# Reliability-Based Life-Cycle Management of Highway Bridges

By Dan M. Frangopol,[1] Fellow, ASCE, Jung S. Kong,[2] and Emhaidy S. Gharaibeh[3]

**Abstract:** The objective of bridge management is to allocate and use the limited resources to balance lifetime reliability and life-cycle cost in an optimal manner. As the 20th century has drawn to a close, it is appropriate to reflect on the birth and growth of bridge management systems, to examine where they are today, and to predict their future. In this paper, it is attempted to shed some light on the past, present, and future of life-cycle management of highway bridges. It is shown that current bridge management systems have limitations and that these limitations can be overcome by using a reliability-based approach. It is concluded that additional research is required to develop better life-cycle models and tools to quantify the risks, costs, and benefits associated with highway bridges as well as their interrelationships in highway networks.



## INTRODUCTION

The prioritization of scarce funds among the multitude of urgently needed bridge maintenance, repair, and rehabilitation activities is a major problem that bridge authorities everywhere are facing (Das 1999). Despite all the difficulties in using the minimum expected whole life costing as the optimization criterion for the prioritization of funds, bridge authorities are committed to it (Ang et al. 1998). Thus far, however, the implementation of this criterion in the management of highway bridges has been very limited (Frangopol 1999). The challenges presented by the whole life-costing criterion are difficult to meet. In view of this, it seems an appropriate time to present a summary overview of the field and to point the way to future developments. Although the field of bridge management systems is relatively recent, the number of publications is so large that it is beyond the scope of this paper to review all relevant literature. For this reason, this brief overview is by no means considered to be exhaustive. Rather, it is believed that several important developments will be captured. Recent advances in life-cycle engineering, preventive maintenance strategies, reliability, and optimization techniques provide a rich ground for interdisciplinary research in bridge management systems. The results of this research will provide the bridge manager realistic life-cycle costs and lifetime reliabilities and improve the quality of decisions made in the face of uncertainties and fiscal constraints.

The aim of this paper is to shed some light on the past, present, and future of life-cycle management of highway bridges. It is shown that current bridge management systems have limitations and that these limitations can be overcome by using a reliability-based approach. The relationship between lifetime reliability and life-cycle cost in optimal bridge management is emphasized. It is concluded that additional research is required to develop better life-cycle models and tools to quantify the risks, costs, and benefits associated with highway bridges as well as their interrelationships in highway networks.

[1]Prof., Dept. of Civ., Envir., and Arch. Engrg., Univ. of Colorado, Boulder, CO 80309-0428.

[2]Grad. Student, Dept. of Civ., Envir., and Arch. Engrg., Univ. of Colorado, Boulder, CO.

[3]Asst. Prof., Dept. of Civ. Engrg., Mutah Univ., Mutah, Al-Karak, Jordan; formerly, Grad. Student, Dept. of Civ., Envir., and Arch. Engrg., Univ. of Colorado, Boulder, CO.

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## PAST AND PRESENT

Before and during the 1960s and into the 1970s, bridge maintenance, repair, rehabilitation, and replacement activities were performed on an as-needed basis, employing the best existing practice (Thompson et al. 1998). During this time interval, the bridge engineering community focused on new construction (Small and Cooper 1998a), and the reactive (versus preventive) strategies appeared sufficient to address any potential bridge safety issues. In the United States, this situation changed in the late 1960s, when several bridge failures, including the tragic collapse of the Silver Bridge due to instantaneous eyebar fracture, focused national attention on the deterioration of the existing bridges with emphasis on bridge safety (Small and Cooper 1998a; Small et al. 1999).

Subsequent standard provisions (i.e., the National Bridge Inspection Standards issued in 1971), mandated standardized bridge inspection procedures. Several conditions that could compromise bridge safety were flagged, including material deterioration, fatigue, and overloading. As indicated by Small and Cooper (1998a), the standard provisions ''served as the basis for today's better understanding of the condition of the bridge network and ways of making better infrastructure investments to provide safe, useful bridges.'' Since 1971, the bridge inspection program, based on periodic inspections by bridge owners, has provided data maintained in the National Bridge Inventory (NBI) database (Turner and Richardson 1994). The NBI data provided the basis for bridge management in the United States from the 1970s.

Since the early 1970s, the Federal Highway Administration (FHWA) utilized the NBI information as the primary source of data for bridge management decision making in allocating funds to the States through the Highway Bridge Repair and Replacement Program and the Special Bridge Program. As indicated by Small et al. (1999), the increasing differential between funds available and needs became an area of greater concern in the mid-to-late 1980s. Therefore, a new form of bridge management decision support based on optimization procedures was desired.

In the 1980s, research initiated by the FHWA and the National Cooperative Highway Research Program (NCHRP) through FHWA Demonstration Project 71 (O'Connor and Hyman 1989) and NCHRP Project 12-28(2) (Hudson et al. 1987) resulted in the identification of tools and techniques available for bridge management decision support systems (Small et al. 1999). Out of these results, the FHWA, in cooperation with state departments of transportation (DOTs), pursued the development of the Pontis bridge management system (Thompson et al. 1998), and the NCHRP research continued with the development of the BRIDGIT bridge management system (Hawk and Small 1998). Pontis is the predominant bridge management system employed in the United States, including



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about 40 state DOTs. BRIDGIT is employed in Maine, with several other states examining it for possible implementation. Also, several metropolitan planning organizations are expected to implement BRIDGIT (Small et al. 1999). Both Pontis and BRIDGIT use similar mathematical procedures for optimizing the economic efficiency of the bridge network. They express the concerns of deterioration and performance in economic terms.

