Total Cost-Benefit Analysis of Alternative Corrosion Management Strategies for a Steel Roadway Bridge

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Abstract: This paper describes a methodology for evaluating alternative corrosion management strategies for a steel roadway bridge based on a total cost-benefit analysis. In this analysis, the impacts of girder type and preservation intervention selection on the bridge owner, users, and public are considered. The methodology is demonstrated for a steel girder bridge in Wallis, Switzerland. Painted carbon steel and unpainted weathering steel girders are investigated. The investigated preservation interventions are the following: protection by painting, protection by metalizing, and replacement. Deterioration of the girders by corrosion is modeled probabilistically. Following the methodology demonstration, sensitivity studies are performed, wherein the corrosion environment, traffic volume, and detour length during interventions are varied. The effects of these variations on the various benefit types are then discussed and the conditions under which the various corrosion management strategies may be optimal are identified. **DOI: 10.1061/(ASCE)BE.1943-5592.0000374.** *© 2013 American Society of Civil Engineers.*

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Introduction

This paper describes a methodology for evaluating alternative corrosion management strategies for a steel roadway bridge based on a total cost-benefit analysis, wherein the impacts on all of the bridge stakeholders (i.e., affected persons) are considered, including the owner, the users, and the public. This methodology combines user and public cost models previously developed for the management of road (pavement) sections by Adey et al. (2012) with deterioration and maintenance cost models specific to steel-concrete composite bridges. The methodology is demonstrated for a steel girder bridge in the Canton of Wallis, Switzerland, with the main objective of showing how the consideration of costs other than those attributed to the bridge owner can influence the optimality of a corrosion management strategy for such structures.

Background

To determine the total costs and benefits, they must first be classified and structured, and appropriate models must be developed or selected to allow their approximation. A number of researchers and organizations have structured benefits and assembled models from which to approximate the total costs and benefits to provide guidance on how to evaluate infrastructure projects. Watanada et al. (1987) developed a model for analyzing the total transport costs of road improvement and maintenance strategies through life-cycle economic evaluation. The model enables detailed simulation of pavement deterioration and maintenance effects, and calculates the annual costs of road construction, maintenance, vehicle operation, and travel time. Land Transport New Zealand (LTNZ 2006) developed a manual to ensure that project economic evaluations are presented in a consistent format, project alternative costs and benefits are clear, assumptions are standardized between projects, and appropriate levels of data collection and analysis are undertaken. In this manual, the benefits are structured in terms of (1) travel time, (2) vehicle operation, (3) accidents, (4) comfort, (5) productivity, (6) driver frustration, and (7) emissions. Herrmann et al. (2008) and Adey et al. (2012) conducted a research project with the goal of synthesizing all of the main benefits related to pavement interventions on highway networks. Their benefit structure considers reductions in (1) routine maintenance, (2) travel time, (3) vehicle operating, (4) discomfort, (5) accidents, and (6) environmental costs. It assumes that the beneficiaries are the owner, the users, or the public.

Several possibilities exist for preventing or retarding the corrosion of steel bridge girders, including the use of corrosion resistant alloys (e.g., weathering steel) and the application of protective coatings (e.g., painting or metalizing). In the former case, higher corrosion resistance is achieved by adding small amounts of certain elements (e.g., copper, nickel, chromium) that promote the formation of a protective oxide layer when the steel is exposed to the environment (Damgaard et al. 2010). From the point of view of corrosion performance, an advantage of using weathering steel in bridges is that, under normal conditions, it may be left unpainted, leading to reduced maintenance costs.

Compilations of general corrosion data for plain carbon and weathering steel subjected to various corrosion environments are presented in Albrecht and Naeemi (1984) and Albrecht and Hall (2003). Kayser and Nowak (1989) used data from Albrecht and

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Naeemi (1984) to determine the statistical distributions for the corrosion constants, A and B, in the following power law:

$$C = A \cdot t^B \tag{1}$$

where t = exposure time in years and C = corrosion penetration in μm. Other researchers have subsequently used these distributions to calculate the structural reliability of steel girder bridges subjected to corrosion (Cheung and Li 2001; Czarnecki and Nowak 2008; Damgaard et al. 2010). In (Albrecht and Hall 2003). A two-part linear corrosion model is described, where

$$\begin{aligned} C &= \alpha \cdot t \quad \text{for} \quad t \leq 1 \text{ year} \\ C &= \alpha \cdot t + \beta \cdot (t-1) \quad \text{for} \quad t > 1 \text{ year} \end{aligned} \tag{2}$$

A C versus t envelope for weathering steel in a medium corrosion environment is then compared with test data for plain carbon, copper-bearing, and weathering steel specimens exposed to various environments for periods of up to 20 years. Eqs. (1) and (2) are both empirical in nature. The shortcomings of using such models (rather than one of the more complicated, mechanistic models that are available) are discussed in Melchers (1999) and Straub and Faber (2007) and include the possibility of errors resulting from extrapolation beyond the tested exposure time. The main advantages of these equations are their simplicity and wide use.

To improve the corrosion resistance of plain carbon steel girders, they are normally painted during fabrication. In the case of weathering steel girders, critical locations, such as directly below expansion joints, are sometimes painted. Paint can also be applied to existing bridges in the field. However, this remedial measure is not always effective and it can result in high owner and user costs if frequent repeated paint applications are needed (Lai et al. 2010).

As an alternative to painting, metalizing has received recent attention (Damgaard et al. 2010; Kuroda et al. 2006). Metalizing is a method of applying a layer of molten metal to a surface, usually by flame or plasma spraying. The sprayed metal acts as a protective coating and a sacrificial anode to slow the corrosion process. An advantage of metalizing, when compared with galvanizing (which is a more common process and similar in some respects) is that field application to larger elements is possible. The metalizing material is normally high-purity zinc; however, other alloying materials such as aluminum and indium are sometimes added.

Metalized steel surfaces can have remarkable corrosion resistance. For example, in Damgaard et al. (2010) corrosion tests on two metalizing alloys applied to weathering steel specimens showed little deterioration after cyclic exposure to saline solution and humid and dry cycles simulating ~40 years of exposure to a marine environment, as defined by Albrecht and Naeemi (1984).

With respect to the evaluation of the costs and benefits of intervention strategies for corroding steel bridges, significant work has been done, including the life-cycle cost analysis (LCCA) studies by Albrecht et al. (1989) and Lee et al. (2006). In the approach employed by Albrecht et al. (1989), only owner costs were considered and deterministic intervention frequencies were assumed for painting and girder replacement. The consideration of only owner costs has been common in the past and is still done by many road agencies. Lee et al. (2006) used a reliability-based approach to optimize the design of steel bridges subjected to deterioration by corrosion. Road user (i.e., vehicle operating and time delay) costs were considered, as were socioeconomic costs, which were taken as a percentage of the road user cost. The effects of road user costs on the LCCA have also been considered for generic bridge types (Pakrashi et al. 2011). Others have discussed the design and maintenance of bridges within a so-called sustainability framework (i.e., Gervásio et al. 2008; Hauf et al. 2010; Bastidas-Arteaga et al. 2010). This framework and the total cost-benefit analysis methodology employed in the current study share many similarities. However, the majority of the recently published works within the sustainability framework have focused on the environmental impacts of material selection and disposal decisions. These impacts could be considered in the total cost-benefit analysis methodology as an additional cost type. However, this was not done in the current study because initial investigations have shown that these impacts have little influence on the determination of the optimal management strategies. The reason for this is that the environmental costs related to material selection and disposal decisions are dwarfed by the other cost types, such as environmental costs related to the interruption of traffic flow and travel time costs. Others have used intergenerational discounting to consider the impact of decisions on resource availability and the state of the environment in the future (e.g., Sumaila and Walters 2005; Prager and Shertzer 2006). Although this concept could also be incorporated into the employed methodology, this possibility and its implications have not been explored in the current study.

