ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

ABC-UTC GUIDE FOR:

LIFE CYCLE COST ANALYSIS OF ULTRA HIGH-PERFORMANCE CONCRETE (UHPC) IN RETROFITTING TECHNIQUES FOR ABC PROJECTS

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ABSTRACT

Bridge components are affected by loads and environmental stressors, deteriorating faster or even collapse without effective maintenance and rehabilitation strategies. Furthermore, wet-dry cycling and higher concentrations of chlorides in coastal areas accelerates the deterioration process of bridges while increasing the frequency of maintenance and cost of the repairs. To address this problem, innovative materials like Ultra High-Performance Concrete (UHPC) should be considered in the development and implementation of maintenance and rehabilitation strategies. Performance requirements, life-expectancy, and life-cycle cost are considered in the selection of the repair material. Life-Cycle Cost Analysis (LCCA) is part of a step-by-step framework identify cost-effective retrofitting techniques to preserve bridges in a "State of Good repair". Three case studies demonstrate the applicability of the LCCA methodology to compare conventional and UHPC retrofitting techniques for bridge repair. It was found from the results of the case studies that the use of UHPC in bridge retrofitting techniques could result in a significant reduction in the total life cycle cost.

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1. INTRODUCTION

Accelerated Bridge Construction (ABC) projects combine construction methods and innovative systems to reduce the time to build new bridges and to rehabilitate old bridge components. Planning, design, construction, maintenance, rehabilitation, reconstruction, and/or recycling activities affect the performance of ABC projects in their service life. Therefore, it is crucial to foresee the challenges and costs associated with bridge retrofitting techniques.

The main objective of this ABC-UTC guide is to assist practitioners to adopt long-term cost-effective bridge maintenance strategies. This guide is a product of the research project "Life Cycle Cost Analysis of Ultra High-Performance Concrete (UHPC) in Retrofitting Techniques for ABC Projects", and it complements the Final Report. This guide focusses on the Life-Cycle Cost Analysis (LCCA) methodology with the aim to support the maintenance and rehabilitation decision-making process at the network and project management level. Three case studies are provided to compare conventional and UHPC techniques demonstrating the applicability of the LCCA methodology.

1.1. BACKGROUND

Ultra-High-Performance Concrete (UHPC) is an innovative material with the potential to become a viable alternative for improving the sustainability of infrastructure components. UHPC is exceptional cementitious material durable against freeze-thaw attack and permeation of gases and liquids. It has a low water-to-cement ratio and a low maximum grain size diameter with the addition of pozzolanic filler materials like silica fume.

There is a need to recognize the potential benefits of UHPC technology and developing decision-making tools for determining when and how to use UHPC. Life-cycle cost analysis (LCCA) is one of the tools that can assist to compare treatment solutions for bridge maintenance strategies to preserve ABC projects in good condition. To determine the best cost-effective maintenance strategy, it is important to understand the deterioration characteristics of the bridge components. For reinforced concrete elements, the deterioration process can be modeled as a function of the corrosion affecting bridge elements. LCCA can quantify the total costs of alternative investment options using software tools with deterministic or probabilistic approaches.

The life cycle of Accelerated Bridge Construction (ABC) projects includes several phases: planning, design, construction, maintenance, rehabilitation, reconstruction, or recycling. Most of the research studies for ABC projects have been focused on the design and construction phases, although maintenance and rehabilitation play an important role to preserve a bridge in good condition. This research is conducted to develop a life-cycle cost performance-based methodology to incorporate Ultra High-Performance Concrete (UHPC) applications for retrofitting techniques in ABC projects.

Bridges located in coastal areas are expected to face the risks of sea level rise and flooding more frequently. Sea level rise and flooding will result in more stress to the bridge network; therefore, maintenance, repairs, and rehabilitation activities must be performed more often unless innovative long-lasting materials are used. Unfortunately, there are no standard life expectancy models for new concrete materials like UHPC. This is because the deterioration pattern is very distinctive for each bridge element, and the aging process depends on many variables. However, to quantify the potential benefits of these innovative concrete materials, a deterioration model is required for LCCA to compare the performance of different concrete materials. Furthermore, there is no open database available with construction costs including UHPC. Based on the comprehensive literature review, it is found that a UHPC concrete mix design is developed for a specific project. As a result, there is not standard mix design for UHPC that could be used as a reference for LCCA.

1.2. SCOPE OF THE GUIDE

This ABC-UTC guide follows a practical approach to facilitate the decision-making process for identifying cost-effective bridge maintenance and rehabilitation strategies based on LCCA. This Section 1 provides a brief introduction, scope of the guide, and intendent users.

Section 2 of this guide describes the Life Cycle Cost Analysis (LCCA) methodology for UHPC retrofitting applications for ABC projects. The LCCA methodology allows compare maintenance and rehabilitation strategies with conventional concrete and UHPC. LCCA includes agency costs and user costs over the period of analysis.

Section 3 summarizes conclusions and recommendations.

Section 4 includes the list of references cited in the guide.

Section 5 provides a description of the educational material developed to support the implementation of the LCCA methodology.

Appendix A, Appendix B, and Appendix C describes three case studies of life cycle cost analysis which compares conventional concrete with UHPC retrofitting techniques.

1.3. INTENDED USERS

This guide presents useful information to highway officials, operations engineer, and researchers in related fields. Life-expectancy deterioration models can estimate the intended repair maintenance time for bridge elements. LCCA methodology is explained in detail, and case studies are included with numerical examples for practitioners to follow in new projects.

Products from this research aim to facilitate management decisions at the network and project level. It is expected that the use of new repair materials and timely maintenance strategies will increase the life expectancy of bridges using ABC systems. Findings from the development and application of UHPC performance models and LCCA have great potential for inclusion in bridge specifications. In addition, the implementation of UHPC in bridge projects should reduce the frequency of reactive maintenance as part of a proactive cost-effective strategy saving time and money.

2. LIFE CYCLE COST ANALYSIS METHODOLOGY

A Life Cycle Cost Analysis (LCCA) methodology to evaluate conventional concrete with UHPC applications for ABC projects is described in this guide. Retrofitting techniques are categorized into preventive maintenance and rehabilitation activities. FHWA guidelines are followed to quantify the life cycle costs including agency and user costs.

2.1. OVERVIEW OF LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis (LCCA) is an economical assessment of a project that considers all present and future costs required to provide the desired level of service. The purpose of LCCA is to identify the project alternative that meets the technical requirements at the lowest cost over the expected period of service. Initial construction costs, future maintenance costs, rehabilitation costs, and user costs over the life cycle of a project are considered in the analysis. The main parameters to establish in the LCCA are:

- Length of the analysis period
- Costs to be included in the analysis
- Salvage value
- Discount and inflation rates

Length of Analysis Period
The length of the analysis period must be carefully selected, and it is related to the project service life. An analysis period of twenty to fifty years is recommended at the network level. Longer periods of time increase the uncertainty of forecasting traffic, bridge performance, treatment costs, and other factors involved in the analysis.

Costs to be Included in the Analysis
All costs anticipated over the life of the bridge retrofitting technique including initial costs, maintenance and rehabilitation costs, salvage value, and user costs are considered in the LCCA. The costs used in the analysis should be current and accurate. Agency construction and maintenance costs are gathered with reasonable precision by transportation agencies, while user costs are more complex to determine.

Salvage Value
Salvage value represents the worth of the bridge at the end of the analysis period, and it is related to its condition. The salvage value decreases as the bridge condition deteriorates. The salvage value will be the value of the salvageable materials at the end of the analysis period, or the value of the bridge remaining life. Agencies estimate the remaining life using performance models to forecast the bridge condition. An approach to obtain the salvage value is to subtract the funds needed to restore the bridge condition to current standards from the replacement cost. Therefore, the salvage value can be estimated at any time of the bridge service life.

Discount and Inflation Rates
Discount rates are used to bring back costs incurred at different times of the analysis period to a base year. Costs and benefits are normally expressed in constant monetary terms, usually as today’s dollars at the base year of analysis. Discount rates are used to calculate the present value

of future life cycle costs. The effect of inflation must also be removed to compare alternatives on the same basis over time. In the LCCA, future costs and benefits are both affected by the same inflation; therefore, the effect of inflation could be ignored in the analysis if the purpose is to identify the best alternative.

A real discount rate can be estimated by removing the rate of inflation (as measured by a general price index such as the CPI) from a market (or nominal) interest rate for government borrowing. The selected market rate for government borrowing should be based on government bonds with maturities comparable in length to the analysis period used for the economic analysis. Real discount rates calculated in this manner have historically ranged from just below 0 percent to 5 percent (NCHRP 2003). These are the rates most often used by states for discounting highway investments. The U.S office of Management and Budget (OMB) currently requires U.S Federal agencies to use a 7 percent real discount rate to evaluate public investments and regulations.

The discount rate depends on the source of financing. If the project is funded by a local government, the municipal bond rate may be more applicable as a discount rate. If private investors undertake the project, corporate bond is a good indicator. In federal fund is associated with the project, the market rate for government borrowing which is based on analysis period may be used as mentioned earlier (Ozbay et al. 2003).

2.1.1. LCCA ECONOMIC EVALUATION

Discounted cash-flow methods including net present value, equivalent uniform annual cost, and internal rate of return are often used in the economic evaluation of the alternatives under consideration. A brief description of these methods follows.

Net Present Value (NPV)

The Net Present Value (NPV) is the sum in constant monetary terms of all present and future costs incurred in the analysis period. To calculate the NPV, future costs are converted to the present at the selected discount rate. The present cost of a future cost is obtained with the following formula:

$$\$P = \$F\ (1+r)^{-n} \qquad \text{………………} (1)$$

Where:
$P = Present Cost
$F = Future Cost
r = Discount Rate
n = Number of periods between the present and future cost

NPVs of the alternatives under consideration are compared over the period of analysis. If the alternatives do not have equal lives, the comparison assumes identical replacement when an alternative reaches the end of its life, and the life cycle restarts again. This problem is also solved by estimating the salvage values at the end of the analysis period.

Equivalent Uniform Annual Cost (EUAC)

Present and future costs are converted to an Equivalent Uniform Annual Cost (EUAC) using a discount rate. This method allows flexibility in the economic analysis, particularly when the alternatives have different service lives. If decisions are made based on annual budgets, EUAC facilitates the comparison of LCCA results, and the alternative with the lowest EUAC is recommended.

2.2. LCCA METHODOLOGY TO COMPARE BRIDGE RETROFITTING ALTERNATIVES

An overview of LCCA step-by-step methodology is shown on Figure 1. First, retrofitting techniques alternatives must be defined for the economic comparison. The workflow of each alternative should be documented with their corresponding associated costs. The analysis period is then established based on the type of project and bridge element under study. The deterioration model to forecast the expected performance should be selected accordingly. Maintenance and rehabilitation activities and corresponding cost estimates are determined for the entire period of analysis. The NPV and EUAC for each retrofitting alternative calculated and compared. Finally, a retrofitting technique is recommended based on the LCCA results.

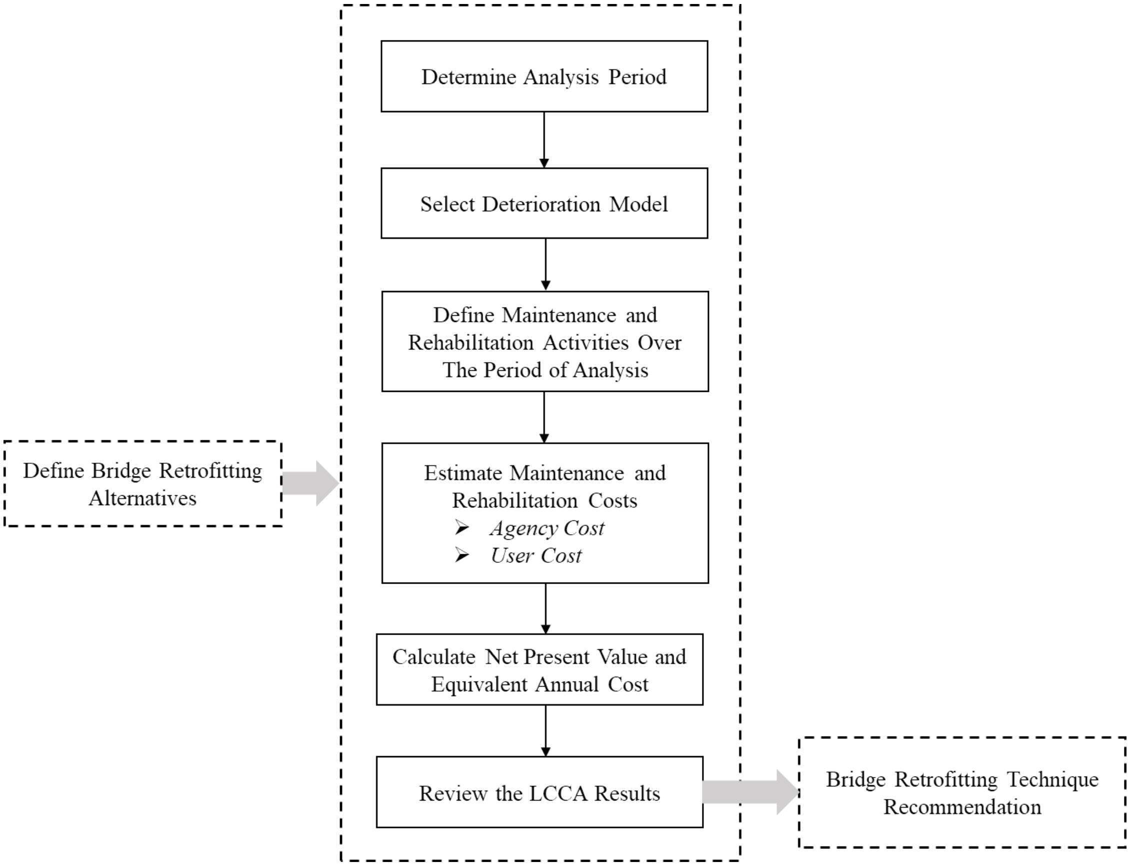


Figure 1. Process diagram to select retrofitting materials for ABC projects

2.2.1. ANALYSIS PERIOD

The life expectancy of the retrofitting alternatives under consideration is a reference to determine the length of the analysis period. For example, a short period of time may be adequate for determining when a deck overlay should be scheduled for a standard highway design (e.g., ten years) while a longer period is recommended for bridge replacement systems (e.g., 25 to 50 years). AASHTO recommends a 75-year design service life for new bridges (AASHTO 2009).

Life expectancy of UHPC is greater than conventional concrete, and it can reach up to 100 years (Farzad et al. 2020). Based on the life expectancy of new concrete structural materials, the analysis period might be even extended over 100 years (NCHRP 2012). Previous studies have used 75 years to compare bridge systems with UHPC and conventional concrete (Dong 2018). Retrofitting alternatives with service lives longer than the analysis period should estimate the salvage value in the LCCA. It is recommended to study the specific project conditions and material properties to determine the length of the analysis period for LCCA.

