Life-Cycle Cost Evaluation of Conventional and Corrosion-Resistant Steel for Bridges

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Abstract: Steel bridges that are under severe chloride exposure due to deicing salts or marine environmental effects require frequent maintenance and repair activities to extend their service life and maintain an adequate performance level. In addition to the direct maintenance cost, these maintenance actions may lead to indirect costs associated with traffic delays and environmental effects that can significantly increase the life-cycle cost of the bridge under consideration. The use of more sustainable materials, such as maintenance-free steel, may increase the initial cost of the structure; however, the life-cycle cost, including the maintenance actions during the service life and their associated indirect effects, can be significantly reduced. This paper presents the computational approach and results of an analytical investigation to quantify the life-cycle cost of a steel bridge constructed using conventional painted carbon steel and to compare this cost to that of the same bridge constructed using maintenance-free steel. Indirect environmental, social, and economic impacts of maintenance actions are computed to quantify the sustainability metrics associated with steel bridges during their life cycle. The approach is illustrated using an existing bridge located in Pennsylvania. DOI: 10.1061/(ASCE)BE.1943-5592.0000647. © 2014 American Society of Civil Engineers.

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Introduction

Bridges represent a critical component of the United States’ transportation infrastructure system. They require routine inspections to monitor their performance and to ensure their safety for public use. Steel bridges represent more than 30% of the total number of highway bridges in the United States [Federal Highway Administration (FHWA) 2012]. These bridges, if placed in an environment that is highly corrosive due to deicing salts or marine exposure, may require frequent maintenance and repair actions during their service life. Bridge maintenance activities can cause delays on the transportation network, which, in turn, will lead to other indirect effects in addition to the direct cost of maintenance. These indirect effects include social, economic, and environmental impacts that are directly connected to the sustainability measures of the bridge and the bridge network to which the bridge belongs.

Several steel types offering better corrosion resistance have been introduced by steel manufacturers to reduce the need for maintenance in corrosive environments. Examples are the weathering steel and the corrosion-resistant steel codified as ASTM A1010 (ASTM 2013). Although weathering steel provides maintenance-free operation in low-chloride environments, it is unsuitable for bridges under heavy chloride exposure. In such cases, coated carbon steel is used, and multiple repainting maintenance actions are performed during the service life of the bridge to ensure its acceptable performance. The ASTM A1010 steel, as a maintenance-free alternative, is superior in such applications; however, it has a considerably higher initial cost when compared with the painted carbon steel. Therefore, there exists a need to quantify the life-cycle cost of both alternatives such that bridge managers can rationally select the appropriate material that suits their needs.

A recent study by Okasha et al. (2012) computed the life-cycle cost of a steel bridge girder constructed using conventional painted steel and compared it to that of the same girder constructed using the ASTM A1010 steel. The life-cycle cost included the initial cost of materials as well as the direct cost of repainting actions. However, other indirect user and environmental costs of life-cycle maintenance actions were not included in that study. The aim of this paper is to evaluate the life-cycle cost of a representative steel bridge constructed using painted conventional carbon steel and compare it to that of the same bridge constructed using the ASTM A1010 corrosion-resistant steel while considering different direct and indirect effects of life-cycle maintenance actions.

Life-Cycle Cost Analysis

The effect of bridge maintenance on life-cycle cost and cost-oriented bridge maintenance planning was addressed in several studies, including Frangopol (1999), Estes and Frangopol (2001), Kong and Frangopol (2003), and Neves et al. (2006a, b). In this paper, the life-cycle cost of the bridge under investigation is considered to be composed of the initial cost of materials and fabrication in addition to the direct and indirect costs of life-cycle maintenance actions. The initial cost of conventional carbon steel bridges consists of the material, fabrication, initial painting, shop inspection, and transportation costs. Actions performed to maintain/repair corroded bridge elements include spot repair, zone painting, spot repair and overcoat, and complete painting of the bridge; the choice of the repair type depends on several factors, such as the degree of corrosion, budgetary limits, other ongoing maintenance tasks, and appearance to the public [Minnesota DOT (MNDOT) 2014]. Because complete painting will
have the highest impact on the total life-cycle cost of a bridge, it is used for the life-cycle cost evaluation in this paper.

