# DEVELOPMENT OF UNIT COST ESTIMATING MODELS WITH RESPECT TO SCALE ECONOMIES AND MATERIAL PRICE VOLATILITY FOR USE IN PROBABILISTIC LIFE CYCLE COST ANALYSES

by

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A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in the Department of Civil,
Construction, and Environmental Engineering
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2013

## EXECUTIVE SUMMARY

When faced with multiple viable alternatives, an effective economic comparison tool is to examine the total life cycle costs of each alternative using life cycle cost analysis (LCCA) techniques. Conducting an LCCA requires an analyst to estimate the initial cost of an alternative as well as future costs which are then discounted based on the time value of money. One such application of LCCA is during the pavement type selection process. This research examined the pavement LCCA process and the factors that are used in the calculation of the life cycle costs; the sensitivity of the costs to the adjustments caused by price adjustment clauses (PAC); and the forecasting of asphalt pavements based on the project's location, point in time, and the quantity of material required to complete the paving project.

The first objective of this research was to identify and discuss issues and challenges associated with performing an LCCA during the pavement type selection process and provide recommendations on those key factors. Several important factors were identified during this research as key elements during an LCCA performed during the pavement type selection process. Two critical factors identified were the analysis period used to frame the analysis and the discount rate used to calculate the present value of future expenditures. From the review of pertinent LCCA literature and the outcomes of the meetings between the asphalt and concrete pavement industries and the Alabama Department of Transportation (ALDOT), it was determined that an analysis period of 40 to 45 years would provide an analyst with a long enough period to calculate the true life cycle costs of the pavement alternatives. It is also recommended

that a ten-year rolling average of the Office of Management and Budgets (OMB) real discount rate should be used in the LCCA.

Other factors, such as adjusting the asphalt initial construction cost based on the price adjustment clause (PAC) and material specific escalation rates, were also examined in this research. These two factors were brought up by the concrete pavement industry in an effort to make sure that the actual cost of asphalt materials is calculated due to the recent volatility in asphalt prices. Other recommendations, such as transitioning to the use of probabilistic analyses and the use of RealCost to facilitate the calculation of the life cycle costs of the alternatives, were also provided by this research.

The next objective in the research was to examine the effect that PACs have on the initial construction cost when used in a probabilistic LCCA. To accomplish this objective, an example paving project near Birmingham, Alabama was used to provide thickness designs, material quantities, and unit costs for asphalt and concrete pavement alternatives. After conducting a sensitivity analysis on the example project, it was determined that the outcome of the analysis was sensitive to factors such as the discount rate and analysis period. Another important element in the calculation of the total life cycle costs discovered during the analysis was the initial construction cost estimates of the pavement alternatives. It was found that, for the example paving project, an estimating error of five percent for either material would change which alternative is deemed the most attractive from an economic standpoint.

Since an LCCA is concerned with the actual costs paid out during the life-cycle of an alternative, the sensitivity to PACs were also examined. To accomplish this phase of the research, a probabilistic analysis of the example project was constructed by creating probability distributions for the pay item unit costs and the initial and rehabilitation performance periods of the pavement alternatives using historical data. To simulate the effect that PACs could have on what is actually paid for the alternatives, the mean of the unit costs of the asphalt paving materials were adjusted each month based on the adjustments caused by ALDOT asphalt index for the year 2011. After simulating the cost models at each month, it was discovered that the PACs increased the probability that the wrong pavement type is selected by as much as 18 percent. After these simulations, it was determined that a new framework for estimating the initial construction costs for pavement LCCAs was needed.

The estimation of construction costs is one of the most important considerations during the preliminary phases of a construction project, and when comparing alternatives during pavement type selection process, the initial construction costs typically constitute a majority of the total life cycle costs of the pavement alternatives. To provide a true representation of the total costs, an estimator must have enough information so that an accurate forecast of the costs can be made at the time the project is bid or, if PACs are used in the contract, at the time the project is constructed. An estimate of the initial construction cost based on the current costs at the time the LCCA is conducted could lead to the selection of the wrong pavement alternative from an economic point-of-view.

To accomplish the third and final objective of this research, which involved developing and exercising a new framework for estimating the unit costs of pay items used in the calculation of initial construction costs of asphalt pavements, Alabama asphalt paving data from the year 2000 to 2012 was gathered and examined. Before any analysis of the data was conducted, all cost data was adjusted for time by deflating the historical costs using the Consumer Price Index (CPI) and location through the use of location adjustment factors. Doing so brought all the cost data to the same point in time and to the same geographic location. To account for any variation in price due to asphalt layer, the data was grouped into three categories based on the asphalt layer: lower binder, upper binder, and wearing surface. The cost data was also categorized based on the quantity of material so that any variations in cost due to economies of scale could be analyzed. Once the data was sorted into the appropriate categories, the mean unit cost of the pavement cost data was calculated for each time period so that forecasting models could be constructed.

To allow an estimate of the initial construction costs of the asphalt pavements to be made, forecasting models were created using time series analysis and regression analysis of the paving data for each layer and quantity category for the first 65 time periods (nine time periods were withheld during the model fitting for validation). After fitting the models to the data groups, the models were compared based on the fit during the model estimation period and multiple step ahead forecasting accuracy during the validation period. In general, the time series models performed better than the regression models during the validation period and these models were chosen as the forecasting models for the asphalt unit cost data.

While the forecasting models provide an estimate of the unit cost in the future, a measure of uncertainty is also needed so that the estimates can be used in a probabilistic analysis of the total life cycle costs. To determine this level of uncertainty, the data for each layer and quantity group at each time period was analyzed to determine which probability distributions provide the most realistic modelling of the unit cost uncertainty. From the analysis, it was determined that lognormal and normal distributions fit the data the best. For a given layer and quantity grouping, the shape parameters of the distribution fits at each time period were recorded and averaged for the data. These values would then be used to populate the simulations for the calculation of the initial construction costs.

In conclusion, several factors were identified as having a significant bearing on the outcome of an LCCA during the pavement type selection process. One of the critical factors identified was the estimation of the initial construction costs. A small error in the estimated cost could result in one pavement being chosen although it is not the best economic option. To improve the estimation of the initial construction costs for a pavement LCCA, a framework was devised that will allow an analyst to use forecasting models to estimate the actual cost of the asphalt material at the time of bid or construction based on the project's location. While the framework for forecasting the construction costs in this research used pavements as an example, this framework can also be applied to multiple types of construction and construction materials.

ABSTRACT

In regard to pavement materials, some state highway agencies are naturally inclined to favor one material over others based on familiarity with construction of the pavement and the typical distress and failure characteristics of the material. Both asphalt and portland cement concrete pavements have their own unique advantages and disadvantages, and their use by state highway agencies is contingent upon numerous factors including technical performance and engineering economy. Traditionally, one of the main factors in pavement material selection has been the analysis of initial construction costs. However, with more transportation assets added to the state's inventory each year and financial resources becoming more restricted, state highway agencies have recognized the need to choose the best pavement option for their citizens that will require minimum agency resources to maintain and rehabilitate requires more than an analysis of initial costs.

This research seeks to analyze the life cycle costs of these two paving materials in the state of Alabama while investigating which projects warrant a life cycle cost analysis (LCCA). Design and construction practices of concrete pavements will also be examined so that factors that significantly influence the life cycle costs of this pavement material can be identified. This research will also examine the availability of engineering and economic data, determine what data is necessary to provide a practical estimate to the total cost of ownership for both pavement alternatives, and address such issues as forecasting initial construction costs for use in a stochastic LCCA and identifying significant issues with the current LCCA process.

ACKNOWLEDGMENTS

An undertaking such as a dissertation is not accomplished without the ever present support of many people. The completion of this work could not have been realized without the help of several groups of people. The first group I wish to thank are the members of my committee. The first person to acknowledge is Dr. Ed Back, my committee chair, for sharing his wisdom and enthusiasm for the subject matter at hand and for his mentorship during some trying times. The other members of my committee, Dr. Ken Fridley, Dr. Eric Giannini, Dr. Jay Lindly, Dr. Philip Johnson, and Dr. Marcus Perry, also deserve a wealth of gratitude due to their support and eagerness to provide invaluable input throughout the duration of this endeavor.

The completion of this research could not have been possible without the enduring love and patience provided by my wife, Tamara. Words cannot fully describe how grateful and blessed I am for her constant support and optimism. I am forever thankful. I am also extremely appreciative for the support provided by my parents, Ronnie and Janis, my parents-in-law, Sam and Katrina Smelley, and grandparents-in-law, James and Kayo Booth. I could not have come this far without them believing in me and helping me reach my goals.

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# CHAPTER I

# INTRODUCTION

## 1.1 Overview

A significant portion of the highway system in the United States of America is in dire need of repair. As a conduit for vehicular travel and freight distribution, the vitality of the nation's economy is contingent upon a national roadway system that permits a smooth, reliable, and safe flow of persons and goods. The American Society of Civil Engineers (ASCE), in their 2009 America's Infrastructure Report Card, gave the nation's roadways a "D-" grade and estimated that one-third of the nation's major roads are in poor to mediocre condition (2009). In their state specific report cards, ASCE rated Alabama's roadways as the top infrastructure concern due to the fact that 16 percent of the state's major roads have pavements that are in poor to mediocre condition and 52 percent of the urban highways are considered congested (ASCE 2009).

Due to its geographic location, the state of Alabama witnesses the movement of millions of pounds of goods through and within the borders of the state every year by multiple modes of transportation. A study by the Alabama Department of Transportation (ALDOT) found that approximately 53 percent of freight shipments (by weight) into, out of, and within the state of Alabama were executed by truck, with commodities ranging from raw materials to daily necessities such as food and clothing (ALDOT 2010). To ensure its economic growth and sustainability, Alabama must thoroughly analyze viable options with regard to new roadway construction and maintenance activities to maintain and support the free flow of goods and services across the state.

According to the Federal Highway Administration's (FHWA) Highway Statistics Manual, the state of Alabama contains 15,162 centerline miles of high-type paved roadways, with ALDOT owning and maintaining 10,938 centerline miles of those roads (FHWA 2009). Within the total state road system, 96.0 percent of the total centerline miles are paved with asphalt concrete while just 2.5 percent of the roadways are paved with portland cement concrete (FHWA 2009). When these roadways deteriorate, the state must rehabilitate, repair, restore, or replace these existing pavements while maintaining fiduciary control of the department budget. To ensure the responsible management of funds, ALDOT must carefully examine all possible construction and material based options and make decisions based on multiple factors and parameters that appropriately address risk and uncertainty.

## 1.2 Background

### 1.2.1 Current Practice in Alabama Regarding Life Cycle Cost Analysis

The Alabama DOT, like many other state highway agencies, performs a life cycle cost analysis (LCCA) when selecting between several pavement alternatives. The triggers currently in place for the analysis include new construction projects, flexible pavement reconstruction projects, and projects that include the addition of a separate roadway to an existing roadway. To qualify, the project must also have a flexible pavement design structural number of 6.0 or higher. The structural number of the pavement reflects the strength contributions of all of the pavement layers (Brockenbough 2009). Projects less than four miles in centerline length do not require a

LCCA. If the proposed project is located along the same route as a comparable project, a LCCA will not be required for a new project if:

- An analysis was performed on a similar project, and
- The two projects have approximately ± 20% the same traffic volume and percentage of commercial vehicles, and
- Are located within ten miles of each other, or
- Will be constructed on the same geologic formations.

However, if the cost analysis performed on the previous project is more than five years old and there is a change to the number of traffic lanes on the roadway, a LCCA is required. All concrete pavement reconstruction projects require a LCCA for all applicable alternatives. LCC analyses for special projects and projects not requiring mainline paving are required at the discretion of ALDOT's Materials and Test Engineer.

To perform the analysis, ALDOT utilizes DARWin software, a program produced by the American Association of State Highway and Transportation Officials (AASHTO), to calculate the life cycle costs (Rangaraju et al. 2008). ALDOT does not include user costs and routine maintenance costs in the analysis. A real discount rate of four percent is used for all pavement cost analyses. Currently, the state of Alabama uses an analysis period of 28 years in their life cycle cost calculations, one of the lowest analysis periods represented in the national survey (Rangaraju et al. 2008). The initial performance life of flexible pavements used by ALDOT is set at 12 years; rigid pavement initial performance life is fixed at 20 years and the type of rigid pavement, such as continuously reinforced or jointed reinforced concrete pavements, does not affect this value. The life expectancy of the rehabilitation measures for flexible and rigid pavements is set at eight years for both alternatives. The analysis period, discount rate, and rehabilitation timing values used by ALDOT are fixed, discrete values in the life cycle analysis. The method of LCCA that the state DOT currently follows is a deterministic approach, with input factors coming solely from state data. A concise summary of ALDOT's approach to LCCA and the factors used in the analysis for pavement selection are shown in Table 1.

Table 1. ALDOT Approach/Factors for LCCA for pavement type selection

| **ALDOT LCCA for Pavement Type Selection** *LCCA Approach/Factors* | |
|---|---|
| Software used to calculate LCCA | DARWin 3.1 |
| User Costs Included? | No |
| Discount Rate | 4% |
| Analysis Period | 28 Years |
| Initial Performance Life: | |
| *Flexible Pavements* | 12 Years |
| *Rigid Pavements* | 20 Years |
| Routine Maintenance Costs Included in LCCA? | No |
| Usage of Salvage/Residual Values? | No |
| Type of LCCA Approach | Deterministic |
| Sensitivity Analysis | No |

*Source Data: ACPA 2012, Rangaraju et al. 2008*

### 1.2.2 Current Concerns with ALDOT Pavement Type Selection Process

The concrete pavement industry has had numerous concerns with several state DOTs about the competiveness of concrete pavements versus asphalt in their pavement type selection process (R. Taylor, letter to Governor of Alabama, 2005; S. Joiner, unpublished internal report, 2011). These concerns include issues such as economic factors, design parameters, construction, and rehabilitation strategies that are included in the decision making process. One of the major concerns is that the concrete industry does not believe most states provide equivalent designs for both concrete and asphalt alternatives. For a LCCA between two alternatives to be conducted accurately, both alternatives must provide the same level of performance. In a case study of the Alternate Pavement Bidding (APB) procedures in place at the North Carolina Department of

Transportation (NCDOT), Mack et al. (J. Mack, unpublished report, 2012) found that concrete pavements were designed based on 30-year ESAL counts whereas the competing asphalt alternatives were designed using a 20-year ESAL count. Since the concrete alternative was designed with a higher anticipated loading strategy, the resulting concrete pavement design was too thick for the agency's required level of performance. Because of this inequality, the extra thickness would result in inflated life cycle costs for the concrete alternative and would ultimately result in higher bids by concrete pavement contractors to cover the additional material needed to meet the design.

The concrete industry believes that many states, including Alabama, use particularly conservative design standards and specifications for rigid pavements when compared to flexible pavements (R. Taylor, letter to ALDOT Materials Engineer, 2008; J. Mack, unpublished report, 2012). These designs will not only inflate initial construction cost estimates but could also result in unrealistic design lives, especially when coupled with a fixed rehabilitation strategy for concrete pavements. For example, the concrete pavement industry examined designs for a paving project in Jefferson County, Alabama based on current design specifications. The three-lane project was designed to carry 27 million ESALs over a 20-year design life, and a rigid pavement alternative was designed by ALDOT engineers as a 13-inch jointed plain concrete pavement (JPCP) with 1.625-inch diameter dowels constructed on a permeable asphalt treated base using current ALDOT design specifications. Given the engineering design parameters, the concrete industry found that an 11-inch pavement with 1.5-inch diameter dowels using the AASHTO-93 design procedure would not only provide adequate performance but would also last well beyond the 20-year design life.

In the life cycle cost analysis (LCCA) of the pavement alternative, the concrete pavement was scheduled to receive a costly pavement rehabilitation after 20 years. Based on current ALDOT practices, the major rehabilitation measures would likely include replacement of damaged slabs, spall repair, joint sealing, and diamond grinding. However, performance predictions indicated that an 11-inch JPCP, subjected to the forecasted ESAL loads, would result in insignificant joint faulting and minimal slab cracking at the 20-year mark, greatly reducing the rehabilitation measures that would be needed. At a 95 percent reliability level, the concrete pavements were predicted to last well beyond the initial performance period of 20 years. The concrete industry also noted that a similar 13-inch JPCP designed for Interstate 65 in Nashville, Tennessee was designed to carry 92 million ESALs over its lifetime (3.4 times greater than the Alabama design), highlighting the conservative nature of the design for the Jefferson County project. In this case, a set initial performance period and fixed rehabilitation strategy would result in higher life cycle costs for the concrete pavement alternative.

The concrete pavement industry also had concerns over the values and the approach used in the ALDOT LCCA process. From the industry's viewpoint, the discount rate currently in use was established on outdated recommendations from the FHWA and is not the correct representation of current conditions. The concrete industry also supports the use of material specific inflation (or escalation) rates in the LCCA for pavements. The industry's position is that the current LCCA procedures in place are not an accurate gauge of future asphalt costs because it assumes that asphalt prices will inflate at the same similarly to the general inflation rate. Another concern is the deterministic approach (without a sensitivity analysis) that ALDOT takes when performing the analysis. Other concerns specified by the industry included indexing of asphalt, incentive/disincentive policies in construction contracts, and the lack of comparable measurement of area or volume of materials used during the estimating and bidding process.

ALDOT also expressed some concerns with revising the LCCA process currently used by the agency. One concern was the factors, or triggers, that would require an LCCA to be conducted. If the triggers were not practical, ALDOT could perform too many LCCAs during the pavement selection process, and valuable resources, which could be used for other pressing issues within the state transportation infrastructure, would be squandered when an LCCA was performed when it was not necessary. Conversely, performing too few analyses would miss opportunities to increase competition and save money as well as providing the taxpayers with the best available option. Another concern highlighted by ALDOT dealt with the practicality of the procedure. If the process became too robust the state could again waste time, money, and labor performing complex calculations that did not reduce much of the uncertainty within the analysis or add any benefit to the process.

To address the concerns held by both the concrete pavement industry and the State of Alabama, a research project was initiated in June 2012 to reexamine the methods and input parameters used by ALDOT to determine life cycle costs for asphalt and concrete pavement alternatives. The reasoning behind the request is that the current procedures and values used in the LCCA may not provide an accurate representation of life cycle costs due to advancements in materials and construction techniques as well as changes in economic factors that could influence the final results. The research effort is a cooperative effort between ALDOT, FHWA, the University of Alabama, Auburn University, and asphalt and concrete pavement industry representatives. The University of Alabama will gather data, research, and analyze factors for use in a LCCA for concrete pavements while Auburn University will research and analyze LCCA inputs for asphalt pavements. Both research thrusts will focus on the LCCA parameters to be used in the analysis for pavement type selection for large paving projects in the state of Alabama.

## 1.3 Objectives

The main goal of the research is to provide a review of the current, state of the practice, scientific data to support the factors and values that are used in calculating life cycle costs for pavement alternatives and to provide a framework for estimating the initial construction cost of asphalt pavement based on historical paving cost data. To accomplish this goal, the research effort will consist of three primary objectives:

1. Identify and discuss issues and challenges associated with performing an LCCA during pavement type selection process and provide recommendations on these key factors,

2. Examine the effect that price adjustment clauses (PAC) have on the initial construction cost when used in a probabilistic LCCA, and

3. Develop and exercise a new methodology for estimating the unit costs of pay items used in the calculation of initial construction costs of asphalt pavements.

## 1.4 Research Methodology

A well-defined, structured methodology is an important consideration in this research. The flow from one stage of the methodology to the next is shown in Figure 1. The process started with the motivation for the research and proceeded to exploring the background of the problem so that gaps in knowledge can be identified. Once the background was established and the gaps in knowledge substantiated, the next step in the process involved the creation of the problem statement and the generation of research objectives to provide the structure for the research.

The first research objective included gathering pertinent data on the research problem in order to identify key issues and challenges with the current LCCA process for pavement type selection process. The sources of data for this project include historical paving data from Alabama and other states in the Southeastern United States. Input from ALDOT personnel responsible for conducting the LCCA as well as industry representatives were also be considered to determine the important criteria of the LCCA. Major economic factors in the LCCA analysis, such as the analysis period and real discount rate, were determined from reviews of pertinent literature, expert opinion, and state of the practice values. Based on the review of literature and expert opinion, appropriate values of LCCA factors were recommended for inclusion in the pavement type selection process.

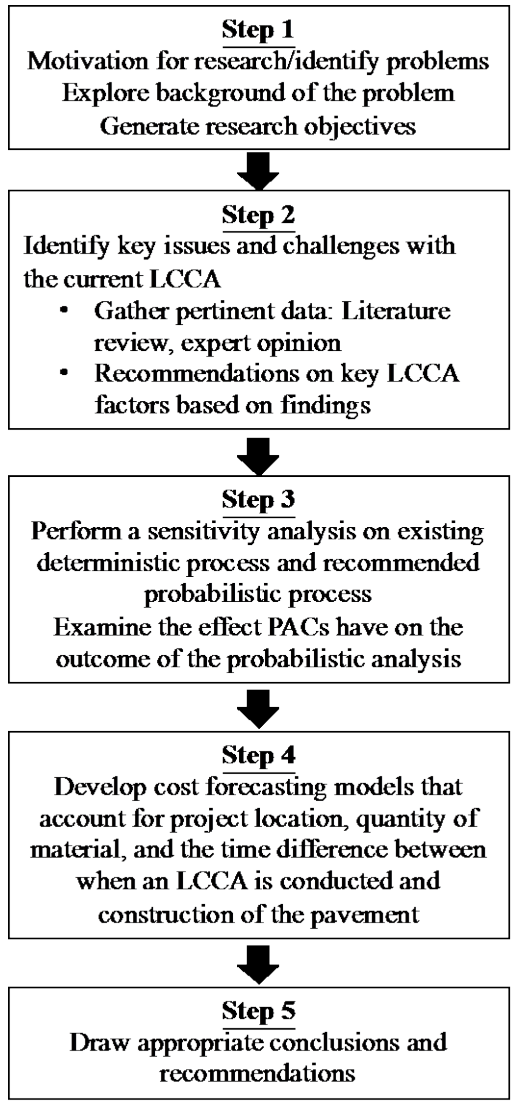


Figure 1. Research methodology flow chart

The first portion of the second research objective involved conducting a sensitivity analysis on the current LCCA procedure in place at ALDOT. To accomplish this portion of the research objective, an LCCA conducted on a paving project in Birmingham, Alabama was used as a case study. From this case study, factors in the deterministic LCCA such as analysis period, discount rate, and initial construction costs of the asphalt and concrete pavement alternative were varied to examine the amount of influence those factors have on the final life cycle costs of the pavement alternatives.

The final portion of the second research objective required a sensitivity analysis to be conducted on a new probabilistic analysis framework that was created using recommendations outlined in the first research objective. The sensitivity analysis was focused exclusively on the initial construction cost estimate of the pavement alternatives to examine how failure to accommodate for the variability in asphalt prices could lead the analyst to choose the wrong pavement material. The mean unit costs of the asphalt pay items used in the calculation of the initial construction cost distribution of the pavements were varied to examine the effect that PACs could have on the difference in life cycle costs between the two pavement materials. During this analysis, all life cycle cost simulations were conducted using RealCost software; however, while RealCost software can be used to run the simulation of the full probabilistic life cycle cost model, the program does not allow the user to include the values and probability distributions of individual bid item unit costs used in the calculation of initial construction costs and rehabilitation costs of the pavement alternatives. To account for the uncertainty associated with unit costs, a separate probabilistic model to calculate the initial construction costs and rehabilitation costs was created using JMP software.