Total Cost-Benefit Analysis Methodology

Calculation of Costs and Benefits

According to the methodology employed in this paper, the total cost of a management strategy is taken as the sum of all of the costs to the stakeholders over the considered time period; i.e.

$$\mathrm{TC}_i = \int_0^T \left[\sum_{\text{all } m} C_m^i(t) \right] \cdot e^{-\gamma t} \cdot dt \tag{3}$$

where TC_i = total cost of management strategy i over time period T, $C_m^i(t)$ = cost for cost type m and management strategy i at time t, and γ = discount rate.

A benefit of a management strategy is defined as a positive or negative consequence of the strategy on a stakeholder. The total benefit of a management strategy is defined as the net benefit for all stakeholders over an investigated time period; i.e., the difference between the costs for all stakeholders of one management strategy when compared with that of a reference strategy

$$\mathrm{TB}_i = \int_0^T \left[\sum_{\text{all } m} B_m^i(t) \right] \cdot e^{-\gamma t} \cdot dt \tag{4}$$

$$B_m^i(t) = C_m^r(t) - C_m^i(t) \tag{5}$$

where TB_i = total benefit of strategy i over time period T, $B_m^i(t)$ = benefit for cost type m and strategy i at time t, and $C_m^r(t)$ = cost for cost type m and the reference strategy at time t.

Some cost types may vary based on the bridge performance between interventions. For example, travel time costs may vary as a function of the longitudinal unevenness of the road surface, which in turn can be attributed to the asphalt condition, settlement of the bridge supports, and changes in the superstructure flexural stiffness. Furthermore, the condition states (CSs) of the various bridge elements will generally have differing impacts on the overall bridge performance with respect to the various cost types. Most LCCA methodologies currently do not consider this because they are

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mainly concerned with optimizing owner costs and sometimes user costs as a result of disruption of normal bridge function, which only occurs during interventions. In the current study, these costs were considered using an approach described in Fernando et al. (2011), which accounts for the effects of various element CSs on the overall performance of the bridge with respect to the various cost types that may be incurred between interventions.

Cost Structure

The cost structure used in this paper is shown in Table 1, in which the cost type is attributed to one or several stakeholders. Further discussion is provided in Adey et al. (2012) regarding the various cost types. Brief definitions and formulas for their calculation are provided in Appendix S1.

Deterioration Modeling

The deterioration processes are modeled in this paper using a modified Markov chain approach, commonly used in existing bridge management systems (BMSs) (Elbehairy 2007). Discrete CSs are defined and deterioration is modeled by estimating the probability of passing from one CS to another in a fixed period of time. These probabilities are the elements of the transition probability matrix, p (Jiang and Sinha 1989; Scherer and Glagola 1994). In the current study, unit jump transition probability matrices are used (see Table 2). At any given time t

$$p_t = p_{t-1} \cdot P \tag{6}$$

where P_t = matrix containing the probabilities of being in each CS at time t. Transition probability matrices allowing multiple CS jumps in one time increment may also be used to model corrosion deterioration, allowing more flexibility, as discussed in Sheils et al. (2010). However, unit jump matrices are employed herein because they are more commonly used in existing BMSs. Example descriptions of the five CSs for painted steel girders are given in Table 3. Existing BMSs use various numbers of CSs and definitions of performance for determining each CS. The CS and performance definitions used in this paper are thought to be representative of what may be done in practice. However, their intended purpose is primarily illustrative.

Table 1. Cost Structure

Cost type	Stakeholder
Construction	Owner
Maintenance	Owner
Travel time	Users
Vehicle operation	Users
Discomfort	Users
Accident	Users, public
Environment (noise)	Public
Environment (air pollution)	Public
Environment (climate)	Public

Table 2. Unit Jump Probability Transition Matrix, P

	CS at time $t+1$				
CS at time t	CS1	CS2	CS3	CS4	CS5
CS1	$1-q_1$	q_1	0	0	0
CS2	0	$1-q_2$	q_2	0	0
CS3	0	0	$1-q_3$	q_3	0
CS4	0	0	0	$1-q_4$	q_4
CS5	0	0	0	0	1

Calculating Annual Bridge Closure Times

For the analysis presented in this paper, it is assumed that if multiple interventions are needed in a given year, then the annual number of days of bridge closure will equal the number of closure days associated with the most time consuming of the interventions. It is further assumed that other interventions can be performed simultaneously, causing no additional closure time. The possibility of delaying and grouping together interventions into larger projects to be executed at time intervals greater than 1 year is not considered. The expected number of days of bridge closure, $E(n_{\text{closed}})$, is thus a function of the probabilities of each element being in a CS triggering an intervention and the durations of each intervention type; i.e.

$$\begin{aligned} E(n_{\text{closed}}) &= P^1_{\text{CSI}} \cdot n^1_I + \left(1 - P^1_{\text{CSI}}\right) \cdot P^2_{\text{CSI}} \cdot n^2_I + \cdots \\ &\quad + \left(\prod_{i=1}^{m-1}\left(1 - P^1_{\text{CSI}}\right)\right) \cdot P^m_{\text{CSI}} \cdot n^m_I \\ &\quad \text{for} \quad n^1_I \geq n^2_I \geq \cdots \geq n^m_I \end{aligned} \tag{7}$$

where n^i_I = number of days of bridge closure associated with a preservation intervention of element i when it reaches the CS at which the CS intervention (CSI) is required and P^i_{CSI} = probability of element i in the CSI.

Case Study Bridge

Bridge and Network Description

The selected bridge for this study was a newly proposed steel-concrete composite roadway bridge (see Fig. 1) in the Canton of Wallis, Switzerland, with two lanes of vehicular traffic and a sidewalk. The bridge has a total width of 12 m and consists of two simply supported spans (24.8-m long). The main support structure is composed of three steel girders placed on a bridge abutment and an intermediate pier. In turn, a 250-mm-thick concrete deck was built compositely with the steel girders to carry the traffic. The deck is covered with a 100-mm-thick asphalt wearing surface. After construction the bridge is expected to see an initial average daily traffic (ADT_i) volume of 650 vehicles/day. This traffic volume is expected to increase at a compounded rate of 0.5% per year. The freight traffic share is estimated at 35%.

