Optimizing Bridge Network Maintenance Management under Uncertainty with Conflicting Criteria: Life-Cycle Maintenance, Failure, and User Costs

Min Liu, A.M.ASCE[1]; and Dan M. Frangopol, F.ASCE[2]

Abstract: During the past decade, a variety of bridge maintenance management methodologies have been developed to cost-effectively allocate limited budgets to deteriorating highway bridges for performance enhancement and lifespan extension. In most existing research and practice, however, bridges are treated individually rather than collectively as integral parts of a transportation network. In addition to safety issues, failure of bridges renders a highway network inaccessible, either partially or completely. This may lead to considerable economic consequences, ranging from agency costs caused by repair/reconstruction to user costs as a result of disrupted network service (e.g., congestion and detour). Therefore, it is both natural and important to maintain the satisfactory long-term performance of not only individual bridges but the highway network. In this paper, a novel analytical/computational framework for network-level bridge maintenance management using optimization is presented. This framework integrates time-dependent structural reliability prediction, highway network performance assessment, and life-cycle cost analysis. Failure occurrences of individual bridges and their effects on the overall performance of the highway network are evaluated probabilistically. The maintenance resources are prioritized to deteriorating bridges through simultaneous and balanced minimization of three objective functions, i.e., maintenance cost, bridge failure cost, and user cost. Each of these cost metrics is computed as the present value of the expected economic expenditure accrued over the specified time horizon. The resulting multiobjective optimization problem is solved by a genetic algorithm. An application example is provided for maintenance management of deteriorating reinforced concrete deck slabs of an existing bridge highway network in Colorado. It is shown that the proposed methodology is effective for enhancing the bridge maintenance management practice at network-level through probabilistic quantification and preferred balance of various life-cycle costs.

DOI: 10.1061/(ASCE)0733-9445(2006)132:11(1835)

CE Database subject headings: Bridges, highway; Life cycle cost; Deterioration; Maintenance; Optimization.

Introduction

Sustained economic growth and social development of any country is intimately linked to the reliability and durability of its civil infrastructure systems such as highway structures. Bridges are the most critical yet vulnerable elements in highway transportation networks. The bridge infrastructure throughout the United States, especially in the dense urban regions of the country, has been constantly exposed to aggressive environments and facing ever-increasing traffic volumes and heavier truck-loads. This may exert serious, widespread, and prolonged adverse impacts on various societal sectors. Failure of a bridge (i.e., exceedance of prescribed performance limit states) can cause enormous adverse impacts locally to the bridge site and also globally to the network. For example, posted or failed bridges disrupt normal traffic flows, leading to reduced network accessibility and increased user costs in terms of travel delay, detour, and extra vehicle fuel consumption as well as accidents. In the United States, delayed on-time delivery of goods and services due to slow moving traffic over posted bridges as well as traffic jams due to insufficient access can cost a staggering amount in lost wages and wasted fuel (Wu 1999). In order to ensure satisfactory long-term safety and performance of highway networks, proactive/reactive maintenance, rehabilitation, and/or replacement must be carried out in a timely and adequate manner for mitigating progressive deterioration and for correcting major structural defects.

Maintenance needs for deteriorating highway bridges, however, have far outpaced available scarce funds that the U.S. federal and state highway agencies can provide. To resolve this situation, advanced technologies including new inspection/monitoring techniques, innovative preservation strategies, and improved assess management practice all become very important. Bridge management systems (BMSs) are thus developed to cost-effectively allocate maintenance resources to deteriorating bridges (e.g., Hawk and Small 1998; Thompson et al. 1998). The major limitations of most existing BMSs, including their inability to address the fact that different bridges at different geographical locations in the network may have different impacts on the net-

[1]Formerly, Research Associate, Dept. of Civil, Environmental, and Architectural Engineering, Univ. of Colorado, Boulder, CO 80309-0428. E-mail: minliu@illinoisalumni.org

[2]Professor and Fazlur R. Khan Endowed Chair of Structural Engineering and Architecture, Center for Advanced Technology for Structural Systems, (ATLSS Center), 117 ATLSS Dr., Imbt Labs, Lehigh Univ., Bethlehem, PA 18015–4729; formerly, Professor, Dept. of Civil, Environmental, and Architectural Engineering, Univ. of Colorado, Boulder, CO 80309-0428. E-mail: dan.frangopol@lehigh.edu

Note. Associate Editor: Christopher M. Foley. Discussion open until April 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 7, 2005; approved on March 20, 2006. This paper is part of the ***Journal of Structural Engineering***, Vol. 132, No. 11, November 1, 2006. ©ASCE, ISSN 0733-9445/2006/11-1835–1845/$25.00.

work performance, are well known (Frangopol et al. 2001; Estes and Frangopol 2003; Phares et al. 2004). Therefore, there is an urgent need to maintain satisfactory performance of the highway network instead of merely that of individual bridges in the network (e.g., Augusti et al. 1998; Adey et al. 2003; Thoft-Christensen 2003; Shinozuka et al. 2003).

In order to resolve the problems associated with existing BMSs, more rational bridge management decisions should be made with the following considerations: (1) the real capacity of deteriorating bridges needs to be properly addressed; (2) enhancement of long-term structure performance and reduction of life-cycle expenditures need to be considered simultaneously; and (3) maintenance management needs to be conducted from a highway network perspective while ensuring satisfactory performance of individual bridges. The time-dependent structural reliability analysis provides a rigorous means of quantifying the safety level of deteriorating bridges under various sources of uncertainty associated with gradual aging, aggressive environmental stressors, and increasing traffic loads over the life cycle or remaining service life (e.g., Akgül and Frangopol 2004). Meanwhile, the transportation network theory (Bell and Iida 1997) enables one to evaluate the overall performance of a highway network with and without bridge failures. Note that in this study, it is assumed that bridges are the only vulnerable elements subject to failure; roads that link bridges to form the network always operate at full capacities. Computationally speaking, multiple and usually competing criteria can be handled separately and simultaneously by harnessing the recent advances in multiobjective optimization via evolution-inspired computation (Coello Coello et al. 2002).

Efforts in the direction of optimizing bridge network performance from a probabilistic viewpoint were recently made by Liu and Frangopol (2005). However, the methodology proposed in Liu and Frangopol (2005) is limited to the consideration of only two objectives (i.e., network connectivity and lifetime maintenance cost) and does not address the problem of balancing the reduction of both agency cost and user cost by considering simultaneously maintenance expenses, bridge failure cost, and increased travel expenses due to the disruption of the bridge network. In this paper, an analytical and computational framework is presented to optimize life-cycle maintenance management decisions for bridge networks based on simulated performance profiles of individual bridges and life-cycle expenses of different origins. This framework integrates time-dependent structural reliability prediction, bridge network performance assessment, life-cycle cost analysis, and evolutionary computation. The adverse effects of probabilistic bridge failures on the overall performance of the network are evaluated via an exhaustive enumeration-based bridge network analysis. Cost-effective maintenance management decisions are then made by balancing reduction of both agency cost and user cost. Specifically, three objective functions of maintenance expenses, bridge failure cost, and increased travel expenses due to network disruption are considered simultaneously. The three cost metrics are computed, respectively, as present values of expected cumulative economic consequences over the specified time horizon. Multiobjective optimization is then carried out for the best possible economical investment decisions in highway network management while maintaining an adequate reliability level of each individual bridge.