Given what was learned in the first and second research objectives, the third research objective focused solely on the initial construction cost estimate of the asphalt alternative used in both deterministic and probabilistic analyses. Because little guidance is given on forecasting the unit costs of asphalt pay items and how to accommodate the use of PACs in the paving contract, time series and regression models were constructed to forecast the unit cost of asphalt paving based on the paving layer, the quantity of material needed to construct the project, and the project location. A new methodology to account for the time difference between the point in time an LCCA is conducted and the time the project is actually bid or constructed by using the forecasting models is also outlined.

## 1.5 Contribution

The significant contributions of this research include:

- Determination of the applicability of key factors within a LCCA for pavement type selection used by state highway agencies.
- Identification of economic, design, and construction factors that significantly influence the life cycle costs of pavement alternatives.
- Development of a new methodology for forecasting the initial construction costs of asphalt paving operations for use in deterministic and probabilistic LCCAs that account for project size, project location, and price adjustment clauses (PAC)
- Identify issues and challenges with the current state-of-the-practice LCCA procedure used during the pavement type selection process.

# CHAPTER II

# LITERATURE REVIEW

## 2.1 Flexible Pavements

Flexible pavements consist of asphalt concrete placed on top of granular base/subbase layers and a soil subgrade layer (Papagiannakis and Masad 2008). The asphalt concrete consists of crushed stone, sand, filler material, and asphalt, a by-product of the petroleum distillation process. Asphalt pavements are constructed in multiple layers (or lifts) that are laid upon prepared base and subbase layers atop the subgrade (Papagiannakis and Masad 2008). Each of these layers possesses a different relative stiffness, and the stiffness differential between the layers allows the pavement to carry vehicular loads. The stiffest layer is typically the uppermost lift, or wearing surface, and the relative stiffness of each layer decreases from top to bottom. As a load is applied to the top of the pavement surface, the stresses are distributed through the layers over greater and greater areas (Blades and Kearney 2004; Mannering et al. 2005). The thickness of each layer has a cumulative effect on the amount of stress absorbed by the subgrade; sufficient pavement thickness is required to prevent permanent deformation of the subgrade material. Since flexible pavements rebound with the subgrade, the properties of both the subgrade and subbase layers are important when designing the asphalt pavement layers (Brockenbrough 2009).

Several design mixes of asphalt concrete are available for use in highway pavements. The most widely used mixture for roadway construction is hot-mix asphalt (HMA). HMA is composed of approximately five percent asphalt binder and 95 percent aggregate. Prior to placement, both the asphalt and aggregate are heated to over 300° F and combined so that the binder completely mixes with both the coarse and fine aggregate in the mixture. Subsets of HMA mixtures are classified based on the gradation of the aggregated within the mixtures and include dense-graded, open-graded, and gap-graded mixes. Another subtype of HMA mixtures is stone matrix asphalt (SMA) pavements. This type of pavement is a gap-graded HMA that contains relatively few mid-size particles within the aggregate mix, allowing the coarse aggregate particles to interact within the asphalt layers. Under vehicular loading, the interaction between the coarse stone particles allows the stresses to act more on the aggregate rather than the asphalt binder, greatly increasing durability and its ability to withstand rutting and permanent deformation.

Another mixture type that has garnered considerable research is warm-mix asphalt (WMA). WMA has chemical additives in the asphalt binder that reduces the viscosity of the binder at lower temperatures, allowing the aggregate to be coated with asphalt binder at temperatures below 300° F; the reduction in mixing temperatures for WMA has been shown to reduce the energy costs needed to heat the mix and the emission of noxious gases when compared to traditional HMA production (Gandhi 2008; Bernier 2011). However, several concerns exist with WMA pavements and include the mixture’s durability, long-term performance, and its susceptibility to moisture (Kvasnak and West 2009).

The two main types of asphalt concrete pavements are deep-strength asphalt concrete pavements (DSACP) and full-depth asphalt concrete pavements (FDACP). DSACP are characterized by the use of a granular subbase material overlain by asphalt layers. The subbase is compacted and left untreated after placement, and this allows for the drainage of moisture the layer. The use of granular bases is also advantageous when dealing with weak subgrades that may lose compaction after construction (Brockenbough 2009). FDACP are categorized as using asphalt mixtures for all courses overlying the prepared subgrade (Brockenbrough 2009). By utilizing HMA courses for all layers within the pavement section, water penetration through the layers to the subgrade is negated. The retardation of water penetration through the layers prevents premature deterioration and allows for the pavement to be more resistant to the effects of multiple freeze-thaw cycles.

Asphalt pavement distresses are similar in nature to those witnessed in concrete pavements. Cracking is the prevalent distress type and can include longitudinal, transverse, block, and alligator cracking (Papagiannakis and Masad 2008). Longitudinal cracking can occur anywhere on the pavement surface, including the edge, wheel paths, and center joints and are typically the result of fatigue and weathering of the pavement. Transverse cracks manifest themselves in the pavement due to thermal shrinkage as result of temperature fluctuations and the hardening of the asphalt binder over time (Brockenbough 2008). Block cracking is a combination of longitudinal and transverse cracking, creating rectangular blocks on the surface and is a result of binder hardening and weathering. Alligator cracking is similar to block cracking, but alligator cracking is characterized by smaller, polygonal cracks in the pavement surface. Alligator cracking is loading or fatigue related and is a symptom of insufficient strength of the pavement, weak subgrade, or overloading of the pavement (Lavin 2003). This type of cracking is typically localized in the wheel paths of the pavement.

Other major asphalt pavement distresses include raveling, potholes, rutting, and shoving. Raveling is considered a flexible pavement surface defect and is a result of aggregate loss. This type of defect is caused by poor adhesion between the aggregate particles and the asphalt binder at the pavement surface, and over time, the loss of aggregate will progress downward through the wearing surface layer. Potholes are a common type of flexible pavement failure and are a consequence of poor or weak subbase and/or subgrade materials; since they are a deep pavement failure and the hole created by the failure is uncomfortable to drive over, potholes are highly noticeable by roadway travelers.

The asphalt pavement industry in the United States considers asphalt as the superior pavement material for a multitude of reasons. According to the Asphalt Pavement Alliance (APA), asphalt's low cost of installation, flexibility and speed of construction and rehabilitation, ease of maintenance, and smoothness are advantages recognized by both the paving agency and the public and promotes the material's superiority over concrete pavements (APA 2010). Other desirable features of asphalt pavements listed by the industry include the ability for the pavement to be completely recycled at the end of its useful life and the capability for the pavement to be designed, constructed, and maintained under a wide range of climate and geotechnical conditions (APA 2010).

## 2.2 Rigid Pavements

Rigid pavements are typically designed as a portland cement concrete layer overlying a granular base layer and the soil subgrade or with the concrete layer lying directly on the subgrade. These pavements resist the surface wheel loading from vehicles through flexure of the concrete layer itself. Due to this action, a smaller proportion of the stress directly applied to the surface layer is transmitted to the subgrade layer because the stress is distributed across a wider area. In addition to wheel loads, other stresses act on concrete pavements as well and are the result of expansion and contraction of the slabs due thermal fluctuations, yielding of the subgrade (or base) layer that supports the pavement, and volumetric changes (Garber and Hoel 2009). The behavior of concrete pavements under various load and stress configurations is an important consideration during the selection of the type of rigid pavement to be used and the structural design of the pavement.

There are several types of concrete pavements used in the United States, and each type has their own unique design and load transmitting characteristics of the joints to control cracking of the pavement slabs. One of the most straightforward types of concrete pavements is jointed plain concrete pavements (JPCP). This type of pavement consists of unreinforced concrete slabs ranging from 12 feet to 20 feet in length with transverse contraction joints uniformly spaced between the slabs (Delatte 2008; Mallick and El-Korchi 2008). Joints are constructed in the pavement at closer intervals to reduce the chances of cracks forming in the central section of the slabs. To transfer loads from one slab to another, JPCP relies upon the interaction of coarse aggregate within the joint. Aggregate interlock joints are created during the construction of the roadway by sawing a shallow cut through the pavement at defined intervals. As the concrete shrinks following construction, a crack will then propagate through the remaining thickness of the slab at the saw cut location and the roughness of the aggregate within the crack will allow the transmission of loads between slabs (Delatte 2008).

Another method of transferring the loads across slabs is the use of jointed dowel-reinforced concrete pavements (JDRCP). This type of joint utilizes corrosion resistant epoxy coated steel dowels at the transverse joints that allow vertical loads to be transmitted between slabs without inhibiting the expansion and contraction of the slabs due to environmental influences (Papagiannakis and Masad 2008, Snyder 2011). Continuously reinforced concrete pavements (CRCP) are constructed with longitudinal steel reinforcement throughout the entire length of the pavement. These pavements are constructed without joints, and any transverse cracks, typically at three to five foot intervals, that form along the pavement are held together by the reinforcement so that aggregate interlock is achieved to allow for vertical and shear load transfer (Brockenbough 2009; Delatte 2008). Hybrid designs, such as jointed reinforced concrete pavements (JRCP), incorporate certain characteristics present in the aforementioned rigid pavement types into one design.

As part of the Long Term Pavement Performance (LTPP) program, the FHWA has created a Distress Identification Manual to identify rigid pavement distress types and to classify their severity (Delatte 2008). The manual categorizes the four main types of pavement distress for JPCP and JRCP as cracks, joint deficiencies, surface defects, and miscellaneous defects (Miller and Bellinger 2003). The distress types for CRCP are similar but do not include joint deficiencies and removes corner breaks from the cracking category. Cracking in rigid pavements may result from fatigue due to repeated loadings over an extended period of time or an extreme one-time loading that causes immediate distress in the pavement. Corner breaks, longitudinal cracking, and transverse cracking are the most common distress types in this category (Delatte 2008). Durability, or “D”, cracking is another failure mode that may occur and is typically attributed to the use of non-durable materials and severe climate conditions (Mindess et al. 2003). Most unplanned cracking scenarios, if left unattended, may lead to the ultimate structural failure of the concrete pavement.

Joint deficiencies are another major type of concrete pavement distress. Joint seals, which are implemented to keep out debris and water that may inhibit the designed function of the joint, may become ineffective due to damage or faulty construction (Delatte 2008; Papagiannakis and Masad 2008). Damaged seals can eventually lead to the accelerated deterioration of the concrete and the supporting base/subgrade layers. Joint spalling is the result of inadequate dowel selection during design or poor construction (Huang 2004). Surface defects are typically the result of poor concrete mix materials or poor construction activities. This type of distress in concrete pavements includes map cracking, spalling, popouts, and polished aggregates (Brockenbough 2009). While typically not considered structural failures, these distresses may facilitate damage to the pavement in the future.

Other types of failure witnessed with concrete pavements include pumping, faulting, and punchouts. If the subgrade is comprised of high plasticity clay that is saturated, heavy wheel loads may cause entrapped water between the subgrade and pavement slab to be pumped to the surface of the pavement (FHWA 2009). This water usually carries with it fine particles that can slowly erode the subgrade layer directly underneath the joint or crack. Faulting occurs when there is a height differential across the joint of two adjacent slabs or across a crack within a slab, and the cause of these faults may be failure of an aggregate interlock or doweled joint or the movement of the base material as a result of pumping (FHWA 2009). Punchouts occur only with CRCP and are characterized by rectangular pieces of concrete that have failed and have been punched down below the surface of the surrounding pavements (Delatte 2008). Faulted joints or cracks and punchouts are the most often failures of the pavement noticed by the travelling public.

The concrete pavement industry views concrete pavements as the more durable and cost effective alternative to commonly used asphalt pavements. In addition to the long term cost benefits of the pavement, the industry exalts the longevity and versatility of concrete pavements, noting their ability to last longer than comparable asphalt pavements while also requiring minimal maintenance over the term of their service life. The environmental benefits are also a selling point for concrete pavements. Old concrete pavements are completely recyclable, and since concrete is not produced from the distillation of crude oil, concrete pavements do not release harmful compounds such as polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds  (VOCs) during the construction of the pavement as compared to asphalt (Michigan Concrete Association 2012). Concrete pavements also provide a safe surface due to the increased visibility of the pavement and its superior traction properties (Wisconsin Concrete Pavement Association 2012).

## 2.3 Pavement Maintenance and Rehabilitation

After repeated wheel loadings and stresses induced by environmental factors, both flexible and rigid pavements will deteriorate and require attention to reduce the likelihood of complete failure. For state highway officials and other pavement asset managers, triggers for maintenance and rehabilitation activities may exist in the form of designated periods, visual inspection of the pavement, thresholds of pavement distress such as rutting and cracking, and the analysis of performance measures/indices such the pavement structural condition (PSC), pavement quality indicator (PQI), and measures of roughness such as the International Roughness Index (IRI) (Ford et al. 2012). Dependent upon a multitude of factors, these triggers may occur before the pavement has reached its design life or, in some instances, not at all if a scheduled rehabilitation has already taken place.

Routine maintenance of highway pavements is a critically important activity for many highway agencies. The timing of pavement maintenance is vital to maintain a quality level of service and extend the period of time between initial construction and full rehabilitation activities (Delatte 2008). For concrete pavements, common maintenance practices include joint and crack resealing. Joints, on average, will not last as long as the concrete pavement and must be resealed periodically; resealing joints in the pavement that are damaged or that have lost adhesion with the concrete prevents debris from infiltrating the joints and causing extensive damage to the pavement slabs. The basic process typically involves removing the old sealant, cleaning and shaping the joint, and applying the sealant (Delatte 2008). Depending upon the sealant material, the joint seals, on average, will last three to eight years before needing resealing; compression seals can provide an even longer level of service, exceeding 15 years, with proper maintenance and cleaning (Delatte 2008). Cracks in the pavement slabs are typically repaired in the same manner as those employed to repair joints. The number of joints and cracks needing repair work and the amount of work required to prepare the joints and cracks will determine the length of time required to complete the work and open the lanes up to normal traffic flow.

If regular maintenance is no longer a viable option to restore the concrete pavement to an acceptable level of serviceability, more extensive actions are necessary. This level of rehabilitation is referred to as concrete pavement restoration (CPR). These restoration measures include activities such as diamond grinding, cross-stitching, dowel retrofits, full and partial depth repairs (patching), and thin asphalt concrete overlays (Delatte 2008; Jung 2008). Diamond grinding removes inconsistencies on the pavement surface while increasing friction and restoring ride quality. A study by Caltrans (2005) indicated that, on average, concrete pavements within the state that have received diamond grinding treatment maintained their smoothness for 16 to 17 years. Cross-stitching and dowel retrofits are both measures to restore load transfer capabilities; cross-stitching is used to reestablish transfer between longitudinal cracks or joints while dowel retrofits are employed to maintain load transfer at transverse joints (ACPA 2001; Delatte 2008). Typically, these activities are performed while shutting down one lane, minimizing user delays, and the length of time needed to perform the work is dependent upon the severity of the repair needed and the existing condition of the pavement.

A partial depth repair, or patch, is employed when the level of deterioration of the pavement surface is not severe enough to warrant more sweeping measures. Spalled sections, delamination, and other distresses can be repaired without the complete removal of slab using this method (Jung 2008). Full depth repairs are accomplished by completely removing a damaged section of pavement. While more labor and time intensive, this method allows for a thorough examination of the concrete cross section and subgrade. With proper design and construction methods, full depth repairs can be very reliable and can last as long as the surrounding pavement sections (Delatte 2008). Both types of repair will require a shutdown of the traffic lanes until the deteriorated material is removed and the concrete patch has had time to cure long enough to withstand traffic loads.

Routine maintenance for asphalt pavements includes three main categories: crack repair, surface treatments, and patching and pothole repairs. Crack treatments includes crack filling and sealing, with the sealants typically lasting between two to three years, but if the crack is severe, a full depth repair may be necessary (Brockenbough 2008). Surface treatments can include activities such as surface coats, microsurfacing, and thin hot-mix overlays. A surface coating, such as fog seals and chip seals, are used to restore the pavement surface and slow down the weathering of the pavement. The life expectancies of these methods ranges from one to six years depending on the pre-existing condition of the pavement, environmental factors, and traffic. Microsurfacing is used to restore a skid-resistant surface to the roadway, reduce water infiltration, and correct minor surface irregularities (Brockenbough 2008). This method involves the application of a thin layer of polymer-modified asphalt mixture to the roadway surface

(Morian 2011). Normal traffic flow can typically resume an hour after application, and the service life for microsurfacing treatments can range from four to seven years (Wade et al. 2001; Peshkin et al. 2004). Patching and pothole repair is similar in nature to the corrective methods used for rigid pavements, where the deteriorated or damaged areas of the pavement are removed and new material is added to restore the structural serviceability of the roadway.

If an asphalt or concrete pavement has reached a decreased level of serviceability and other restoration methods would prove too time consuming and costly, one option utilized by many state agencies is covering the existing pavement with an asphalt concrete overlay (ACOL). A thin HMA overlay, generally categorized as an overlay that is less than two inches in thickness but greater in thickness than microsurfacing applications, is typically considered a restoration activity for both rigid and flexible pavements and provides an improvement to the smoothness and friction capacity of the roadway without adding much structural capacity (Johnson 2000; Walubita and Scullion 2008; Zhou and Scullion 2008; Newcomb 2009). While they can restore functional capabilities to a worn pavement surface, thin HMA overlays are not considered long-term solutions; expected service lives of the thin overlays typically range from five to eight years, although a range of seven to ten years is possible (Johnson 2000; Irfan et al. 2005; Anastasopoulos et al. 2009). However, after the pavement surface is prepped, the time required to perform the overlay is minimal and the delays experienced by the public is lessened compared to other restoration and rehabilitation activities.

More substantial ACOL methods are used by DOTs to provide a long-term solution to rehabilitate pavements that have reached a specified performance level without having to incur the cost of full reconstruction of the roadway. Both pavements types can receive an ACOL after a performance threshold is reached, and the overlay is used to restore the performance of the existing pavement while also increasing the structural capacity of the roadway. Typically, thick ACOLs are designed in the same manner as new asphalt concrete pavements with the exception that the existing pavement is substituted for the base and subbase layers. For example, when an ACOL is performed on a rigid pavement, the original concrete surface is regarded as a high strength granular base (Papagiannakis and Masad 2008). Due to the nature of the material, a disadvantage of ACOLs is that they typically can only remedy functional failures of the pavements, such as cracking, rutting, and shoving (Asphalt Institute 1994). Structural deficiencies within the original pavement are more problematic and require additional work in addition to the ACOL to ensure an adequate service life of the rehabilitation.

The length of time required executing an ACOL and the resulting cost is dependent on a multitude of factors. The existing condition of the original pavement will play a decisive role when estimating the work duration and cost due to the amount of preparation the pavement will need before it is ready to accept an overlay. Major distresses such as rutting and potholes in flexible pavements and D-cracking and faulted joints in rigid pavements must be corrected to ensure that the design life of the overlay will not fall short of expectations. Any joint repairs for concrete pavements must be conducted before an overlay is constructed since ACOLs also do not allow for load transfer across joints (Brockenbough 2008). The anticipated repairs to the pavement prior to the overlay project will influence the duration of the work zone being in place and the cost of the total project. Typically, the cost and the duration of the rehabilitation project is estimated based on historical data compiled by the highway agency and from engineering judgment based on presiding design factors and project conditions.

While thick ACOLs are the prevailing method of major rehabilitation, distressed and damaged pavements may also be overlain with portland cement concrete as a rehabilitation measure (Hutchinson 1982). This method is commonly referred to as "whitetopping" when the procedure is performed over an existing asphalt roadway, but concrete overlays are used to treat both flexible and rigid pavements (Burnham and Rettner 2003). The two main types of whitetopping include bonded and un-bonded applications (Rasmussen and Rozycki 2004; Harrington 2008). Bonded overlays are constructed so that an intentional bond between the new concrete overlay and the existing pavement is created, and this bond reduces the tensile stress at the bottom of the concrete slab, reducing the thickness requirements of the concrete section (Delatte 2008). These overlays are typically used to increase the structural capacity while also controlling surface distresses in the original pavement. Bonded overlay treatments are typically used as a resurfacing and minor rehabilitation procedure (Harrington 2008). Unbonded overlays are generally used for major rehabilitation projects where the original pavement has several structural deficiencies; these overlays increase the structural capacity of the pavement from their current condition and are designed and constructed as if the existing pavement was a high quality base.

Concrete overlays are further subdivided into different categories based on the thickness of the overlay. Conventional overlays include sections that are eight inches or more thick and typically do not have an intentional bond between the existing pavement and the overlay. The strength of conventional overlays is obtained from the thickness of the slab. Thin whitetopping (TWT) sections are concrete overlays that are designed with a thickness that is greater than four inches and less than eight inches thick (Kim et al. 2008; Sultana 2010). TWT overlays can be constructed with or without bonding, but an overlay with a bond to the existing surface is capable of handling heavier loads (Rasmussen and Rozycki 2004). The third category of concrete overlays is classified as ultra-thin whitetopping (UTW). The thickness of a UTW overlay is less than four inches and is designed with an intentional bond with the existing pavement surface to create a composite pavement system (Mack et al. 1993; Rajan et al. 2001; Roesler et al. 2008; Li and Wen 2011). The performance of the UTW overlay is heavily dependent on the bond condition between the pavement and the overlay to support vehicle loads. Given the relative thinness of the concrete slab overlay, UTW overlays are typically reserved for lower volume roadways (Delatte 2008; Newbolds and Olek 2008).

Portland cement concrete overlays offer several advantages over conventional ACOLs in terms of performance and cost. Some benefits of concrete overlays include improved safety, reduction in vehicle fuel consumption costs, and increased visibility due to the light-reflective nature of concrete (Han et al. 2005). If designed and constructed properly, TWT and UTW applications on flexible pavements can last two to three times longer than ACOLs, and these measures are capable of reaching service lives of 20 years or more, greatly reducing the costs associated with user delays during future maintenance and rehabilitation (Burnham and Rettner 2003; Han et al. 2005). Research sponsored by the Colorado DOT concerning TWT usage within the state has shown that, when agency costs are solely considered, a TWT overlay cost only one percent more than a comparable ACOL option over a 20-year analysis period. Interestingly, the life cycle costs of the TWT overlay were determined to be 11 percent less than the ACOL when user delay costs were considered for the lives of both projects (Lowery 2005). However, concrete overlays do have some disadvantages as well. While whitetopping applications are cost effective over their design life, the initial cost of construction is much higher when compared to commonly used ACOLs. Unless fast-track concrete construction methods are employed to complete the project, the time to properly cure the TWT or UTW after the overlay has been constructed will result in higher user costs as well when compared to ACOL rehabilitation.