2.2.2. SELECT DETERIORATION MODEL

Bridge deterioration models are broadly classified into deterministic and probabilistic. Deterministic models used closed-form equations to model deterioration of bridge condition as a function of age and other explanatory variables. Deterministic models are generally based on an empirical relationship between two or more variables that affect the bridge condition with one dependent variable and one or more independent variables. Some research studies recommended a polynomial curve to predict the condition state of concrete bridges as a function of age (Bolukbasi et al. 2004; Lu et. al. 2016). Probabilistic performance models address the uncertainty of the factors that influence the bridge deterioration process. Probabilistic performance models are classified as state-based or time-based. In state-based probabilistic models, the deterioration process is modeled by the probability of transition to move from one condition state to another in a discrete time interval. Markov chain is the most common renowned state-based model (NCHRP 2012).

To estimate the life expectancy of both conventional concrete and UHPC, it is assumed that the corrosion will occur because of chloride ingress. Fick’s second law governs the chloride ingress in concrete (Morcous and lounis 2007). It is assumed that, in a de-icing salt environment, diffusion is the leading transport mechanism in concrete once the chloride has passed the surface zone.

A Monte Carlo simulation-based model is an option to estimate life expectancy. Fick's 2nd law determines the time to initiate corrosion. Corrosion is expected to begin at the rebar surface when the chloride content reaches a threshold level. The concrete cover works as a physical barrier to prevent direct exposure of the reinforcement to the surrounding environment, as well as the detrimental impacts of deicing salt, seawater, and other environmental factors. By solving Fick’s second law in an inverse manner, the time to initiation can be determined from the following equation:

$$t_1 = \frac{c \cdot erf^{-1}\left(1 - \frac{C_{th}}{C_0}\right)^{-2}}{4D}$$

Where:

t_1 = Time to corrosion initiation

Co = Surface Chloride Concentration

D = Diffusion Coefficient

Cth = Threshold Chloride Content

It should be emphasized that applying Fick's second rule to concrete assumes that the diffusion coefficient and surface chloride concentration remain constant throughout time. Other assumptions made in this model:

- The steel is initially protected from corrosion by the chloride-free concrete that surrounds it. Corrosion occurs when the concrete in contact with the steel is infiltrated with chloride ions to a threshold concentration CT (given as mass of chloride per unit volume of concrete).
- Simple diffusion drives chloride contamination inward, with an apparent diffusion coefficient D, driven by the gradient of chloride ion concentration in the concrete. D is a characteristic of the concrete between the surface and the steel, and its value is constant throughout time and space.
- The crack percentage on the concrete surface is used to estimate post-cracking behavior. Nonetheless, the majority of mathematical and empirical functions shows a linear relationship between rebar loss section and crack width propagation.

Chloride concentration at the concrete surface, concrete compressive strength, concrete diffusion coefficient, chloride concentration threshold at the steel level, corrosion rate, concrete cover depth, are simulated assuming probability distributions. The cover depth can be simulated with a normal distribution. The surface chloride concentration, diffusion coefficient and threshold chloride concentration can be simulated with lognormal distribution (Morcous and Lounis 2007).

The bridge element is divided into a certain number of small elements with similar properties. But the small sections have separate probabilities for corrosion due to monte carlo simulation. Since the small elements are independent, the cumulative damage is just the multiplication of the probabilities of the small sections. Crack diffusivity on the concrete element is modeled with derating factors that assume a crack percentage in the concrete when built. The process is further described in FDOT report titled "Corrosion Forecasting for 75-Year Durability Design of Reinforced Concrete" (Sagues et al. 2001) and article "Modeling the effects of Corrosion on the Lifetime of Extended Reinforced Concrete Structures" (Sagues 2003). The research monitored chlorides in regions close to the crack or at the reinforcing surface since local transport conditions influence damage evolution. From the simulation results in this particular study, Figure 2 shows that more than 40 % of spalling damage is expected in 30 years, while UHPC is expected to have 40% of spalling damage in 80 years as shown in Figure 3.

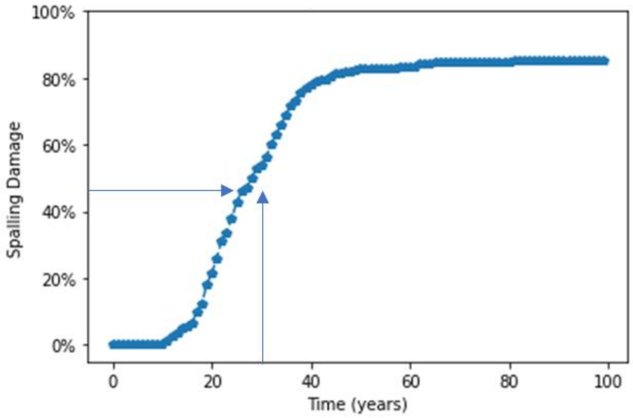


Figure 2. Fraction of elements with spall damage for CSC bridge element.

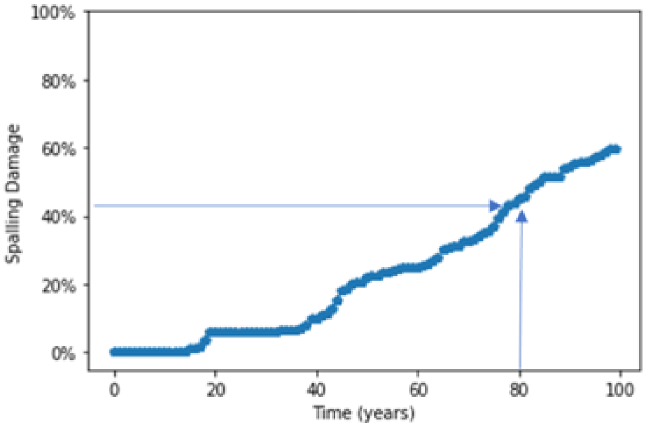
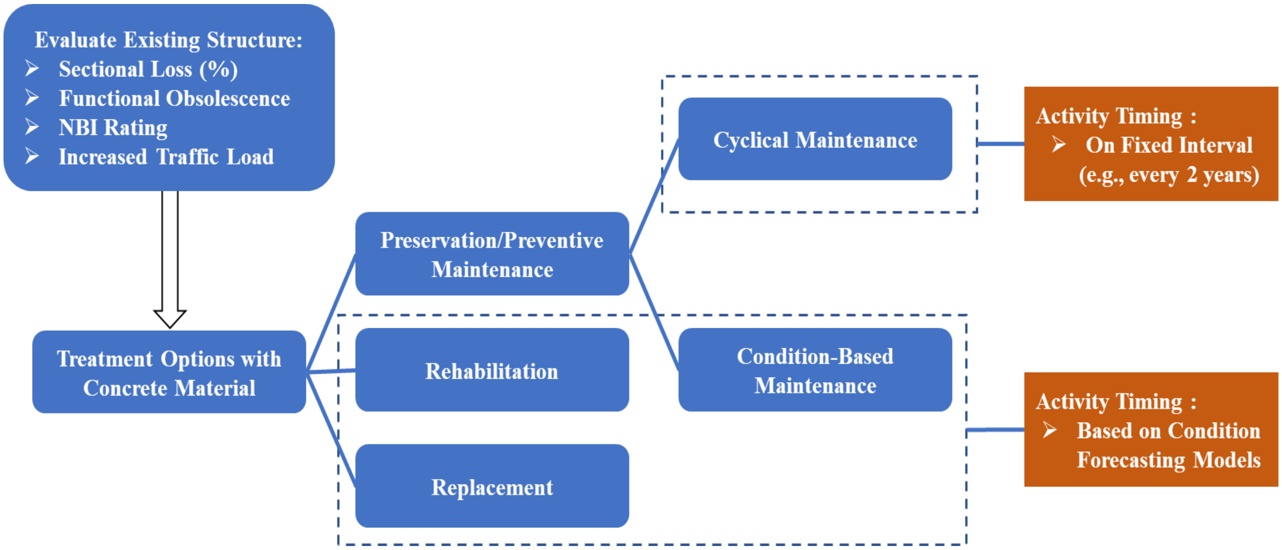


Figure 3. Fraction of elements with spall damage for UHPC bridge element.

2.2.3. DEFINING MAINTENANCE AND REHABILITATION ACTIVITIES OVER THE PERIOD OF ANALYSIS

To define maintenance and rehabilitation activities, FHWA guidelines have been followed (FHWA2018). Bridge retrofitting techniques are determined according to the bridge element condition, type and extend of the damage. UHPC can be utilized in overlays, claddings, and shells to preserve or rehabilitate bridge concrete decks, girders, or columns (Graybeal 2011). Entire deck, beam and bridge systems can be built with UHPC to replace damaged elements. As shown in Figure 4, FHWA classified the bridge actions into three categories: preservation/preventive maintenance, rehabilitation, and replacement (FHWA 2018).



Source: Adapted from FHWA 2018

Figure 4. Bridge action categories.

Preventive Maintenance and Rehabilitation with UHPC

UHPC can be used in both preventive maintenance and rehabilitation activities. The most common activities are deck closure pours for precast deck elements, bridge deck overlay, and shell encapsulation.

Table 1 summarizes the maintenance and rehabilitation techniques with UHPC for ABC, and brief descriptions for each bridge activity follow.

Table 1. Preventive maintenance and rehabilitation techniques with UHPC for ABC.

Bridge Activity	UHPC Technique	Conventional Alternatives
Column/Pier *(Rehabilitation)*	UHPC Shell Encapsulation	Normal Concrete Shell
		steel Casing
Deck Closure Joints *(Preventive maintenance and Rehabilitation)*	Ultra-High-Performance Concrete (UHPC) with straight bars.	Normal Strength Concrete (NSC) with straight bars
		Normal Strength Concrete (NSC) with headed bars.
		Normal-Strength concrete with 180-degree hooked bar
		Epoxy Joint
Deck Overlay *(Preventive maintenance and Rehabilitation)*	UHPC Deck Overlay	Standard Concrete Overlay
		High Performance Concrete (HPC) Overlay
		Asphalt Overlay w/membrane
		Asphalt Overlay w/o membrane
		Latex-Modified Overlay
		Micro Silica Overlay
		Polymer Concrete Overlay
		Thin Bonded Epoxy Overlay
Link slab connection *(Rehabilitation)*	UHPC link slab connection	Link slab using compressive strength >4 ksi, Low Shrinkage Class A4 Concrete

UHPC Shell Encapsulation for Bridge Columns

Field-cast UHPC is a rehabilitation technique applied for improving the strength and ductility of superstructure supporting elements such as driven piles and bridge columns. The seismic performance of bridge columns with deficient lap splices in the plastic hinge zone can be improved by UHPC jacketing (Dagenais et. al. 2014). For combination of axially and laterally loaded sub-structural reinforced concrete (e.g., bridge columns), replacement of existing surface concrete and shell encapsulation with UHPC is an alternative. UHPC should decrease the steel corrosion deterioration rate by confining the concrete and providing a barrier with low permeability (Farzad et al. 2020).

UHPC Bridge Deck Closure Pours

UHPC is frequently used as bridge deck closure pours in preventive maintenance and more frequently in accelerated bridge rehabilitation. The rebar formation in the closure joints varies according to the UHPC application (Jaberi Jahromi et al 2020). It can be used effectively as a shear connector in both longitudinal and transverse connecting joints (Russel and Graybeal 2013). With the use of prefabricated elements, field-cast UHPC can simultaneously resolve several conventional concerns. Because of UHPC's mechanical properties, field-cast connections can be smaller, use less costly connectors, and outperform the connected components by removing the connections as a weak link in the framework. The fresh properties of UHPC allow fill of tight and potential hidden link spaces without honeycombing or unintended voids. The field-cast UHPC connections can withstand the aggressive conditions that have caused field-cast grouts on traditional concrete mixes that have prematurely degraded in the past (Graybeal 2011).

UHPC Bridge Deck Overlay

Concrete overlays on bridge decks are used to rehabilitate the structure to avoid deterioration due to fatigue cracking. UHPC overlays can be considered as a preventive measure in conjunction with spot repairs of isolated distresses. Concrete overlays are grouped in bonded and unbonded (Shann 2012). UHPC high durability and mechanical properties can reduce the time of traffic closures and extend the service life of the bridge deck. UHPC overlays with minimum 25mm (1in.) thickness could be a more cost-effective alternative when compared to conventional bonded concrete overlays (Khayat and Valipour 2018). Also, the absence of mechanical consolidation due to the high fluid nature of UHPC materials can reduce construction time for the rehabilitation of bridge decks.

UHPC Link Slab Connection

Studies have developed an innovative link slab design utilizing UHPC to eliminate transverse deck joints wherever feasible (Royce 2016). Link slab design assumes that the UHPC section is subject to bending. The link slab also acts as a semi-rigid link between spans transferring compressive, tensile, and shear stresses due to various loads. The ability of UHPC to develop ultimate tensile strains up to 0.007 by developing internal micro cracks allows the link slab to accommodate girder end rotations (Royce 2016). Limiting the tensile strain increase the service life of the link slab by preventing the penetration of moisture and chlorides. The design of the link slab is influenced by variables such as span arrangement, bearing type and arrangement, girder end rotation due to live load, and bridge skew. Several rehabilitation projects have utilized UHPC link slabs to eliminate joints.

Bridge Element Replacement with UHPC

UHPC allows innovative bridge element replacement techniques that accelerates the rehabilitation process, extending the bridge service life with minimum road user delays and community disruptions (Aaleti et al. 2014). UHPC has several benefits due to its greatly enhanced physical qualities. Due to UHPC's strength, smaller sections may be designed resulting in lighter structures.

Table 2 shows a summary of the most common bridge element replacement techniques with UHPC for ABC projects.

Table 2. Bridge element replacement techniques with UHPC for ABC projects.

Bridge Activity	UHPC Technique	Conventional Alternatives
Beam and Girder	Box Girder	Conventional Concrete Girder/Beam
	Bulb T girder	Prestressed beam
Deck	I girder	Conventional Concrete Deck
	Full-Depth Waffle Deck panel	
Pier and Column	Precast pile for deep foundation	Cast in place pile
Combination of Structural Elements	Steel truss- UHPC plate bridges	Conventional girder and deck systems
	Precast UHPC girder with ordinary concrete slab	
	FRP girder with UHPC slab	
Wall and Barrier	Precast Cantilever Retaining Wall	Cast in place retaining walls

UHPC pi-girder

UHPC pi girders can be up to 65 ft (Graybeal 2009). This system is good for sites with clearance limitations. This girder is also good for short and medium span bridges. Cost savings can be achieved by using partial prestressing in UHPC pi-girder design.