The bridge superstructure was designed according to the Swiss Society of Engineers and Architects (SIA 2003a, b) and Lebet and Hirt (2009), assuming a nominal girder steel yield strength of 355 MPa, and 35-MPa concrete and 500-MPa (nominal yield) reinforcing steel in the deck. The moment (M), shear (V), and bearing (B) ultimate limit states were verified. The moment verification assumed fully plastic section behavior. A reduction in the moment capacity

Table 3. Condition State Descriptions for Steel Girders

CS	Description
1	Paint system sound and functioning as intended.
2	Surface or freckled rust has formed.
3	Paint system badly deteriorated.
3	Exposed metal but no significant section loss.
4	Significant section loss.
5	Alarming section loss.

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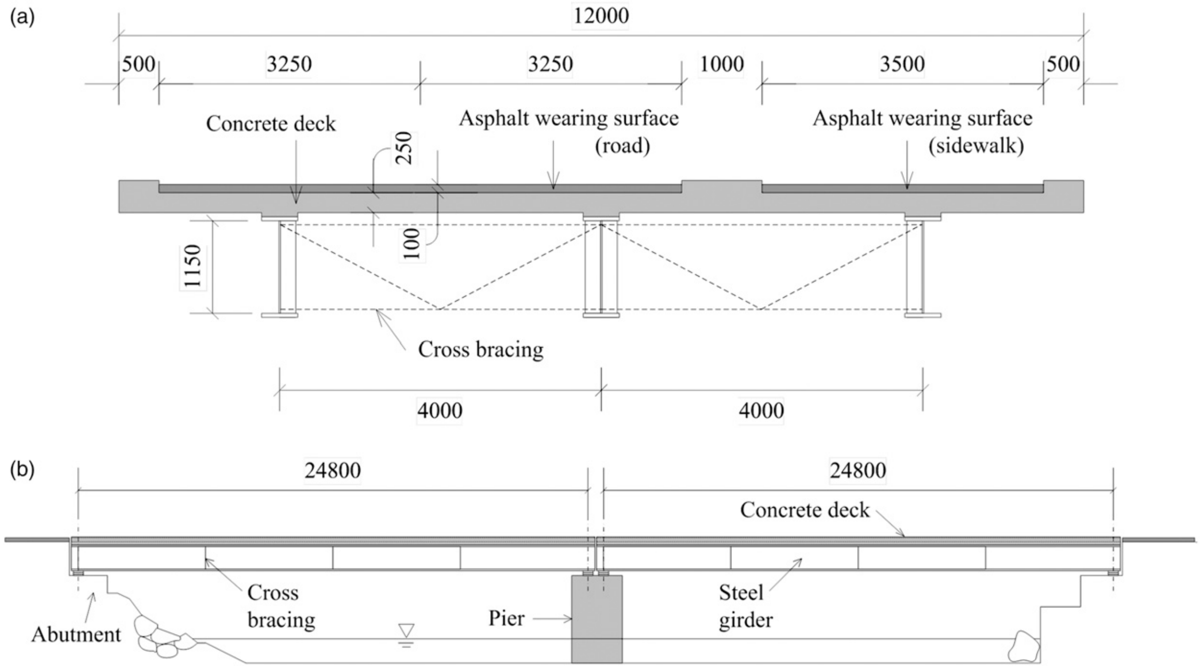

Fig. 1. Case study bridge (all dimensions in mm): (a) typical cross section; (b) elevation

was calculated to account for the interaction between moment and shear.

Along with the three limit-state verifications, live load (LL) and dead load (DL) deflections were compared with the code limits. The code-based design is summarized in Fig. 2, in which a resistance fraction (i.e., load/strength or deflection/code limit) of less than 1.0 indicates a satisfactory (i.e., safe or serviceable) design. In addition to the code-based design, an elastic finite-element model of the bridge was used to verify the stresses and deflections and to determine the performance indicators required to calculate the costs between the interventions based on Fernando et al. (2011).

Depending on the type of intervention, temporary closure of the bridge may be required. In this case it was assumed that the traffic would be diverted onto the shortest alternate route, which was 2.4-km long. The assumed travel speed is a function of the road surface CS and posted speed limit. It was assumed that the detour road surface would on average have a constant, intermediate CS of 3 for calculation of the detour travel time, assuming the road surface CSs ranged from 1 to 5. The posted speed limit on both the bridge and detour was 50 km/h.

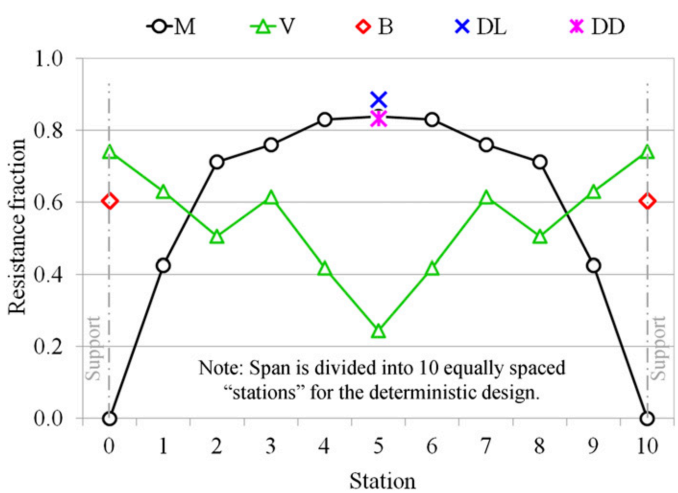

Fig. 2. Deterministic design summary

Cost Modeling

The various user and public costs were calculated based on Adey et al. (2012). The assumed values for a number of the key input parameters are summarized in Table 4.

Deterioration Modeling

The important bridge elements were identified as the asphalt layer, joints, deck, girders, bearings, and abutment/pier. The q_i values for each bridge element and CS are given in Tables 5 and 6. To determine the q_i values in Table 5, linear deterioration to an expected service life was assumed for all elements except the deck. The transition probabilities were then established by fitting the Markov model to the linear deterioration model. For the deck, the transition probabilities were established by fitting the Markov model to the results obtained using the probabilistic analytical model described in Roelfstra et al. (2004).

The CS definitions for the steel girders were assumed as shown in Table 3. If the girders were painted, then linear deterioration and a 20-year expected life of the paint were assumed for estimating q_1 and q_2. Unpainted girders were assumed to start out at CS3. Beyond CS3, the q_i values were established by fitting the Markov model to two-part linear envelopes based on Eq. (2) of the thickness loss data from Albrecht and Hall (2003). This empirical model was adopted on the basis that there was little available in the way of data to support the use of a more complicated model. This model was selected rather than Eq. (1) on the basis that the data in Albrecht and Hall (2003) includes more long duration test results.

To fit the Markov deterioration model, it was assumed that the uncertainty associated with the corrosion penetration, C, at a given year can be modeled using a lognormal distribution, based on

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Table 4. Input Parameters for the Case Study Bridge Analysis

Parameter	Value	Unit
Discount rate	2%	—
Initial ADT (ADT_i)	650	Vehicles/day
ADT increase	0.5	%/year
Percent of freight traffic (x)	35%	—
Annual routine maintenance cost	5.00	CHF/m^2
Travel time unit cost (UC_{TT})	26.24	CHF/h
Truck fuel unit cost ($UC_{F,truck}$)	0.595	CHF/L
Car fuel unit cost ($UC_{F,car}$)	0.544	CHF/L
Accident cost per event		
Property damage ($C_{property}$)	46.30	10^3 CHF
Injury (C_{injury})	301.3	10^3 CHF
Fatality ($C_{fatality}$)	3742	10^3 CHF
Accident cost user share		
Property damage	70%	—
Injury	80%	—
Fatality	85%	—
People affected by noise (ρ)	10	Number
Annual noise cost per person (C_{dB})	118	CHF/dB
Air pollution cost per truck ($C_{AP,truck}$)	0.151	CHF/km
Air pollution cost per car ($C_{AP,car}$)	0.024	CHF/km
CO_2 emission per truck (γ_{truck})	2.647	kg/L
CO_2 emission per car (γ_{car})	2.404	kg/L
Climate unit cost per kg CO_2 (UC_{CO_2})	0.051	CHF/kg

Note: All costs are the expected costs in 2010 CHF (Swiss francs).

