THESIS

LIFE-CYCLE COST ANALYSIS OF A BRIDGE IN REMOTE MOUNTAINOUS TERRAIN

Submitted by

Saurabh Alnewar

Department of Construction Management

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2018

Master's Committee:

Advisor: Kelly C. Strong

Bolivar Senior
Rebecca Atadero

ABSTRACT

LIFE-CYCLE COST ANALYSIS OF A BRIDGE IN REMOTE MOUNTAINOUS TERRAIN

There are various approaches documented and researched to calculate life cycle cost, yet many researchers and applications fail to incorporate user costs to optimize total life cycle costs. To perform a holistic bridge life cycle cost analysis, all the cost components are to be considered. The bridge life cycle cost is divided into: agency cost, user cots and environmental costs. The agency cost comprises of acquisition cost, construction cost, maintenance and repair cost, deck replacement cost and debris removal cost. The user cost constitutes vehicle operation cost (VOC), travel delay costs and crash costs. The environmental costs are out of the scope of the study hence are not calculated. In this study, the impact of user cost on total life cycle cost are calculated for a hypothetical bridge failure in remote mountainous terrain based on two alternative detour routes.

The study focuses on using a deterministic approach to calculate total bridge life cycle cost with emphasis on user cost. Detailed mathematical calculations are performed using readily available data on bridge characteristic, agency and user cost components. A sensitivity analysis is performed on two detour route alternatives. The selection of the two detour routes is done based on the availability of possible options around the selected bridge.

The results from the user cost calculation for the two detour routes and their impact on total life cycle cost are presented in this study along with the total bridge life cycle cost.

ACKNOWLEDGEMENTS

I would firstly like to thank my family and friends for their support and encouragement. I would also like to sincerely thank my advisor Dr. Kelly C. Strong for his guidance throughout the research. It was due to his encouragement that I took the topic of life cycle cost analysis for bridge. His enthusiasm to undertake a difficult research question and solve it with multi-disciplinary perspective have motivated to look at problems from different perspective now. I would also like to thank my graduate committee Dr. Bolivar Senior and Dr. Rebecca Atadero for their help and guidance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

CHAPTER 1

INTRODUCTION

1.1 Background Problem Statement:

Technological innovation has been a driver of economic growth in various industries throughout the modern era of industrialized production. The construction industry has also benefited from emerging technology, paving way for research advances that can support industry needs. In Colorado, bridge infrastructure in the high terrains is particularly vulnerable to constant weather changes, increased traffic demand, and heavier freight loads. The bridges in these adverse conditions are often more vulnerable to bridge failure than similar bridges in normal or moderate conditions. In case of a bridge failure due to any unforeseen circumstances the whole bridge network in the region can be affected (Liu & Frangopol, 2006). Bridge failure in remote, mountainous regions can result in large detour costs which in turn add to the transportation costs of goods.

Many of these bridges are maintained by local county agencies. At the local level of transportation administration, limited availability of bridge maintenance and repair funds is a major test for engineers to efficiently manage these assets. Authorities at local agencies generally prioritize bridge repair and rehabilitation along with allocating funds based on their condition assessment and professional experience of their area under jurisdiction (Anand, 2014). Development of an analytical tool utilizing the emerging technology that can make use of their knowledge and judgement to support their decision making is imperative. Thus, use of a robust Life Cycle Cost Analysis (LCCA) as a decision-making tool can benefit in making informed decisions regarding maintenance and replacement by providing objective metrics to compare the life cycle costs of investments in bridge assets.

Researchers often stress upon the importance of including user costs in the life cycle cost analysis, yet fail to incorporate the same in order to optimize the total life cycle cost of the project as it is data intensive. For instance a study conducted by California Department of Transportation (Caltrans) in 2011 on 17 states using LCCA as a decision-making tool found out that 6 states don't include user costs in their evaluation methods (Anand, 2014). It is well documented that the monetary value paid by the road users is an indirect cost and could possibly outweigh the direct costs of projects (Mallela & Sadavisam, 2011). In Colorado, many bridge structures located are in extreme environments and terrain. The de-icing salts and chemicals used in colder regions increase the possibility of corrosion which can weaken the structure and may go unnoticed during visual inspections (Cusson, Lounis, & Daigle, 2011). The bridge structures located in harsh mountain terrains are more likely to experience extensive deterioration because of their exposure to vehicles using chains in winter months (Hema, Guthrie, & Fonseca, 2004). The thermal variance in these regions is also a very likely contributor to structural weakening of bridge structures (Kulprapha & Warnitchai, 2012). Often times the visibility during extreme weather events can be a cause of bridge and vehicle collision, resulting in a sudden bridge failure (El-Tawil, Severino, & Fonseca, 2005). The impact of these unquantifiable factors increases the likelihood of an unexpected bridge failure in these regions causing a great deal of inconvenience to the population of daily road and bridge users (Deng, Wang, & Yu, 2015). Incorporating user costs in life cycle cost analysis where there are limited or no alternative routes for the bridge and road users is extremely important. The impact of user costs during bridge closure on total life cycle cost analysis is a possible way to reaffirm the need of user cost inclusion in robust life cycle cost analysis.

1.2 Research Objective:

The focus of the study is to illustrate the importance of considering user costs in life cycle cost analysis (LCCA) in bridge management and decision-making. The primary objectives of the research are to:

1) Reemphasize the importance of including user costs in life cycle cost analysis,

2) Quantify the impact of user costs on life cycle cost analysis in case of a bridge failure,

These objectives were accomplished by first selecting a bridge in the Colorado Bridge Center database to perform life cycle cost analysis and calculating user cost by determining the possible alternative detour routes. Secondly, by incorporating easily accessible cost data and methods from existing research on bridge life cycle cost analysis, the following steps were performed to achieve the purpose of the research;

1) The available literature on life cycle and bridge life cycle cost was studied to develop the proposed method incorporated in the study;
2) The various cost flows associated with bridge life cycle cost analysis were established;
3) Life cycle cost analysis with sensitivity analysis was performed with emphasis on user cost over alternate detour lengths.

1.3 Organization of the Thesis

This thesis contains five chapters and their sub topics. The first chapter of the thesis describes the background of the problem statement with the research objective of incorporating user cost in LCCA. Chapter 2 gives a literature review of the various research studies and papers to support the analysis of the fundamental research question. Chapter 3 presents the methodology, the equations and parameters incorporated in the study to calculate LCCA. Chapter 4 presents the conducted LCCA with emphasis on user cost. The conclusions of the research, contribution to the body of knowledge and future research directions are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

1) Introduction:

In our daily life reliability assumes various meanings. Reliability in an engineering context can be defined as, the probability that a product performs its intended function without failure under specified conditions for a specified period. The crux of the definition hinges on three important elements which are: function intended, specified time horizon and specified conditions (Yang, 2007). Sustained economic growth and social development of any economy is very closely linked with the reliability of its civil infrastructure systems (Frangopol & Liu, 2007). Bridges are one of the most important yet most susceptible elements in transportation networks. The transportation networks are constantly exposed to aggressive environments and are facing increased traffic volumes and heavier truck loads. Public involvement and scrutiny has made it imperative for transportation agencies to justify and explain the decisions taken with regards to the taxpayers money (Rahman & Vanier, 2004). The focus on managing and maintaining the nation's transportation assets is becoming a high priority for the transportation agencies at federal, state and local levels (US DOT, 2007).

Rahman and Vanier (2004) defined the life cycle cost of an asset as, the total cost, in present value or annual value, that includes the initial costs, maintenance costs; repair and renewal costs over the service life or a specified life cycle. Life Cycle Cost analysis (LCCA) could help ensure optimum selection and informed decisions for asset management. The consideration of LCCA as a decision making tool has been acknowledged by various transportation authorities and decision makers (Hawk, 2003).The design costs, construction costs and maintenance repair and rehabilitation are considered to be direct costs and the costs that are not visible directly but are paid by the user are called indirect costs or user costs (Chan, Keoleian, & Gabler, 2008).

The user cost for a bridge construction project can be divided into three main components: travel delay costs (TDC), additional vehicle operating costs and crash costs (Gilchrist & Allouche, 2005; Mallela & Sadavisam, 2011). When a bridge failure occurs the travel time in that segment increases due to reduced work zone speeds or traffic congestion resulting in delays. The total economic value of these delays paid by the user is called traffic delay costs (TDC). The extra time added due to delays and work zone conditions increases braking and acceleration affecting the operation of vehicles. This additional indirect cost to user is referred to as vehicle operating cost (VOC). The crash costs is another component of user cost which is often a result of the work zone's susceptibility to accidents compared to normal operating conditions (Ghaffari Dolama, 2017). The user costs resulting from work zones in high traffic volume segments with or without an alternative crossing, restricted work zone and lack of layout options could be more important than the direct costs associated with the project (Ghaffari Dolama, 2017; Jia et al., 2016). A similar work zone condition may arise due to a sudden bridge failure in the mountains or similar remote areas where there are limited or no options to cross the affected bridge segment. Quantifying user costs due to a bridge failure and its impact on the total life cycle cost is the primary objective of this study. A review of available research on LCCA and user costs is conducted and presented in the following sections.

2. LCCA Models and Methods:

2.1 Methods formulated for bridge LCCA

The life cycle cost analysis as a method for decision making has received a great deal of attention. The early work on articulating the principle steps for life cycle cost analysis was done

100 years ago, but the systematic approaches to life cycle cost analysis in the United States showed up in the last 25 to 30 years (Hawk, 2003). Kirk and Dell'Isola (1995) established certain guidelines for design professionals for life cycle costing and the data requirements that can be used to evaluate design alternatives to best suit the financial and non-monetary needs of the owners. There is an apparent difference between the practices and techniques followed by the State Highway Agencies (SHA's) in the United States and that followed by academicians and researchers in the economic and engineering fields (Kaan Ozbay, Jawad, Parker, & Hussain, 2004). The early use of LCCA as a decision-making tool was limited primarily to the pavement design process and the implementations of bridge life cycle cost analysis was restricted. The approaches and implementation are varied and are mostly affected by the lack of data (Lamptey, Ahmad, Labi, & Sinha, 2005; Rangaraju, Amirkhanian, & Guven, 2008).

Several studies have demonstrated the benefits of applying life cycle cost analysis on bridges and bridge management systems. A summary of the various life cycle cost analysis studies and their intended focus are presented in Table 1.

Table 1: Summary of Literature on Bridge Life Cycle Cost Analysis

Authors (Year)	Summary
Mohammadi, Guralnick, and Yan (1995)	In their study, the authors presented a method to best fit the requirements of various bridge decisions, called Value index (VI) model.
Horvath and Hendrickson (1998)	Life cycle inventory analysis was performed between steel and steel reinforced concrete structures to their overall impact on environment. The study found that steel reinforced concrete structures have low environmental impact and the reusable nature of steel girders was also affirmed.
Frangopol, Kong, and Gharaibeh (2001)	A reliability based bridge management system was proposed in the study based on the limitations of highway bridge management systems.

