Life-Cycle Cost Assessment for Bridge Management: An Application to Nebraska Bridges

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ABSTRACT

Life-cycle cost analysis (LCCA) is a necessary component in bridge management systems for assessing investment decisions and identifying the most cost-effective improvement alternatives. The LCCA helps to identify the lowest cost alternative that accomplishes project objectives by providing critical information for the overall decision-making process. The main objective of this paper is to present LCCA performed for different deck overlay alternatives using the recently developed deterioration models and latest cost data for Nebraska bridges. Deterministic and probabilistic LCCA using RealCost software for deck overlay decisions are presented. Silica fume overlay, epoxy polymer overlay, and polyester overlay are compared against bare deck with respect to the net present value.

INTRODUCTION

According to the U.S. Department of Transportation (USDOT), life-cycle cost analysis (LCCA) is a scientific approach that provides comprehensive means to select among two or more project alternatives (USDOT 2002). LCCA is a necessary component in bridge management systems for assessing investment decisions and identifying the most cost-effective one. NCHRP project 12-43 “Bridge Life-Cycle Cost Analysis” resulted in standardized procedures for conducting life-cycle costing of bridges and guidelines for applying LCCA to the repair of existing bridges or the evaluation of new bridge alternatives (NCHRP 483, 2003). LCCA enables cost effectiveness comparison of competing design alternatives that provide benefits in terms of service life and cost. LCCA accounts for relevant costs to the sponsoring agency, owner, operator of the facility, and roadway user throughout the life of an alternative. This includes initial construction, future maintenance and rehabilitation, and user costs. The objective of this paper is to present LCCA performed for different deck overlay alternatives using the recently developed deterioration models and latest cost data for Nebraska bridges. The main source for obtaining maintenance costs data is recent bridge contracts. Nebraska Department of Roads (NDOR) has developed spreadsheets for recording the different types of maintenance work performed on bridge deck, which were used in this study.

LCCA can be conducted using either deterministic or probabilistic approaches. Deterministic LCCA is the traditional methodology in which the user assigns each input variable (e.g. service life, analysis period, discount rate, timing and cost of maintenance activities) a fixed value usually based on historical data and user judgment. Probabilistic methods allow decision makers to evaluate the risk of an investment utilizing uncertain input variables, assumptions, or estimates (FHWA 1998). Probabilistic LCCA tools conduct a simulation (typically using Monte Carlo simulation) to sample the input and generate a probability distribution function (PDF) for the different economic indicators considered in the analysis.

DECK OVERLAY DECISION USING DETERMINISTIC MODELS

Selecting the most cost-effective deck overlay system is a good example for applying LCCA. Three types of deck overlay are considered: a) Silica Fume Overlay (SFO); b) Epoxy Polymer Overlay (EPO); and c) Polyester Overlay (PO). The three alternatives are compared with the bare deck option. Table 1 lists the basic information of the bridge project considered in this investigation. The following subsections present the LCCA conducted for each alternative and the comparison to determine the one with lowest life cycle cost. Analysis period equal to 60 years is considered to include the major activities for all alternatives. Also, a discount rate of 3% is used based on the Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs (Circular A094).

Table 1. Project information

Project number	77-2(1060)	**Structure length**	257 ft.
Control number	12893	**Roadway width**	47 ft.
Bridge ID	S077 06205L	**Number of spans**	3
Location	Lincoln W bypass	**Functional classification**	Urban
Year built	1989	**Deck structure type**	Concrete
Year reconstruction	-	**Type of wearing surface**	Concrete
Inspection date	22-FEB-2011	**Average daily traffic (ADT)**	14910
Design type	Steel continuous	**Average daily truck traffic (ADTT)**	1491
Design type	Steel continuous	**Deck condition rating**	8
Construction type	Stringer/Multi beam or girder	**Area of bridge deck**	12,079 SF

