e., $P^*_{f,RL}$ = 0.00135, where $P^*_{f,RL}$ is the failure probability associated with β^*_{RL}).

The cumulative-time failure probability of the bridge is shown in Figure 9 for repair times t_{Rl} ranging from 20 to 70 years. From Figure 9, it can be observed that if the repair is performed too early (i.e., t_{Rl} = 20 years) or too late (i.e., t_{Rl} = 60 or 70 years) in the life of the bridge, the probability of failure of the system at the end of the service life exceeds the target lifetime failure probability $P^*_{f,RL}$ (i.e., $\beta_{RL} < \beta^*_{RL}$). Values for the upper, t_{RU}, and lower, t_{RL}, bounds for the repair time, t_{Rl}, are 51.1 years and 24.7 years, respectively. These bounds define the range of feasible values for the repair time (i.e., range of values for t_{Rl} in which the reliability constraint (Eq. 6) is not violated).

In Figure 10, optimum repair times t_{Rl} associated with several values of the failure cost coefficient C_F are shown for an assumed discount rate of 4%, mean values of the degradation parameters k_1 and k_2 of 0.014 and 0.00007, respectively, and mean value of damage initiation time of 3.18 years (see (*13*) for details). Also shown are the values for the upper and lower bounds (i.e., t_{RU} and t_{RL}, respectively) for the repair time t_{Rl}. In each case, the optimum repair time is the value which minimizes expected total cost yet satisfies the failure probability constraint.

CONCLUSIONS

As the need for cost-effective maintenance strategies for the deteriorating infrastructure increases, BMS will become more sophisticated. Most of the current BMS are based on visual or subjective condition assessment, and do not predict optimum maintenance requirements based on balancing life-cycle cost and bridge system reliability requirements. Optimum reliability-based life-cycle cost analysis provides the following advantages:

- Identifies the total life-cycle cost associated with maintaining a bridge at or above a target reliability level.
- Identifies maintenance strategies which minimize total life-cycle cost and satisfy reliability constraints.
- Establishes future bridge maintenance needs based on safety and serviceability rather than on the visible condition state of the structure.
- Provides a rational basis for prioritization of bridge maintenance fund allocations.

As shown in this study, the integration of maintenance, repair, and replacement decisions in bridge management based on reliability, optimization, and life-cycle cost is a practical possibility. This integration has the potential to provide significant cost savings and improved safety of the bridge infrastructure. Programs, policies, and practices need to be developed to promote this integration.

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