## 2.4 Life Cycle Cost Analysis Procedure and Parameters

The planning, design, construction, and maintenance of transportation infrastructure assets require the careful consideration of a multitude factors. Before a concrete or asphalt pavement alternative is selected, a thorough examination of both engineering and economic factors is made to determine the most cost effective solution. Several economic analyses exist that allow the decision maker to compare the costs of multiple alternatives. One of the most used analyses is the benefit/cost analysis or ratio (BCA). When conducting a BCA, the planner will sum the net benefits and net costs separately for all available alternatives; to calculate the ratio of benefits to cost, the analyst will divide the calculated net benefits by the net costs (Walls and Smith 1998). If the ratio is greater than one, then the analysis indicates that the benefits exceed the costs and the project may be an appropriate option. However, if the ratio is less than one, then the costs of the project outweigh the benefits and the project should be avoided. The alternative that delivers the greatest net benefit is chosen as the best viable option to undertake. Due to challenges with determining the appropriate benefits and costs associated with pavement construction, this method is typically not used when comparing paving alternatives.

While there are several economic analyses available, engineers and planners typically perform an LCCA as a decision-making tool during the evaluation of viable project alternatives (Thuesen 2001; Steiner 1996). Unlike a BCA, the LCCA method requires that the design alternatives be examined on the basis that all alternatives will deliver the same desired level of performance during normal operation (Brockenbrough 2009; Walls and Smith 1998). If this is not possible, another economic comparison should be employed that will recognize the costs associated with the investment as well as any differences in the benefits provided by the competing options.

In a report sponsored by the South Carolina DOT the authors found that 92 percent of the state DOT agencies performed a LCCA during the decision-making process for selecting pavement alternatives (Rangaraju et al. 2008). While a majority of the states perform an LCCA when analyzing pavement alternatives, the methods and values used in the analysis can vary considerably among states.

The alternative with the lowest total life cycle cost is chosen as the best economic solution for the given design. Once completed the decision maker may conduct a sensitivity analysis to determine the influence major LCCA inputs have on the results, and once influential factors are identified, the initial design may be altered to lower the overall life cycle cost.

The FHWA has recommended the following steps for carrying out a LCCA for pavement type selection:

1. Establish alternative pavement design strategies for the analysis period
2. Determine performance periods and activity timing
3. Estimate agency costs
4. Estimate user costs
5. Develop expenditure stream diagrams
6. Compute net present value
7. Analyze the results
8. Reevaluate design strategies (Walls and Smith 1998).

Before the calculation of life cycle costs is performed, the owner will typically develop possible solutions that will satisfy the objectives of the project. For pavements, one of the key considerations is the initial construction of the project and any required maintenance, preservation, and rehabilitation activities the paving system will endure during the life cycle of the pavement. Assessments of the future maintenance and rehabilitation activities should be reliable to make informed decisions when quantifying costs for a life cycle analysis (Irfan et al. 2010). Required rehabilitation strategies and timings may come from estimates provided during the design using mechanistic-empirical software (DarwinME), historical data from the state's pavement database, and engineering experience and judgment. Other methods for predicting flexible and rigid pavement performance include models of pavement deterioration and data generated through Pavement Management Systems (PMS).

Previous research on the performance and reliability of pavements has generated numerous models that predict the rate of deterioration of both new pavement construction as well as the rehabilitation and maintenance activities (George et al. 1989; Gopinath et al 1994; Abaza 2002; Al-Suleiman and Shiyab 2003; Irfan et al. 2009; Mandapak et al. 2012; Reimer and Pittenger 2012; Thomas and Sobanjo 2012). Overall, the severity of the repair or rehabilitation that is necessary, the construction methods employed by the agency, and an analysis of the impact the project will have on traffic flow should receive considerable attention to determine the most likely scenario that will be encountered when determining the performance lives of the initial construction and all pavement rehabilitations. The estimation of the costs required and the amount of time necessary to perform the work based on the aforementioned factors is also critical to determine the most cost effective solution and quantify the impact on the agency and public.

Before the estimation of the agency and user costs, the analyst needs to know the time frame that will be analyzed. This period of time is known as the analysis period, and this value encompasses the period from the initial construction of the roadway until some point in the future. The analysis period typically contains the life of the pavement after its initial placement as well as any maintenance, rehabilitation, replacement, and reconstruction activities. Depending on the performance lives of the initial pavement system and the subsequent rehabilitations, the analysis period may coincide with the point in time an alternative will require a remedial action to return it to a satisfactory level of serviceability or it may end while the alternative still has a useful service life. It is during this period that all costs incurred by the agency and the users of the roadway will experience.

The next step of the pavement LCCA outlined by the FHWA is the calculation of agency costs. These costs include any costs that are expected by the agency during the pavement's life cycle. Agency costs can include any direct or indirect costs of planning, design, and administration; installation and construction; maintenance; operation; rehabilitation or reconstruction; and salvage (Markow 2012). Any agency cost that is unique to an alternative being considered should be included in the analysis; similar costs between alternatives for the project, which may include items such as earthwork, drainage structures, and signage, can be excluded from the analysis if the activities of two pavement alternatives are performed at the same time. However, any items that are incidental to construction or rehabilitation activities that occur at different times should be included in the LCCA. Typically, the largest percentage of costs in a pavement LCCA is associated with the material costs and costs related to installing the material.

The estimates of the costs associated with the construction and rehabilitation of the pavement alternatives are typically made using either unit cost estimating and/or cost-based estimating methods (Hallin et al. 2011). Since most state highway agencies have ample historical cost data for paving operations, unit cost estimates are the most prevalent. These estimated costs incurred by the agency is made by multiplying the physical quantity of material needed to construct the roadway with the unit cost of that particular pay item. Paving bid data from recent paving projects is typically used, and the estimator may choose to use all bids, the three lowest bids per project, or the low bid price when calculating the unit cost (Hallin et al. 2011). To account for inflation, these pay item bid costs are usually deflated (depending on the range of historical data used) and adjusted for other factors such as quantity and project location. Adjustments for seasonality is also an important consideration when compiling the cost data; the unit costs of some pay items for bids accepted during the winter months may differ significantly from the unit costs of those same pay items for bids accepted during the summer.

The next set of life cycle costs are comprised of any user costs that will be incurred by the travelling public as a result of initial construction and pavement rehabilitation activities (Walls and Smith 1998). These costs are typically divided into two main categories: costs incurred during normal operation of the roadway and costs incurred during restricted (work zone) operation of the roadway. User costs are also categorized into three components and include travel delay costs, vehicle operating costs, and crash costs (Lamptey et al. 2005). Typically, only the vehicle operating costs are calculated during normal operation of the highway. Due to difficulties in the calculation and the prediction of some components, the recommended practice when using user costs in a pavement LCCA is to only consider delay costs and vehicle operating costs when works zones are present.

The first step in the calculation of the costs associated with travel delays and vehicle operating costs during restricted highway operation is determining the details of the work zones. These details can include the duration the work zone will be in place, the hours of the day that work will be conducted, and the work zone length (Walls and Smith 1998). If the duration of the work zones are similar for both alternatives and they occur at the same point in time, they may be excluded from the calculations. This situation typically occurs during the initial construction of the roadway, but if rehabilitation activities of the alternatives are scheduled at different points in time in the future, these costs should be calculated and used in the analysis. The next step is determining the volume of traffic that will be affected by the work zones. This step includes estimating factors such as the AADT at the point in time the work zone will be established as well as a breakdown of the vehicle classifications. To calculate the user costs associated with road construction, a cost per vehicle is typically estimated for vehicle operating costs and delay costs. The vehicle operating costs experienced during work zones can include those costs associated with speed changes when entering the work zone and idling. Delay costs are typically assigned to account for the cost of time lost by the user.

The next step of the pavement LCCA process outlined by FHWA includes developing expenditure stream diagrams for both pavement alternatives. These illustrations are used to help an analyst visualize the costs for each alternative throughout the project life cycle. In an LCCA expenditure stream, the costs incurred by the agency are typically shown as pointing upward while benefits are shown pointing downward (Hallin et al. 2011). An example of an LCCA expenditure stream for two pavement alternatives is shown in Figure 2. In this illustration, all costs encountered by the agency are shown as arrows pointing upward while the negative costs associated with the salvage value of the alternatives are shown pointing downward. Depending on the alternatives being considered in the analysis, the magnitude and timing of these costs may vary, and the expenditure stream diagram displays this information in an easy-to-follow format.

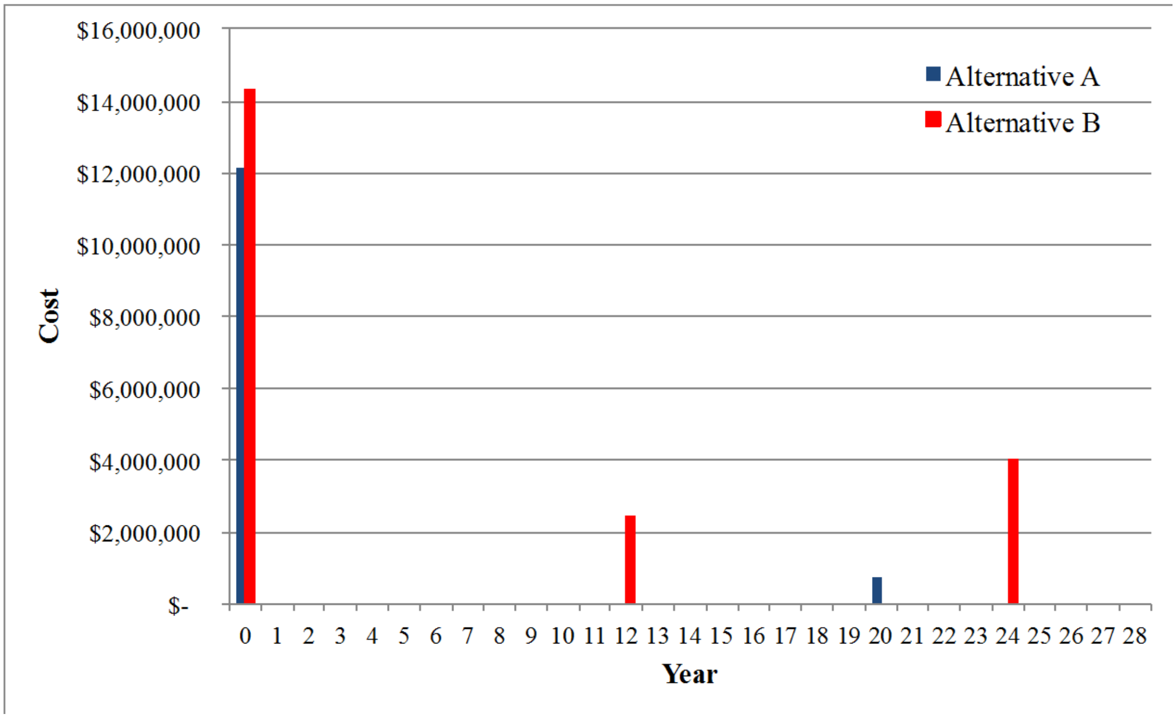


Figure 2. Expenditure stream of two pavement alternatives

The general LCCA model is the summation of all recurring and nonrecurring costs of the project throughout the designated analysis period and presents the total cost of ownership throughout the estimated design life of the asset. Recurring costs typically include items such as operation, maintenance, and inventory costs while nonrecurring costs may incorporate one-time expenditures such as procurement, installation, and training costs (Dhillon 2010). To account for the time value of money, a discount rate is included in LCCA calculations when determining all future costs (ACPA 2002). The discount rate chosen can have a significant influence on the results of the LCCA. The influence that various discount rates have on the present value of money ($100 in this example) is shown in Figure 3.

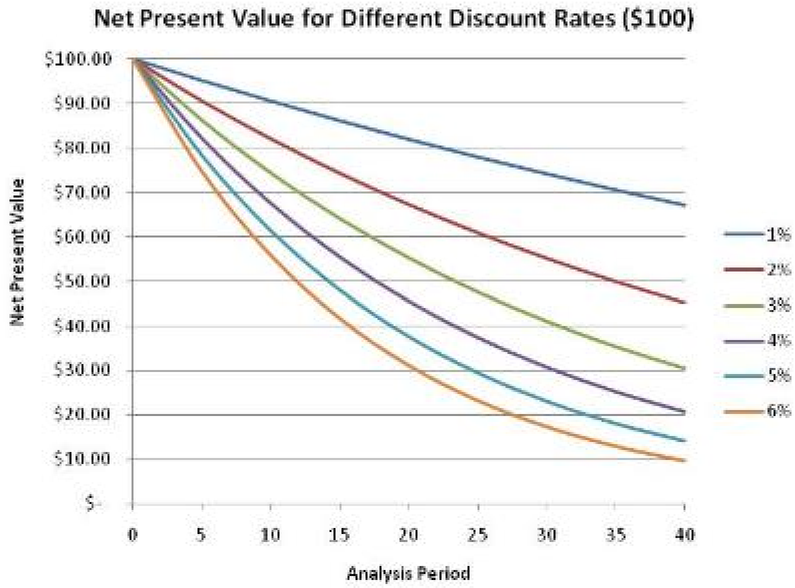


Figure 3. Influence of different discount rates on the net present value of $100 over a 40-year period.

After all factors and inputs are selected and rigorously evaluated, the life cycle cost is calculated for each alternative using either the net present value (NPV) method or the equivalent uniform annual cost (EUAC) method (Walls and Smith 1998; VDOT 2002; Ozbay et al. 2011). The NPV method is calculated using the formula shown below:

$$NPV = Initial\ Cost + \sum_{k=1}^{N} Rehab\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right]$$

where: $i$ = discount rate; $n$ = year of expenditure

After the NPV of all alternatives have been calculated, the next step of the LCCA procedure for pavement type selection is to analyze the results. If the deterministic approach to LCCA is the chosen method of analysis, the NPV will result in a single value for the total life cycle cost for each alternative. These values can be used in a straightforward comparison between all possible alternatives to determine which alternative is the most viable economic option. A sensitivity analysis may be conducted to determine which factors have the greatest influence on the results. The analysis allows the analyst to systematically vary the input values for a single factor while holding all other factor inputs constant. From a sensitivity analysis, the factors that have a significant influence on the total life cycle costs can be determined so that further investigation can be conducted, if necessary.

If a probabilistic approach to LCCA is utilized, the results of the analysis will produce distributions of the total life cycle costs. This method will typically produce both cumulative and frequency probability distributions. The cumulative distributions allow the decision maker to examine the amount of cost risk exists between pavement alternatives and examine the percent probability that the NPV of one option will be more or less than another option (Hallin et al. 2011). The frequency distributions of the NPV will allow the analyst to visually interpret the mean NPV as well as the standard deviation in the total life cycle costs. Using the frequency distributions, for example, an analyst may determine that the mean NPV of Alternative A is less than the mean NPV of Alternative B, but by examining the frequency distributions, the analyst may discover that the standard deviation is greater for Alternative A, raising the risk of higher total life cycle costs.

The last step in the pavement LCCA procedure is to reevaluate the pavement designs. This step may include revisions to the original pavement structure as well as the timing of rehabilitations and the rehabilitation activities (Hallin et al. 2011). If a sensitivity analysis was performed during the analysis, the factors with the most influence could be used to make adjustments to the original pavement design (Walls and Smith 1998).

## 2.5 Alternate Pavement Bidding

In the traditional pavement project selection approach, the agency will recognize the need for a new pavement construction project or rehabilitation and identify any feasible pavement type alternatives that may satisfy their needs. The agency will then create an initial design for each alternative and develop a life cycle model that will estimate initial construction costs, service lives of the alternatives, and future rehabilitation costs. After the life cycle analysis has been executed and the results have been analyzed, the agency will choose the alternative that is the most cost effective and provides the best option for the agency in terms of pavement performance. This design alternative will ultimately be used in the solicitation of bids from qualified contractors.

Some states employ a different method to the selection of pavement types used in projects. The agency still designs the alternatives and performs the LCCA, but in the alternate pavement bidding (APB) method, the contractor chooses which alternative they would like to use in their bid. The design they choose must be selected from the approved list of alternative designs generated by the agency. While added costs will result from creating alternative pavement sections for a given project, the goal of this method is increased competition among pavement contractors, which the agency hopes will translate into ultimately lower bids. However, since the life cycle costs for alternatives will not be equal, several agencies have developed strategies to account for the cost differentials by including life cycle cost adjustment factors into the decision making process.

If projects with alternative pavement designs have comparable costs and there are no engineering or economic factors that supersede the process and require special attention, the KYTC employs an “A + C” formula to determine the best pavement alternative. The “A” component in the equation is the contractor's bid price to perform all of the work, and the "C" component is added to the contractor's bid and represents the future life cycle costs the agency will incur over the life of the pavement (KYTC 2009). If daily work zone costs to the user are greater than $2,000,000 then a "B" component will be added to the aforementioned equation to compare the amount of time and costs associated with performing the work. User costs such as vehicle operating costs and future delays resulting from rehabilitation activities are not included in the analysis (Wimsatt 2009). The Louisiana DOT (LADOTD), Ohio DOT, and Florida DOT employ a similar method to adjust the contractor's base bid to include life cycle costs and their effect on the total cost of the pavement asset during its service life (Lindly and Clark 2003; Temple 2004).

In a 2011 survey conducted by Georgia DOT in conjunction with the AASHTO Standing Committee on Research (SCOR) and Research Advisory Committee (RAC), the group found that 16 of the 34 responding states have let an APB project in the last few years (AASHTO 2011). Of those states that let an APB project, nine used an adjustment factor based on the life cycle costs of the alternatives. The Kansas DOT indicated that the life cycle cost adjustment factor used with the bidding process of three APB projects did not affect the determination of the lowest bidder (AASHTO 2011). Missouri indicated similar results, with only four projects out of approximately 200 APB projects being affected by the adjustment factor.

## 2.6 Summary

The design characteristics, the construction methods employed, and the forecasted maintenance and rehabilitation strategies are vitally important to estimate initial construction costs, predict future performance, and estimate rehabilitation activities for both asphalt and rigid pavements. While the costs borne by the agency and the users of the roadway during the initial construction of the project will have a significant bearing on which material is ultimately considered, the ultimate performance of the pavement as well as the future rehabilitation and maintenance costs throughout the required service life of the pavement should also factor into the pavement selection process. This analysis will require a thorough examination of both engineering and economic factors. The pavement type selection process employed by state highway agencies should be systematic and exhaustive so that the best option is chosen for a given project. One effective method employed by many state DOTs when comparing alternative pavement types is examining the life cycle costs of both pavement materials to determine which option will offer a the highest level of performance while providing the most cost effective means to accomplish the project.

# CHAPTER III

# PAVEMENT TYPE SELECTION PROCESS: STATE OF THE PRACTICE

## 3.1 Introduction

The purpose of this chapter is to highlight and examine the factors used in an LCCA during the pavement type selection process and the values that are used in the calculation of the life cycle costs of pavement alternatives. The pavement LCCA research initiated by ALDOT in 2012 resulted in a multi-university collaboration that included input and recommendations from paving industry experts with knowledge of the LCCA process. The discussion during meetings with ALDOT, researchers from the University of Alabama and Auburn University, and pavement industry representatives provided the basis of this research objective. Both industries provided recommendations on key LCCA factors and values that should be used when comparing pavement alternatives. After reviewing literature pertaining to pavement LCCA and the comments and suggestions made by the asphalt and concrete pavement industries, recommendations on factors and related values are given to improve the pavement LCCA process.

During the research meetings, 13 key pavement LCCA factors were brought forth for discussion during the research meetings. These factors included common components of the LCCA process, such as analysis period and discount rate, as well as factors that have not been traditionally considered during the pavement type selection process. The factors discussed during the research effort include:

- Triggers for LCCA
- Agency costs
- User costs
- Analysis period
- Discount rate
- Salvage value
- Approach to LCCA
- Price adjustment clauses (indexing)
- Material specific escalation rates
- Performance period/rehabilitation schedule
- Specification issues
- Pavement design
- LCCA software

## 3.2 Triggers for LCCA for Pavement Type Selection

A key element in the pavement type selection process is what type of pavement project necessitates a LCCA by the governing agency. Mandatory analysis of the life cycle costs of the pavement options may come from the Federal, state, or local level. The requirement for a LCCA of a project will typically come in the form of a project cost estimate threshold that will be surpassed or at the request of the pavement selection committee (Wimsatt 2009). The network level the project is categorized under is also used as a deciding factor for the requirement of a LCCA. For example, a state may require that all projects on the National Highway System (NHS) and major state routes meeting certain criteria must include alternative pavement types and the total life cycle costs for all alternatives must be considered during the decision making process. Other triggers may come in the form of engineering traffic factors such as ADT and ESAL estimates or any other factors that would require the agency to provide alternate designs for the project and analyze all of the factors to determine the best option.

State highway agencies across the country have developed their own set of requirements for when an LCCA is conducted. In the Rangaraju et al. study (Rangaraju et al. 2008), a majority of the states that responded to the data survey indicated that cost, pavement structure, and other criteria were the main triggers for a required analysis of life cycle costs. Wisconsin, Utah, and Kansas indicated that an analysis is required for almost all pavement projects under their direction; several states, such as California, Nebraska, and Vermont, listed multiple criteria that could trigger an analysis for alternative pavement type selection. The Kentucky Transportation Cabinet (KYTC), for example, requires a LCCA on all interstate system projects that are new construction, reconstruction, major widening (projects that will add additional lanes to the roadway), or pavement rehabilitation projects. To be considered a pavement rehabilitation project, the work section must consist of a mile in pavement length that requires more than two inches of pavement milling. The analysis requirements for projects on state parkways and all other NHS routes within the state are similar to those for the interstate system, except the minimum pavement milling thickness is increased to four inches. For projects off the NHS network, the state requires an LCCA if there is new construction, reconstruction, or pavement rehabilitation that is over one mile in length and needs four inches of new pavement, along with a requirement of a current ADT above 2,500 or a forecasted ESALs estimate of 1,000,000 in 20 years.

Several states have passed legislation that requires the state highway agency to conduct an LCCA as part of the pavement alternative selection process when projects meet certain criteria. In 2007, the state legislation in Michigan enacted Public Act 79. This legislation requires the state DOT to perform an LCCA for each project with total pavement costs exceeding one million dollars funded in whole, or partially, by state funds (Michigan DOT 2012). More recently, a bill (Public Act 96-715) with similar provisions was passed in Illinois and became effective in August 2009. This piece of legislation requires the Illinois DOT to develop and implement a LCCA for every State road project under its jurisdiction with total pavement costs surpassing 500,000 dollars (Illinois Office of the Auditor General 2012). The Minnesota DOT, under direction provided by HF 3486 (Chapter 287), is required to perform a LCCA for all resurfacing, reconditioning, and road repair projects. This requirement went into effect for projects constructed after July 1, 2011 (Minnesota Legislature 2008). Table 2 highlights some of the LCCA triggers for various state DOTs across the country.