UHPC Waffle Deck Panel System

A UHPC waffle deck system consists of precast UHPC waffle panels with shear pockets, transverse panel-to-panel connections, longitudinal panel-to-girder connections, some type of overlay to improve rideability if desired, and in situ UHPC material to fill the connections and shear pockets (Aaleti et al. 2013). The use of UHPC waffle deck panels has several advantages. UHPC waffle slabs are 30 to 40% lighter than solid precast full-depth panels constructed of standard strength concrete for decks of the same thickness and capacity (Aaleti et al. 2013). When compared to decks made with solid precast panels, the lighter UHPC panels can have longer span lengths, increase girder spacing, and improve bridge load capacity.

UHPC in Prefabricated Element Systems

The high strength of UHPC results in a substantial reduction of dead-load and less restricted structural member shapes (Plevny 2020). As compared to conventional concrete, UHPC allow longer span bridge structures with smaller member sizes, as well as a substantial reduction in volume and self-weight. A UHPC beam, for example, needs half the section depth of reinforced or pre-stressed concrete beams, resulting in a weight reduction of 70% (Ghoneim et al. 2006). UHPC piles can be cast successfully in a pre-casting plant (Voort et al. 2008). High strengths of 26 to 29 ksi (179 to 200 MPa) are achieved by UHPC with heat treatment procedures. To avoid the formation of air pockets in UHPC members, limited vibration of UHPC piles during casting is recommended at locations every five to ten feet along the pile for approximately ten seconds at each site (FHWA 2014).

2.2.4. ESTIMATING AGENCY COSTS

Agency costs include initial construction, maintenance, and rehabilitation activities. Salvage value may also be considered in the LCCA depending on the retrofitting techniques under comparison and length of the analysis period. Initial construction, maintenance, and rehabilitation costs can be determined by adding material, labor, and equipment costs. The cost of the materials is affected by the manufacture process. Certain materials need specialized workers or must be manufactured off-site and shipped, material manufacture can have a significant impact on the cost. Use of special equipment may speed up the construction activity but at the expense of additional costs. Construction procedures also affects the cost of retrofitting activities.

The details of construction vary from project to project. Other agency costs that may be considered in LCCA are related to the design, condition assessment, right-of-way, and utility adjustments. The costs of preliminary engineering (PE), construction engineering (CE), traffic maintenance (MOT), and demolition activities can be added to the costs. Figure 5 summarizes the agency costs that should be considered for LCCA.

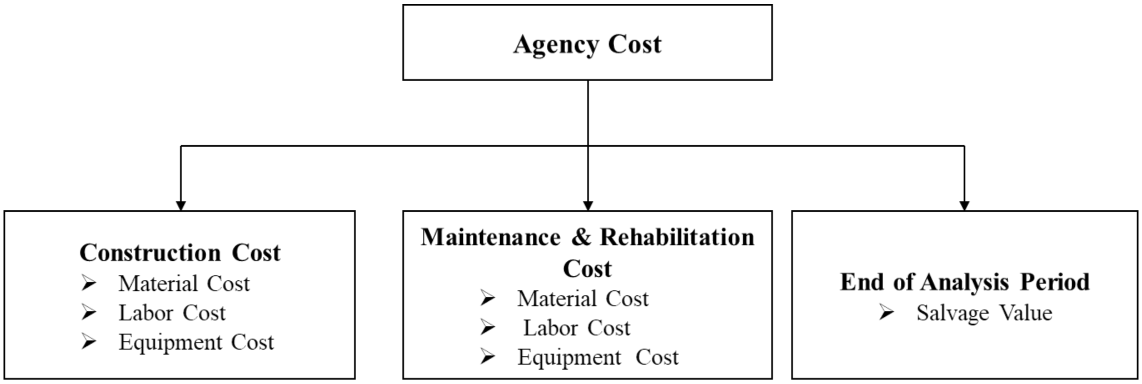


Figure 5. Agency costs.

2.2.5. ESTIMATING USER COSTS

For this study, only traffic delay and vehicle operating costs are considered as user costs. User cost estimates are based on time delays, vehicle operation (Watts et al. 2012). The user costs in a work zone can be grouped into two categories: (Ozbay et al. 2003)

- Vehicle operating costs during normal operation and work zone operation.
- Cost of travel delay time during normal operation and work zone operation.

As a reference, FHWA technical bulletin “Life -Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin” describes a twelve-step procedure for calculating user costs (Walls and Smith 1998). The user cost calculation process can also be applied to bridges, and it is summarized as follows:

Step 1 Project future year traffic demand

Step 2 Calculate work zone directional hourly demand

> Hourly demand can be determined from agency traffic data. If this information is not available, the default hourly distribution from MicroBENCOST can be used.

Step 3 Determine roadway capacity

Three capacities to be determined from HCM: the free flow capacity of the facility under normal operating condition, the capacity of the facility when the work zone is in place, and the capacity of the facility to dissipate traffic from a standing queue. Capacity during queue dissipation is less than the capacity for free-flow condition. Work zone capacity is estimated based on how many lanes are closed.

Step 4 Identify the user cost components

Compare the roadway capacity with the hourly demand for the facility.

Step 5 Quantify traffic affected by each cost component

Quantify the number of vehicles involved with each cost component.

Step 6 Compute reduced speed delay

To calculate work zone delay, work zone length, speed and upstream speed are needed.

Step 7 Select and assign VOC rates

Step 8 Select and assign delay cost rates

Step 9 Assign traffic to vehicle classes.

Step 10 Compute individual user costs components by vehicle class.

Step 11 Sum total work zone user costs.

Step 12 Address circuity and crash costs.

Crash costs are not included in the analysis. Work zones may have fewer lanes or narrower clearances between vehicles and roadside objects (e.g., owing to decreased or deleted shoulders), reducing capacity. In work zones, speed restrictions may decrease as well (Highway Capacity Manual 2010). Temporary road closures may cause traffic to be diverted to other routes, resulting in higher traffic volumes. Therefore, road users experience delays during a construction project because of the following situations:

- Temporary closures of bridge lanes for routine maintenance, repair, and rehabilitation.
- Congestion that develops when such closures slow down traffic and create secondary queuing delays.
- Traffic impending effects of poor roadway conditions.

2.2.6. CALCULATE NET PRESENT VALUE (NPV) AND EQUIVALENT UNIFORM ANNUAL COST (EUAC)

Life cycle costs over a specified period are discounted to the present to calculate the Net Present Value (NPV) using the following equation:

$$NPV = CC + \sum_{j=1}^{n1} \frac{MC}{(1+r)^{t2}} + \sum_{k=1}^{n2} \frac{RC}{(1+r)^{t3}} + (-S) or\ (+D) \frac{1}{(1+r)^{N}}$$

Where:

r = Discount rate

CC = Initial construction cost including material and labor cost

MC = Maintenance cost in terms of the agency and user cost of maintenance actions

RC = Rehabilitation cost in terms of the agency and user cost of maintenance actions

S = Salvage value

D = Disposal cost

n1 = Number of maintenance activities over analysis period

n2 = Number of rehabilitation activities over analysis period

N = Length of analysis Period

The life cycle cost of alternatives with different expected life service (e.g. conventional concrete versus UHPC) can be compared using the Equivalent Uniform Annual Cost (EUAC). The EUAC can be computed with the following equation:

$$EUAC = LCC(NPV)\ \frac{r.(1+r)^N}{(1+r)^N-1}$$

Where:

N = Length of the analysis period

r = Discount rate

2.2.7. REVIEW OF LCCA RESULTS

The life cycle cost analysis results are reviewed based on the NPV and EUAC. Also, a sensitivity analysis is used to identify input parameters that could have the most impact on the total life-cycle cost. Sensitivity analysis can be conducted by changing one input parameter while all the others remain constant. Changing one parameter at a time is the simplest manner to perform sensitivity analysis. The change in a parameter is defined as a percentage of a reference value. Tornado plots, spider plots, and elasticity diagrams are representations of the results of sensitivity analysis. These diagrams show output changes when an input variable changes from a minimum to a maximum value while holding all other parameters at their average values (NCHRP 2012).

3. CONCLUSIONS AND RECOMMENDATIONS

A Life Cycle Cost Analysis (LCCA) approach is described in this ABC-UTC guide to quantify the potential benefits of UHPC applications in retrofitting techniques. LCCA is needed to evaluate retrofitting alternatives to identify long-term cost-effective maintenance strategies. The LCCA approach includes: (a) a framework for pre-selecting concrete repair material, (b) life expectancy performance models, and (c) a step-by-step methodology to compare life-cycle costs of UHPC to conventional concrete (CSC) in retrofitting techniques. Products delivered from this research aim to support decisions at the network and project management levels.

3.1. LIFE-EXPECTANCY PERFORMANCE MODELS FOR UHPC RETROFITTING TECHNIQUES

Deterministic and probabilistic models can be developed of life expectancy models. Most of the studies use state-based Markov chain models based on NBI data. Whether deterministic or probabilistic, the dataset mostly registers the NBI. To address the life expectancy of specific concrete materials, mechanistic-empirical models are required (e.g. chloride corrosion model).

A chloride corrosion deterioration model is recommended to consider the influence of concrete properties in the expected performance. The reinforced concrete deterioration model is based on chloride corrosion activity. Concrete materials have critical chloride content thresholds that varies with the bridge site location and concrete mix composition. Diffusivity of chloride content depends on the concrete mix properties that affects the expected corrosion cracking time.

Life expectancy models for UHPC and conventional concrete differ in the chloride diffusion coefficient, water cement ratio, and crack diffusivity. The corrosion initiation period is longer in UHPC reinforced concrete elements than in conventional concrete elements. The derating factors and crack diffusivity result into spalling damage over time in concrete bridges. Figure 6 shows that the life expectancy model predicts that 40% spalling damage is expected for conventional concrete after 30 years, and the same amount of spalling damage is projected for UHPC after 80 years.

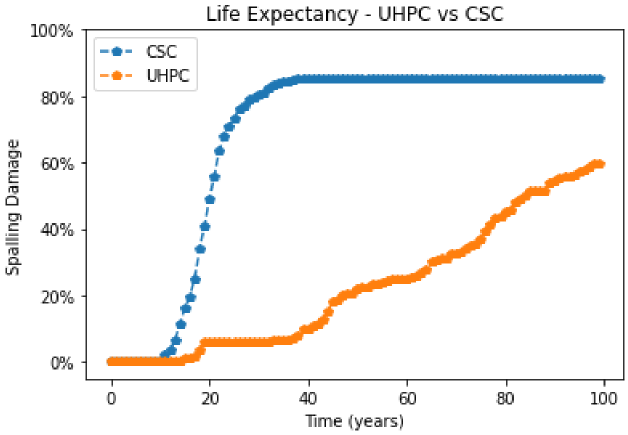


Figure 6. Spalling damage and life expectancy of CSC and UHPC.

3.2. LIFE CYCLE COSTS COMPARISON OF CONVENTIONAL CONCRETE AND UHPC ALTERNATIVES FOR BRIDGE MAINTENANCE AND REHABILITATION.

UHPC is used in both preventive maintenance and rehabilitation techniques for ABC projects. A wide variety of UHPC mix designs have been developed for retrofitting applications in bridge elements. Examples of UHPC retrofitting applications are column shell encapsulation, deck closure joints, thin deck overlay, and link slab connections. Other examples are box girder, bulb T girder, I girder, full depth waffle deck panel, precast pile for deep foundation, precast cantilever retaining walls.

The initial construction cost of ABC projects with UHPC may be higher than projects with conventional concrete. However, maintenance and rehabilitation interventions could balance this difference over time. The high life expectancy of UHPC result in less frequent maintenance and consequently influences the user costs. Therefore, it is important to consider agency and user costs in LCCA.

In the three case studies presented in the Appendices, the total life cycle cost is lower for the UHPC alternative when compared to conventional concrete. The agency cost difference is not significant except for UHPC link slab. On the other hand, the user costs influence the total life cycle cost. A summary of the results from the case studies is shown in Table 3.

Table 3. Summary of results from case studies.

Case Study	Summary of Results
Conventional Expansion Joint vs UHPC Link Slab with GFRP	Conventional expansion joint results in approximately 30% increase in total LCC when compared to UHPC link slab.
Cast in Place Deck Slab vs Precast Deck Slab with UHPC Closure Joints	Total LCC of conventional is about three times higher than UHPC. User cost is significantly higher for conventional construction due to construction days. User cost versus agency cost ratio for the conventional concrete alternative is higher than the user cost versus agency cost ratio for the UHPC alternative (4.54 versus 0.78). The sensitivity analysis of the variables involved in the LCCA revealed that the Average Daily Traffic (ADT) and construction duration of the rehabilitation activity have the most significant effects on the total life cycle cost.
Epoxy Deck Overlay vs UHPC Deck Overlay	UHPC overlay has less frequent maintenance than the conventional concrete alternative due to high life expectancy.

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APPENDIX A: CONVENTIONAL EXPANSION JOINT VERSUS UHPC LINK SLAB REINFORCED WITH GLASS FIBER REINFORCED POLYMER (GFRP)

Appendix A describes a case study based on the LCCA methodology developed in the research project titled: "Life Cycle Cost Analysis of Ultra High-Performance Concrete (UHPC) in Retrofitting Techniques for ABC".

A.1 DESCRIPTION OF CASE STUDY 1

In case study 1, a two span simply supported Florida Slab Beam bridge needs repair. As an alternative to replace bridge conventional expansion joints, UHPC with Glass Fiber Reinforced Polymer (GFRP) is considered as a link slab. Therefore, the two alternatives for LCCA comparison are:

Alternative 1: Conventional Expansion Joint

Alternative 2: UHPC Link Slab Reinforced with Glass Fiber Reinforced Polymer (GFRP)

This case study illustrates LCCA calculations for agency costs only over a period of 60 years with a discount rate of 3%. Agency costs are based on references provided by the Florida Department of Transportation.

A.2 ALTERNATIVE 1: CONVENTIONAL EXPANSION JOINT

In alternative 1, conventional expansion joints are considered for cast in place bridge deck slab. For FDOT practice on slab-on-girder and PSU bridges, the deck is cast continuously over the simply supported precast units with prescriptive reinforcing requirements. Following design guidelines, Florida Slab Beam bridges must use expansion joints at each support due to potential cracking.

Deterioration Model and Life Expectancy for Alternative 1

For the conventional expansion joint alternative, life expectancy is estimated in 10 years (Morcous 2013).

Maintenance and Rehabilitation Activities for Alternative 1

Joint replacement is scheduled every 10 years in the maintenance and rehabilitation program as shown in Figure A-1.

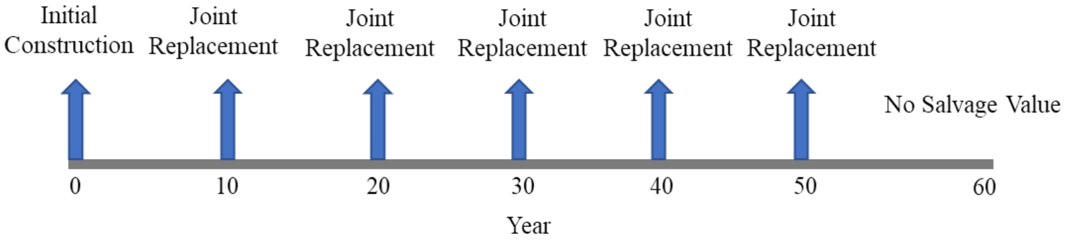

Figure A-1. Life cycle activity diagram for alternative 1, Case Study 1.