In the 1990s, the need for expansion of bridge data, including element condition, cost, traffic and accident, and historical data, has been recognized by the American Association of State Highway and Transportation Officials (AASHTO) (1992) and the Intermodal Surface Transportation Efficiency Act of 1991. This act required state highway agencies to implement bridge management systems to support optimum planning of maintenance activities. As a result, there was a need to review and evaluate Pontis and BRIDGIT in order to determine their capabilities. For this reason, both Pontis and BRIDGIT released beta versions of the software in the early 1990s. The beta testing processes identified several enhancements for consideration. Most of these enhancements have been implemented. The Seventh Conference on Bridge Management held in Austin, Texas, in September 1993 (Transportation 1994), provided an excellent forum for the exchange of information about the state of the art in bridge management systems. At this conference, the two U.S. national systems, Pontis and BRIDGIT, were evaluated. In 1995, the National Highway System Designation Act repealed the mandate for bridge management system implementation by state highway agencies. However, state DOTs continue to pursue the use of bridge management systems including Pontis and BRIDGIT (Small and Cooper 1998b). These systems have the capacity to prioritize needs and select the most cost-effective options for given budgets over the planning horizon (Hawk and Small 1998; Thompson et al. 1998). Several cities, states, and countries, including Denmark and Finland, developed their own bridge management systems. For a review of the capabilities of these systems, the reader is referred to Johnston and Lee (1994), Das (1998), Lauridsen et al. (1998), Söderqvist and Veijola (1998), Yanev (1998), and Roberts and Shepard (2000), among others.

The state of the practice and state of the art in bridge management systems as of 1999 were both reported at the International Bridge Management Conference held in Denver in April 1999 (*International* 1999). Current bridge management systems, including both Pontis and BRIDGIT, are, in most cases, based on the following assumptions: (1) Elements are characterized by discrete condition states describing the type and severity of element deterioration in visual terms; (2) a Markovian deterioration model to predict the probability of transitions among condition states is used; (3) deterioration is assumed to be a single step function (i.e., quantities may not transit more than one condition state within any given year); and (4) transition probabilities are not time variant.

Some of the above assumptions are quite restrictive. The limitations of the current approach have been revealed by Frangopol and Das (1999). The main limitations are summarized as follows: (1) Bridge element performance is not addressed from a reliability viewpoint (i.e., damage and not reliability is assumed as the single reason for repair and replacement actions); (2) the Markovian approach is not able to take into account the entire history of the bridge deterioration process (i.e., future condition states are independent of the history of the element deterioration); and (3) bridge system performance (reliability) is not generally addressed (i.e., only single failure modes are considered in spite of the fact that the performance of the bridge system can be vastly different from the performance of its components) (Frangopol et al. 1998). Therefore, one of the most severe limitations is that bridge reliability is not directly incorporated in bridge management.

## RELIABILITY-BASED BRIDGE MANAGEMENT: FUTURE

In the United States, the safety evaluation of bridge systems has traditionally followed long-established and strict codified procedures. This may explain why the application of reliability concepts and techniques in bridge management has lagged behind application in other types of structural systems, including offshore platforms. On the other hand, the first edition of the *AASHTO LRFD Bridge Design Specifications* (AASHTO 1994) and the *Structural Reliability in Bridge Engineering* international workshop (Frangopol and Hearn 1996) have alerted the bridge engineering community to the benefits of using reliability concepts and techniques (Frangopol et al. 1998). Today, it is generally recognized that bridge management decision support systems have to consider the uncertainties associated with the bridge management process. In short, bridge management decisions have to be made in the face of uncertainty. Therefore, concepts and methods of probability are the proper bases for bridge management. For the purpose of formulating rational bridge management decisions, reliability-based bridge management has to be used.

Thoft-Christensen (1995) proposed to apply reliability theory in bridge management systems. Frangopol (1999) developed the basis for cost-effective bridge management incorporating lifetime reliability and life-cycle cost. Very recently, Frangopol and Das (1999) and Thoft-Christensen (1999) defined bridge reliability states and proposed a reliability-based approach to bridge maintenance. Furthermore, Das (2000) provided additional background information on this novel approach, and Frangopol et al. (2000a,b) presented realistic examples of optimum bridge maintenance planning based on minimum expected cost.

This new approach opens the avenue to incorporate bridge reliability in life-cycle management and hence to form the basis of a more rational approach to bridge management. In this manner, the limitations associated with the present approach to bridge management are overcome. In the following, the basis of the reliability-based approach to bridge management (Frangopol and Das 1999; Thoft-Christensen 1999; Frangopol et al. 2000a,b; Kong et al. 2000a,b) is reviewed and further developed.

