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Bridge preventive maintenance based on life-cycle assessment

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Abstract

A criterion for preventive maintenance scheduling (PMS) is proposed based on the history of previous damage occurrences, duration of repairs or maintenance, and the development of cost functions. The PMS method describes the performance of the bridge for the deterioration/damage events and maintenance actions during the bridge's service life. The time to failure and repair time are modeled as random variables. Sensitivity studies show that the maintenance cost by damage consequence, an indirect measure of the bridge importance, plays a significant role on the optimal maintenance period.

Key words: Bridge maintenance, life-cycle cost, time to damage, repair time, optimal maintenance schedule.

Mantenimiento preventivo de puentes basado en evaluación en el ciclo de vida

Resumen

Se propone un criterio para programación de mantenimiento preventivo de puentes (PMS) basado en la historia previa de daños y reparaciones o duración del mantenimiento, y en el desarrollo de funciones de costo en el ciclo de vida. El método PMS describe el desempeño del Puente a medida que ocurren los eventos de daño/deterioro así como sus respectivas acciones de mantenimiento durante la vida de servicio u operación del puente. El tiempo a la falla y el de reparación se modelan como variables aleatorias. Estudios de sensitividad demuestran que los costos por consecuencias del daño, una medida indirecta de la importancia del puente, juegan un papel significativo en el periodo óptimo de mantenimiento.

Palabras clave: Mantenimiento de puentes, costo en el ciclo de vida, tiempo al daño, tiempo de reparación, programa de mantenimiento óptimo.

1. Introduction

Design and maintenance of bridges require the explicit and systematic consideration of the life-cycle balance between costs and safety. To be effective, maintenance scheduling ought to be based on the quantitative assessment of the likelihood and consequences of events that may cause fatalities, injuries, bridge damage, economic activities disruption, jammed traffic costs, and other loss causing events [1]. Bridge managers in charge of maintenance and operation require priorization indexes to justify the funding of conservation actions. It is well known that increasing traffic loads accelerates bridge deterioration. It is necessary to be careful with an evaluation of the bridge [2]. The referred assessment may be used to assist operators and managers of these facilities in their tasks of making decisions on money allocation to anticipate the undesirable events occurrence, and mitigate the consequences of those according to the specific risks and available resources for bridge repairs under their management.

RAM (Reliability, Availability and Maintainability) techniques have been successfully applied on industrial and mechanical engineering [3, 4] to assess engineering systems performance. In addition to that, life-cycle evaluation has given bases for decision making on bridge engineering [5- 7]. These techniques are migrating, and adapted with the proper modifications, into proposing optimal maintenance schedules for specific bridge types. These concepts have probed their efficiency to assess operational safety and to set preventive maintenance schedules for industrial plants [8, 1]. On the other hand, life-cycle analysis has been used to predict bridge safety conditions and remaining life [9, 10].

Based on those advances, a criterion for preventive maintenance scheduling is proposed in this paper, which resorts on the history of damages and maintenance/repair events, describing the bridge performance as the deteriorating/damaging events and maintenance actions occurred during the bridge's life. The basis of the formulation is the consideration of two random variables: the waiting time to damage (time to detect a damage), and the duration of the maintenance (works required to restore the bridge capacity). It is assumed that the bridge failure is prevented by using this scheme. The probability of bridge deterioration/damage increases as a result of intense traffic and inadequate (or insufficient) maintenance, which results in a series of consequences (specially the economical losses due to service interruption) included in the calculation of the expected cost of deteriorating/damaging events derived, for example, from the bridge exposure to heavy traffic conditions. The procedure may be adapted to represent other types of hazards, i.e. seismic hazard.

Monte Carlo simulation is used as a means to estimate the expected life-cycle cost associated with a given maintenance schedule [11]. Based on such simulations, simplified cost functions are developed, then alternative schedules are compared, and finally the optimal alternative, corresponding to the minimum expected life-cycle cost, is chosen.