Agency Costs for Alternative 1

The cost of a conventional expansion joint is 350 $/linear ft (Kelly et al. 2018). Total construction cost for bridge expansion joints is $16,800 since there are 4 expansion joints along the width of the bridge (12 ft clear distance). Table A-1 shows the agency cost over time for alternative 1. There is no salvage value at the end of the analysis period.

Table A-1. Activities and life-cycle costs with Net Present Value for Alternative 1, Case Study 1.

Year	Activities	Agency Cost	Discount Factor (3% Rate)	Present Cost
0	Initial Construction	16,800	1	$16,800
10	Replacement	16,800	0.744093915	$12,501
20	Replacement	16,800	0.553675754	$9,302
30	Replacement	16,800	0.41198676	$6,921
40	Replacement	16,800	0.306556841	$5,150
50	Replacement	16,800	0.22810708	$3,832
60	Salvage Value	0		$0
			Total NPV	**$54,506**
			EUAC	**$1,969.46**

A.3 ALTERNATIVE 2: UHPC LINK SLAB REINFORCED WITH GLASS FIBER REINFORCED POLYMER (GFRP)

The elimination of joints and bearings in the bridge superstructure is becoming increasingly popular in bridge design. A UHPC link-slab reinforced with steel or Glass Fiber Reinforced Polymer (GFRP) is one option. GFRP is non-corrosive, and it is equal to or greater in tensile strength to structural steel. One of the major advantages of GFRP bars is the low modulus of elasticity compared to that of steel. This means less tensile force is required to deform the bars and micro cracks can develop. Figure A-2 shows configuration of a full depth cast in place link slab.

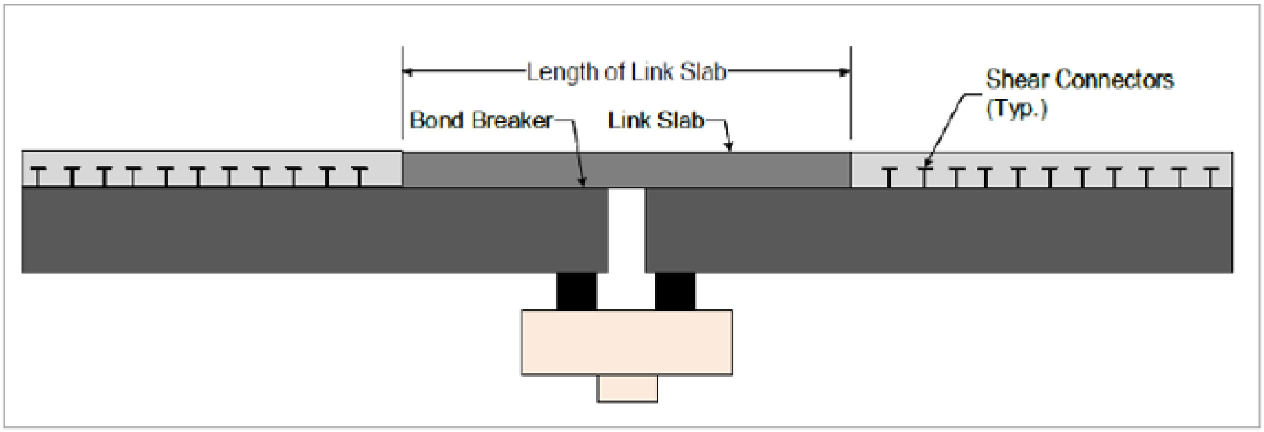

Figure A-2. Typical Full depth cast in place link slab configuration.

The UHPC link slab size is 6’3” by 12’2” and 4-inch-thick according to AASHTO construction guidelines (AASHTO 2020). The bridge will require 2 link slabs.

Deterioration Model and Life Expectancy for Alternative 2

To evaluate the life expectancy of UHPC link slab reinforced with GFRP, the rapid chloride permeability of 49 coulombs for the UHPC concrete mix is assumed. This information is based on FDOT test reports. Then, the diffusion coefficient is estimated based on the following equation (Issa and Khalil 2010):

$$Coulomb = 5602.9\,Dc - 7642.1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where:

Dc = Diffusion Coefficient (ft2/s)

Figure A-3 shows the corrosion initiation and cumulative damage for the UHPC link slab. It is observed that approximately 40% of damage is expected in 80 years. Therefore, there is no full slab replacement since the analysis period for the LCC is 60 years.

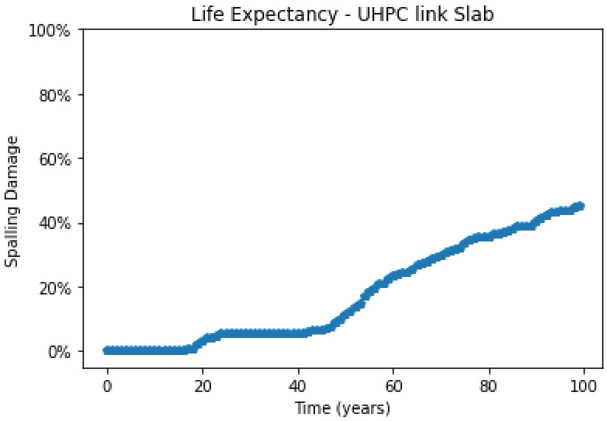

Figure A-3. Corrosion initiation and cumulative damage for the UHPC link slab, Case Study 1.

Maintenance and Rehabilitation Activities for Alternative 2

A 1-inch UHPC deck overlay is considered for preventive maintenance every 20 years. The maintenance area is assumed 10% of the total deck area. There is no rehabilitation activities or slab replacement during the life cycle. The life cycle activity diagram is shown on Figure A-4.

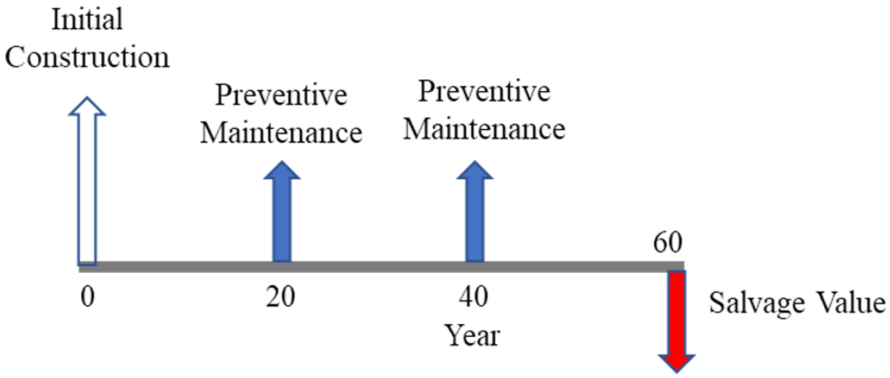

Figure A-4. Life cycle activity diagram for Alternative 2, Case Study 1.

Agency Costs for Alternative 2

Table A-2 shows the activities and life-cycle agency costs for alternative 2. The salvage is calculated based on the remaining life.

Considering 20 years of remaining life: Salvage value = (20/80) * $39,800 = $9,950.

Table A-2. Activities and life-cycle costs with Net Present Value for Alternative 2, Case Study 1.

Year	Activities	Agency Cost	Discount Factor (3% Rate)	Present Cost
0	Initial Construction	39,800	1	$39,800
20	Preventive Maintenance	4,728	0.553675754	$2,618
40	Preventive Maintenance	4,728	0.306556841	$1,449
60	Salvage Value	- 9,950	0.16973309	- $1,689
			Total	**$42,178**
			EUAC	**$1,524.02**

A.4 RECOMMENDATION BASED ON LCCA RESULTS OF CASE STUDY 1

It is observed that the total agency cost for UHPC link slab in alternative 2 is lower than the conventional expansion joint in alternative 1. Figure A-5 shows the NPV for the agency cost of the two alternatives. Alternative 1 with conventional expansion joint results is about 30% higher costs than alternative 2 with the UHPC link slab. Less frequent maintenance for UHPC to high life expectancy explains the reason for this difference.

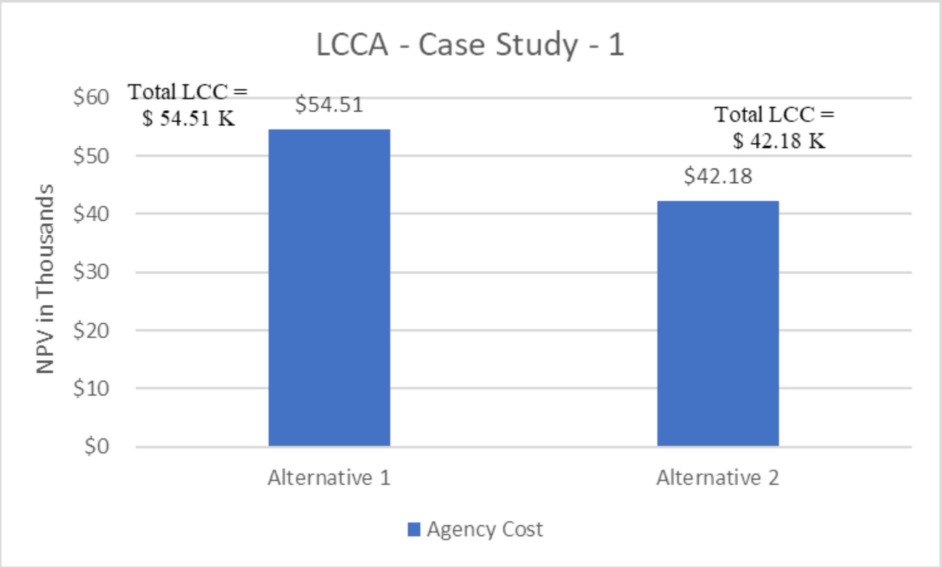

Figure A-5. NPV cost of alternative 1 and alternative 2, Case Study 1.

In this case study, user costs were not included in the LCCA due to limited data regarding the construction schedule. In alternative 2, the life expectancy of UHPC link slab is very high compared to conventional expansion joints. In addition, maintenance and rehabilitation activities for the UHPC link slab are less frequent when compared to joint expansion causing less traffic disruption. Therefore, user costs in alternative 2 should be lower than in alternative 1.

A.5 REFERENCES

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APPENDIX B: CONVENTIONAL CAST IN PLACE CONCRETE DECK SLAB VERSUS PRECAST DECK SLAB WITH UHPC CLOSURE JOINTS

Appendix B describes a case study based on the LCCA methodology developed in the research project titled: "Life Cycle Cost Analysis of Ultra High-Performance Concrete (UHPC) in Retrofitting Techniques for ABC".

B.1 DESCRIPTION OF CASE STUDY 2

In case study 2, the bridge deck area is 1375 sq. ft. with a slab width of 42 ft., and there are two bridge deck retrofitting alternatives under consideration:

Alternative 1: Conventional cast in place concrete deck slab.

Alternative 2: Precast deck slab with UHPC closure joints.

LCCA is conducted over a period of 60 years with a discount rate of 3%. Agency costs are based on references provided by the Florida Department of Transportation (FDOT) (FDOT 2020). and user costs are estimated following FHWA guidelines.

B.2 ALTERNATIVE 1: CONVENTIONAL CAST IN PLACE CONCRETE DECK SLAB

In this alternative, conventional concrete type II is used for building the in-place bridge deck slab. This type of concrete is recommended when the environmental condition is slightly aggressive. According to the Structure Design Guidelines from the Florida Department of Transportation (FDOT), the environmental condition is classified as slightly aggressive when the chloride content is less than 500 ppm, and the sulphate content is between 150 - 1000 ppm. (FDOT 2022).

Deterioration Model and Life Expectancy for Alternative 1

It is assumed that the structure is exposed to chloride with a surface concentration of 10 kg/m3 (moderate for a marine splash zone). The chloride initiation period is calculated and spalling concrete slab damage is projected over time. For cast in place (CIP) conventional concrete slab, the spalling damage evolution over time is observed in Figure B-1. In this case study, it is considered that the end-of-life service is when the concrete slab reaches 40% of damage. Therefore, the expected life for the conventional concrete slab is reached in 30 years.

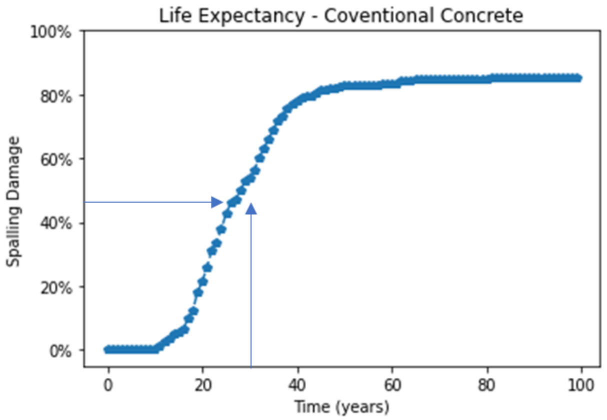


Figure B-1. Corrosion initiation and cumulative damage for the conventional concrete slab, Case Study 2.

Maintenance and Rehabilitation Activities for Alternative 1

Figure B-2 shows a schematic life-cycle activity diagram for alternative 1 with maintenance and rehabilitation interventions during the period of analysis.

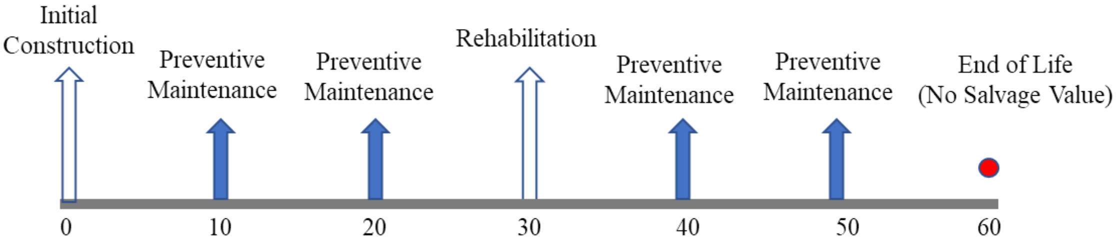


Figure B-2. Life cycle activity diagram for alternative 1, Case Study 2.

A thin bonded epoxy overlay is scheduled every 10 years as preventive maintenance (Chang et al. 2016). One disadvantage of epoxy overlays is that they are difficult to repair when they spall or break. The epoxy overlay is removed and replaced as part of bridge maintenance.

The conventional concrete slab has a life expectancy of 30 years. Therefore, rehabilitation with the replacement of the concrete slab scheduled at year 30. A new life cycle for the conventional concrete slab begins at year 30 and it ends at year 60. At year 60, there is no remaining life neither salvage value.