The reliability index, $\beta$, is used as a measure of bridge safety (Ghosn and Frangopol 1999). In general, individual bridges in a bridge group have different ages and their reliability is time dependent. The service life of a bridge is a progression of reliability states—excellent (i.e., state 5, where $\beta \geq 9.0$); very good (i.e., state 4, where $9.0 > \beta \geq 8.0$); good (i.e., state 3, where $8.0 > \beta \geq 6.0$); fair (i.e., state 2, where $6.0 > \beta \geq 4.6$); and unacceptable (i.e., state 1, where $\beta < 4.6$).

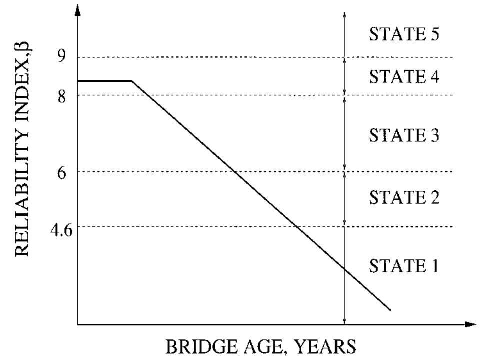


**FIG. 1. Bridge Reliability Profile without Maintenance and Reliability States**





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Fig. 1 shows this progression assuming no maintenance. Notice that a new bridge is not necessarily in state 5 (i.e., $\beta > 9.0$) and that the linear bridge reliability profile represents an approximation of the nonlinear reliability degradation that might exist in reality. Fig. 2 shows the whole life performance (i.e., reliability) profile as affected by essential and preventive maintenance, and Fig. 3 shows the probability density functions of several random variables associated with the whole-life process. The notations for the probability density functions shown in Fig. 3 are as follows: (a) = initial performance (i.e., reliability) level; (b) = time of damage initiation; (c) = performance (i.e., reliability) deterioration rate without maintenance; (d) = first rehabilitation time [i.e., age at which the minimum acceptable (target) reliability level is reached for the first time]; (e) = improvement in reliability level due to essential maintenance; (f) = time of damage initiation after essential maintenance has been done; (g) = reliability deterioration rate after essential maintenance has been done; and (h) = second

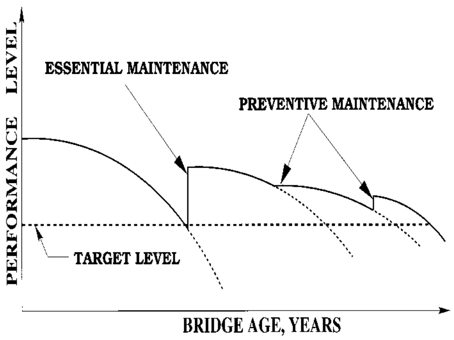


**FIG. 2. Whole Life Bridge Performance Profile as Affected by Essential and Preventive Maintenance**

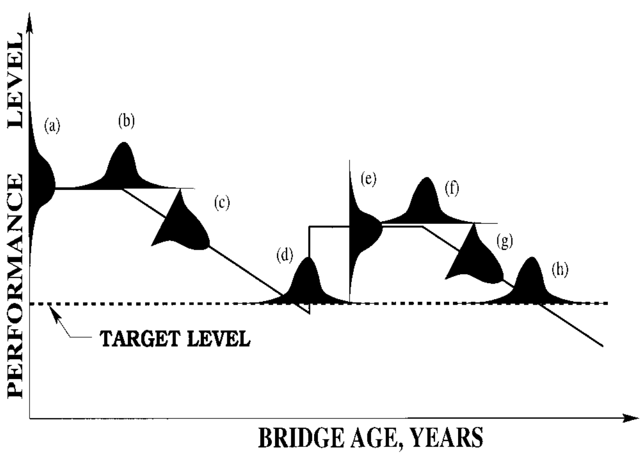


**FIG. 3. Uncertainties during Whole Life Process**

rehabilitation rate. The random variables affecting lifetime reliability of a bridge group are shown in Fig. 4. They include the following: initial reliability index, $B_0$; time of damage initiation, $T_I$; reliability deterioration rate without maintenance, $A$; time of first application of preventive maintenance, $T_{PI}$; time of reapplication of preventive maintenance, $T_P$; duration of preventive maintenance effect on bridge reliability, $T_{PD}$; reliability deterioration rate during preventive maintenance effect, $\Theta$; and improvement of reliability index (if any) immediately after the application of preventive maintenance, $\Gamma$. The probability density distributions of these variables are also shown in Fig. 4. If no preventive maintenance has been done, the distribution of the rehabilitation time (i.e., time at which the reliability index downcrosses the target value, also called the rehabilitation rate, $T_R$) depends on the initial reliability index, time of damage initiation, and reliability deterioration rate without maintenance. Conversely, if preventive maintenance has been done, the distribution of the rehabilitation rate $T_{RP}$ depends on all the random variables defined earlier. Table 1 (Kong et al. 2000a,b) defines the distributions and the main descriptors of the random variables in Fig. 4.

