A General Code to Represent the Mathematical Life Cycle Cost Model of Bridge

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A GENERAL CODE TO REPRESENT THE MATHEMATICAL LIFE CYCLE COST MODEL OF BRIDGE

by

Bajel Mohammed Alshadeedi

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering (Industrial)
Industrial and Entrepreneurial Engineering and Engineering Management
Western Michigan University
December 2016

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A GENERAL CODE TO REPRESENT THE MATHEMATICAL LIFE CYCLE COST MODEL OF BRIDGE

Bajel Mohammed Alshadeedi, M.S.E.

Western Michigan University, 2016

There are many factors that play a role in the overall cost of any bridge. The life cycle cost needs deep knowledge of bridge components to calculate its subcategories costs. The bridge life cycle cost is divided into; agency, user cost, and society costs. The agency cost includes the expected value of the final bridge construction cost, the inspection cost, better value of repainting cost, and replacing asphaltic deck cost. The user cost includes traffic delay cost and vehicle operation cost under different traffic conditions, accident cost, and failure cost. The society cost includes aesthetical and environmental impact. All costs are estimated during the same analysis period.

This thesis focuses on using a mathematical life cycle cost model for bridges that emphasizes on the agency, user, and society costs of a bridge over its useful life. MATLAB program is used to build a program that is used to calculate the life cycle cost of any bridges based on its characteristics.

The mathematical life cycle model for bridges is calculated in six different case studies in Michigan state. “Pontis 4”, which is a database of bridges, and Michigan department of transportation MDOT are both used to get the bridges characteristics for each case study.
Acknowledgments

I would like to express appreciation for several people who have helped and supported my degree and this thesis work. First, I would like to thank my thesis supervisor and committee chair, Dr. Azim Houshyar who offered valuable advice, support, and feedback throughout my project. Secondly, I would like to thank Dr. Osama Abudayyeh, Dr. Steven Butt, and Dr. Diana Prieto for their participation on the thesis committee, and for their evaluation and feedback. Thanks for Michigan Department of Transportation for their collaboration with me. Next, I would like to thank my devoted husband Mohammed Khalil Hussain and my daughters for their love and patience, my mother for her prayers. Finally, I would like to thank all of my sisters and brothers, relatives, and friends for hoping good wishes to me during this chapter of my life.

Bajel Mohammed Alshadeedi
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CHAPTER I

INTRODUCTION

1.1 Introduction

Reliability has a wide meaning in our daily life. In technical terms, reliability is defined as ‘the probability that a product performs its intended function without failure under specified conditions for a specified period of time’. The reliability definitions give three important elements which are: intended function, specified period of time, and specified condition. Probabilistic and statistical methods measure the reliability. Therefore, probability theory and statistics are important mathematical tools for reliability engineering. Reliability engineering is used to ensure the user that the operated product is dependable during its service life. In other words, the function of reliability engineering is to avoid failures [1].

Life cycle cost LCC attempts to ensure the optimum selection and represent different alternatives of physical assets. LCC is appropriately applied to compare project implementation alternatives that would yield the same level of service and benefits to the project user. The agency that uses this tool has already decided to undertake a project or improvement and is seeking to determine the most cost-effective means to accomplish the project’s objectives. Life cycle cost analysis LCCA is an economic analysis tool that is used to identify the preferred option among the population of possible alternatives [2].
Generally, bridge investment and management decisions are multi-alternative-oriented. Life-Cycle Cost (LCC) is the cost of an asset, or of its parts, throughout its life cycle while it fulfills the performance requirements. To effectively implement LCC for bridges, it is important to be aware of the different bridge investment phases and their internal activities. It is also important to be familiar with the various types of bridge contracts [3].

Bridges agencies and the projects managers may be district by an attractive acquisition cost. However, they will pay high running costs in later years. Lowest constructing price does not necessarily minimize total cost over the whole life of the asset, therefore, does not maximize profits. The whole life cycle cost of a bridge consists of the total investment throughout the life of the bridge. The investment includes the initial construction cost, repair and rehabilitation costs, traffic delay cost, vehicle operation cost, environmental impact and aesthetical cost, and all maintenance costs. An ability to determine the whole life cost of a bridge will help agencies evaluate the asset value of existing bridges, make better decisions on the design and construction of new bridges, and choose methods and approaches for rehabilitating existing structures. In this case, the lowest life cycle cost is achieved rather than the lowest initial cost [4].

In the United States (2003) there are about 590,000 bridges of which 27% are considered to be structurally deficient or functionally ignored. When building a new bridge or preserving and improving an existing bridge, it is necessary to estimate how long the bridge will last and how much it will cost initially and overtime [4].
Several indicators demonstrate significant deficiencies in United States infrastructure systems. In 2001, an estimated one-third of United States roadways are in poor or normal condition, burdening the public with construction-related impacts such as congestion and vehicle damage. Poor roadway conditions continue despite the continued investment in highways and roads of approximately 260 million tons of concrete annually in the United States. While United States consumption is significant, global construction related concrete production exceeds 12 billion tons/year. This production rate, which represents huge flows of material between natural and human systems, is expected to increase significantly as world population urbanizes. Concrete consumption plays a key role in global development. Cement, the key constituent in concrete, poses several major environmental challenges. Cement production is energy intensive and accounts for 5% of global anthropogenic CO2 emissions and significant levels of SO2, NOx, particulate matter and other pollutants. As global concrete and thus cement production rise, environmental burdens will increase too. Implementation of alternative materials in design and repair could serve to improve the environmental performance of concrete infrastructure [5].

Concrete pavements and structures such as bridges are fundamental components of the transportation network, and thus also fundamental to economic vitality and personal mobility. The American Society of Civil Engineers estimates that the poor conditions of United States roads cost users $117.2 billion in added operating costs and time lost in traffic delay annually. Poor roadway conditions persist despite economic and material investment in highways and roads of approximately $64.6 billion and 260 million metric
tons of concrete annually in the United States. An integrated LCCA model was developed to provide an assessment of the economic costs of concrete bridge deck [6].

The average American bridge is now 43 years old. The American Society of Civil Engineers (ASCE) estimates that the total investment needed to bring the nation’s bridge infrastructure up to over 5 years is $930 billion, but in that time only $549.5 billion is being spent. Funding is limited but its allocation may make up the difference in the long run. Better management of funds used to inspect and maintain existing bridge infrastructure could reduce costs [7].

For state transportation agencies that have already adopted asset management practices, the goal is to maintain their infrastructure at its current condition. Infrastructure managers also model the performance of a structure over time to predict when maintenance, repair or rehabilitation will be necessary [7].

The objective of LCC is to compare alternative bridge deck designs from a sustainability perspective that accounts for total life-cycle costs including agency, user, aesthetical costs and environmental impact. To calculate the life-cycle cost, information on the time and cost of bridge replacement is needed. In this thesis, a bridge life cycle cost analysis is used to satisfy the agency, user, and social decision standard to minimize overall cost. It has been successfully used by many agencies for decision making regarding the repair, maintenance, rehabilitation and replacement of bridge infrastructure.

A mathematical life cycle cost model for bridges uses to emphasize on the all subcategories related to agency, user, and society costs of a bridge over useful life. It calculates six different case studies in Michigan. “Pontis 4”, which is a database of
bridges, and Michigan department of transportation MDOT are both used to get the bridges characteristics for each case study. MATLAB program is used to build a program that is used to calculate the life cycle cost of any bridges based on its characteristics.

1.2 Objectives
- Building a bridge life cycle cost mathematical model by using previous researches.
- Computing the expected cost of bridge life cycle cost as a function of time and age to find the lowest cost.
- Building a computer model to make the life cycle cost calculation e for any bridge.

1.3 Literature Review

The following are some important works related to the calculating a bridge life cycle cost, also known as illuminated line.

In 2008, A. Kendall et al. developed and applied a life cycle cost analysis model to enhance the sustainability of concrete bridge infrastructure. The model is compared between two alternative bridge deck designs; a conventional concrete bridge deck and an alternative engineered cementitious composite link slab design. Model results show reduced costs for the engineered cementitious composite link slab design [6].

In 2002, T. Zayed et al. [8] used an economic analysis EA, which is a deterministic method, and the Markov decision process MDP, which is a stochastic method, to carry out the life-cycle cost analysis. The methods were used to analyze and differentiate among the proposed rehabilitation scenarios. The results of the EA were different from those of MDP.
The EA proved its superiority over MDP. The results indicated that the best rehabilitation scenario for four paint categories, interstate paint types 1 and 2 and state paint types 1 and 2, is doing spot repairs every 10 years.

In 2001, D. Frangopol et al. [9] showed that current highway bridge management systems have limitations. The limitations can be overcome by using a reliability-based approach. Future bridge management systems have to be reliability based.

In 2014, A. Saviotti [10] provided a review of recent studies and research accomplishments in the field of bridge assessment, management and life cycle analysis. The study highlighted a need to focus these studies on relevant problems.

In 2004, M. Stewrat et al. [11] investigated the effect of limit state selection (strength versus serviceability) on bridge deck life-cycle costs and thus on optimal repair strategies. Life-cycle costs for deck replacement based on a serviceability are generally larger than those obtained for a strength. The researchers in lifetime of concrete structures under aggressive environments and in structural reliability must work together to develop a rational procedure for life-cycle cost analysis.

In 2013, S. Lee et al. [12] examined an effective repair system for deteriorated steel bridge piles without the need of dewatering. Three federal-level LCCA computer programs (BLCCA, BridgeLCC and RealCost) were evaluated and compared comprehensively, with the emphasis on their adaptability and suitability to bridge pile repair projects.
In 2005, Keoleian et al. [13] developed an integrated life cycle assessment and cost model to evaluate infrastructure sustainability. The study compared alternative materials and designs using environmental, economic and social indicators. The model is applied to two alternative concrete bridge deck designs: one a conventional steel reinforced concrete (SRC) deck with mechanical steel expansion joints, and the other an SRC deck with engineered cementitious composite (ECC) link slabs. The results showed that the ECC link slab bridge deck design resulted in significantly lower environmental impacts and costs over a 60-year bridge deck service life compared to the conventional steel expansion joint system.

In 2014 P. Panetsos et al, [14] used Deterioration models to predict future needs during the life cycle of concrete bridges. The study developed empirical deterioration curves representing Greek climate conditions and construction reality. These empirical curves represent bridges that were not systematically inspected and maintained, due to the lack of available financial resources.

In 2009 L. Du et al, [15] analyzed several life cycle cost methods and models to help engineers to make a decision and the life cycle reliability-based design model is provided. The study analyzed several life cycle cost methods and models to help designers to choose a suitable life cycle cost model. Then proper design to-cost or design-for-cost model can be reasonable established. The robust design optimization model is also provided.
In 2001 A. Estes et al., [16] proposed the use of serviceability flags as a means to incorporate serviceability concerns into a strength-based reliability analysis. The study demonstrated how an optimum inspection plan can be developed based on nondestructive evaluation test results for a strength-based system reliability analysis.

In 2009 P. Manamperi et al., [17] developed a statistical model to predict the future condition of bridges using the condition inspection data collected over the last 15 years. The study verified various models for structural deterioration. A stochastic process was considered to provide the best method for the estimation of continuous deterioration of elements over time. A study was conducted for the fit of various distributions in the data to corresponding probability distributions of the stochastic process.

In 2008 Y. Zhang et al., [4] showed that the achievable useful life of bridge can be more than 100 years, total life cycle cost for 100 years old bridge can be less than five times its initial cost, and timely MMR actions can lower the total life cycle cost of a bridge.

In 2005, Keoleian et al. [5] showed that the engineered cementitious composite ECC link slab bridge deck design resulted in significantly lower environmental impacts over 60 years’ bridge deck service life compared to the conventional steel expansion joint system.

In 2014 M. Safi et al., [3] discussed the need of a bridge management system BMS with integrated comprehensive LCC tools that can assist decision makers in selecting the most cost-effective alternative.
In 1998, A. Horvath et al. [18] presented a life cycle inventory analysis of steel and steel-reinforced concrete bridge girders. The study showed that the concrete design appears to have lower environmental effects overall. However, steel girders are reusable and recyclable at the end of their useful life.

In 1999, I. Molnar et al. [19] presented the problems related to bridges on the other side of the Atlantic Ocean. The study showed the major causes of deterioration are a shortage of funds for proper maintenance, leaking joints, and increase of traffic.

1.4 Thesis Structure

Chapter 1, Introduction: This chapter includes introduction, objectives, literature review, and thesis structure.

Chapter 2, Bridge Components: This chapter explains the bridge major components to determine the bridge life cycle cost. Bridge life cycle cost analysis is a process of evaluating total costs over the life of an asset.

Chapter 3, A Bridge Life Cycle Cost Mathematical Model: This chapter reviews developing the mathematical Life Cycle Costing model about bridges in Michigan. The bridge life cycle cost mathematical model uses Agency cost, User cost, and Social cost for different assigned bridges Concrete and Steel Span Deck.

Chapter 4, Propose Methods for Study: The proposed method for calculating lifetime cost and future replacement costs has been applied on bridges in Michigan. Every bridge consists of major bridge component which are deck superstructure, bearings, and
substructure. The main purpose in this chapter is to present the methodology and perform a thorough comparative analysis for all the different cost categories of bridges.

Chapter 5, Results: The results for life-cycle costs demonstrate that overall the bridges have a cost advantage over their life in all categories assessed. These costs are based on the 75-year service schedule for construction events shown in figures and tables in this chapter.

Chapter 6, Conclusions and Future Work: The main results and contributions of this thesis are summarized.
CHAPTER 2

BRIDGE COMPONENTS

2.1 Introduction

In spite of great variation in the types of bridges, the major components of a bridge are the same. Bridges represent an essential investment of capital. Bridges are expected to provide satisfactory performance and remain in service for many years [20]. Therefore, structural analysis is important to analyze the bridge major components. The main objective of structural analysis is to determine the bridge life cycle cost. Bridge life cycle cost analysis is a process of evaluating total costs over the life of an asset [21].

A bridge is a structure with supports that is helping to cross the barriers, such as water, highway, or railway, and having a route or lane for carrying traffic or other moving loads. Component. The bridge makes the trucks movement easy from one place to another [22].