The remainder of this paper is organized as follows. The methodology for evaluating time-dependent reliability index of deteriorating bridges is discussed using established mechanistic models and accounting for various uncertainties in quantifying time-varying structure resistance and live load demands. Based on this, approaches to probabilistic analysis of bridge networks and to calculating the expected life-cycle costs due to maintenance actions, bridge failure, and loss of network service are presented. The network-level maintenance management is then formulated as a nonlinear, combinatorial optimization problem. The goal is to search for a number of different scenarios of prioritizing maintenance actions among bridges in the network and over the specified time horizon. Each of these scenarios represents a unique tradeoff among minimization of the three different life-cycle costs. A genetic algorithm (GA) is used to automate the present multiobjective bridge network management problem. Finally, as an illustrative example, maintenance scheduling of reinforced concrete deck slabs of an existing bridge network in Colorado is investigated.

Time-Dependent Bridge Reliability Analysis

Accurate modeling of the complex structure deterioration process is the most critical component in maintenance management of civil infrastructure. In doing so, it is essential to understand mechanisms responsible for structure deterioration of interest. Deterioration of highway bridges may be caused by combined effects of progressive structure aging, aggressive environmental stressors (e.g., alkali-silica reaction, chloride contamination, sulfate attack), and increasing traffic demands. In contrast to the visual inspection practice, the structural reliability method provides a systematic and rigorous approach to addressing these contributing factors (Mori and Ellingwood 1993, 1994; Estes and Frangopol 1999; Val et al. 2000). Conceptually, the structural reliability reflects the probability of structural capacity exceeding load demand, given performance limit states in terms of force, displacement, and others (Melchers 1999). In particular, by considering time-varying structural capacity and load demand variations for existing bridges, one is able to obtain the structural reliability profiles. Based on this information, the effects of maintenance on bridge performance can be evaluated and maintenance prioritization can be made advantageously.

A bridge is a very complex structural system that is composed of superstructure and substructure components. Series-parallel system idealization may be used to conduct the reliability analysis (Estes and Frangopol 1999). For illustration, the time-dependent reliability analysis in the present study focuses on modeling of reinforced concrete bridge deck slabs. The performance limit states are defined in terms of standard code formulations in AASHTO specifications (1996). Deterioration of reinforcement in reinforced concrete slabs is mainly caused by chloride-induced corrosion, whose propagation can be reasonably predicted by Fick's law of diffusion. The reinforcement area is reduced gradually as corrosion worsens with time. Thus, the time-dependent structural capacity can be calculated. The time-variant loads are represented by the annual average truck traffic, based on the bridge load model used in the development of the AASHTO LRFD bridge design specifications (Akgül 2002). Uncertainties in corrosion initiation time and rate as well as other relevant parameters are considered via Monte Carlo simulation. The structural reliability level over the specified time horizon is then obtained (Akgül and Frangopol 2004).

Probabilistic Bridge Network Analysis

Due to the uncertainty in predicting the time-dependent performance of bridges with and without maintenance actions, the

J. Struct. Eng. 2006.132:1835-1845.

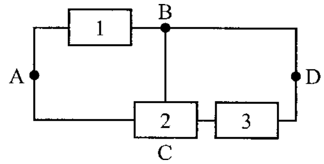

Fig. 1. Block diagram of a three-bridge network

bridge network performance, as a function of those of individual bridges in the network, cannot be exactly predicted either. The key issue pertaining to bridge network analysis is to properly relate the probabilistic failure of individual bridges to the probabilistic network performance. The bridge failure cost and detour-induced user cost accrued over the given time horizon are evaluated accordingly.

Bridge Network Modes

According to Liu and Frangopol (2005), the bridge network is analyzed systematically through exhaustive enumeration of all possible combinations of binary bridge states (failure or operation). Each combination represents a unique network mode; the pattern of traffic flow detour can then be determined based on the particular bridge failure induced path disruption. The occurrence probability of each network mode is obviously a function of state probabilities of individual bridges. Note that these different modes represent a mutually exclusive and collectively exhaustive partitioning of the original network. Therefore, the overall network performance can be obtained by synthesizing those of individual network modes.

As an illustration, consider the simple bridge network in Fig. 1. This network consists of three bridges (1, 2, and 3) and there are four locations (A, B, C, and D). There are a total of $2^3=8$ different network modes by enumerating failure and operation of all three bridges. Therefore, a network analysis can first be carried out at each mode level and then be summed at the original bridge network level while being weighted by the occurrence probability of each mode. For example, consider the network mode where Bridges 1 and 2 operate and Bridge 3 fails. The failure probability of this particular network mode is expressed as

$$P_{\text{network mode}}=f(1-P_{f,1};1-P_{f,2};P_{f,3};\text{Corr}) \tag{1}$$

where $P_{f,i}$=failure probability of ith bridge and Corr =correlations among bridge states. Under this situation, the traffic flow originally moving between Locations C and D has to detour by taking the alternative path consisting of Links BC and BD.

Life-Cycle Bridge Network Maintenance Cost

The maintenance actions are applied to different bridges in the network as well as over the specified time horizon. The present value of total life-cycle maintenance cost is calculated as

$$\text{LCC}_{\text{maint,network}}=\sum_{i=1}^{N_B}\sum_{j=1}^{N_i^{\text{maint}}}\frac{C_{ij}^{\text{maint}}(t_{ij})}{(1+\nu)^{t_{ij}}} \tag{2}$$

where N_B=number of bridges in the network; N_i^{maint}=number of maintenance actions for ith bridge over the life-cycle; t_{ij}, C_{ij}^{maint} =application time and unit cost of the jth maintenance for ith bridge; and ν=monetary discount value (NCHRP 2002).

Life-Cycle Bridge Network Failure Cost

Bridge failure (and the subsequent repair/reconstruction) cost plays an important role in life-cycle cost analysis for bridge maintenance management decision-making (Kong and Frangopol 2005). The present value of expected total life-cycle failure cost of all bridges in the network is computed as

$$\text{LCC}_{\text{failure,network}}=\sum_{i=1}^{N_B}\text{LCC}_{\text{failure},i} \tag{3}$$

where $\text{LCC}_{\text{failure},i}$=present value of the expected life-cycle failure cost of ith bridge, which is

$$\text{LCC}_{\text{failure},i}=\int_{t=0}^{T}C_{\text{failure},i}(t)\left(\frac{1}{1+\nu}\right)^t dP_{f,i}(t) \tag{4}$$

where T=the specified time horizon; $C_{\text{failure},i}(t)$=failure cost of ith bridge at time t; $dP_{f,i}(t)$=failure probability of ith bridge per unit time interval at time t. Note that it is implicitly assumed in Eq. (4) that bridge failure events are independent within different time intervals; that is, whether or not a bridge fails during one time interval does not affect its failure probability during another time interval.

If the bridge annual failure probability is available, Eq. (4) is approximated as

$$\text{LCC}_{\text{failure},i}\approx\sum_{j=1}^{N_T}C_{\text{failure},i}(j)P_{\text{failure},i}^{\text{annual}}(j)\left(\frac{1}{1+\nu}\right)^j \tag{5}$$

where N_T=number of years in the time horizon T and $P_{\text{failure},i}^{\text{annual}}(j)$=annual failure probability of ith bridge in jth year.