Liu and Frangopol (2004)	The researchers developed a maintenance planning procedure using Genetic Algorithm (GA) and Monte-Carlo simulation by addressing the uncertainties in deterioration process.
Liu and Frangopol (2006)	The research presented a novel analytical framework using time dependent structural reliability prediction, highway network performance and life cycle assessments. The maintenance cost, bridge failure cost and user cost were minimized to prioritize maintenance resources to deteriorating bridges.
Strauss, Bergmeister, Hoffmann, Pukl, and Novák (2008)	Reliability assessment of reinforced concrete structures is the main focus of the research. The reliability index of the structures is inversely proportional to its life and is affected by material degradation. The authors presented an innovative methodology by integrating life cycle cost and decision-making tool that could help maintenance planning of the structures.
Ahlroth, Nilsson, Finnveden, Hjelm, and Hochschorner (2011)	The authors used monetary–weighted results obtained from environmental system analysis to comprehensively discuss the viability of including the monetary value of environmental costs during the complete life cycle cost analysis.
Mullard and Stewart (2011)	The researchers performed LCCA on reinforced concrete structures considering the repair and user costs to find the appropriate timing and duration of maintenance actions.
Pittenger, Gransberg, Zaman, and Riemer (2012)	The researchers found that bridge management systems have not been used to their potential due to the complexity in collecting worthwhile input data and difficulty in implementation of engineering economic concepts.
Anand (2014)	This research focused on developing a conceptual life cycle cost analysis model for low volume bridges for county engineers. The limited availability of the data to populate the classic LCCA model was the major limitation of the research.

Even with authors stressing the importance of incorporating user costs in the life cycle cost analysis, the user costs are mostly neglected in selecting optimal maintenance and decision-making strategies. Life cycle cost analysis is mostly focused on reducing the total cost of structure over its service life (Thoft-Christensen, 2015).

2.2 Currently used models for bridge LCCA:

Various models have been developed and refined to calculate LCCA of bridges in the last 25 to 30 years. There are currently two types of LCCA models being used, deterministic and stochastic. These models have their perceived benefits and drawbacks based on the need and level of expertise required for the analysis.

2.2.1 Deterministic model:

Deterministic models are the simplest LCCA models, where input variables are treated as fixed values for cost identification and the resulting cost is found. The calculated total life cycle cost in this model is deterministic in nature with an acceptable range but is not detailed and reliable in nature (Mirzaee, Estekanchi, & Vafai, 2010). The accountability of the estimate is questionable in the deterministic modelling approach as the model does not account for uncertainties, variations or cost arising due to unforeseen events that may affect the bridge structure. The average values of costs do not account for probabilities due to various events thus making it difficult to quantify certain costs like user costs and environmental costs. Input cost parameters are therefore rough estimates and the availability of historical data is important in the deterministic approach (Kang et al., 2007; Kelly & Lee, 2017).

2.2.2 Stochastic model:

Stochastic models are probability based models and often use probability distribution functions to calculate various cost components. Depending on the availability of the data, the variance associated with the cost streams can be analyzed and a probabilistic estimate for the components can be determined through this modelling approach. However, if data is not easily accessible, risk assessment through qualitative approaches is conducted (Kelly & Lee, 2017). For most stochastic life cycle cost analysis models, a basic net present worth analysis is performed on the probability distribution functions of the various cost components. By performing basic net present value analysis all the cost streams are brought to a same present worth value, thus allowing for uncertainties related to monetary changes of various elements over the service life to be incorporated in the analysis for accurate life cycle cost (Girmscheid, 2008).

Performing LCCA in private sector design and building poses limitation due to the unavailability of large amounts of data related to costs, performance, simulation and statistical manipulations (Osman, 2005). On the contrary with the availability of reliable bridge inspection and maintenance data within the federal and state transportation agencies a reasonably precise Life Cycle Cost Analysis (LCCA) estimate can be made using a stochastic modelling approach for public sector bridges.

The models discussed above have their advantages and disadvantages. Integrating the various benefits of these approaches allows for a more comprehensive model for quantifying the impact of user costs on life cycle costs.

3. User costs in life cycle cost analysis:

The inclusion of user costs is debated and often, even when researchers note the importance of including user costs, they are excluded in the selection of optimum maintenance strategies and decision-making process. The emphasis on reducing the total life cycle cost is so high that the significant impact of user costs of the bridge are mostly neglected (Thoft-Christensen, 2015). On the contrary, this study incorporates user costs in a conceptual life cycle cost analysis model to study its impacts in case of a bridge failure.

The most significant contribution to the study of user costs and its components is done by the American Association of State Highway and Transportation Officials (AASHTO) in its book titled “User and Non-User Benefit Analysis for Highways” also known as the AASHTO “Red Book”(AASHTO, 2010). Other significant contributions to the study of user cost and its components is provided in the Federal Highway Administration-Office of Operations report-12-005 (Mallela & Sadavisam, 2011). These publications discuss the various components of User Cost including Travel delay cost (TDC), additional vehicle operating costs (VOC) and crash cost (CC). Other work zone instigated costs like environmental costs are not considered and are beyond the scope of this study. The bridge user cost is the summation of the traffic delay costs (TDC), the vehicle operating costs (VOC) and the crash costs (CC) (Mallela & Sadavisam, 2011). The concept of user cost is further explained through the applications discussed in the following sections.

4. Applications of user costs:

The importance of user costs and its wide-ranging applications can be well understood by the amount of work that has been done over the years on research related to user costs. The emphasis on maximizing the road user benefits due to restricted amount of available funds lead to the consideration of user costs in highway projects (FHWA, 2000). Some of the applications of user costs are.

4.1 Work zone optimization:

The user costs considerations in highway construction would facilitate work zone optimization as recommended by Chein and Schonfeld in (2001), who optimized the work zone by developing a mathematical model to minimize total life cycle cost for a four-lane highway due to work zone closure. Their findings further validated the importance of shorter work zones that would help lower user costs.

4.2 Contractual incentive/ disincentive computations:

User costs have played an important part in deciding the incentives and disincentives for various transportation agencies. The incentive/disincentive calculations incorporate a multiplier which is often in the region of 0.2 -1.0. California DOT recommends a multiplier of 0.5 in their guidelines while New Jersey DOT uses 0.25 (Sadasivam & Mallela, 2015). The importance of incorporating user costs in life cycle cost analysis is thus further emphasized as it helps the agency share the project risk with the contractor (Sadasivam & Mallela, 2015) .

4.3 Accelerated bridge construction decision making:

Jia et. al. (2016) performed research comparing accelerated bridge construction (ABC) versus conventional construction method by developing a framework based on regression of available construction cost from 1998 to 2013. They compared data from one interstate bridge construction for conventional vs ABC method. The construction costs of ABC are higher than conventional methods, but the total life cycle costs are lower than conventional construction. Total costs in construction should be emphasized in alternate analysis as shown in the results, rather than any one specific cost such as construction cost.

The wide-ranging applications of user costs in work zone optimization (Chien & Schonfeld, 2001), incentive/disincentive calculations (Sadasivam & Mallela, 2015) and alternative analysis like ABC vs conventional construction (Jia et al., 2016) further strengthen the importance of continuing the research on the impact of user costs on life cycle cost analysis. The research described in the following chapters adds to this important stream of research.

CHAPTER 3

METHODOLOGY FOR LIFE CYLCE COST ANALYSIS WITH EMPHASIS ON USER COST.

3. LCCA Equations and Parameters

A project level analysis of user cost impacts in the case of a bridge failure will be done using a life cycle costs analysis (LCCA) research methodology. Analyzing the various components of life cycle cost that are related to bridge maintenance and rehabilitation: The study focuses on implementing LCCA analysis on an existing pre-stressed concrete continuous girder bridge in a scenario of hypothetical failure of the two south bound lanes of the four-lane bridge. The bridge is in Morrison, Jefferson County, CO on US 285 two miles south of Morrison. The bridge was built in the year 1995 and has four lanes with the total span length of 242.1 ft. [73.8 m] with deck width edge to edge of 58 ft. [17.7 m]. The LCCA study analyzes the user costs from two alternate detour route selections during the rehabilitation of the collapsed bridge segment.

The parameters and equations that will be used for calculating the LCCA for the study are discussed below.

3.1 Economic Indicator:

The NPV (Net Present Value) is selected as the economic indicators for this study. The selection of the economic indicator is based on the following considerations for the project level analysis:

- Inclusion of benefits in the analysis.
- The perceived benefits of NPV in comparing economic benefits of the projects.

The additive nature of the NPV indicator will be used to analyze the differential costs and maintain consistency in the analysis. This will reduce computational needs for the analysis.

The net present value equation is given by:

$$NPVC= \sum_{t=0}^{T} \frac{C_t}{(1+d)^t} \text{ .... } (3.1)$$

Where,

NPVC= Net Present Value Cost

d = Discount rate

t = time of analysis

C_t= Total life cycle cost occurring at time t which includes all types of costs, monetary and non-monetary encountered throughout the analysis period (K Ozbay, Parker, Jawad, & Hussain, 2003).

3.2 LCCA procedure:

The LCCA procedure proposed for the analysis utilizes the following steps:

1) Selection of analysis approach: A deterministic approach is incorporated for the study.
2) Selection of general economic parameters: The real discount rate and analysis period for the study are selected as general economic parameters and are accordingly defined for the analysis.
3) Establishing the cost streams for the analysis:
    - Estimating agency cost and benefits
    - Estimating user cost and benefits

4) Computing Total Net Present Value and the impact of user costs on the total life cycle cost.
5) Performing Sensitivity Analysis: The sensitivity analysis will be performed for the sensitivity of detour lengths and work zone delay times on the total life cycle cost of the bridge.

3.2.1 Selection of analysis approach:

Considering the exploratory nature of the thesis, and the available historical data a deterministic approach is incorporated. The approach tries to answer the fundamental question of the thesis, which is to "reemphasize the need of incorporating user cost in estimating total life cycle cost of a bridge", by using the readily available cost data. This study incorporates the benefits presented by the deterministic approach for calculating life cycle cost analysis (K Ozbay et al., 2003).

3.2.2 Selection of general economic parameters:

The discount rate in the context of LCCA can be defined as a value in percent used as a mean for comparing the alternative uses of funds and costs over a period of time by adjusting the future amounts to present worth (Hawk, 2003),giving a common basis to economically compare alternatives.

The discount rate excluding the possible rate of inflation for prices is called the real discount rate. The estimates will be kept consistent with the use of real discount rates for the bridge life cycle cost analysis. The real discount rate considerations are simple and generally acceptable as the possibility of wage rates rising faster than the material prices is low. In case of such a rise in differential inflation, there is a small impact on agency costs but the consequences of user cost involving time are much greater. Therefore inflation is usually excluded from the prevailing discount rate (Hawk, 2003).

The currently used discount rates by most of the states are in the range of 3% to 5%, with 4% being the most commonly used rate in LCCA (Anand, 2014). The discount rate used in this model is 4%.

Analysis Period: The time-period over which the LCCA of the bridge structure will be performed is called the analysis period. The analysis period for the study is assumed to be 75 years as recommended by Hawk (2003).

3.2.3 Establishing cost streams for analysis:

All the expenditure streams can be broken down into three basic cost components which are agency costs, user costs and environmental cost.

3.2.3.1 Agency Costs:

The cost component paid by the owner of the structure during the complete project life is termed as agency costs. The agency cost can be divided into different parts based on acquisition costs, construction costs, maintenance repair and rehabilitation costs, deck replacement costs and bridge debris removal cost (Carse et al., 2002).