2.2 Major Bridge Components

Most bridges can be divided into four basic parts which are Deck, Superstructure, Bearing and Substructure as shown in Figure 2.1 below [22].
2.2.1 Decks

The deck is component of a bridge which the live load is directly applied on it, as shown in figure 2.2. The live load is the weight of traffic using the bridge. The purpose of the deck is to provide a smooth and safe riding surface for the traffic employing the bridge. The function of the deck is to transfer the traffic loads to the responsible carrying parts. Figure 2.2 shows the bridge deck cross section [23].

Figure 2.1 Major bridge components

Figure 2.2 Typical cross-section of the surfacing on a bridge deck
Following are the main portion of deck in bridge:

A. Deck Joints it is shorten the length of the deck because the short deck controls concrete cracking. The main goal of joint is to provide an easy and smooth riding and enable an easy maintenance as possible. All joints require preventive maintenance to keep joints functioning and avoid costly structural damage. The performance of all common deck joints can be classified according to their usage because of the wide application of each type. There are two types of Deck Joints: Joints Over Fixed Bearings and Joints Over Expansion Bearings [23].

1. Joints Over Fixed Bearings allow rotation of a beam end, but prohibit translation (longitudinal movement). The fixed bearing is attached to the beam end and anchored in the bridge seat. These joints are typically not as wide as expansion joints [23].

2. Joints Over Expansion Bearings (expansion joints) accommodate motions that occur in the superstructure. Similar to joints over fixed bearings, they accommodate rotational movement. Temperature change has a direct effect on Bridge decks by making a translation movement. As the temperature rises, the deck expands in length, and as the temperature decreases, the deck shrinks. Permanent span length changes over time could happened because of Creep, shrinkage, and prestressing of concrete. Expansion joints can be divided into two categories; open joints and closed joints [23].

a. Open joint systems are used to protect the edges of the concrete deck and transition traffic smoothly across the opening as shown in the figure 2.3.
b. Closed joint systems also protect the bridge components below the joint from damage due to water, salt, and other roadway contaminants associated with deck runoff as shown in the figure 2.4.

There is main different between the two types; Closed joints are designed to be fitted so that no water enters or passes through, while open joints are not.

B. The traffic barriers minimize hazards for traffic on the bridge. Bridge barriers can be broken down into two categories:
1. Bridge railing is important to guide, contain, and redirect askew vehicles.

2. Pedestrian railing is necessary to protect pedestrians.

C. Sidewalks and Curbs used to maintain safety for pedestrians and to direct water to the drainage system. Curbs serve to lessen the chance of vehicles crossing onto the sidewalk and endangering pedestrians.

D. Signing used to inform the drivers about bridge or roadway conditions that may be hazardous. Most important signs likely to be set on the bridge are: weight limit and/or lane restrictions, speed traffic marker, vertical clearance, lateral clearance, narrow underpass, informational and directional, and object markers.

E. Lighting may be faced on a bridge is any of the following; highway lighting, traffic control lights, aerial obstruction lights, navigation lights, signing lights, and illumination and drawbridge operation flashing lights.

2.2.2 Superstructure:

It is a part of the bridge structure which supports traffic and includes deck, slab and girders. All the parts of the bridge which is mounted on a supporting system can be classified as a Superstructure. The basic purpose of the superstructure is to carry loads from the deck across the span and transfer the loads to the substructure. The superstructure is the component of the bridge which supports the deck and the loads applied to the deck. A span is the distance between two bridge supports, whether they are columns, towers or the wall of a canyon.
In this thesis, bridges are categorized by their span type. Steel simple span bridge and concrete simple span bridge crossing different areas are considered in the study. All bridges are beam bridge which is the simplest type of bridge. It is made from a rigid, straight structure resting on supports at either end. Girder and Stringer Elements are main portions of superstructure to carry primary live load. Girders is a strong, supporting beam. In this thesis there are two types of girders, steel and precast prestressed concrete girders [22].

2.2.3 Bearings

Bearing is a component which supports part of the bridge and transmits forces from superstructure part to substructure part of the bridge while permitting angular and/or linear movement between parts. A bridge bearing is an element which provides a point where the superstructure and the substructure meet and interact. There are three primary functions of a bridge bearing:

A. Transmit all loads from the superstructure to the substructure
B. Permit longitudinal movement of the superstructure due to thermal expansion and contraction
C. Allow rotation caused by dead load and live load deflection. Dead load is the weight of the bridge’s structure, and live load is the weight of traffic using the bridge

Bridge bearings are different according to the movement allowance as shown in figure 2.5. First, bearings that do not allow for horizontal movement of the superstructure are referred to as fixed bearings. Second, bearings that allow for horizontal movement of
the superstructure are known as expansion bearings. Both fixed and expansion bearings permit rotation.

Expansion rocker bearing  
Fixes rocker bearing

Figure 2.5 Bearing types

A bridge bearing can be normally categorized into four basic elements, sole plate, stainless steel pin assembly, rocker assembly, and masonry plate [22].

2.2.4 Substructure

The substructure is the component of a bridge which includes all the elements which support the superstructure. The purpose of the substructure is to transfer the loads from the superstructure to the foundation soil or rock. Typically, the substructure includes all elements below the bearings. The loads are then distributed to the earth. Substructures are divided into two basic categories, abutment and pier.

A. Abutment is the portion of the bridge that supports the end of a bridge span, provides lateral support for the approach roadway and approach slab. Abutments may be classified
by their location relative to the approach embankments. The following explains the
details of the main abutment parts as shown in figure 2.6 [24], [25], [26].

1. Approach slab provides a transition between roadway pavement and the bridge. The
approach slab represents an intermediate bridge to help the embankment stretching
directly behind the abutment/backwall [24], [25], [26].

2. Seat is the part of an abutment that the superstructure sits on it.

3. Walls should be used where the construction of a roadway pavement cannot be
accomplished with slopes. Walls can be classified as either retaining walls, or wingwalls.
Wingwalls are used to provide lateral support for the bridge approach roadway
embankment. The whole wingwall would be called a retaining wall for bridges with long
wingwalls that are parallel to the roadway,

4. Foundation: The foundation is that part of the structure that serves to transmit the
forces acting on the abutments, piers, or walls to the ground. Foundations are classified
as either shallow or deep.

5. Piles and Footing: Pile is a slender compression member driven into or formed in the
ground to resist loads. Pile cap (Footing) a reinforced concrete mass cast around the head
of a group of piles to ensure they act together and distribute the load among the piles.
B. A pier is that portion of the bridge to provide an intermediate support between the superstructure and the foundation. Pier types would be selected according to structure aesthetics, foundation recommendations, structure location, and the loads it must transmit to the foundation. Pier Parts can be classified into: pier cap, columns, and piles. Figure 2.7 shows the main parts of a bridge pier [22].
2.3 Bridge Aesthetical and Cultural Value

There is a real balance between safety and appearances. The designers need to achieve the appearance of safety to start the project. The robust aesthetic bridge component should be designed in right way that will decrease its cost. The right design shapes of bridge components need to improve the appearance of bridge not the cost. It is important to put in mind that the cheapest bridge could give the high cost maintenance [27]. Cost and sustainability are assured to the agency to explain and put the future maintenance burden to create such a beautiful bridge. It is valuable to ask the community about the points that they are really want to be improved and included in a bridge or the parts that each bridge. To do this, some steps need to be followed to calculate the bridges aesthetics costs [26].

2.3.1 Bridge Aesthetics Design Guidelines

This must first be considered for aesthetics to be successful. It should be an integral part of design and must be considered both in the general form and all the details that support it. The parts must be considered as to how they contribute to the whole. Generally, bridges seem aesthetically more pleasing if they are simple in form and shape of the structural members. The aesthetics of a bridge should be considered at the conception of a project and through every stage of development. Aesthetics is not something that can be added at the end, it is the final product of the planning, design and procurement process, from initial route selection, through environmental assessment, to detail design and construction [27].
2.3.2 Evaluation Procedure

At the first sight, the easiest way seems to be to establish some jury to evaluate different proposal. The judgment of the jury would be based on individual opinions without an exact scale of measuring. However, the challenge would be converting the judgment to money when comparing different bridges. A jury in the case of bridge construction should consist of experts with right education, profession and position, e.g. owners, bridge engineers and architects. In some cases, even ordinary people of the local community could be represented. For the decision making and base of the work of the jury some guiding principals have to be set up [27].

2.3.3 Comparing Alternatives

The main issue to be clearly stated is, where to put weight when comparing different alternatives. In the decision making the following issues at least should be considered: the whole, the parts, the details, and the finishes [27].

1. The Whole: this part will focus on the following bridge aspects; context and form.
   a. Context sensitive design is a key design value. Indeed, all design requires an understanding of its context. In the past context sensitive design was something that would have occurred naturally. Design that is sensitive to context is valued by communities. Structures and landscapes that fit and enhance context are good for community pride and local identity. They are often more sustainable and self-reliant.
   i. Bridges in the landscape: There are a number of ways to approach bridge design in rural and natural landscape settings, including:
• Hiding the bridge in the landscape, by reducing its size and screening it.

• Making the bridge as distinctive as possible to contrast and stand out in the landscape.

• Making the bridge as simple and elegant as possible to complement the natural landscape or urban setting.

Hiding the bridge in the landscape work on smaller bridges than larger more visible ones. Making the bridge as distinctive as possible can be expensive and is perhaps better suited to urban situations. Making the bridge as simple and elegant as possible is a practical, cost effective objective for overpasses and larger bridges and can lead to good looking bridge solutions. In areas of high scenic value, the following principles should be considered. The built and natural environment should be made as visible as possible through the bridge.

ii. Views from the bridge towards the surrounding landscape or built environment setting should be maximized. Allowing good views of the landscape from the bridge helps establish milestones and landmarks on the route, makes the most of the height of the bridge, improves road user interest and helps make drivers more alert and aware of their surroundings.

iii. The complexity of a bridge should be minimized in a rural setting. Complexity tends to attract the eye and compete with views of the landscape. A simple structure frames the landscape and provides an aesthetically pleasing contrast with the natural textures of the backdrop. Avoiding complexity provide a good landscape contrast.

iv. Bridges with a horizontal form are generally preferable to bridges on a grade over flood plains and significant expanses of water. If this is unable to be achieved due to
differing levels either side of the water body, then fine-tuning the location of the bridge should be considered, or adjusting the levels along the bridge approaches. Water always forms a horizontal plane and a bridge structure when skewed to this plane can appear false. This may be because it introduces another plane adding unnecessary complexity. Figures 2.8 and 2.9 show a skewed and horizontal bridges respectively.

![Figure 2.8 Bridge structure skewed to the water horizontal plane](image1)

![Figure 2.9 Horizontal bridge](image2)

b. Form refers to the external shape or appearance of a bridge and this broadly relates to the bridge type, the parts are arrangement relative to one another and the order or rhythm of elements to create an overall visual result. It is influenced specifically by the following: proportion, symmetry and asymmetry, order and rhythm, simplicity, unity of design, consistency, and detailing.

i. Proportion a random approach to the proportion between different elements of a bridge is unlikely to lead to an aesthetically valued structure. There are fast rules and guidelines can be provided which help to eliminate some of the worst ratios between bridge elements and assist to achieve proper proportion. However, there are always exceptions,
once a bridge type has been selected, there are important factors in creating a well-proportioned Bridge. All of the following things in relationship that influence the aesthetic outcome:

• The slenderness ratio is an important ratio between depth of superstructure and bridge span. It is referred to as the slenderness of the bridge and defined as the span length divided by the superstructure depth. A high slenderness ratio does not necessarily indicate a good appearance, since the visual slenderness of a bridge can be affected by solid parapets making the bridge appear chunkier than is necessary. The setting and scale of the bridge can also influence whether a bridge appears slender or chunky and whether slenderness or chunkiness is appropriate. It is for these reasons that the slenderness ratio should be understood as a guide only.

• The relationship between pier thickness and superstructure depth is the ratio of pier width to superstructure depth which should be considered carefully. Bridges with tall thin piers relative to superstructure depth can appear odd and non-preferable.

• The relationship between deck overhang and parapet depth is the ratio of deck overhang relative to parapet depth should be also considered as a significant aesthetic proportion. Figure 2.10 show the relationship between deck overhang and parapet depth.
ii. Symmetry and asymmetry is another important aspect of form is symmetry. Symmetrical bridges are often more aesthetically pleasing than non-symmetrical bridges. They appear balanced, refined and also thought about. Asymmetry can be perfectly justifiable due to site constraints, technological innovation making new forms possible, symbolic imperatives or artistic endeavor.

iii. Order and rhythm is designing a rational order and rhythm to a bridge and its parts to improve its appearance. A designed order to individual bridge elements can look more pleasing than chaotic randomness. For example, spans should match where possible and show a consistent order. The cumulative effect of all bridge elements including lighting columns, barrier supports and piers should be considered. All the bridge elements can be well designed individually, but lacking an order and rhythm together, create an inconsistent appearance. While rearranging the parts provides an ordered and pleasing whole. Figures 2.11 and 2.12 compare between consistent and inconsistent appearance spans.

Figure 2.10 The relationship between deck overhang and parapet depth
iv. Simplicity: Refinement of design should generally be pursued. Nonetheless, it is unwise to insist that a bridge is perfect only if nothing can be omitted; there may be good reasons for avoiding total refinement based upon local context.

v. Unity of design: A bridge is a whole, not an assemblage of parts. Consequently, consider the parts as to how they contribute to the whole of a bridge. The approaches to the bridge are an integral element of the whole bridge design and must be considered in the design process. The landscape design, the approach road design, and all the associated signage contribute to the bridge design as a whole.
vi. Consistency of form is an important aesthetic consideration. This is not to say that everything must look the same but that in a particular context there should be a relationship between elements in terms of materials, proportion, color or details.

vii. Detail: Attention to detail is essential to good bridge design. Lack of attention to detail can spoil an otherwise beautiful bridge. Careful consideration of the interrelationship of each element and their relationship with the whole is necessary at all stages of the design process.

2. The parts: this part will focus on the parts of the bridge. The main parts are; superstructure, substructure, and the bridge curtilage [27].

a. Superstructure: which is contain the following parts; parapet and girder.

i. Parapet: The outer face of the parapet can be one of the most important aesthetic elements of a bridge. For most bridges it is the highest element and often the most dominant in long distance views. It can also be the longest piece of the bridge and as such an opportunity to express the span and horizontal nature of the structure. Figure 2.13 shows the bridge parapet dimensions.
ii. Girder: The girder seen in elevation and its cross sectional shape are important considerations discussed below. The horizontal alignment of the girders is also important especially on curved bridges.