Silica Fume Overlay (SFO). Three alternatives are investigated: 1) bare deck; 2) SFO applied to bare deck at condition 5; and 3) SFO applied to bare deck at condition 6. Figure 1 shows the deterioration curves of bare decks in state bridges with average daily traffic (ADT) less than 1000, between 1000 and 5000, and more than 5000 (Hatami and Morcous, 2011). The example bridge has ADT of 14,910, which is presented by the green curve (ADT > 5000). Because bridge decks are usually replaced at condition 4, the service life of bare concrete deck is considered to be about 40 years. Age of deck at condition 5 and 6 is about 38 and 30 years, respectively. SFO have been used as a wearing surface on bridge decks in Nebraska since the early 1980s. This overlay is used on bridge deck which has condition rating 5 or 6. According to 2010 data, there are only 70 state bridges with SFO on their decks. Figure 2 presents the histogram of bridge decks which have been overlaid by silica fume. This figure clearly shows that most of the state bridges overlaid by silica fume have duration to overlay between 25 to 30 years. A service life of 25 is used to extend the deck life when applied at conditions 5 or 6.

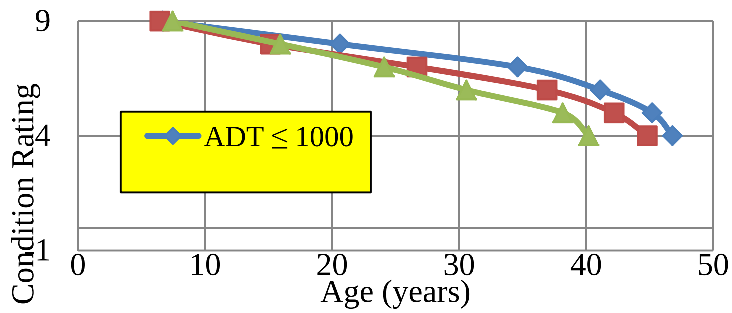

Figure 1. Original deck deterioration curve in state bridges

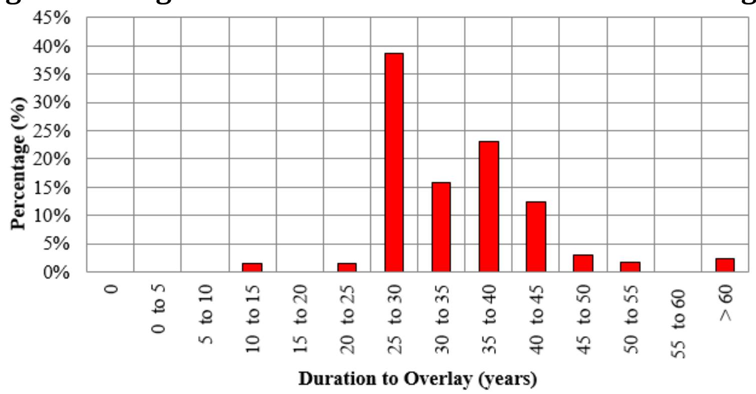

Figure 2. Duration to overlay histogram of SFO – year 2010

To compare SFO versus bare deck, the following sequence of activities is considered. For alternative 1, no action until the deck is at condition rating 4, then, deck is replaced. For alternative 2, no action until the deck is at condition rating 5, then, SFO is applied. For alternative 3, no action until the deck is at condition rating 6, then, SFO is applied. It is assumed that deck condition will remain the same after each application of SFO. Based on collected cost data, cost of alternative 1 (deck replacement) is 50$/SF and area of bridge deck is 12,079. Therefore, the cost of deck replacement will be $603,950. Cost of deck repair and applying silica fume overlay on deck at condition 5 and 6 are 30$/SF and 25.3$/SF, respectively. Therefore total cost of applying SFO on bridge deck at condition 5 will be $362,370 and at condition 6 will be $305,599. User costs are eliminated from the analysis of all alternatives due to the difficulty of getting reliable estimate for user cost in each alternative. In order to compare different alternatives, RealCost program has been used. Table 2 lists the results of net present

Table 2. LCCA results for SFO

Agency Cost ($1,000)	Alternative 1: Bare Deck	Alternative 2: SFO at Condition 5	Alternative 3: SFO at Condition 6
Undiscounted Sum	*$326.46*	*$333.38*	*$277.82*
NPV	$138.05	$116.47	$111.12
EUAC	$4.99	$4.21	$4.02

value (NPV) and equivalent uniform annual cost (EUAC) for alternatives 1, 2 and 3. The results show that alternative 3 (SFO at condition 6) has a lowest net present value and is the best alternative.