Analytical expressions are proposed for the expected cost functions. As these events occur at random periods in the future within the bridge's service life, their respective costs need to be expressed in present value including the country's exchange rate where the bridge is located. The damage cost (C_d) consequences, mainly the operation component interruption cost in heavy traffic bridges, have a crucial impact on the optimal maintenance schedule. If the maintenance period (this investigation assumed constant Δt to simplify the illustration) is short enough, the whole maintenance cost (C_m) during the bridge's service life increases and, as a consequence of the limited number of damage events, the expected C_d in the lifetime decreases. On the other hand, for a long maintenance period, many damaging events may occur within the bridge life-cycle. As a result, the expected cost C_d increases while the associated C_m decreases. These trends suggest the existence of a particular value of the maintenance period for which the expected life-cycle cost becomes a minimum value.

2. Description of probabilistic assessment

A deterministic operating cost equation has been proposed in the literature (Goble 1992):

$$C_o = (C_d + C_m) * L \quad (1)$$

where C_o = operating cost, C_d = damage cost, C_m = average maintenance cost and L = bridge service life. Eq. (1) is re-written now in probabilistic terms and it is composed by the average damage costs C_d^L and the average maintenance costs C_m^L that may occur during the bridge's service life. As the damage and repair times are random, a proper description of the average cost will be as an expected cost. Once the damage and repair times are modeled by probability distributions, trials of these times may be performed through simulation to represent the time varying sequence of events within the bridge service life.

First of all, a set of alternative maintenance schedules is proposed in order to appraise the economical effectiveness of each alternative. For a given maintenance schedule, the random generation of time series up to the bridge service life is repeated, the life-cycle cost is calculated and its average represents the expected life-cycle cost. For the *j-th* alternative of maintenance schedule, the expected damage costs for all the possible bridge damages (which can be accumulated for the bridge operating life and for all the number of damages *nd*), is:

$$E(C_d^L)_j = E\left\{\sum_{i=1}^{nd} C_{di}(\Delta td_i) PVF(td_i)\left[1 - F_{td}(\Delta td_i)\right]\right\} \quad (2)$$

where the present value factor *PVF* of expenditures made at time td_i, is expressed in terms of the annual net discount rate *r* as:

$$PVF(td_i) = \frac{1}{(1+r)^{td_i}} \quad (3)$$

Also, $C_{dj}(\Delta td_i)$ is the damage cost and $F_{td}(\Delta td_i)$ is the annual cumulative distribution of damage times associated to the time increment to the next damage time Δtd_i.

Other concept commonly used is the availability, which is defined for the maintenance schedule *j* and time td_{ij}:

$$A(\Delta td_{ij}) = \frac{\Delta td_{ij}}{(\Delta td_{ij} + \Delta tr_{ij})} \quad (4)$$

The availability, adapted from Mechanical Engineering, is the average percent time that the bridge is available for service respect to the lifetime.

If the damage and repair times are random, the expected value is approximated:

$$E[A(\Delta td_{ij})] = \frac{E(\Delta td_{ij})}{E(\Delta td_{ij} + \Delta tr_{ij})} \quad (5)$$

In a simplified representation, the bridge performance is assumed to be described by a random series of damage events (including all the adverse consequences of insufficient maintenance) and maintenance/repair (with restoring capacity effect) events. These events cause that the bridge manager has to spend money on tasks either due to programmed preventive actions or remedial corrective works. These costs may be estimated from Monte Carlo simulation, for the bridge's operating life *L*, according to the potential occurrence of the damage or maintenance events. The bridge's historical failure and maintenance (or repair) time events are collected, and fitted to proper probability distributions once the damage event is defined. The corresponding costs are step functions of either, the time to damage, or the repair duration. This intends to represent the damage cost consequences in terms of the interruption time, and the repair cost in terms of the repair duration. Monte Carlo techniques allows for the simulation of random times to represent the occurrence of damage or maintenance events. An enough large of random numbers are used throughout the repetition of a deterministic process to get a sample of results where statistics can be made.

Here Δt_j is the prescribed as a constant period for bridge maintenance according to the schedule *j*, and Δtd_{ij} is the random time to damage, both modeled from the bridge's history of previous damage and repair times. A damage event (and its subsequent repair) occurs whenever a simulated value of Δtd_{ij} is less than Δt_j and, given no maintenance action during this time period, the maintenance cost $C_m(\Delta td_{ij})$ is 0. On the other hand, when $\Delta td_{ij} > \Delta t_j$ a maintenance event occurs and the corresponding damage cost $C_d(\Delta td_{ij})$ is 0.