Agency Cost = Acquisition cost + Construction costs + MR&R + deck replacement cost+ bridge debris removal cost… (3.2)

Acquisition Cost:

All relevant costs for programming and design of the project that are needed to gain a project are called acquisition costs. Design and programming costs are influenced by construction costs. The acquisition cost for the project is assumed to be 10% of the total construction costs as considered by CDOT (Hunter, 2014) . A probability of 100% is assigned to the acquisition cost based on the assumption that the estimate is reliable and no probability distributions are logical (Hawk, 2003).

Construction Cost:

Construction cost are the total cost for building the bridge incurred by the owner including all relevant costs like material and labor. The NPV is used to calculate the cost at time T= 0 or opening time of the bridge.

Construction cost per square feet for 3-inch precast deck panel bridges is estimated at $180.00 per sq. ft. from CDOT 2017 Cost Data Book.

Construction cost = Cost per one square feet * deck area… (3.3)

Construction is scheduled to take two months. A 30-day payment cycle for the project is considered with 50% cost assumed to be paid at the end of the first month and the remaining 50% of the cost is assumed to be paid at the end of the second month. Thus, opening the bridge at the start of the third month.

The present value of the best estimate of construction cost using the basic period discounting equation is calculated as shown in equation (3.4) given below.

$$\text{PV}= \frac{0.50*construction\ cost}{(1+\frac{real\ discount\ rate\ \%}{12})^{\frac{0}{12}}} + \frac{0.50*construction\ cost}{(1+\frac{real\ discount\ rate\ \%}{12})^{\frac{1}{12}}} \ldots.\ (3.4)$$

The expected value [EV_0] for the bridge construction cost will be used as the final cost. The cost is treated as uncertain as various factors like competition within bidders, changes in material prices, and cost growth would influence the final construction cost. The probability mass function for the final cost is given in Table 2.

Table 2: Probability Mass Function of Final Construction Cost (adapted from Hawk (2003))

Contract/Final	10% below estimate= PV_1	At estimate of construction cost= PV_2	10% above estimate= PV_3	20% above estimate= PV_4
PV of cost	PV-0.1*PV	PV	PV+0.1*PV	PV+0.1*PV
Probability	0.10	0.60	0.10	0.20

The value of the final construction cost discounted to time zero can be calculated as shown in equation (3.5) given below.

$$EV_0 = (PV_1 \text{ of cost } *\text{probability } 10\%) + (PV_2 \text{ of cost } *\text{probability } 60\%) + (PV_3 \text{ of cost } *\text{probability } 10\%) + (PV_4 \text{ of cost } *\text{probability } 20\%) \quad ... (3.5)$$

The expected value is regarded as a better value to use than just the best estimate as it reflects the average cost rather than median cost. The uncertain cost are represented by a distribution which is skewed to the left (Hawk, 2003).

Maintenance repair and rehabilitation costs:

The operation, maintenance, repair and disposal costs incurred in the future are called the maintenance repair and rehabilitation costs. The inspection and repair costs are considered in this study. Inspection costs are based on a bridge inspection every two years for 75 years. The incurred average bi-annual maintenance costs are 0.5% and repair costs equal to 0.5% of the construction costs with linear increase until they reach 5% and 5% respectively at the end of service life and the MR&R costs are treated as relatively certain. The total maintenance repair and rehabilitation cost for the study assumed to be 10% of construction costs at the end of service life (Brito & Branco, 1994; Mallela & Sadavisam, 2011).

Deck replacement cost:

The deck overlay replacement costs are a recurring cost value for maintenance. According to the CDOT Cost Data Book 2017, it is assumed that deck overlay costs are $10.20/sq. meter to replace the asphalt deck overlay area every 10 years.

The cost of each replacement overlay = the overlay costs $10.20/sq. m.*deck area

The present value cost of replacing overlaying is given by the equation (3.6) (Hawk, 2003).

$$\text{PV of Replacement Cost} = \text{The cost of each overlay replacement} * [(1+r)^{(-12)}] + [(1+r)^{(-22)}] + [(1+r)^{(-32)}] + [(1+r)^{(-42)}] + [(1+r)^{(-52)}] + [(1+r)^{(-62)}] + [(1+r)^{(-72)}] \quad \ldots.\ (3.6)$$

Bridge debris removal cost:

At bridge failure, there will be cost incurred to remove the debris of the structure. According to the CDOT Cost Data Book 2017, the cost associated with the removal of debris is an estimated lump-sum value of $45,000, for a similar 3 span pre-stressed concrete bridge.

Thus, the net present value of agency cost is equal to the sum of acquisition cost, construction cost, inspection cost, the deck overlay replacement cost and the debris removal cost.

3.2.3.2 User Costs:

The bridge user cost is the summation of the traffic delay costs (TDC), the vehicle operating costs (VOC) and the crash costs (CC), given below in equation (3.7) (Mallela & Sadavisam, 2011).

User Costs = Travel delay Costs (TDC) + Vehicle Operating Costs (VOC) + Crash Costs (CC) …. (3.7)

Travel Delay Costs:

The travel delay costs are represented by the equation (3.8) given below (Safi, 2009),

$$TDC = \sum_{t=0}^{TE}[\left(T * ADT_t * N_t * \left(r_t * w_t + (1 - r_t)w_p\right) * \frac{1}{(1+r)^t}\right) + FIDC] \ldots (3.8)$$

Where,

T = the travel time delay in hours for one vehicle in the work zone,

N_t= the number of days required to complete the work at time t, assumed here to be 60 days.

ADT_t= the average daily traffic at time t, measured in number of vehicle/day

FIDC = Freight inventory delay cost

r = the discount rate.

r_T = the percentage of trucks from average daily traffic is equal to 3.1% (OTIS, 2017).

w_t= the hourly value of truck travel time.

w_p = the hourly value of passenger car travel time.

Work Zone Delay Time (T)

a) Traffic Flow conditions:

The work zone delay time (T) is strongly associated with the traffic flow conditions and calculated in various flow characteristics. There are three types of flow conditions associated with traffic, but the thesis mainly focuses on analyzing the impacts of detours on the bridge life cycle cost analysis in case of a bridge failure in a circuit flow traffic condition and other traffic flow characteristics are not considered in the analysis.

Circuit Flow Conditions, the additional distance travelled by the users in-order to avoid the work zone or due to bridge closure.

During a non-detour case, it is assumed that traffic will flow through the work zone at reduced speeds which would result in queue formations. The travel delay time (T) is thus given by the equation,

$$T = T_D - T_0 \ldots (3.9)$$

Where,

T = the travel delay time (hour),

T_0 = the time required to cross the impacted bridge length (L) during the normal flow conditions at normal velocity (V_0) in hours.

$$T_0 = \frac{L}{V_0} \ldots (3.10)$$

T_D = the time taken to complete the detour in hours

$$T_D = \frac{L_D}{V_D} \ldots (3.11)$$

L_D = the length of the detour in miles.

V_D = the posted detour speed in miles per hour.

$$V_D = 0.85 * V_0 \ldots (3.12)$$

Average Daily Traffic at time t (ADT_t)

The number of vehicles using the bridge per day is called average daily traffic (ADT_t). The average daily traffic can be converted to hourly distribution to aggregate speed reduction delay using the distribution factor. Hourly traffic can be calculated as follows (Safi, 2009),

$$\text{Hourly traffic} = \text{ADT} \times \text{Distribution Factor} \ldots (3.13)$$

$$\text{ADT}_t = \text{ADT}*(1+1.1\%) \wedge (\text{Year}_t - \text{Year}_i) \ldots (3.14)$$

Where,

ADT: the average daily traffic, (veh/day)

$Year_t$ = the years in which deck replacement will occur at 12, 22, 32,42,52,62 and 72 years of the bridge life.

$Year_i$ = the year in which ADT is measured.

Vehicle Operating Costs (VOC):

VOC's are the expenses incurred by the road user due to work zone or detour. VOC's are the running costs associated with the vehicle and thus depend on the mileage of the vehicle and are independent of the fixed costs like insurance, time dependent depreciation and so on (Mallela & Sadavisam, 2011). The VOC includes fuel, engine oil, lubrication, maintenance and depreciation and are derived as follows (Safi, 2009),

$$\text{VOC} = \sum_{t=0}^{TE} T * ADT_t * N_t * \left(r_{T^*} O_T + (1 - r_T) O_p\right) * \frac{1}{(1+r)^t} \ldots (3.15)$$

Where,

OT = the average operating cost of one truck per mile, According to American Transportation Research Institute (ATRI) September 2016 update for the Midwest region is $1.782(ATRI, September 2016).

OP = the average operating cost of one passenger car per mile According to American Automobile Association (AAA) estimate for 2017 to be $0.608 (AAA, 2017)

Crash costs:

The crash costs associated with the work zones and work zone related detours are a function of expected change in crash rates due to the presence of work zones (Mallela & Sadavisam, 2011). With the limitation on validity and availability of crash rates, crash cost can be computed by, multiplying the crash rates by types to vehicle traffic exposure rate in vehicle miles of travel (VMT) during the duration of work, the length of the section in consideration and crash cost rates (Smith, 1998). The Colorado interstate (Rural) fatality rate and other rural roads fatality rates are 1.04 and 2.09 (FHWA, 2015). The cost of death, injury, and property damage were: Death $1,500,000; Nonfatal Disabling Injury $80,700; Property Damage Crash $9,300 (CDOT, 2016).

3.3 Work Zone Configuration and boundary conditions:

The road user costs are a result of the construction, maintenance or the rehabilitation activities being carried inside a work zone around which traffic operates in a restricted pattern. The road user costs are mainly impacted by the time, AADT and work zone characteristics, present traffic volume and operating conditions and the associated cost of vehicle classification and delays (Ates, 2014). The boundary conditions of the work zone that are considered in the study are defined below-

Length of work zone

The length of a work zone influences the time required to allow batches of vehicles to pass through the work area/ zone. The lengths at the start of the work zones are impacted by this time required which in turn commands the amount of right-of-way time required to dissipate vehicle queues. Thus, the vehicle delay can be increased or minimized by shortening or extending work zone length. The work zone typically extends from ½ km to 6km (Cassidy & Han, 1993).

Considering the hypothesis of the study, during a bridge failure the traffic is diverted away from the affected site (Xie & Levinson, 2011) and a similar approach would be use in the study.

Number of lanes open and their capacity

The number of lanes open during road work plays a crucial part in calculating road user cost assuming a steady flow during work zone as found out by Chien and Schonfeld (2001). In this thesis, the traffic is diverted through the detour with both lane closures allowing work to be performed in both lanes of the affected segment of the four-lane bridge.

Duration of lane closures

The lane closures for four lane divided highways usually have two basic configurations, 1) one lane closure in one direction (single lane closure) which has minimal impact on the traffic in the opposite direction and 2) complete closure of the roadway in one direction with traffic being diverted onto a single lane in opposite direction resulting in two lane head-to-head traffic. A third option is full closure, direct the traffic to an alternate route (Dudek, Richards, & Buffington, 1986) . Usually complete closures in one direction are adopted for reducing the required total cost and duration of a large construction project resulting in lower overall traffic control costs and road user costs (Dudek et al., 1986; Martinelli & Xu, 1996). As a bridge collapse and rehabilitation is considered a large project, full lane closures of the impacted lanes are considered with the traffic being diverted onto the adjacent alternate route for the thesis. The duration of closures for the study is considered equal to the duration of the project which is sixty days.