Monte Carlo simulation is used to generate the random numbers from the probability-density functions indicated in Table 1. The time-dependent simulation aspect is taken into account by considering three different cases for the start of the damage initiation time $T_I$. As shown in Fig. 5, these cases are as follows: (1) starting before application of first preventive maintenance (case 1); (2) starting after application or reapplication of preventive maintenance, but within the duration of the preventive maintenance effect (case 2); and (3) starting after application of preventive maintenance and after the duration of the preventive maintenance effect (case 3). The equations associated with these cases are as follows:

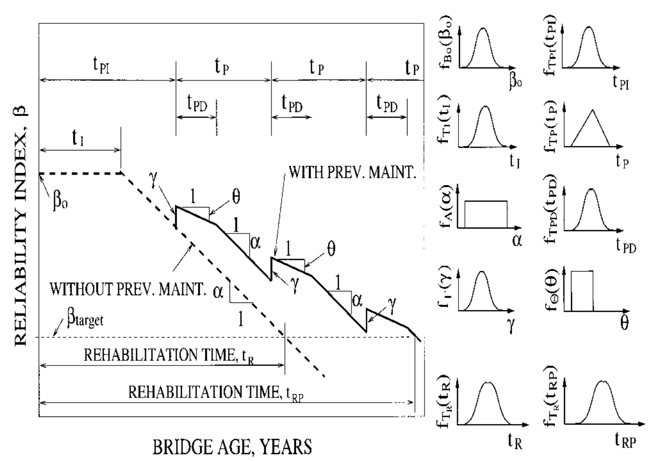


**FIG. 4. Random Variables Affecting Lifetime Reliability of Bridge Group**

**TABLE 1. Random Variables Associated with ($B_0$, $T_I$, $A$, $T_{PI}$, $T_p$, $T_{PD}$, $\Theta$, and $\Gamma$) or without ($B_0$, $T_I$, $A$) Preventive Maintenance for Shear and Bending Moment Failure Modes**

| Random variable (1) | Distribution type (2) | Main Descriptors of Failure Modes: Shear (3) | Bending moment (4) |
|---|---|---|---|
| $B_0$ | Lognormal | Mean = 8.5, standard deviation = 1.5 | Mean = 7.5, standard deviation = 1.2 |
| $T_I$ (years) | Lognormal | Mean = 15, standard deviation = 5 | Mean = 15, standard deviation = 5 |
| $A$ (years$^{-1}$) | Uniform | Minimum = 0.005, maximum = 0.20 | Minimum = 0.002, maximum = 0.100 |
| $T_{PI}$ (years) | Lognormal | Mean = 20, standard deviation = 5 | Mean = 20, standard deviation = 5 |
| $T_P$ (years) | Triangular | Minimum = 10, mode = 15, maximum = 20 | Minimum = 10, mode = 15, maximum = 20 |
| $T_{PD}$ (years) | Lognormal | Mean = 10, standard deviation = 2 | Mean = 10, standard deviation = 2 |
| $\Theta$ (years$^{-1}$) | Uniform | Minimum = 0.00, maximum = 0.05 | Minimum = 0.000, maximum = 0.025 |
| $\Gamma$ | Lognormal | Mean = 0.2, standard deviation = 0.04 | Mean = 0.2, standard deviation = 0.04 |



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- Case 1

$$\beta(t)=\begin{cases}\beta_0 & \text{if } 0 \le t \le t_I & (1a)\\ \beta_0-(t-t_I)\alpha & \text{if } t_I < t \le t_{PI} & (1b)\\ \beta_1-(t-t_{PI})\theta & \text{if } t_{PI} < t \le t_{PI}+t_{PD} & (1c)\\ \beta_1'-[t-(t_{PI}+t_{PD})]\alpha & \text{if } t_{PI}+t_{PD} < t \le t_{PI}+t_P & (1d)\\ \beta_n-\{t-[t_{PI}+(n-1)t_P]\}\theta & \text{if } t_{PI}+(n-1)t_P < t \le t_{PI}+(n-1)t_P+t_{PD} & (1e)\\ \beta_n'-\{t-[t_{PI}+(n-1)t_P+t_{PD}]\}\alpha & \text{if } t_{PI}+(n-1)t_P+t_{PD} < t \le t_{PI}+nt_P & (1f)\end{cases}$$

- Case 2

$$\beta(t)=\begin{cases}\beta_0 & \text{if } 0 \le t \le t_I' & (2a)\\ \beta_0-(t-t_I')\theta & \text{if } t_I' \le t < t_{PI}+(m-1)t_P+t_{PD} & (2b)\\ \beta_0'-\{t-[t_{PI}+(m-1)t_P+t_{PD}]\}\alpha & \text{if } t_{PI}+(m-1)t_P+t_{PD} \le t < t_{PI}+mt_P & (2c)\\ \beta_n-\{t-[t_{PI}+(n-1)t_P]\}\theta & \text{if } t_{PI}+(n-1)t_P \le t \le t_{PI}+(n-1)t_P+t_{PD} & (2d)\\ \beta_n'-\{t-[t_{PI}+(n-1)t_P+t_{PD}]\}\alpha & \text{if } t_{PI}+(n-1)t_P+t_{PD} \le t \le t_{PI}+nt_P & (2e)\end{cases}$$