Epoxy Polymer Overlay (EPO). Epoxy Polymer Overlays (EPOs) have been used to seal bridge decks in the United States for over 40 years. EPO consists of an epoxy polymer binder and aggregates with a thickness not exceeding 10 mm (3/8 in.). An EPO overlay is more expensive than a traditional overlay; however it has the following advantages: lightweight, fast curing, shallow depth which eliminates the need for raising the approach slabs and transition from overlaid lane to non-overlaid lane during construction, waterproof, long-lasting, excellent skid resistance, and allows better appraisal of deck condition under the overlay than thicker concrete or asphalt overlays. EPO could provide a service life of 20 to 25 years when properly installed on sound decks (NCHRP report 423, 2011). Engineering expertise at NDOR recommended an average service life about 10 years for EPO as there are evidences of failure in early ages. In order to compare the results of bare deck, SFO, and EPO, the following alternatives are considered:

- Alternative 1: Bare deck;
- Alternative 2: SFO applied on deck after 25 years;
- Alternative 3: EPO applied on deck after 15 years and repeat every 10 years.

There is no action in alternative 1 (bare deck) until 40 years, then, deck is replaced, which extends its service life for additional 37 years. For alternative 2, there is no action until 25 years, then, SFO is applied to extend the service life of the deck for 25 years and after that, the deck is replaced. For alternative 3, there is no action until 15 years, then, EPO is applied every 10 years until the end of the analysis period. Initial cost of 30$/SF is used for all alternatives, which results in a total construction cost of a new bare deck of $362,370. This initial cost extends structural service life of alternatives 2 and 3 for 70 years. However, because of deck replacement in alternative 1, structural service life extends for 40 years. The cost of deck replacement in alternative 1 costs $603,950. Cost of deck repair and applying SFO in alternative 2 is $362,370. Cost of EPO is equal to 6$/SF for each application and after 2 applications cost increases by 3$/SF for overlay removal. Table 3 lists the results of NPV and EUAC for alternatives 1 to 3. The results clearly show that the life cycle cost of bare deck and EPO are almost same and are lower than SFO alternative.

Table 3. LCCA results for bare deck, SFO and EPO

Agency Cost ($1,000)	Alternative 1: Bare Deck	Alternative 2: SFO	Alternative 3: EPO@10 Years
Undiscounted Sum	*$707.48*	*$760.98*	*$691.09*
Present Value	$503.58	$550.82	$504.68
EUAC	$18.20	$19.90	$18.24

To determine the service life of EPO required to be cost effective when different structural life of the deck is used, sensitivity analysis was conducted. EPO with structural life of 10, 15, and 20 years and deck structural life of 60, 65, 70, 75, 80, and 85 years were considered. Figure 3 shows the results of the analysis and indicates that the minimum required service life of deck to delay a more expensive action to be cost effective is about 73 years for EPO with service life of 10 years.