Table 2. Projects that require an LCCA for various state DOTs (*Source: Rangaraju et al. 2008, Michigan DOT 2012, Illinois Office of the Auditor General 2012, Minnesota Legislature 2008*)

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|---|---|
| *California* | LCCA must be performed for all projects that include pavement work on the State Highway System except: major maintenance, minor A and minor B, permit engineering evaluation reports (PEER), maintenance pullouts, and landscape paving. |
| *Colorado* | An LCCA comparing concrete to asphalt pavements will be prepared for all new or reconstruction projects with more than $2,000,000 initial pavement material cost. An LCCA comparing asphalt and concrete should also be prepared for all surface treatment projects with more than $2,000,000 initial pavement cost where both pavement types are considered feasible alternatives as determined by the RME. |
| *Illinois* | Public Act 96-715 requires the Illinois Department of Transportation (IDOT) to develop and implement a life cycle cost analysis for each State road project under its jurisdiction for which the total pavement costs exceed $500,000. |
| *Indiana* | Alternate pavement design analysis is required for a new pavement, pavement replacement, or major rehabilitation project with mainline pavement of more than 10,000 SY. Life cycle cost analysis required using RealCost. |
| *Iowa* | Major rehabilitation and resurfacing projects and all projects containing 5,000 SY or tons of full depth paving. |
| *Florida* | Pavement type selection of new construction projects and reconstruction projects greater than one half mile in length where work includes a modification to the base materials. |

Table 2. Projects that require an LCCA for various state DOTs (*Source: Rangaraju et al. 2008, Michigan DOT 2012, Illinois Office of the Auditor General 2012, Minnesota Legislature 2008*)

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|---|---|
| *Georgia* | Projects with full FHWA oversight. |
| *Kansas* | All new construction, reconstruction, and rehabilitation projects. |
| *Kentucky* | All projects (Interstates; Parkways; NHS route; and others) over one mile in length that require 4" or greater new pavement and greater than 2,500 ADT or greater than 1,000,000 ESALs |
| *Michigan* | The department shall develop and implement a life cycle cost analysis for each project for which total pavement costs exceed $1,000,000 funded in whole, or in part, with state funds. |
| *Minnesota* | Legislation [HF 3486 (Chapter 287)] requires a LCCA be performed for all pavement projects in the reconditioning, resurfacing, and road repair funding categories that are to be constructed after July 1, 2011. |
| *Mississippi* | Federal funding being utilized. |
| *Missouri* | Only consistent use of LCCA is for alternative pavement bidding selection. |
| *Pennsylvania* | NHS and all projects over $15 million. All interstate projects over $1 million and all other projects over $10 million. |
| *Washington* | New mainline pavement greater than 1/2 mile in length, ramps with high ADT or truck percentage, collector distributors and acceleration/deceleration lanes same as ramps, and intersections with chronic rutting problems. |
| *Wisconsin* | All resurfacing projects 5 miles in length or greater, pavement replacement, reconstruction, expansion, and new construction paving projects require an LCCA. |

Currently, ALDOT requires an LCCA when selecting between pavement alternatives for new construction projects, flexible pavement reconstruction projects, and projects that include the addition of a separate roadway to an existing roadway when certain criteria are met. To qualify, the project must also have a flexible pavement design structural number of 6.0 or higher. Projects shorter than four miles in centerline length do not require an LCCA. If the proposed project is located along the same route as a comparable project, an LCCA will not be required for a new project if an analysis was performed on a similar project, and the two projects have approximately ± 20% the same traffic volume and percentage of commercial vehicles, and are located within ten miles of each other, or will be constructed on the same geologic formations.

However, if the cost analysis performed on the previous project is more than five years old and there is a change to the number of traffic lanes on the roadway, an LCCA is required. All concrete pavement reconstruction projects require an LCCA for all applicable alternates. Analyses for special projects and projects not requiring mainline paving are required at the discretion of ALDOT's Materials and Testing Engineer.

While the current ALDOT requirements do provide some opportunities for an analysis between concrete and asphalt pavement alternatives, projects worthy of examination could be missed by ALDOT. For example, lane additions on a short section of a major interstate running through a heavily traveled urban environment could cost tens of millions of dollars and create major impacts in terms of user delays and costs. However, if this project did not meet the criteria under the current system, an LCCA would not be performed, increasing the risk of higher agency and user costs throughout the life cycle of the pavement.

An increase in the number of life cycle cost analyses can also increase the level of competition between the concrete and asphalt pavement industries. A study by the ACPA indicated that as the percentage of concrete pavement market share within a state increased, the unit costs for both concrete and asphalt decreased (ACPA 2009). If this increased market competition versus price relationship holds for Alabama, the resulting competition between asphalt and concrete paving contractors may lower bid prices, increase quality, and provide the greatest opportunity for a return on the agency's investment. Any savings could then be applied to other infrastructure projects within the state, allowing ALDOT to increase the number of projects let while remaining within the limits of their yearly budget.

Other studies have also shown that increased competition between highway contractors lowers bid prices. An audit by the Office of Inspector General (OIG) on American Recovery and Reinvestment Act of 2009 (ARRA) projects receiving FHWA oversight found that approximately 19 percent of the ARRA contracts awarded by state DOTs received just one or two bids through the competitive bidding process. Those projects that received only one or two bids averaged 93 percent of the engineer's estimate of the work (Office of Inspector General 2012). However, as the number of bidders increased and the level of competition increased, the average bid price percentage of the engineer's estimate began to decrease. The bid price averages for projects with three bidders were found to be 82 percent of the engineer's estimate. The reduction in bid price averages as the number of bidders increased is illustrated in Figure 4.

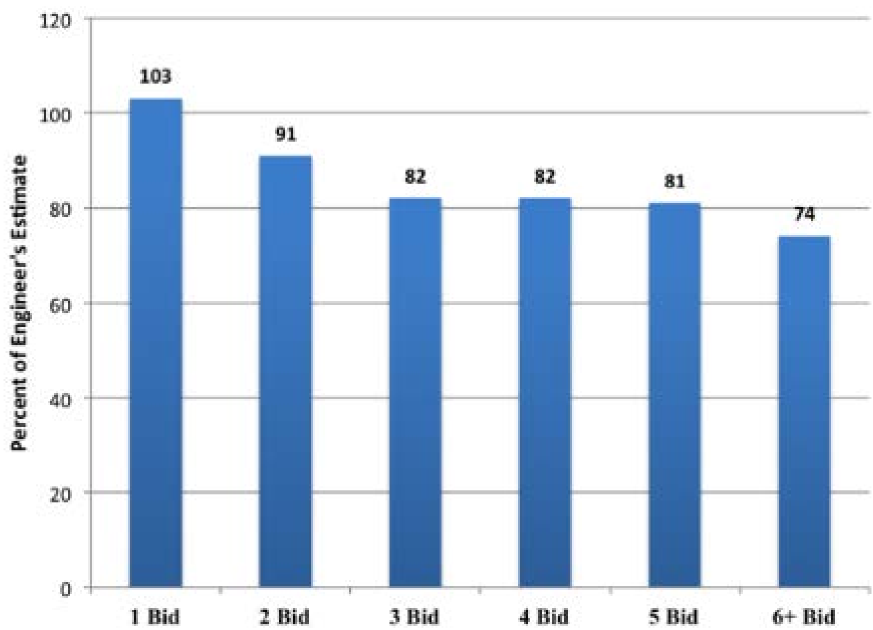



Figure 4. Average price percentage of engineer's estimate by number of bids (*Source: Self-reported ARRA contract award data supplied by sampled states in OIG Audit Report Number ZA-2012-084)*

The Missouri Department of Transportation (MoDOT) has used the alternate pavement bidding (APB) process since 2003. Since that time, the agency has tracked the impact the APB process has had on the number of bidders per project and pavement bid prices. The process has resulted in the number of bidders increasing from an average of 4.2 on non-APB projects to 5.5 for APB projects. The average asphalt and concrete bid prices have decreased as a result of the APB process. In 2009, the three-year average asphalt price per ton for APB projects was 5.1 percent lower than the three-year average asphalt price per ton for non-APB projects. The three-year average concrete price per cubic yard (CY) for APB projects was shown to be 8.6 percent below the average concrete price per CY of non-APB projects (Ahlvers 2009).

One common concern linked to performing more LCCAs is the added cost. Some administrators believe that generating an additional design for a given pavement project will tie up much needed resources and time. Research by the Louisiana Department of Transportation and Development (DOTD) tracked the costs associated with their ADAB process and compared those costs associated with common pavement design projects. In their study, the Louisiana DOTD estimated that the departmental design cost to develop one design for one pavement type was approximately 500 dollars per project. For an ADAB project, the average departmental cost to develop two pavement alternative designs and conduct an LCCA for both alternatives was approximately 2,000 dollars per project. When analyzing the 32 ADAB projects, the Louisiana DOTD found that the bids for those projects came in at $62.5 million below the engineer's estimates, resulting in savings of approximately two million dollars per project. This results in a cost benefit ratio of 1,000 to 1 for a typical ADAB project (Temple 2007).

To gain context concerning the number of paving projects executed by ALDOT in a given year, ALDOT provided paving data for fiscal years (FY) 2007 through 2011 including the project number, a short description of the project type, and the total cost of the paving project. ALDOT provided the data in two categories: new paving projects and existing (rehabilitation and resurfacing) paving projects. Analysis of that data shows that a total of 56 new pavement projects and 750 existing paving projects were completed during the five-year span. Of the new paving projects, 48 projects had total costs in excess of three million dollars. Additionally, 139 projects out of the 750 total existing paving projects showed costs above three million dollars. A summary of the paving cost data for FY 2007 through FY 2011 can be seen in Table 3.

Table 3. ALDOT pavement project cost summary (FY 2007 to FY 2011)

| | ***New Paving Projects*** | | | ***Existing Paving Projects*** | | |
|---|---|---|---|---|---|---|
| **Year** | **Total Number of Projects** | **Number of Projects >$3M** | **% of New Paving Projects >$3M** | **Total Number of Projects** | **Number of Projects >$3M** | **% of Existing Paving Projects >$3M** |
| FY 2007 | 11 | 9 | 81.8% | 128 | 19 | 14.8% |
| FY 2008 | 9 | 8 | 88.9% | 127 | 23 | 18.1% |
| FY 2009 | 14 | 12 | 85.7% | 208 | 44 | 21.2% |
| FY 2010 | 10 | 8 | 80.0% | 140 | 25 | 17.9% |
| FY 2011 | 12 | 11 | 91.7% | 147 | 28 | 19.0% |
| ***All Years*** | ***56*** | ***48*** | ***85.7%*** | ***750*** | ***139*** | ***18.5%*** |

| | |
|---|---|
| Avg. Number of New Paving Projects per Year = | 11.2 |
| ***Avg. No. of New Paving Projects Greater than $3M per Year =*** | ***9.6*** |
| Avg. Number of Ex. Paving Projects per Year = | 150.0 |
| ***Avg. No. of Ex. Paving Projects Greater than $3M per Year =*** | ***27.8*** |
| ***Avg. Number of All Paving Projects Greater than $3M per Year =*** | ***37.4*** |

On average, approximately 161 total paving projects were performed by ALDOT in a given year that consisted of approximately 11 new pavement projects (6.8 percent of total) and 150 existing paving projects (93.2 percent) each year. An average of 9.6 new paving projects and 27.8 existing paving projects had total costs exceeding three million dollars. Figures 5 and 6 illustrate the average number of projects per year with total costs exceeding a given threshold for new and existing paving projects, respectively.

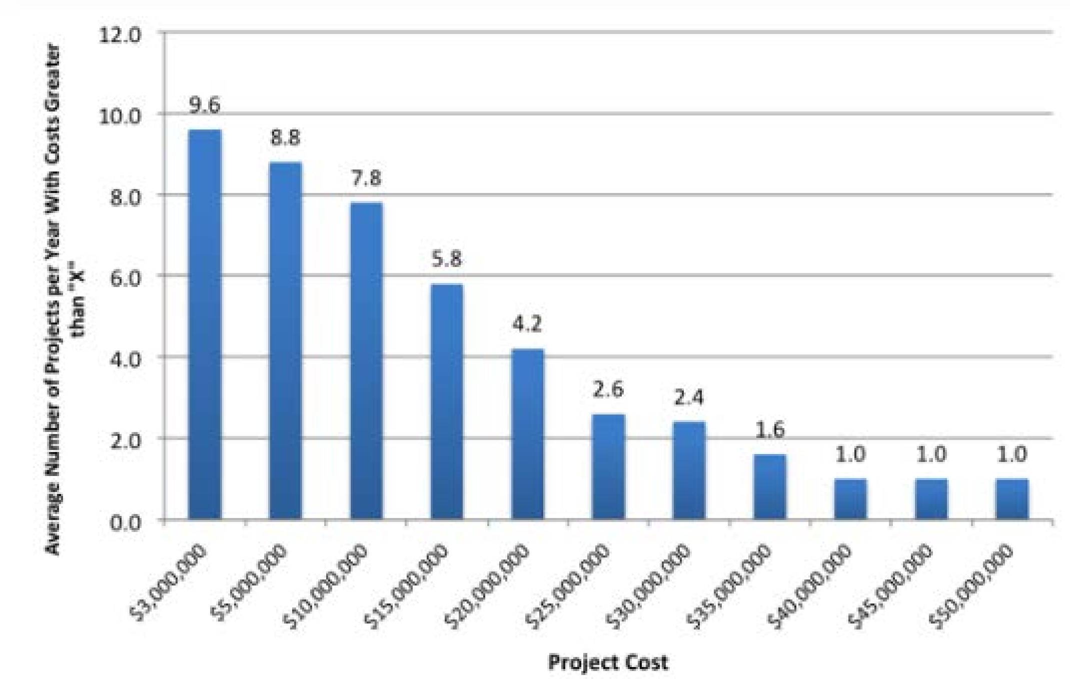



Figure 5. Average number of new ALDOT projects per year for a given cost threshold (FY 2007 to FY 2011)

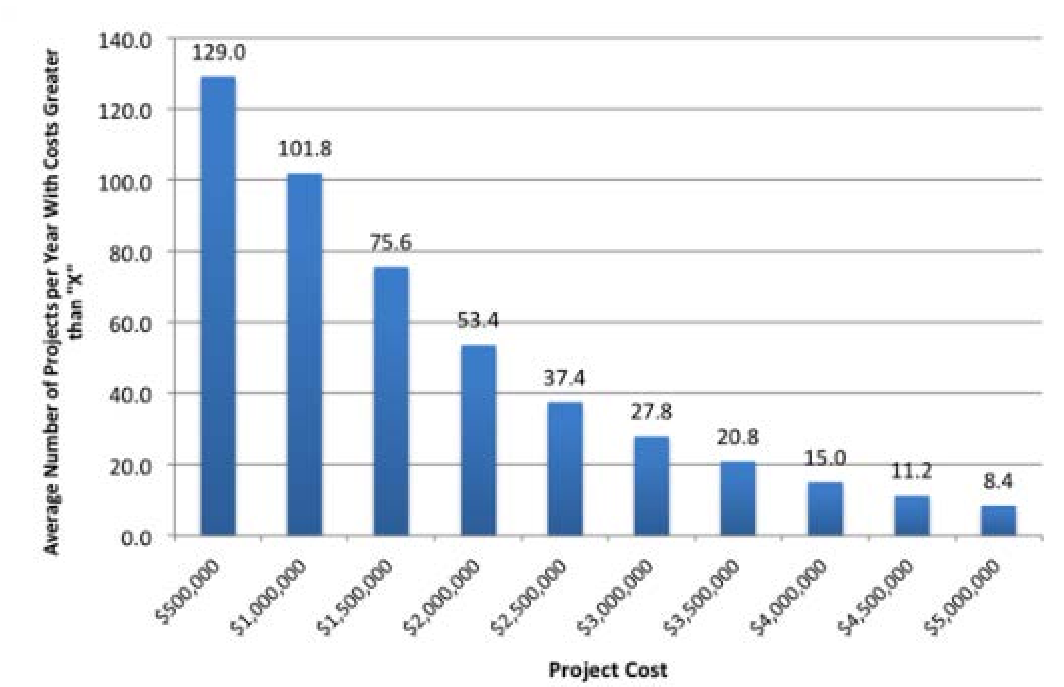



Figure 6. Average number of existing ALDOT projects per year for a given cost threshold (FY 2007 to FY 2011)

### 3.2.1 Recommendations for Triggers for LCCA

On April 19, 2012, State Representative McCutcheon introduced a bill (Alabama House Bill 730) to the House Committee on Transportation, Utilities, and Infrastructure. This bill sought to require an LCCA to be performed on all major infrastructure projects, including highway, transit, rail, high-speed rail, airport, seaport, public housing, energy, water, bridge, and military construction projects using state appropriated funds. The bill defined major infrastructure projects as projects with costs greater than three million dollars. Because project cost is one of the major deciding factors in pavement type selection, the concrete pavement industry agreed with this legislation and recommended that all pavement projects, including new construction, reconstruction, rehabilitation, and resurfacing projects, with cost estimates totaling over three million dollars require a thorough LCCA for both concrete and asphalt alternatives. The concrete industry believes that this threshold provides a reasonable analysis of pavement alternatives each year that could increase competition between the concrete and asphalt pavement industries while also providing the taxpayers of the state of Alabama the best pavement material in terms of cost and quality for a given project.

The asphalt industry and researchers from Auburn University, however, did not believe that the three million dollar project cost threshold was the best trigger for conducting an LCCA for pavements. The main concern they voiced during the final collaborative meeting in December was number of infrastructure projects outside of paving that would require an LCCA. Another concern with the three million dollar threshold was inflation. They argued that the three million dollar threshold would require ALDOT to perform an LCCA on an increasing percentage of projects due to the time value of money. For example, assuming a general inflation rate of 2.5 percent, the real value of three million dollars ten years in the future would be approximately

2.34 million dollars. If the three million dollar threshold, instituted in given year, were set by policy as a static value, then the number of paving projects per year requiring an LCCA would gradually increase into the future. The asphalt researchers were concerned that this increase would create an unnecessary encumbrance to ALDOT due to increased manpower and time necessary to conduct more LCCAs (West et al. 2012b). Another concern expressed by the Auburn researchers included the competiveness of concrete pavements when bidding on paving projects within the state of Alabama.

Based on the literature review of current pavement LCCA triggers and the arguments made by both the asphalt and concrete paving industries, it is recommended that more research be conducted on the subject of LCCA triggers. Other factors such as the network level of the proposed project, traffic characteristics of the roadway, and project location should also be examined to determine the number of projects that would require an LCCA. If a project cost threshold is chosen as an LCCA trigger, it is advised that the threshold value is updated annually to account for general inflation.

## 3.3 Agency Costs

The LCCA procedure for pavement type selection contains several economic and engineering factors that can have a substantial impact on the final life cycle cost for each alternate. These factors are typically categorized as agency costs, expenditures that the paving agency will incur during the life of the pavement, and user costs, the costs that are absorbed by the public who travel on the roadways. Agency costs can include administration/engineering costs; initial construction costs; and reconstruction, rehabilitation, repair, and routine maintenance costs (FHWA 2003, NCTA 2010). The salvage value at the end of a pavement's performance life is also considered an agency cost. Agency costs contain both recurring and nonrecurring costs, and these costs are typically calculated using historical data, models, and engineering judgment.

The FHWA recommends that all construction costs, including administrative costs, design/engineering costs, management costs, and maintenance/rehabilitation costs be included in the total agency costs for all pavement alternatives (Walls and Smith 1998). The American Concrete Pavement Association (ACPA) recommends that all the costs incurred by the highway agency should be included within the agency cost calculations, including the following items:

- "Initial design and construction/inspection costs,
- Preservation/rehabilitation costs (including engineering, inspection and traffic control),
- Operation and maintenance costs (including staffing),
- Either demolition/removal costs or the residual value of the pavement structure,
- Costs associated with material price escalators, and
- Direct savings associated with sustainable benefits of a particular pavement type (ACPA 2012)."

In the 2008 South Carolina LCCA study, the researchers found that all of the states surveyed included construction costs and rehabilitation costs in their agency cost calculations. Approximately half of the state DOTs include routine and preventive maintenance in their LCCA calculations. Of the 23 state DOTs that responded to the survey, nine states incorporate preliminary engineering costs into the total agency cost, while eight state DOTs include construction management costs. Only three states include administrative costs in the agency cost calculations (Rangaraju et al. 2008).

### 3.3.1 Recommendations on Agency Costs

Based on the review of the literature, it is recommended that an LCCA used in the pavement type selection process include all administrative, design/engineering, and construction management costs in the total agency cost calculations. Because these costs will usually be similar for both concrete and asphalt alternatives during initial construction, these agency costs may be excluded. However, due to the time value of money and the differential timing of rehabilitation measures for pavement alternatives, these costs should be included when calculating rehabilitation costs. The inclusion of these costs will allow ALDOT to fairly assess the future costs of both pavement alternatives.

## 3.4 User Costs

User costs are the costs that roadway users incur by using the roadway with a given pavement design and can form a significant component of the total life cycle costs associated with any transportation asset. These costs can be separated into two types: user cost categories and user cost components (Lamptey et al. 2005; ACPA 2012). Users cost categories include those costs that are experienced by the roadway users under normal traffic flow conditions and periods when the roadway is under construction. User cost components contain the costs incurred from normal use of the roadway and include vehicle-operating costs, travel time costs, and crash costs.

The largest percentage of user costs is typically experienced during the initial construction of the roadway and during maintenance and rehabilitation activities. The features of the initial construction and future rehabilitation work zones are important when calculating the user costs experienced by the travelling public. The number of days the work zone will be in place, the work zone length, and the work zone speed limit are a few of the characteristics needed to analyze the costs that will be accumulated during periods of construction and rehabilitation (Lindly and Clark 2004). The period during the day and the day of the week the work zone activities will occur are also critical to the timing of work zone operations to reduce the number of work zone related traffic accidents and delays (Back and Bell 2004; Bai and Li 2006; Ullman et al. 2006). In addition to work zone characteristics, traffic data, such as average annual daily traffic (AADT), annual traffic growth rate, and free flow capacity, is needed to estimate the delays experienced by the public. The work zone and traffic data will allow the decision makers to predict the costs incurred by the user during the initial construction of a pavement alternative and what impact rehabilitation activities will have on the user in the future based on forecasted traffic increases (Borchardt et al. 2009). The knowledge of these factors will also permit the agency to attempt to minimize the cost to those that rely on the roadway.

Another aspect of user costs is the cost experienced by the travelling public during normal operation of the roadway between periods of construction and rehabilitation. Differential performance characteristics, such as roughness, between the pavement alternatives will result in different costs incurred by the roadway users (Mellano et al. 2009). Vehicle operating costs can include items such as fuel consumption, vehicle repair/maintenance costs, and tires (Walls and Smith 1998; Daniels et al. 1999; Papagiannakis 2008).  Several studies have shown that concrete pavements, in certain situations such as driving during the summer months, have statistically significant lower user fuel consumption rates when compared to equivalent asphalt pavement sections (Taylor and Patten 2006; Arkedani and Sumitsawan 2010; Yoshimoto et al. 2010; Santero et al. 2011; Zaabar and Chatti 2011). However, since the costs are very difficult to estimate reliably and the total costs of these components can overwhelm the agency costs and other user costs on high volume roadways, these components of user costs are frequently not included in the analysis calculations.

Studies have indicated that approximately 40 percent of state DOT agencies include user costs in their LCCA approach (Shah et al. 2011; Rangaraju et al. 2008). Several of the states that currently do not include user costs are conducting research to determine the feasibility of the inclusion of these costs within their life cycle analysis procedures (Rangaraju et al. 2008). Most of the states that include user costs in their analysis only consider those costs attributable to periods of construction or rehabilitation. Washington and Pennsylvania include all of the user costs when analyzing life cycle costs while states such New Mexico, Massachusetts, and Colorado indicated that they only incorporate a percentage of the user costs and the percentage used was dependent upon the inherent characteristics of the projects (Shah et al. 2011). Louisiana is one of the few states that include both work zone user costs and vehicle operating costs in their analyses (Rangaraju et al. 2008). Both the asphalt and concrete pavement industries recommend the analysis of user costs over a pavement's life cycle during the pavement type selection process (APA 2010; ACPA 2012).