where

$$\beta_0'=\beta_0-\{[t_{PI}+(m-1)t_P+t_{PD}]-t_I'\}\theta \qquad (2f)$$

- Case 3

$$\beta(t)=\begin{cases}\beta_0 & \text{if } 0 \le t \le t_I' & (3a)\\ \beta_0-(t-t_I')\alpha & \text{if } t_I' \le t < t_{PI}+mt_P & (3b)\\ \beta_n-\{t-[t_{PI}+(n-1)t_P]\}\theta & \text{if } t_{PI}+(n-1)t_P \le t \le t_{PI}+(n-1)t_P+t_{PD} & (3c)\\ \beta_n'-\{t-[t_{PI}+(n-1)t_P+t_{PD}]\}\alpha & \text{if } t_{PI}+(n-1)t_P+t_{PD} \le t \le t_{PI}+nt_P & (3d)\end{cases}$$

where main notations are indicated in Figs. 4 and 5; and $m$ and $n$ = positive integers ($m \ge 1$, $n > m$) representing the number of preventive maintenance actions applied before the occurrence of damage initiation and the total number of preventive maintenance actions (i.e., applied before and after the occurrence of damage initiation), respectively. The time of damage initiation

$$t_I' = t_I + \eta m t_{PD} \qquad (4)$$

has the following two components: $t_I$ = damage initiation time not affected by preventive maintenance actions, and $\eta m t_{PD}$ = extended damage initiation time due to $m$ preventive maintenance actions. The coefficient $\eta$ (Fig. 5) is a multiplier representing the effectiveness of preventive maintenance on the extension of the damage initiation time ($\eta = 0.5$ in the present study).

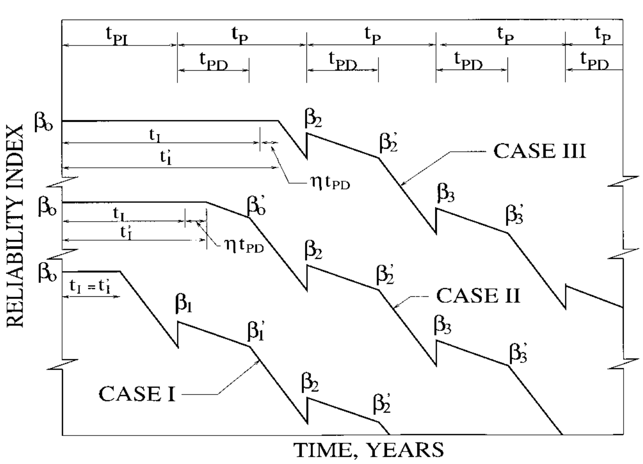


FIG. 5. Three Cases for Starting Damage Initiation Time

Eqs. (1)–(4) were used for simulating the rehabilitation times $T_R$ and $T_{RP}$ indicated in Fig. 4. Fig. 6 compares the probability-density functions of rehabilitation rates for steel/concrete composite bridges with and without maintenance. The results in Fig. 6 were obtained by simulation followed by quadratic fitting. As indicated, the effect of preventive maintenance on the rehabilitation rate is substantial. In Fig. 7, this effect is quantified in terms of the expected number of bridges in reliability state 1 (i.e., $\beta < 4.6$) from a stock of 713 steel/

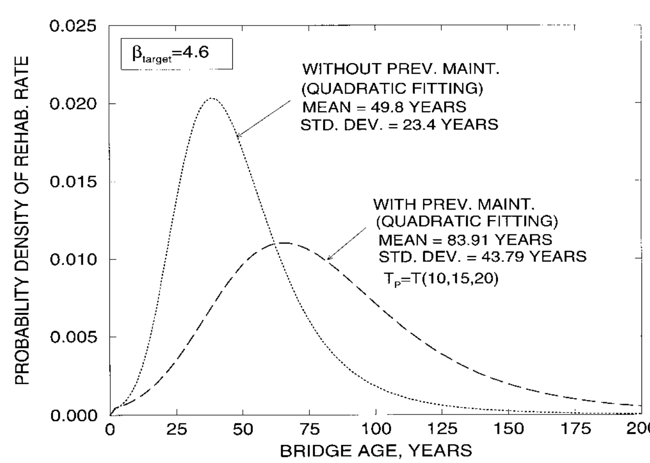


FIG. 6. Probability-Density Functions of Rehabilitation Rate with and without Preventive Maintenance (Results Based on Simulation Followed by Quadratic Fitting)

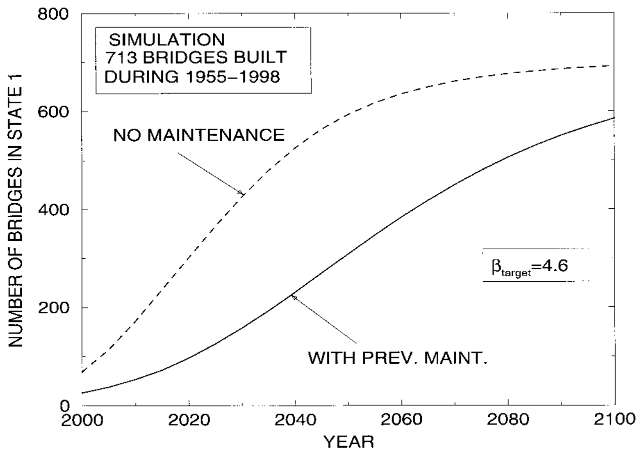


**FIG. 7. Expected Number of Bridges in Reliability State 1 from Stock of 713 Bridges Built from 1955–98—with and without Preventive Maintenance (Results Based on Simulation)**