Life-Cycle Network User Cost

The life-cycle user cost of a bridge network is calculated as the increase in cumulative travel expenses compared to that associated with the fully operational network. The present value of total expected life-cycle user cost of the network is

$$\text{LCC}_{\text{user,network}}=\sum_{k=1}^{N_{\text{mode}}}\text{LCC}_{\text{user},k} \tag{6}$$

where N_{mode}=number of all network modes; $\text{LCC}_{\text{user},k}$=present value of the expected life-cycle user cost of kth network, which is approximated as

$$\text{LCC}_{\text{mode},k}\approx\sum_{j=1}^{N_T}C_{\text{user},k}(j)P_{\text{user},k}^{\text{annual}}(j)\left(\frac{1}{1+\nu}\right)^j \tag{7}$$

where $C_{\text{user},k}(j)$=total (increased) user cost given the occurrence of kth network mode in jth year; and $P_{\text{user},k}^{\text{annual}}(j)$=annual occurrence probability of kth network mode in jth year, which is calculated by considering the annual probability of state S (operational or failed) for each bridge in the network as well as possible correlations among bridge states. The correlations can be at project level and/or at network level. At project level, correlations may be a result of, for example, common environmental stressors and deterioration mechanisms. At network level, common traffic loads can be responsible for the correlation among bridge failures. An accurate consideration of such correlations necessitates information that is usually difficult to obtain. Due to lack of this information on correlations, it is assumed that the correlations are negligible. It is noted that, due to correlation effects, the "real" values of probabilities can be different from those reported in this

J. Struct. Eng. 2006.132:1835-1845.

paper. If the correlations are weak and can be neglected, $P_{\text{user},k}^{\text{annual}}(j)$ is simply calculated as a product of annual state probabilities of all individual bridges in the network, i.e.,

$$P_{\text{user},k}^{\text{annual}}(j) = P\left(\bigcap_{i=1}^{N_B} S_i(j)\right) \approx \prod_{i=1}^{N_B} P_{k,i}^{\text{annual}}(j) \quad (8)$$

where $P_{k,i}^{\text{annual}}(j)$=annual occurrence probability of the state of ith bridge in kth network mode in jth year. As indicated in Estes and Frangopol (2001), if multiple failure modes are present, it is straightforward to include them into the proposed formulation.

It is assumed that $C_{\text{user},k}(j)$ in Eq. (7) is proportional to the total increase in travel time and distance, i.e.,

$$C_{\text{user},k}(j) \approx \left\{\sum_{m=1}^{N_{\text{link}}} [(t_{k,m} - t_{0,m})a + (l_{k,m} - l_{0,m})b]\text{AADT}_m(j)\right\} T_k(j) \quad (9)$$

where N_{link}=number of links in the network; $t_{0,m}, t_{k,m}$=travel times of the traffic originally designated on mth link in kth network mode, when the link is operational and broken (i.e., detour occurs), respectively; a=monetary cost per unit travel time; $l_{0,m}, l_{k,m}$=travel distances of the traffic originally at mth link in kth network mode when the link is operational and broken, respectively; b=monetary cost per unit travel distance; and $\text{AADT}_m(j)$ =annual average daily traffic volume on mth link in jth year. The period of time needed for restoring to the full network functionality from kth network mode in jth year is approximated by

$$T_k(j) \approx T_{0,k} + T_{1,k}[N_{\text{failed bridges}}(j) - 1] \quad (10)$$

where $T_{0,k}$=period of time needed to replace one failed bridge in kth network mode; $T_{1,k}$=period of time needed to replac e each additional failed bridge in kth network mode; $N_{\text{failed bridges}}$=expected number of failed bridges in the network in jth year. The calculation of $N_{\text{failed bridges}}$ will be illustrated in the later application example with an existing bridge network.

Problem Statement and Numerical Strategy

The bridge network maintenance management in this study is readily formulated as a combinatorial multiobjective optimization problem. A generic solution involves scheduling of different maintenance actions to different bridges in the network at discrete years over the specified time horizon. This problem can be stated conceptually as:

1. *Given*: Performance deterioration patterns of individual bridges, network flow patterns of individual network modes, and effects of different maintenance types on bridge performances;
2. *Find*: A group of optimized maintenance planning solutions that, in a Pareto-optimal sense,
   - Reduce the present value of life-cycle network maintenance cost,
   - Reduce the present value of life-cycle network failure cost, and
   - Reduce the present value of life-cycle network user cost;
3. *Subject to*: performance of individual bridges in the network stay above or at the prescribed lower-bound performance level over the entire prescribed time horizon.

Note that the Pareto-optimal (i.e., nondominated) solutions exhibit the optimized tradeoff in compromising these conflicting objectives. A solution is Pareto-optimal if and only if there does not exist another solution that is no worse in all objectives and is strictly better in at least one objective.

Effective numerical tools are needed to solve the present bridge maintenance management formulated as a multiobjective optimization problem. Most traditional optimization algorithms are problem-dependent. They usually rely on gradient information to guide the search process and often assume continuous-valued design variables. This may cause significant numerical difficulties when design variables can only take discrete values as in the present maintenance management problems where a variety of different maintenance actions are to be allocated at discrete years over a specified time horizon. More importantly, most traditional algorithms can only handle single-objective optimization problems and thus lead to a single optimal solution. Compared to most traditional optimization methods, GA has the following distinct advantages (Goldberg 1989): (1) GA works with a population of solutions instead of one solution at each iteration. By starting with a random set of solutions, the current population evolves to an offspring population at each iteration. Working with a number of solutions provides GAs with the ability of capturing multiple optimized tradeoff solutions in a single algorithm run. (2) Gradients are not required in guiding the genetic search, which makes GA insusceptible to pitfalls of traditional gradient-based hill-climbing searching procedures. This feature is especially useful for practical engineering problems where either objectives or constraints or both are nondifferentiable with respect to discrete-valued design variables. (3) GA is a problem-independent universal search tool, which makes it more flexible as well as robust for application to problems of different natures; the requirement on users' capabilities is greatly reduced.

GAs have been used as an effective numerical optimizer in most existing research on multiobjective optimization based maintenance management of civil infrastructure (e.g., Furuta et al. 2004; Liu and Frangopol 2005). In fact, GAs have been successfully applied to a wide range of science and engineering problems because of the ease of implementation and robust performance (Coello Coello et al. 2002). GAs are general-purpose numerical solvers. Gradients are no longer needed and discrete-valued design variables can be handled without any difficulty. This is particularly useful for the present bridge maintenance management problems. More importantly, GAs can handle multiple conflicting objectives directly and simultaneously using the concepts of nondominance. Because GAs keep a population of solutions at the same time, a distribution of optimized tradeoff solutions can be obtained by a single algorithm run.