Table 5. Bridge Element q_i Values Excluding Girders

Bridge element value	Expected life				
	Asphalt (25 years)	Joint (25 years)	Deck (43 years)	Bearing (35 years)	Abutment/pier (100 years)
q_1	0.179	0.179	0.152	0.132	0.033
q_2	0.170	0.170	0.163	0.120	0.080
q_3	0.174	0.174	0.140	0.121	0.053
q_4	0.096	0.096	0.030	0.070	0.019

Table 6. Girder q_i Values

Steel (corrosion environment)	Painted plain carbon steel			Unpainted weathering steel	
	Mild	Medium	Severe	Mild/medium	Severe
q_1	0.150	0.150	0.150	—	—
q_2	0.051	0.051	0.051	—	—
q_3	0.000	0.004	0.027	0.000	0.012
q_4	0.000	0.031	0.117	0.000	0.065

Melchers (1999), with the mean ± 1 SD for this distribution defined by the lower and upper bounds of the test-based corrosion penetration envelopes. The reason for using this approach is that these envelopes were established for a limited number of test sites, where only flat, small metal coupons were tested. Thus, the actual uncertainty in the uniform corrosion rate is believed to be higher than indicated by the envelopes of the test data. Using this approach, the distribution parameters and probabilities of the unpainted steel being in CS3, CS4, or CS5 in a given year could be calculated. The Markov model was then fit, using a least-squares approach, to probabilities thus calculated for exposure periods of up to 100 years.

To determine the corrosion penetration values, C, corresponding to the CSs in Table 3, a structural reliability analysis of the bridge was first performed, using the model described in Damgaard et al. (2010), modified for the assessment of 355-MPa steel I-girders based on the design formulas in SIA (2003a, b). Uniform corrosion on one side of the top flange and both sides of the web and bottom flange was simplistically assumed. The statistical variables used to model the uncertainties in the material strengths were based on Melcher et al. (2004) for the girder steel and Bailey (1996) for the concrete and rebar. To determine the extreme LL effect distributions, the approach described in the Canadian Standards Association (CSA 2007) was used, along with Swiss truck weight histograms from Kunz and Hirt (1991), modified based on Imhof et al. (2001) to account for an increase in the truck weight limit to 40 t. The possible effects of simultaneous truck crossings on the LLs were modeled based on Nowak (1993).

To relate the uniform corrosion penetration to the girder CS, reliability indices corresponding to significant and alarming thickness loss were assumed. Using the modified model from Damgaard et al. (2010), uniform corrosion penetration values of $C = 1.5$ and 2.5 mm were found to correspond to the assumed reliability indices for CS4 ($\beta = 3.5$) and CS5 ($\beta = 2.0$), respectively. Deterioration models were developed using this approach for plain carbon and weathering steel in mild (rural), medium (urban), and severe (marine) corrosion environments, as defined by Albrecht and Hall (2003).

Fig. 3 presents the assumed thickness loss (i.e., corrosion penetration) envelopes and fitting of the Markov deterioration model for unpainted weathering steel in a severe environment. For this environment, both the carbon and the weathering steel exhibited very high corrosion rates, leading to probabilities of reaching CS5 in 100 years or less, well over 50%. Under these conditions, the fit illustrated in Fig. 3 is typical. A much better fit was achieved for lower corrosion rates, such as those seen for the unpainted carbon steel in a medium environment. The Markov model is similar to the models used in many existing BMSs (i.e., a unit jump model, with fixed time increments, a fixed small number of CSs, and fixed transition probabilities). There are several ways the fit may be improved (e.g., by allowing the number of CSs or transition probabilities to vary). However, in its current form the model does an adequate job of predicting the general trends for the various corrosion environments, given the objectives of the current study.

The mild environment was effectively benign for both steel types. With limited site-specific knowledge regarding the actual corrosion environment, a medium environment was first assumed for the case study bridge. However, in the subsequent sensitivity studies the implications of the corrosion environment actually being severe were also examined. This possibility was considered to be plausible for the case study bridge; for example, if large amounts of deicing salt are used on the road network. The assumed steel girder q_i values for the various investigated steel grades and corrosion environments are summarized in Table 6.

Corrosion Management Strategy Modeling

To perform the total cost-benefit analysis, the construction costs, intervention costs, and bridge closure times associated with construction of the bridge and each of the investigated preservation

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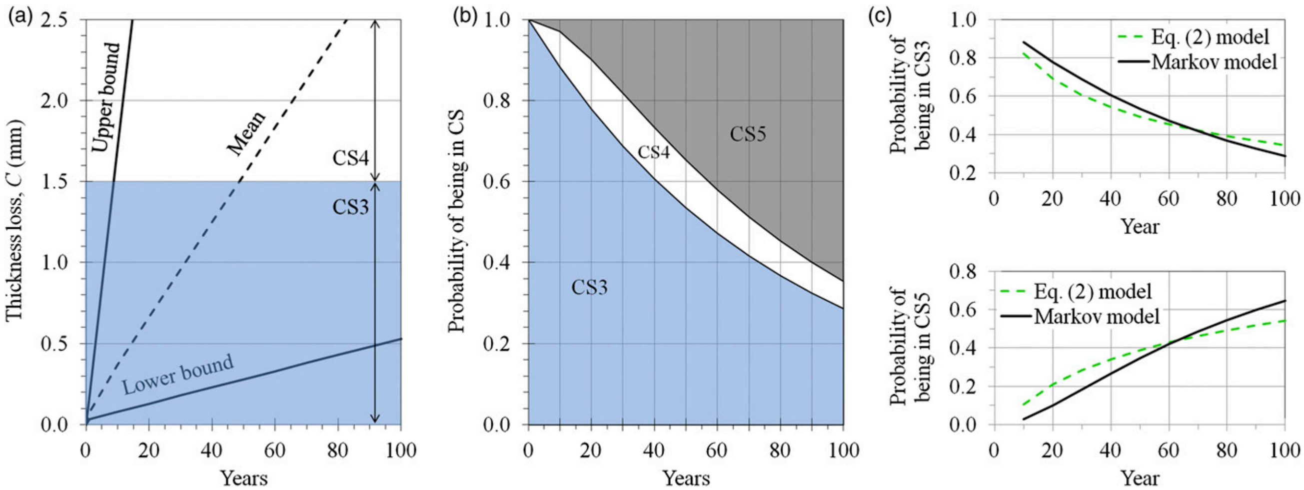

Fig. 3. Girder deterioration (unpainted weathering steel, severe environment): (a) thickness loss envelope based on Eq. (2); (b) Markov model output; (c) probabilistic model comparison

interventions for both types of girders were estimated, based on input from the Cantonal Road Authority and other industry experts. Table 7 summarizes the assumed interventions and costs for the reference strategy, S0. Asphalt repair at CS3 was assumed to improve the asphalt condition to CS2 in the time step following the intervention. Replacement of the other bridge elements was assumed to return each to CS1. Interactions resulting from the replacement of elements were not considered; i.e., it was assumed that the replacement of one element would not affect the deterioration of the others.