A model of a real bridge located in Pennsylvania is used to illustrate the life-cycle cost computational procedure. The bridge, which carries the State Route (SR) 987 (PA 987) over the SR 22 (U.S. 22) was built in 1973 and has a deck area of 3,047.22 m² (32,800 ft²) with an estimated weight of 498 t. In 2013, after 40 years of service life, a complete bridge repainting maintenance was performed on the bridge. To compute the initial cost of the model bridge constructed using both types of steel, the purchase price of carbon steel is considered deterministically to be $975/t, whereas that of the ASTM A1010 steel is considered to be $2,265/t (Okasha et al. 2012). Other initial cost items, including the cost of fabrication, the cost of initial painting, the cost of shop inspection, and transportation total cost, are assumed, for carbon steel, to be $2,400/t. For the ASTM A1010 steel, the bridge does not require initial painting, the cost is reduced by 5%, yielding $2,280/t (Okasha et al. 2012).

For conventional carbon steel, maintenance actions are considered to have direct and indirect cost components. The direct component $C_R$ represents the cost of removing the old paint, repairing corroded areas, and applying new paint. Additionally, this cost covers the traffic control expenses during the maintenance period. The cost of repainting maintenance was given by the Pennsylvania DOT (PENNDOT) as a range from $215.28/m² ($20/ft²) to $376.74/m² ($35/ft²) of the bridge deck area (PENNDOT, personal communication, 2013). This cost depends on the location of the bridge, the bridge type, and the capacity of the road below the bridge, among other factors. To properly consider the variability in this cost, the direct maintenance cost is considered to be a random variable following a triangular distribution with a lower limit of $215.28/m² ($20/ft²), an upper limit of $376.74/m² ($35/ft²), and a most probable value of $322.92/m² ($30/ft²) [i.e., $\text{Tri}(215.28, 322.92, 376.74)]$.

The indirect cost of maintenance can also affect the life-cycle cost and sustainability considerations of the bridge. Because more sustainable infrastructure systems are desired, different social, environmental, and economic sustainability aspects must be considered to evaluate various designs and material alternatives. Social and environmental aspects can be rationally integrated into the life-cycle analysis by evaluating their monetary value (Bocchini et al. 2014; Dong et al. 2013; Adey et al. 2014). These costs arise because of the delays associated with maintenance actions and their social and environmental impacts.

In the case of repainting steel girder bridges and to access the steel beams, maintenance activities are implemented on the underside of the bridge. These require traffic control procedures for the road under the bridge. Depending on many factors, such as the average daily traffic (ADT), road conditions, and the number of lanes, different traffic control procedures, ranging from only reducing the speed limit to completely closing the road and directing the traffic through a detour, may be adopted. For the bridge under consideration, it is assumed that the traffic control procedures are performed by reducing the speed limit within an effective distance. Therefore, traffic delays may occur, along with their associated social, environmental, and economic dimensions. As the traffic speed is reduced on the road below the bridge, an increase in the travel time will occur, leading to time losses, which can be expressed, based on Shiraki et al. (2007), as

$$TL = d \cdot ADT \cdot \left( l \cdot \left( \frac{1}{S_D} - \frac{1}{S_R} \right) \right)$$

(1)

where ADT is considered as 40,000 vehicles/day; $d =$ duration of maintenance, assumed to be 15 days; $l =$ length of the traffic control region, considered to be 1.609 km (1 mi); $S_R =$ unrestricted traffic speed, considered to be 88.51 km/h (55 mi/h); and $S_D =$ restricted traffic speed, which is assumed as 32.19 km/h (20 mi/h).

The cost associated with the time loss $C_{TL}$ for users and goods is (Stein et al. 1999)

$$C_{TL} = \left[ c_o \cdot (1 - T) + (c_i \cdot O_i + c_k)T \right] \cdot TL \cdot 52$$

(2)

where $c_o =$ average wage per hour [U.S. dollars (USD)/h], considered as a random variable following a lognormal distribution, with a mean of 23.36 USD/h and a coefficient of variation of 0.28 [i.e., ln(23.36, 0.28)]; $c_i =$ average compensation per hour for truck drivers (USD/h), following a lognormal distribution ln(29.28, 0.31); $c_k =$ time value of the goods transported in a cargo (USD/h), considered as ln(3.81, 0.2); $O_i$ and $O_r =$ average occupancies for cars and trucks, respectively, assumed to follow the respective distributions ln(1.5, 0.15) and ln(1.05, 0.15); and $T =$ ratio of the average daily truck traffic to the average daily traffic, considered as ln(0.12, 0.2). The parameters of the random variables in Eq. (2) are assumed based on Decò and Frangopol (2011).