Posted speed and traffic characteristics

The establishment of the work zone on roadway construction is usually accompanied with reduced posted speeds. The reduced posted speed add to excess travel time due to time required to deaccelerate and accelerate from work zone speeds to approach speeds (Ghaffari Dolama, 2017). The US 285 bridge over North Turkey Creek Road has an average daily traffic (ADT) of 26,000. This thesis assumes that during construction two south bound lanes of the bridge would be closed with a posted speed of 30 mph on the detour route, thus diverting 13000 ADT of the SB lanes to the detours.

Availability of the alternate routes

The remote location of the US 285 bridge over North Turkey Creek Road in Morrison, Colorado impacts the selection of alternate routes. The featured intersection of the bridge, N Turkey Creek road in Morrison, Colorado on US 285 is shown in Figures 1A and 1B. The possible detour routes for this thesis are shown in Figure 2 and Figure 3. Alternate route 1 through N Turkey Creek Road has a total length of 8 miles with a daily traffic count equal to 1500 vehicles per day (Town of Morrison Police Department, 2017). Alternate route 2 through N Turkey Creek Road with exit at Twin Fork Tavern has a total length of 6.4 miles with a daily traffic count equaling 1500 vehicles per day (Town of Morrison Police Department, 2017). The detour routes would additionally absorb an ADT of 13,000 which is the traffic diverted from SB lanes of the selected US 285 bridge along with their average daily traffic of 1500 vehicles per day. The total ADT for the detour routes equals to 14500 vehicles per day. The new ADT represents a significant increase in traffic volume for alternate routes which is a result of lack of alternatives routes in remote mountainous regions.

These characteristics play a crucial role in bridge life cycle costs as they contribute to delays due to construction which is the most significant contributor to increased total life cycle cost of the project (Martinelli & Xu, 1996).

CHAPTER 4
LIFE CYCLE COST ANALYSIS COMPUTATIONS

Selected Bridge Description

The analysis deals with selection of two detour lengths during a bridge closure due to a sudden hypothetical bridge failure to analyze the impact of detours on user cost.

The national bridge inventory database is used to determine bridge properties such as length, number of lanes, area of deck, featured intersection average daily traffic and the average daily truck traffic. The traffic represents fulltime closure for 24 hours for 60 working days. American Association of State Highway Transportation Officials (AASHTO) specifies that the service life of a new bridge should be 75 years (Anand, 2014). The most important input parameter for life cycle cost analysis is the discount rate. Discount rate brings any future costs to present value and is measures the time value of money.

In this chapter, user costs and life cycle cost of pre-stressed concrete bridge are calculated using a deterministic approach. The mathematical equations from the previous chapter are used to calculate the life cycle costs and the sub category cost streams. The length of the bridge is 242.1 ft (73.8 m) and was built in the year 1995. The bridge has an average daily traffic of over 26000 on its four lanes (OTIS, 2017). The featured intersection of the bridge is N Turkey Creek road in Morrison, Colorado on US 285 as shown in Figures 1A and 1B.

Figure 1: A The Top View of Selected Bridge

Figure 1: B Side Elevation of the Selected Bridge

The details of the selected bridge on US 285 for the study are given in Table 3. The details of the selected bridge.

Table 3. The details of the selected bridge

NBI Structure Number	Bridge length (ft.)	Built	Type	Lanes	Featured intersection
F-16-SB	242.1	1995	Concrete Cast-in-place	4	N Turkey Creek Road

The life cycle costs analysis of the bridge includes the computation of related agency costs and user costs. The environmental costs are out of the scope of study and therefore are not included in the analysis in this study.

Agency Cost:

The agency cost includes construction costs, acquisition costs, maintenance repair and rehabilitation costs, deck replacement costs and the debris removal costs.

Construction costs:

Construction cost = Cost per one square meter * deck area = \$180.00*242.1*58= \$2,527,524.00

Using the equation (3.4), the present value (PV) of the construction cost estimate calculated is:

$PV = (0.5*2{,}527{,}524.00)/\ (1.0033)^{0} + (0.5*2{,}527{,}524.00)/\ (1.0033)^{0.0833} = \$2{,}527{,}178.00$

The present value of the construction cost is estimated at \$2,527,178.00.

Table 4: Construction Costs Computations using Probability Mass Function

Contract/Final	10% below estimate= PV_1	At estimate of construction cost= PV_2	10% above estimate= PV_3	20% above estimate= PV_4
PV of cost	\$ 2,274,460.00	\$2,527,178.00	\$2,779,896.00	\$3,032,614.00
Probability	0.10	0.60	0.10	0.20

The expected value of the final construction costs is calculated using Equation (3.5) from Chapter 3.

Therefore, $EV_0 = (\$2{,}274{,}460.00*0.10) + (\$2{,}527{,}178.00*0.60) + (\$2{,}779{,}896.00*0.10) + (\$3{,}032{,}614.00*0.20)$

$= \$\ 2{,}628{,}266.00$

The expected value of final construction cost for the project is estimated at \$ 2,628,266.00.

Acquisition Costs:

The acquisition costs for the project are considered to be equal to 10% of the construction cost (Hunter, 2014).

Therefore, Acquisition cost = 10% of construction cost = **$ 262,827.00**

The acquisition cost for the project is $ 262,827.00.

Maintenance, Repair and Rehabilitation Costs:

Maintenance, repair and rehabilitation cost is considered equal to 10% of the construction cost at the end of service life.

Therefore, the MR&R cost = 10% * construction cost = 0.1 * $ 2,628,266.00= **$ 262,827.00**

The maintenance, repair and rehabilitation cost for the project are estimated at $ 262,827.00.

Deck replacement cost:

The deck overlay replacement costs are a recurring cost value for maintenance. According to the CDOT Cost Data Book (2017), it is assumed that deck overlay costs are $10.20/sq. meter to replace the asphaltic deck area every 10 years.

Overlay replacement cost = $ 10.20 *73.8*17.7 = $13,324.00

PV of Replacement Cost = $13,324.00* [(1.04) ^ (-12)] + [(1.4) ^ (-22)] + [(1.04) ^ (-32)] + [(1.04) ^ (-42)] + [(1.04) ^ (-52)] + [(1.04) ^ (-62)] + [(1.04) ^ (-72)] = **$ 24,004.00**

Debris removal cost:

According to the CDOT Cost Data Book (2017), the cost associated with the removal of debris is an estimated lump-sum value of $45,000, for a similar 3 span pre-stressed concrete bridge.

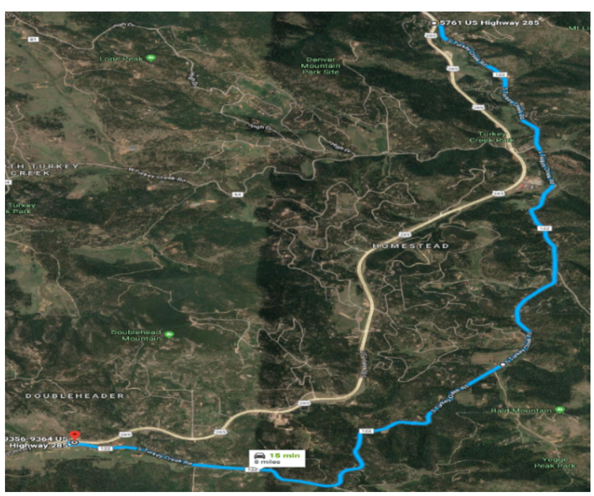
User Costs:

The significance of user costs, in the study are examined by considering two detour routes. The detour routes selected for the study are discussed as Alternative 1 which examines the impact of an 8-mile detour around the affected bridge location and the Alternative 2 examines a 6.4-mile detour. The lack of alternate routes in the area are the reason for these two-detour route selection.

The bridge user cost is the summation of the traffic delay costs (TDC), the vehicle operating costs (VOC) and the crash costs (CC) (Mallela & Sadavisam, 2011).

<u>Alternative 1</u>:

The detour length (L_D) selected for Alternative 1 is the longest possible detour around the selected bridge. The longest selected alternative detour route1 has an 8-mile detour with a posted speed detour speed of 30 mph. The values of the pertinent parameters of the selected detour route are presented in Table 5. Selected parameters for alternate detour route 1. Followed by the cost computations. Figure 2. Selected detour route for Alternative 1, is shown below.



<u>Figure 2. Selected detour route as Alternative</u> 1

Table 5. Selected parameters for detour route alternate 1.

Parameters	Values
T	0.075 hr.
ADT	14500
N_T	60 days
r_t	3.1
w_p	$22.10
w_t	$32.07
R	4%

Travel Delay Costs:

Travel delay costs considered for this study are cost of passenger and truck delay costs and freight inventory delay costs.

Average detour delay time for a vehicle = Detour delay time ((detour length 1/detour speed) - (normal travel length/upstream speed)) * ADT (Detour 1) = ((8.0/30) – (6.8/55)) * 14500/ (26000+1500) = 0.075 hr.

Value of travel time for passenger cars (w_p):

a) Hourly value of personal travel time in dollars:

Median annual household income in 2015 inflation adjusted dollars for Jefferson county area is $71,136 (Data USA 2017).

US DOT recommends using 50% of hourly household income as the value of time (Belenky, 2011)

Hourly value of a person on personal travel (assuming local travel) = 50% of $71,136/ 2080 (40 hrs. a week, 52 weeks a year) (Mallela & Sadavisam, 2011).

Therefore, Hourly value of a person on personal travel = 0.50*$71136/2080 = 17.1$/hr

Average vehicle occupancy for personal travel = 1.24 (A. Santos, 2011)

Hourly travel time value of passenger car on personal travel = 17.1*1.24 = 21.20/vehicle-hr.

b) Hourly value of passenger cars on business time in dollars:

The sum of hourly wages for Lakewood area were estimated using Denver-Aurora-Lakewood Colorado metropolitan area statistics on BLS website.

Hourly employment cost for the quarter of May 2016 = $ 26.88 (BLS, 2017)

Average vehicle occupancy for business travel = 1.24

Hourly travel time value of passenger car on business travel = $ 26.88 * 1.24 = $33.33/vehicle-hr.

c) Weighted average of travel time value of passenger cars:

The weighted average of travel delay time values for passenger cars on both personal and business travel are computed using the ratios presented in 2017 NHTS statistics (93.7% and 6.3%) (A. Santos, 2011).

Hourly time value of passenger cars = (93.7% * Hourly travel time value of passenger car on personal travel) + (6.7% * Hourly travel time value of passenger car on business travel) = (0.937*21.20) + (0.067*33.33) = $22.10

Weighted hourly value of passenger car travel time = **$22.10**

Travel Delay cost for passenger cars (Per day) **=** Hourly value of passenger car * travel delay time*no of passenger cars = 22.10*0.075*96.9%*14500 = $ 23289.00

Total travel delay Cost of passenger cars = project duration * cost of passenger delay (per day) = 60*23289.00 = **$ 1,397,340.00**

Total travel delay cost of passenger cars for the project duration of 60 days is equal to **$ 1,397,340.00**

Value of travel time for trucks (w_t):

Average vehicle occupancy for Single unit truck = 1.025 and Combination truck = 1.12 (Brod, 2013).

a) Average wages and benefits of truck drivers

Truck Drivers, Heavy and Tractor-Trailer (Colorado) = $47340 / 2080 = $22.76 from Bureau of Labor Statistics (2017).