Agency Costs for Alternative 1

Table B-1 provides a breakdown of initial construction cost estimates for the conventional concrete slab. Cost data are retrieved from the report prepared by FDOT titled “FDOT Bridge Development” with Financial Project ID no 442667-1-22-01 (FDOT 2020).

Table B-1. Initial construction cost estimation of cast in place concrete slab, Alternative 1, Case Study 2.

Description	Unit	Cost per Unit	Quantity	Cost
Cast in Place Concrete -Class II	Per Cubic Yard	250	1375	$343,750
Reinforcing Steel	Per Pound	1.05	274600	$288,330
Expansion Joint	Per Linear ft	45	42.25	$1901
			Total	$633,981

The cost estimate for a thin bonded epoxy overlay, is $ 22 per sq. ft. (NDOR 2013). Therefore, the cost for a preventive maintenance activity is: 1375 x $22 = $30,250.

The cost of rehabilitation for the replacement of the slab is assumed the same as the initial construction cost: $ 633,981.

Table B-2 shows the agency costs over the period of analysis with calculations of the present cost using a 3% discount factor.

Table B-2. Agency life cycle costs for Alternative 1, Case Study 2.

Year	Activities	Agency Costs	Discount Factor (3% Rate)	Present Cost
0	Initial Construction	$633,981	1	$633,981
10	Preventive Maintenance	$30,250	0.744	$22,509
20	Preventive Maintenance	$30,250	0.554	$16,749
30	Rehabilitation (Replacement of the concrete slab)	$633,981	0.412	$261,192
40	Preventive Maintenance	$30,250	0.307	$9,273
50	Preventive Maintenance	$30,250	0.228	$6,900
60	Salvage Value	0		$0
			Total	**$950,604**

Note: It is assumed in the analysis that there is no inflation.

User Costs for Alternative 1

User costs assumptions and calculation process follows FHWA references (Walls and Smith 1998). In this guide, the assumptions are summarized while the details of the calculation process are described in the final report. Cost estimates are based on traffic projections distributed by time periods during the day. Time periods are considered as work zone time and non-work zone times. The calculated user costs are illustrated for the rehabilitation activity at year 30 for 14 days of construction activity. The 24-hours work schedule for the rehabilitation activity is provided in Table 8 with distributed work and non-work zone time periods. The projected Annual Average Daily Traffic (AADT) is assumed to be 114,000 at year 30. In this example, traffic delay and vehicle operation costs are included in the calculations. There is no crash data available to calculate crash costs. Default hourly distribution factors generated by MicroBENCOST are used to calculate delay costs and VOC in this case study (Ozbay et al. 2003). It is worth to mention that work zone directional hourly demand should be calculated from agency traffic records.

Table B-3 shows the directional hourly traffic distribution for the inbound and outbound trips. The calculation process is the same for inbound and outbound traffic. In this calculation, only inbound trips are considered.

Work zone capacities by vehicles per hour are provided in Exhibit 10-14 of the 2010 Highway Capacity Manual (HCM) (Highway Capacity Manual 2010). The vehicles per hour are calculated based on the number of lanes open at the work zone. This example assumes that there are three bridge lanes open for traffic with one work zone lane. According to the HCM, the work zone capacity is 1450 veh/hr/lane for this traffic work zone conditions. Non work zone capacity is assumed to be 1900 veh/hr/ln. Lane closures and capacity ranges during construction are described in more detail in Chapter 10 of the 2010 HCM.

Table B-3. Directional hourly traffic distribution.

WZ Status	Time Period	Distribution Factor	Inbound (%)	Outbound (%)	Demand	
					Inbound	Outbound
WZ	12-1	1.2	47	53	752	725
WZ	1-2	0.8	43	57	458	520
WZ	2-3	0.7	46	54	429	431
WZ	3-4	0.5	48	52	320	296
WZ	4-5	0.7	57	43	532	343
WZ	5-6	1.7	58	42	1314	814
Non-WZ	6-7	5.1	63	37	4282	2151
Non-WZ	7-8	7.8	60	40	5700	3557
Non-WZ	8-9	6.3	59	41	4953	2945
Non-WZ	9-10	5.2	55	45	3811	2668
WZ	10-11	4.7	46	54	2881	2893
WZ	11-12	5.3	49	51	3461	3081
WZ	12-13	5.6	50	50	3731	3192
WZ	13-14	5.7	50	50	3798	3249
WZ	14-15	5.9	49	51	3852	3430
Non-WZ	15-16	6.5	46	54	3984	4001
Non-WZ	16-17	7.9	45	55	4737	4953
Non-WZ	17-18	8.5	40	60	4531	5814
Non-WZ	18-19	5.9	46	54	3617	3632
WZ	19-20	3.9	48	52	2495	2312
WZ	20-21	3.3	47	53	2067	1994
WZ	21-22	2.8	47	53	1754	1692
WZ	22-23	2.3	48	52	1471	1363
WZ	23-24	1.7	45	55	1019	1066

Table B-4 shows the cost factors associated with work zone activities based on the number of queued vehicles and operating conditions. The delay cost components are speed change delay, total stopping delay, and total queue reduced speed delay. The step-by-step calculation of the delay cost are from FHWA manuals and reports (Walls and Smith 1998) (Ozbay et al 2003).

Based on the work zone hour that the queue occurred, the following costs are calculated:

- Speed change VOC and delay cost.
- Stopping VOC and delay cost.
- Total idling VOC or queue reduced speed delay cost.

These costs are incurred by vehicles traversing the work zone, traversing queue, stopping during the queue, or slowing down due to the queue. From the FHWA reference, the value of time ($/hr) is $11.58 for passenger cars and $20.43 for trucks (Walls and Smith 1998). The case study uses the cost or value of time per vehicle directly from the FHWA reference assuming that there is no inflation. The costs or value of time per vehicle should be updated by the agency for each specific project. Speed change VOC and delay costs are calculated from slowed down vehicles. The case study used the values from the FHWA reference assuming that there is no inflation over time.

The stopping VOC and delay costs are calculated from stopped vehicles. It is noted that the truck percentage is assumed to be 1.55%. The idling VOC is calculated for the three work zone time periods and added to the user costs.

Total VOC for inbound vehicles: Speed Change VOC + Stopping VOC + Idling VOC

Total VOC for inbound vehicles = $5,145 + $,74,414+$533,485 = $613,044.

Table B-4. Work zone and non-work zone operating conditions based on vehicle delayed.

WZ Status	Time of day	Future traffic	Capacity	Queue rate	Queued Vehicle	Operating Conditions	Cost Factors
WZ	12AM - 1AM	752	1450	-698	0	Free flow work zone in place no queue	no costs
WZ	1AM-2AM	458	1450	-992	0		
WZ	2AM-3AM	429	1450	-1021	0		
WZ	3AM-4AM	320	1450	-1130	0		
WZ	4AM-5AM	532	1450	-918	0		
WZ	5AM-6AM	1314	1450	-136	0		
Non-WZ	6AM-7AM	4282	5700	-1418	0	No work zone, free flow	no costs
Non-WZ	7AM-8AM	5700	5700	0	0		
Non-WZ	8AM-9AM	4953	5700	-747	0		
Non-WZ	9AM-10AM	3811	5700	-1889	0		
WZ	10AM-11AM	2881	1450	1431	1431	Forced Flow, WZ in place	Speed change VOC and Delay Cost Stopping VOC and Delay Cost Total idling VOC or queue reduced speed delay
WZ	11AM-12PM	3461	1450	2011	3442		
WZ	12PM-1PM	3731	1450	2281	5723		
WZ	1PM-2PM	3798	1450	2348	8071		
WZ	2PM-3PM	3852	1450	2402	10473		
Non-WZ	3PM-4PM	3984	5700	-1716	8758	Forced Flow, WZ in place	Speed change VOC and Delay Cost Stopping VOC and Delay Cost Total idling VOC or queue reduced speed delay
Non-WZ	4PM-5PM	4737	5700	-963	7795		
Non-WZ	5PM-6PM	4531	5700	-1169	6626		
Non-WZ	6PM-7PM	3617	5700	-2083	4542		
WZ	7PM-8PM	2495	1450	1045	5587	Forced Flow, WZ in place	Speed change VOC and Delay Cost Stopping VOC and Delay Cost Total idling VOC or queue reduced speed delay
WZ	8PM-9PM	2067	1450	617	6204		
WZ	9PM-10PM	1754	1450	304	6507		
WZ	10PM-11PM	1471	1450	21	6529		
WZ	11PM-12AM	1019	1450	-431	6098		

The calculation process was shown in detail for the inbound trips. A similar calculation process should be followed for the outbound trips. In this case study, there are not calculations for outbound trips and the same assumption is made for both alternatives 1 and 2.

Total Delay Cost = Speed Change Delay Cost + Stopping Delay Cost + Queue Speed Delay Cost

= $3,349 + $58,644 + $9,809,327 = $9,871,320.

Total User Costs at year 30 = Total VOC for inbound vehicles + Total Delay Cost

Total User Costs at year 30 = $613,044 + $9,871,320 = $10,484,364.

Present User Cost at year 0 = (1/ (1+0.03) ^30) x 1048364 = $4,319,557.

Net Present Value and Equivalent Annual Costs for Alternative 1

Table B-5 shows the Net Present Value (NPV) broken down by agency and user costs and the corresponding Equivalent Uniform Annual Cost (EUAC) for alternative 1.

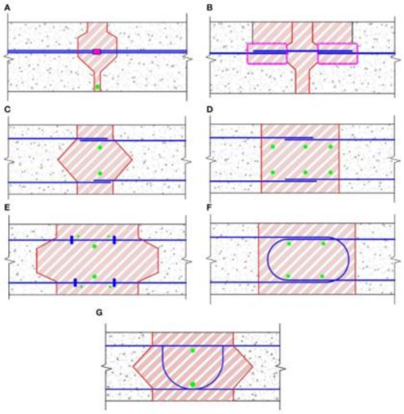
Table B-5. Net Present Value and EUAC, Alternative 1, Case Study 2.

Cost	Alternative 1 Cast in place concrete slab
Agency Cost	$950,604
User Cost	$4,319,557
Total Net Present Value	$5,270,161
Equivalent Uniform Annual Cost	$190,427

The total user cost is about four times than the total agency cost. This is an indication of the importance of including user costs in the LCCA. In this example, user costs were only calculated for the rehabilitation activity which is the replacement of the concrete slab at year 30. If user costs for the initial construction had been also considered, the total user costs would have been higher.

B.3 ALTERNATIVE 2: PRECAST DECK SLAB WITH UHPC CLOSURE JOINTS

Alternative 2 is a prefabricated deck slab with UHPC closure joints and an overlay to protect the deck surface. Common closure joint types used for ABC techniques are shown in Figure B-3 (Jaberi Jahromi et al. 2020). The joint configuration for the project corresponds to Figure B-3 C. The prefabricated bridge deck is also made with UHPC. Construction can be completed in 4 days at the site according to FDOT information.



Source: Jaberi Jahromi et al. 2020

Figure B-3. Schematic configurations for common closure joints in ABC. (A) posttensioning, (B) mechanical connectors, (C) ultra-high performance with straight bars, (D) normal-strength concrete with straight bars, (E) normal-strength concrete with headed bars, (F) normal-strength concrete with 180◦ hooked bar, (G) normal-strength concrete with 90◦ hooked bar.

The UHPC mix design reference is from a research study conducted in 2021 for nonproprietary UHPC transverse field joints (Abokifa et al. 2021).

Deterioration Model and Life Expectancy for Alternative 2

The life expectancy of the precast deck slab with UHPC is calculated with the corrosion model. It is also assumed that the bridge is exposed to chloride with a surface concentration of 10 kg/m3 (moderate for a marine splash zone). The difference with the deterioration model used for alternative 1 is in the parameters used for the equations that changes according to the concrete properties (e.g., diffusion coefficient, chloride threshold value). The corrosion initiation time is longer for UHPC, although chloride propagation still causes concrete spalling damage over time.

Figure B-4 shows that 40% of deck spalling damage of the slab is expected to be reached in 80 years. There is no full slab deck replacement in this alternative since the analysis period for the LCC is 60 years. However, the overlay to protect the deck surface reaches 20% of spalling damage at year 50 and its replacement is scheduled for rehabilitation.

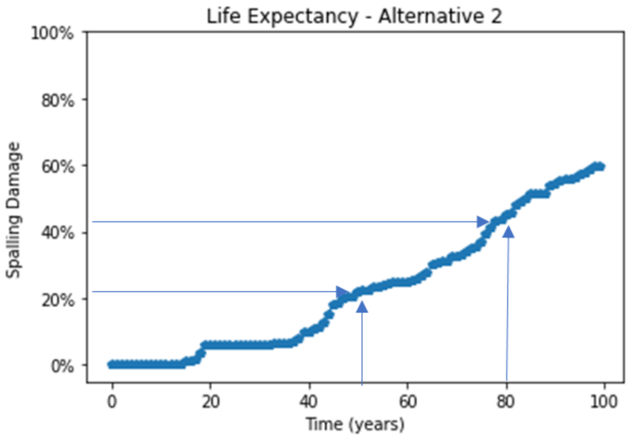


Figure B-4. Corrosion initiation time and cumulative damage for the UHPC slab, Case Study 2.

Maintenance and Rehabilitation Activities for Alternative 2.

Figure B-5 shows a schematic life-cycle activity diagram for alternative 2 with maintenance and rehabilitation interventions over the period of analysis.

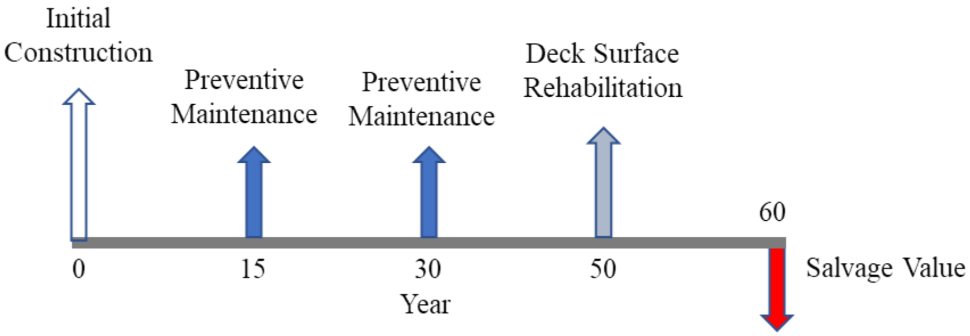


Figure B-5. Life cycle activity diagram for alternative 2, Case Study 2.

UHPC overlay repair in 10% of the deck area (1375 * 10% = 137.5 sq. ft.) is scheduled every 15 years as preventive maintenance. At year 50, a 1-inch overlay is scheduled for deck surface rehabilitation. At year 60, there are 20 years of remaining life for the precast deck slab since the service life is 80 years.