The bridge's life-cycle simulation process of damage and maintenance sequential events consists of two stages: damage time event (Δtd_{ij}) and repair time event (Δtr_{ij}), which are randomly generated times according to a predetermined distributions, and subsequently added up to reach the bridge service life. If nm_j is the number of maintenance actions:

$$\sum_{i=1}^{nd}(\Delta td_{ij} + \Delta tr_{ij}) + \sum_{k=1}^{nm_j} nm_j(\Delta tr_k) \approx L \quad (6)$$

Once all the failure, repair, and maintenance time events are accommodated into the service life *L*, the life-cycle failure cost and the maintenance costs are accumulated and the total life-cycle cost is estimated for the maintenance schedule *j*. After several trials of the simulation process are completed, the expected value of the life-cycle cost $E(C_T^L)_j$ is estimated for maintenance schedule *j*. Finally, the optimal maintenance schedule will be the one corresponding to the minimum expected life-cycle cost.

Conceptually it is expected that, as the maintenance period decreases, the maintenance cost (C_m^L) increases, and the damage cost (C_d^L) decreases. Conversely, for a maintenance period large enough, C_m^L decreases whereas C_d^L goes up. See Figure 1 for a graphical view of these concepts. With the procedure described above, the corresponding conceptual cost functions for the expected life-cycle costs may be outlined. An optimal scheme will correspond to the combination of bridge performance and maintenance schedule that minimizes the total expected life-cycle cost.

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3. Cost functions for damage and maintenance

The shape of the cost functions corresponding to the alternative events of damage and repair (or maintenance) may also be plotted. For every simulation of Δtd_{ij}, the costs shall result as may be seen in Figure 2, where c_R and c_{SI} are the repair cost (per year) and the loss associated with the interruption of service on the bridge (per year), respectively, in case that a damage event occurs and a repair is required. Similarly, c_m is the maintenance cost (per year).

Usually the availability at a specific time is expressed as the ratio between the time the system is available (before the damage event), and the cycle for that damage event, i.e., the ratio of the time to damage respect to the sum of the time to damage and the repair time:

$$A(t_i) = \frac{\Delta td_{ij}}{(\Delta td_{ij} + \Delta tr_{ij})} \quad (7)$$

If these times are random, the availability at the cycle "*i*" is the ratio between the expected value of the time to damage and the expected value of the cycle duration (which corresponds to the sum of the damage time and the repair time):

$$A_i = \frac{E(\Delta td_{ij})}{E(\Delta td_{ij} + \Delta tr_{ij})} \quad (8)$$

4. Application to two Mexican bridges

The formulation is applied to the bridges Cuto and Guadalupe, see Figure 3, two reinforced concrete bridges with a structural system

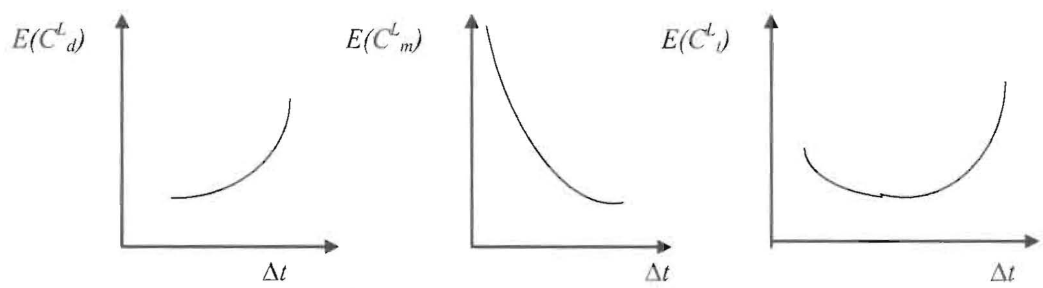

Figure 1. Conceptual maintenance cost functions.

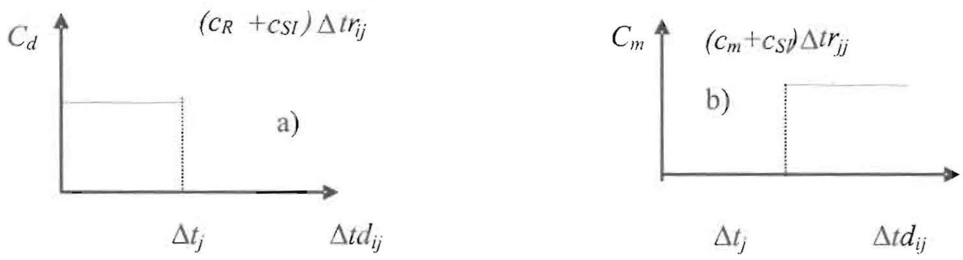

Figure 2. Cost functions for (a) damage and (b) repair or maintenance.