Application Example

An Existing Bridge Network

The present reliability-based life-cycle maintenance management approach is applied to an existing bridge network in Colorado (Akgül and Frangopol 2004). As shown in Fig. 2, this network consists of thirteen bridges of different types. A complete description of this bridge network is provided in Akgül (2002). The schematic of this bridge network is shown in Fig. 3. Five geographical nodes (denoted 1–5) are identified, which lead to six "global" links named I–VI, as opposed to "local" links between individual bridges. The global link is briefly referred to "link" hereafter. For each link, the AADT data are obtained from the Colorado Department of Transportation traffic database (CDOT

J. Struct. Eng. 2006.132:1835-1845.

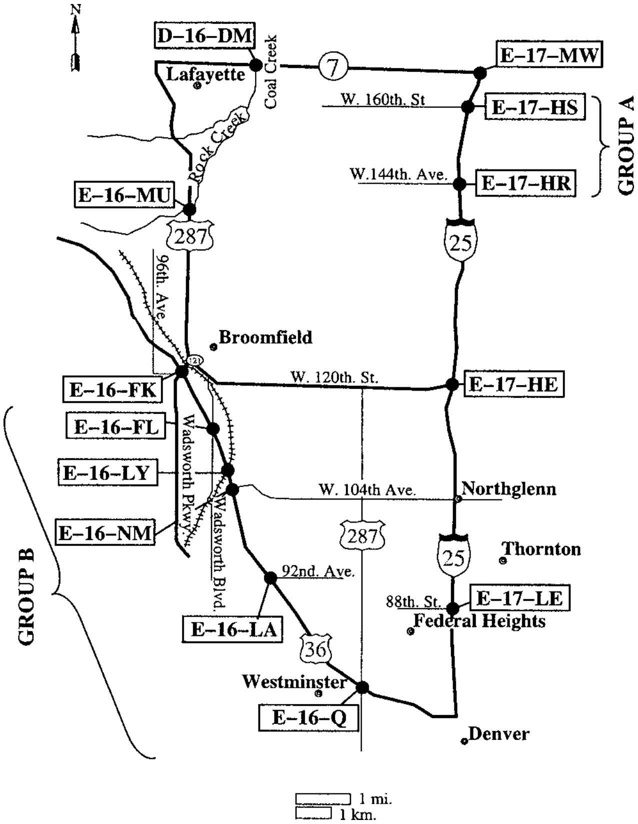

Fig. 2. An existing bridge network in Colorado (adapted from Akgül and Frangopol 2004)

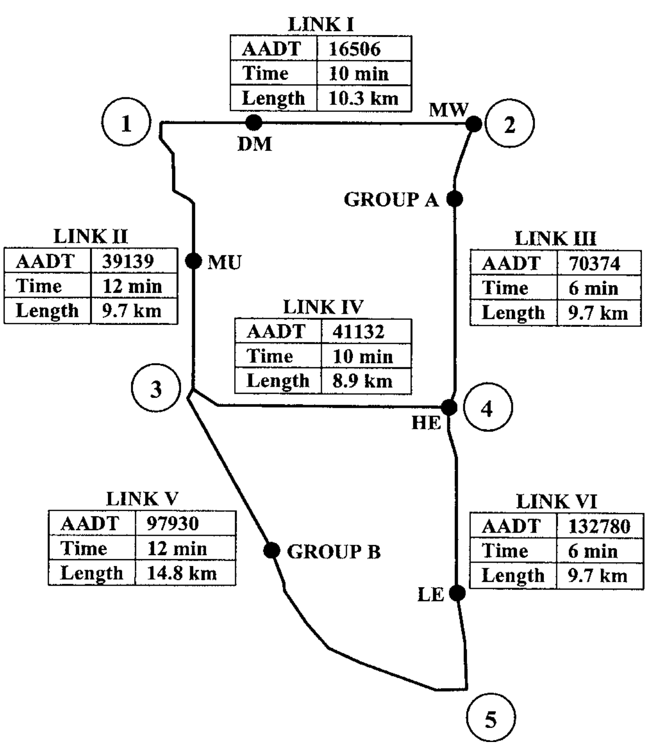

Fig. 3. Annual average daily traffic (AADT), travel time, and distance for each link of the bridge network

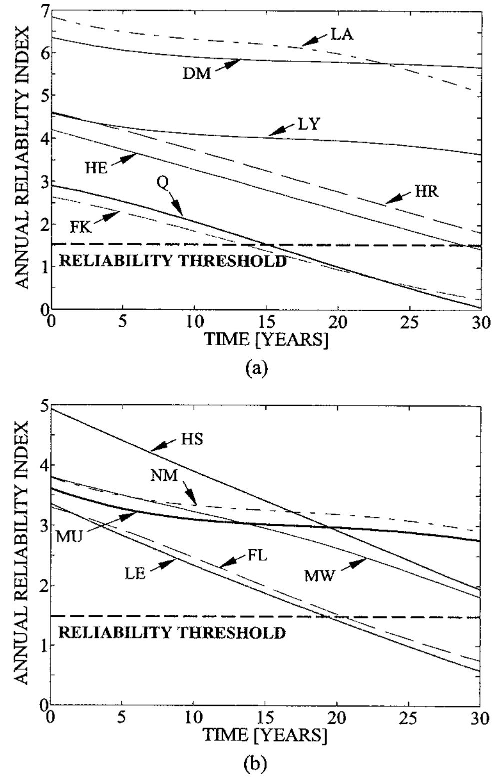

Fig. 4. Annual reliability index profiles of bridge decks in the network without maintenance

2004); the travel time and distance are obtained using the Microsoft Streets and Trips Software (Microsoft 2002). All these data are shown in Fig. 3. Of these bridges, bridges HS and HR are in Link III and Form Group A; similarly, Bridges FK, FL, LY, NM, LA, and Q are in Link V and Form Group B. The use of bridge groups simplifies the enumeration process in finding the network modes. The other bridges, DM, MW, MU, HE, and LE, are treated individually.

Bridge Reliability Profiles

Figs. 4(a and b) show the annual reliability index profiles of reinforced concrete deck slabs of individual bridges in the present network without maintenance (Akgül 2002; Akgül and Frangopol 2004). Flexure failure is considered as the single failure mode. It is clear that, over the time horizon of 30 years, these structures undergo different levels of deterioration. In this study, a minimum reliability level of 1.5 or equivalently a maximum annual failure probability of 0.067 is assumed. As a result, some of the bridges (i.e., FK, Q, LE, FL, and HE) must receive maintenance actions in order to meet this lower-bound reliability level. Although the reliability levels of other bridges do not violate the constraint, maintenance actions may still be applied to some of them in order to improve the overall performance of the bridge network other than that of individual bridges. It is emphasized that maintenance management from a network viewpoint as opposed to an individual bridge viewpoint while considering life-cycle costs of different origins makes the present study unique from most existing methodologies in the literature.

Bridge Network Analysis

For the present bridge network that consists of five individual bridges (DM, MW, MU, HE, and LE) and two bridge groups (A

J. Struct. Eng. 2006.132:1835-1845.

Table 1. Unit Travel Time and Distance for Traffic Volume of Each Link

Link ID	Travel time (min): Link is working	Travel time (min): Link is broken, but alternative routes are available in the network (links taken)	Travel distance (km): Link is working	Travel distance (km): Link is broken, but alternative routes are available in the network (links taken)
I	10	28 (II, III, IV)	10.3	28.3 (II, III, IV)
II	12	26 (I, III, IV)	9.7	28.9 (I, III, IV)
III	6	32 (I, II, IV)	9.7	28.9 (I, II, IV)
IV	10	Not available	8.9	Not available
V	12	16 (IV, VI)	14.8	18.6 (IV, VI)
VI	6	22 (IV, V)	9.7	23.7 (IV, V)

and B), as indicated in Fig. 3, there are in total $2^7=128$ different network modes. Failure of any bridge breaks the link in which the bridge is located. For example, if bridge MU fails, Link II is broken, which disrupts the traffic volume that is originally scheduled to flow between Nodes 1 and 3. Failure of a bridge at the intersection of two or more links affects traffic flows on these links simultaneously. For example, bridge MW is common to Links I and III; Bridge HE is common to Links III, IV, and VI.