Agency Costs for Alternative 2

The initial construction cost was from a FDOT project that consist of an approach slab replacement with a construction area of 1375 sq. ft. This project was managed by FDOT District Three (Project Name: I-10 (SR 8) over CR-268A, Bridge No. 500080 FPID: 445645-1). In this project, the deck slab with UHPC closure joints has an initial construction cost of $980,000.

The unit cost reference for the UHPC overlay is from project BR 1-438 on N463 Blackbird Station Road Over Blackbird Creek stored in the ABC-UTC database. Form this project, the UHPC unit cost for an overlay is $375 per cubic ft. Therefore, the unit cost for the 1-inch UHPC overlay will be: $375 x 0.083 = 31 $/sq-feet (Note: 1 inch = 0.083 ft).

For preventive maintenance, it is assumed that 10% of the deck needs an overlay repair every 15 years. Therefore, the cost per preventive maintenance activity is: 31 x 0.10 x 137.5 sq-feet = $4,263.

The cost of rehabilitation for the overlay replacement to protect the deck surface at year 50 is: 31 x 1375 sq-feet = $42,625.

At year 60, the bridge slab deck has 20 years of remaining life and consequently a salvage value. There is no consensus on how to estimate the salvage value. One approach is to account for the costs of demolition and removal while considering the recycled value of the material waste. Another approach seeks the relative value of the serviceability with respect to cost of rehabilitation. In this case study, the remaining life of the pre-cast slab is 25% of the total expected service life of 80 years. Therefore, the salvage value is estimated as 25% of the initial construction cost.

Salvage value at year 60: 980,000 x 25% = $245,000.

Table B-6 shows the agency costs over the period of analysis with calculations of the present cost using a discount rate of 3 %.

Table B-6. Agency life cycle costs for alternative 2, Case Study 2.

Year	Activities	Agency Costs	Discount Factor (3% Rate)	Present Cost
0	Initial Construction	$980,000	1	$980,000
15	Preventive Maintenance	$4,263	0.642	$2,736
30	Preventive Maintenance	$4,263	0.412	$1,756
50	Rehabilitation	$42,625	0.249	$9,723
60	Salvage Value	- $245,000	0.170	-$41,585
`			Total	$952,630

User Costs for Alternative 2

User costs calculations for alternative 2 follow similar steps and assumptions as alternative 1. The difference is that the construction work duration is 4 days instead of 14 days. For user cost calculations, it is assumed that the working hours in alternative 2 are the same as alternative 1. In practice, this assumption should be reviewed for specific project conditions since ABC projects may require a different work schedule than conventional construction practices. Only inbound trips are considered in the user cost calculations. Following the user cost calculation process explained in detail for alternative 1, the total VOC and delay costs for alternative 2 are summarized as follows:

Total VOC for alternative 2 = $175,155.

Total Delay Costs for alternative 2 = 2,820,377.

Total Present User Costs = ($175,155+$2,820,377) x (1/ (1+0.03) ^47) = $746,662.

Net Present Value and Equivalent Annual Costs for Alternative 2

Table B-7 shows the total Net Present Value (NPV) broken down by agency and user costs and the corresponding Equivalent Uniform Annual Cost (EUAC) for alternative 2.

Table B-7. Net Present Value and Equivalent Uniform Annual Costs, Alternative 2, Case Study 2.

Cost	Alternative 2 Precast Deck Slab UHPC Joints
Agency Cost	$953,516
User Cost	$746,662
Total Net Present Value	$170,0178
Equivalent Annual Cost	$61,432

B.4 REVIEW OF LCCA RESULTS OF CASE STUDY 2

An overview of the LCCA results for the two alternatives is shown in Table B-8.

Table B-8. Overview of LCCA results for alternatives 1 and 2, Case Study 2.

Cost	Alternative 1 (Cast in place slab with conventional concrete)	Alternative 2 (Precast Deck Slab with UHPC Joints and Overlay)
Agency Cost	$950,604	$952,630
User Cost	$4,319,557	$746,662
Total Net Present Value (NPV)	**$5,270,161**	**$1,700,178**
Equivalent Annual Cost	**$190,427**	**$61,432**

Figures B-6 and B-7 show the bridge life-cycle projected cost expenditures over the period of analysis for alternatives 1 and 2. The total NPV for alternative 1 is about three times higher than the total NPV for alternative 2. Although, the agency cost in alternative 1 with conventional concrete is higher than alternative 2 with UHPC, the total NPV of alternative 1 with conventional concrete is higher in the long-term. The final total net present value and equivalent uniform annual cost are lower in alternative 2 with UHPC because of the user costs.

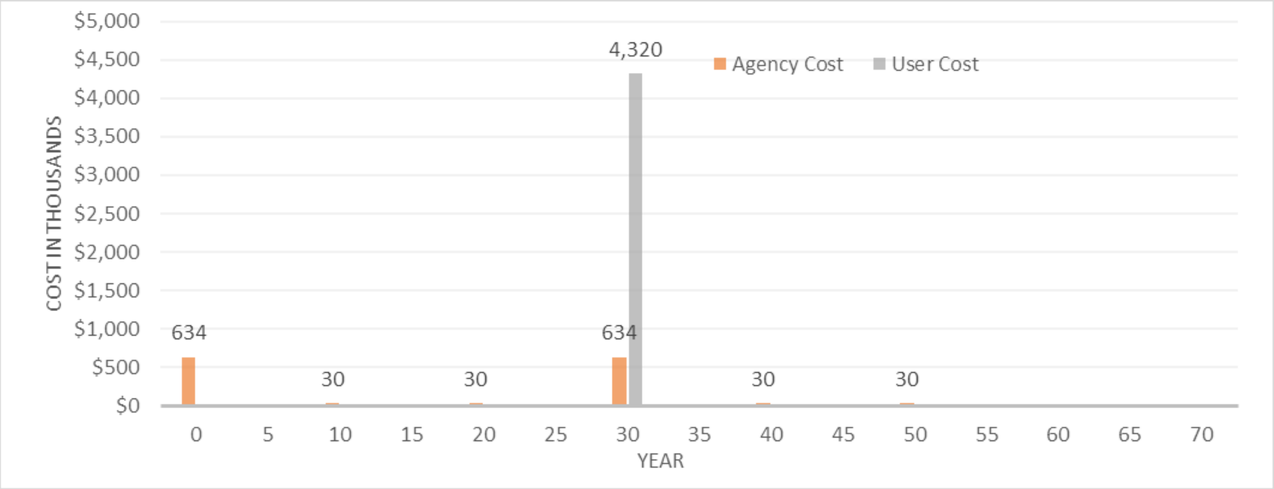


Figure B-6. Projected cost expenditures over time, Alternative 1.

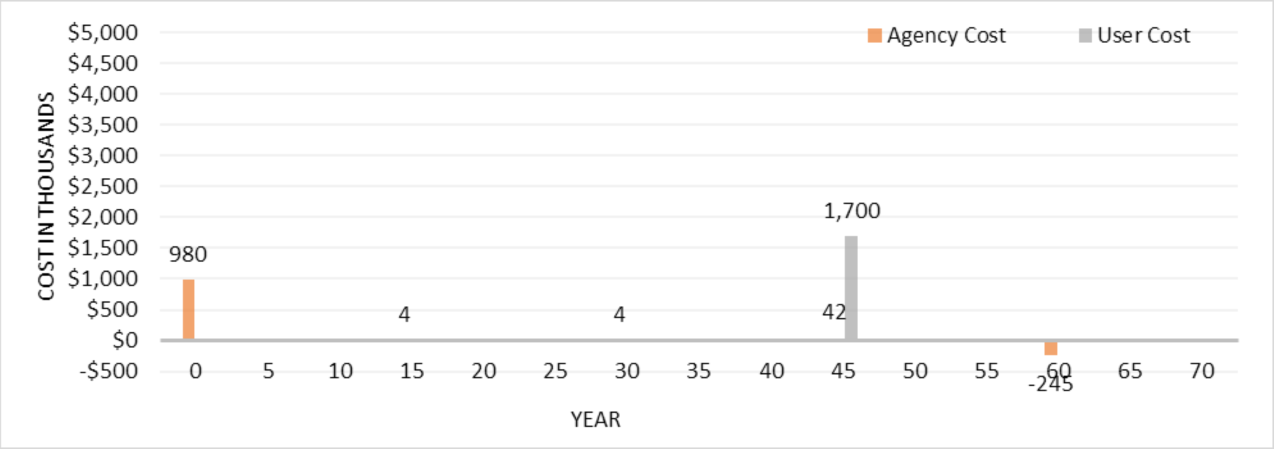
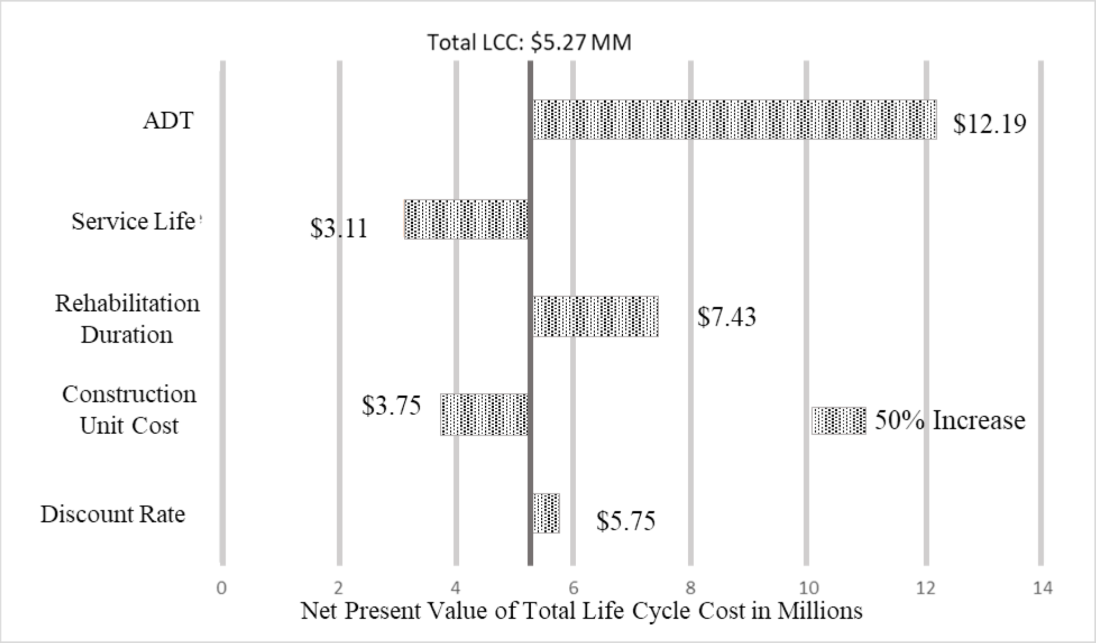


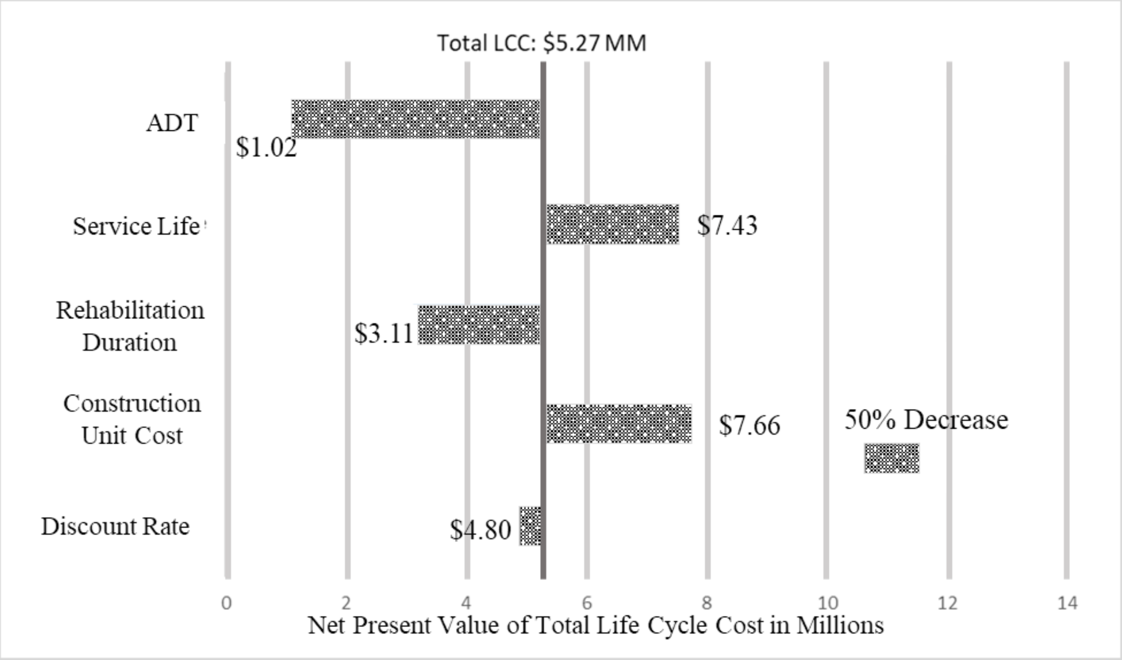
Figure B-7. Projected cost expenditures over time, Alternative 2.

B.5 SENSITIVITY ANALYSIS FOR CASE STUDY 2

Figure B-8 shows the tornado diagram with the results of a life cycle cost sensitivity analysis for alternative 1. Each individual variable was varied 50% while the other variables remain constant. The construction unit cost, average daily traffic, rehabilitation duration, and discount rate values were varied positive 50% and negative 50% in the sensitivity analysis. The sensitivity analysis was performed to identify the most relevant factors that influence the life cycle costs. It also provides insights of the best and worst-case scenarios. Figure B-8 (a) shows the effect of 50% increase of the individual data input variables in the life cycle costs and Figure B-8 (b) the effect of 50% decrease.