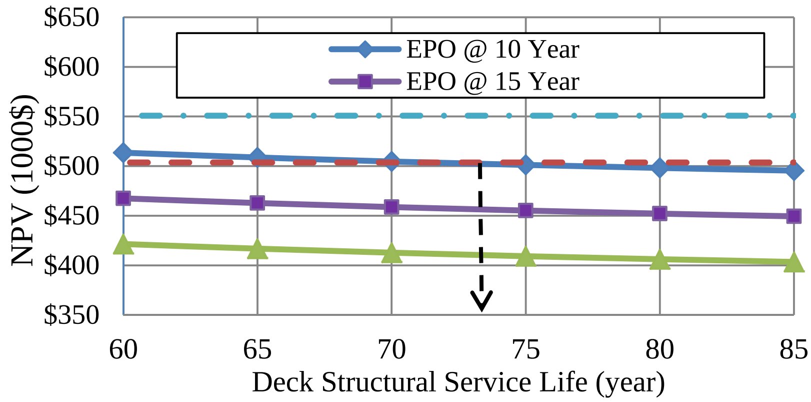

Figure 3. Minimum required deck service life for EPO with variable service life

Polyester Overlay. Polyester concrete is a composite material consisting of a polyester binder and aggregate. In other words, polyester concrete is similar to Portland cement concrete, with the cement binder being replaced by polyester resin. Polyester concrete is rapid setting, and bridge decks receiving a polyester concrete overlay (typically ½ to 2 inches in depth) can typically be opened to traffic two to four hours after placement. Polyester concrete has higher compressive and flexural strengths (8,000 psi and 2,200 psi, respectively), higher abrasion and chemical resistance, and lower permeability to chloride ions than Portland cement concrete. Polyester Overlays (POs) constructed in accordance with AASHTO Specifications should have a service life of 25 years. Engineering expertise at NDOR conservatively suggested an average service life of 16 years for PO when applied at deck condition 7. Figure 4 shows the NPV versus service life for EPO and PO. This figure clearly shows that PO has a better performance than EPO. For example, when NPV equals to $150,000, EPO has a service life of 10 years, however, PO has a service life of 15 years. Figure 5 also shows that the minimum service life of PO to delay a more expensive action is between 17 to 22 years.

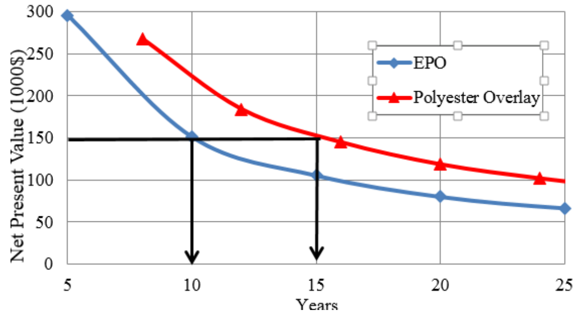

Figure 4. Comparison of service life and net present value for PO and EPO

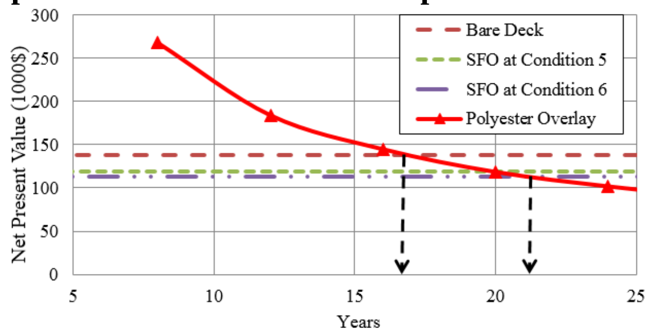

Figure 5. Minimum required service life of PO

DECK OVERLAY DECISION USING PROBABILISTIC MODELS

In the probabilistic analysis, probability distributions are assigned to uncertain input parameters. Random numbers are generated to perform simulation runs to compare multiple alternatives. For instance, discount rate has uniform distribution with minimum value equal to 3% and maximum value equal to 8% based on the discount rate history (NCHRP report 483, 2003). Based on NDOR cost data, normal probability distribution function with 10% variation of mean value is considered in analysis. Probability distribution function for bare deck is considered as normal distribution (Hatami and Morcous, 2011). Table 4 lists mean value and standard deviation for bare deck at different condition rating. Because there is limited data for SFO, EPO and PO performance, triangular probability distribution functions are considered as shown in Table 5. Figure 6 shows the distribution of agency cost for the following alternatives: 1) bare deck; 2) SFO on bare deck at condition 5; 3) SFO on bare deck at condition 6; 4) EPO on bare deck at condition 7; and 5) PO on bare deck at condition 7.

Table 6 shows LCCA results for alternatives 1 to 5 using the deterministic analysis, which shows that EPO applied to bare deck at condition 7 has the lowest LCC.