Light or Delivery Services = $37,240 / 2080 = $17.90 from Bureau of Labor Statistics (2017).

Per the BLS ECEC Data, the average benefit for employees in transportation and material moving jobs is $9.62 (Bureau of Labor Statistics, 2017).

b) Per hour monetary value of truck travel time,

Single unit truck = 1.025*(17.90 + 9.62) = $28.20

Combination unit truck = 1.12*(22.76 + 9.62) = $36.26

Total number of trucks = Number of single unit trucks + Number of combination trucks

= 420 + 390 = 810

Therefore, Weighted average of monetary value of truck travel time = (52% * Hourly monetary value of single unit truck) + (48% * Hourly monetary value of combination truck)

= (0.52*28.20 + 0.48*36.26) = $32.07

Hourly value of truck travel time = **$32.07**

Travel Delay cost for truck travel (Per day) **=** Hourly value of Truck travel time * travel delay time*no of trucks = 32.07*0.075*3.1%*14500 = $ 1082.00

Total travel delay Cost of Truck = project duration * cost of passenger delay (per day) = 60*1082.00 = **$ 64,920.00**

Total travel delay cost of trucks for the project duration of 60 days is equal to **$ 64,920.00**

Cost of freight inventory delay

Determine the average value of commodities by truck:

Average discount rate = 4.0%

a) **Hourly discount rate** for 2017= (4.0%) / 8760 = 0.000457%

   Number of hours per year = 8760

b) **Average value of commodities shipped by truck**

Average value of commodities shipped by truck = $ 1.35 / lb. (Year 1993) (Mallela & Sadavisam, 2011).

Implicit price deflator for GDP – Goods = 93.786 for 1993 (FRED Economic Data, 2017).

Implicit price deflator for GDP Goods = 113.630 for 2017 (FRED Economic Data, 2017).

Adjusted value of commodities shipped by trucks in 2017 = $1.35 * (113.63/93.786) = $1.63/lb.

Therefore, **Hourly value of freight inventory** for 2017 = $1.62*0.000570% = **$7.40E-06/lb./hr.**

c) **Hourly freight inventory costs for single unit truck** = $7.40E-06* 23312 (Average payload in Colorado) = $0.1725 (FHWA, 2007)

Hourly freight inventory costs for combination trucks = $9.234E-06 * 51000 (Average payload in Colorado) = $0.38 (FHWA, 2007)

d) **Estimating number of loaded trucks**

Estimated percent of empty single unit trucks = 29% (Bureau of Transportation Statistics, 2016).

Estimated percent of empty combination trucks = 27% (Bureau of Transportation Statistics, 2016).

AADT= 14500

Total no of single unit trucks = 420 (OTIS, 2017)

Estimated number of empty single unit trucks = 0.29* Total no of single unit trucks = 0.29*420= 122

Estimated no of loaded single unit trucks = Total no of single unit trucks - Estimated number of empty single unit trucks = 420-122= 298

Total no of combination unit trucks = 390 (OTIS, 2017)

Estimated number of empty combination unit trucks = 0.27* Total no of combination unit trucks = 0.27*390 = 106

Estimated no of loaded combination unit trucks = Total no of combination unit trucks - Estimated number of empty combination unit trucks = 390-106= 284

e) **Estimating the cost of freight delay due to detour**

Average detour delay time for a vehicle = 0.075 hr.

Cost of freight inventory delay for single-unit trucks = Hourly freight inventory costs for single unit truck * number of loaded single-unit trucks * average detour delay time for a vehicle = 0.21*308*0.075 = $14.87/hr.

Cost of freight inventory delay for combination unit trucks = Hourly freight inventory costs for combination unit truck * number of loaded combination unit trucks * average detour delay time for a vehicle = 0.38*284*0.075 = $ 22.35/hr.

Total Cost of freight Inventory delay = 60*24*(14.87+22.35) = $ 53.597.00

Vehicle operating Cost (VOC):

VOC = $\sum_{t=0}^{TE} T * ADT_t * N_t * \left(r_{T^*} O_T + (1 - r_T) O_p\right) * \frac{1}{(1+r)^t}$ … (3.5)

Where,

OT = the average operating cost of one truck per mile, According to American Transportation research Institute (ATRI) September 2016 update for the Midwest region is \$1.782 (ATRI, September 2016).

OP = the average operating cost of one passenger car per mile, according to AAA estimate for 2017 to be \$0.608 (AAA, 2017).

r_T = is the percentage of trucks in the average vehicle distribution

= 3.1(OTIS, 2017).

VOC= 0.075*14500*60*(3.1*1.782 + (1-3.1) *0.608) *(1/ $(1+0.04)^{0.04}$) = \$ 276,710.00

Vehicle operating cost = \$ 276,710.00

Crash Costs:

With the limitation on validity and availability of crash rates, crash cost can be computed by, multiplying the crash rates by types to vehicle traffic exposure rate in vehicle miles of travel (VMT) during the duration of work (60 Days), the length of the section in consideration (8.0 Miles) and crash cost rates (Smith, 1998). The Colorado interstate (Rural) fatality rate and other rural roads fatality rates are 1.04 and 2.09 (FHWA, 2015). The cost of death, injury, and property damage were: Death \$1,500,000; Nonfatal Disabling Injury \$80,700; Property Damage Crash \$9,300 (CDOT, 2016). The total crash cost due to fatalities only are computed and presented in Table 6. Crash Cost due to fatalities only for Alternative route 1.

Table 6: Crash Cost due to fatalities only for Alternative route 1

Facility	Crash Rate		Exposure				No. of Crashes (c)x(g)	Crash cost rate	Crash Cost ($) (h)x(i)
	Type	Crash/ 100 VMT	Vehicles per day	No. of days	miles	VMT (100 M) (d)x(e)x(f)			
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Detour Alternative 1	Fatality	2.08	14500	60	8	0.0696	0.14477	1,500,000.00	217152

The total life cycle cost for alternative route 1 is presented below in Table 7. Total life cycle cost for Alternative detour route 1.

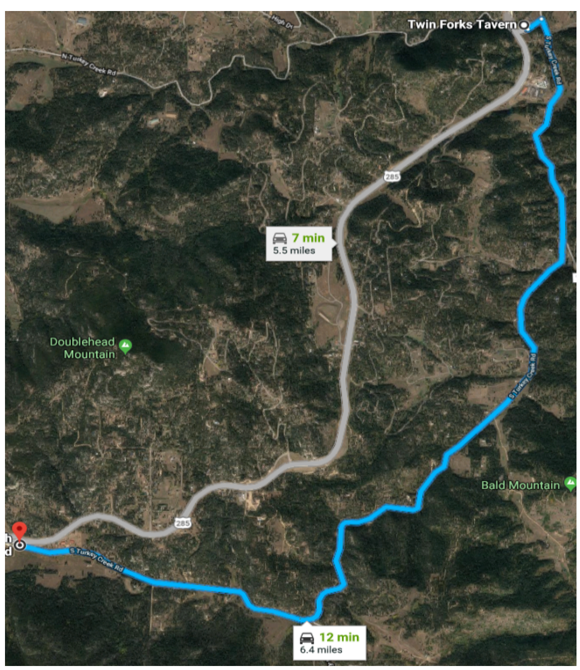
Table 7. Total life cycle cost for Alternative detour route 1.

Cost Components	Discount Rate	Duration of the project	Cost
			Length of Detour
			Alternative 1
	(4%)	(60 days)	(8.0 Miles)
Agency Cost			
Construction Cost	4%	60 Days	$2,628,266.00
Acquisition costs			$262,827.00
Maintenance and repair costs			$262,827.00
Deck replacement costs			$24,004.00
Debris removal cost			$45,000.00
		Total Agency Cost	**$3,222,924.00**
User Cost			
Travel delay cost for:			
Passenger cars			$1,397,340.00

Trucks	4%	60 Days	$64,920.00
Freight Inventory delay cost			$53,597.00
Vehicle Operation costs			$276,710.00
Crash costs			$217,152.00
		Total User Cost	**$ 2,009,719.00**
		Total Life Cycle Cost for alternative 1 detour route	**$ 5,232,643.00**

<u>Alternative 2:</u>

The detour length (L_D) selected for alternative 2 is the shortest possible detour around the selected bridge. This shortest selected detour route 2 has a 6.4-mile detour with a posted speed detour speed of 30 mph. The values of the pertinent parameters of the selected detour route are presented in Table 8. Selected parameters for alternate detour route 2. Followed by the cost computations. Figure 3. Selected detour route for Alternative 2, is shown below



<u>Figure 3 Selected detour route for Alternative 2</u>

Table 8: Selected parameters for alternate detour route 2

Parameters	Values
T	0.047 hrs.
ADT	14,500
N_T	60 days
r_t	3.1
w_p	$22.10
w_t	$32.07
R	4%

Travel Delay Costs:

Travel delay costs considered for this study are cost of passenger and truck delay costs and freight inventory delay costs.

Average detour delay time for a vehicle = Detour delay time ((detour length 1/detour speed) - (normal travel length/upstream speed)) * ADT (Detour 2) = ((6.4/30) – (6.8/55)) * 14500/27500 = 0.047 hr.

Value of travel time for passenger cars (w_p):

a) Hourly value of personal travel time in dollars:

Median annual household income in 2015 inflation adjusted dollars for Jefferson county area is $71,136 (Data USA 2017).

US DOT recommends using 50% of hourly household income as the value of time (Belenky, 2011)

Hourly value of a person on personal travel (assuming local travel) = 50% of $71,136/ 2080 (40 hrs. a week, 52 weeks a year) (Mallela & Sadavisam, 2011).

Therefore, Hourly value of a person on personal travel = 0.50*$71136/2080 = 17.1$/hr

Average vehicle occupancy for personal travel = 1.24 (A. Santos, 2011)

Hourly travel time value of passenger car on personal travel = 17.1*1.24 = 21.20/vehicle-hr.

b) Hourly value of passenger cars on business time in dollars:

The sum of hourly wages for Lakewood area were estimated using Denver-Aurora-Lakewood Colorado metropolitan area statistics on BLS website

Hourly employment cost for the quarter of May 2016 = $ 26.88 (BLS, 2017)

Average vehicle occupancy for business travel = 1.24

Hourly travel time value of passenger car on business travel = $ 26.88 * 1.24 = $33.33/vehicle-hr.

c) Weighted average of travel time value of passenger cars:

The weighted average of travel delay time values for passenger cars on both personal and business travel are computed using the ratios presented in 2017 NHTS statistics (93.7% and 6.3%) (A. Santos, 2011).