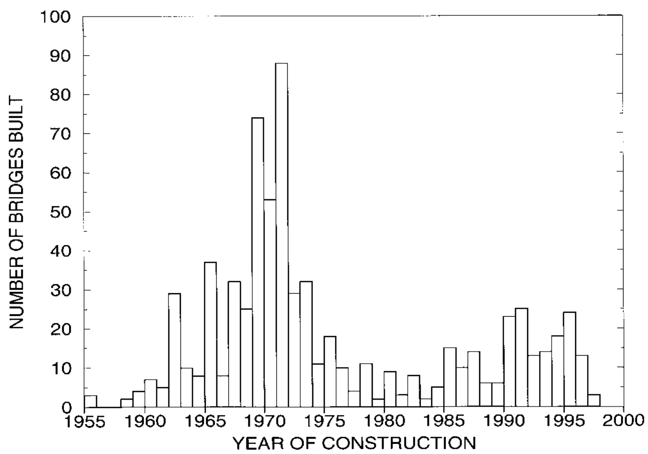


**FIG. 8. Year of Construction Distribution for Stock of 713 Bridges**

**TABLE 2. Expected Number of Bridges in Different Reliability States from Stock of 713 Steel/Concrete Composite Bridges Built during 1955–98 Assuming No Maintenance**

| Year | Reliability State | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| (1) | (2) | (3) | (4) | (5) | (6) |
| 2000 | 69 | 224 | 355 | 55 | 10 |
| 2005 | 114 | 245 | 303 | 43 | 8 |
| 2010 | 172 | 252 | 253 | 31 | 5 |
| 2015 | 237 | 248 | 205 | 20 | 3 |
| 2020 | 302 | 235 | 161 | 13 | 2 |
| 2025 | 366 | 215 | 123 | 8 | 1 |
| 2030 | 426 | 190 | 91 | 5 | 1 |
| 2035 | 479 | 162 | 67 | 4 | 1 |
| 2040 | 525 | 135 | 50 | 3 | 0 |
| 2045 | 563 | 110 | 38 | 2 | 0 |
| 2050 | 593 | 89 | 29 | 2 | 0 |
| 2055 | 617 | 72 | 23 | 1 | 0 |
| 2060 | 636 | 58 | 18 | 1 | 0 |
| 2065 | 649 | 48 | 15 | 1 | 0 |
| 2070 | 661 | 39 | 12 | 1 | 0 |
| 2075 | 669 | 33 | 10 | 1 | 0 |
| 2080 | 676 | 27 | 9 | 1 | 0 |
| 2085 | 681 | 23 | 8 | 1 | 0 |
| 2090 | 685 | 20 | 7 | 1 | 0 |
| 2095 | 689 | 17 | 6 | 1 | 0 |
| 2100 | 692 | 15 | 5 | 1 | 0 |

Note: Results are based on simulation.

**TABLE 3. Expected Number of Bridges in Different Reliability States from Stock of 713 Steel/Concrete Composite Bridges Built during 1955–98 Assuming Preventive Maintenance**

| Year | Reliability State | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| (1) | (2) | (3) | (4) | (5) | (6) |
| 2000 | 26 | 183 | 419 | 72 | 13 |
| 2005 | 39 | 208 | 396 | 60 | 10 |
| 2010 | 53 | 234 | 371 | 48 | 7 |
| 2015 | 72 | 257 | 341 | 38 | 5 |
| 2020 | 98 | 275 | 307 | 29 | 4 |
| 2025 | 126 | 288 | 274 | 22 | 3 |
| 2030 | 158 | 295 | 241 | 17 | 2 |
| 2035 | 194 | 295 | 210 | 13 | 1 |
| 2040 | 232 | 290 | 180 | 10 | 1 |
| 2045 | 270 | 280 | 154 | 8 | 1 |
| 2050 | 309 | 266 | 131 | 6 | 1 |
| 2055 | 346 | 250 | 111 | 5 | 1 |
| 2060 | 384 | 231 | 94 | 4 | 0 |
| 2065 | 419 | 212 | 79 | 3 | 0 |
| 2070 | 450 | 193 | 67 | 3 | 0 |
| 2075 | 480 | 174 | 57 | 2 | 0 |
| 2080 | 506 | 156 | 49 | 2 | 0 |
| 2085 | 529 | 140 | 42 | 2 | 0 |
| 2090 | 550 | 125 | 36 | 2 | 0 |
| 2095 | 570 | 111 | 31 | 1 | 0 |
| 2100 | 586 | 99 | 27 | 1 | 0 |

Note: Results are based on simulation.

concrete composite bridges built from 1955 to 1998 (Fig. 8, based on data provided by Maunsell Ltd.). Considering this bridge stock and using simulation based on the data in Table 1, Tables 2 and 3 show the expected number of bridges in each reliability state assuming no maintenance and preventive maintenance, respectively. The results in Tables 2 and 3 were obtained by computing the probability that a bridge built in any particular year will require rehabilitation in the future years. The beneficial effect of preventive maintenance is clearly demonstrated by the drastic reduction in the expected number of bridges in reliability state 1 as compared to the case of no maintenance.