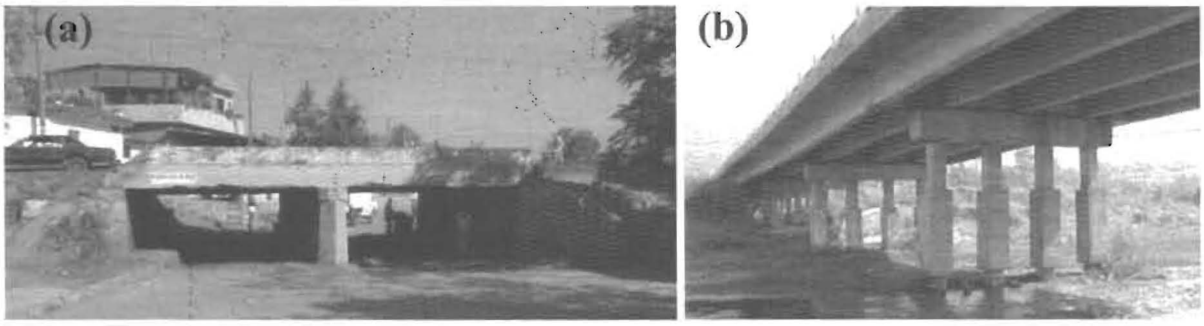

Figure 3. The two bridges analyzed: (a) Cuto Bridge, and (b) Guadalupe Bridge.

composed by a flat reinforced concrete slab supported by squared reinforced concrete piles. The first bridge is a two 12.5-m span whereas the second one has 6 spans with a total length of 169.5m. Figure 3 shows photographs of the two bridges analyzed. At the time this paper was prepared, the bridges have had only two repairs. Data about the observed times to damage and repair times are shown in Table 1.

The repair, service interruption and maintenance costs (c_R, c_{SI}, c_m) are in Table 2. $T = 200$ years (this lifetime is the time limit to perform and add simulation times, see Table 3).

From surveys performed to the bridges in 2001, damage and repair data were obtained [12, 13]. The time to damage (t_d) and time to repair (t_r) were modeled as random variables, and with a χ^2 test of fit goodness, their corresponding distributions were obtained (Figure 3).

Weibull (Eq. 9) was found to be the best fit over exponential and lognormal distributions for t_d, t_r and the Availability function. The parameters of this distribution are shown in Table 4.

$$F(x) = 1 - \exp\left(\frac{-x}{\beta}\right)\alpha \qquad (9)$$

The mean availability for the Bridge Cuto is 92.1% whereas the one for the Bridge Guadalupe is 86.2%. Finally, the expected life-cycle cost analysis was estimated for several prescribed maintenance periods. A sample of the calculations to obtain $E(C_t^L)$ for $\Delta t = 1$ year and for Cuto Bridge appears in Table 3. In the column "Failure or mainten." the indicator 0 expresses maintenance ($\Delta t < t_d$) and 1 means damage ($\Delta t > t_d$) and, once t reaches 200 years, all the C_t^L are added up

Table 1
Damage (Δtd) and repair (Δtr) times for both bridges (in years)

Time	Cuto	Guadalupe
Δtd_1	2.5	1
Δtd_2	8	4
Δr_1	0.4	0.3
Δr_2	0.5	0.5

Table 2
Annual costs (million pesos per year) (1USD = 11 Mexican pesos)

Cost item	Cuto	Guadalupe
c_R	0.01	0.2
c_{SI}	0.3	0.4
c_M	0.02	0.3

and the total is the value of $E(C_t^L)$. The results are shown in Figures 4 and 5. Costs are expressed in million USD (MUSD).

In order to assess sensitivity, the exercise was repeated for other two values of service interruption losses, 3 and 0.1 MUSD for Cuto bridge and 4 and 0.1 million for Guadalupe bridge. See Figures 6 and 7.