Hourly time value of passenger cars = (93.7% * Hourly travel time value of passenger car on personal travel) + (6.7% * Hourly travel time value of passenger car on business travel) = (0.937*21.20) + (0.067*33.33) = $22.10

Hourly value of passenger car travel time = **$22.10**

Travel Delay cost for passenger cars (Per day) **=** Hourly value of passenger car * travel delay time*no of passenger cars = 22.10*0.047*96.9%*14500 = $ 14595

Total travel delay Cost of passenger cars = project duration * cost of passenger delay (per day) = 60*14595.00 = **$ 875,700.00**

Total travel delay cost of passenger cars for the project duration of 60 days is equal to **$ 875,700.00**

Value of travel time for trucks (w_t):

Average vehicle occupancy for Single unit truck = 1.025 and Combination truck = 1.12 (Brod, 2013).

a) Average wages and benefits of truck drivers

Truck Drivers, Heavy and Tractor-Trailer (Colorado) = $47340 / 2080 = $22.76 from Bureau of Labor Statistics (2017).

Light or Delivery Services = $37,240 / 2080 = $17.90 from Bureau of Labor Statistics (2017).

Per the BLS ECEC Data, the average benefit for employees in transportation and material moving jobs is $9.62 (Bureau of Labor Statistics, 2017).

b) Per hour monetary value of truck travel time

Single unit truck = 1.025*(17.90 + 9.62) = $28.20

Combination unit truck = 1.12*(22.76 + 9.62) = $36.26

Weighted average of monetary value of truck travel time = (52% * Hourly monetary value of single unit truck) + (48% * Hourly monetary value of combination truck) =

(0.52*28.20 + 0.48*36.26) = $32.07

Hourly value of truck travel time = **$32.07**

Travel Delay cost for truck travel (Per day) **=** Hourly value of Truck travel time * travel delay time*no of trucks = 32.07*0.047*3.1%*14500 = $ 680.00

Total travel delay Cost of Truck = project duration * cost of truck delay (per day) = 60*680 = **$ 40,800.00**

Total travel delay cost of trucks for the project duration of 60 days is equal to **$ 40,800.00**

Cost of freight inventory delay

Determine the average value of commodities by truck:

Average discount rate = 4.0%

a) **Hourly discount rate** for 2017= (4.0%) / 8760 = 0.000457%

Number of hours per year = 8760

b) **Average value of commodities shipped by truck**

Average value of commodities shipped by truck = $ 1.35 /lb. (Year 1993) (Mallela & Sadavisam, 2011).

Implicit price deflator for GDP – Goods = 93.786 for 1993 (FRED Economic Data, 2017).

Implicit price deflator for GDP Goods = 113.630 for 2017 (FRED Economic Data, 2017).

Adjusted value of commodities shipped by trucks in 2017 = $1.35 * (113.63/93.786) = $1.63/lb.

Therefore, **Hourly value of freight inventory** for 2017 = $1.62*0.000457% = **$7.40E-06/lb./hr.**

c) **Hourly freight inventory costs for single unit truck** = $7.40E-06* 23312 (Average payload in Colorado) = $0.1725 (FHWA, 2007)

Hourly freight inventory costs for combination trucks = $7.40E-06 * 51000 (Average payload in Colorado) = $0.38 (FHWA, 2007)

d) **Estimating number of loaded trucks**

Estimated percent of empty single unit trucks = 29% (Bureau of Transportation Statistics, 2016).

Estimated percent of empty combination trucks = 27% (Bureau of Transportation Statistics, 2016).

AADT= 14500

Total no of single unit trucks = 420 (OTIS, 2017)

Estimated number of empty single unit trucks = 0.29* Total no of single unit trucks = 0.29*420= 122

Estimated no of loaded single unit trucks = Total no of single unit trucks - Estimated number of empty single unit trucks = 420-122 = 298

Total no of combination unit trucks = 390 (OTIS, 2017)

Estimated number of empty combination unit trucks = 0.27* Total no of combination unit trucks = 0.27*390 = 106

Estimated no of loaded combination unit trucks = Total no of combination unit trucks - Estimated number of empty combination unit trucks = 390-106 = 284

e) **Estimating the cost of freight delay due to detour**

Average detour delay time for a vehicle = 0.047 hr.

Cost of freight inventory delay for single-unit trucks = Hourly freight inventory costs for single unit truck * number of loaded single-unit trucks * average detour delay time for a vehicle = 0.1725* 298*0.047 = $11.32/hr.

Cost of freight inventory delay for combination unit trucks = Hourly freight inventory costs for combination unit truck * number of loaded combination unit trucks * average detour delay time for a vehicle = 0.38*284*0.047 = $ 18.71/hr.

Total Cost of freight Inventory delay = 60*24*(11.32+18.71) = $ 43,244.00

Vehicle operating Cost (VOC):

VOC = $\sum_{t=0}^{TE} T * ADT_t * N_t * \left(r_{T^*} O_T + (1 - r_T) O_p\right) * \frac{1}{(1+r)^t} \ldots$ (35)

Where,

OT = the average operating cost of one truck per mile, According to American Transportation research Institute (ATRI) September 2016 update for the Midwest region is \$1.782 (ATRI, September 2016).

OP = the average operating cost of one passenger car per mile, according to AAA estimate for 2017 to be \$0.608 (AAA, 2017).

$r_{T} = 3.1$

VOC= $0.047*14500*60*(3.1*1.782 + (1-3.1) *0.608) *(1/ (1+0.04)^{0.04}) = \$ 173,410.00$

Vehicle operating cost = \$ 173,410.00

Crash Costs:

Similarly, crash cost for Detour Alternate Route 2 can be computed by, multiplying the crash rates by types to vehicle traffic exposure rate in vehicle miles of travel (VMT) during the duration of work (60 Days), the length of the section in consideration (6.4 Miles) and crash cost rates (Smith, 1998). The Colorado interstate (Rural) fatality rate and other rural roads fatality rates are 1.04 and 2.09 (FHWA, 2015). The cost of death, injury, and property damage were: Death \$1,500,000; Nonfatal Disabling Injury \$80,700; Property Damage Crash \$9,300 (CDOT, 2016). The total crash cost due to fatalities only are computed and presented in Table 9. Crash Cost due to fatalities only for Alternative route 2.

Table 9: Crash Cost due to fatalities only for Alternative route 2

Facility	Crash Rate		Exposure				No. of Crashes (c)x(g)	Crash cost rate	Crash Cost ($) (h)x(i)
	Type	Crash/ 100 VMT	Vehicles per day	No. of days	miles	VMT (100 M) (d)x(e)x(f)			
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
Detour Alternative 2	Fatality	2.08	14500	60	6.4	0.05568	0.11581	1,500,000.00	173722

The total life cycle cost for alternative route 2 is presented below in Table 10, Total life cycle cost for Alternative detour route 2.

Table 10. Total life cycle cost for Alternative detour route 2.

Cost Components	Discount Rate	Duration of the project	Cost Length of Detour Alternative 2
	(4%)	(60 days)	(6.4 Miles)
Agency Cost			
Construction Cost	4%	60 Days	$2,628,266.00
Acquisition costs			$262,827.00
Maintenance and repair costs			$262,827.00
Deck replacement costs			$24,004.00
Debris removal cost			$45,000.00
		Total Agency Cost	**$3,222,924.00**
User Cost			
Travel delay cost for:			
Passenger cars			$875,700.00

Trucks	4%	60 Days	$40,800.00
Freight Inventory delay cost			$43,244.00
Vehicle Operation costs			$173,410.00
Crash costs			$173,722.00
		Total User Cost	**$ 1,306,876.00**
		Total Life Cycle Cost for Alternative route 2	**$ 4,529,260.00**

CHAPTER 5

RESULTS

To reaffirm the importance of incorporating user cost and the ease of computing user costs based on existing readily available data in project decision making, the results for the hypothetical bridge failure in remote mountainous region are presented in this chapter. A life-cycle cost analysis with the user cost is performed for a remote mountainous pre-stressed concrete bridge on US 285 at N Turkey Creek road intersection in Morrison, Colorado, using a deterministic approach. The total life cycle costs are analyzed against the sensitivity of the lengths of available detour routes. Two different detour route scenarios were evaluated. The detour routes selected for the sensitivity analysis are represented as “Alternative Route 1” and “Alternative Route 2” and measure 8.0 miles and 6.4 miles respectively in detour lengths.

The results for the computed total life cycle costs for the study are presented below in Table 11. Total Life Cycle Costs for the study.

Table 11. Total Life Cycle Costs for the study

Cost Components	Discount Rate	Duration of the project	Cost	
			Length of Detour	
			Alternative 1	Alternative 2
	(4%)	(60 days)	(8.0 Miles)	(6.4 Miles)
Agency Cost				
Construction Cost			$2,628,266.00	
Acquisition costs			$262,827.00	

Maintenance and repair costs	4%	60 Days	$262,827.00	
Deck replacement costs			$24,004.00	
Debris removal cost			$45,000.00	
		Total Agency Cost	**$3,222,924.00**	
User Cost				
Travel delay cost for:	4%	60 Days		
Passenger cars			$1,369,924.00	$875,700.00
Trucks			$64,920.00	$40,800.00
Freight Inventory delay cost			$53,597.00	$43,244.00
Vehicle Operation costs			$276,710.00	$173,410.00
Crash costs			$217,152.00	$173,722.00
		Total User Cost	**$ 2,009,719.00**	**$ 1,306,876.00**

The agency costs for the study are assumed to be equal for the two selected detours. The total agency costs at 4% discount rate for a project duration of 60 days are calculated and equal to $3,222,924.00.