### 3.4.1 Recommendation on User Costs

Two major issues with user costs were brought forth during the meeting between the asphalt and concrete industry research teams. The first issue concerned what factors should be used when calculating the user costs. In what situation should user costs be calculated and used in the decision making process was the other major concern expressed by both research teams. The concrete pavement industry research team recommended that ALDOT calculate the user costs separate from agency costs and use them as a “tie-breaker” when the life cycle costs of the pavement alternatives are within ten percent of each other. When calculating user costs, the research team recommended that ALDOT consider travel delay costs and vehicle operating costs during periods of pavement construction and rehabilitation as well as the vehicle operating costs for each alternative during normal traffic conditions (when work zones are not present). The researchers at Auburn University also recommended that user costs be considered when the NPV of the pavement alternatives are within ten percent of each other and should include delay costs and vehicle operating costs when work zones are present (West et al. 2012e).

A point of contention between the two research teams involved the inclusion of vehicle operating costs during normal traffic conditions. The concrete pavement industry argued that the vehicle operating costs between asphalt and concrete can be significant and that the methodology used to calculate these costs has been validated. The asphalt research countered that calculating these costs is ultimately not reliable. Depending on the project location and traffic characteristics such as AADT, the vehicle operating costs during normal traffic flow can constitute a large percentage of the total user costs. Given the difficulties in accurately predicting future traffic flow and the costs associated with operating a vehicle during normal traffic flow, it is recommended that only the delay costs and vehicle operating costs when work zones are used during the initial construction phase and subsequent rehabilitation activities be used when calculating the user costs for a pavement alternative. During the decision making process, user costs should only be used as a "tie-breaker" when the NPV of the agency costs are within ten percent of each other.

## 3.5 Analysis Period

The analysis period that defines the LCCA can play a significant role in the final life cycle cost during the pavement type selection process. Shorter analysis periods tend to favor pavement alternatives that require frequent maintenance and rehabilitation, as well as multiple reconstructions, after their useful life has passed (OMB 2012). This is especially true if a higher discount rate was chosen for the analysis. The advantage of pavement options that typically have longer initial performance periods may not be fully realized if the analysis period is too short because advancements in concrete pavement design have allowed engineers to design these pavements with initial performance periods that can reach 40 years (Delatte 2008). Another downside of shorter analysis periods is inconsistency. For example, a 28-year analysis period may show that pavement A is the more economic choice. However, if a 35-year analysis period were used, pavement B might be the better choice due to additional rehabilitations needed by pavement A. An analysis period should be long enough to provide consistent results and not change with any additional extensions of time.

Key components of defining an analysis period and calculating the associated costs are the design life of the pavement and the rehabilitation strategy, which accounts for the rehabilitation triggers, methodology (i.e. crack sealing, overlays), and timing of the activities during the designated analysis period (Hall et al. 2003). However, for most pavement LCCA purposes, this period will encompass the entire estimated physical life of the pavement, which includes both the initial service life of the new pavement and the expected life expectancies of subsequent rehabilitation measures (Ford et al. 2012). When the end of the physical life is over, the pavement will be retired and a new pavement system will be constructed. However, due to variations in traffic, environmental factors, and unforeseen conditions, there is a high level of uncertainty in regard to the timing and magnitude of both flexible and rigid pavement rehabilitation measures, and this uncertainty requires careful consideration during the planning of a LCCA for pavements.

Assessments of the future maintenance and rehabilitation activities should be reliable to make informed decisions when quantifying costs for a life cycle analysis (Irfan et al. 2010). Required rehabilitation strategies and timings may come from estimates provided during the design using mechanistic-empirical software (DarwinME), historical data from the state's pavement database, and engineering experience and judgment. Other methods for predicting flexible and rigid pavement performance include models of pavement deterioration and data generated through Pavement Management Systems (PMS). Previous research on the performance and reliability of pavements has generated numerous models that predict the rate of deterioration of both new pavement construction as well as the rehabilitation and maintenance activities (George et al. 1989; Gopinath et al 1994; Abaza 2002; Al-Suleiman and Shiyab 2003; Irfan et al. 2009; Mandapak et al. 2012; Reimer and Pittenger 2012; Thomas and Sobanjo 2012). Overall, the severity of the repair or rehabilitation that is necessary, the construction methods employed by the agency, and an analysis of the impact the project will have on traffic flow should receive considerable attention to determine the most likely scenario that will be encountered when a restoration or rehabilitation is needed. The estimation of the costs required and the amount of time necessary to perform the work based on the aforementioned factors is also critical to determine the most cost effective solution and quantify the impact on the agency and public.

The FHWA recommends that an analysis period of at least 35 years be used for LCC analyses during the decision making process (Walls and Smith 1998). Hallin et al. (2011), in a report providing guidance on pavement type selection, encourage an analysis period of at least 40 years for new/reconstruction projects and an analysis period of at least 30 years for rehabilitation projects. The asphalt and concrete pavement industries have also made recommendations based on their respective pavement's historical performance. The Asphalt Pavement Alliance (APA) recommends an analysis period for perpetual pavements of no less than 40 years and that the analysis period should encompass at least one rehabilitation activity (APA 2011). The American Concrete Pavement Association (ACPA) recommends an analysis period of 45 to 50 years or more (ACPA 2012).

In September 2012, the Office of Management and Budget (OMB) released memoranda providing clarification on certain issues with Circular A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs." One such issue was the "appropriate choice of a horizon [analysis period] for life-cycle cost analysis" (OMB 2012). Within the memorandum, the Office made clear that Circular A-94 does not specify a particular period of time to be used as the analysis period to be used in a LCCA; however, the Office does offer recommendations on the selection of the analysis period length based on the durability of materials:

> "The time horizon for life-cycle analysis is project specific, but should normally be long enough to encompass the likely lifespan of the most durable alternative being compared…With respect to materials, it may be appropriate for the agency to consider the relative durability of materials in assessing lifecycle costs by extending the time frame for analysis. For example, if the durability of one form of a material would extend

> the useful life of a constructed asset as compared to an alternative material, the agency could, consistent with Circular A-94, extend the time frame used for analysis in comparing all of the relevant alternatives."

In their 2008 study, Rangaraju et al. found that the analysis period used by state DOTs in the United States ranged from 20 to 50 years. Several states, such as Alabama, Georgia, and Missouri, use analysis periods that were fixed and did not change even when factors such as highway network classification, traffic, or pavement type do change. Other states, such as California, Michigan, and North Carolina, had variable analysis periods determined by pavement type or pavement structure. Overall, the trend is moving toward longer analysis periods. The majority of state DOTs use an analysis period of 40 years, and the percentage of state DOTs using an analysis period of at least 50 years grew from seven percent in 2005 to 20 percent in 2008 (Rangaraju et al. 2008).

The performance of pavements exceeding their planned initial design lives has caused other states to examine their own concrete pavement designs. The states of Illinois, Minnesota, California, and Washington are researching and implementing concrete pavement design procedures with design lives greater than 30 years, with some states looking at pavement designs surpassing 40 years (FHWA 2007). The analysis period chosen for the LCCA should be long enough to fully capture the economic benefit of these long life pavements.

### 3.5.1 Recommendation on Analysis Period

The initial performance period and the performance lives of pavement rehabilitation measures are important when considering the length of the analysis period. Recent advancements in pavement design methodology and pavement design software packages have increased the ability of highway engineers to design pavements with longer initial performance periods and rehabilitation lives. Therefore, longer analysis periods may be necessary to capture the initial performance period and one rehabilitation activity for a pavement alternative.

Given these advancements, the concrete industry recommended that the analysis period in an LCCA for the pavement type selection process be set at 40 to 50 years. In the December 2012 meeting, they stated that an analysis period of this length of time will allow the life cycle costs of both asphalt and concrete pavement alternatives to include at least one rehabilitation activity and will allow the analyst to accurately capture the life cycle costs throughout the useful lives of the pavements. The Auburn researchers and the asphalt industry recommended that ALDOT use an analysis period of 35 years for all pavement LCCA. Their contention with longer analysis periods focused on the amount of risk associated with forecasts made further into the future for items such as traffic projections used in calculating user costs and the design of the rehabilitation activity (West et al. 2012a). Other issues expressed by the asphalt industry were concerned with the average service life of concrete pavements within the state of Alabama.

Based on the review of pavement LCCA literature and the recommendations from pavement industry experts, it is recommended that the analysis period for a pavement LCCA be set for 40 to 45 years. This length of time is consistent with a trend for longer analysis periods shown by other state DOTs and will allow an analyst to capture the initial performance period and a rehabilitation activity for a majority of paving systems, including long life pavements. Recommendations on initial performance periods and rehabilitation performance periods for asphalt and concrete pavements will be presented later in this chapter.

## 3.6 Discount Rate

One of the most influential factors in the execution of an LCCA for pavements is the discount rate. Discounting the costs associated with an asset throughout its useful life provides a means to compare alternatives by providing a common unit of measurement (Walls and Smith 1998). The discount rate accounts for the time value of money and accounts for the fluctuations over time of inflation and interest rates. In LCCA calculations, either nominal or real discount rates are used. Nominal discount rates include an inflation component whereas real discount rates do not include the effects of general inflation and represents the true time value of money. Future costs discounted using a real discount rate provides the analyst with the present value (PV) of future costs expressed in real, or constant, dollars. Due to their unique treatment of the effects of inflation, an analyst should use caution if both real and nominal costs and rates are combined in the same LCCA.

The discount rate used in the pavement selection process is calculated based on two main factors: the interest rate and inflation rate. Paving projects may receive their funding from local, state, or Federal agencies that fund the projects by means of bond sales, levied taxes, and/or tolls (ACPA 2012). While the funds obtained by these measures are invested in a transportation project and will provide a level of benefit to the agency and the public, those funds could have been invested in another project that might have produced equitable benefits. Since public agencies are designated proxies of the taxpayer’s money and cannot save or invest this money and, therefore, generate additional revenue, the discount rate also reflects the fact that the taxpayer has lost their opportunity cost of capital and absolved their chance to invest that money themselves (Harris 2009). This lost opportunity by both the public entity and the general public, referred to as the social discount rate when applied to public projects, is accounted for by the use of the discount rate when calculating the PV of future costs (Jawad and Ozbay 2005). The value used in these calculations should be modeled after what entity is generating the money and how it will be collected, such as the interest rate for 30-year United States Treasury bills (ACPA 2012).

The inflation rate value is also important when calculating the discount rate. There are several inflation indexes available, ranging from broad determinations generated from the Gross Domestic Product chain deflator to narrow indices for specific industries and commodities (FHWA 2002). One of the most common inflation rate values used is generated from the general inflation rate indices produced by the United States Department of Labor's Bureau of Labor Statistics (BLS); the Consumer Price Index (CPI) represents the change in prices for a set "basket" of goods and services for the general public over time and is commonly used as a general model for inflation in the United States.

In 1998, the FHWA recommended that a real discount rate of three to five percent was practical when performing a LCCA for a transportation project (Walls and Smith 1998); however, in a memorandum clarifying the FHWA's policy on bidding alternate pavement types, the agency indicated that the trend over the past decade was that a real discount rate in the two to four percent range was more reasonable (FHWA 2008). The Asphalt Pavement Alliance (APA) defers to the American Association of State Highway Transportation Official (AASHTO) recommendation of using the rates published by the Office of Management and Budgets (OMB) for use in the analysis (APA 2011). The ACPA also endorses the use of the real discount rates published by the OMB when performing a LCCA for pavement type selection (ACPA 2012).

The discount rate used by state DOTs in their life cycle cost calculations varies from state to state. A majority of states use a fixed rate based upon the FHWA recommended life cycle analysis “good practice.” Thirty states use a value in the three to five percent range, and eighteen of those states use a discount rate of four percent (Mack 2012). The states of Colorado, Ohio, Michigan, Minnesota, Missouri, Nevada, South Carolina, and West Virginia use the 30-year real discount rate listed in Appendix C of Circular A-94 published annually by the OMB. Six states perform a sensitivity analysis of the discount rate, and three states, including Maryland and Colorado, utilize a probabilistic approach in regard to the discount rate when performing a LCCA (Rangaraju et al. 2008).

### 3.6.1 Recommendation on Discount Rate

Since high discount rates favor pavement alternatives with lower initial construction costs but higher (and more frequent) rehabilitation costs, the concrete pavement industry recommended that ALDOT use the 30-year real discount rates in Appendix C of Circular A-94 published by the OMB. They stated that the real rates reflect the difference between current interest and general inflation rates and will provide a means to accurately compare the life cycle costs of the pavement alternatives throughout the analysis period. To ensure that the most up-to-date OMB discount rates are used they also recommended that the discount rate used by ALDOT be updated each January when the OMB publishes its revised discount rates. The researchers from Auburn and the asphalt industry also recommended the use of the 30-year real discount rate published by OMB. However, the researchers noted that the 30-year real discount rates published by OMB can fluctuate wildly between consecutive years and that a ten-year moving average of the real discount rate provides a better representation of economic conditions (West et al. 2012).

Figure 7 shows the annual 30-year real discount rate published by OMB from 1980 to 2013. The figure also contains a five-year moving average (represented by the blue markers and line) and a ten-year moving average (shown as green markers and line) for the real discount rates. From this graph, it is seen that both the five-year and ten-year moving averages are not as sensitive to the year-to-year fluctuations of the discount rate and provide a consistent summary of the economic climate. Therefore, it is recommended that a five-year or ten-year moving average of the 30-year real discount rate be used for pavement LCCA calculations. This average will provide a better representation of the economic condition instead of a static value set by policy, such as four percent, or a single real discount rate published by OMB the year the LCCA is performed.

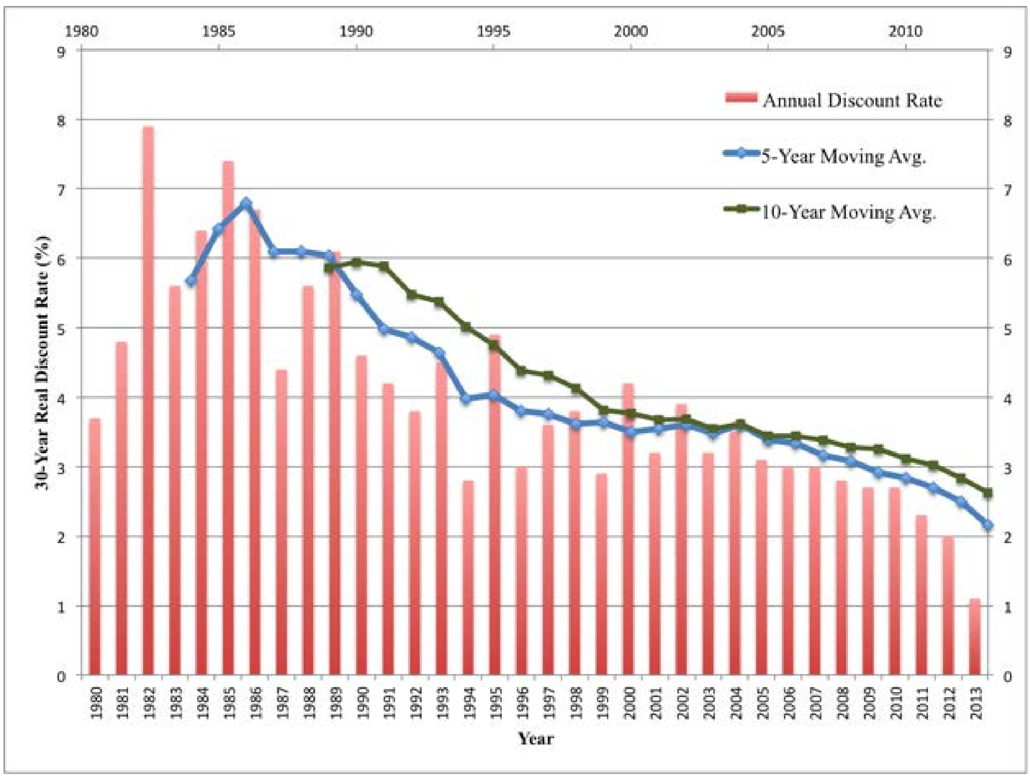



Figure 7. OMB 30-Year Real Discount Rate (1980 to 2013)

### 3.7 Salvage Value (Remaining Service Life/Residual Value)

Salvage value represents the value of a pavement alternative at the end of the analysis period (Wilde et al. 2001; Ozbay et al 2003; Wimsatt et al. 2009; Hallin 2011). When the analysis period and the estimated performance life of an alternative end at the same time, the "residual value" form of salvage value can be calculated. The residual value is the net value that can be realized by selling the recycled components of the pavement. When the performance life of the alternative exceeds the analysis period, the "remaining serviceable life" form of salvage value can be calculated. This remaining service life value is usually higher than the residual value would be and can be calculated as a percent of the remaining service life multiplied by the cost of the most recent rehabilitation (FHWA 2002). While they may be used in the LCCA, the present value of the residual value for a given alternative will have a miniscule effect on the total life cycle cost due to discounting. However, failure to consider the remaining service life of one alternative when the end of the analysis period coincides with the end of the design life for a competing alternative creates a bias in the analysis.

Both the asphalt and concrete pavement industries recommend the consideration of the salvage value of the pavement alternatives at the end of the analysis period. The ACPA recommends that the salvage value should be included in LCCA whenever the residual values of the pavement alternatives are significantly different (ACPA 2012). The APA emphasizes including the salvage value of the pavement alternatives in the analyses "because some or all of the pavement structure continues to serve its purposes beyond the analysis period (APA 2010)."

Approximately 56% of the respondents to the South Carolina LCCA survey include salvage value in their analysis. Out those responding agencies, approximately 80% calculate only remaining serviceable life, and the rest calculate both residual value and remaining serviceable life (Rangaraju et al. 2008).

### 3.7.1 Recommendation on Salvage Value

During the December 2012 meeting, the concrete pavement industry asserted that if the end of a pavement's service life does not coincide with the end of the analysis period, the salvage value should be calculated so that the value of the pavement asset at the end of the analysis period may be recognized. They recommended that only the remaining service life of an alternative be calculated because the difference of the residual values between flexible and rigid pavement alternatives is small (especially when discounted back to the present value) and typically do not significantly influence the total life cycle cost. The Auburn researchers recommended that the salvage value of the asphalt be calculated using the remaining service life of the wearing surface layer used during the last rehabilitation cycle and residual value of the lower asphalt layers left intact from the initial construction of the pavement system (West et al. 2012d). These values would then be discounted and subtracted from the NPV of the life cycle cost for the asphalt alternative. The salvage value of the concrete pavements, however, would consist of costs necessary for the removal of the entire concrete pavement system. This value, after discounting, would be added to the NPV for the concrete pavement alternative.

A couple of problems are apparent with the asphalt industry's recommendation for the calculation of salvage values for asphalt and concrete pavements. The first issue concerns the residual value of the lower asphalt layers. Using their methodology, the residual value of the lower asphalt layers (before discounting) is equal to the cost to initially construct those layers. While the lower layers would have a value associated with them, either as a base for an asphalt overlay or the net value of the recycled material, this value would not be equal to the cost to initially install those layers due to the depreciation of the material over time. Another problem arises with their use of the initial construction unit cost of the lower asphalt layers to calculate the residual value. Since the unit cost of asphalt paving includes labor, equipment, and markup components in addition to the material cost, the use of the full unit cost in calculating the residual value would also provide costs not related to true cost of the material itself; only of a percentage of the unit cost would include the actual material cost.

Based on this research and the variation of opinions expressed during the December 2012 meeting on what should be included in the residual value calculations, it is recommended that only the remaining serviceable life be considered when calculating a pavement alternative's salvage value. This value should be calculated using straight-line depreciation when the end of the pavement's functional life does not occur at the same time as the analysis period. The remaining service life is calculated as the product of the percentage of design life remaining for the last rehabilitation activity and the last rehabilitation cost. The remaining service life is then discounted back to the present using the discount rate used in the LCCA.

$$Value\ of\ Remaining\ Service\ Life = \ Cost\ of\ Last\ Activity \times \frac{Remaining\ Service\ Life\ of\ Last\ Activity}{Service\ Life\ of\ Last\ Activity}$$

Example: A pavement alternative has an initial performance period of 18 years and three rehabilitations with service lives of ten years each. This will require a rehabilitation of the pavement system at year 18, year 28, and year 38. The analysis period of the LCCA is 45 years. The cost of the last rehabilitation is estimated to be \$500,000. The OMB real discount rate is 2.8%.

*Remaining Service Life of Last Activity = Service Life of Last Activity – (Year at End of Analysis Period – Year of Last Rehabilitation Activity)*

$$\begin{aligned} \textit{Remaining Service Life of Last Activity} &= \textit{10 years} - (\textit{45 years} - \textit{38 years}) \\ &= \textit{3 years} \end{aligned}$$

$$Value\ of\ Remaining\ Service\ Life = \$500{,}000\ \times \frac{3\ years}{10\ years}$$

$$\boldsymbol{Value\ of\ Remaining\ Service\ Life = \$150{,}000}$$

This value of the remaining service life ($150,000) is then discounted using the OMB real discount rate to obtain the present value of the remaining service life:

$$PV = Remaining\ Service\ Life\ Value\left[\frac{1}{(1+i)^n}\right]$$

*where: i = discount rate*

*n = year of expenditure*

$$PV = \$150{,}000\left[\frac{1}{(1+0.028)^{45}}\right]$$

$$\boldsymbol{PV \approx \$43{,}290}$$

This value is then subtracted from the total life cycle cost of the pavement alternative.

## 3.8 Approach to LCCA

Deterministic and probabilistic approaches are the prevailing methodologies used when conducting an LCCA for pavement selection. A deterministic approach to LCCA uses fixed, discrete values for input variables derived from historical data or professional judgment (Chan 2008; Hallin 2011; ACPA 2012). This method allows for a straightforward summation of all the costs associated with a pavement's life cycle. However, one of the main disadvantages to employing this method is that any uncertainty associated with important input values, such as initial construction costs, discount rates, and rehabilitation timing, are not accounted for during the analysis. A probabilistic, or stochastic, approach to life cycle costs analysis is defined by the use of a frequency distribution for one or more (but not necessarily all) input parameters (Demos 2006; Ford et al. 2012; Hallin 2011, Markow 2012). During the analysis, sample input values are randomly selected from a user defined probability distribution multiple times, generating numerous life cycle costs values for a given design alternative. This process allows the analyst to identify the net present value (NPV) for an alternative at a specified level of probability. For example, an analyst using the probabilistic approach might find that there is a 90% probability that the NPV for Alternative A is $4 million or less, but there is only a 40% probability that the NPV for Alternative B is $4 million or less.