The assumed interventions and costs for Strategies S1–S4 are given in Table 8. These strategies differ from S0 only in the corrosion management of the girders. The following assumptions were made regarding the effectiveness of each of the investigated interventions:

- Replacement returns the girders to their initial CS (either 1 or 3).
- Repainting the plain carbon steel girders at CS3 returns them to CS1.
- If unpainted steel is to be repaired at CS4 by applying a coating (paint or metalizing) in the field, then two additional CSs, with definitions matching CS1 and CS2 for painted girders, are used to model future deterioration of the coating. It is further assumed that if a repair coating is applied, then it will be maintained for the remainder of the analysis period.
- The repair paint coating is assumed to have the same expected life as new paint; i.e., 20 years. An expected life of 40 years is assumed for the metalizing (Damgaard et al. 2010).

Table 7. Reference Management Strategy S0

Element	CS3	CS4	CS5	Cost (10^3 CHF)	Bridge closure (days)
Asphalt	Repair	NA	NA	15	5
Joint	—	—	Replace	32	5
Deck	—	—	Replace	315	30
Girder	—	—	Replace	550	20
Bearing	—	—	Replace	62	5
Abutment/pier	—	—	Replace	266	20

Note: CHF = Swiss francs.

Table 8. Investigated Corrosion Management Strategies

Strategy	Girder type	Girder CS: CS3	CS4	CS5	Cost (10^3 CHF)	Bridge closure (days)
S0	PPC	—	—	Replace	550	20
S1	PPC	Repaint	NA	NA	56	3
S2	UW	—	—	Replace	550	20
S3	UW	—	Paint	NA	56	3
S4	UW	—	Metalize	NA	84	3

Note: PPC = painted plain carbon; UW = unpainted weathering; CHF = Swiss francs.

Case Study Results

The total cost-benefit analysis results for corrosion management Strategy S1 (plain carbon steel/repair paint) and Strategy S2 (weathering steel/replace) are summarized in Figs. 4 and 5. The cumulative net present values (NPVs) of each benefit type at 25, 50, 75 and 100 years are plotted for Strategy S1 in Fig. 4(a). Corresponding curves for each stakeholder are plotted in Fig. 4(b) according to Table 1. For this strategy, the benefit was negative for all stakeholders and cost types through the duration of the analysis period. This means that the reference strategy of not maintaining the girders until they need replacement actually results in a lower total cost than Strategy S1, wherein the girders are painted when they reach CS3. The explanation for this result is that the expected corrosion penetration for plain carbon steel in the medium environment is sufficiently low and the cost of painting is sufficiently high with respect to the girder replacement cost; thus, there is little gained by painting when the girders reach CS3. In Fig. 4(b), it can be seen that the owner benefits are much larger in magnitude than the other stakeholder benefits. For Strategy S2 (Fig. 5), the benefits were positive for all stakeholders and for the entire analysis period. Again, the owner benefits were the most important. This can be explained by the low traffic volume, the short bridge and detour lengths, and the low number of people affected by noise. The benefits of Strategies S3 and S4 were the same as those for Strategy S2 because the expected rate of corrosion penetration for the weathering steel girders was very small.

Based on the results presented in Figs. 4 and 5, the optimal corrosion management strategies for the case study bridge are any of those involving the selection of unpainted weathering steel at the design stage (i.e., Strategies S2, S3, and S4). Looking at Figs. 4 and 5,

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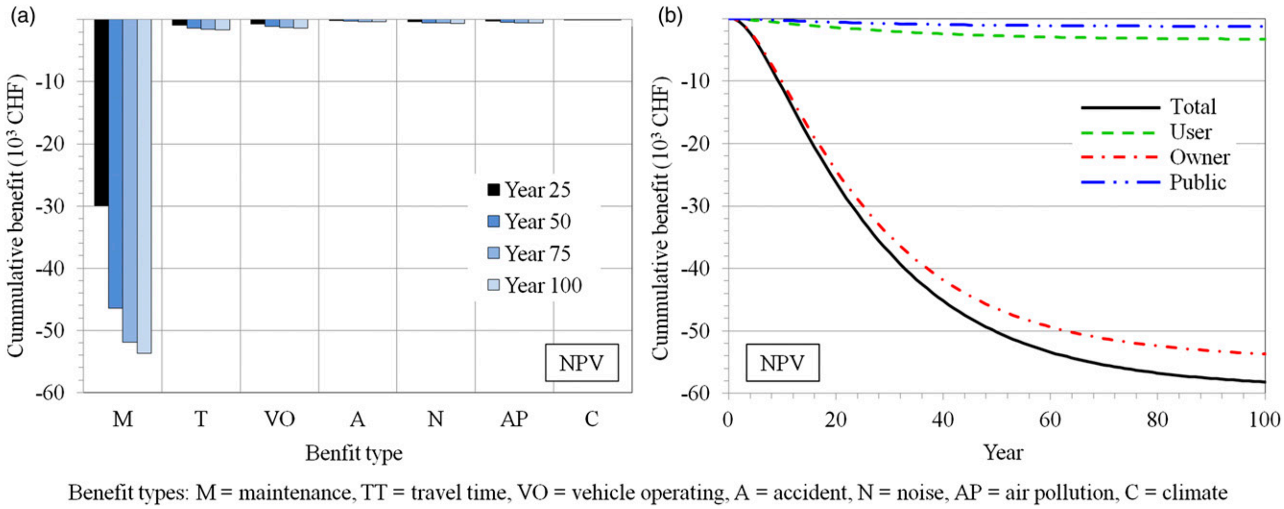

Fig. 4. Comparison of benefits for Strategy S1 (plain carbon steel/repair paint): (a) by type; (b) by stakeholder