- Girder elevation: Hunched girders are expressive and responsive to the forces in the bridge. They can often be more distinctive and elegant than single depth beams as shown in figures 2.14 and 2.15.
The following principles should be considered in the design of hunched girders; Three or five span haunches are generally aesthetically very elegant, balanced structures as shown in figure 2.16.

Long haunches smoothly tapering out are much more graceful and responsive than short abrupt haunches as shown in figure 2.17. As well as, avoiding a sharp angle between haunch and beam is recommended as shown in figure 2.18. Even with single spans, curving the girder can provide an expression of elegance as shown in figure 2.19.
Figure 2.17 Long versus short haunches

Figure 2.18 Avoid a sharp angle between haunch and beam.

Figure 2.19 Curving the girder

iii. Girder cross section: Different girder cross sections can have different aesthetic effects. The cross sectional shape of the girder should be considered with attention to the following principles:
A right angled connection can catch the light and a double line may be visible; maximizing the overhang will increase the duration of shadow as shown in figure 2.20. An angled connection will minimize this effect as shown in figure 2.21. On the other hand, a very acute angle provides a deep shadow nearly all of the time as shown in figure 2.22.

Figure 2.20 Right angled girder cross section

Figure 2.21 An angled connection
A curved soffit will provide a gradation of tone and minimize a sharp line at the base of the beam as shown in figure 2.23.

b. Substructure: which is contain the following parts; headstocks, piers, pile caps, and abutments.

i. Headstocks (Pier Caps) transfer the load from multiple girders to the pier column. They are the equivalent of the post and lintel construction in architecture. They should be
integrated with the pier rather than designed as a separate, visually unrelated element to avoid additional visual complexity. If possible headstocks should not extend up and across the outer face of the girder. This introduces unnecessary complexity and appears in elevation as if the headstock is providing support to the deck. Where possible the headstock should be the same width and shape as the pier column.

ii. Piers: Longitudinal pier spacing which is the result of a number of factors including; the nature of the space being bridged (eg a deep valley or ecologically sensitive environment will require wide spans), the height of the bridge, and the balance between superstructure cost and pier cost.

In general, long spans on low bridges can look odd, as can short spans on high bridges. A balance is required which should respond to the best structural form and the wisest use of resources.

• Multiple piers: Where multiple piers are used, consideration should be given to allowing them to be separate elements. When placed too closely multiple piers can appear complex or wall as shown in figure 2.24.

Figure 2.24 Separate versus closely piers
Single pier units are more simple, reduce the number of elements in the view and allow the superstructure to become the dominant visual element. Multiple piers on the other hand can provide a sense of strength and durability and if well designed can provide interest and character. The selection of multiple or single piers should be a consequence of the context and the requirements of the bridge.

- Pier cross section: Pier shapes with only two lines of symmetry (e.g., rectangles or ellipses) and transverse to the centerline of the deck is generally preferable to squares and circles as they present the thinnest edge to the side view (short elevation) as shown in figure 2.25. However, where bridges are used in multiples as at large interchanges or when they are highly skewed a circular column can be an aesthetically effective solution. Elliptical shapes have the additional feature of providing a softer graduated reflection of light when seen in elevation.

![Figure 2.25 Elliptical shape](image)
Where complex shapes are used, such as a rectangle with semicircular ends, care must be taken to ensure a consistent smooth finish. Joints in shuttering and different color and finish between concrete pours can cause visual problems. Rounding off the corners of rectangular piers provides a softer form, which may be preferable in certain contexts, for example, where the presence of the pier needs to be downplayed so that superstructure is dominant, as in a rural setting. A sharper edge may be preferable where the pier is to be accentuated because it is the dominant element, such as in an urban context or where piers are particularly high as shown in figure 2.26.

![Figure 2.26 Rectangle with semicircular ends pier](image)

- Pier longitudinal elevation: The shape of the pier long elevation (ie perpendicular to the road alignment) is also an important aesthetic consideration. It can have a profound influence on the appearance of the bridge. Wall type piers can appear simple and remove the need for a headstock as shown in figure 2.27. However, on wide bridges such as duplicated highway river crossings, they can use a significant amount of concrete and can
appear heavy, increasing shade and darkness. As an alternative a frame type pier can allow more light to penetrate the underside of the bridge and can also eliminate the need for a headstock.

![Wall type pier](image)

Figure 2.27 Wall type pier

The long elevation of the pier can also be tapered. Again a taper can appear elegant and better represents the structural forces acting upon the pier. A strong rigid connection between pier and superstructure may be desirable with a light contact on the ground. Alternatively, a wide splay on the ground visually supporting large side forces may be desirable as shown in figure 2.28.

![Taper pier type](image)

Figure 2.28 Taper pier type
An open voided pier type is also an option. They can reduce bulkiness, appear refined and allow views, but care should be taken not to introduce further complexity than is necessary. They can be effective visually as they give a light connection to the girder.

iii. Pile caps: As piles are needed to support piers in soft ground, pile caps are often a feature of bridges crossing water courses as shown in figure 2.29. They perform an additional function in navigable waterways in that they help protect the pier. For safety reasons, they need to be visible to boats and shipping. They present an aesthetic challenge in that they form the footing to the pier.

![Figure 2.29 Pile cap](image)

Where pile caps are visible there are some guiding principles:

- Pile caps should mimic the shape of the pier as far as possible.
- The proportion of pier size to pile cap size should be considered. Imbalanced proportions should be avoided as shown in figure 2.30.
• In a tidal watercourse the view of the piles below the cap should be avoided. To do this, the pile cap may require a skirt as shown in figure 2.31.

iv. Abutments: In an open landscape setting, spill through abutments are generally preferable, as walled abutment structures can block views. In some circumstances walled abutments can be appropriate and help provide a good fit with surrounding built form.
They can also heighten the visual effect when used to mark change points in the character of the landscape, such as at the edge of a forest or at the high point of the road. Walled abutments can reduce the slender appearance of the bridge, block the flow of the landscape and confine views as shown in figure 2.32:

![Figure 2.32 Walled abutments](image)

Reducing the abutments can create a more refined and better looking bridge. It does however increase the span and therefore depth of beam as shown in figure 2.33:

![Figure 2.33 Reducing abutments](image)

Continuing the superstructure or the parapet above the abutment allows the shadow line to reduce the dominance of the abutment, and makes the bridge appear longer and more elegant as shown in figure 2.34:

![Figure 2.34 A continuous parapet above the abutments](image)
Angling the abutments provides a more open sleek look and helps visually anchor the span as shown in figure 2.35.

Figure 2.35 Angled abutment

Spill through abutments allow open views to the landscape and better visibility to the road beyond as shown in figure 2.36.

Figure 2.36 Spill through abutments

c. The bridge curtilage is the space around and under the bridge. It is integral to the visual success of a structure, just as a garden is integral to a house. It is distinct from the context of the bridge. The design of the bridge curtilage is integral to the success of the bridge as a whole. The curtilage can be addressed in terms of the space around the bridge and the space under the bridge.

i. The space around the bridge; There should be continuity between the existing landscape and the space around the bridge. Where possible the space should be designed so that it complements the adjacent landscape character.
ii. The space under the bridge; The space under a bridge must be considered in the concept design phase of the bridge and integrated into the design of the whole structure.

3. The Details: It is often the small things that can make or break a design, and this is especially important with bridges where the details are highly visible.

a. Joints and connections: The joints in bridge structures at the ends of the span or along the superstructure are an opportunity to enhance the bridge design and provide another level of detailed aesthetic interest. Differentiate between bearings and other connections and recognize these in the design.

b. Bridge barriers: The design of the bridge barrier can influence views from the bridge, influence the apparent depth of the superstructure and reduce the slenderness ratio. If views and slenderness are to be maximized the bridge barrier should be as transparent as possible which means using bridge rail rather than a full height parapet. A two rail barrier is better than a single rail barrier in this respect as shown in figures 2.37 and 2.38.

Figure 2.37 A single rail barrier
Consideration should be given to the transition between the bridge barrier and the road safety barrier. A neat simple connection should be designed. The post for bridge barriers should generally be perpendicular to the bridge.

c. Safety screens is designed to prevent objects being thrown from the bridge and damaging vehicles or injuring people below. These screens should be an integral part of the bridge design. There are several aesthetic considerations; Screen posts should align with the safety barrier posts and be perpendicular to the Bridge. Also, the screens should extend to the ends of the bridge span as shown in figure 2.39.

d. Signage and advertising: With the exception of name plates and navigation signs, signage should be kept off bridges if at all possible. They add clutter and complexity and
detract from the structure. They also obstruct views from the bridge. If a bridge and its location is deemed suitable as an outdoor advertising site, then the advertising structure needs to be designed as an integrated bridge element with consideration of its visual effect. As a minimum, the soffit of the bridge should not be obscured and the sign should not block views of the key structural elements such as cables, arches and bearings or views from the bridge.

e. Lighting fixtures: Where possible lighting on bridges should be minimized or avoided. Where necessary it should be designed as part of the bridge with supports elegantly designed and well detailed. The light columns should relate to the other bridge elements in position and form.

4. Finishes: this part deals with the last touch after a bridge were constructed. The main aspects in finishes part are; color, concrete quality and feature lighting.

a. Color: The choice of color can cause the bridge to relate to its setting or contrast with it. It can relate to the land colors or sky colors. The effects of colors will not always be dramatic. The use of bright primary colors, tend to represent a culturally appropriate design; such as traditional Chinese bridges or unique icon bridges such as; the Golden Gate. A neutral palette of black, grays and white tend to give a clear definition of the bridge as an object in the landscape. RMS bridge grey is often a wise choice. The use of white on old and modified timber bridges have become favored as a distinguishing characteristic of such bridges and marks them well in the landscapes in which they sit. The urban context may give better opportunities for the use of color, but as bridges tend to be highly visible elements in the townscape the use of color should be carefully
considered. There is also the opportunity to introduce color in the lighting of the bridge. This can be cost effective and, in the case of LED lights, able to be changed.

b. Concrete quality: Bridge aesthetics can be affected by the quality of the concrete finish. A poor finish with staining or voids can mar an otherwise fine structure. This is particularly important if the bridge structure is visible and accessible. It is preferable to use steel shuttering and pre-cast factory made elements for highly visible bridge parts such as piers, girders and parapets to ensure a controlled, high quality finish. Concrete surfaces close to traffic and accessible to the public should have a class one finish.

c. Feature lighting: There is an opportunity to light the bridge as a whole depending on context, cost, safety and environment constraints. Where appropriate feature lighting of bridges can extend the aesthetic benefits of a bridge throughout a day and make them a positive presence in the night. Lighting can also enhance the safety and passive surveillance around a bridge. Lighting should be energy efficient, avoid light spill and be easy to maintain. It should also respect the structural qualities of the bridge – accentuating the materials and main structural elements such as piers, arches and girders. That is not to say the feature lighting should not be dynamic and creative. LED lighting systems can be designed to provide both subdued and imaginative effects at different times of the day or calendar.
CHAPTER 3

A BRIDGE LIFE CYCLE COST MATHEMATICAL MODEL

3.1 Introduction

Life cycle cost analysis is defined as “a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment.” [28]

Life cycle cost analysis is an economic analysis tool that is used to identify the preferred option among the population of possible alternatives. It is used to satisfy the asset management decision criterion that minimizes the overall cost. Also it has been successfully used by many bridge construction agencies to decide the best alternative regarding the repair, maintenance, rehabilitation and replacement of pavement [29] [2]. Most life cycle cost analysis is focused largely on pavement management systems to make better investment decision than others [30].

Life Cycle Cost (LCC) is the total cost of owning an item during its life. The cost of using and maintaining a bridge over its life cycle is frequently more than the initial constructing cost. Properly applied, LCC analyses include, in addition to the initial constructing cost, a specification of using requirements, a prediction of maintenance expenses, and a plan illustrating major life-cycle activities for the bridge. LCC concepts can be used to develop a financial model where appropriate consideration is placed on
recurring costs such as maintenance, operating, and disposal costs [31]. This thesis reviews a developing mathematical Life Cycle Costing model of bridges in Michigan which are studied and analyzed. The bridge life cycle cost mathematical model uses Agency cost, User cost, and Social cost. The assigned bridges in Michigan are Concrete and Steel Span Deck [17].

3.2 Basic Calculation Methods For Bridge Life Cycle Cost

Different contributions in a complete LCC analysis of a bridge structure could be divided into:

Bridge Life Cycle Cost = Agency cost + User cost + Society cost (Aesthetical & Cultural Value and Environmental Impact costs). [32] Figure 3.1 shows the bridge life cycle categories.

![Figure 3.1 Life cycle cost analysis](image)
3.3.1 Agency Costs

Agency cost is the part of the total life cycle cost. It is paid by the owner of the structure during the project whole life. The economical tool used for evaluating the agency cost of the different bridges in this thesis is net present value. Net present value was used to calculate the discounted future agency cost over the total life of the bridge [33]. The agency cost can be divided into different parts according to; acquisition cost, construction cost, maintenance rehabilitation and repair MR&R costs (the cost for future operation, maintenance, repair and disposal of the bridge), and deck replacing cost as shown in equation (3.1) [2].

\[
LCC_{Agency} = acquisition\ cost + construction\ cost + MR&R\ costs + deck\ replacing\ cost \quad (3.1)
\]

A. Acquisition cost is the cost for gaining of the project including all relevant costs for programming and designing of the project. The cost of study and design work prior to construction is estimated $100,000. The probability that these costs will be $100,000 is assumed to be 100 percent. So, the estimate is judged to be relatively reliable and no probability values will be assigned [2].

B. Construction cost: is the cost for building the bridge including all relevant costs for material and labor of the bridge construction. The net present value is used to calculate the cost to a first opening time of the bridge.