The environmental impacts of traffic delays due to maintenance include an increase in air pollutants and emissions, energy consumption, and potential for global warming (Dong et al. 2013, 2014). The increase in carbon dioxide emissions is used herein as the environmental impact of maintenance. Based on Kendall et al. (2008), this environmental impact is

$$E = ADT \cdot l \cdot d \cdot \left[ E_{d,c} \cdot (1 - T) + E_{d,t} \cdot T \right] \frac{E_{So} - E_{Si}}{E_{So}} \cdot 52$$

(3)

where $E_{d,c}$ and $E_{d,t} =$ environmental metric per unit distance for cars and trucks, respectively, quantified as the carbon dioxide emissions per kilometer (i.e., carbon dioxide kg/km). The environmental metrics $E_{d,c}$ and $E_{d,t}$ are assumed to follow the lognormal distributions ln(0.22, 0.2) and ln(0.56, 0.2), respectively (Gallivan et al. 2010; Dong et al. 2013). $E_{So}$ and $E_{Si}$ represent the carbon dioxide emissions per kilometer at speeds $S_D$ and $S_R$, respectively, and are considered herein as 0.416 and 0.298 kg/km, respectively (Gallivan et al. 2010). The costs of carbon dioxide emission can be transferred into monetary value by

$$C_E = E \cdot c_{Env}$$

(4)

where $c_{Env} =$ cost value of the environmental metric (e.g., carbon dioxide USD/t). The cost value $c_{Env}$ of carbon dioxide emissions is assumed to follow the lognormal distribution ln(26, 2.93) (Kendall et al. 2008). Similarly, the cost of other pollutants due to maintenance, such as carbon monoxide, can be computed.

The total cost of a maintenance action $C$ can be found as the summation of the repainting cost, time loss cost, and environmental cost as

$$C = C_R + C_{TL} + C_E$$

(5)

The cost of maintenance is subjected to a discount rate of money at the application time $t$. The present cost of the $k$th maintenance action at time $t$ is

$$C_{PV,k} = \frac{C}{(1 + r)^t}$$

(6)

where $C_{PV,k} =$ present cost of the $k$th maintenance action performed at time $t$; $C =$ cost of the maintenance at the application time; and $r =$ discount rate of money. As can be seen from Eqs. (1)
and (3), the indirect maintenance cost depends, to a great extent, on the ADT. Because the ADT may be subjected to an annual increase rate, the maintenance cost will also be time dependent. Assuming a constant rate of increase, the ADT at time $t$ can be calculated as

$$\text{ADT}_t = \text{ADT}_0 (1 + \nu)^t$$

(7)

in which $\text{ADT}_0 = \text{ADT}$ at time $t$; and $\nu = \text{annual increase rate in the average daily traffic}$.

To evaluate the total cost of a single maintenance, a Monte Carlo simulation is performed with 100,000 samples. For the studied case, Fig. 1(a) shows the probability density function (PDF) of the total cost of a single maintenance, including direct and indirect components at time $t = 0, 20, 40, 60, 80,$ and $100$ years and considering the annual increase in ADT to be 0.5%. Fig. 1(b) shows the mean value and the SD of the time-variant total maintenance cost for $\nu = 0.5\%$ and an annual discount rate of money $r = 0.00$. Fig. 2(a) depicts the PDF of the maintenance costs at various times with $\nu = 1.0\%$ and $r = 0.00$, whereas Fig. 2(b) shows the mean and SD of the time-variant maintenance cost for the same values of $\nu$ and $r$. Fig. 3 presents the mean value of the time-variant total maintenance cost for $\nu = 0.5, 1.0,$ and $1.5\%$. As shown in Fig. 3, the present value of the maintenance cost is significantly affected by the increase rate of the average daily traffic. An increase in $\nu$ from 0.5 to $1.5\%$ will lead to a corresponding increase of 88% in the present value of a maintenance performed after 100 years. This also shows that the indirect maintenance cost cannot be neglected in the life-cycle cost evaluation.