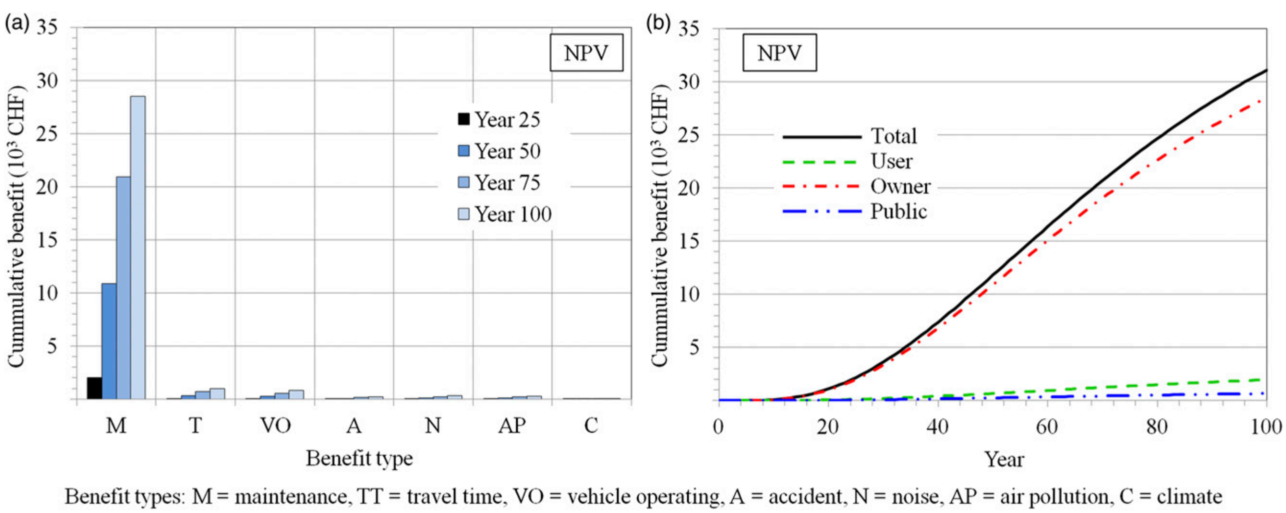

Fig. 5. Comparison of benefits for Strategy S2 [weathering steel/replace ($ADT_i = 650$)]: (a) by type; (b) by stakeholder

it must also be recognized that for the investigated bridge—because the user and public costs are so small—the same conclusion would be obtained by only considering owner benefits in the cost-benefit analysis. However, further investigation is needed to determine the sensitivity of these findings to variations in the key parameters, such as the corrosion environment, traffic volume, and detour length.

Sensitivity Studies

Sensitivity studies were conducted to investigate the stability of the optimal corrosion management strategy. The varied parameters included the traffic volume and corrosion environment. Several cost ratios were also varied to determine the critical ratios for selecting Strategies S2, S3, and S4 for a range of traffic volumes and detour lengths.

Traffic Volume and Corrosion Environment

In Fig. 6, the cost-benefit analysis results are again presented for corrosion management Strategy S2 with the initial traffic volume increased to $ADT_i = 6,500$. The resulting traffic volume remained well below the capacity of the network link for the entire analysis period. By comparing Figs. 5(b) and 6, it is seen that with the increased traffic volume, the user benefits have a much greater impact on the total cost.

In Fig. 7, the cost-benefit analysis results are summarized for a range of traffic volumes and corrosion environments. In Fig. 7(a), the total benefit results for the S1 and S2 management strategies in the medium corrosion environment show the same trends as described previously for a wider range of initial traffic volumes; that is, Strategy S1 is always worse than the reference strategy (i.e., has a negative total benefit) and Strategy S2 is always better than the reference strategy in the medium corrosion environment. In Fig. 7(b), it can be seen that in the severe corrosion environment, the long-term total benefits of all four strategies are positive, over the entire ADT_i range. Under these conditions, Strategy S2 is always inferior to Strategy S1. On the other hand, Strategies S3 and S4 are superior to Strategy S1 over the entire ADT_i range.

On this basis, it can be concluded that under the investigated range of conditions and with no knowledge of the actual corrosion

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environment, it would always be better to construct the new bridge out of unpainted weathering steel. If the actual corrosion environment turns out to be a medium environment, then a higher total benefit will result. If the corrosion environment turns out to be severe, then a higher total benefit will still result if a corrosion management strategy of preserving the girders by either field painting or metalizing is subsequently followed.

Critical Cost Ratios versus Detour Length and Traffic Volume

The results presented in the previous section depend on assumptions made regarding the preservation intervention costs for the various corrosion management strategies. Because these costs can vary significantly from site to site and over time, in this section, certain costs are varied to determine the critical cost ratios for selecting one strategy over another. Specifically:

- The cost of painting (as a fraction of the girder replacement cost) is varied, to determine the cost above which Strategy S2 will result in a higher total benefit than Strategy S1.

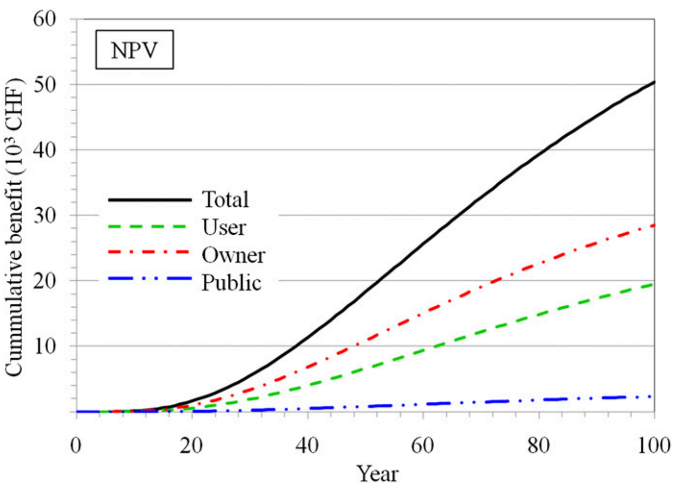

Fig. 6. Benefits of Strategy S2 [weathering steel/replace ($ADT_i = 6{,}500$)]

- The cost of painting is varied, to determine the cost below which Strategy S3 will result in a higher total benefit than Strategy S2.
- The cost of field metalizing is varied to determine the cost below which Strategy S4 will result in a higher total benefit than Strategy S3.

The initial traffic volume, ADT_i, was varied from 500 to 8,000 vehicles/day and the detour length was varied from 2.4 to 10 km. The analysis was done both (1) considering only owner costs and (2) considering total costs. A severe corrosion environment was assumed for illustrative purposes because the differences between Strategies S2 and S4 were seen to be negligible in the medium environment. The results are summarized in Fig. 8. If total costs are considered, rather than only owner costs, then for $ADT_i = 8{,}000$ vehicles/day and a 10-km detour length the following results are obtained:

- The critical painting cost above which Strategy S2 yields a higher benefit than Strategy S1 increases from 0.18 to 0.48 times the girder replacement cost [Fig. 8(a)].
- The critical painting cost below which Strategy S3 yields a higher benefit than Strategy S2 increases from 0.30 to 1.02 times the girder replacement cost [Fig. 8(b)].
- The critical metalizing cost below which Strategy S4 yields a higher benefit than Strategy S3 increases from 1.43 to 2.73 times the painting cost [Fig. 8(c)].