Construction cost per one square meter is estimated at $1,818/ square meter for the steel alternative and $2000 per square meter for concrete bridge.
Construction Cost = cost per one square meter * deck area

Construction is scheduled to take two years following a one-year final design period. The cost is assumed to be paid half in year 2 and half in year 3. This alternative would open for service at the start of year 4. Because this is a new bridge, to be constructed under “greenfield” conditions and with minimum need to work within existing roadways, user costs, e.g., for traffic delays, during construction is neglected.

The present value (PV) of the best estimate of construction cost by using the basic one-time-event discounting equation is calculated as shown in equation (3.2).

\[
P V = \frac{0.5 \times \text{Construction cost}}{(1 + \text{Discount Rate})^2} + \frac{0.5 \times \text{Construction cost}}{(1 + \text{Discount Rate})^3}
\]  

(3.2)

The expected value (EVo) which is bridge construction cost used of the final construction cost. Competition among bidders, changes in material prices, or other cost variances could influence the final construction cost, so the cost will be treated as uncertain as shown in table 3.1:

Table 3.1 Probability mass function of the final construction cost [2]

<table>
<thead>
<tr>
<th>Contract/final</th>
<th>10% below estimate = PV₁</th>
<th>At estimate of Construction Cost = PV₂</th>
<th>10% above estimate = PV₃</th>
<th>20% above estimate = PV₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV of cost</td>
<td>PV - 0.1 * PV</td>
<td>PV</td>
<td>PV + 0.1 * PV</td>
<td>PV + 0.2 * PV</td>
</tr>
<tr>
<td>Probability</td>
<td>0.10</td>
<td>0.60</td>
<td>0.20</td>
<td>0.10</td>
</tr>
</tbody>
</table>
The expected value of the final construction cost discounted to time zero can be calculated as shown in equation (3.3) [2],

\[ EV0 = (PV_1 \text{ of cost} \times \text{Probability 10\%}) + (PV_2 \text{ of cost} \times \text{Probability 60\%}) + (PV_3 \text{ of cost} \times \text{Probability 20\%}) + (PV_4 \text{ of cost} \times \text{Probability 10\%}) \]  

(3.3)

The expected value is generally a better value to use than the best estimate since it reflects the “average” or mean cost rather than the median cost. In general, uncertain costs can be represented by a distribution that is skewed to the left: i.e., there is more cost uncertainty to the up-side that to the down-side. For this case the best estimate is less than the expected value. If the analysis including uncertainty were conducting, the individual PVs and probabilities would be used instead of the expected value [2].

C. LCCMR&R (sometimes denoted LSC Life Support Cost): is the cost for future operation, maintenance, repair and disposal of the bridge. The inspection cost and the repainting cost are studied in this thesis [2]

1. Inspection cost: It will be assumed that the bridge is inspected every two years at a cost of $1000 per occurrence. This can be treated as a uniform annual payment of $500 per year for 75 years using the standard uniform-annual payment formula as shown in equation (3.4).

\[ PV_{75} = 500 \times [(1 + r)^{75} - 1]/[r \times (1 + r)^{75}] \]  

(3.4)
The inspections will not start until year 6, two years following the completion of construction. The present value of the first four payments is then deducted (i.e., $500 are accrued in years 5 and 6 for the first inspection) as shown in equation (3.5):

\[
P_{V_4} = 500 \times \frac{((1 + r)^4 - 1)}{r \times (1 + r)^4}
\] (3.5)

The estimated present value of inspections then is \( P_{V_7} - P_{V_4} \); this number will be treated as relatively certain.

2. Repainting cost: The bridge requires repainting frequently. These painting projects will be assumed that they can be carried out from beneath the bridge and do not affect the traffic. There are no painting-related user costs. The probable agency cost is uncertain. Repainting methods could reduce future repainting costs and new paints may last longer; on the other hand, environmental regulations may become more stringent. To model these uncertainties individually would be excessive for hand calculation, so assumptions will be made simplifying:

The paint-job’s service life is estimated to be 15 years, with a 10% chance of being only 12 years and a 20% chance of being 18 years; estimated cost is $136.36/m², with a 20% chance of being 20% less and a 20% chance of being 30% more. The following table 3.2 summarizes these assumptions [2].

<table>
<thead>
<tr>
<th>Service life</th>
<th>12 years</th>
<th>15 years (best est.)</th>
<th>18 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.1</td>
<td>0.7</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 3.2 - continued

<table>
<thead>
<tr>
<th>Cost</th>
<th>$C_1 =$ estimated cost -0.2* estimated cost</th>
<th>$C_2 =$ estimated cost</th>
<th>$C_3 =$ estimated cost +0.3* estimated cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.2</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Expected Cost</td>
<td>= 0.2* $C_1$+0.6* $C_2$+0.2* $C_3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The best estimate is that repainting will be required in years 15, 30, 45, 60, and 75. The best estimate of the expected present value of repainting costs is then computed as shown in equation (3.6) [2].

\[
PV_E = \frac{\text{Expected Cost}}{(1 + r)^{15}} + \frac{\text{Expected Cost}}{(1 + r)^{30}} + \frac{\text{Expected Cost}}{(1 + r)^{45}} + \frac{\text{Expected Cost}}{(1 + r)^{60}} + \frac{\text{Expected Cost}}{(1 + r)^{75}}
\]  

(3.6)

This can be considered the median value. If the costs and timing are assumed independent, a better value can be calculated by considering all possible combinations as shown in equation (3.7) [2]:

\[
PV = 0.1 \times [\text{Expected Cost} \times ((1 + r)^{-12} + (1 + r)^{-24} + (1 + r)^{-36} + (1 + r)^{-48} + (1 + r)^{-60} + (1 + r)^{-72})] + 0.7 \\
+ [\text{Expected Cost} \times ((1 + r)^{-15} + (1 + r)^{-30} + (1 + r)^{-45} + (1 + r)^{-60} + (1 + r)^{-75})] + 0.2 \times [\text{Expected Cost} \times ((1 + r)^{-18} + (1 + r)^{-36} + (1 + r)^{-54} + (1 + r)^{-72})]
\]  

(3.7)
D. Deck replacing cost: Another recurring maintenance item will be replacing the asphaltic deck overlay every 10 years. Assuming that the overlay costs $25/square meter to replace the deck area in square meter [2].

The cost of each replacement overlay

\[ \text{The overlay costs } $25/\text{square meter} * \text{deck area} \]

The timing and cost will be assumed that these are not uncertain; the present value of replacement overlay costs is then calculated as shown in equation (3.8) [2].

\[ PVR = \text{The cost of each replacement overlay} * [(1 + r)^{(-12)} + (1 + r)^{(-22)} + (1 + r)^{(-32)} + (1 + r)^{(-42)} + (1 + r)^{(-52)} + (1 + r)^{(-62)} + (1 + r)^{(-72)}] \]  

The expected present value of agency costs is approximately ACA = Plans and studies cost + Design & construction cost + Inspections cost + Painting cost + Deck overlay replacement cost

3.3.2 User Costs

User costs are typically costs for drivers, the cars and transported goods on or under the bridge due to delays by roadwork. There are different kinds of user costs, like detours needed when the bridge is closed for repair etc., but these costs are specified for a particular site. Some other user costs are easier to calculate, because those are better related to the bridge itself.

Driver delay cost is the cost for the drivers who are delayed by the roadwork. Vehicle operating cost is capital cost for the vehicles, which are delayed by roadwork. Cost for goods is all kinds of costs for delaying the time for delivering the goods in time. Bridge
user costs are not direct costs, but they do directly affect the public it serves. The deck-overlay replacements will clearly produce traffic delays and road user cost [34].

Bridge user cost during a work zone are usually evaluated with respect to; the traffic delay costs (TDC), the additional vehicle operating costs (VOC) to cross the work zone, the related-accident costs (AC), and the risk of failure of structure cost (FC). The following equation (3.9) is used to determine bridge user cost during a work zone [34].

\[
\text{User Cost} = \text{Traffic Delay Cost} + \text{Vehicle Operation Cost} + \text{Accident Cost} + \text{Failure Cost}
\]  

A. Traffic Delay Cost (TDC): Traffic Delay Cost (TDC) can be represent on equation (3.10) below [34]

\[
TDC = \sum_{t=0}^{TE} T \times \text{ADT}_t \times N_t \times \left( r_T \times w_T + (1 - r_T)w_p \right) \times \frac{1}{(1 + r)^t}
\]

Where

T: is the travel time delay for one vehicle in case of work zone, (hour),

ADT\textsubscript{t}: is the average daily traffic at time t, measured in number of, (vehicle/day)

N\textsubscript{t} : is the number of days needed to perform the work at time t, (Day), assumed five days.

r\textsubscript{T}: is the percentage of trucks from all AVD. It can be calculated by using equation (3.11) below.

53
\( r_T = 0.0001 \times ADT + 8.4 \)  

(3.11)

\( w_T \): is the hourly time value for one truck which assumed 8\$ [2]

\( w_p \): is the hourly time value for one passenger care, the average hourly wage assumption is $22 for each person inside the vehicle and there are two persons inside each vehicle [35].

\( r \): discount rate considered 4\% [28]

Delay time \((T)\) and the average daily traffic at time \(t\) \((ADT_t)\) are explained below:

1. The duration of work zone delay time \((T)\) is strongly associated with the traffic flow condition. Three types of the traffic flow condition are explained:

a. Unrestricted flow conditions where the traffic operates under “Base Case” situation. In this case the traffic volume is below the work zone capacity. All traffic that flows through the work zone, must slow down while traveling through it and then accelerate back to normal operating speed. The duration of work zone delay time \((T)\) for unrestricted flow condition can be calculated by using equations (3.12) to (3.18) [34]

\[
T = Twz - T0
\]  

(3.12)

\[
T0 = \frac{L}{V0}
\]  

(3.13)

\[
Twz = T1 + T2 + T3
\]  

(3.14)

Where

\( T \): the travel time delay for one vehicle in case of work zone, (hour)

\( T_0 \): the time required to cross the bridge during the normal flow conditions, (hour)

\( L \): the affected bridge length, (km), assumed the bridge length
$V_0$: the traffic speed in the normal traffic flow condition, (km/hr), assumed 110 km/hour

$T_{wz}$: the time required to finish the detour or to cross the work zone, (hour),

$T_1$: the time required to decelerate from the normal speed ($V_0$) to the work zone speed ($V_{wz}$), (hour),

\[ T_1 = t_r + \left[ \frac{2 \times d_{dec}}{V_0 + V_{wz}} \right] \]  \hspace{1cm} (3.15)

\[ d_{dec} = \frac{(V_0^2 - V_{wz}^2)}{245(f \pm G)} \]  \hspace{1cm} (3.16)

Where

$d_{dec}$: The minimum deceleration distance (m)

$V_{wz}$: the work zone speed, (km/hr), assumed 90 km/hour

$t_r$: The perception/reaction time (Sec.), average equal to 2.5 sec.

$f$: The American Association of State Highway Transportation Officials AASHTO stopping friction coefficient (dimensionless), at $V_0 = 110$ km/hour, $f$ equals 0.28

$G$: The roadway grade (dimensionless), assume it equal to zero (horizontal bridge)

$T_2$: is the time required to cross the work zone driving by the posted work zone speed ($V_{wz}$), (hour),

\[ T_2 = \frac{L_0}{V_{wz}} \]  \hspace{1cm} (3.17)
$L_0$: Is the optimum work zone length, which is the suitable length to fit; the work equipment, workers, and the working area itself. It depends on; the type of the working activities, the bridge length, and the technology used in the work. However, the minimum acceptable safe working length should not be less than 150 m regardless the bridge length. $L_0$ has three values depend on length of bridges. The table blow represents the recommended optimum work zone length $L_0$ with the bridge length as shown in table 3.3.

<table>
<thead>
<tr>
<th>Bridge Length</th>
<th>&lt;150</th>
<th>150-500</th>
<th>&gt;500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recommended optimum work zone length $L_0$ (m)</td>
<td>150</td>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

Where

$T_3$: is the time required to accelerate back from the work zone speed ($V_{WZ}$), to the normal speed ($V_0$), (hour).

$a$: is an average vehicle acceleration rate which is equal to 2.28 m/Sec$^2$ (29458.8km/hr)

$$T_3 = \frac{V_0 - V_{WZ}}{a} \quad (3.18)$$

b. Forced flow conditions where the traffic volume exceeds the work zone capacity. In this case a queue of vehicles develops. Once a queue develops, all oncoming vehicles must stop at the approach to the work zone and creep through the length of the physical queue under forced flow conditions. All vehicles must be at significantly reduced speeds. It is common for queues to develop in the morning peak traffic period, and then
redevelop in the afternoon peak traffic period. The delay time components (T) associated with the forced flow condition are described in the equations (3.19) to (3.31) [34].

\[ T = T_{wz} - T_0 \]  

(3.19)

\[ T_0 = \frac{L}{V_0} \]  

(3.20)

\[ T_{wz} = T_1 + T_q + T_2 + T_3 + T_4 \]  

(3.21)

Where

T: the travel time delay, (hour).

\( T_0 \): the time required to cross the affected bridge length (L) during the normal flow conditions, (hour),

\( T_1 \): is the time required to stop the vehicle from the normal speed (V0), (hour),

\[ T_1 = t_r + \left( 2 \cdot \frac{d_b}{V_0} \right) \]  

(3.22)

\( d_b \): The minimum breaking distance (m),

\[ d_b = \frac{V_0^2}{245 \cdot (f \pm G)} \]  

(3.23)

\( T_q \): is the time required to creep through the queue by the queue speed (\( V_q \)), (hour),

\[ T_q = \frac{L_q}{V_q} \]  

(3.24)

\( L_q \): Is the average length of the queue, (m).

\[ L_q = AVL \cdot AQV \]  

(3.25)

Maximum Queue Length Estimation:
During the time the work zone is in closure, the maximum number of queued vehicle is estimated. The maximum queue length is estimated by using the traffic demand-capacity model as shown in figure below [36].

Figure 3. 2 Demand and capacity for number of vehicles during the day time
The figure above explains that when demand is more than capacity, the queue is increasing. The maximum number of queued vehicles is measured where the difference between the demand curve and the capacity curve is the greatest. Then, the maximum queue length can be obtained by multiplying the maximum number of queued vehicles by the average vehicle length.

\[
AVL = \max \{7.62 + 7.62 \times (V_q/16), 12.2m\}
\]

(3.26)

Where
AVL: Average vehicle length includes an assumed vehicle length (VL) and the space between vehicles. The maximum vehicle length is 7.62m. The space between vehicles is computed as one vehicle length for every 16km/h of the average queue velocity ($V_q$) the minimum average vehicle length is 12.2m [34].