Table 4. Mean and standard deviation for bare deck at different condition ratings

Bare Deck	State Bridges – From 1998 to 2010					
Condition Rating	9	8	7	6	5	4
Number of Data	2530	3191	988	1096	896	280
Average Age	6.7	16.6	34.0	37.5	44.0	46.4
Std. Deviation	4.6	7.6	9.5	9.9	10.3	10.5
Coeff. Of Variation	67.7%	45.9%	28.1%	26.5%	23.5%	22.5%

Table 5, Probability distribution functions for service life of SFO, EPO and PO

Type of Overlay	Triangular Probability Distribution of Service Life (years)		
	Minimum	Most Likely	Maximum
Silica Fume Overlay (SFO)	20	25	30
Epoxy Coated Overlay	10	15	20
Polyester Overlay (PO)	15	20	25

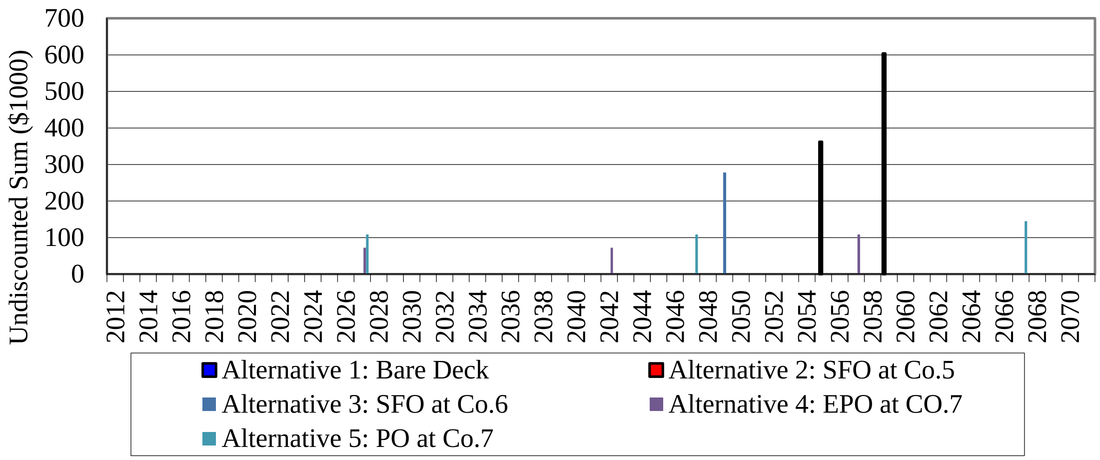

Figure 6. Distribution of agency cost for alternatives 1 to 5

Table 6. LCCA results for deck overlay alternatives

Agency Cost ($1,000)	Alternative 1: Bare Deck	Alternative 2: SFO at Co.5	Alternative 3: SFO at Co.6	Alternative 4: EPO at CO.7	Alternative 5: PO at Co.7
Undiscounted Sum	$326.46	$333.38	$277.82	$253.66	$253.66
NPV	$138.05	$116.47	$111.12	$105.12	$118.48
EUAC	$4.99	$4.21	$4.02	$3.80	$4.28

The agency costs include the initial construction cost, cost for rehabilitation, and cost for maintenance activities carried out during the life time of the deck. The cumulative distribution of agency cost shown in Figure 10 are obtained from Monte Carlo simulation in RealCost. The analysis period over which the life cycle costs are calculated for the design alternatives is 60 years and with discount rate of 3%. The bare deck (alternative 1) is the most expensive alternative and EPO on bare deck at condition 7 (alternative 4) is the most economical alternative. The results show a 90% probability (cumulative) for the EPO on bare deck at condition 7 to yield the lowest agency cost.

Another way to read Figure 7 is that, for a net present value of $130,000 there is a 40% probability that the bare deck can be constructed at that cost. There is a 90% probability that the EPO on bare deck at condition 7 can be constructed for the same cost. The probabilities for the SFO on bare deck at condition 6 and PO on bare deck at condition 7 for a net present value of $130,000 are 77% and 70%, respectively. Table 7 shows the mean, standard deviation, minimum and maximum values of the agency costs. Figure 8 plots the probability distribution of the NPV for each of the five investigated alternatives. It indicates that EPO on bare deck at condition 7 (alternative 4) has the highest probability of having less NPV than the other deck overlay alternatives followed by SFO on bare deck at condition 6 (alternative 3).