It is assumed that the bridge network provides the most efficient means for the traffic flows of the region in terms of travel time and distance. When one global link is broken due to failure of at least one bridge in this link, the traffic flow on this link firstly attempts to be detoured to remaining operational links in the network in order to reach the original destinations most economically. Table 1 provides information on travel time and distance necessary for traffic volume originally on each link when the link is operational and broken, respectively. If such alternative routes are not available because of simultaneous failure of several bridges, as is the case in some network modes, the affected traffic flows take detours outside of the network. Under such situation, the necessary travel time and distance are generally much larger than those associated with the most costly alternative route in that network mode. In this study, the travel time and distance for detour outside the network are assumed equal to those associated with the alternative routes in the network multiplied by prescribed factors. These empirical factors may be determined on the basis of observed traffic data and/or sound engineering judgments. A value of 1.5 is assumed for the multiplier used in all links in this study.

Bridge Group Analysis

In the forgoing enumeration of network modes, bridges in a bridge group (A or B) are treated collectively rather than individually in order to significantly reduce the analysis effort. Accordingly, the expected number of failed bridges in a group given failure of this group (treated as a series system) is needed in Eq. (10) to calculate the time necessary for repairing all failed bridges in the group. This expected number is obtained as

$$E[N_{\text{failed bridges}}|\text{group fails}] = \frac{E[N_{\text{failed bridges}}]}{P(\text{group fails})} \tag{11}$$

In Eq. (11), the failure probability of the group, i.e., probability that at least one bridge in the group fails, assuming failure events of individual bridges in the group are statistically independent, is approximated as

Table 2. Different Maintenance Types (Adapted from Furuta et al. 2004)

Maintenance type	Deterioration rate reduction (year^{-1})	Reliability index increment	Unit cost (US\$/m^2)
Resin injection	0.03 (duration=15 years)	0	200
Slab thickness increasing	0	0.7	300
Steel plate attaching	0	2.0	600
Replacement	0	Return to the initial reliability level	900

$$P(\text{group fails}) = 1 - \prod_{i=1}^{N_{bg}} (1 - P_{f,i}) \tag{12}$$

with N_{bg}=number of bridges in the group and $P_{f,i}$=failure probability of ith bridge in the group; the expected number of failed bridges in the group is calculated as

$$E[N_{\text{failed\_bridges}}] = \sum_{i=1}^{N_{bg}} P_{f,i} \tag{13}$$

As an illustration, consider a particular network mode in which all bridges operate except that Bridge HE and Group B fail (i.e., at least one bridge in Group B fails). The occurrence probability of this network mode is computed as the product of occurrence probabilities of individual bridges and groups, i.e.,

$$P_{\text{scenario}} = (1 - P_{f,\text{DM}})(1 - P_{f,\text{MW}})(1 - P_{f,\text{Group A}})(1 - P_{f,\text{MU}}) \times (1 - P_{f,\text{LE}})P_{f,\text{HE}}P_{f,\text{Group B}} \tag{14}$$

where

$$P_{f,\text{Group A}} = 1 - (1 - P_{f,\text{HS}})(1 - P_{f,\text{HR}}) \tag{15}$$

$$P_{f,\text{Group B}} = 1 - (1 - P_{f,\text{FK}})(1 - P_{f,\text{FL}})(1 - P_{f,\text{LY}})(1 - P_{f,\text{NM}}) \times (1 - P_{f,\text{LA}})(1 - P_{f,\text{Q}}) \tag{16}$$

Finally, the expected number of failed bridges in Group B given Group B fails is, using Eqs. (11) and (13),

$$E[N_{\text{failed bridges}}|\text{group B fails}] = \frac{P_{f,\text{FK}} + P_{f,\text{FL}} + P_{f,\text{LY}} + P_{f,\text{NM}} + P_{f,\text{LA}} + P_{f,\text{Q}}}{P_{f,\text{Group B}}} \tag{17}$$

Maintenance Types

Four different types of maintenance for bridge reinforced concrete decks are considered in this study. They are resin injection, slab thickness increasing, steel plate attaching, and replacement. Effects of each type of maintenance on enhancing structure performance are described in terms of their effects on structural reliability levels. These data are based on Furuta et al. (2004) and are provided in Table 2. Resin injection requires a unit cost of $\$200/\text{m}^2$, which is the cheapest among the four maintenance types. It injects epoxy resin into voids and thus seals cracks in concrete. This type of maintenance repairs the aging deck slabs by reducing the corrosion of reinforcement due to exposure to the open air. The other three maintenance types improve with various degrees the reliability level immediately upon application. In par-

J. Struct. Eng. 2006.132:1835-1845.

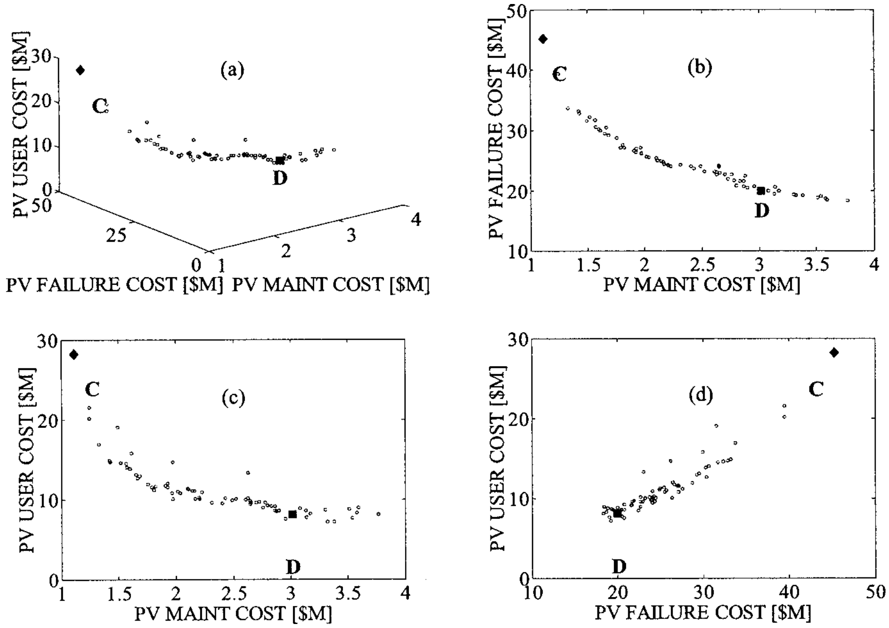

Fig. 5. Tradeoff among three objective functions, i.e., present values (PVs) of cumulative maintenance, failure, and user costs for 73 optimized maintenance planning solutions: (a) 3D plot; (b)–(d): 2D projections

ticular, increasing slab thickness and attaching steel plate enhance the reliability index values by 0.7 and 2.0, respectively. Unit costs of these two types are $300 and $600 per square meter, respectively. Complete replacement of bridge slabs is the most effective but the most expensive maintenance option. With a unit cost of $900 per square meter, this type of maintenance restores the structural reliability of the deck slab to its initial level.

Computational Issues

In order to achieve computational tractability, reliability profiles of all bridges in the network are needed. To this end, it is assumed that (1) once a bridge deck fails, it is repaired at its reliability level immediately prior to failure; and (2) such repair does not alter the original deterioration process. The effects of such unexpected repair are reflected in the failure cost as defined previously. In this computation, the failure cost is assumed equal to the initial bridge deck construction cost multiplied by the ratio of the current to initial reliability index level. Note that the prescribed lower-bound reliability level prevents unsatisfactory structure performance from occurring over the specified life cycle.