Durable protective coatings, such as metalizing, are typically considered to be expensive. Thus, based on initial cost comparisons only, such coatings are rarely considered for the corrosion protection of steel bridge girders. However, the results in Fig. 8(c) show that under certain conditions the total cost-benefit analysis predicts that the extra initial cost of the more durable protective coating will be more than offset by reduced owner, user, and public costs over the long term. In Fig. 8(c), it can be seen that as the traffic volume and detour length increase, the readiness to pay to use a more durable protective coating to repair the weathering steel, to reduce the intervention frequency, increases. The cost of applying a protective coating in the field includes (1) providing access to the structure, (2) removing and collecting the corrosion product and old coating system (which is particularly important in environmentally sensitive locations), and (3) applying the new coating system. Costs (1) and (2) can be very high and are normally insensitive to the selected coating system. Thus, it can be concluded that the use of a more durable coating will make the most economical sense for structures

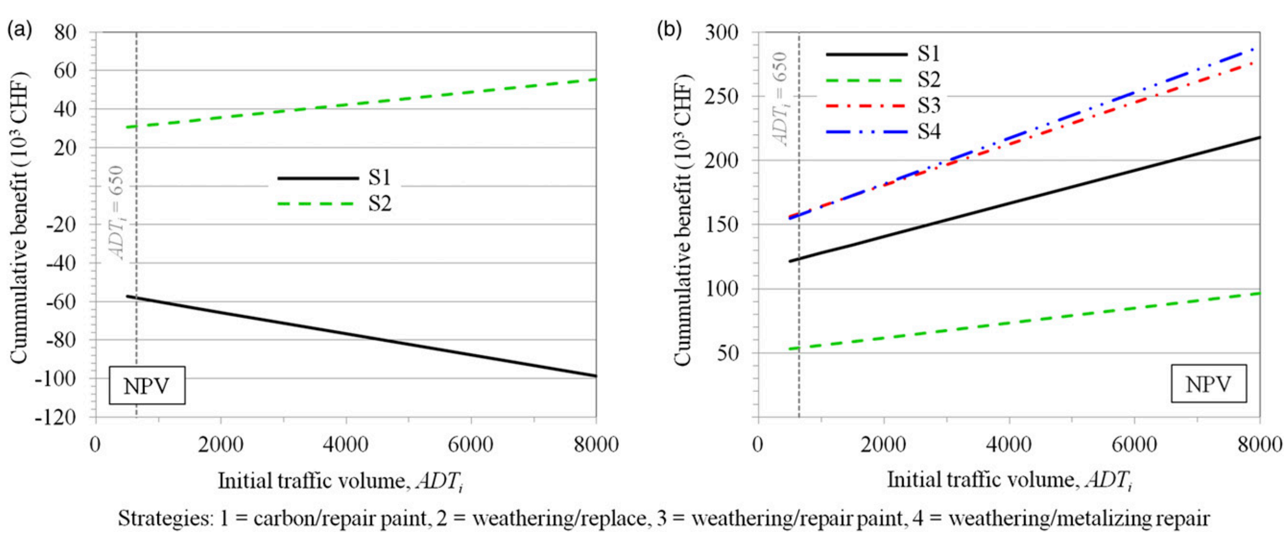

Fig. 7. Sensitivity study results for Strategies S1–S4 (total benefit at Year 100): (a) medium corrosion environment; (b) severe corrosion environment

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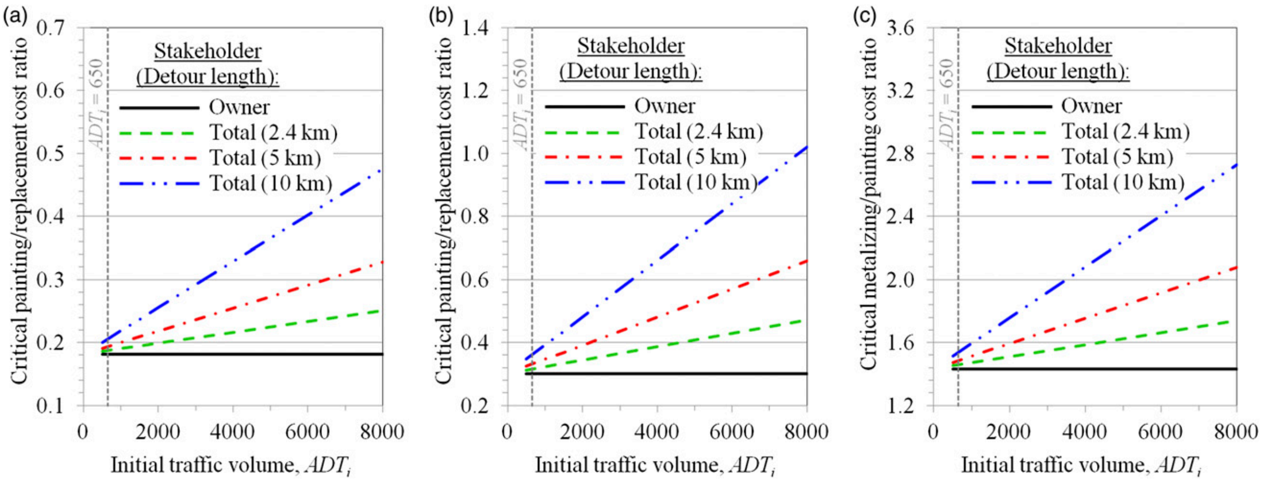

Fig. 8. Critical cost ratios (severe environment) when choosing: (a) S2 over S1; (b) S3 over S2; (c) S4 over S3

in either hard to access or environmentally sensitive locations because the cost ratio will be lower in either case.

In Fig. 8, the region between the owner and total cost curves indicates the cost range wherein the optimal management strategy selected when total costs are considered will be different than the one selected by only considering owner costs. In certain cases this range is rather large. In general, it is seen to increase with an increase in the traffic volume and/or detour length.

Conclusions

Based on the work presented in this paper, the following conclusions are drawn:

- Consideration of the benefits associated with stakeholders other than the owner can have a significant influence on the corrosion management strategy selection.
- In general, the relative importance of the user and public benefits increases with an increase in the traffic volume and/or detour length.
- For the investigated case study bridge and estimated preservation intervention costs, it is always better to use unpainted weathering steel in the initial bridge construction.
- If the weathering steel girders deteriorate to CS4, then the benefit of replacement versus protection by painting or metalizing can be assessed using the described methodology.

Although the presented analysis focuses on a case study bridge in Switzerland, this structure has a common configuration and the reported cost ratios are nondimensional. Thus, it is believed that the observed general trends are applicable to a large number of similar bridges in other developed regions where the relationship between labor and material costs are similar.

In the presented analysis, only uniform corrosion was modeled and the possibility of partial coating of the structure (i.e., only coating critical areas) was not considered. Further work to investigate the implications of these assumptions is recommended. In this paper, optimality is determined by comparing expected benefits for a limited subset of management strategies. This approach is sufficient to demonstrate the application of the methodology and to draw useful conclusions regarding the investigated strategies. However, another recommended area of further work would be to reformulate the problem as a full optimization problem, with key parameters treated statistically and allowed to vary. Further investigation along these lines could reveal other strategies that are more optimal than those investigated herein. Extension of the presented case study to incorporate the impacts of material selection and disposal associated with the various investigated strategies is another recommended future work area.

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Supplemental Data

Appendix S1 is available online in the ASCE Library (www.ascelibrary.org).

References

Adey, B. T., Herrmann, T., Tsafatinos, K., Lüking, J., Schindele, N., and Hajdin, R. (2012). "Methodology and base cost models to determine the total benefits of preservation interventions on road sections in Switzerland." *Struct. Infrastruct. Eng.*, 8(7), 639–654.

Albrecht, P., Coburn, S. K., Wattar, F. M., Tinklenberg, G. L., and Gallagher, W. P. (1989). "Guidelines for the use of weathering steel in bridges." *National Cooperative Highway Research Program Rep. 314*, Transportation Research Board, National Research Council, Washington, DC.