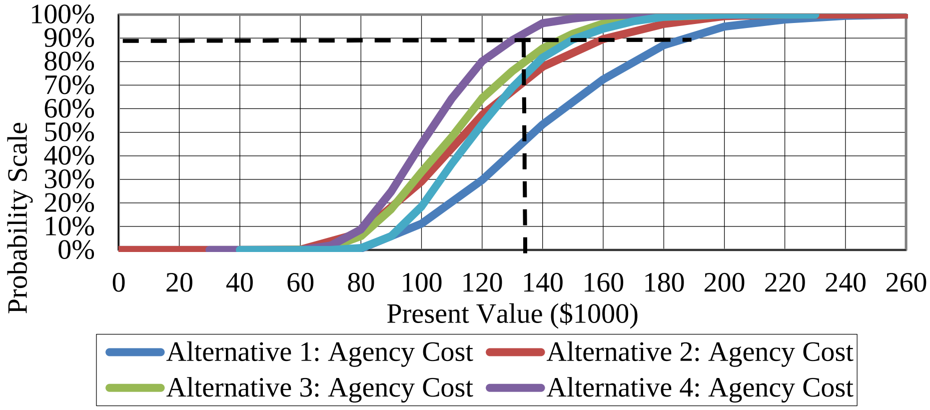

Figure 7. Cumulative probability distributions of deck overlay alternatives

Table 7. Mean distributions of costs for deck overlays (simulation values)

NPV $1,000	Alternative 1: Bare Deck	Alternative 2: SFO at Co.5	Alternative 3: SFO at Co.6	Alternative 4: EPO at CO.7	Alternative 5: PO at Co.7
Mean	$140.68	$118.63	$113.52	$104.12	$120.40
Std. Deviation	$33.52	$29.76	$24.58	$18.93	$22.35
Minimum	$67.71	$57.35	$59.45	$63.28	$76.45
Maximum	$257.88	$214.94	$196.88	$163.13	$194.84

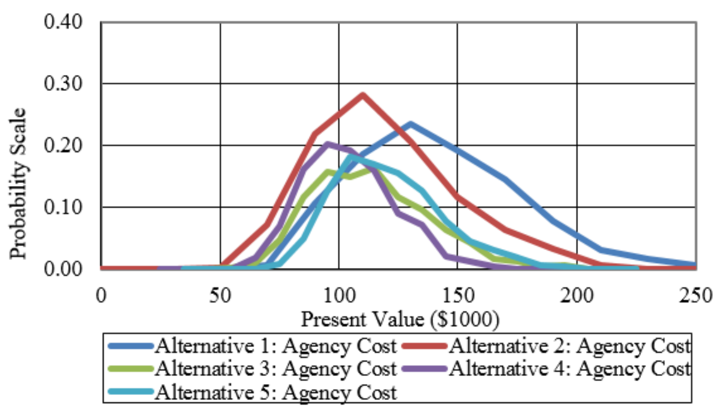

Figure 8. Agency cost distributions of deck overlay alternatives

CONCLUSIONS

Deterministic and probabilistic LCCA using the RealCost software was conducted for bare deck, SFO on bare deck at condition 5, SFO on bare deck at condition 6, EPO and PO on bare deck at condition 7. The main conclusions are:

1) SFO on bare deck at condition 6 has a lower net present value than bare deck and SFO on bare at condition 5.
2) EPO on bare deck at condition 7 has a lower net present value than bare deck, SFO on bare deck at condition 5 and 6, and PO on bare deck at condition 7.
3) Minimum service life of EPO and PO required to delay a more expensive

action are from 11 to 14 and 17 to 22 years, respectively depending on the action type.

4) Probabilistic analysis results are consistent with those of deterministic analysis.

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