The two main sources of uncertainty in both the design of the pavement alternatives and LCCA are the inherent variability of the input parameters and model uncertainty (Huang 2004; Retherford 2012). For example, in the context of estimating the life expectancy of a given pavement design, sources of uncertainty may exist due to errors in modeling techniques, errors in input values, inaccuracies in parameters, and the impact of unforeseen causes that may accelerate the deterioration of the pavement (Ford et al. 2012). During the performance of an LCCA, highway agencies assume a level of risk as a result of the variability associated with both economic and engineering factors. This risk may manifest itself in the form of estimated costs that are too high or too low or overly optimistic or pessimistic rehabilitation strategies (Harbuck 2009). The level of risk that will be inherited by the modeling of life cycle costs will differ from project to project because of the variable level of the uncertainty in input values and the impact the factor will have on the total life cycle costs (Li 2009).

The approach that many DOT agencies rely upon while conducting an LCCA is the deterministic method, accounting for 80 percent of the responding agencies (Chan 2008; ACPA 2012). Only ten percent of the state DOT agencies utilize a probabilistic approach. Approximately ten percent of the responding state agencies use a combination of probabilistic and deterministic approaches. Of those agencies that use the deterministic method during their LCCA, only 25 percent perform a sensitivity analysis to examine the impact that parameters within the analysis would have on the total life cycle cost of the pavement alternatives (Rangaraju et al. 2008). LCCA analysis software such as RealCost allows the user to choose among several different probability distributions to define an input. The Colorado DOT uses triangular distributions to evaluate initial construction costs based on historical data to quantify the scale and to estimate first rehabilitation cycle of rigid pavement alternatives (Harris 2009; CDOT 2012). The Colorado DOT also uses a log normal distribution with a mean value of 3.3 and a standard deviation of 0.19 to model the variability associated with the discount rate over time (Demos 2006). Other states, such as Maryland and Washington, also use probability distributions in their life cycle cost analyses.

Several sources recommend the use of a probabilistic approach to analyze the life cycle cost of project alternatives (Walls and Smith 1998; Tighe 2001; ACPA 2012). Several software packages, such as FHWA's RealCost, allow the decision maker to conduct both deterministic and probabilistic analyses with user control of factor values and probability distributions. RealCost is the preferred software of state DOTs around the nation for LCCA. RealCost allows only a single input for all materials and costs that make up initial construction cost and rehabilitation/maintenance costs. That is, the user can only input one distribution for the cost. Distributions for all the different elements that make up the initial construction cost or rehabilitation costs cannot be added to the analysis within RealCost. Thus, to account for the variability of each element that makes up an initial construction cost (or a rehabilitation cost), the user must combine the costs for all the elements and their individual distributions into one cost and one distribution outside of the RealCost platform.

### 3.8.1 Recommendation on Approach to LCCA

A deterministic approach to LCCA for the pavement type selection process allows for a direct comparison of total life cycle costs between asphalt and concrete pavements, but that approach ignores the uncertainty associated with LCCA inputs. The concrete industry recommended that ALDOT adopt a probabilistic approach to LCCA for the pavement type selection process. The team also recommended that ALDOT use RealCost software to conduct the probabilistic analysis. Because RealCost software does not allow for a probabilistic analysis of individual pay items during the calculation of initial construction costs and pavement rehabilitation costs, the concrete research team also recommended that ALDOT develop an Excel-based cost-estimating program that combines the costs for all elements and their individual distributions into one cost and one distribution.

Given the amount of asphalt data available to the state of Alabama, it is recommended that ALDOT begin analyzing historical pavement data to develop probability distributions that can be used in a probabilistic analysis of pavement life cycle costs. Initially, ALDOT could develop probability distributions for costs associated with initial construction and rehabilitation activities as well as distributions for the initial and rehabilitation performance periods of asphalt pavements. Concrete cost and performance data from other states in the Southeast should be added to increase the robustness of the existing ALDOT concrete pavement data set. The next step would be to create probability distributions for factors used in the calculation of user costs.

### 3.9 Price Adjustment Clauses (Indexing)

One significant risk factor that can have an impact on the cost of infrastructure projects is the price volatility of commonly used construction commodities such as fuel, steel, and asphalt (Zhou and Damnjanovic 2010). During the 1970's, oil prices in the United States were extremely volatile, and oil-based products such as asphalt were not immune to the uncertainty in prices. The unpredictable nature of asphalt prices forced many paving contractors across the country to include premiums in their bids to account for this risk (Kosmopoulou and Zhou 2011). In an attempt to remove these premiums from the bids, state highway agencies began incorporating price adjustment clauses (also called indexing) into their contracts. By assuming the price escalation risk, the agencies hoped that contractors would lower their total bid price (Damnjanovic and Zhou 2009).

It is important to understand that for the agency, the risk associated with material price volatility is not mitigated through the use of indexing. Depending on the details of the price adjustment clause, the majority of the price increase risk is transferred to the agency, especially if there is no minimum change in price between bid stage and construction, often called a "trigger" value that would prompt a price adjustment to be made. If there is no "trigger" value stipulated in the contract, even minor fluctuations in the asphalt index will initiate a price adjustment. While a perceived benefit may be initially realized through lower bids, the agency ultimately risks paying more in the end if the price of the material being indexed is extremely volatile. This risk places a great deal of pressure on the agency to effectively manage the project's overall cost and budget for future expenditures (Skolnik 2011).

Figure 8 shows the historical trend of the ALDOT's monthly performance grade (PG) liquid asphalt index, the bi-monthly percent change, and the yearly percent change of the index from January 1998 through May 2012. During this time period, the monthly PG liquid asphalt index (the continuous, bold, blue line) has increased 345 percent. The average yearly percent change is 15.4 percent, and the average percent change over a two-month period is 2.1 percent. While some of the price fluctuations were negative, a majority of the yearly changes in the price of PG asphalt were positive during this time span, indicating that for a majority of the time, the indexing for asphalt led to higher construction costs. This analysis means that the actual construction costs are also higher than would have been used in an LCCA.

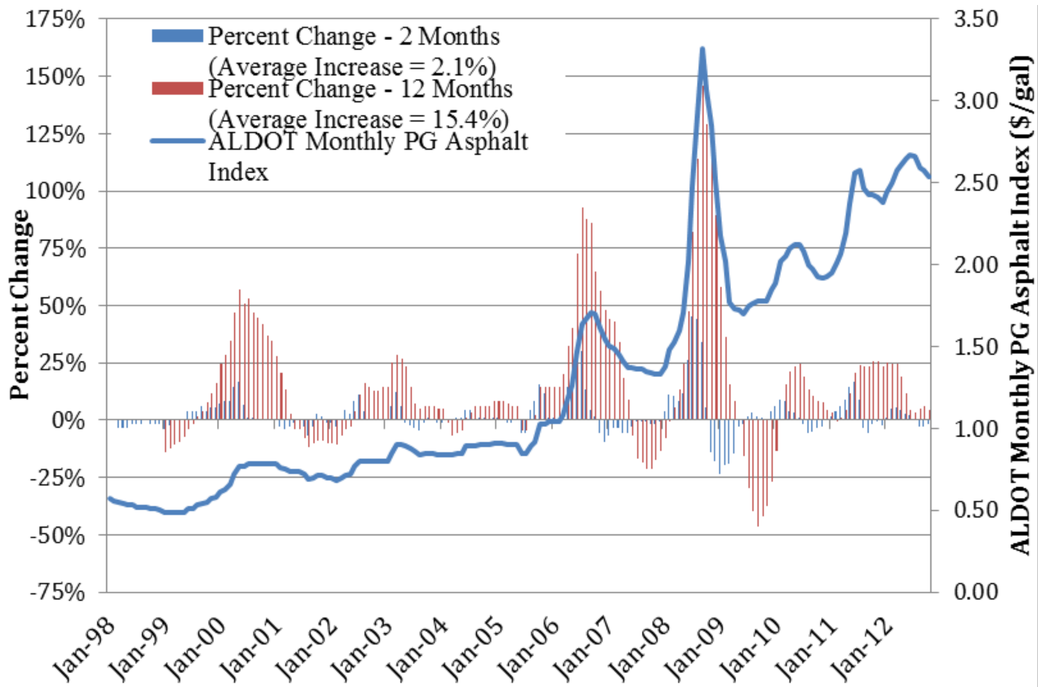


Figure 8. ALDOT Monthly PG Asphalt Index (January 1998 to October 2012)

To demonstrate the impact that indexing can have on the actual costs paid for asphalt, Figure 9 was developed to show the average monthly asphalt concrete (not liquid asphalt) bid price and the average adjusted asphalt bid price over a 15-month period for ALDOT projects. In the graph, the light blue columns represent the average asphalt bid price for a given month. The dark blue dots represent the average adjusted bid price over a 15-month time period after the bid date, and the red lines show the range of the adjusted bid prices over the 15-month period. The 15-month range was used under the assumption that all paving occurred between one month and 15 months after the project was bid. This time span allowed for 15 months' worth of adjusted bid prices to be averaged so that extremely low or high index values would not drastically distort the adjusted bid prices.

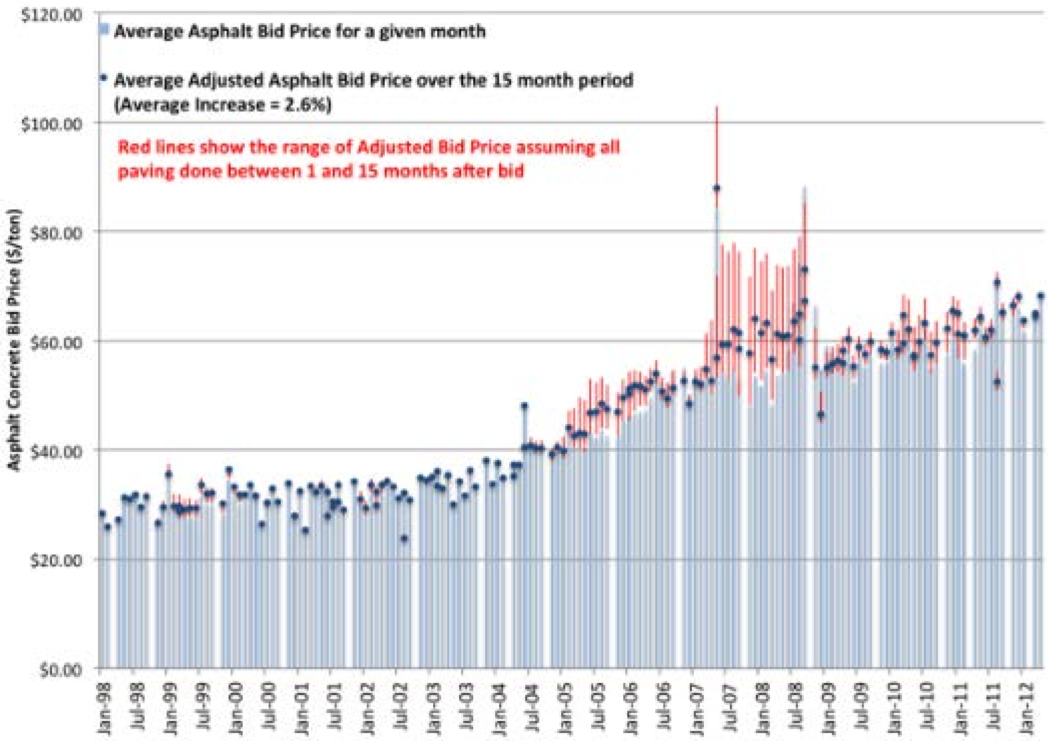



Figure 9. Estimated adjusted bid prices from January 1998 to May 2012 (Data obtained from OMAN Systems)

The adjusted bid prices in Figure 10 were calculated using the conversion factor and procedures outlined in the 2012 edition of the ALDOT *Standard Specifications for Highway Construction*. The fact that most of the dark blue dots (representing average adjusted asphalt concrete bid prices) are above the average asphalt concrete bid price indicates that an LCCA calculated for most flexible paving alternatives would contain an estimate for initial construction cost that is lower than the actual construction cost will be, which would artificially decrease the LCCA results.

Overall, from January 1998 to May 2012, the average increase of the average adjusted asphalt concrete bid price over the average actual bid price for asphalt was 2.6 percent. From January 1998 to the end of 2004, there was not much of a difference between the average adjusted bid prices and the average asphalt bid price. However, from early 2005 to May 2012, the average adjusted bid prices were 3.6 percent higher than the actual bid prices. This difference is important because historical bid data used for the calculation of initial construction costs for asphalt pavements during this period would not accurately represent the price actually being paid for asphalt during this time period.

To examine how indexing could potentially affect LCCA initial construction costs, data from the *Flexural Structural Design Module: I-20 CRC from MP 130.301 to MP 132.651 Full Depth HMA* LCCA example that had been provided by ALDOT was used to estimate the effects of rising asphalt prices could have on the LCCA. The initial construction cost for the full-depth asphalt alternative was $2,456,258 in one direction. The example indicated that the project construction year is 2011, and it was assumed for this example that the bid was submitted in January 2011. The PG asphalt unit cost adjustment for each following month of 2011 using ALDOT's PG asphalt index was then calculated. The PG asphalt adjustment was used to adjust the value per ton of asphalt concrete, assuming five percent liquid asphalt in the mix, and then calculated the additional project cost that would result for the remaining 11 months of the year. The results are shown in Table 4. Each month after January showed an increase in initial construction price. The biggest total initial construction cost increase (approximately $610,000 or 12.4%) was in July 2011, but all months had higher initial construction costs than January.

Table 4. Effects of asphalt indexing on an example ALDOT project

| **Date** | **ALDOT Index ($/ton PG binder)** | **Unit Cost Adjustment ($/ton AC)** | **Total Cost (One Direction) ($)** | **Total Cost (Both Directions) ($)** | **Difference between Anticipated Bid and LCCA Estimate ($)** | **Percent Increase from Jan 2011 Estimate** |
|---|---|---|---|---|---|---|
| Jan 2011 | 458.28 | $0.00 | 2,456,258 | 4,912,516 | *0* | 0.0% |
| Feb 2011 | 472.39 | $0.71 | 2,485,262 | 4,970,525 | *58,009* | 1.2% |
| Mar 2011 | 486.49 | $1.41 | 2,514,267 | 5,028,534 | *116,018* | 2.4% |
| Apr 2011 | 514.69 | $2.82 | 2,572,276 | 5,144,552 | *232,036* | 4.7% |
| May 2011 | 556.99 | $4.94 | 2,659,289 | 5,318,578 | *406,063* | 8.3% |

Table 4. Effects of asphalt indexing on an example ALDOT project

| | | | | | | |
|---|---|---|---|---|---|---|
| Jun 2011 | 601.65 | $7.17 | 2,751,137 | 5,502,273 | *589,757* | 12.0% |
| Jul 2011 | 606.35 | $7.40 | 2,760,805 | 5,521,610 | *609,094* | 12.4% |
| Aug 2011 | 580.49 | $6.11 | 2,707,630 | 5,415,260 | *502,744* | 10.2% |
| Sep 2011 | 571.09 | $5.64 | 2,688,294 | 5,376,587 | *464,071* | 9.4% |
| Oct 2011 | 571.09 | $5.64 | 2,688,294 | 5,376,587 | *464,071* | 9.4% |
| Nov 2011 | 566.39 | $5.41 | 2,678,626 | 5,357,251 | *444,735* | 9.1% |
| Dec 2011 | 559.34 | $5.05 | 2,664,123 | 5,328,247 | *415,731* | 8.5% |

The American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Construction surveyed each DOT in the fall of 2009 to determine the use of PACs in highway construction contracts (AASHTO 2009). The survey found that 40 states, including Alabama, currently use PACs for asphalt cement in their contracts, while only four states, not including Alabama, have a PAC for Portland cement. The only state found to adjust for the volatility in asphalt prices based on PAC in their LCCA calculations is Pennsylvania. In their Pavement Policy Manual (Publication No. 242), the Pennsylvania DOT (PennDOT) specifies that an Asphalt Adjustment Multiplier (AAM) be applied to the unit costs of all bituminous materials considered in an LCCA (PennDOT 2010). This multiplier is calculated semi-annually and is based on the total of bituminous payments made over the preceding twelve months and bituminous price adjustments earned on those payments.

### 3.9.1 Recommendation on Price Adjustment Clauses (Indexing)

To account for the uncertainty in asphalt prices, the concrete research team recommended that ALDOT develop a procedure to account for asphalt indexing during the calculation of an asphalt pavement alternative's initial construction costs when performing an LCCA. The procedure should factor in past asphalt index values and should have the ability to provide short-term forecasts of index values so that proper adjustment may be made. These price adjustments should be made to all bituminous materials being considered in the initial construction of the asphalt pavement system.

The concrete industry recommended adding a sub-step (step 2a) to the general LCCA methodology outlined by FHWA and used by ALDOT to account for indexing:

1. Design equivalent pavement sections
2. Estimate the initial construction costs

   a. Adjust unit costs of all bituminous materials to account indexing using the following equation:

$$\textbf{Adjusted Unit Cost} = \textbf{Current Unit Cost} * (\mathbf{1+AAM})^{n}$$

where: AAM = Asphalt Adjustment Multiplier (AAM)

n = number of years to the year of activity

3. Estimate the initial life of each alternative
4. Determine the maintenance and rehabilitation strategies (activities and timing) to be used on the pavement over the analysis period
5. Estimate rehabilitation costs for each activity in today's dollars
6. Estimate user costs (optional)
7. Compute net present value (NPV) of rehabilitation costs using the real discount rate
8. Analyze results (Mack 2012).

The asphalt pavement research team and Auburn University researchers claimed that the use of price adjustment clauses is a popular method of mitigating the risks with asphalt price volatility and their use may lower bids and more stability for smaller paving contractors (Skolnik et al. 2012). While the clauses may be effective in those regards, the short-term volatility and any trends in asphalt and concrete prices should be accounted for during the estimation of initial construction costs of both alternatives. A method to account for the trend and variability with paving material prices is presented in Chapter Five of this dissertation.

### 3.10 Material Specific Escalation Rates

When performing an LCCA, one general assumption made about the discount rate is that material prices will inflate parallel with the general rate of inflation throughout the entirety of the life cycle analysis period. However, some materials may inflate at a higher or a lower rate than the general rate of inflation due to market volatility and other economic factors. Accounting for material specific inflation rates addresses instances where certain materials or commodities such as steel, utilities, and asphalt may inflate at a rate that is significantly higher or lower than the general inflation rate used to calculate the real discount rate (Lee and Grant 1965; Rao 2003; ACPA 2012; Markow 2012).

Accounting for commodity or material specific inflation rates has been in use for building LCC analyses for several years. The National Institute of Standards and Technology (NIST), in their life cycle costing manual for the Federal Energy Management Program (FEMP), requires that energy-related costs be adjusted by Department of Energy (DOE) projections of real escalation rates for fuel types used in the operation of government buildings (Fuller 1995). The escalation rate of a material is defined as the difference between the material's inflation rate and the general rate of inflation. For example, if a material's inflation rate is 5.5 percent and the general inflation rate is 3.5 percent, then the escalation rate is two percent (5.5 percent minus 3.5 percent). These escalation rates are then coupled with real discount rates to calculate a modified uniform present value (UPV) factor that is used to forecast future energy costs (Fuller 2005). The American Society for Testing and Materials (ASTM) has also established procedures for measuring life cycle costs of buildings and building systems. In Standard Practice Designation: E917-05, ASTM recommends the use of differential price escalation rates if future costs are expected to inflate faster than the general rate of inflation (ASTM 2005).

Currently, no state highway agencies account for the volatility in asphalt prices during the calculation of life cycle costs of pavement alternatives. However, 42 states do recognize the volatility of asphalt prices and use price adjustment clauses to limit contractors' exposure to these price fluctuations (only four states use a cement index). Accounting for price volatility in the bidding process but not accounting for it in the LCCA process is an inconsistency that biases LCCA results.

The Concrete Sustainability Hub at the Massachusetts Institute of Technology (MIT) studied the volatility of asphalt concrete and portland cement concrete prices used in the construction industry and how this uncertainty can impact the decision making process (Kirchain 2012). The researchers at MIT have found that for many commodities, projecting future prices is an effective endeavor and outperforms calculations that assume no price volatility, as long as adequate historical data are used to create the projection.

Figure 10 plots the trend in the producer price indices (PPIs) for concrete products and for asphalt paving mixtures and blocks, from 1970 to 2010. The graph illustrates the increased rate of change in the asphalt products PPI, while the concrete products PPI tracks closely with the general inflation rate (as expressed by the CPI). Examination of historical PPI data showed that, from a period from 1977 to 2010, the annual percentage real price change of asphalt increased an average of 1.25 percent per year with a standard deviation of 6.3 percent while concrete decreased 0.17 percent with a standard deviation of 2.9 percent (Lindsey 2011).

Figure 10. PPI values for concrete and asphalt

Due to the non-normal distributions of the data for both materials, the MIT researchers found that logistic and log-logistic distributions were the best fit for the concrete and asphalt data, respectively. The values and distributions calculated by the researchers were used in stochastic simulations to model the uncertainty of each material. After 1,000 simulations, their results estimated the mean annual real escalation rate of concrete to be -0.5 percent and asphalt's escalation rate to be 1.1 percent (Lindsey 2011).

MIT created cost adjustment factor tables for both asphalt and concrete using the output of the simulations; these factors were created for each year up to a given point in the future. Table 5 (portland cement concrete) and Table 6 (asphalt concrete) allow a decision maker to use current material prices along with the cost adjustment factors to calculate an estimate of future costs at a given point in the future. To assist in quantifying the level of risk involved with predicting future costs of economically volatile materials, percentiles were added that would allow users to choose the level of risk they are willing to accept when estimating the future costs of concrete and asphalt.

To use the “mean escalation rate,” the analyst selects the escalation rate for year of the future rehabilitation and escalates the costs with it. For example, an LCCA calls for $1 million concrete expenditure at year twenty. The concrete escalation rate at year 20 is -0.49%, so the future concrete rehabilitation costs is $\$1,000,000 * (1-0.049)^{20} = \$906,430$.