5. Discussion

The optimal maintenance schedule may be identified through the minimum expected life-cycle cost. The expected life-cycle costs for several alternative maintenance schedules, shown in Figures 4 and 6, indicate that a maintenance work every 2 years should be the optimal mainte-

Table 3
Sample of calculations to get $E(C_t^L)$ for Δt = 1 year for Cuto Bridge (Costs in MUSD)

per year	per year	per year		t_m =	0.1				
c_R	c_{SI}	c_m	α_d	β_d	α_r	β_r	α_a	β_a	
0.010	0.3	0.02	2.224	2.948	2.3546	0.467	6.166	92.96	t
F_A^d	t_d (years)	Δt (years)	F_A^r	t_r (years)	Damage or mainten.	C_d^L	C_m^L	C_t^L	0
0.224	1.59	1	0.837	0.60	0	0	0.032	0.032	1
0.380	2.11		0.010	0.06	0	0	0.032	0.032	2
0.082	0.97		0.219	0.25	1	0.079	0	0.079	3.23
0.804	3.67		0.326	0.31	0	0	0.032	0.032	4.23
0.161	1.35		0.477	0.38	0	0	0.032	0.032	5.23
...	...	...	...	...	...	...	...	...	...
									200.43
							$E(C_t^L)$ = 8.49		

Table 4
Weibull parameters for t_d, t_r and A for both bridges

Variable	Parameter	Cuto	Guadalupe
t_d	α	2.224	1.866
	β	2.948	1.217
t_r	α	11.59	5.064
	β	0.413	0.322
A	α	0.261	0.240
	β	0.212	0.371

nance time for the Cuto Bridge. On the other hand, for the Guadalupe Bridge, this optimal time of maintenance should be every 1.1 years. This reflects the bridge condition: i.e. there was longer times for damage in the history of Cuto Bridge, as compared to the shorter times for damage observed in the data for Guadalupe Bridge. The sharpness of the $E(C_t^L)$ vs t curve for Cuto Bridge contrasts with the flat shape (near to the optimal) of the Guadalupe Bridge $E(C_t^L)$ vs t curve. A possible meaning of such performance might be due to the fact that the structural type of

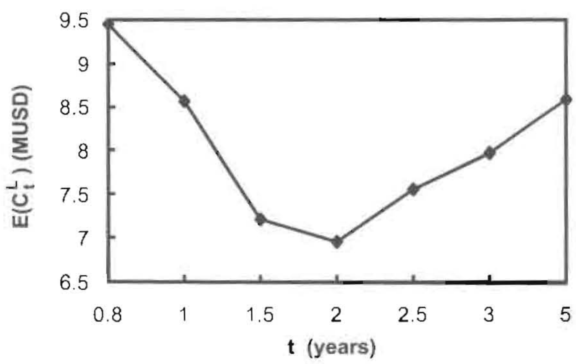

Figure 4. Expected life-cycle costs of Cuto Bridge.

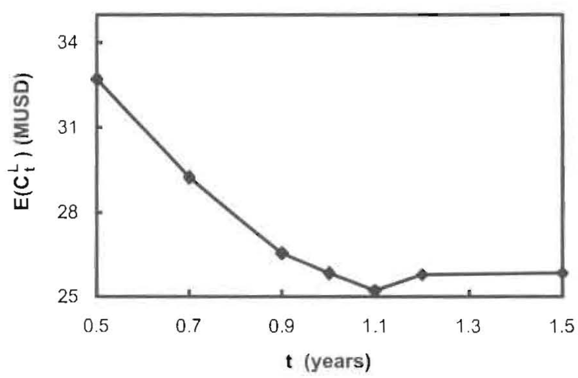

Figure 5. Expected life-cycle costs of Guadalupe Bridge.

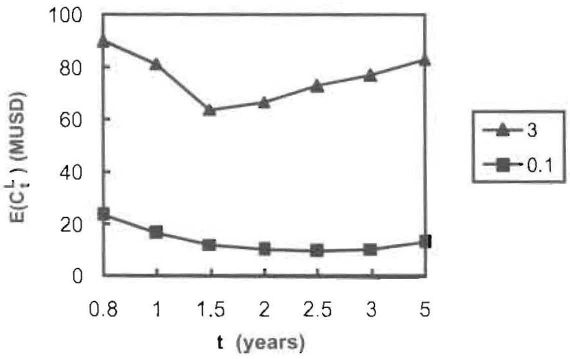

Figure 6. Expected life-cycle costs for Cuto Bridge. Optimal points are indicated for C_{SI} = 3 and 0.1 million USD (MUSD).