The cost values presented in Figs. 1–3 illustrate only the total cost of one maintenance action performed at different times during the service life. However, depending on the environmental conditions at the bridge location, multiple maintenance actions may be needed throughout the service life of the structure to maintain an acceptable performance level. As previously indicated, the bridge under consideration was constructed in 1973, and the first complete painting

![Fig. 1. Present value of total cost of single repainting maintenance with $\nu = 0.5\%$ and $r = 0.00$: (a) PDF of cost at $t = 0, 20, 40, 60, 80,$ and $100$ years; (b) time-variant mean and SD of present value of maintenance cost](image1)

![Fig. 2. Present value of total cost of single repainting maintenance with $\nu = 1.0\%$ and $r = 0.00$: (a) PDF of cost at $t = 0, 20, 40, 60, 80,$ and $100$ years; (b) time-variant mean and SD of present value of maintenance cost](image2)
maintenance was performed after 40 years of service life. Personal communication with PENNDOT revealed that the time for the first complete maintenance can be up to 50 years later, whereas some other bridges may be required to be repainted after 30 years (PENNDOT, personal communication, 2013). Therefore, to compute the total life-cycle cost, the time for the first maintenance was assumed as a random variable following a triangular distribution Tri(30, 40, 50 years). However, the repainting maintenance may not be as effective as the initial painting for protecting the bridge from corrosion. This is mainly due to the effect of site conditions on the quality of the repainting. This quality is affected by multiple factors, such as the weather conditions, bridge location, and layout of the bridge. Thus, it is assumed that the time interval between subsequent maintenance actions follows a triangular distribution Tri(20, 25, 30 years).

To determine the total life-cycle cost of the bridge, a Monte Carlo simulation with 100,000 samples is also adopted. Fig. 4(a) shows the life-cycle cost profile for the carbon steel and the ASTM A1010 steel considering the discount rate of money \( r = 0.00 \). Similarly, Fig. 4(b) presents the life-cycle cost profiles considering \( r = 0.03 \). The results in Figs. 4(a and b) assume no annual increase in the ADT (i.e., \( v = 0.0\% \)).

Fig. 5(a) depicts the life-cycle cost profiles considering the discount rate of money to be a random variable following a uniform distribution with values ranging from 0.00 to 0.03 [i.e., U(0.00, 0.03)]. Finally, Fig. 5(b) shows the life-cycle cost of the bridge for the case of carbon steel and the ASTM A1010 steel considering the rate of increase in traffic \( v = 1.0\% \). As shown in Figs. 4 and 5, the life-cycle cost of the bridge constructed using the corrosion-resistant steel ASTM A1010 is constant throughout the service life of the bridge. Moreover, although the ASTM A1010 provides higher initial cost than the carbon steel, the life-cycle cost of the bridge constructed using carbon steel is significantly higher and can reach a value up to two times that of the same bridge constructed using the ASTM A1010 steel after 100 years of service life. It should also be noted that including other frequent corrosion-related maintenance actions, such as zone panting, will further increase the life-cycle cost of the bridge constructed using conventional carbon steel.

### Conclusions

This paper presents the computational results of a probabilistic study to evaluate the life-cycle cost of bridges constructed using conventional painted carbon steel and to compare it to that of the same bridge constructed using the corrosion-resistant ASTM A1010 steel. The life-cycle cost consisted of the initial cost and the cost of repainting maintenance performed during the service life. The initial cost includes the cost of materials, fabrication, initial painting, shop inspection, and transportation. The cost of maintenance covers the repainting and traffic control costs in addition to the indirect costs arising from the traffic delays and their social and environmental impacts.

The cost of a single maintenance action was computed for various values of the average-daily-traffic increase rate, and it was shown that this rate has a significant effect on the indirect cost of maintenance. Moreover, the total life-cycle cost of the bridge...
considering multiple maintenance actions during the service life was computed for the conventional steel and the corrosion-resistant alternative. It was shown that, although the corrosion-resistant steel has a higher initial cost, its life-cycle cost is less than that of the conventional steel, even when using a discount rate of money of 0.03. Therefore, the ASTM A1010 steel represents a more-sustainable alternative to the conventional carbon steel for bridge construction in corrosive environments.

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