$V_q$: Average queue velocity.

$$V_q = 19.18 \left(\frac{V}{C}\right)^2 + 21.48 \left(\frac{V}{C}\right) + 0.0057$$  \hspace{1cm} (3.27)

Where

V/C: The volume to capacity ratio (V/C) ratio is calculated by dividing capacity of the bridge in case of work zone by the normal capacity of the bridge.

AQV: Average queue vehicle, veh/lane/hr for different lane road.

$T_2$: the time required to accelerate from $V_q$ to $V_{wz}$ through the work zone, (hour),

$$T_2 = \frac{V_{wz} - V_q}{a}$$  \hspace{1cm} (3.28)

$T_3$: the time required to creep through the work zone by second step, driving by work zone speed ($V_{wz}$), (hour).

$$T_3 = \frac{L_0 - L_2}{V_{wz}}$$  \hspace{1cm} (3.29)
Where

$L_2$: the minimum distance needed to accelerate from $V_q$ to $V_{wz}$

\[ L_2 = V_q * T_2 + \frac{a(T_2^2)}{2} \quad (3.30) \]

$T_4$: the time required to accelerate back from the work zone speed ($V_{wz}$), to the normal speed ($V_0$), (hour).

\[ T_4 = \frac{V_0 - V_{wz}}{a} \quad (3.31) \]

c. Circuity Flow Condition describes the additional distance that users travel on a detour to avoid a highway work zone or because of the bridge closing situations. For non-detour cases, it is assumed the traffic will remain on the bridge and travel the queue and/or work zone situations. A formal detour is established and traffic is forced to detour to calculate the associated cost components. The delay time components ($T$) associated with the ciruicy flow condition are described in the equations (3.32) to (3.36) [34].

\[ T = T_D - T_0 \quad (3.32) \]

\[ T_0 = \frac{L}{V_0} \quad (3.33) \]

\[ T_D = \frac{L_D}{V_D} \quad (3.34) \]
Where

\( T \): the travel time delay, (hour)

\( T_0 \): the time required to cross the affected bridge length (L) during the normal flow conditions, (hour)

\( L_D \): the length of the detour, (km)

\[
L_D = 3 \times \text{The Bridge Length} \quad (3.35)
\]

\( V_D \): the posted detour speed, (km/hr)

\[
V_D = 0.85 \times V_0 \quad (3.36)
\]

2. \( ADT_t \) the average daily traffic at time t, measured in number of vehicle per day. Hourly traffic distribution is the effective procedure to quantify speed reduction delay and convert the ADT into an hourly volume. Based on this distribution factor, the hourly traffic can be calculated as shown in equations (3.37) and (3.38) [34]:

\[
\text{Hourly Traffic} = ADT \times \text{Distribution Factor} \quad (3.37)
\]

\[
ADT_t = ADT \times (1 + 1.1\%)^{(\text{year } t - \text{ year } m)} \quad (3.38)
\]

Where

\( ADT \): the measured average daily traffic, (Vehicle/Day)

Year \( t \): is the current year varied during deck replacement which occurs in years 12,22,32,42,52,62,72 of the bridge life.
Year m: is the last year in which the ADT is measured

B. Vehicle Operation Cost (VOC): VOC is an additional cost incurred by the bridge user, expressed as extra costs to operate the vehicle additional time due to the traffic disturbances because of the work zone or detour. The operating costs include fuel, engine oil, lubrication, maintenance, and depreciation and can be calculated by using equation (3.39) below [34].

\[
VOC = \sum_{t=0}^{TE} T * ADT_t * N_t * (r_T O_T + (1 - r_T) O_P) * \frac{1}{(1 + r)^t} \tag{3.39}
\]

Where:

OT: is the average hourly operating cost for one truck including its goods operation, assumed $25 [2].

OP: is the average hourly operating cost for one passenger car. Assumed $5 [2].

C. The accident costs for roadwork could be calculated using the formula (3.40) below [34]:

\[
LCC_{accident} = \sum_{t=0}^{T} (A_r - A_n) * ADT_t * N_t * C_{acc} * \frac{1}{(1 + r)^t} \tag{3.40}
\]

Where

An: is the normal accident rate per vehicle-kilometers
Ar: is the accident rate during roadwork

Cacc: is the cost for each accident

ADTt: is the average daily traffic, measured in numbers of cars per day at time t

Nt: is the number of days of road work at time t.

The costs should be calculated to present value and added up for all foreseen maintenance and repair works for the studied time interval T.

It is difficult to accurately quantify the work zone exposure rate such as the length and the time of work zone in place. Further, the crash rate higher in work zones than non-work zones. The crash rate in work zone is still low enough that there may not be any crashes because the exposure period is too short to give considerable values. Work zones deal with the traffic during maintenance period in different ways. For example; some work zones use permanent barriers, others use cones or drums, some narrow the lanes, while others maintain lane width and shoulders, etc. While there is a limited amount of work zone crash data, while the validity of the data used to compute the crash rates is sometimes suspected.

D. Failure costs There is a small risk for the total failure of a structure. To get the cost for failure, one has to calculate all costs (KH,j) for the failure, accidents, rebuilding, user delay costs and so on and then multiply these costs with the probability for failure and with the appropriate present value factor according to the formula (3.41) below [34]:

63
\[ FC = \sum_{j=0}^{n} K_{H,j} \cdot R_j \cdot \frac{1}{(1 + r)^j} \]  

Where:

Rj is the probability for a specified failure coupled to KH,j. For normal bridges the probability of failure is so small that the failure costs could be omitted in the analysis.

Due to the limited availability of probability of failure data, the inclusion of the failure costs as part of the Bridge user costs is not recommended.

3.3.3 Society Cost

This cost is evaluated according to the environmental damaging due to bridge material production and aesthetics cost according to the bridge parts evaluation. The following formula (3.42) tells the society components [37].

\[ Costs \ for \ the \ society = Aesthetical \ and \ Cultural \ Value + \ environmental \ impact \]  

Most construction materials consume energy for production and transportation. Poor roadway conditions carry approximately 260 million tons of concrete annually in the United States. While concrete consumption plays a key role in global development, cement causes several environmental challenges. Cement production is energy intensive and accounts for 5% of global CO2 emissions and significant levels of SO2, NOx and other pollutants. Environmental burdens increase because cement production rises to meet the
global concrete demand. The alternative materials in bridge design could serve to reduce the environmental effect of concrete infrastructure [5].

The other society cost is aesthetical cost. Aesthetics cost deals with set of beauty principles guiding the bridge structure appearance. One way to evaluate the aesthetics cost is by multiplying the agency cost of materials for construction and repair with some factor that is estimated by the bridge component appraisal [37].

A. Environmental impact: Typical costs are costs occurring due to damage to the environment, and society costs for health-care and deaths due to traffic accidents. Most construction materials consume energy for production and transportation. Production of concrete and its ingredients does require energy. This energy in turn results in the generation of carbon dioxide, or CO2. The amount of CO2 produced during manufacturing and using concrete as a building material is relatively small. However, transportation have an effect on climate change and greenhouse gas emissions. Early development of tools focused on the transportation activities themselves and made studies and tools for energy efficiency and consumption. Given the smaller contribution to GHG emission from road construction and maintenance. It has looked at these activities contribution and tools have just started to be developed. The choice of materials and techniques for road construction and maintenance has direct impacts on local pollution and environmental degradation expanded to the contribution to greenhouse gases and climate change. Manufacturers and engineering companies have conducted studies on the GHG contribution of their material and alternate construction techniques. Figure 3.3 below shows the total CO2 emissions over a 40 years’ period for a 1 km long and 13 m wide road during construction,
maintenance and operation. Recycling at the end of the life cycle may also provide substantial gains [38], [5].

Figure 3.3 Total CO2 emissions over a 40 years’ period for a 1 km long and 13 m wide road during construction, maintenance and operation

B. Bridge Aesthetical and Cultural Value:

The athletics Calculation: The relative aesthetical and cultural cost of a design or a bridge is obtained by equation [37]:

$$C_{RAV} = K_{Aes} \times C_{Ag}$$  \hfill (3.43)

Where:

$C_{RAV}$: is the corresponding relative aesthetical and cultural value cost

$C_{Ag}$: is the corresponding agency cost
For evaluating the effect of aesthetical and cultural aspects, aesthetical coefficient $K_{Aes}$ calculated by the equation [37]:

$$K_{Aes} = -\alpha \times \frac{\sum_{i=1}^{n} w_i p_i}{p_{max} \sum_{i=1}^{n} w_i}$$  \hspace{1cm} (3.44)

Where:

$\alpha$: The value 0.3 recommended in this thesis sounds reasonable,

$w_i$: The weights considered as “fixed values” and may not be changed during the evaluation process.

$p_i$: is point that one has to decide between five different values, i.e. -2, -1, 0, 1 and 2, when only integer values are allowed. Table 3.4 shows the Numerical values for the evaluation system and its meaning:

<table>
<thead>
<tr>
<th>Category</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>Poor</td>
</tr>
<tr>
<td>-1</td>
<td>Modest</td>
</tr>
<tr>
<td>0</td>
<td>Medium</td>
</tr>
<tr>
<td>1</td>
<td>Good</td>
</tr>
<tr>
<td>2</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

A method can as easily be used by an individual as by a jury or group of evaluators.

1. The first stage one has to consider the bridge site and determine, which class the bridge site belongs to. A four-grade system is used for evaluation of a bridge site [39]:

Class I Very demanding considering the landscape and city view.
Class II Demanding considering the landscape and city view.

Class III Remarkable considering the landscape and city view.

Class IV Ordinary considering the landscape and city view.

2. The second stage is to agree about the items that will be evaluated and to determine weight to each item. This should be done before the evaluation process begins. The weights should be considered as “fixed values” and may not be changed during the evaluation process. One is totally free to choose any items and their number is by no means restricted. Too detailed items, however, may cause difficulties to the evaluator. A good practice might be that items and their weights are determined by the bridge owner in advance. When so, there could be a standard list with standard weights that then can easily be altered to meet the requirements of the project in question.

A similar value as the weights is the scaling factor $a$. It also needs to be determined in advance, because it has a decisive influence on the level of appreciation of aesthetical values compared to costs. The value 0.3 recommended in this thesis sounds reasonable, because in extreme cases it restricts the effect of aesthetics up to $\pm 20\%$, but of course also any other value between 0 and 1 is possible. Even this value should be determined by the bridge owner.

The third and final stage includes the evaluation itself, i.e., the determining of points $p_i$. Before that, however, the scale to be used has to be determined. With steps equal to 1 recommended here one has to decide between five different values, i.e. $-2, -1, 0, 1, 2$, when only integer values are allowed. That scale should be dense enough to obtain
distinction between different categories but scare enough to keep the evaluation simple.

But here again any numbers, integer or decimal ones, are possible.

With the values mentioned above Eq. (3.45) takes a reduced form [37]

\[ K_{Aes} = -0.3 \star \frac{\sum_{i=1}^{n} w_i p_i}{2 \star \sum_{i=1}^{n} w_i} \]  \hspace{1cm} (3.45)

It can be simplified into:

\[ K_{Aes} = -0.15 \star \frac{\sum_{i=1}^{n} w_i p_i}{\sum_{i=1}^{n} w_i} \]  \hspace{1cm} (3.46)

To cover all evaluation cases, a matrix presentation is used. Thus,

\[ \{k_{Aes}\} = -\frac{0.3}{2 \star \sum_{i=1}^{n} w_i} \star (p_i)^T \star \{w_i\} \]

\[ \{k_{Aes}\} = -\frac{a}{2 \star \sum_{i=1}^{n} w_i} \star (p_i)^T \star \{w_i\} \]
CHAPTER 4

PROPOSED METHODS FOR STUDY

4.1 Introduction

The proposed method for calculating lifetime cost and future replacement costs has been applied on bridges in Michigan. Every bridge consists of major bridge component which are deck superstructure, bearings, and substructure. The main purpose of this thesis is to present the methodology and perform a thorough comparative statistical analysis for all the different cost categories of structures. Furthermore, the data that has been used for determining the life cost and the expected replacement cost must still be improved.

4.2 Implementation

The analysis deals with selection of two types of bridges have different total life-cycle cost over the bridge’s lifetime. The two alternatives defined in this section are; Conventional steel design, and Conventional concrete design.

The characteristics of the work zone such as work zone length, number and capacity of lanes open, duration of lane closures, timing (hours of the day and days of the week) of lane closures, posted speed, and the availability and traffic characteristics of alternative routes must be defined. The work zone characteristics are important in order to calculate bridge life cycle costs.

The bridge properties such as bridge length, number of lanes, deck area, the average daily traffic (ADT), and the feature that bridge intersected are given in Pontis. Truck rate
is calculated in the traffic stream for different travel lanes. The traffic represents full time
closure 24 hour per day for five working days. The practical service life of bridges in
Michigan is between 10- 55 years; American Association of State Highway Transportation
Officials AASHTO specifies that the service life of new bridges should be 75 years
[28]. This value varies according to different states. The primary input into the life cycle
cost analysis model is the discount rate, which accounts for the time value of money and
converts any future costs into the current value. Most states use a discount rate within the
range of 3% to 5% with 4% being the most commonly used [40] [28]. Michigan follows
the commonly used interest rate of 4% and this rate has been used in the model [28].

In this chapter, the life cycle cost of one steel span bridge is calculated. The
mathematical equations from previous chapter are used to calculate the life cycle cost
subcategories: agency cost, user cost and aesthetical cost. The length of the bridge is 52m
which is built at 1948. It is a two lanes bridge and services 5600 vehicle per day intersected
M-37 highway roads in Michigan.