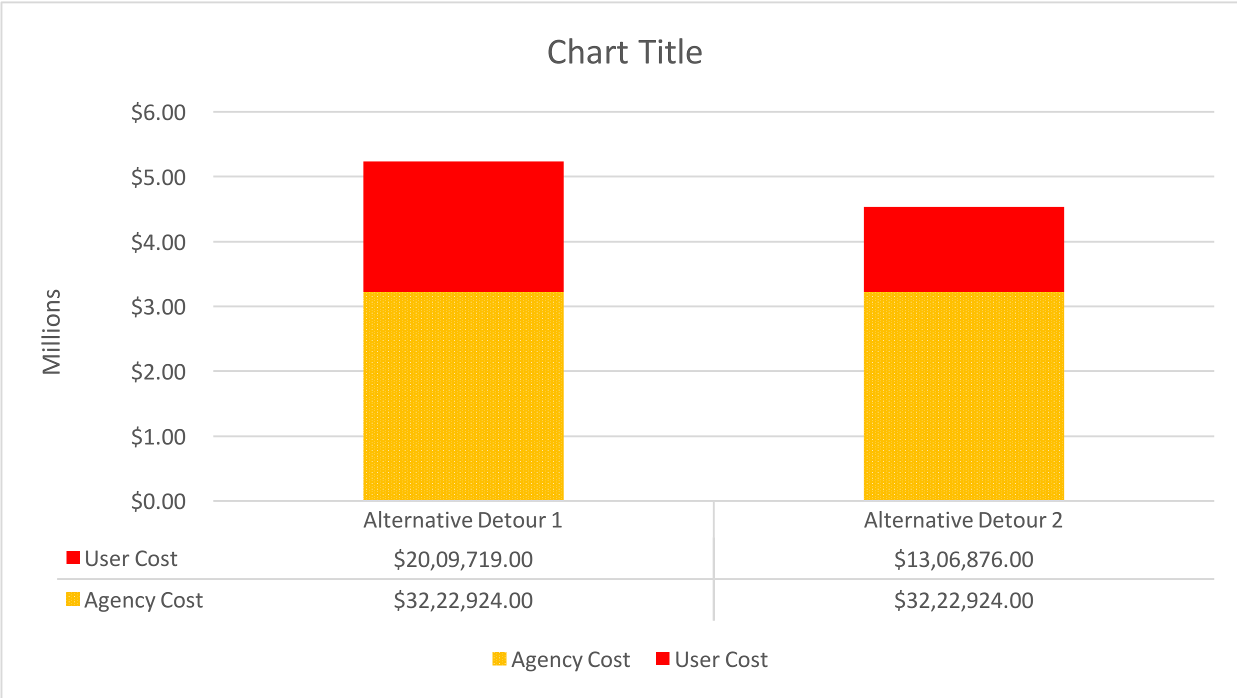
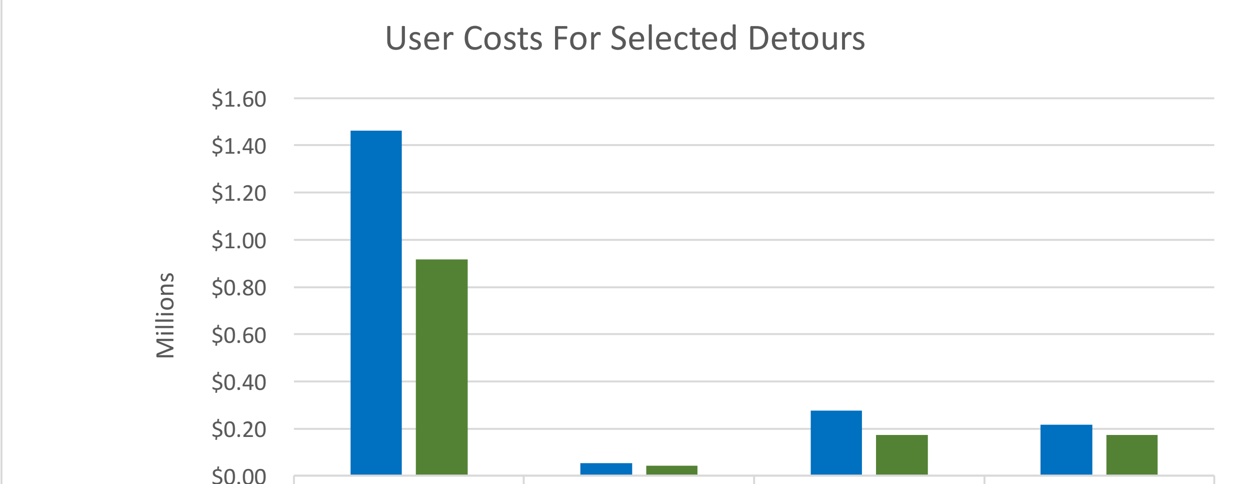


Figure 4. Total Life Cycle Costs of Selected Alternatives

As seen from the graphs in Figure 4, the user costs constitute as much as 38 % of the total life cycle cost of the impacted bridge for alternative detour route 1 and 29% of the total life cycle cost for the alternative detour route 2.

The Figure 6 and Figure 7, show that the costs due to travel delays are the primary contributor to user costs of the study making up to 72% and 71% for alternative detour routes 1 and alternative detour routes 2 respectively. The vehicle operation costs are the second biggest contributors to the user costs with 14% and 13% for alternative detour routes 1 and alternative detour routes 2 respectively. The freight inventory delay costs for the study are at 3% and 3%. The crash costs due to fatalities only, making up 11 % and 13% of the total user costs for alternative detour routes 1 and alternative detour routes 2 respectively.



	Travel delay Costs	Freight Inventory Delay Costs	Vehicle Operation Costs	Crash Costs
Alternative Detour 1	$14,62,260.00	$53,597	$2,76,710.00	$2,17,152.00
Alternative Detour 2	$9,16,500.00	$43,244.00	$1,73,410.00	$1,73,722.00

Figure 5. User Costs for Selected Detours

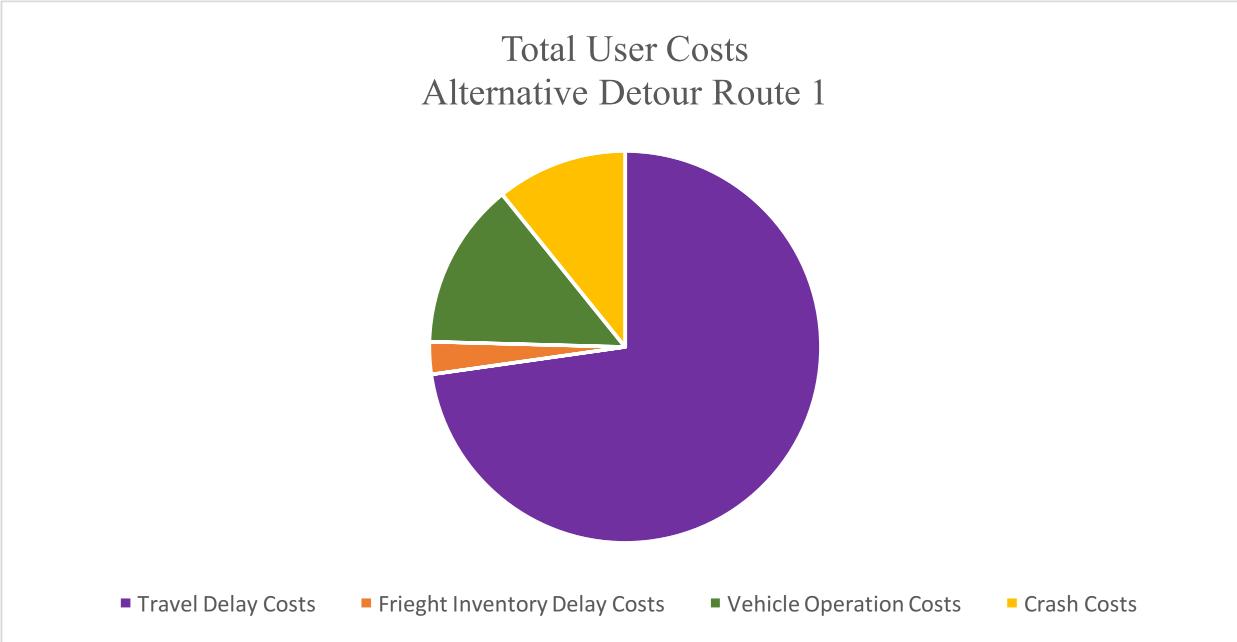


Figure 6. Total User Costs Alternative Detour Route 1

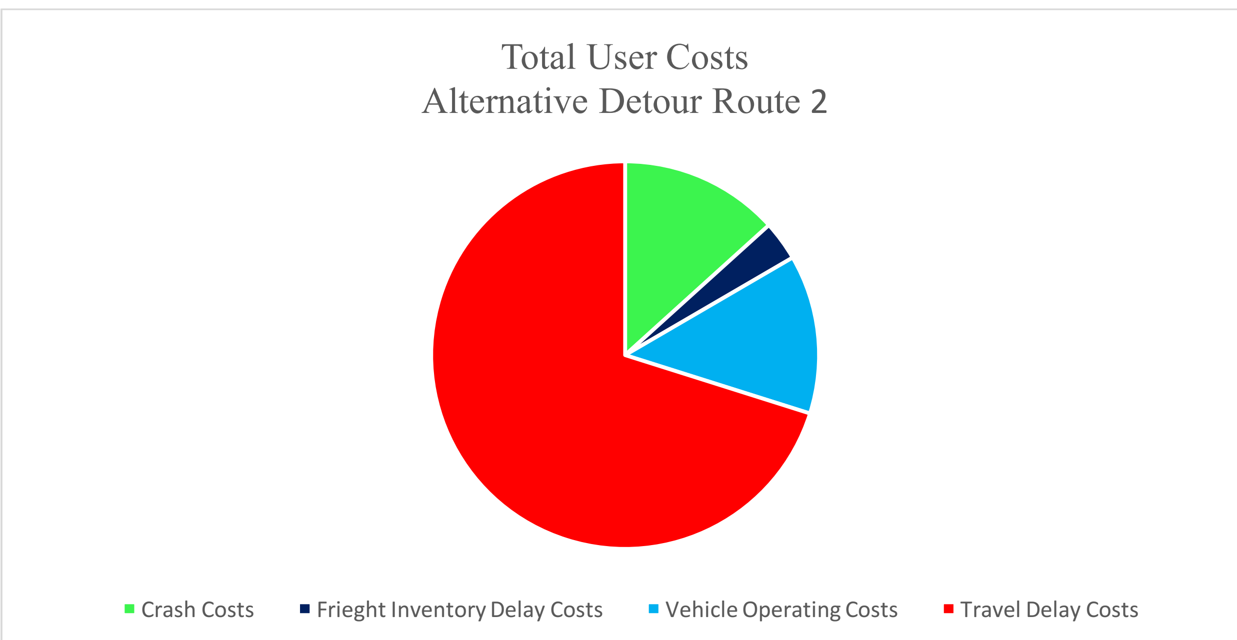


Figure 7 Total User Costs Alternative Detour Route 2

Even though the crash cost due to fatalities are 11% and 13%, with the availability of the costs due to injuries and Public Damage Only (PDO) the value of total crash cost can significantly change. According to Centers for Disease Control and Prevention, State-specific Costs of Motor vehicle crash deaths for the state of Colorado amounted to $90 Million for the year 2013, underlining the need for motorist safety on the highways and its segments (CDC, 2017). The circuitry flow condition adopted in this study gives a lower user cost because of the absence of queue of vehicles reducing the travel delay costs. Average daily traffic has a significant and direct effect on the value of user cost. The remoteness of the bridge in the study, allows for moderate average daily traffic (ADT), thus amounting to reasonable values of user costs in the study. The total life cycle cost analysis of the bridge is swayed by the values of user costs and their significance as seen in Figure 4. Total life cycle cost analysis for selected alternatives.

Conclusion:

A thorough bridge life cycle cost analysis is done with emphasis on user cost. The study advocates incorporating user costs in life cycle cost analysis, it is important to acknowledge that the life cycle cost analysis is far from perfect. And its results can be biased by the perceptions and forecasts of future costs, reliability of the data used, discount rates applied and stages of assets life cycle included in the analysis. The deterministic approach used in this study shows the ease of calculating and incorporating user costs in a holistic life cycle cost analysis. The study tries to present an argument to the study conducted by California Department of Transportation in 2011 (Caltrans) which saw 6 out of 17 states that were part of study, did not include user costs in their evaluation methods. The numerical calculations performed in this study present the significance of user cost calculated based on readily available user cost data. The two detour routes used in the sensitivity analysis showed that user costs contribute up to 38% and 29% to the total life cycle cost analysis. Thus, providing a strong reason to incorporate user costs in total life cycle cost analysis and decision making for a project. The limited availability of alternate detour routes in mountainous terrains where the bridge infrastructure is subjected to harsh environments emphasizes incorporating user costs in total bridge life cycle cost analysis.