The relevant parameters used in this numerical example include a unit time value of $8 per hour; a unit cost of $0.25/km, based on data reported in the literature (Schrank and Lomax 2003; IRS 2005); a and b used in Eq. (9) for calculating length of time for repair are equal to 20 and 2, respectively. The failure cost of a bridge deck, if being restored to the initial reliability level, is assumed equal to the product of deck area, unit cost of $900 per square meter, and a multiplier of 100 that accounts for consequences following disastrous bridge deck failure. For bridge decks that are repaired to reliability levels lower than the initial value, the associated failure cost is equal to the full repair cost multiplied by the ratio of the current to the initial reliability values. In addition, it is assumed that the link traffic volume given in Fig. 3 increases by 2% per year, the specified time horizon for this bridge network is considered 30 years, and the monetary discount rate is 6%.

A GA-based procedure previously developed for maintenance management of deteriorating bridge networks (Liu and Frangopol 2005) is used in this study. Detailed GA implementation techniques are reported in Liu and Frangopol (2005). The initial GA population consists of 1,000 trial solutions and each of the subsequent GA generations has 200 offspring solutions in addition to the nondominated elite solutions from the parent generation. Uniform crossover and mutation operations are used with probabilities of 50% and 5%, respectively.

Numerical Results

A total of 73 optimized network-level maintenance solutions are obtained at the 50th GA generation. Fig. 5(a) shows the tradeoff among the three different cost objective functions. The distributions of these solutions between pairs of objective functions are further displayed in Figs. 5(b–d), respectively. It is clear that these solutions require different maintenance budgets and accordingly lead to different levels of network performance enhancement in terms of reducing the life-cycle failure cost and user cost, respectively. Therefore, this allows bridge managers to compare alternative solutions and choose one that preferably compromises the conflicting criteria of improving network performance and reducing maintenance expenditure.

For illustration, two representative Pareto-optimal solutions denoted as C and D in Fig. 5 are selected from the solution population for detailed comparison. Solution C is the least costly with respect to maintenance expenditure in the optimized solutions. It requires a maintenance budget of $1.11 million for the time horizon of 30 years. As a tradeoff, Solution C incurs life-cycle network failure cost and user cost of $45.21 million and $28.19 million, respectively. In contrast, the maintenance cost associated with Solution D is $3.01 million. This increase in maintenance budget reduces the life-cycle failure cost and user cost to $20.02 million and $8.09 million, respectively. The distribution patterns of maintenance actions among bridges and over the time horizon

J. Struct. Eng. 2006.132:1835-1845.

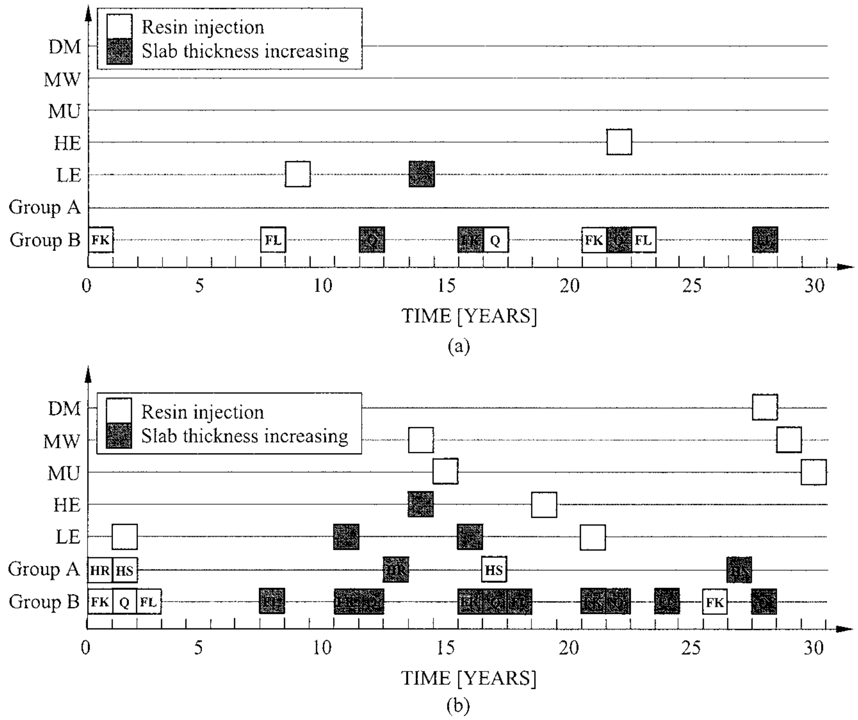

Fig. 6. Allocation of maintenance actions among different bridges and over the time horizon: (a) Solution C; (b) Solution D

are shown in Fig. 6. The profiles of cumulative maintenance costs, user costs, and failure costs of these two representative solutions are compared in Figs. 7–9, respectively.

The annual reliability index profiles of bridge decks in the network with the two representative Solutions C and D are provided in Figs. 10 and 11, respectively. With Solution C, the maintenance budget is needed essentially to ensure that the reliability profile of each bridge deck stays above the prescribed target level of 1.5 over the time horizon of 30 years. This is achieved by enforcing a reliability constraint in the optimization formulation. Therefore, this solution can be regarded as one that is obtained by treating these bridges in the network separately. That is, effects of individual bridge performances on the overall network performance are not taken into consideration. When a larger maintenance budget is available, bridge managers are not only able to maintain adequate bridge reliability levels individually but able to selectively allocate additional maintenance resources to bridges for which failures will affect the long-term network performance more significantly. Solution D is one such maintenance option. The bridges subject to maintenance include not only those already identified in Solution C but those that meet the prescribed target deck reliability level even without maintenance (see Fig. 4). This extra maintenance expenses are justifiable as they lead to significant reductions in the bridge failure cost and network user cost, respectively.

It should be noted that the computed cost values of different maintenance solutions deserve a prudent interpretation. In this numerical example, the failure cost and user cost are much larger than the computed maintenance cost for all solutions. This is in part due to the presently assumed parameter values. For example, a factor of 100 is used in this study for calculating the failure cost. It is shown that this type of factor has significant impact on failure costs and subsequently on the optimized solutions (Kong and Frangopol 2005). Consequently, if the three different life-cycle

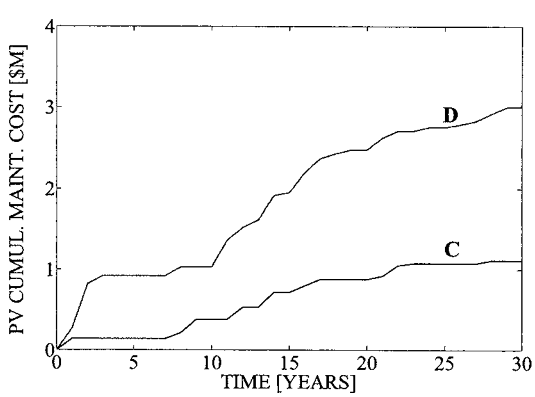

Fig. 7. Profiles of present values of cumulative network maintenance costs of two representative solutions