(a) 50% increase of LCCA data input variables

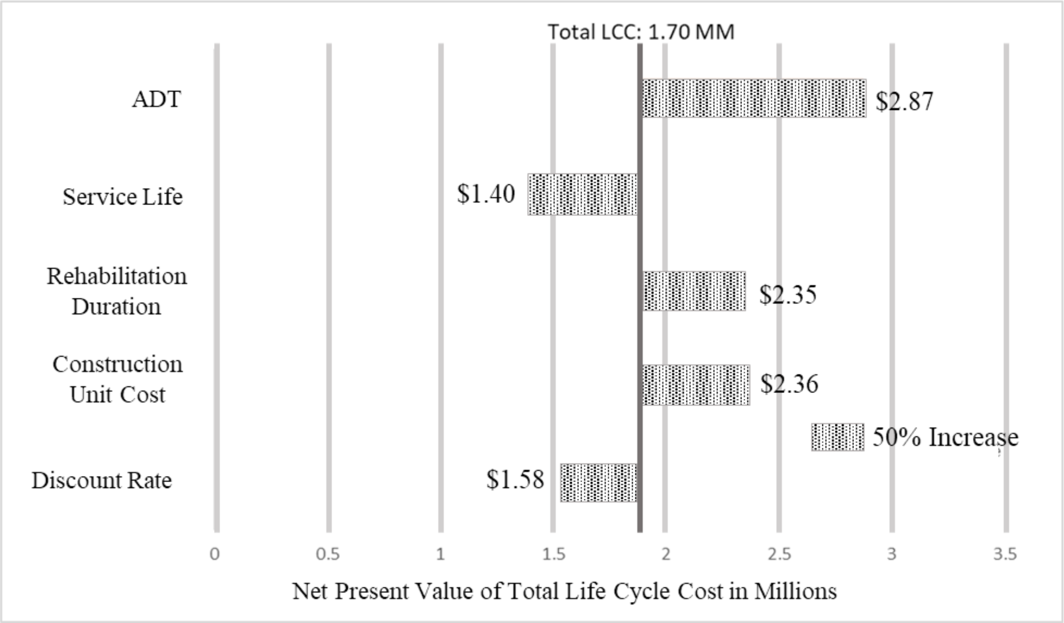


(b) 50% decrease of LCCA data input variables

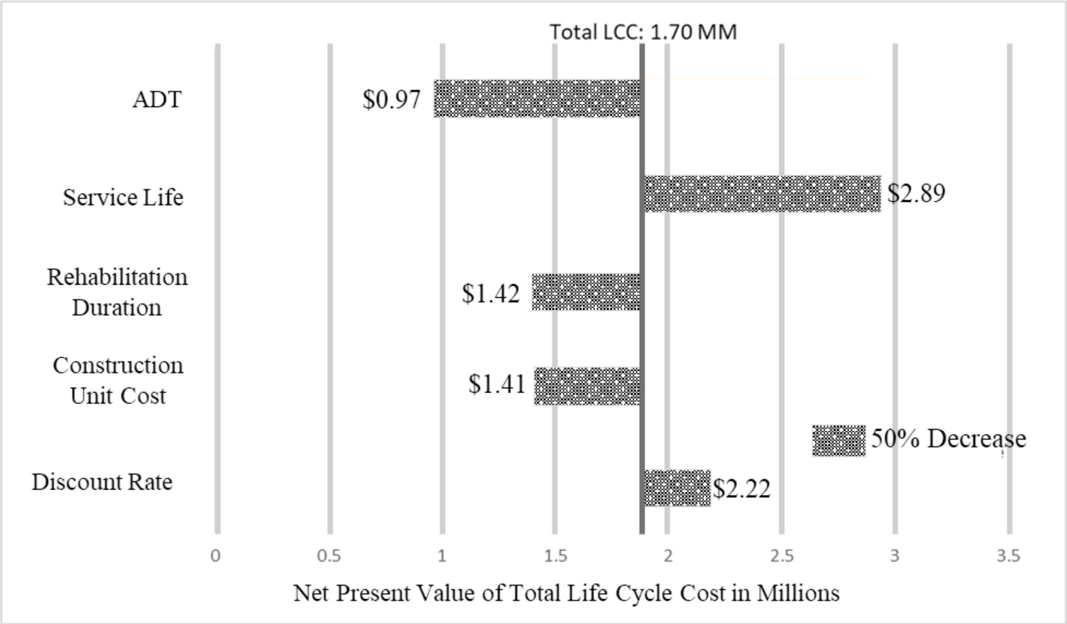
Figure B-8. Life cycle cost sensitivity analysis tornado diagram, Alternative 1.

Figure B-8 (a) shows that a 50% increase of service life significantly decreases the total life cycle costs. The opposite is observed in Figure B-8 (b). Whereas if the duration of rehabilitation increases by 50%, the total life cycle cost increase significantly. Decreasing the duration of rehabilitation decreases the total life cycle costs.

Figure B-9 shows the tornado diagram with the results of the life cycle cost sensitivity analysis for alternative 2. It is observed that the total life cycle cost for alternative 2 is less sensitive to ADT variations when compared to alternative 1. These results are influenced by the difference in construction days between alternatives 1 and 2 (14 days versus 4 days). For this reason, the user cost/agency cost ratio in alternative 1 is higher than in alternative 2 (4.54 versus 0.78). It is also observed that that total life cycle cost is more sensitive to construction unit cost variations in alternative 2.



(a) 50% increase of LCCA data input variables



(b) 50% decrease of LCCA data input variables

Figure B-9. Life cycle cost sensitivity analysis tornado diagram, Alternative 2.

The results of the sensitivity analysis show that in both alternatives the Average Daily Traffic (ADT) has the most significant effect on the total life cycle cost.

Figure B-10 shows the results of the sensitivity analysis in spider plots for alternatives 1 and 2 with the influence of the variables in LCCA results. The horizontal axis shows the change of the variable values from positive 50% to negative 50%. The vertical axis shows the change of total life cycle costs as the values of each variable changes.

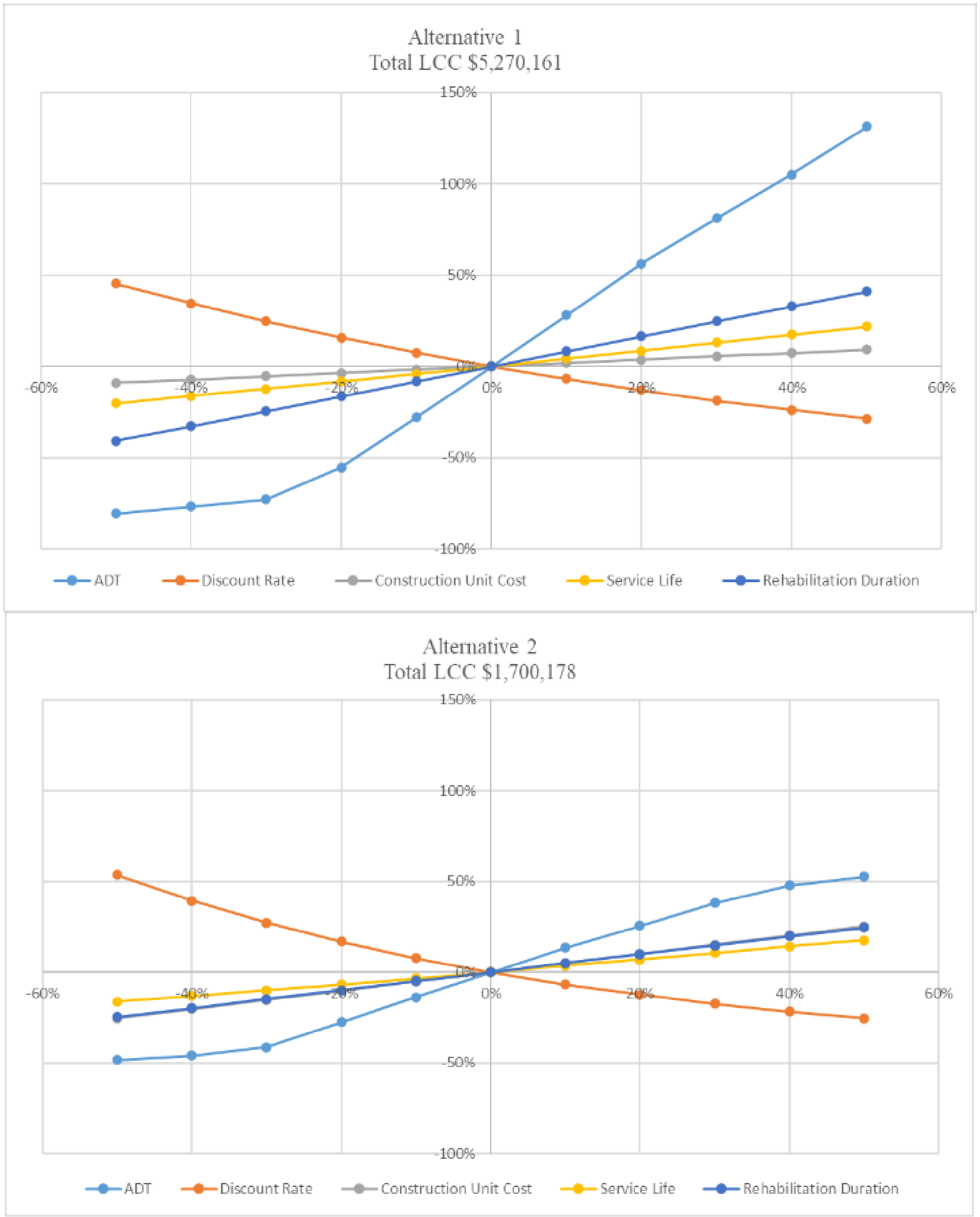


Figure B-10. Sensitivity analysis spider plots for CSC and UHPC retrofitting alternatives.

In alternative 1, the spider plot unfolds that if the ADT increases in 50%, then the total life cycle cost increases in about 150%, and if the duration of the rehabilitation activity increases by 50%, the total life cycle cost increases approximately 50%. It is also observed that the sensitivity of the total life cycle costs to the ADT and duration of the rehabilitation activity in alternative 1 is higher than in alternative 2. The reason is that the construction time in alternative 2 with UHPC and ABC techniques is significantly less than alternative 1 with conventional concrete (4 days versus 14 days).

In alternative 2, the total life cycle cost is more sensitive to the construction unit cost when compared to alternative 1. The line of the construction unit cost in the spider plot overlaps with the duration of the rehabilitation activity in alternative 2, and both variables have similar effects in the total life-cycle cost under this alternative. Overall, agency costs in alternative 2 have more influence in the total life cycle cost when compared to alternative 1.

B.6 RECOMMENDATION BASED ON LCCA RESULTS OF CASE STUDY 2

The agency cost is about the same for both alternatives. In alternative 1 with conventional concrete, the agency cost is slightly lower than alternative 2 with UHPC. However, the different frequency of maintenance activities and cost influence the agency costs. The lower frequency of preventive maintenance in alternative 2 due to the higher durability of UHPC is reflected in the results balancing the initial construction cost. At the end of the 60-year analysis period, the total agency cost of the alternatives is very close ($950,604 in alternative 1 versus $952,630 in alternative 2). Figure B-11 shows the comparison of agency and user cost for both alternatives.

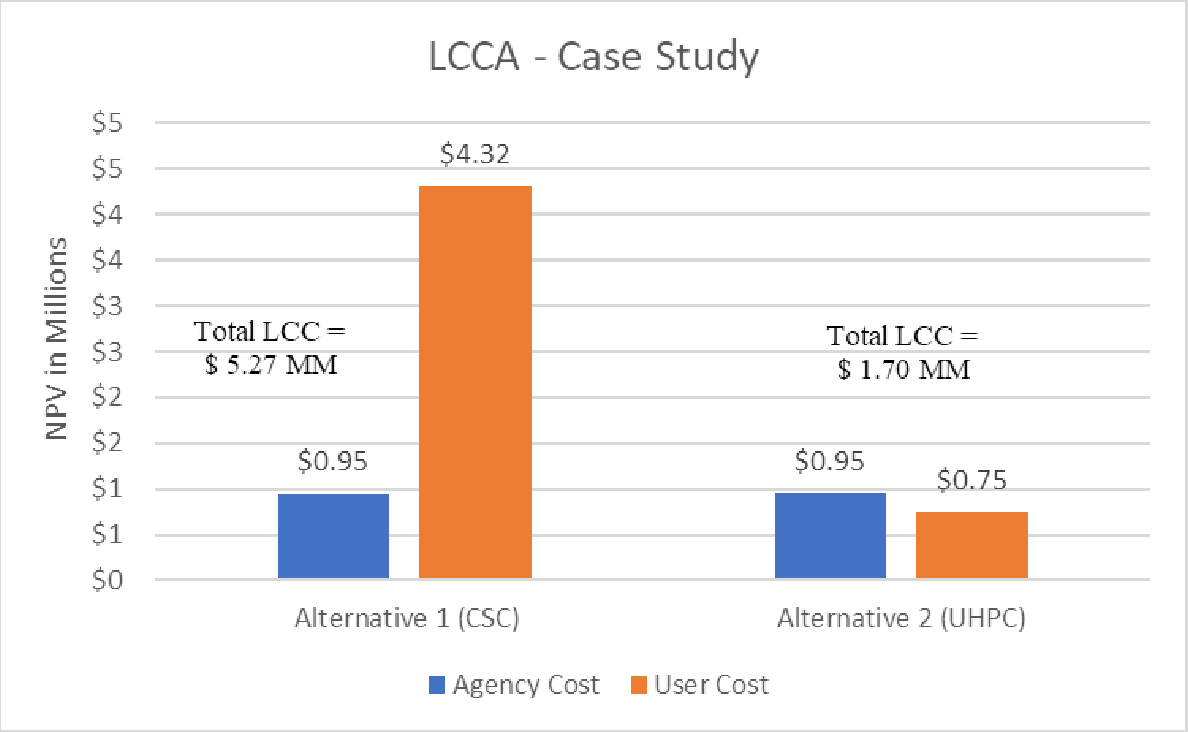


Figure B-11. Comparison of life cycle costs for CSC and UHPC retrofitting alternatives.

The user cost is lower for alternative 2 because the construction time is lower than alternative 1 (4 days versus 14 days). ABC projects have higher initial construction costs, however, there are time savings due to shorter construction times that are reflected in the user costs. When user costs are included in the analysis, the total life-cycle cost of alternative 1 – including agency and user costs - is about three times the total life cost of alternative 2 ($ 5,270,161 versus $1,700,178). Therefore, alternative 2 with UHPC is recommended as the most cost-effective solution in the case study.

It is also concluded that the concrete life expectancy significantly affects agency and user costs over the lifetime of a bridge element. The life expectancy of the precast deck slab with UHPC was almost twice than conventional cast in place concrete deck slack, and this difference is reflected in the LCCA results.

B.7 REFERENCES

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Jaberi Jahromi A, Valikhani A, Mantawy IM and Azizinamini A. 2020. "Service Life Design of Deck Closure Joints in ABC Bridges: Guidelines and Practical Implementation." Front. Built Environ. 5:152. doi: 10.3389/fbuil.2019.00152.

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APPENDIX C: EXPOXY OVERLAY VERSUS UHPC BRIDGE DECK OVERLAY

Appendix C describes a case study based on the LCCA methodology developed in the research project titled: “Life Cycle Cost Analysis of Ultra High-Performance Concrete (UHPC) in Retrofitting Techniques for ABC”.

C.1 DESCRIPTION OF CASE STUDY 3

In this case study, a single span bridge with a deck area of 2179 sft (width of 40ft and length of 53.1 ft.) is repaired. In the last 40 years, Epoxy Polymer Overlays (EPOs) have been used to seal bridge decks. A UHPC deck overlay alternative is analyzed. Therefore, the two retrofit alternatives under comparison are:

Alternative 1: Epoxy Polymer Overlay (EPO)

Alternative 2: Ultra High-Performance Concrete (UHPC) Overlay.