Table 4.1 Bridges characteristics

<table>
<thead>
<tr>
<th>No.</th>
<th>NBI Bridge ID</th>
<th>Bridge Length</th>
<th>Built</th>
<th>Type</th>
<th>Deck Area (sq.m)</th>
<th>Lanes</th>
<th>Feature Intersected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41141031000S010</td>
<td>52 m</td>
<td>1948</td>
<td>Steel</td>
<td>587</td>
<td>2</td>
<td>M-37</td>
</tr>
<tr>
<td>2</td>
<td>34134062000B030</td>
<td>67 m</td>
<td>1929</td>
<td>Steel</td>
<td>940.179</td>
<td>2</td>
<td>Maple River</td>
</tr>
<tr>
<td>3</td>
<td>33133035000R020</td>
<td>54 m</td>
<td>1966</td>
<td>Steel</td>
<td>699.04600</td>
<td>2</td>
<td>Conrail</td>
</tr>
</tbody>
</table>
Table 4.1 – continued

<table>
<thead>
<tr>
<th></th>
<th>34134044400S100</th>
<th>108 m</th>
<th>1957</th>
<th>Concrete</th>
<th>1096.38</th>
<th>2</th>
<th>I-96</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>39435380157B01</td>
<td>61 m</td>
<td>1992</td>
<td>Concrete</td>
<td>1193.64</td>
<td>4</td>
<td>Kalamazoo River</td>
</tr>
<tr>
<td>6</td>
<td>11111015000R033</td>
<td>51 m</td>
<td>2003</td>
<td>Concrete</td>
<td>1003.028</td>
<td>3</td>
<td>CSXRR</td>
</tr>
</tbody>
</table>

1. Agency Cost

A. Acquisition cost= it is constant value and equals $100,000

B. Construction cost= cost per one square meter * deck area=$1818*587= $1,067,166

Using equation (3.2) to calculate the present value (PV) of the best estimate of construction cost:

PV= (0.5*1067166)/(1.04)² + (0.5*1067166)/(1.04)³ = $967,680.8219

Table 4.2 Probability mass function of the final construction cost

<table>
<thead>
<tr>
<th>Contract/final</th>
<th>10%below estimate = PV₁</th>
<th>At estimate of Construction Cost = PV₂</th>
<th>10%above estimate = PV₃</th>
<th>20%above estimate = PV₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV of cost</td>
<td>870912.7397</td>
<td>967680.8219</td>
<td>1064448.904</td>
<td>1161216.986</td>
</tr>
<tr>
<td>Probability</td>
<td>0.10</td>
<td>0.60</td>
<td>0.20</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Using equation (3.3) to calculate the expected value of the final construction cost

EV₀= 870912.7397*0.1 + 967680.8219*0.6 + 1064448.904*0.2 + 1161216.986*0.1 =

$996,711.2465

C. LCCMR&R
Using equation (3.4) and (3.5) to calculate the inspection cost that the bridge is inspected every two years for 75. Also the present value of the first four payments is then deducted accrued in years 5 and 6 for the first inspections.

\[ PV_{75} = 500 \times [(1.04)^{75} - 1] / [0.04 \times (1.04)^{75}] = 11,840.20417 \]

\[ PV_4 = 500 \times [(1.04)^{4} - 1] / [0.04 \times (1.04)^{4}] = 1,814.947612 \]

The estimated value of inspections then = 11840.2041 - 1814.947612 = 10,025.25649

2. Repainting cost: It assumed constant value equals $80,043.3

<table>
<thead>
<tr>
<th>Service life</th>
<th>12 years</th>
<th>15 years (best est.)</th>
<th>18 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.1</td>
<td>0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Cost</td>
<td>64034.7</td>
<td>80043.3</td>
<td>104056</td>
</tr>
<tr>
<td>Probability</td>
<td>0.2</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Expected Cost</td>
<td>= 0.2* 64034.7+0.6* 80043.3+0.2* 104056 = $81644.18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using equation (3.6) to calculate the best estimate of the expected present value of repainting costs:

\[ PV_E = 81644.18 \times ((1.04)^{-15} + (1.04)^{-30} + (1.04)^{-45} + (1.04)^{-60} + (1.04)^{-75}) = $96554.5 \]

Using equation (3.7) to calculate the better value which considering all possible combinations:

\[ \text{Better PV} = 0.1 \times (81644.18 \times ((1.04)^{-12} + (1.04)^{-24} + (1.04)^{-36} + (1.04)^{-48} + (1.04)^{-60} + (1.04)^{-72})) + 0.7 \times (81644.18 \times ((1.04)^{-15} + (1.04)^{-30} + (1.04)^{-45} + (1.04)^{-60} + (1.04)^{-72})) \]
$95338.385

D. Deck replacing cost:

The cost of each replacement overlay = the overlay cost/square meter * deck area=$25*587= $14,675

Using equation (3.8) to calculate the present value of replacement overlay costs:

\[ \text{PV}_{\text{R}} = 14675 \times ((1.04)^{-12}+(1.04)^{-22}+(1.04)^{-32}+(1.04)^{-42}+(1.04)^{-52}+(1.04)^{-62}+(1.04)^{-72}) = 26,437.67522 \]

To find the overall agency cost, use equation (3.1)

\[ \text{Agency cost} = $100,000 + $996,711.2465 + $10,025.25649 + $95338.385 + $26,437.67522 = $1228512.56 \]

2. User costs:

Some bridge characteristics are important to start user cost calculation. Table 4.4 shows the specified bridge characteristics as shown in table 4.4.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>52</td>
</tr>
<tr>
<td>v0</td>
<td>110</td>
</tr>
<tr>
<td>ADT</td>
<td>5600 vpd</td>
</tr>
<tr>
<td>Nt</td>
<td>5</td>
</tr>
<tr>
<td>wT,wp</td>
<td>$8 and $44</td>
</tr>
</tbody>
</table>
At the establishing year, the ADT at 1948 was 5600 vpd

Using equation (3.11) to calculate the truck rate, \( r_t = 8.9 \)

a. Unrestricted flow conditions

Using equations (3.12,3.13,3.14,3.15,3.16,3.17, and 3.18) to calculate the duration of work zone delay time (T) for unrestricted flow condition as shown in table 4.5.

Table 4.5 Time calculation of unrestricted flow condition

<table>
<thead>
<tr>
<th>Unrestricted Flow Condition Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0</td>
</tr>
<tr>
<td>Vwz</td>
</tr>
<tr>
<td>T1</td>
</tr>
<tr>
<td>T2</td>
</tr>
<tr>
<td>T3</td>
</tr>
<tr>
<td>Twz</td>
</tr>
<tr>
<td>T0</td>
</tr>
<tr>
<td>T</td>
</tr>
</tbody>
</table>

To calculate the overall user cost, it is necessary to find its categories:
A. Traffic Delay Cost (TDC):

Using equations (3.10) to find the TDC value as shown in table 4.6.

<table>
<thead>
<tr>
<th>ADT_1</th>
<th>life</th>
<th>TDC_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>12</td>
<td>1830074.84</td>
</tr>
<tr>
<td>7124</td>
<td>22</td>
<td>1379262.77</td>
</tr>
<tr>
<td>7947</td>
<td>32</td>
<td>1039501.63</td>
</tr>
<tr>
<td>8866</td>
<td>42</td>
<td>783435.666</td>
</tr>
<tr>
<td>9891</td>
<td>52</td>
<td>590447.791</td>
</tr>
<tr>
<td>11035</td>
<td>62</td>
<td>444999.645</td>
</tr>
<tr>
<td>12310</td>
<td>72</td>
<td>335380.515</td>
</tr>
</tbody>
</table>

The traffic delay cost in this specific case is TDC = $6,403,103

B. Vehicle Operation Cost (VOC):

Using equation (3.39) to find the VOC value as shown in table 4.7.

<table>
<thead>
<tr>
<th>ADT_1</th>
<th>life</th>
<th>VOC_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>12</td>
<td>304844.91</td>
</tr>
<tr>
<td>7124</td>
<td>22</td>
<td>229750.842</td>
</tr>
</tbody>
</table>
The vehicle operation cost in this specific case is \( \text{VOC} = $1,066,598 \)

Using equation (3.9) to calculate the user cost at Accident cost and Failure costs= $0.00

User cost=$6,403,103+$1,066,598+$0+$0= $7,469,700

b. Forced flow conditions

Using equations (3.19,3.20,3.21,3.22,3.23,3.24,3.25,3.26,3.27,3.28,3.29,3.30, and 3.31) to calculate the delay time components \( (T) \) associated with the forced flow condition as shown in table 4.8.

<table>
<thead>
<tr>
<th>Forced Flow Condition values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_0 )</td>
</tr>
<tr>
<td>( V_{wz} )</td>
</tr>
<tr>
<td>( T_0 )</td>
</tr>
</tbody>
</table>
Table 4.8 – continued

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>3.207691529</td>
</tr>
<tr>
<td>Tq</td>
<td>0.458718986</td>
</tr>
<tr>
<td>T2</td>
<td>0.002425761</td>
</tr>
<tr>
<td>T3</td>
<td>1.665203933</td>
</tr>
<tr>
<td>T4</td>
<td>0.000678914</td>
</tr>
<tr>
<td>T</td>
<td>5.334719123</td>
</tr>
</tbody>
</table>

A. Traffic Delay Cost (TDC):

Using equations (3.10) to find the TDC value as shown in table 4.9.

Table 4.9 TDCt calculation of forced flow condition

<table>
<thead>
<tr>
<th>ADTt</th>
<th>life</th>
<th>TDCt2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>12</td>
<td>4337814.382</td>
</tr>
<tr>
<td>7124</td>
<td>22</td>
<td>3269257.489</td>
</tr>
<tr>
<td>7947</td>
<td>32</td>
<td>2463923.9</td>
</tr>
<tr>
<td>8866</td>
<td>42</td>
<td>1856972.418</td>
</tr>
<tr>
<td>9891</td>
<td>52</td>
<td>1399534.523</td>
</tr>
<tr>
<td>11035</td>
<td>62</td>
<td>1054779.739</td>
</tr>
<tr>
<td>12310</td>
<td>72</td>
<td>794950.2346</td>
</tr>
</tbody>
</table>

The traffic delay cost in this specific case is TDC = $15,177,233

B. Vehicle Operation Cost (VOC):
Using equation (3.39) to find the VOC value as shown in table 4.10.

Table 4.10 VOCt calculation of forced flow condition

<table>
<thead>
<tr>
<th>ADTt</th>
<th>life</th>
<th>VOCt2</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>12</td>
<td>722571.8903</td>
</tr>
<tr>
<td>7124</td>
<td>22</td>
<td>544576.9126</td>
</tr>
<tr>
<td>7947</td>
<td>32</td>
<td>410428.3847</td>
</tr>
<tr>
<td>8866</td>
<td>42</td>
<td>309325.3773</td>
</tr>
<tr>
<td>9891</td>
<td>52</td>
<td>233127.6115</td>
</tr>
<tr>
<td>11035</td>
<td>62</td>
<td>175700.0468</td>
</tr>
<tr>
<td>12310</td>
<td>72</td>
<td>132418.9196</td>
</tr>
</tbody>
</table>

The vehicle operation cost in this specific case is VOC= $2,528,149

Using equation (3.9) to calculate the user cost at Accident cost and Failure costs= $0.00

User cost= $15,177,233+$2,528,149+$0+$0= $17,705,382

c. Circuity Flow Condition

Using equations (3.32,3.33,3.34,3.35, and 3.36) to calculate the delay time components (T) associated with the circuity flow condition are as shown in table 4.11.
Table 4.11 Time calculation of circuity flow condition

<table>
<thead>
<tr>
<th>Circuity Flow Condition Values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>V0</td>
<td>110</td>
</tr>
<tr>
<td>T0</td>
<td>0.000472727</td>
</tr>
<tr>
<td>TD</td>
<td>0.001668449</td>
</tr>
<tr>
<td>T</td>
<td>0.001195722</td>
</tr>
</tbody>
</table>

A. Traffic Delay Cost (TDC):

Using equations (3.10) to find the TDC value as shown in table 4.12.

Table 4.12 TDCt calculation of circuity flow condition

<table>
<thead>
<tr>
<th>ADT,</th>
<th>life</th>
<th>TDC,</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>12</td>
<td>972.2761</td>
</tr>
<tr>
<td>7124</td>
<td>22</td>
<td>732.7701</td>
</tr>
<tr>
<td>7947</td>
<td>32</td>
<td>552.263</td>
</tr>
<tr>
<td>8866</td>
<td>42</td>
<td>416.2211</td>
</tr>
<tr>
<td>9891</td>
<td>52</td>
<td>313.6911</td>
</tr>
<tr>
<td>11035</td>
<td>62</td>
<td>236.4179</td>
</tr>
<tr>
<td>12310</td>
<td>72</td>
<td>178.1798</td>
</tr>
</tbody>
</table>
The traffic delay cost in this specific case is \( TDC = $3,402 \)

B. Vehicle Operation Cost (VOC):

Using equation (3.39) to find the VOC value as shown in table 4.13.