Table 5. Escalation rates for concrete (reproduced from Lindsey 2011)

| Year | Mean | Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| 1 | -0.46% | -3.81% | -2.58% | -1.75% | -1.08% | -0.46% | 0.16% | 0.83% | 1.65% | 2.88% |
| 2 | -0.48% | -2.92% | -1.99% | -1.46% | -0.89% | -0.41% | 0.00% | 0.42% | 1.06% | 1.88% |
| 3 | -0.48% | -2.47% | -1.74% | -1.26% | -0.84% | -0.47% | -0.08% | 0.32% | 0.79% | 1.58% |
| 4 | -0.49% | -2.32% | -1.69% | -1.22% | -0.83% | -0.44% | -0.11% | 0.24% | 0.65% | 1.26% |
| 5 | -0.49% | -2.11% | -1.54% | -1.18% | -0.85% | -0.51% | -0.17% | 0.15% | 0.54% | 1.10% |
| 6 | -0.49% | -1.86% | -1.43% | -1.11% | -0.80% | -0.53% | -0.23% | 0.10% | 0.47% | 0.95% |
| 7 | -0.49% | -1.72% | -1.37% | -1.04% | -0.76% | -0.52% | -0.24% | 0.06% | 0.39% | 0.81% |
| 8 | -0.49% | -1.64% | -1.29% | -1.02% | -0.76% | -0.49% | -0.27% | 0.03% | 0.34% | 0.73% |
| 9 | -0.49% | -1.64% | -1.24% | -0.94% | -0.70% | -0.50% | -0.28% | -0.03% | 0.27% | 0.62% |
| 10 | -0.49% | -1.59% | -1.21% | -0.93% | -0.71% | -0.48% | -0.30% | -0.06% | 0.20% | 0.57% |
| 11 | -0.49% | -1.57% | -1.18% | -0.93% | -0.70% | -0.48% | -0.29% | -0.06% | 0.21% | 0.55% |
| 12 | -0.49% | -1.51% | -1.12% | -0.90% | -0.70% | -0.49% | -0.29% | -0.08% | 0.16% | 0.44% |
| 13 | -0.49% | -1.44% | -1.11% | -0.88% | -0.69% | -0.49% | -0.29% | -0.12% | 0.13% | 0.46% |
| 14 | -0.49% | -1.39% | -1.10% | -0.85% | -0.66% | -0.50% | -0.32% | -0.13% | 0.10% | 0.42% |
| 15 | -0.49% | -1.37% | -1.05% | -0.83% | -0.66% | -0.50% | -0.33% | -0.16% | 0.10% | 0.40% |
| 16 | -0.49% | -1.33% | -1.02% | -0.82% | -0.65% | -0.48% | -0.33% | -0.18% | 0.05% | 0.36% |
| 17 | -0.49% | -1.31% | -1.03% | -0.81% | -0.63% | -0.48% | -0.33% | -0.18% | 0.02% | 0.32% |
| 18 | -0.49% | -1.30% | -1.01% | -0.80% | -0.63% | -0.49% | -0.35% | -0.17% | 0.01% | 0.27% |
| 19 | -0.49% | -1.30% | -0.98% | -0.80% | -0.64% | -0.50% | -0.36% | -0.17% | 0.01% | 0.26% |
| 20 | -0.49% | -1.26% | -1.00% | -0.81% | -0.65% | -0.47% | -0.33% | -0.18% | -0.01% | 0.28% |
| 21 | -0.49% | -1.22% | -0.99% | -0.80% | -0.63% | -0.51% | -0.35% | -0.20% | -0.02% | 0.25% |
| 22 | -0.49% | -1.22% | -0.98% | -0.80% | -0.64% | -0.49% | -0.35% | -0.19% | -0.01% | 0.25% |
| 23 | -0.49% | -1.21% | -0.96% | -0.79% | -0.64% | -0.50% | -0.34% | -0.21% | -0.02% | 0.22% |
| 24 | -0.49% | -1.19% | -0.96% | -0.78% | -0.64% | -0.49% | -0.33% | -0.20% | -0.03% | 0.23% |
| 25 | -0.49% | -1.16% | -0.95% | -0.79% | -0.63% | -0.49% | -0.34% | -0.22% | -0.07% | 0.23% |
| 26 | -0.49% | -1.14% | -0.94% | -0.78% | -0.62% | -0.48% | -0.36% | -0.22% | -0.06% | 0.22% |
| 27 | -0.49% | -1.16% | -0.93% | -0.78% | -0.61% | -0.49% | -0.35% | -0.24% | -0.07% | 0.20% |
| 28 | -0.49% | -1.13% | -0.93% | -0.78% | -0.61% | -0.49% | -0.38% | -0.23% | -0.08% | 0.20% |
| 29 | -0.49% | -1.13% | -0.93% | -0.77% | -0.60% | -0.49% | -0.38% | -0.24% | -0.07% | 0.18% |
| 30 | -0.49% | -1.11% | -0.93% | -0.76% | -0.62% | -0.49% | -0.37% | -0.24% | -0.05% | 0.15% |

Table 6. Escalation rates for asphalt (reproduced from Lindsey 2011)

| Year | Mean | Percentile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| 1 | -0.46% | -3.81% | -2.58% | -1.75% | -1.08% | -0.46% | 0.16% | 0.83% | 1.65% | 2.88% |
| 2 | -0.48% | -2.92% | -1.99% | -1.46% | -0.89% | -0.41% | 0.00% | 0.42% | 1.06% | 1.88% |
| 3 | -0.48% | -2.47% | -1.74% | -1.26% | -0.84% | -0.47% | -0.08% | 0.32% | 0.79% | 1.58% |
| 4 | -0.49% | -2.32% | -1.69% | -1.22% | -0.83% | -0.44% | -0.11% | 0.24% | 0.65% | 1.26% |
| 5 | -0.49% | -2.11% | -1.54% | -1.18% | -0.85% | -0.51% | -0.17% | 0.15% | 0.54% | 1.10% |
| 6 | -0.49% | -1.86% | -1.43% | -1.11% | -0.80% | -0.53% | -0.23% | 0.10% | 0.47% | 0.95% |
| 7 | -0.49% | -1.72% | -1.37% | -1.04% | -0.76% | -0.52% | -0.24% | 0.06% | 0.39% | 0.81% |
| 8 | -0.49% | -1.64% | -1.29% | -1.02% | -0.76% | -0.49% | -0.27% | 0.03% | 0.34% | 0.73% |
| 9 | -0.49% | -1.64% | -1.24% | -0.94% | -0.70% | -0.50% | -0.28% | -0.03% | 0.27% | 0.62% |
| 10 | -0.49% | -1.59% | -1.21% | -0.93% | -0.71% | -0.48% | -0.30% | -0.06% | 0.20% | 0.57% |
| 11 | -0.49% | -1.57% | -1.18% | -0.93% | -0.70% | -0.48% | -0.29% | -0.06% | 0.21% | 0.55% |
| 12 | -0.49% | -1.51% | -1.12% | -0.90% | -0.70% | -0.49% | -0.29% | -0.08% | 0.16% | 0.44% |
| 13 | -0.49% | -1.44% | -1.11% | -0.88% | -0.69% | -0.49% | -0.29% | -0.12% | 0.13% | 0.46% |
| 14 | -0.49% | -1.39% | -1.10% | -0.85% | -0.66% | -0.50% | -0.32% | -0.13% | 0.10% | 0.42% |
| 15 | -0.49% | -1.37% | -1.05% | -0.83% | -0.66% | -0.50% | -0.33% | -0.16% | 0.10% | 0.40% |
| 16 | -0.49% | -1.33% | -1.02% | -0.82% | -0.65% | -0.48% | -0.33% | -0.18% | 0.05% | 0.36% |
| 17 | -0.49% | -1.31% | -1.03% | -0.81% | -0.63% | -0.48% | -0.33% | -0.18% | 0.02% | 0.32% |
| 18 | -0.49% | -1.30% | -1.01% | -0.80% | -0.63% | -0.49% | -0.35% | -0.17% | 0.01% | 0.27% |
| 19 | -0.49% | -1.30% | -0.98% | -0.80% | -0.64% | -0.50% | -0.36% | -0.17% | 0.01% | 0.26% |
| 20 | -0.49% | -1.26% | -1.00% | -0.81% | -0.65% | -0.47% | -0.33% | -0.18% | -0.01% | 0.28% |
| 21 | -0.49% | -1.22% | -0.99% | -0.80% | -0.63% | -0.51% | -0.35% | -0.20% | -0.02% | 0.25% |
| 22 | -0.49% | -1.22% | -0.98% | -0.80% | -0.64% | -0.49% | -0.35% | -0.19% | -0.01% | 0.25% |
| 23 | -0.49% | -1.21% | -0.96% | -0.79% | -0.64% | -0.50% | -0.34% | -0.21% | -0.02% | 0.22% |
| 24 | -0.49% | -1.19% | -0.96% | -0.78% | -0.64% | -0.49% | -0.33% | -0.20% | -0.03% | 0.23% |
| 25 | -0.49% | -1.16% | -0.95% | -0.79% | -0.63% | -0.49% | -0.34% | -0.22% | -0.07% | 0.23% |
| 26 | -0.49% | -1.14% | -0.94% | -0.78% | -0.62% | -0.48% | -0.36% | -0.22% | -0.06% | 0.22% |
| 27 | -0.49% | -1.16% | -0.93% | -0.78% | -0.61% | -0.49% | -0.35% | -0.24% | -0.07% | 0.20% |
| 28 | -0.49% | -1.13% | -0.93% | -0.78% | -0.61% | -0.49% | -0.38% | -0.23% | -0.08% | 0.20% |
| 29 | -0.49% | -1.13% | -0.93% | -0.77% | -0.60% | -0.49% | -0.38% | -0.24% | -0.07% | 0.18% |
| 30 | -0.49% | -1.11% | -0.93% | -0.76% | -0.62% | -0.49% | -0.37% | -0.24% | -0.05% | 0.15% |

In light of historic volatility in energy and commodity prices, the Office of Management and Budgets (OMB) released clarifications in regard to Circular A-94 “Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs,” which discusses the treatment of inflation in constant-dollar analyses. While the Circular does not recommend making general inflation assumptions, the Circular does permit analysts to estimate future changes in relative material prices when there is a reasonable basis (OMB 2012). The OMB indicates that these estimates may include variations in the future material prices through the use of material specific inflation rates.

A recent study sponsored by the National Asphalt Pavement Association (NAPA) describes three methods that an analyst may use to properly conduct an LCCA:

1. Conduct in today's dollars and deflate for the opportunity value of time
2. Conduct in future dollars (where available) and deflate for both opportunity value and inflation
3. Inflate today's dollars to reflect "expected future changes in relatives prices…where there is a reasonable basis," and deflate for both opportunity value and inflation (NAPA 2012).

The first method is the most common method that state DOTs use when performing an LCCA. However, this method does not account for any differences between a material's inflation rate and the general rate of inflation. As described earlier, 42 state DOTs recognize the volatility of asphalt prices; the use of price adjustment clauses in highway construction contracts demonstrates that there are significant risks associated with fluctuating asphalt prices. Method three is the only method that acknowledges variability with a material's price in the future. The historical trend of asphalt prices provides a reasonable basis for a DOT to expect a change in the relative price of asphalt in the future.

### 3.10.1 Recommendation on Material Specific Escalation Rates

The concrete industry purported that the process to account for material specific inflation is critical to ensure that all materials are analyzed fairly in an LCCA. If there is no difference between a material's inflation rate and the general inflation rate, no adjustments to the price of the materials need to be made. However, if there is a difference between a material's inflation rate and the general inflation rate, the process should account for this difference. The concrete industry research team recommended that ALDOT adopt a process to track the inflation rates of both portland cement concrete and asphalt concrete and to develop escalation rates for these materials for use in LCCAs.

The concrete industry also endorses adding a step (step 6) to the general LCCA methodology outlined by FHWA and used by ALDOT to account for material inflation:

1. Design equivalent pavement sections
2. Estimate the initial construction costs
3. Estimate the initial life of each alternative
4. Determine the maintenance and rehabilitation strategies (activities and timing) to be used on the pavement over the analysis period
5. Estimate rehabilitation costs for each activity in today's dollars
6. Escalate today's cost of the specific products to the activity year using the appropriate escalation rate and the following equation:

$$\textit{Escalated Cost} = \textit{Current Costs} * (1+e)^n$$

where $e$ = Escalation rate for the material

$n$ = number of years to the year of activity

7. Estimate user costs (optional)
8. Compute net present value (NPV) of rehabilitation costs using the discount rate
9. Analyze results (Mack 2012).

During the meeting, the asphalt industry researchers were directly opposed to the use of material specific escalation rates in the calculation of life cycle costs for asphalt. The group pointed out that the use of material specific escalation rates is not an accepted methodology in use by economists. They also noted that the inflation rates of asphalt and concrete have not differed significantly in recent decades and that the use of these escalation rates is not directly endorsed by FHWA or OMB (West et al. 2012).

One issue with the methodology of calculating future costs using material specific escalation rates is application of the rate. In the equation above, the escalation rate is applied directly to the paving cost. If, for example, the escalation rate were applied to a future rehabilitation activity such as an ACOL, the total cost of that activity would be increased by the escalation rate. Doing so falsely assumes that the cost components for labor, equipment, and markup associated with the rehabilitation activity will also increase by the same rate as the cost of the material. Using a lower escalation rate for one material and a higher rate for another material also creates a bias in this regard. The lower escalation rate assumes that the labor cost for the material, for example, will escalate at a slower rate than the labor cost of the competing material. Therefore, it is recommended that material specific escalation rates not be included in the calculation of pavement life cycle costs until further research is conducted in this area.

## 3.11 Performance Period/Rehabilitation Schedule

As noted in the analysis period section of this chapter, the performance periods are important consideration in a pavement LCCA. These periods will determine when rehabilitation activities must be commenced to maintain an acceptable level of performance, and they signify points in the pavement’s life cycle that costs will be incurred by the agency. The choice in rehabilitation activities is also an important factor in the calculation of an alternative’s life cycle costs.

The initial performance period of flexible pavements used by state highway agencies in LCCA ranges from eight to 40 years while the initial performance period of rigid pavements ranges from 15 years to 40 years (Rangaraju et al. 2008). Some states choose to utilize fixed initial performance periods for both flexible and rigid pavements regardless of pavement type or other design considerations, while other states such use variable initial performance lives based on factors such as traffic or pavement mix properties. The service lives of flexible rehabilitation measures ranged from eight to 15 years while the service lives of rigid pavement rehabilitations ranges from eight years to 21 years (Rangaraju et al. 2008). Currently, ALDOT sets the initial performance period for flexible pavements at 12 years while the initial performance period for rigid pavements is 20 years. The rehabilitation performance period in LCCAs is eight years for both flexible and rigid pavements.

### 3.11.1 Recommendations on Performance Period

During the research project, the concrete industry recommended that the initial performance period of concrete pavements and the performance periods of rehabilitation activities be modified to keep pace with advancements in materials, design methodologies, and construction methods. As shown in the literature review, there are several options available to an engineer when rehabilitating a concrete pavement. Jim Mack, an expert from the concrete pavement industry, recommended several rehabilitation activities and their performance periods that are common methods used when performing a concrete pavement LCCA. A summary of these activities is provided below.

The first set of concrete pavement preservation (CPP) activities can include full depth patching, slab replacement, diamond grinding, and cleaning and resealing joints. All or some of these activities may be included when calculating the rehabilitation costs for concrete pavements, and these activities are typically only performed on the mainline paving areas, not including the shoulders. These activities may be used up to three times (i.e. first rehabilitation, second rehabilitation, and third rehabilitation) before more extensive rehabilitation measures are needed. The typical performance lives of CPP activities are approximately ten to 15 years. Also, the lives of these activities decreases for each subsequent round of activities. The first round of CPP activities will have a longer life than the second round of activities. An outline of the first set of CPP activities is shown in Table 7.

Table 7. First set of concrete pavement preservation (CPP) activities

| First Set of Activities | | |
|---|---|---|
| **Activity** | **Expressed As** | **Notes** |
| Full Depth Patching/Slab Replacement | Percentage of pavement surface area | First CPP – 5 percent<br>Second CPP – 8 percent<br>Third CPP – 10 percent |
| Diamond Grinding | Percentage of pavement surface area | Typically 100 percent of pavement surface area |
| Clean and Reseal Joints | Length of joints | Typically all transverse and longitudinal joints |

The main activity in the second set of activities includes asphalt concrete overlays (ACOL) of the concrete pavement. These overlays are typically two or more inches thick and occur after the second or third round of CPP activities and are performed on both the mainline pavement and shoulders areas. Depending on the condition of the concrete pavement, some full depth patching may be necessary before the ACOL is applied. The performance life of these activities ranges from ten to 15 years. Other rehabilitation options, such as bonded and unbonded concrete overlays of the original concrete pavement, are listed in Table 8.

Table 8. Additional second set of activities for concrete rehabilitation

| Additional Second Set of Activities | | |
|---|---|---|
| **Activity** | **Method** | **Typical Performance Life** |
| Rubbilize concrete pavement and ACOL | Breaking the concrete into small pieces in place and overlaying with a 2” to 10” thick ACOL over 100 percent of the surface | Essentially a form of reconstruction with a performance life similar to that of a new asphalt pavement |

Table 8. Additional second set of activities for concrete rehabilitation

| | | |
|---|---|---|
| | Rubbilized concrete pavement acts as a high quality base | |
| Unbonded Concrete Overlay | Placing a 1” to 2” thick ACOL over 100 percent of the surface and then placing a 4” to 10” thick concrete overlay on top | Essentially a form of reconstruction with a life as long or longer than a new concrete pavement |
| Bonded Concrete Overlay | Shot blasting 100 percent of the pavement surface and repairing distress slabs with full depth repair (typically 3 to 5 percent of joints) and then placing a 2” to 4” concrete overlay | Hard to determine – may require extensive engineering analysis |

The researchers at Auburn University also felt that the performance periods currently used by ALDOT during a pavement LCCA were too short and that advancements in asphalt mix materials and design have allowed asphalt pavements to last longer before rehabilitation was needed. Based on data from within the state of Alabama, Missouri, and Florida, they recommend that the initial performance period be set at 19 years for interstate and freeways and 21 years for other pavements such as United State highways and state routes. The researchers also recommended that the performance period of overlays be set at 13.5 years for all roadways (West et al. 2012f)

Under ALDOT’s current LCCA procedure, when an asphalt pavement is rehabilitated for the first time, the wearing surface layer is completely milled away and replaced with a new wearing surface. The second rehabilitation requires that the wearing surface layer and the upper binder layer be removed and replaced. The asphalt industry did not provide any changes to this methodology. Therefore, it is recommended that this rehabilitation schedule of activities be maintained when performing asphalt LCCAs.

Based on the input from both pavement industries, it is recommended that the aforementioned rehabilitation schedules be utilized when calculating the life cycle costs for both pavement alternatives. Although both industries wanted to increase the performance lives in the calculation of life cycle costs, until reliable data is available for the performance lives of the initial construction of both pavements and rehabilitations in the state of Alabama, it is recommended that the current initial performance periods and the performance periods be kept for all pavement LCCAs.

## 3.12 Specifications Issues

During the LCCA research project, the concrete pavement industry expressed concerns with the current ALDOT specifications for highway construction. They felt that the current specifications created a bias in favor of the asphalt industry and did not allow concrete paving contractors to be competitive with asphalt paving contractors. Possible inequities highlighted during the project included testing requirements, incentive/disincentives, and coarse aggregate specifications.

The inequalities in pavement specifications may directly or indirectly affect the cost of concrete paving and may create unfairness conditions that could ultimately influence the life cycle costs of concrete pavements. An example of a specification having a direct influence on the cost of concrete paving is the coarse aggregate specification. Limestone, a common coarse aggregate in the state of Alabama, is disallowed in the concrete mix for mainline or ramp pavements. Therefore, if an acceptable coarse aggregate alternative is not located near the project location, the paving contractor may have to transport the coarse aggregate that meets the specifications from a greater distance, adding to the material cost of the project.

The specifications may also create an indirect influence on concrete paving costs. If the concrete paving contractors perceive that the specifications and requirements concerning concrete pavement are unduly strict for items such as thickness testing or rideability they may add a premium to cover any additional risks they anticipate during the construction of the roadway. If historical data is used to estimate construction costs for the LCCA calculations, any costs for past projects that have been adjusted for biased specifications (actual or perceived) may not represent an accurate estimation of concrete paving costs. It is recommended that these specifications be reviewed for fairness. However, any recommendations on changes to these specifications are not directly related to LCCA procedures for pavement type selection and are not within the scope of this research effort.

### 3.13 Pavement Design

The design of each pavement alternative will have a significant bearing on the LCCA. The thickness of the material will determine how much of the paving material is needed to construct the roadway as well as the initial performance of the pavement system and the performance lives of the rehabilitations. Several pavement design guidelines are used by state DOTs. According to the Rangaraju survey, state highway agencies use the 1972, 1986, 1993, and 1998 versions of AASHTO design guidelines (Rangaraju et al. 2008). Several states utilize a design guideline developed for their state or a combination of the AASHTO guidelines and the state design pavement design. Approximately 50 percent of the responding state highway agencies utilize the 1993 AASHTO guidelines when designing asphalt pavements while approximately 32 percent of the respondents indicated that they use AASHTO 1993 when designing rigid pavements (Rangaraju et al. 2008). Currently, ALDOT uses the 1993 AASHTO guidelines and DARWin 3.1 when designing both asphalt and concrete pavement alternatives.

The latest edition of the AASHTO design guidelines is the Mechanistic Empirical Pavement Design Guide (MEPDG). This iteration contains both mechanistic and empirical properties that allow a pavement designer to generate initial construction and rehabilitation designs based on detailed traffic loadings, pavement structure, material properties, and climatic conditions (Baus and Stires 2010; McDonald and Madanat 2012). The design process is intended to be iterative, allowing the design to develop trial pavement structures that are analyzed against designated performance criteria. The latest release in the DARWin series, DARWin-ME, facilitates the use of MEPDG guidelines. Several states, including Florida, Indiana, Montana, and North Carolina have implemented MEPDG and have conducted research on the effectiveness of the design guideline (Baus and Stires 2010).

### 3.13.1 Recommendations on Pavement Design

Due to advancements in pavement design guidelines and software, the concrete pavement industry recommended that the transition be made to MEPDG and DARWin-ME software. They indicated that using MEPDG would allow engineers to design a pavement that matches a desired level of performance. They also stated that state DOTs that have used the software for rigid pavement design found that the default conditions within DARWin-ME were fairly accurate and that little calibration was needed. To facilitate the design of better pavements in terms of cost and performance, the asphalt industry also recommended that DARWin-ME be used in the future. Before it is implemented, they recommended that ALDOT calibrate the procedure for local conditions and that state personnel that will use the software be properly trained in the use of the software and the proper inputs for pavement design in the state of Alabama (West et al. 2012g).

It is recommended that ALDOT begin the transition to MEPDG design guidelines and the use of DARWin-ME software when designing both pavements. Before they are fully adopted, it is advised that the models are calibrated for the state of Alabama and that the anticipated performance characteristics produced by the software are verified with real world applications.

## 3.14 LCCA Software

Due to the effectiveness of life cycle analyses in assisting in the decision making process for the best pavement alternatives for a given new construction or rehabilitation project, several computer software programs have been created to assist state agencies in determining the correct values for components in the analysis and running simulations. One of the main advantages of these programs is that they aid the designer in the calculation of the life cycle costs and organizes the costs in a user-friendly format that allows for comparisons between the alternatives to be made efficiently.

One such program is the DARWin pavement design software developed by AASHTO in 1991. This program is based off the pavement design guidelines generated by AASHTO and allows for both flexible and rigid pavement to be designed with the software. The life cycle cost module is an analytical tool built into the main program, and this feature allows the designer to include initial construction costs, maintenance costs, rehabilitation costs, and salvage value costs. The analysis can be performed using the NPV or EUAC evaluation techniques. The latest version of the software is based upon the mechanical-empirical design guide; adjustable factors within the program, such as traffic, materials, and climate information, allows for reliable estimates of pavement performance and the timing of rehabilitation actions.

Another popular life cycle cost software program is RealCost. Developed by FHWA and based off their LCCA best practices, this program is solely dedicated to helping the decision maker calculate life cycle costs for the pavement alternatives. One asset of the program is that it allows the user to choose between a deterministic or probabilistic approach. The probabilistic approach within the software permits the use of Monte Carlo simulation techniques that allows for user adjustment of the parameters within the simulation including probability distributions and the number of iterations the simulator will run. These simulations will provide the agency conducting the analysis a model of the uncertainty associated with key input parameters such as discount rate, analysis period, and timing of rehabilitation activities. The decision maker may also choose to let the program calculate user costs incurred during work zones periods; the work zone user costs are calculated from input traffic data the decision maker has gathered for the project area.