This case study illustrates LCCA calculations over a period of 60 years with a discount rate of 3%. Agency costs are based on references provided by the Florida Department of Transportation, and user costs are estimated following FHWA guidelines.

C.2 ALTERNATIVE 1: EPOXY POLYMER OVERLAY (EPO)

Thin Polymer Overlays (TPOs) consist of an epoxy polymer binder and aggregates with a thickness not exceeding 10 mm (3/8 in.) (NDOR 2013). EPO overlay can provide a service life of 20 to 25 years when properly installed on sound decks (NCHRP 2012). In this case study, the service life of EPO is 25 years based on a research study titled “Life-Cycle Assessment of Nebraska Bridges” (Morcous 2013). For preventive maintenance activity, it is assumed that 10% of the deck area needs preventive maintenance every 10 years (Chang et al. 2016). Figure C-1 shows the life cycle activity diagram with maintenance and rehabilitation activities.

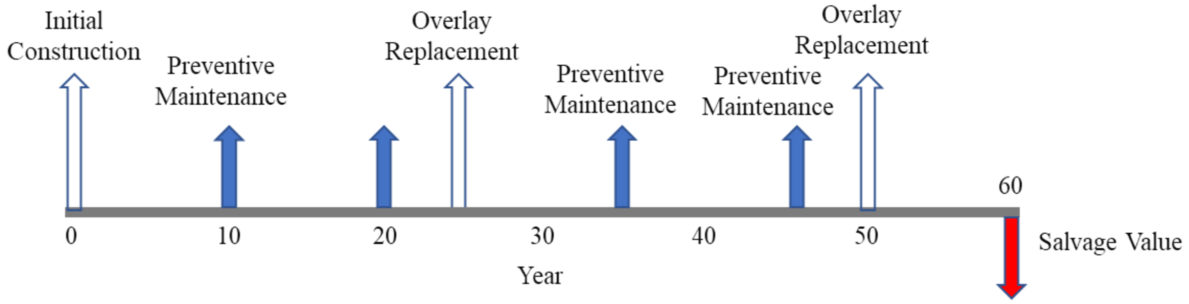


Figure C-1. Life cycle activity diagram for alternative 1, Case Study 3.

Agency Costs for Alternative 1

For thin bonded epoxy overlay, the agency cost estimate is $ 22 /sft (Morcous 2013). The agency cost over the life cycle is shown on Table C-1. For preventive maintenance, it is assumed that 10% of the deck area needs overlay repair. For salvage value, 15 years of remaining life is considered for the overlay.

Table C-1. Agency costs for Alternative 1 (Epoxy overlay).

Year	Activities	Agency Costs	Discount Factor	Present Value
0	Initial Construction	$47,938	1	$47,938
10	Preventive Maintenance	$4,794	0.744	$3,567
20	Preventive Maintenance	$4,794	0.554	$2,654
25	Overlay Replacement	$47,938	0.478	$22,895
35	Preventive Maintenance	$4,794	0.355	$1,704
45	Preventive Maintenance	$4,794	0.264	$1,268
50	Overlay Replacement	$47,938	0.228	$10,935
60	Salvage Value	-$28,763	0.17	-$4,890
			Total	**$86,071**

User Costs for Alternative 1

Travel and Work Zone Delay Cost

A simple approach has been adopted to calculate the user cost for this case study. Average daily traffic (ADT) is assumed to be 30000 veh/day. The duration of construction activities for the Epoxy overlay is laid in two separate segments over the course of two days. The epoxy overlay needs more frequent preventive maintenance and rehabilitation activities than the UHPC overlay. To estimate the user costs, it is assumed that one lane is closed during the overlay construction. It is assumed that traffic demand during closures is 6% of ADT, equal to 1800 veh/day, and 10% is composed by truck traffic. Over the 2-day overlay construction period, the total number of delayed vehicles is 3600. The number of delayed vehicles increases proportionally to the total traffic volume.

The travel delay cost for cars is estimated as 18.12 $/h and 54.94 $/h for trucks (Soliman 2019). It is also assumed that the delay time is 0.25 hr per vehicle. The travel delay cost is calculated with the following equation:

$$\text{Travel Delay Cost (TDC)} = (\text{ADT} \times \text{TDC}_c + \text{ADTT} \times \text{TDC}_T) \times \Delta T$$

Where:

TDC = Total Travel Delay Cost

TDC_c = Travel Delay Cost for Cars ($/hr)

TDC_T = Travel Delay Cost for Trucks ($/hr)

ΔT = Time Delay per Vehicle

ADTT = Number of truck traffic delayed

ADT = Number of Passenger cars delayed

Travel and work zone delay cost per replacement activities for alternative 1: (3240 * 18.12 + 360 * 54.94) *0.25 = $19,620.

Since Alternative 1 has two overlay replacements and initial construction activities:

Total delay cost for Epoxy Overlay= $39,240.

For vehicle operating costs, it is assumed that vehicles do not use a detour around the bridge during maintenance activities. Therefore, these costs are not considered in the LCCA calculations. The crash costs and environmental costs are also assumed to be negligible.

Net Present Value and Equivalent Annual Costs for Alternative 1

The Net Present Values (NPV) and Equivalent Uniform Annual Costs (EUAC) for alternative 1 is shown in Table C-2. NPV and EUAC includes the agency and user costs.

Table C-2. Net Present Value and Equivalent Uniform Annual Costs, Alternative 1, Case Study 3.

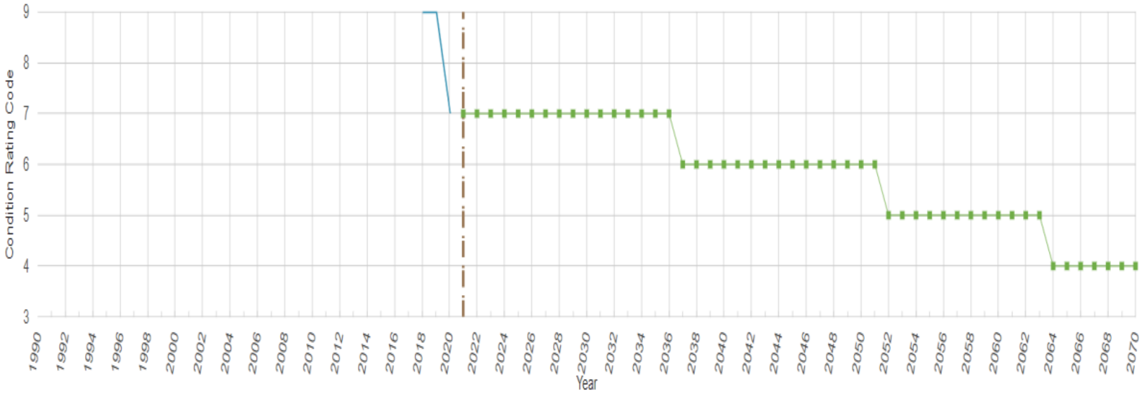
Cost	Alternative 1 Epoxy Overlay
Agency Cost	$86,071
User Cost	$39,240
Total Net Present Value	$126,311
Equivalent Annual Cost (EUAC)	$4,319

C.3 ALTERNATIVE 2: ULTRA HIGH-PERFORMANCE CONCRETE (UHPC) OVERLAY

For alternative 2, a 1-inch UHPC overlay is considered as an alternative to conventional concrete. The overlay placement construction duration is the same as in alternative 1.

Deterioration Model and Life Expectancy for Alternative 2.

To estimate the life expectancy of UHPC deck overlay, condition bridge data from the Long-Term Bridge Performance (LTBP) database is used as a reference. Figure C-2 shows the evolution of the bridge condition rating over time using historical data from the LTBP InfoBridge (InfoBridge Web portal). The National Bridge Inventory (NBI) rating system uses a 0 to 9-point condition scale for three primary bridge structural components: (i) deck; (ii) superstructure; and (iii) substructure (9 being excellent condition and 0 implies absolute failure). A bridge is considered structurally poor if one component has a condition rating of 4 or less. It is observed that the bridge deck reaches condition State 4 in 2064. Therefore, the service life of UHPC overlay is about 50 years.



Source: Adapted from LTBP InfoBridge database

Figure C-2. Bridge deck condition rating over time.

Maintenance and Rehabilitation Activities for Alternative 2

Figure C-3 shows a schematic life-cycle activity diagrams for alternative 2 with maintenance and rehabilitation interventions over the period of analysis. Preventive maintenance is scheduled every 15 years considering that 10% of the deck area needs repair. At year 50, the entire slab overlay is replaced.

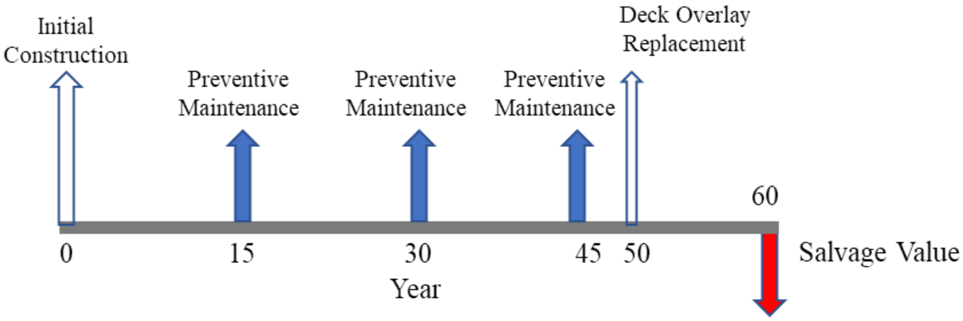


Figure C-3. Life cycle activities for alternative 2, Case Study 3.

Agency Costs for Alternative 2

In this example, the UHPC material costs are $375 per cubic ft. The cost estimate is based on information from the ABC-UTC project database.

So, for 1-inch UHPC overlay:

1 inch = 0.083 ft, and

$375 * 0.083 = 31 $/sft`

The summary of agency costs over the period of analysis is shown on Table C-3. The salvage value is calculated based on remaining life of the bridge deck which is 40 years.

Table C-3. Agency costs for alternative 2 (UHPC overlay), Case Study 3.

Year	Activities	Agency Costs	Discount Factor (3% rate)	Present Value
0	Initial Construction	$67,549	1	$67,549
15	Preventive Maintenance	$6,727	0.642	$4,318
30	Preventive Maintenance	$6,727	0.412	$2,771
45	Preventive Maintenance	$6,727	0.264	$1,776
50	Overlay Replacement	$67,549	0.249	$16,837
60	Salvage Value	-$54,039	0.17	-$9,187
			Total	**$84,064**

User Costs for Alternative 2

The UHPC overlay is built in two separate segments over the course of two days as same as epoxy overlay. Therefore, the traffic delay effects for alternative 1 and 2 are similar.

Alternative 2 has initial construction and one overlay replacement. The assumptions and calculations are the same as described in alternative 1. The difference is that alternative 2 has only one replacement activity. Therefore, the total delay cost for alternative 2 is $19,620.

Net Present Value and Equivalent Annual Costs for Alternative 2

Table C-4 shows the total net present value and equivalent annual cost.

Table C-4. Total Net Present Value and Equivalent Annual Cost for alternative 2, Case Study 3.

Cost	Alternative 2 UHPC Overlay
Agency Cost	$84,064
User Cost	$19,620
Total Net Present Value	$103,684
Equivalent Annual Cost (EUAC)	$3,746

C.4 RECOMMENDATION BASED ON LCCA RESULTS OF CASE STUDY 3

The UHPC overlay in alternative 2 is recommended since the total NPV, including agency and user costs, is lower than the epoxy overlay in alternative 1. For the UHPC overlay, the life expectancy is higher than epoxy overlay in alternative 2 and needs less maintenance. The user cost has a great effect on the total net present value. Figure C-4 shows the NPV cost of the two alternatives.

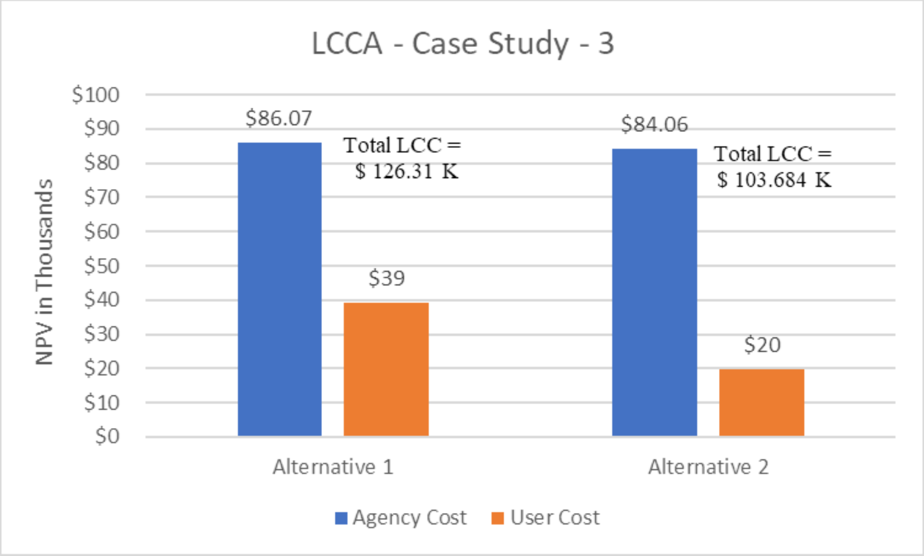
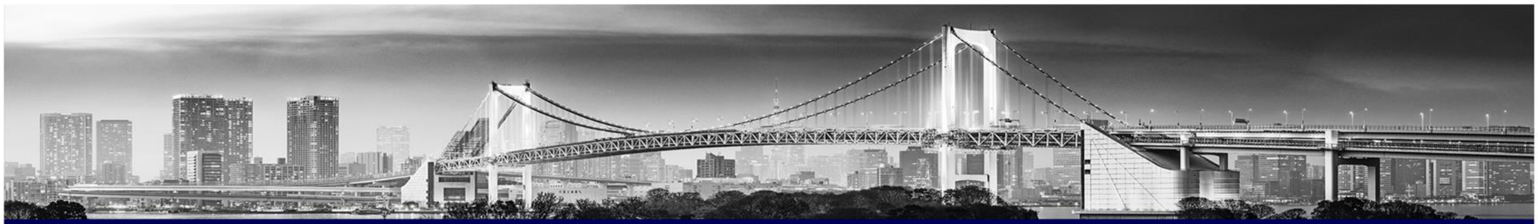


Figure C-4. NPV cost of alternative 1 and alternative 2, Case Study 3.

C.5 REFERENCES

Morcous, G. 2013. "Life-Cycle Assessment of Nebraska Bridges" Final Report. Project Number SPR-P1(12) M312. Nebraska Department of Transportation (NDOR).

Soliman, M., Ahmed, S. A., Shen, L. 2019. "A Comprehensive Framework for Life-Cycle Cost Assessment of Reinforced Concrete Bridge Decks".Transportation Consortium of South-Central States (Trans-SET) ,USDOT.



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