Table 4. 13 \( \text{VOC}_t \) calculation of circuity flow condition

<table>
<thead>
<tr>
<th>ADT (_t)</th>
<th>life</th>
<th>( \text{VOC}_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6386</td>
<td>12</td>
<td>161.957</td>
</tr>
<tr>
<td>7124</td>
<td>22</td>
<td>122.0613</td>
</tr>
<tr>
<td>7947</td>
<td>32</td>
<td>91.99326</td>
</tr>
<tr>
<td>8866</td>
<td>42</td>
<td>69.33207</td>
</tr>
<tr>
<td>9891</td>
<td>52</td>
<td>52.25313</td>
</tr>
<tr>
<td>11035</td>
<td>62</td>
<td>39.38134</td>
</tr>
<tr>
<td>12310</td>
<td>72</td>
<td>29.68033</td>
</tr>
</tbody>
</table>

The vehicle operation cost in this specific case is \( \text{VOC} = $567 \)

Using equation (3.9) to calculate the user cost at Accident cost and Failure costs= $0.00

User cost= $3,402+$567+$0+$0= $3,968

3. Aesthetical cost

Aesthetics appraisal form is shown in table 4.14 with the \( w_i \) values for all classes I,II and III.
Table 4.14 Aesthetics appraisal form

<table>
<thead>
<tr>
<th>The Considered Items</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_i$</td>
<td>$w_i$</td>
<td>$p_i$</td>
</tr>
<tr>
<td>Bridge type sensitivity to the context and structure simplicity</td>
<td>12</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>The Bridge Form as a Whole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symmetry, order &amp; rhythm</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Unity of design &amp; Harmony of spans</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Depth to span ratio</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>The Parts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superstructure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Girder elevation</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Girder cross section</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Substructure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Headstock and pier combination</td>
<td>8</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Longitudinal pier spacing</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 4.14 - continued

<table>
<thead>
<tr>
<th>Details</th>
<th>Pier cross section</th>
<th>4</th>
<th>3</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abutment</td>
<td>Abutment visible size</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Abutment placement</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Abutment shape</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Joints and connections</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Barriers &amp; Railings</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Lighting, color, &amp; embellishments</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Using equation (3.45) to calculate $k_{aes}$

According to Table 4.14 Class II

\[
\sum_{i} W_{i \, \text{max}} = \sum_{i=1}^{15} W_{i \, \text{class}}
\]

\[
= 12 + 6 + 6 + 4 + 6 + 6 + 8 + 4 + 4 + 3 + 4 + 4 + 3 + 4 + 5 + 6 = 81
\]
\( \{w_i\}^T_{\text{classII}} = \{8 4 4 3 4 4 5 3 3 2 3 2 3 3 4\} \)

Then, all four evaluators applied the \( p_i \) values for the same bridge and the mean and median for the four evaluators. The values are shown below as a matrix form:

\[
\begin{bmatrix}
1 & 2 & 1 & 0 & 1 & 1 \\
1 & 0 & 1 & 0 & 0.5 & 0.5 \\
1 & 2 & 2 & 2 & 1.75 & 2 \\
1 & 2 & 1 & 0 & 0.75 & 1 \\
2 & 0 & 1 & 0 & 0.25 & 0 \\
1 & 0 & 1 & 1 & 0.75 & 1 \\
1 & 1 & 1 & 0 & 0.75 & 1 \\
0 & 1 & 0 & 1 & 0.5 & 0.5 \\
1 & 2 & 1 & 1 & 1.25 & 1 \\
1 & 2 & 1 & 2 & 1.5 & 1.5 \\
1 & 1 & 1 & 1 & 1 & 1 \\
1 & 2 & 2 & 0 & 1.25 & 1.5 \\
1 & 0 & 1 & 0 & 0.5 & 0.5 \\
1 & 0 & 1 & 1 & 0.75 & 1 \\
-1 & 0 & -1 & -2 & -1 & -1
\end{bmatrix}
\]

Finally, use equation 3.43 to calculate the aesthetical cost as shown in table 4.15.

<table>
<thead>
<tr>
<th>Results</th>
<th>eva1</th>
<th>eva2</th>
<th>eva3</th>
<th>eva4</th>
<th>mean</th>
<th>median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi*Pi</td>
<td>40</td>
<td>52</td>
<td>50</td>
<td>20</td>
<td>40.5</td>
<td>44</td>
</tr>
<tr>
<td>K Aes</td>
<td>-0.074</td>
<td>-0.096</td>
<td>-0.092</td>
<td>-0.037</td>
<td>-0.075</td>
<td>-0.081</td>
</tr>
<tr>
<td>Agency cost</td>
<td>1228512.5</td>
<td>1228512.5</td>
<td>1228512.5</td>
<td>1228512.5</td>
<td>1228512.5</td>
<td></td>
</tr>
<tr>
<td>Aesthetic s cost</td>
<td>-$91000.9</td>
<td>-$118301.2</td>
<td>-$113751.1</td>
<td>-$45500.4</td>
<td>-$92138.4</td>
<td>-$100101</td>
</tr>
</tbody>
</table>

Table 4.15 Aesthetics cost bridge1
CHAPTER 5

RESULTS

5.1 Introduction

Bridges investment decision should consider all costs incurred during the bridge life cycle. Nowadays, the decision makes to build the bridge are not only base on initial cost, but also on the other life costs. Agency cost is the initial bridge construction cost and the service cost over the bridge’s life. However, there are future costs that should be considered. User cost, aesthetics cost, and environmental impact are costs that exceed the initial cost during the whole bridge life cycle.

The case studies in this thesis are focused on different bridges in Michigan state. MATLAB program is used to build a general code program that is used to calculate the life cycle cost in any bridges (See Appendix A). The data of each bridge is taken from Pontis data base and Michigan Department of Transportation. All these bridges types are important to make a comparison in agency, user, and aesthetics costs between them.

5.2 Life Cycle Cost

In this thesis, two main bridge alternatives are considered: steel and concrete bridges. Then, each of them is located on different region. The bridge life cycle cost is calculated for three locations of both alternatives which crosses different regions: roads, waterway, and railroad.
5.2.1 Agency Cost

Different parts of agency cost are calculated in this part. First, the probable agency cost is uncertain because repainting methods could reduce future repainting costs and increase the painting life. Simplifying assumptions would be made to model the uncertainties. The cases considered that the paint service life is estimated to be 12, 15, and 18 years. The probability of these lives are 10%, 70%, and 20%. Applying the expected cost form to get the repainting costs in all probabilities for all six bridges. Figures 5.1, 5.2, and 5.3 show the repainting costs during the bridges life.

![Figure 5.1 Repainting cost at 10% chance of being 12 years for all bridges](image-url)

Figure 5.1 Repainting cost at 10% chance of being 12 years for all bridges
Figure 5.2 Repainting cost at 70% chance of being 15 years for all bridges

Figure 5.3 Repainting cost at 20% chance of being 18 years for all bridges

Repainting through the bridge service life reduces future repainting costs. New paints last longer and reduces the painting costs to the half because it confirms the past painting against the environmental effects. Figures 5.1, 5.2, and 5.3 show different probability chances of repainting service lives. The maximum costs are at repainting
service estimated life 15 years because it gives the maximum probability of 60% chance the same estimated cost. On the other hand, the 12 years repainting service life gives the minimum costs because the probability equals 20% chance is less than 60% the estimated cost.

Another cyclic maintenance cost is replacing the bridge asphaltic deck every ten years. Figure 5.4 shows the deck replacing costs for all six bridges during their life cycle.

![Figure 5.4 Replacing the asphaltic deck overlay every 10 years](image)

Figure 5.4 shows the highest and lowest deck replacing cost in all bridges. The calculated replacing cost gives different deck replacing costs for different bridge deck areas. Bridge 5 gives the maximum deck replacing cost because it has the maximum deck area. On the same time, the minimum deck area for bridge 1 gives the minimum deck replacing cost.

The overall agency cost is given in figure 5.5 below.
Figure 5.5 Agency cost

Figure 5.5 shows that the highest agency cost is given by the biggest deck area for bridge 5. This conclusion is realistic because the biggest deck area need more material, work hours and labor per each meter square.

5.2.2 User Cost

Bridge user costs are not direct costs, but they do directly affect the public it serves. The deck-overlay replacements will clearly produce traffic delays and road user cost. Bridge user cost during a work zone are usually evaluated with respect to the traffic delay costs (TDC) and the additional vehicle operating costs (VOC) to cross the work zone.

The same pattern of traffic delay cost shown in figures 5.6, 5.7, and 5.8 in all bridges is noticeable. The cost at year 12 is more than the cost in year 22 and so on. The reason of this pattern is the monetary inflation which decreases the value of currency over time. The greater the inflation, the greater the difference in value between the cost values.
over bridge life. For this reason, it is better to encourage the agency to do the bridge deck replacement in specific years to reduce the future user costs. The forced flow condition gives the maximum costs in all bridges because the traffic volume exceeds the work zone capacity. A queue of vehicles develops and increases the waiting hours and costs.

Figure 5.6 Unrestricted flow condition on TDC

Figure 5.7 Forced flow Condition on TDC
The obtained Traffic Delay Cost (TDC) during all bridge lives according to different traffic situations; unrestricted, forced, and circuity flow conditions are shown in table 5.1 below.

### Table 5.1 The traffic delay cost for all bridges

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Unrestricted flow condition</th>
<th>Forced Flow Condition</th>
<th>Circuity flow Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6403102.85</td>
<td>15175887.78</td>
<td>3401.81</td>
</tr>
<tr>
<td>2</td>
<td>1238590.28</td>
<td>2935665.10</td>
<td>847.90</td>
</tr>
<tr>
<td>3</td>
<td>10169249.47</td>
<td>24102081.90</td>
<td>5608.65</td>
</tr>
<tr>
<td>4</td>
<td>3357706.51</td>
<td>7959085.28</td>
<td>3705.80</td>
</tr>
<tr>
<td>5</td>
<td>17645559.67</td>
<td>39761192.17</td>
<td>10997.61</td>
</tr>
<tr>
<td>6</td>
<td>19844090.49</td>
<td>46192586.36</td>
<td>10339.91</td>
</tr>
</tbody>
</table>
The same pattern of vehicle operation cost shown in figures 5.9, 5.10, and 5.11 for all bridges is noticeable. The cost at year 12 is more than year 22 and so on. The reason of this pattern is the monetary inflation which decreases the value of currency over time. The greater the inflation, the greater the difference in value between the cost values over bridge life. For this reason, it is better to encourage the agency to do the bridge deck replacement in specific years to reduce the future user costs. The forced flow condition gives the maximum costs in all bridges because the traffic volume exceeds the work zone capacity. A queue of vehicles develops and increases the waiting hours and costs.

Figure 5.9 Unrestricted flow condition on VOC
The obtained Vehicle Operation Cost (VOC) during all bridge lives according to different traffic situations; unrestricted, forced, and circuity flow conditions are shown in table 5.2:
Table 5.2 The vehicle operation cost for all bridges

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Unrestricted flow condition</th>
<th>Forced Flow Condition</th>
<th>Circuity flow Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1066597.53</td>
<td>2527925.11</td>
<td>566.65</td>
</tr>
<tr>
<td>2</td>
<td>202762.30</td>
<td>480580.39</td>
<td>138.80</td>
</tr>
<tr>
<td>3</td>
<td>1715532.81</td>
<td>4065974.82</td>
<td>946.15</td>
</tr>
<tr>
<td>4</td>
<td>554822.98</td>
<td>1315148.73</td>
<td>612.34</td>
</tr>
<tr>
<td>5</td>
<td>3052473.10</td>
<td>6878215.94</td>
<td>1902.45</td>
</tr>
<tr>
<td>6</td>
<td>3458206.79</td>
<td>8049928.81</td>
<td>1801.92</td>
</tr>
</tbody>
</table>

The user costs in figures 5.12, 5.13, and .14 bellow show different costs values for each traffic type during the periodic deck replacement for all bridges.

Figure 5.12 User cost during the unrestricted flow condition
In most cases, it is clear that the unrestricted and circuity flow conditions give the lowest cost for the user. The traffic in these two flow conditions are operating under base case situation. Therefore, the queue of vehicles doesn’t develop.
It is also clear to notice the difference in costs between bridges 1, 2, 3, and 4 in spite of the same number of lanes. The reason for this, the design average daily traffic ADT has the direct effect on the user cost. It is better to avoid the forced flow condition because it costs the user more than the other two conditions. While the unrestricted and circuity flow condition costs less.

In all flow cases, it is clear that bridges 5 and 6 give the highest costs. This is because of the average daily traffic (ADT) is high. The design ADT has the direct effect on the user cost. Bridges with low number of lanes have less costs than bridges with high number of lanes because they designed for low average daily traffic.

5.2.3 Aesthetical and Cultural Cost

This cost is obtained by asking people some question related to the parts of the bridge which aesthetically important to take in consideration. The survey results then used to calculate the aesthetical cost.

The evaluated bridges in this thesis are beautiful and seem good for evaluators. Good aesthetical and cultural bridges will reduce the agency cost by a specific amount. Table 5.3 below sows the aesthetics cost in all bridges.

Table 5.3 Aesthetics cost

<table>
<thead>
<tr>
<th>Bridge</th>
<th>$K_{Aes}$</th>
<th>Aesthetics Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.0750</td>
<td>-92138.442</td>
</tr>
<tr>
<td>2</td>
<td>-0.0634</td>
<td>-120602.518</td>
</tr>
</tbody>
</table>
Table 5.3 - continued

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-0.0453</td>
<td>-65424.453</td>
</tr>
<tr>
<td>4</td>
<td>-0.1111</td>
<td>-264964.346</td>
</tr>
<tr>
<td>5</td>
<td>-0.1018</td>
<td>-263599.691</td>
</tr>
<tr>
<td>6</td>
<td>-0.0953</td>
<td>-209019.9606</td>
</tr>
</tbody>
</table>

Figure 5.15 below shows that the reduction in agency cost of all bridges. The steel bridges give less values in cost reduction than the concrete bridges reduction in agency cost of. The reason behind this is the concrete bridges look better in appearance than steel bridges because the environmental effect on concrete bridges is less than the environmental effect on steel bridges.

Figure 5.15 Aesthetics cost
5.2.4 Total Life Cycle Cost

The total life cycle cost can be calculated by adding agency, user and aesthetical costs together in each bridge. Figure 5.16 represents whole LCC during the unrestricted flow condition. Figure 5.17 represents whole LCC during the forced flow condition. Figure 5.18 represents whole LCC during the circuity flow condition.

![Figure 5.16 Whole LCC during the unrestricted flow condition](image1)

![Figure 5.17 Whole LCC during the forced flow condition](image2)
Figure 5.18 Whole LCC during the circuity flow condition

The unrestricted and circuity flow conditions give the lowest cost for the whole LCC. The traffic in these two flow conditions are operating under base case situation. Therefore, the queue of vehicles doesn’t develop.

It is also clear to notice that the costs of steel deck bridges 1, 2, and 3 are less than the costs of concrete deck bridges. The reason for this is that the design average daily traffic ADT has the direct effect on the user cost. The user cost for all bridges gives the maximum cost values. Therefore, the LCC patterns follow the user cost patterns. It is better to avoid the forced flow. In all flow cases, it is clear that bridges 5 and 6 give the highest LCC. This is because of the average daily traffic (ADT) is high. The design ADT has the direct effect on the user cost.
CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusion

The purpose of the LCCA is to determine the cumulative life cycle costs and relative cost effectiveness of steel and concrete bridge spans as a function of time. Using mathematical model primarily based on the agency cost, user cost and aesthetics cost in the analysis to find that reinforced concrete bridges are significantly more expensive than steel bridges. However, the aesthetic cost of concrete bridges is the least expensive option during the lifetime of the structure. Some specific observations are noticed about the main reasons which rise the bridge life costs are: It was found that traffic volume has a significant impact on LCC. Use of concrete reinforcing bridge span demonstrated the most reduction in LCC from steel bridges in areas of high traffic volume. Although the use of concrete reinforcement more expensive initially, it has the potential to achieve significant reductions in LCC. The results from this thesis yield the following conclusions:

1. The idea behind this study is that, bridges investment decisions should consider all of the costs and considerations incurred during the period over which the alternatives are being compared. Bridges are required to provide service for many years. The ability of a bridge to provide service over time is predicated on its being maintained appropriately by the agency. Thus the investment decision should consider not only the initial activity
that creates a public good, but also all future activities that will be required to keep that investment available to the public.