Another way to quantify the effect of preventive maintenance is to compute the resulting unit benefits [see Maunsell Ltd. and Transport Research Laboratory (1998) report]

$$B_1 = C_{NPM} - C_{WPM} \tag{5}$$

$$B_2 = C_{NPM} - (C_{WPM} - C_{PM}) \tag{6}$$

or the cost-benefit ratio

$$R = C_{PM}/B_1 \tag{7}$$

where $C_{NPM}$ = present value of expected cumulative unit maintenance cost assuming no preventive maintenance has been done; $C_{WPM}$ = present value of expected cumulative unit maintenance cost assuming preventive maintenance has been done; $C_{PM}$ = present value of expected cumulative unit cost of preventive maintenance; $B_1$ = cumulative unit benefit of using preventive maintenance, including the cost of preventive maintenance; $B_2$ = cumulative unit benefit of using preventive maintenance, excluding the cost of preventive maintenance; and $R$ = cost-benefit ratio.

Assuming a net discount rate $r$ associated with all costs of 6%, Figs. 9(a) and 9(b) show the variation in time of both the cumulative and the annual unit benefit (per square meter of deck area) of using preventive maintenance for posttensioned concrete bridges with and without considering the cost of preventive maintenance, respectively. Finally, considering a planning horizon of 50 years, Fig. 10(a) shows the combined effects of user cost (i.e., expenses incurred by users from using a bridge that falls below its service goal, such as extra travel costs from detouring a load-restricted bridge) (Turner and

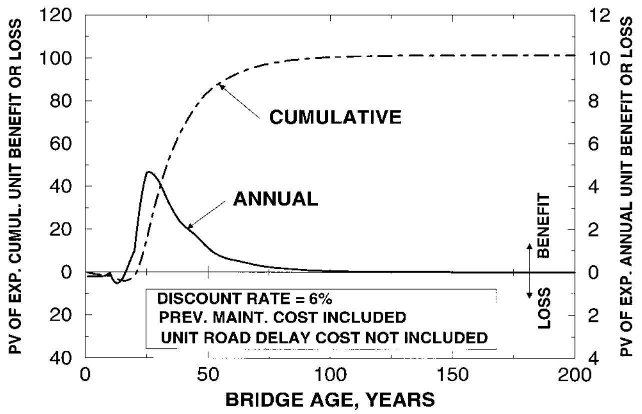


**FIG. 9(a). Present Value (PV) of Annual and Cumulative Unit Benefit of Using Preventive Maintenance on Posttensioned Concrete Bridges—Including Cost of Preventive Maintenance**

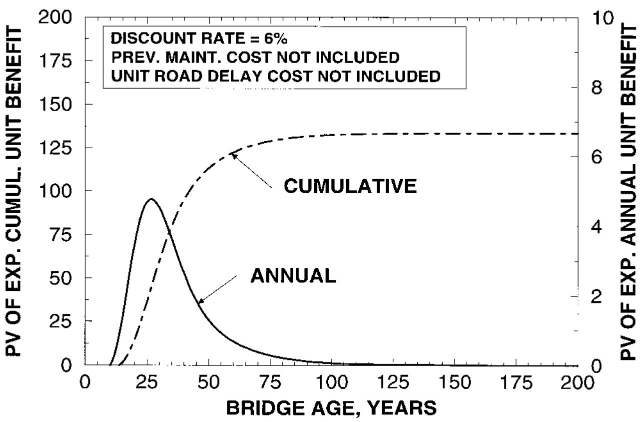


**FIG. 9(b). Present Value (PV) of Annual and Cumulative Unit Benefit of Using Preventive Maintenance on Posttensioned Concrete Bridges—Excluding Cost of Preventive Maintenance**

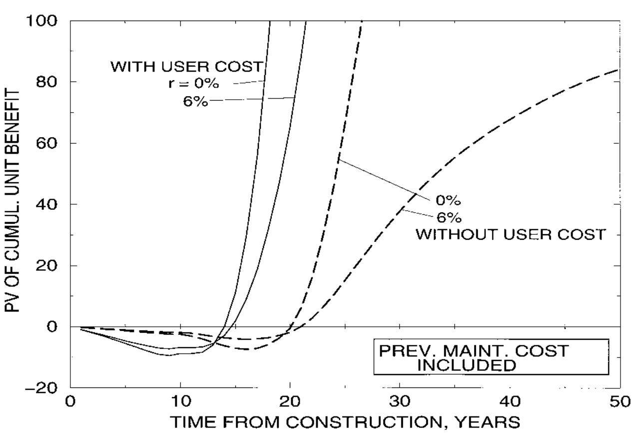


**FIG. 10(a). Effects of User Cost and Discount Rate on Present Value (PV) of Cumulative Unit Benefit for Posttensioned Concrete Bridges**