Albrecht, P., and Hall, T. T. (2003). "Atmospheric corrosion resistance of structural steels." *J. Mater. Civ. Eng.*, 15(1), 2–24.

Albrecht, P., and Naeemi, A. H. (1984). "Performance of weathering steel in bridges." *National Cooperative Highway Research Program Rep. 272*, Transportation Research Board, National Research Council, Washington, DC.

Bailey, S. F. (1996). "Basic principles and load models for the structural safety evaluation of existing road bridges." Doctoral thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

Bastidas-Arteaga, E., Schoefs, F., Chateauneuf, A., Sánchez-Silva, M., and Capra, B. (2010). "Probabilistic evaluation of the sustainability of maintenance strategies for RC structures exposed to chloride ingress." *Int. J. Eng. Uncertainty: Hazards, Assess. Mitigation*, 2(1–2), 61–74.

Canadian Standards Association (CSA). (2007). “Canadian highway bridge design code.” *Calibration Rep. CAN/CSA-S6-06, CSA*, Toronto.
Cheung, M. S., and Li, W. C. (2001). “Serviceability reliability of corroded steel bridges.” *Can. J. Civ. Eng.*, 28(3), 419–424.
Czarnecki, A. A., and Nowak, A. S. (2008). “Time-variant reliability profiles for steel girder bridges.” *Struct. Safety*, 30(1), 49–64.
Damgaard, N., Walbridge, S., Hansson, C., and Yeung, J. (2010). “Corrosion protection and assessment of weathering steel highway structures.” *J. Constr. Steel Res.*, 66(10), 1174–1185.
Elbehairy, H. (2007). “Bridge management system with integrated life cycle cost optimization.” Ph.D. thesis, Univ. of Waterloo, Waterloo, Cananda.
Fernando, D., Adey, B. T., and Walbridge, S. (2011). “A methodology for the prediction of structure level costs based on element condition states.” *Struct. Infrastruct. Eng.*, 1–14.
Gervásio, H., and Simões da Silva, L. (2008). “Comparative life-cycle analysis of steel-concrete composite bridges.” *Struct. Infrastruct. Eng.*, 4(4), 251–269.
Hauf, G., Maier, P., and Kuhlmann, U. (2010). “Sustainable design for steel-concrete bridges.” *Proc., 5th Int. Conf. on Bridge Maintenance, Safety and Management*, R. Sause, D. Frangopol, and C. S. Kusko, eds., CRC, London.
Herrmann, T., Adey, B. T., Lüking, J., Schindele, N., and Hajdin, R. (2008). *Total benefit–benefit-cost ratio of standard interventions for road maintenance*, Swiss Federal Roads Authority, Bern, Switzerland (in German).
Imhof, D., Bailey, S. F., and Hirt, M. A. (2001). “Modèle de charge (trafic 40 t) pour l’évaluation des ponts-routes existants à deux voies avec trafic bidirectionnel.” *Rep. No. 444*, Steel Structures Laboratory (ICOM), École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.
Jiang, Y., and Sinha, K. C. (1989). “Bridge service life prediction model using the Markov chain.” *Transportation Reseacrh Record 1223*, Transportation Research Board, Washington, DC, 24–30.
Kayser, J. R., and Nowak, A. S. (1989). “Reliability of corroded steel girder bridges.” *Struct. Safety*, 6(1), 53–63.
Kunz, P., and Hirt, M. A. (1991). “Grundlagen und annahmen für den nachweis der ermüdungsfestigkeit in den tragwerksnormen des SIA.” *Document D076*, Swiss Society of Engineers and Architects, Zurich, Switzerland.
Kuroda, S., Kawakita, J., and Takemoto, M. (2006). “An 18-year exposure test of thermal-sprayed Zn, Al, and Zn-Al coatings in marine environment.” *Corrosion*, 62(7), 635–647.
Lai, D., Coomarasamy, A., and Ramamurthy, S. (2010). “Durability issues of weathering steel bridges in Ontario and development of new chemical compositions.” *Proc., 8th Int. Conf. on Short and Medium Span Bridges*, Canadian Society of Civil Engineering (CSCE), Montreal.
Land Transport New Zealand (LTNZ). (2006). *Economic evaluation manual*, LTNZ, Wellington, New Zealand.
Lebet, J.-P., and Hirt, M. A. (2009). *Traite de génie civil*, Vol. 12, Polytechniques et Universitaires Romandes, Lausanne, Switzerland.
Lee, K.-M., Cho, H.-N., and Cha, C.-J. (2006). “Life-cycle cost-effective optimum design of steel bridges considering environmental stressors.” *Eng. Struct.*, 28(9), 1252–1265.
Melcher, J., Kala, Z., Holický, M., Fajkus, M., and Rozlívka, L. (2004). “Design characteristics of structural steels based on statistical analysis of metallurgical products.” *J. Constr. Steel Res.*, 60(3-5), 795–808.
Melchers, R. E. (1999). “Corrosion uncertainty modeling for steel structures.” *J. Constr. Steel Res.*, 52(1), 3–19.
Nowak, A. S. (1993). “Live load model for highway bridges.” *Struct. Safety*, 13(1–2), 53–66.
Pakrashi, V., Kelly, J., and Ghosh, B. (2011). “Sustainable prioritisation of bridge rehabilitation comparing road user cost.” *Proc., Transportation Research Board Annual Meeting*, Transportation Research Board, Washington, DC.
Prager, M. H., and Shertzer, K. W. (2006). “Remembering the future: A commentary on ‘Intergenerational discounting: A new intuitive approach’.” *Ecologic. Econ.*, 60(1), 24–26.
Roelfstra, G., Hajdin, R., Adey, B. T., and Bruhwiler, E. (2004). “Condition evolution in bridge management systems and corrosion-induced deterioration.” *J. Bridge Eng.*, 9(3), 268–277.
Scherer, W. T., and Glagola, D. M. (1994). “Markovian models for bridge maintenance management.” *J. Transp. Eng.*, 120(1), 37–51.
Sheils, E., O’Connor, A., Breysse, D., Schoefs, F., and Yotte, S. (2010). “Development of a two-stage inspection process for the assessment of deteriorating bridge structures.” *Reliab. Eng. Syst. Saf.*, 95(3), 182–194.
Straub, D., and Faber, M. H. (2007). “Temporal variability in corrosion modeling and reliability updating.” *J. Offshore Mech. Arct. Eng.*, 129(4), 265–272.
Sumaila, U. R., and Walters, C. (2005). “Intergenerational discounting: A new intuitive approach.” *Ecologic. Econ.*, 52(2), 135–142.
Swiss Society of Engineers and Architects (SIA). (2003a). “Actions on structures.” *SIA 261*, SIA, Zurich, Switzerland.
Swiss Society of Engineers and Architects (SIA). (2003b). “Steel Construction.” *SIA 263*, SIA, Zurich, Switzerland.
Watanada, T., Paterson, W. D. O., Bhandari, A., Harral, C., Dhareshwar, A. M., and Tsunokawa, K. (1987). *The highway design and maintenance standards model*, Johns Hopkins University Press, Baltimore.

J. Bridge Eng. 2013.18:318-327.