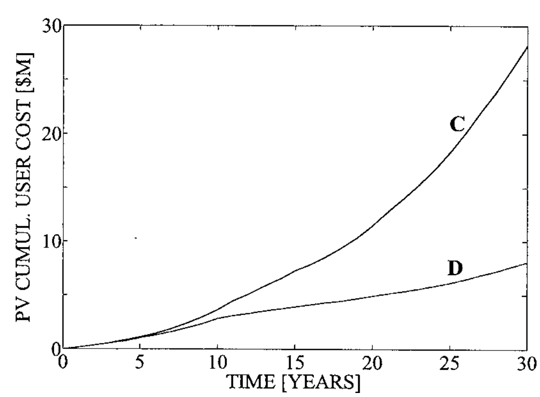

Fig. 8. Profiles of present values of cumulative network user costs of two representative solutions

J. Struct. Eng. 2006.132:1835-1845.

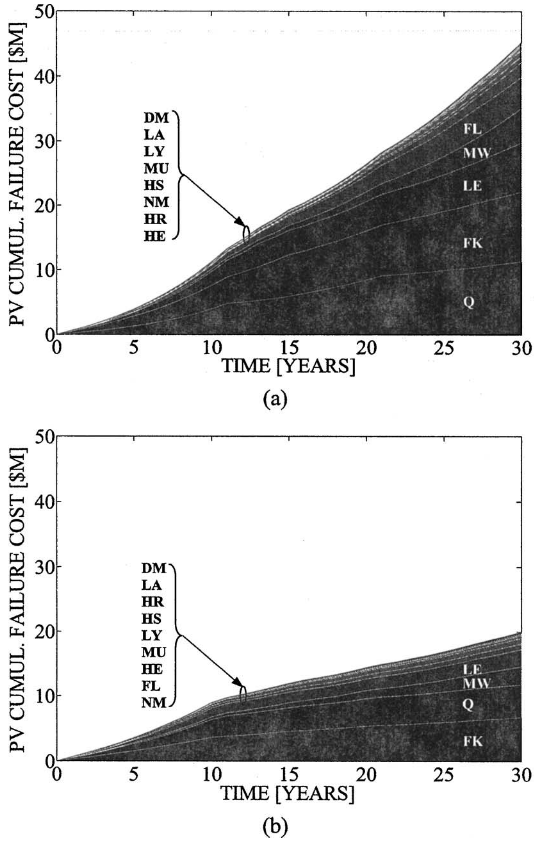

Fig. 9. Profiles of present values of cumulative bridge deck failure costs of two representative solutions: (a) C; (b) D

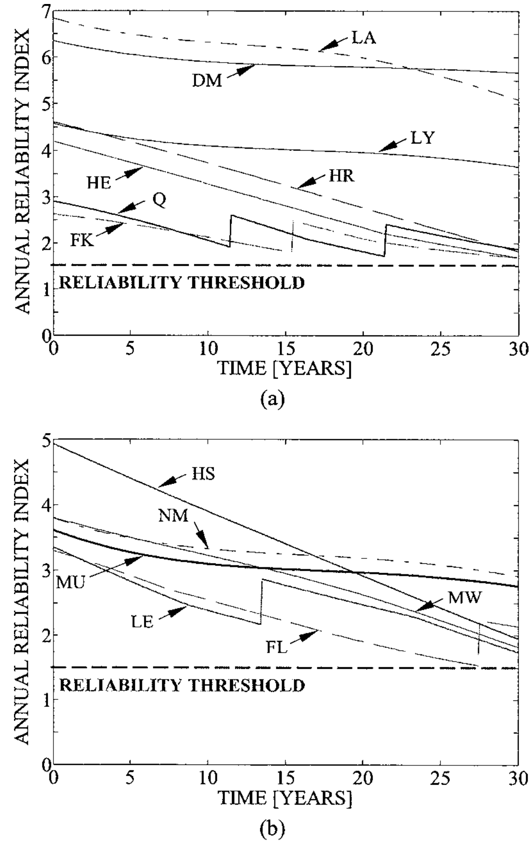

Fig. 10. Annual reliability index profiles of bridge decks in the network with Solution C

costs were lumped to form a single total cost metric for minimization as typically done in traditional single-objective optimization procedures, it is very likely that the solution with the largest maintenance expenditure would be the best choice in order to balance the enormous failure and user costs. Therefore, it is more meaningful to assess the relative merits of alternative solutions with respect to different cost measures other than comparing the absolute cost sums. Hence, a multiple-objective formulation is more appropriate for the present network-level bridge maintenance management. This formulation provides bridge managers with a unique opportunity to make tradeoff decisions by examining a vast population of different solution options.

Conclusions

This paper presents an analytical/computational framework for prioritizing maintenance budgets to a group of bridges that are geographically located to form a highway network. This framework integrates time-dependent structural reliability assessment, highway bridge network analysis, life-cycle cost calculation, and evolutionary computation. A reliability index target value is used to ensure adequate safety of individual bridges in the network. The impacts of time-dependent reliability of individual bridges on the overall network functionality over the specified service life are taken into account explicitly. The optimum maintenance decisions are made based on balanced minimization of conflicting life-cycle maintenance, failure, and user cost criteria at network-level. The reliability-based bridge network maintenance management is thus formulated as a constrained combinatorial multiobjective optimization problem and is solved by genetic algorithm. An application example is provided for maintenance scheduling for satisfactory long-term performance of the deteriorating reinforced concrete deck slabs of an existing bridge network. The following conclusions can be drawn.

- The combination of time-dependent structural reliability techniques and highway network analysis provides a convenient means of relating the probabilistic failure of individual bridges, through an enumeration procedure, to the long-term network performance.
- The proposed procedure can cost-effectively prioritize maintenance budgets to bridges that do not meet the prescribed target performance level and/or that are most important for enhancing the network functionality over the specified time horizon. As the maintenance planning methods currently used do not explicitly consider bridge network effects, it is evident that the proposed approach must be more cost effective than the existing project-level approaches.
- Due to the inevitable uncertainty in the parameter values, it is the relative instead of absolute values of each cost measure, as exhibited by different maintenance solutions, that are more meaningful. Therefore, a single total life-cycle cost obtained by adding all costs of different origins may not be a good objective function for optimization.
- The present multiobjective formulation leads to a group of alternative maintenance solutions that exhibit the optimized tradeoff among conflicting life-cycle cost objectives. This allows bridge managers to actively compare different solution options and choose one that preferably balances improvement

J. Struct. Eng. 2006.132:1835-1845.

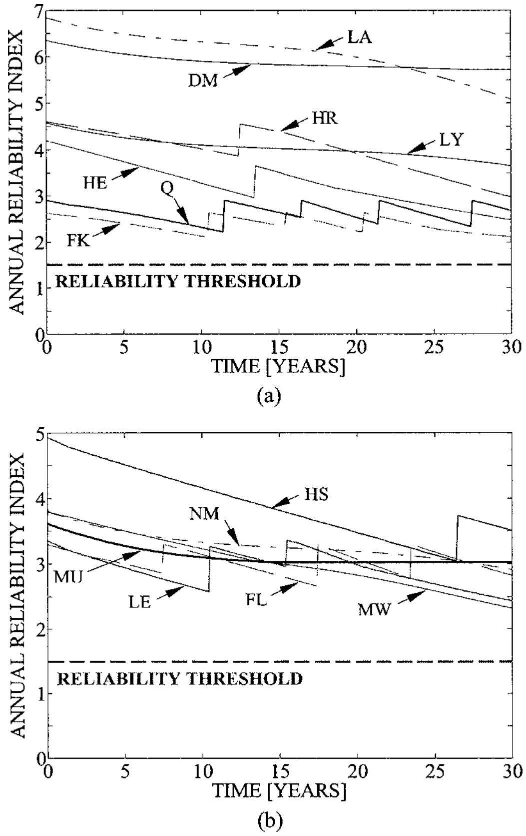

Fig. 11. Annual reliability index profiles of bridge decks in the network with Solution D

of network performance and reduction of maintenance/repair expenditures.