Richardson 1994) and discount rate $r$ on the cumulative unit benefit cost $B_1$ for posttensioned concrete bridges (Miyake and Frangopol 1999). It is noted that the benefit of using preventive maintenance for posttensioned concrete bridges increases with user cost. This is further demonstrated in Fig. 10(b), where the variation in time of the cost-benefit ratio of using preventive maintenance, $R$, for posttensioned concrete bridges is shown. The data considered in the computations associated with Figs. 9 and 10 (Miyake and Frangopol 1999) were all taken from a report by Maunsell Ltd. and Transport Research Laboratory (1998). In this report, the probability-density functions of rehabilitation rates with and without preventive maintenance were provided by experts. Also, the estimated unit maintenance costs (i.e., per square meter of deck area), including the costs of rehabilitation and the user costs, were provided for different bridge types with and without preventive maintenance. The results in Figs. 9 and 10 were obtained by multiplying the unit costs indicated in the Maunsell Ltd. and Transport Research Laboratory (1998) report by the predicted rates of rehabilitation with and without preventive maintenance in order to produce total maintenance cost profiles for the future years. The cost profiles were discounted to present values and the unit benefits and cost-benefit ratios were computed according to (5), (6), and (7), respectively.

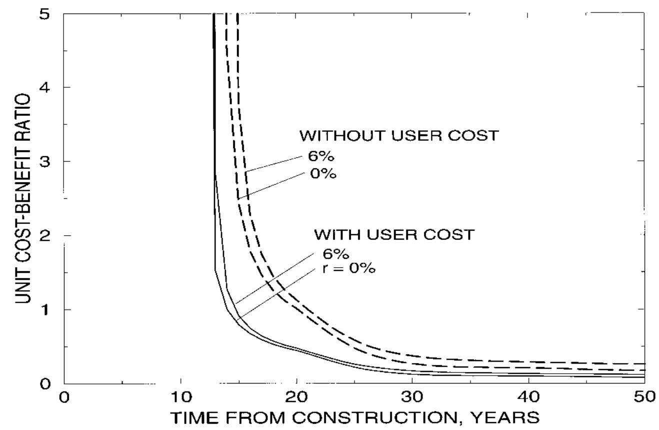


**FIG. 10(b). Effects of User Cost and Discount Rate on Cost-Benefit Ratio for Posttensioned Concrete Bridges**

The reliability-based bridge management approach allows decision makers to consider all uncertainties associated with (1) future reliability states; (2) future essential and/or preventive maintenance interventions; (3) future costs (including user costs); and (4) future demands on individual bridges and on a network of bridges. Using whole-life costing principles (Tilly 1997; Vassie 1997; Wallbank et al. 1999) and lifetime reliability methods, optimization is performed based on the minimization of expected total costs over a planning horizon (say, 10–30 years). Optimum strategies are developed, implemented, and periodically updated as more information becomes available. It should be emphasized that under conditions of uncertainty, bridge management systems have to be reliability based. Indeed, it is through the probabilistic approach that the uncertainties can be reflected properly in bridge management and strategies that integrate capital and maintenance activities at the lowest expected life-cycle cost can be determined.

## CONCLUSIONS

The main objective of this paper is to shed some light on the past, present, and future of life-cycle management of highway bridges. It is shown that current bridge management systems based on condition states and on Markovian deterioration modeling have several limitations, and that these limitations can be overcome by using a reliability-based approach. This approach is briefly described and the results of several examples are presented. To capture the propagation of uncertainties during the whole life process, future bridge management systems have to be reliability based. Bridge management based on lifetime reliability and whole-life costing is considered to be the next generation of bridge management systems. In these systems, bridge interventions are selected in response to distinct changes in reliability states. Application of cost-benefit analysis to reliability-based bridge management decision making guides the selection of the optimum strategy in the face of uncertainties and fiscal constraints. As demonstrated in this



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study, the newly proposed reliability- and cost-oriented computational methodology is feasible. More data expected in the future will reduce uncertainty and, in turn, will provide optimal bridge maintenance strategies with greater confidence.

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## APPENDIX II. NOTATION

*The following symbols are used in this paper:*

$A$ = reliability deterioration rate without maintenance;
$B_0$ = initial reliability index;
$B_1$ = cumulative unit benefit of using preventive maintenance, including cost of preventive maintenance;
$B_2$ = cumulative unit benefit of using preventive maintenance, excluding cost of preventive maintenance;
$C_{NPM}$ = present value of expected cumulative unit maintenance cost assuming no preventive maintenance has been done;
$C_{PM}$ = present value of expected cumulative unit cost of preventive maintenance;
$C_{WPM}$ = present value of expected cumulative unit maintenance cost assuming preventive maintenance has been done;
$m$ = positive integer representing number of preventive maintenance actions applied before occurrence of damage initiation;
$n$ = positive integer representing total number of preventive maintenance actions;



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$R$ = cost-benefit ratio;
$r$ = net discount rate for money;
$T_I$ = time of damage initiation;
$T_p$ = time of reapplication of preventive maintenance;
$T_{PD}$ = duration of preventive maintenance effect on bridge reliability;
$T_{PI}$ = time of first application of preventive maintenance;
$T_R$ = rehabilitation rate assuming no preventive maintenance has been done;
$T_{RP}$ = rehabilitation rate assuming preventive maintenance has been done;
$\beta$ = reliability index;
$\Gamma$ = improvement of reliability index immediately after application of preventive maintenance;
$\eta$ = multiplier representing effectiveness of preventive maintenance on extension of damage initiation time; and
$\Theta$ = reliability deterioration rate during preventive maintenance effect.





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