REFERENCES

A. Santos, N. M., H.Y. Nakamoto, D. Gray and S. Liss. (2011). *Summary of Travel Trends: 2009 National Household Travel Survey* (FHWA-PL-ll-022). Retrieved from National Household Travel Survey:

AAA. (2017). *True cost of Vehicle ownership*. Retrieved from http://newsroom.aaa.com/tag/driving-cost-per-mile/

AASHTO. (2010). American association of state highway and transportation officials *Washington, DC, 10*.

Ahlroth, S., Nilsson, M., Finnveden, G., Hjelm, O., & Hochschorner, E. (2011). Weighting and valuation in selected environmental systems analysis tools–suggestions for further developments. *Journal of Cleaner Production, 19*(2), 145-156.

Anand, R. (2014). Conceptual level life-cycle cost analysis algorithm for low volume bridges.

Ates, O. K. (2014). *A Decision Making Framework for Road User Cost Analysis along Freeway Work Zone Projects.* Ohio University,

ATRI. (September 2016). *An analysis of operating cost of trucking*. Retrieved from http://atri-online.org/wp-content/uploads/2016/10/ATRI-Operational-Costs-of-Trucking-2016-09-2016.pdf

Belenky, P. (2011). Revised departmental guidance on valuation of travel time in economic analysis. *US Department of Transportation, Washington, DC Google Scholar*.

BLS. (2017). Denver-Aurora-Lakewood, Colo. Metropolitan Area Data Tables. Retrieved from https://www.bls.gov/regions/mountain-plains/news-release/occupationalemploymentandwages_denver.htm

Brito, J. d., & Branco, F. (1994). Bridge management policy using cost analysis. *Proceedings of the Institution of Civil Engineers: Structures and Buildings, 104*(4), 431-439.

Brod, D. (2013). *Comprehensive Costs of Highway-Rail Grade Crossing Crashes* (Vol. 755): Transportation Research Board.

Bureau of Labor Statistics. (2017). *Employee costs for employee compensation*.

Bureau of Transportation Statistics. (2016). Colorado Transportation by Numbers,. Retrieved from https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/colorado.pdf

Carse, A., Spathonis, M. J., Chandler, M. L., Gilbert, M. D., Johnson, M. B., UWS, A. J., & Pham, L. (2002). Whole of life cycle cost analysis in bridge rehabilitation.

Cassidy, M. J., & Han, L. D. (1993). Proposed model for predicting motorist delays at two-lane highway work zones. *Journal of Transportation Engineering, 119*(1), 27-42.

CDC. (2017). State-Specific costs of motor vehicle crash deaths. Retrieved from https://www.cdc.gov/motorvehiclesafety/statecosts/index.html

CDOT. (2016). *Colorado Highway Safety Improvement Program*. Retrieved from

Chan, A., Keoleian, G., & Gabler, E. (2008). Evaluation of life-cycle cost analysis practices used by the Michigan Department of Transportation. *Journal of Transportation Engineering, 134*(6), 236-245.

Chien, S., & Schonfeld, P. (2001). Optimal work zone lengths for four-lane highways. *Journal of Transportation Engineering, 127*(2), 124-131.

Cusson, D., Lounis, Z., & Daigle, L. (2011). Durability monitoring for improved service life predictions of concrete bridge decks in corrosive environments. *Computer- Aided Civil and Infrastructure Engineering, 26*(7), 524-541.
Data USA (2017). Jefferson County. Retrieved from https://datausa.io/profile/geo/jefferson-county-co/
Deng, L., Wang, W., & Yu, Y. (2015). State-of-the-art review on the causes and mechanisms of bridge collapse. *Journal of Performance of Constructed Facilities, 30*(2), 04015005.
Dudek, C. L., Richards, S. H., & Buffington, J. L. (1986). *Some effects of traffic control on four-lane divided highways*.
El-Tawil, S., Severino, E., & Fonseca, P. (2005). Vehicle collision with bridge piers. *Journal of Bridge Engineering, 10*(3), 345-353.
FHWA. (2000). *Comprehensive Truck Size And Weight Study* (FHWA-PL-00-029). Retrieved from https://www.fhwa.dot.gov/policy/otps/truck/finalreport.cfm
FHWA. (2007). *FAF2 Freight Traffic Analysis*. Retrieved from
FHWA. (2015). Road Safety Data. Retrieved 2017, from U.S. DOT https://rspcb.safety.fhwa.dot.gov/Dashboard
Frangopol, D. M., Kong, J. S., & Gharaibeh, E. S. (2001). Reliability-based life-cycle management of highway bridges. *Journal of Computing in Civil Engineering, 15*(1), 27-34.
Frangopol, D. M., & Liu, M. (2007). Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost∗. *Structure and Infrastructure Engineering, 3*(1), 29-41.
FRED Economic Data. (2017). Gross Domestic Product: Implicit price deflator. Retrieved from https://fred.stlouisfed.org/series/GDPDEF
Ghaffari Dolama, M. (2017). *Tool For Calculating User Delay Cost Associated With Urban Arterial Construction Zone.* University of Calgary,
Gilchrist, A., & Allouche, E. N. (2005). Quantification of social costs associated with construction projects: state-of-the-art review. *Tunnelling and underground space technology, 20*(1), 89-104.
Girmscheid, G. (2008). Probabilistic risk-based LC NPV Model. *Innovations in structural engineering and construction*.
Hawk, H. (2003). *Bridge life-cycle cost analysis*: Transportation Research Board.
Hema, J., Guthrie, W. S., & Fonseca, F. S. (2004). *Concrete bridge deck condition assessment and improvement strategies*. Retrieved from
Horvath, A., & Hendrickson, C. (1998). Steel versus steel-reinforced concrete bridges: Environmental assessment. *Journal of Infrastructure Systems, 4*(3), 111-117.
Hunter, K. (2014). Estimating preconstruction services costs for highway projects.
Jia, J., Ibrahim, M., Hadi, M., Orabi, W., Ali, M., & Xiao, Y. (2016). *Estimation of the Total Cost of Bridge Construction for use in Accelerated Bridge Construction Selection Decisions.* Paper presented at the Transportation Research Board 95th Annual Meeting.
Kang, J., Lee, S., Hong, T., Koo, K., Hyun, C., & Lee, D. (2007). *Life-Cycle Cost Analysis in Bridge Structures: Focused on Superstructure.* Paper presented at the 5th IABMAS Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructure Systems, LCC05.
Kelly, H.-S., & Lee, A. (2017). *Life Cycle Cost Analysis for Joint Elimination Retrofits and Thermal Loading on Colorado Bridges.* Colorado State University. Libraries,

Kirk, S. J., & Dell'Isola, A. J. (1995). *Life cycle costing for design professionals*.
Kulprapha, N., & Warnitchai, P. (2012). Structural health monitoring of continuous prestressed concrete bridges using ambient thermal responses. *Engineering Structures, 40*, 20-38.
Lamptey, G., Ahmad, M. Z., Labi, S., & Sinha, K. C. (2005). Life cycle cost analysis for INDOT pavement design procedures.
Liu, M., & Frangopol, D. M. (2004). Optimal bridge maintenance planning based on probabilistic performance prediction. *Engineering Structures, 26*(7), 991-1002.
Liu, M., & Frangopol, D. M. (2006). Optimizing bridge network maintenance management under uncertainty with conflicting criteria: Life-cycle maintenance, failure, and user costs. *Journal of Structural Engineering, 132*(11), 1835-1845.
Mallela, J., & Sadavisam, S. (2011). *Work Zone Road User Costs: Concepts and Applications*: US Department of Transportation, Federal Highway Administration.
Martinelli, D. R., & Xu, D. (1996). Delay estimation and optimal length for four-lane divided freeway workzones. *Journal of Transportation Engineering, 122*(2), 114-122.
Mirzaee, A., Estekanchi, H., & Vafai, A. (2010). Application of endurance time method in performance-based design of steel moment frames. *Scientia Iranica. Transaction A, Civil Engineering, 17*(6), 482.
Mohammadi, J., Guralnick, S. A., & Yan, L. (1995). Incorporating life-cycle costs in highway-bridge planning and design. *Journal of Transportation Engineering, 121*(5), 417-424.
Mullard, J. A., & Stewart, M. G. (2011). Life-cycle cost assessment of maintenance strategies for RC structures in chloride environments. *Journal of Bridge Engineering, 17*(2), 353-362.
Osman, H. (2005). Risk-based life-cycle cost analysis of privatized infrastructure. *Transportation Research Record: Journal of the Transportation Research Board*(1924), 192-196.
OTIS. (2017). Traffic Data Explorer. Retrieved 2018, from CDOT http://dtdapps.coloradodot.info/otis/trafficdata#ui/1/1/0/station/105153/criteria/285D/161.789/263.947
Ozbay, K., Jawad, D., Parker, N., & Hussain, S. (2004). Life-cycle cost analysis: State of the practice versus state of the art. *Transportation Research Record: Journal of the Transportation Research Board*(1864), 62-70.
Ozbay, K., Parker, N., Jawad, D., & Hussain, S. (2003). Guidelines for life cycle cost analysis: final report. In: Report No FHWA-NJ-2003-012, Trenton, NJ.
Pittenger, D., Gransberg, D., Zaman, M., & Riemer, C. (2012). Stochastic life-cycle cost analysis for pavement preservation treatments. *Transportation Research Record: Journal of the Transportation Research Board*(2292), 45-51.
Rahman, S., & Vanier, D. J. (2004). *Life cycle cost analysis as a decision support tool for managing municipal infrastructure.* Paper presented at the CIB 2004 triennial congress.
Rangaraju, P. R., Amirkhanian, S. N., & Guven, Z. (2008). *Life cycle cost analysis for pavement type selection*. Retrieved from
Sadasivam, S., & Mallela, J. (2015). Application of Work Zone Road User Costs to Determine Schedule-Related Incentives and Disincentives. *Transportation Research Record: Journal of the Transportation Research Board*(2504), 39-45.
Safi, M. (2009). *Bridge Life Cycle Cost Optimization: Analysis, Evaluation & Implementation*.
Smith, J. W. I. a. M. R. (1998). *Life Cycle Cost Analysis in Pavement Design- Interim Technical Bulletin* (FHWA-SA-98-079). Retrieved from FHWA:

Strauss, A., Bergmeister, K., Hoffmann, S., Pukl, R., & Novák, D. (2008). Advanced life-cycle analysis of existing concrete bridges. *Journal of Materials in Civil Engineering, 20*(1), 9-19.

Thoft-Christensen, P. (2015). *User costs in life-cycle cost-benefit (LCCB) analysis of bridges.* Paper presented at the Advances in Bridge Maintenance, Safety Management, and Life-Cycle Performance, Set of Book & CD-ROM: Proceedings of the Third International Conference on Bridge Maintenance, Safety and Management, 16-19 July 2006, Porto, Portugal-IABMAS'06.

Town of Morrison Police Department. (2017). Community Updates. Retrieved from https://town.morrison.co.us/294/Community-Updates

US DOT. (2007). *Asset Management Overview*. Federal Highway Administration, Washington, D.C.

Xie, F., & Levinson, D. (2011). Evaluating the effects of the I-35W bridge collapse on road-users in the twin cities metropolitan region. *Transportation planning and technology, 34*(7), 691-703.

Yang, G. (2007). *Life cycle reliability engineering*: John Wiley & Sons.