This study represents an important step in creating the necessary basis for the next generation of bridge management systems where optimum maintenance decisions based on life-cycle costs should be made at network-level while explicitly taking into account interaction between the evolutions of bridge reliabilities and the overall network serviceability. This makes the present study unique from most existing methodologies in the literature. In its present format, bridge reliability profiles are simulated and predicted based on appropriate mechanistic deterioration models; necessary approximations and simplifications are made for the sake of computational tractability. Future improvements require more accurate assessment and prediction of bridge performance through long-term health monitoring using advanced inspection and sensing technologies, consideration of other possible failure models such as deck delamination and concrete spalling and cracking, further investigation of possible correlations among bridge failures, more realistic evaluation of maintenance effects on bridge performance, and detailed information on bridge failure consequences, network flow patterns, and user costs for contributing network modes.

Acknowledgments

The writers gratefully acknowledge the support of the U.S. National Science Foundation through Grant Nos. CMS-9912525 and CMS-0217290, and the Colorado Department of Transportation. The opinions and conclusions presented in this paper are those of the writers and do not necessarily reflect the views of the sponsoring organizations.

References

Adey, B., Hajdin, R., and Brühwiler, E. (2003). "Supply and demand system approach to development of bridge management strategies." *J. Infrastruct. Syst.*, 9(3), 117–131.

Akgül, F. (2002). "Lifetime system reliability prediction of multiple structure types in a bridge network." Ph.D. thesis, Dept. of Civil, Environmental and Architectural Engineering, Univ. of Colorado, Boulder, Colo.

Akgül, F., and Frangopol, D. M. (2004). "Computational platform for predicting lifetime system reliability profiles for different structure types in a network." *J. Comput. Civ. Eng.*, 18(2), 92–104.

American Association of State Highway and Transportation Officials, (AASHTO). (1996). *Standard Specifications for Highway Bridges*, 16th Ed., Washington, D.C.

Augusti, G., Ciampoli, M., and Frangopol, D. M. (1998). "Optimal planning of retrofitting interventions on bridges in a highway network." *Eng. Struct.*, 20(11), 933–939.

Bell, M. G. H., and Iida, Y. (1997). *Transportation network analysis*, Wiley, Chichester, U.K.

Coello Coello, C. A., Van Veldhuizen, D. A., and Lamont, G. B. (2002). *Evolutionary algorithms for solving multi-objective problems*, Kluwer Academic/Plenum, New York.

Colorado Department of Transportation (CDOT). (2004). *Traffic data*, Denver.

Estes, A. C., and Frangopol, D. M. (1999). "Repair optimization of highway bridges using system reliability approach." *J. Struct. Eng.*, 125(7), 766–775.

Estes, A. C., and Frangopol, D. M. (2001). "Bridge lifetime system reliability under multiple limit states." *J. Bridge Eng.*, 6(6), 523–528.

Estes, A. C., and Frangopol, D. M. (2003). "Updating bridge reliability based on bridge management systems visual inspection results." *J. Bridge Eng.*, 8(6), 374–382.

Frangopol, D. M., Kong, J. S., and Gharaibeh, E. S. (2001). "Reliability-based life-cycle management of highway bridges." *J. Comput. Civ. Eng.*, 15(1), 27–34.

Furuta, H., Kameda, T., Fukuda, Y., and Frangopol, D. M. (2004). "Life-cycle cost analysis for infrastructure systems: Life cycle cost vs. safety level vs. service life." Keynote paper in *Life-cycle performance of deteriorating structures: Assessment, design and management*, D. M. Frangopol, E. Brühwiler, M. H. Faber, and B. Adey, eds., ASCE, Reston, Va., 19–25.

Goldberg, D. E. (1989). *Genetic algorithms in search, optimization and machine learning*, Addison-Wesley, Reading, Mass.

Hawk, H., and Small, E. P. (1998). "The BRIDGIT bridge management system." *Struct. Eng. Int. (IABSE, Zurich, Switzerland)*, 8(4), 309–314.

Internal Revenue Service (IRS). (2005). *2005 standard mileage rates set*, Washington, D.C.

Kong, J. S., and Frangopol, D. M. (2005). "Probabilistic optimization of aging structures considering maintenance and failure costs." *J. Struct. Eng.*, 131(4), 600–616.

Liu, M., and Frangopol, D. M. (2005). "Balancing connectivity reliability of deteriorating bridge networks and long-term maintenance cost through optimization." *J. Bridge Eng.*, 10(4), 468–481.

Melchers, R. E. (1999). *Structural reliability analysis and prediction*, Wiley, Chichester, U.K.

Microsoft Corporation. (2002). *Microsoft streets and trips*, Seattle.

Mori, Y., and Ellingwood, B. (1993). "Reliability-based service-life assessment of aging concrete structures." *J. Struct. Eng.*, 119(5), 1600–1621.

Mori, Y., and Ellingwood, B. R. (1994). "Maintaining reliability of concrete structures I: Role of inspection/repiar." *J. Struct. Eng.*, 120(3), 824–845.

National Cooperative Highway Research Program (NCHRP). (2002). "Life-cycle cost analysis for bridges." *NCHRP Project No. 12-43*, Washington, D.C.

Phares, B. M., Washer, G. A., Rolander, D. D., Graybeal, B. A., and Moore, M. (2004). "Routine highway bridge inspection condition documentation accuracy and reliability." *J. Bridge Eng.*, 9(4), 403–413.

Schrank, D. L., and Lomax, T. J. (2003). *2003 Urban Mobility Rep.*, Texas Transportation Institute, College Station, Tex.

Shinozuka, M., Murachi, Y., Dong, X., Zhou, Y., and Orlikowski, M. J. (2003). "Seismic performance of highway transportation network." *Proc., China-U.S. Workshop on Protection of Urbana Infrastructure and Public Buildings against Earthquakes and Manmade Disasters*, Beijing.

Thoft-Christensen, P. (2003). "Stochastic modeling and optimization of complex infrastructure systems." *IFIP TC-7 Conf. on System Modeling and Optimization*, Sophia Antipolis, France.

Thompson, P. D., Small, E. P., Johnson, M., and Marshall, A. R. (1998). "The Pontis bridge management system." *Struct. Eng. Int. (IABSE, Zurich, Switzerland)*, 8(4), 303–308.

Val, D. V., Stewart, M. G., and Melchers, R. E. (2000). "Life-cycle performance of RC bridges: Probabilistic approach." *Comput. Aided Civ. Infrastruct. Eng.*, 15(1), 14–25.

Wu, H. F. (1999). "Composites in civil applications." National Institute of Standards and Technology, Gaithersburg, Md., ⟨http://www.atp.nist.gov/atp/focus/99wp-ci.htm⟩ (Oct. 2004).

J. Struct. Eng. 2006.132:1835-1845.