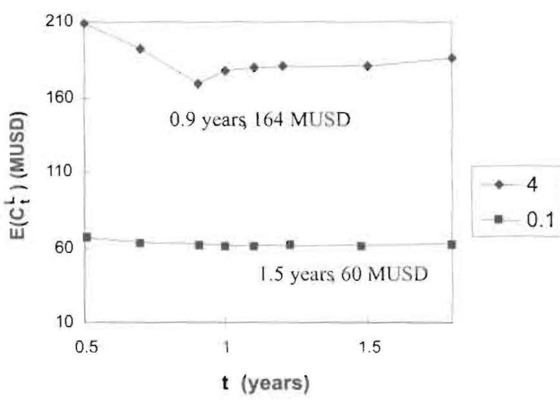

Figure 7. Expected life-cycle costs for Guadalupe Bridge. Optimal points are indicated for C_{SI} = 4 and 0.1 million USD (MUSD).

the Guadalupe Bridge does not make a cost difference on the maintenance time period in the range between 1 and 1.5 years, as compared with the short span type of the Cuto Bridge. These comparisons show that every bridge is different, thus detailed studies should be performed considering span ranges, structural types, age, and current condition before any generalization is made.

From the goodness of fit tests, the Weibull model predicts better the bridge deterioration vs. time data, as compared with the exponential model, which sustains a constant damage rate. It is confirmed the convenience of using the Weibull model, as reported on studies made to mechanical equipment [14].

From the results obtained for optimal maintenance of both bridges, it is observed the better condition of the Cuto Bridge, the lower risk, of the Cuto Bridge whereas the Guadalupe Bridge requires a more careful attention because of its larger span and the more expensive costs of service interruption. Also, the calculated mean availabilities confirm the observation.

The sensitivity of the results against the interruption service cost (the most important item of all costs) showed, from Figs. 6 and 7, that, as expected, the optimal maintenance time moves to shorter periods. This means that the more important is the bridge, the more protection and maintenance care is needed. Also, as the cost of damage consequences gets lower, the expected life-cycle cost gets flatter, which means that for facilities with little important (short span bridge), there is no much room to optimize the maintenance. But, for important bridges (long span), the optimal maintenance corresponds to only specific time periods. Although a constant Δt_j was used to assess the life-cycle costs for every damage and maintenance sequential events trial in this application, the procedure is not limited to such constant Δt_j, and variable maintenance periods may also be used.

An inconvenience of the proposed formulation is that all the maintenance and repair events are mixed up and no difference is made between failure/damage modes. However, an average maintenance hourly cost is used as a rough approximation, and a refined model should include a distinction among the damage modes in both aspects: occurrence times and costs.

6. Conclusions and recommendations

A probabilistic approach to generate optimal maintenance schedules for bridges was proposed and illustrated for two Mexican bridges. As expected, a more cost expensive bridge, with expensive consequences of damage/failure, requires a more frequent maintenance. Whenever the bridge has important damage consequences, a more careful determination of the optimal time between maintenances is justified because the room for optimization gets smaller. The optimal maintenance schedule is especially sensitive to the loss due to service interruption.

It is recommended to extend this formulation to consider several span ranges, ages, structural types, and current condition to generalize the conclusions to a regional or national inventory and maintenance strategy plans. Further research should be undertaken to refine the damage and cost modeling. In particular, a more detailed analysis may be developed by describing damages and maintenance procedures by type and level, according to the required attention from bridge deterioration. Similar schemes may be developed to integrate risk assessment with cost estimations and produce cost-benefit models to be used as a support to managers for decision-making regarding optimal design and upgrading. The proposed formulation may be extended and adapted to derive bridge availability extension and an extension of the operating life for older bridges. Implementation of the model to a specific kind of bridge will require the adjustment of the cost functions to the specifics of the bridge. In the near future, further development and refinement of these models may lead to support bridge managers and operators towards making optimal decisions in the areas of inspection and maintenance.

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