2. This research study demonstrates a unique methodology and present a new systematic way for analysis and evaluation of the bridge life cycle indicators like agency cost, user cost, aesthetical and cultural value, and the environmental impact. Present a unique flexible system integrating all of bridge life cycle issues and make them measurable and comparable like the bridge initial cost.

3. Based on this unique evaluation system, MATLAB computer program was developed to facilitate the usage for calculating the bridge user cost and evaluating the bridge aesthetical and cultural value. The application of this integrated model to bridge design highlighted a critical importance of using the life cycle modeling in order to enhance the sustainability of bridges infrastructure systems.

6.2 Recommendation and Further Research

The application of this integrated model to bridge design highlighted the critical importance of using the life cycle modeling in order to enhance the sustainability the bridges. Fields for future research and development can be in the following issues.

1. Sorting and gathering of agency historical data to feed the LCCA process

2. Studying different degradation models for all kinds of bridges and their structural elements.
3. Considering methodologies for describing bridges regarding their measures, structural parts and their priority conditions.
BIBLIOGRAPHY


[26] Seo, Jeongbok; Ha, Hunsoo; Briaud, Jean-Louis; "Investigation of Settlement at Bridge Approach Slab Expansion Joint: Numerical Simulations and Model Tests," Texas Department of Transportation In Cooperation with the U.S. Department of Transportation Federal Highway Administration, Texas, 2002.


M. Miller, "Develop a social return on investment framework for Iowa rural bridge transportation asset management," Iowa State University , Ames, 2015.

Ariyaratne , Wije; Bennett, Mark; Canceri, Joe; Chapman, Raeburn; Collins, Gareth; Hobson, Ian; Jones, Col; Mould, Peter; Wedgwood, Ray, "Bridge


APPENDIX

General Code Program in MATLAB

%Bridge ID  41141031000S010
%Total Length 52
%Built 1948
%Name  32ND ST over M-37
%Location 0.6 MI S OF M-11
%Steel Highway

~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~parameter
$~~~~~~~~~~~~~~~~~~~~~~~~~$
%T: is the travel time delay for one vehicle in case of work zone, (hour)
%ADTt: is the average daily traffic at time t, measured in number of, (vehicle/day)
%Nt: is the number of days needed to perform the work at time t, (Day) = 5 Days
%rT: is the percentage of trucks from all AVD
%wT: is the hourly time value for one truck
%wP: is the hourly time value for one passenger care
%Twz: is the time taken to finish the detour or to cross the work zone, (hour)
%T0: is the taken to cross the bridge during the normal flow conditions, (hour)
%L: is the affected bridge length, (km)
%v0: is the traffic speed in the normal traffic flow condition, (km/hr)
%vwz: is the work zone speed, (km/hr)
%TE: is the bridge expected life span

Cost per Square = 1818;
Total Area = 587;
Total Cost = 1067166;
r = 0.04;
LI = 2;
PV = ((0.5*Total Cost)/(1+r)^2) + ((0.5*Total Cost)/(1+r)^3);
C1 = PV - (0.1*PV);
C2 = PV;
C3 = PV + (0.1*PV);
C4 = PV + (0.2*PV);
P1 = 0.1;
P2 = 0.6;
P3 = 0.2;
P4 = 0.1;
Expected Value = C1*P1 + C2*P2 + C3*P3 + C4*P4;
Total Probability = P1 + P2 + P3 + P4;
PV75 = 500*(((1+r)^75) - 1)/(r*(1+r)^75);
PV4 = 500*(((1+r)^4) - 1)/(r*(1+r)^4);
Inspection Cost = PV75 - PV4;
C1r = 150000 - (0.2*150000);
P1r = 0.2;
C2r = 150000;
P2r = 0.6;
C3r = 150000 + (0.3*150000);
P3r = 0.2;
Repainting cost = C1r*P1r + C2r*P2r + C3r*P3r;
Life = [15 30 45 60 75];
for ff = 1:1:5
bestestimatrepaintingcostt(ff) = Repainting cost / ((1+r)^Life(ff));
end
bestestimatrepaintingcost=0;
for gg=1:1:5
bestestimatrepaintingcost=bestestimatrepaintingcost+bestestimatrepaintingcostt(gg);
end
C1b=Repaintingcost*((1+r)^-12+(1+r)^-24+(1+r)^-36+(1+r)^-48+(1+r)^-60+(1+r)^-72);
P1b=0.1;
C2b=Repaintingcost*((1+r)^-15+(1+r)^-30+(1+r)^-45+(1+r)^-60+(1+r)^-75);
P2b=0.7;
C3b=Repaintingcost*((1+r)^-18+(1+r)^-36+(1+r)^-54+(1+r)^-72);
P3b=0.2;
betterRepaintingcost=P1b*C1b+P2b*C2b+P3b*C3b;
Replacingtheasphalticdeckoverlaycost=25*TotalArea*((1+r)^-12+(1+r)^-22+(1+r)^-32+(1+r)^-42+(1+r)^-52+(1+r)^-62+(1+r)^-72);
agencycostT1=100000+ExpectedValue+InspectionCost+betterRepaintingcost+Replacingtheasphalticdeckoverlaycost;
save agencycostT1 agencycostT1

%%%%%%%%%%%%%%%%
LifeR1=[12 24 36 48 60 72];
Repper12=P1b*Repaintingcost*(1+r)^-LifeR1(1);
Repper24=P1b*Repaintingcost*(1+r)^-LifeR1(2);
Repper36=P1b*Repaintingcost*(1+r)^-LifeR1(3);
Repper48=P1b*Repaintingcost*(1+r)^-LifeR1(4);
Repper60=P1b*Repaintingcost*(1+r)^-LifeR1(5);
Repper72=P1b*Repaintingcost*(1+r)^-LifeR1(6);
yR11=[Repper12 Repper24 Repper36 Repper48 Repper60 Repper72];
save yR11 yR11

%%%%%%%%%%%%%%%%
LifeR2=[15 30 45 60 75];
Repper15=P2b*Repaintingcost*(1+r)^-LifeR2(1);
Repper30=P2b*Repaintingcost*(1+r)^-LifeR2(2);
Repper45=P2b*Repaintingcost*(1+r)^-LifeR2(3);
Repper60=P2b*Repaintingcost*(1+r)^-LifeR2(4);
Repper75=P2b*Repaintingcost*(1+r)^-LifeR2(5);
yR71=[Repper15 Repper30 Repper45 Repper60 Repper75];
save yR71 yR71

%%%%%%%%%%%%%%%%
LifeR3=[18 36 54 72];
Repper18=P3b*Repaintingcost*(1+r)^-LifeR3(1);
Repper36=P3b*Repaintingcost*(1+r)^-LifeR3(2);
Repper54=P3b*Repaintingcost*(1+r)^-LifeR3(3);
Repper72=P3b*Repaintingcost*(1+r)^-LifeR3(4);
yR21=[Repper18 Repper36 Repper54 Repper72];
save yR21 yR21

%%%%%%%%%%%%%%%%
Lifedeck=[12 22 32 42 52 62 72];
Replacingdeckcost1=25*TotalArea*((1+r)^-Lifedeck(1));
Replacingdeckcost2=25*TotalArea*((1+r)^-Lifedeck(2));
Replacingdeckcost3=25*TotalArea*((1+r)^-Lifedeck(3));
Replacingdeckcost4=25*TotalArea*((1+r)^-Lifedeck(4));
Replacingdeckcost5=25*TotalArea*((1+r)^-Lifedeck(5));
Replacingdeckcost6=25*TotalArea*((1+r)^-Lifedeck(6));
Replacingdeckcost7=25*TotalArea*((1+r)^-Lifedeck(7));
ReplacingdeckcostT=[Replacingdeckcost1 Replacingdeckcost2
Replacingdeckcost3 Replacingdeckcost4 Replacingdeckcost5
Replacingdeckcost6 Replacingdeckcost7];
plot(Lifedeck,ReplacingdeckcostT,'r')
xlabel('Life')
ylabel('Deck Replacing Cost')
title('Replacing Cost')
grid
hold on

To=L/V0;
d=(V0^2-Vwz^2)/(245*(f+G));
rT=((0.0001*ADT)+8.4)/100;
tr=(2.5/3600);
T1= tr+((2*d)/(V0+Vwz));
T2=L0/Vwz;
T3=(V0-Vwz)/a;
Twz=T1+T2+T3;
T=Twz-To;

yearb=1948;
for aa=1:1:7
ADTt(aa)= ADT*(1+0.011)^(Year(aa)-yearb);
t(aa)=(Year(aa)-yearb);
end
for bb=1:1:7
TDCt11(bb)=T*ADTt(bb)*Nt*((rT*wt)+((1-rT)*wP))*(1/(1+r)^t(bb));
end
TDC=0;
for cc=1:1:7
    TDC=TDC+TDCt11(cc);
end

Vehicle Operation Cost (VOC)стоит
OT=25;
OP=5;
for dd=1:1:7
VOCt11(dd)=T*ADTt(dd)*Nt*((rT*OT)+((1-rT)*OP))*(1/(1+r)^t(dd));
end
VOC=0;
for ee=1:1:7
    VOC=VOC+VOCt11(ee);
end
Usercost11=TDC+VOC;

Forced User
cost

111
a=29458.8;
To=L/V0;
d=V0^2/(245*(f+G));
rT=((0.0001*ADT)+8.4)/100;
tr=(2.5/3600);
T1= tr+((2*d)/V0);
AVL=16.45/1000;
AQV=517;
Vq=18.54;
Lq=AVL*AQV;
Tq=Lq/Vq;
T2=(Vwz-Vq)/a;
L2=(Vq*T2)+((a*(T2)^2)/2);
T3=(L0-L2)/Vwz;
T4=(V0-Vwz)/a;
Twz=T1+Tq+T2+T3+T4;
T=Twz-To;

%%%%%%%%%%%%%%%%%%%%%%%%%%calculate TDC %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Yearb=1948;
for aa=1:1:7
ADTt(aa)= ADT*(1+0.011)^(Year(aa)-Yearb);
t(aa)=(Year(aa)-Yearb);
end
for bb=1:1:7
TDCt21(bb)=T*ADTt(bb)*Nt*((rT*wt)+((1-rT)*wP))*(1/(1+r)^t(bb));
end
TDC=0;
for cc=1:1:7
TDC=TDC+TDCt21(cc);
end
%%%%%%%%%%%%%%%%%%%%%%%%% Vehicle Operation Cost (VOC)%%%%%%%%%%%%%%%%%%
OT=25;
OP=5;
for dd=1:1:7
VOCt21(dd)=T*ADTt(dd)*Nt*((rT*OT)+((1-rT)*OP))*(1/(1+r)^t(dd));
end
VOC=0;
for ee=1:1:7
VOC=VOC+VOCt21(ee);
end
Usercost21=TDC+VOC;
%%%%%%%%%%%%%%%%%%%%%%%%%Circuity User cost%%%%%%%%%%%%%%%%%%%%%%%%
To=L/V0;
rT=((0.0001*ADT)+8.4)/100;
LD=3*L;
VD=0.85*V0;
TD=LD/VD;
T=TD-To;

%%%%%%%%%%%%%%%%%%%%%%%%%%calculate TDC %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Yearb=1948;
for aa=1:1:7
ADTt(aa)= ADT*(1+0.011)^(Year(aa)-Yearb);
t(aa)=(Year(aa)-Yearb);
end
for bb=1:1:7
TDCt31(bb)=T*ADTt(bb)*Nt*(((rT)*wt)+((1-rT)*wP))*(1/(1+r)^t(bb));
end
TDC=0;
for cc=1:1:7
TDC=TDC+TDCt31(cc);
end
% %%%%%%%%%%%%%%%%% Vehicle Operation Cost (VOC) %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
OT=25;
OP=5;
for dd=1:1:7
VOCt31(dd)=T*ADTt(dd)*Nt*(((rT)*OT)+((1-rT)*OP))*(1/(1+r)^t(dd));
end
VOC=0;
for ee=1:1:7
VOC=VOC+VOCt31(ee);
end
Usercost31=TDC+VOC;
% %%%%%%%%%%%%%%%%% aesthetics %%%%%%%%%%%%%%%%%
clear all
clc
load agencycostT1.mat
PI= [1 2 1 0 1 1
1 0 1 0 0.5 0.5
1 2 2 2 1.75 2
1 1 1 0 0.75 1
0 0 1 0 0.25 0
1 0 1 1 0.75 1
1 1 1 0 0.75 1
0 1 0 1 0.5 0.5
1 2 1 1 1.25 1
1 2 1 2 1.5 1.5
1 1 1 1 1 1
1 2 2 0 1.25 1.5
1 0 1 0 0.5 0.5
1 0 1 1 0.75 1
-1 0 -1 -2 -1 -1];
Bridgetypesensitivitytotheconextandstructuresimplicit=PI(1,:);
Summetryorderrhythm=PI(2,:);
UnityofdesignHarmonyofspans=PI(3,:);
Depthtospanratio=PI(4,:);
Girderelevation =PI(5,:);
Girdercrosssection=PI(6,:);
Headstockandpiercombination=PI(7,:);
Longitudinalpiespcescng=PI(8,:);
Piercrosssection=PI(9,:);
Abutmentvisiblesize=PI(10,:);
Abutmentplacement=PI(11,:);
Abutmentshape=PI(12,:);
Jointsandconnections=PI(13,:);
BarriersRailings=PI(14,:);
Lightingcolorembellishments=PI(15,:);
W1C1=[8 4 4 3 4 4 5 3 3 2 3 2 3 3 4];
Kes=-0.3*((W1C1*PI)/(2*81));
Aestheticscost1=Kes*agencycostT1;