Approximately half of the state transportation agencies utilize some form of life cycle cost software to conduct their analyses (ACPA 2012). Several states, such as Alabama, Colorado, and Montana, use standard releases of DARWin or RealCost software to calculate costs associated with each pavement alternative. However, several states have modified existing programs or created their own LCCA programs to suit their state's own specific pavement selection making needs. The Idaho DOT, for example, has developed an Excel-based program that is tailored to the state's specific conditions; the software package has the ability to display pavement rehabilitation actions but is not set up to include user costs within the analysis (Lamptey 2005). Industry organizations such as the Asphalt Institute and the ACPA have also created LCCA software packages to be used by paving contractors and state transportation agencies (Lamptey 2005).

### 3.14.1 Recommendations on LCCA Software

Currently, ALDOT uses DARWin Version 3.1 software to calculate the life cycle costs of asphalt and concrete pavement alternatives. The concrete industry recommended that RealCost software be used by the agency; the asphalt industry did not provide a recommendation on the software ALDOT should use during the analysis. Based on this research, it is recommended that ALDOT begin to transition to RealCost so that a probabilistic analysis of each alternative is possible. However, since RealCost does not permit an item-by-item probabilistic analysis of unit costs, it is also recommended that ALDOT develop a program outside of RealCost so that the initial construction costs and rehabilitation costs can be modeled and analyzed stochastically.

## 3.15 Summary and Recommendations

During the research project, the research teams representing the asphalt and concrete pavement industries were only able to reach an agreement on one LCCA factor: discount rate. Both sides agreed that the 30-year real discount rate published by OMB should be used in all LCCA calculations; while both sides agreed to the 30-year real discount rate, the asphalt industry recommended that a moving average be used to determine the actual value to be used in the analysis and the concrete industry accepted that recommendation. The two sides also suggested that changes be made to the analysis period and discount rate. The asphalt and concrete pavement industry both agreed that the analysis period should be increased due to longer lasting pavements. Both groups also agreed that the 30-year OMB real discount rate be used in calculating the discount rate. However, the two sides had completely opposite views on the inclusion of price adjustment clauses when calculating initial construction costs and material specific escalation rates. The concrete pavement industry lobbied for their inclusion in the pavement type LCCA while the asphalt researchers were vehemently opposed to those two factors.

This research objective sought to make recommendations on the LCCA procedure used during the pavement type selection process. Based on a review of pavement LCCA procedures and the discussions between the asphalt and concrete pavement industries during the LCCA project, several recommendations were made concerning factors and values to be used in a pavement LCCA. Summaries of these recommendations are shown in Table 9. However, further research is needed for some factors, such as material specific escalation rates, before they are considered for included in the pavement LCCA process. Since equality is the key to an accurate interpretation of the LCCA results between asphalt and concrete pavements, any potential bias or inequity in regards to the LCCA procedure, design requirements, and construction specifications should also require further investigation so that fair treatment is given to both materials and accurate economic and engineering decisions are made during the pavement type selection process.

Table 9. Summary of LCCA recommendations

| Factors | Current ALDOT Pavement LCCA Procedure | Asphalt Pavement Industry Recommendation | Concrete Pavement Industry Recommendation | Recommended Pavement LCCA Procedure |
|---|---|---|---|---|
| *Trigger to Conduct LCCA* | Flexible pavement structural number of 6.0 or higher | $3,000,000 trigger should not be used | All paving projects with a cost greater than $3,000,000 | More research is needed to determine the number of projects that would require an LCCA based on factors such as project cost, network level, traffic, and project location. |
| *Agency Costs* | Construction costs only (initial and rehabilitation costs) | Does not recommend including engineering and construction management costs in LCCA until more research is conducted | Include administrative, design/engineering, and construction management costs | Construction costs plus administrative, design/engineering, and construction management costs |
| *User Costs* | Not considered | Only consider when the NPV of the alternatives are within ten percent of each or when projects will require lengthy lane closures | Consider when projects are within ten percent of each other and should include vehicle operating costs during normal operation of highway | Use user costs as a "tie-breaker" when the NPV of the pavement alternatives is within ten percent of each other.<br>Calculate user delay costs and vehicle operating costs during construction and pavement rehabilitation activities. |
| *Analysis Period* | 28 years | 35 years | 40 to 50 years | 40 to 45 years |
| *Discount Rate* | Four percent | Ten year moving average of OMB 30-year real discount rate | OMB 30-year real discount rate | Use ten year rolling average of OMB 30-year real discount rate |
| *Salvage Value* | Not considered | Residual value and remaining service life | Remaining service life only | Calculate the remaining service life of a pavement alternative using the straight-line depreciation method (no residual value) |
| *Approach to LCCA* | Deterministic | Did not provide a recommendation | Probabilistic | Probabilistic |
| *Price Adjustment Clause* | Not considered when calculating initial construction costs | ALDOT should continue to use PACs but should not account for them in LCCA | Account for PAC during pavement LCCA | Adjust the initial construction costs to account for any trends in real price |
| *Material Specific Escalation Rates* | Not considered in LCCA calculations | Should not be used in LCCA | Use for both asphalt and concrete costs during LCCA | Not recommended for use until further research is conducted |
| *LCCA Software* | DARWin 3.1 Pavement Design and Analysis System | Did not provide a recommendation | RealCost | RealCost with Excel based spreadsheet that allows for probabilistic model for individual pay items |

# CHAPTER IV

# SENSITIVITY OF LIFE CYCLE COSTS TO PRICE ADJUSTMENT CLAUSES WHEN USED IN A PROBABILISTIC LIFE CYCLE COST ANALYSIS

## 4.1 Introduction

While the calculation of life cycle costs during the pavement type selection process provides the analyst a means to compare two competing alternatives, the values of key factors used in the analysis can have a large effect on life cycle costs. Depending on the rehabilitation structure and other facets of the analysis, the change in one of these values may affect the life cycle cost of one alternative more than the other. To identify these factors and the values that have an effect on the total life cycle costs, a sensitivity analysis on the deterministic model was conducted on an example LCCA project conducted by ALDOT. A probabilistic analysis of the example project was also conducted to examine the effect that overestimation and underestimation of the initial construction cost of the asphalt alternative could have on the difference between the concrete and asphalt total life cycle cost.

## 4.2 Sample Paving Project for LCCA

To run a sensitivity analysis on the LCCA for the original process currently used by ALDOT and the procedure recommended in the previous chapter, an example paving project was needed to provide the quantities of materials needed during initial construction and each rehabilitation cycle as well as the unit prices for the individual pay items used during construction. The example project chosen for this research objective is a pavement reconstruction project on Interstate 65 in Jefferson County, Alabama. This paving project is approximately two miles in length and starts at the interchange with Interstate 459 (at Exit 250) and ends at the interchange US-31 (at Exit 252) near Hoover, Alabama. The current pavement system on this stretch of roadway is an eight inch thick CRCP.

Since this project was located on a major Interstate highway in an urban area, several entrance and exit ramps were included in the paving project. Within the project limits, the Interstate is a four lane divided roadway that transitions into three lanes and features six entrance and exit ramps. To accommodate future traffic lanes, the inside and outside shoulders on the Interstate segment of the project were designed with full depth buildups to meet future traffic demands. To facilitate the calculation of the life cycle costs for both alternatives, the paving project was divided up into ten sections. A summary of these sections and the widths of the inside shoulder, outside shoulder, and traffic lanes are provided in Table 10.

Table 10. Summary of project sections

| **Section** | **Lanes** | **Length (mi)** | **Inside Shoulder Width (ft)** | **Outside Shoulder Width (ft)** | **Total Traffic Lane Width (ft)** |
|---|---|---|---|---|---|
| I-65 Four Lane Southbound | 4 | 1.056 | 15 | 12 | 48 |
| I-65 Four Lane Northbound | 4 | 1.056 | 15 | 12 | 48 |
| I-65 Three Lane Southbound | 3 | 0.667 | 15 | 12 | 36 |
| I-65 Three Lane Northbound | 3 | 0.667 | 15 | 12 | 36 |
| Ramp A (I-65 SB to I-459 SB) | 2 | 0.379 | 4 | 12 | 24 |
| Ramp A1 (I-65 SB to I-459 SB) | 1 | 0.145 | 12 | 10 | 15 |
| Ramp B (I-65 SB to I-459 SB) | 2 | 0.176 | 4 | 10 | 24 |
| Ramp C (I-459 SB to I-65 SB) | 2 and 3 | 0.371 | 4 | 12 | 24 and 36 |
| Ramp D (I-65 NB to US 31) | 2 | 0.222 | 4 | 5 | 24 |
| Ramp E (US 31 to I-65 NB) | 2 | 0.152 | 4 | 5.5 | 24 |

The flexible pavement design for this project was based on rubbilizing the existing CRCP and overlaying it with HMA. Excluding the CRCP and the base materials underlying it, the design called for a total required HMA thickness of 16.25 inches for the four lane and three lane sections of the Interstate. At each of the entrance and exit ramps, the total required HMA thickness was 13.1 inches. The rigid pavement design called for a PCCP overlaying the rubblized CRCP. The design of the concrete pavement consisted of 16 inch PCCP slab with a six inch HMA layer between the new pavement and the rubblized CRCP. All pavement designs were conducted using DARWin pavement design software using 2010 as the base year for traffic calculations and the initial construction year.

Given the current LCCA procedure used by ALDOT, at years 12 and 20, the asphalt pavement alternative requires rehabilitative measures. The rehabilitation at year 12 calls for the wearing surface layer to be milled and replaced, but at year 20, both the wearing surface and upper binder layers are milled up and replaced. For this project, the first rehabilitation required that the 1.4 inch wearing surface be milled and replaced while the second rehabilitation required that the 1.4 inch wearing surface layer and the 2.7 inch upper binder layer be milled and replaced. The concrete alternative only required one rehabilitation cycle at year 20. This rehabilitation consists of cleaning and sealing the joints in the concrete pavement.

The life cycle costs of the asphalt and concrete pavement alternatives were calculated using a 28-year analysis period and a four percent real discount rate. No user costs were calculated for this project. Also, due to the similarity in cost for both alternatives, the costs associated with the rubbilization of the existing CRCP and preliminary earthwork, construction of temporary traffic lanes for traffic control, and the construction of a concrete median safety barrier were excluded from the analysis.

The total life cycle cost of the asphalt alternative for this project was calculated to be $12,228,658. The total cost included the initial construction costs of the asphalt overlay as well as the two rehabilitations of the HMA pavement. A summary of the initial construction costs and rehabilitation costs for the asphalt alternative is shown in Table 11, and an expenditure stream of the non-discounted agency costs for the asphalt alternative is shown in Figure 11.

Table 11. Life cycle costs for asphalt alternative

| **Section** | **Initial Construction Cost** | **Rehab Cost #1** | **NPV Rehab Cost #1** | **Rehab Cost #2** | **NPV Rehab Cost #2** |
|---|---|---|---|---|---|
| I-65 Four Lane SB | $ 2,765,327 | $ 322,530 | $ 201,452 | $ 804,802 | $ 367,312 |
| I-65 Four Lane NB | $ 2,792,360 | $ 331,131 | $ 206,824 | $ 825,895 | $ 376,938 |
| I-65 Three Lane SB | $ 1,588,632 | $ 184,710 | $ 115,370 | $ 461,716 | $ 210,727 |
| I-65 Three Lane NB | $ 1,464,734 | $ 206,441 | $ 128,943 | $ 435,069 | $ 198,565 |
| Ramp A | $ 394,184 | $ 53,296 | $ 31,011 | $ 154,739 | $ 70,623 |
| Ramp A1 | $ 140,140 | $ 18,581 | $ 11,606 | $ 53,562 | $ 24,446 |
| Ramp B | $ 177,311 | $ 23,869 | $ 14,909 | $ 67,872 | $ 30,977 |
| Ramp C | $ 391,881 | $ 52,865 | $ 33,019 | $ 150,283 | $ 68,589 |
| Ramp D | $ 199,028 | $ 26,256 | $ 16,399 | $ 75,811 | $ 34,600 |
| Ramp E | $ 135,700 | $ 17,902 | $ 11,182 | $ 51,689 | $ 23,591 |
| | **$ 10,049,297** | $ 1,237,581 | **$ 770,716** | $ 3,081,438 | **$ 1,406,368** |

**LIFE CYCLE COST = $12,228,658**

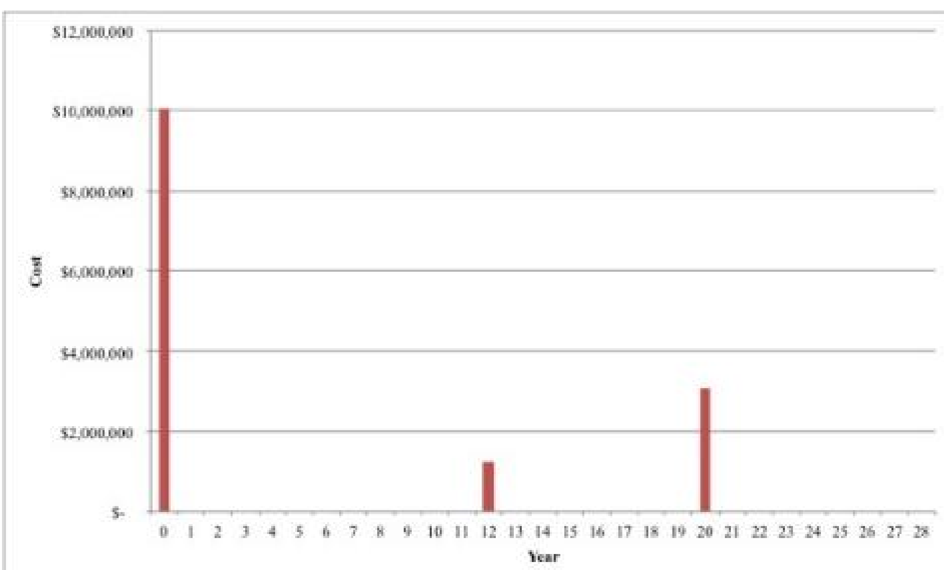



Figure 11. Asphalt pavement alternative expenditure stream

The total life cycle cost of the concrete pavement alternative was $12,467,483. This total includes the initial construction cost of the concrete pavement and the rehabilitation cost at year 20. A breakdown of the total life cycle costs for the concrete alternative is provided in Table 12. An expenditure stream for the concrete pavement alternative is shown in Figure 12.

Table 12. Life cycle costs for concrete alternative

| **Section** | **Initial Construction Cost** | **Rehab Cost #1** | **NPV Rehab Cost #1** |
|---|---|---|---|
| I-65 Four Lane SB | $ 3,222,854 | $ 197,725 | $ 90,242 |
| I-65 Four Lane NB | $ 3,222,854 | $ 197,725 | $ 90,242 |
| I-65 Three Lane SB | $ 1,715,665 | $ 102,280 | $ 46,681 |
| I-65 Three Lane NB | $ 1,715,665 | $ 102,280 | $ 46,681 |
| Ramp A | $ 625,784 | $ 31,173 | $ 14,227 |
| Ramp A1 | $ 221,448 | $ 25,429 | $ 11,606 |
| Ramp B | $ 279,916 | $ 14,496 | $ 6,616 |
| Ramp C | $ 613,060 | $ 30,539 | $ 13,938 |
| Ramp D | $ 304,990 | $ 18,290 | $ 8,348 |
| Ramp E | $ 210,976 | $ 12,471 | $ 5,692 |
| | **$ 12,133,212** | $ 732,417 | **$ 334,266** |

**LIFE CYCLE COST = $12,467,478**

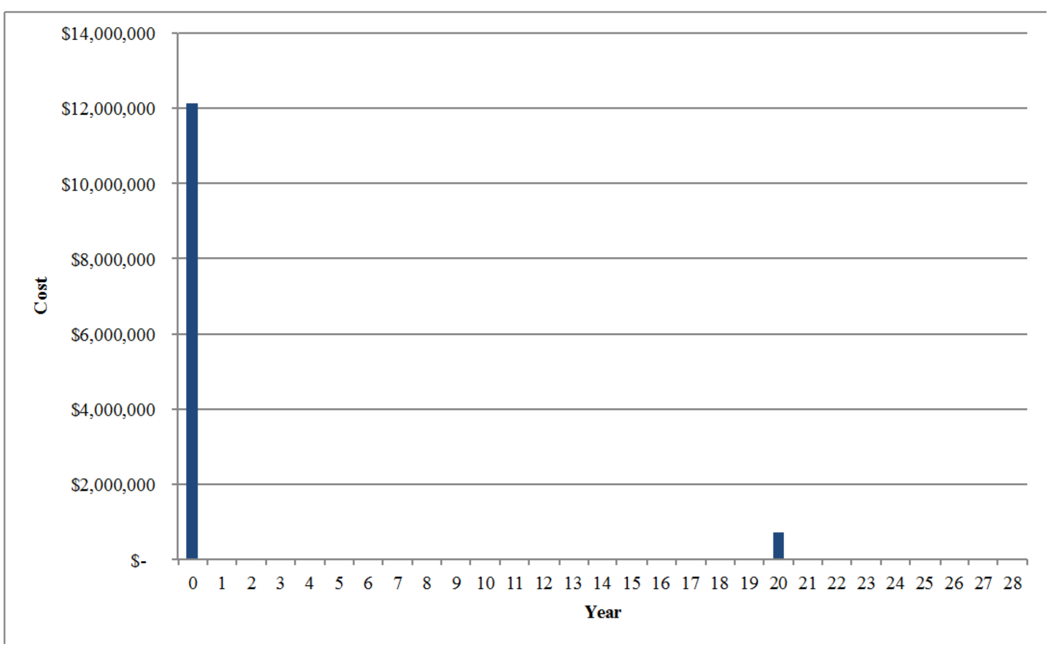



Figure 12. Concrete pavement alternative expenditure stream

Using the current LCCA procedure in use by ALDOT, the difference in life cycle cost between the asphalt alternative and the concrete alternative was $238,825, or 1.93 percent.

### 4.3 Sensitivity Analysis of Original Pavement LCCA

The first factor used in the sensitivity analysis of the LCCA for the paving project was the discount rate. The discount rate used in the LCCA calculations was varied from one percent to seven percent in one percent increments for both alternatives. The total life cycle costs for the asphalt and concrete pavement alternatives with varying discount rates are shown in Table 13. A graphical representation of these costs is shown in Figure 13.

Table 13. Discount rate sensitivity analysis

| **ASPHALT ALTERNATIVE** | | | | |
|---|---|---|---|---|
| **Discount Rate** | **Initial Construction Cost** | **NPV Rehab #1 (Year 12)** | **NPV Rehab #2 (Year 20)** | **LIFE CYCLE COST** |
| 1 | $10,049,297 | $1,098,290.30 | $2,525,375.47 | $13,672,963 |
| 2 | $10,049,297 | $975,824.17 | $2,073,719.44 | $13,098,841 |
| 3 | $10,049,297 | $868,014.41 | $1,706,117.51 | $12,623,429 |
| 4 | $10,049,297 | $772,989.44 | $1,406,328.08 | $12,228,615 |
| 5 | $10,049,297 | $689,131.41 | $1,161,361.57 | $11,899,790 |
| 6 | $10,049,297 | $615,039.84 | $960,806.93 | $11,625,144 |
| 7 | $10,049,297 | $549,500.76 | $796,302.14 | $11,395,100 |

| **CONCRETE ALTERNATIVE** | | | | |
|---|---|---|---|---|
| **Discount Rate** | **Initial Construction Cost** | **NPV Rehab #1 (Year 12)** | **NPV Rehab #2 (Year 20)** | **LIFE CYCLE COST** |
| 1 | $12,133,212 | N/A | $600,248.34 | $12,733,460 |
| 2 | $12,133,212 | N/A | $492,895.68 | $12,626,108 |
| 3 | $12,133,212 | N/A | $405,521.56 | $12,538,734 |
| 4 | $12,133,212 | N/A | $334,265.58 | $12,467,478 |
| 5 | $12,133,212 | N/A | $276,040.28 | $12,409,252 |
| 6 | $12,133,212 | N/A | $228,371.10 | $12,361,583 |
| 7 | $12,133,212 | N/A | $189,270.48 | $12,322,482 |

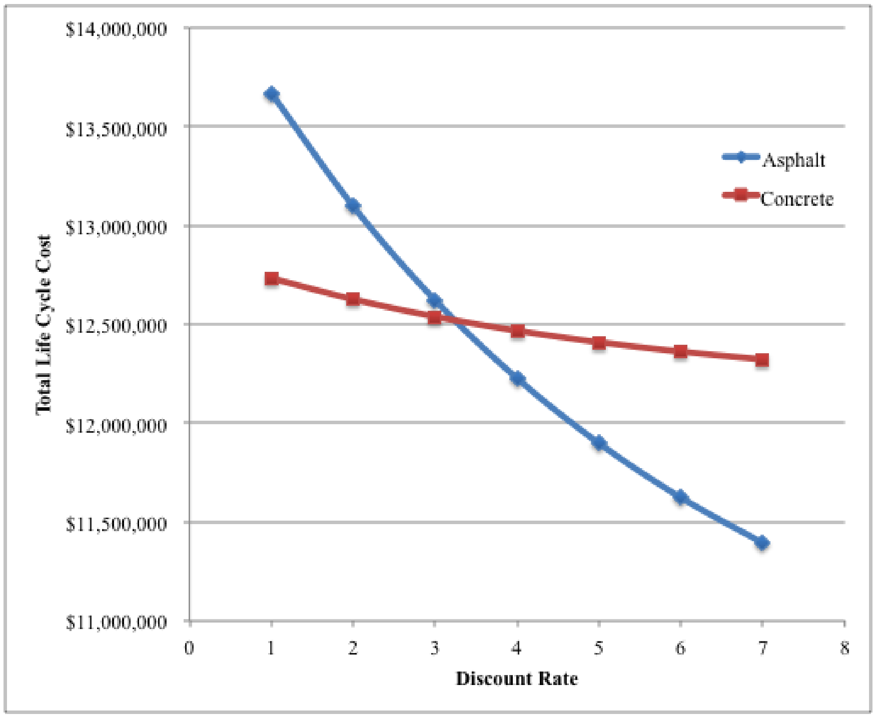


Figure 13. Life cycle costs with various discount rates

From Figure 13, it can be seen that as the discount rate increases, the total life cycle cost of both alternatives decrease. It is also shown that as the discount rate increases, its influence on the total life cycle cost of the asphalt alternative is pronounced when compared to the concrete alternative. A discount rate of seven percent results in the total life cycle cost of the asphalt alternative equaling $927,382 lower than the concrete pavement alternative. From the graph, the break-even point (the discount rate at which the total life cycle cost for both alternatives are equal) is approximately 3.25 percent. At discount rates lower than 3.25 percent, the concrete alternative has the lower total life cycle cost between the two pavement alternatives.

The next factor in the sensitivity analysis was the analysis period. To examine the life cycle cost of each pavement alternative past the 28-year mark, an extended rehabilitation schedule had to be created, but when the schedule was created, some general assumptions were made about the pavement alternatives. The first assumption is that the initial pavement designs for both alternatives have design lives that equal at least 50 years. Doing so ensures that both alternatives will last at least 50 years before needing reconstruction. Another assumption made was the rehabilitation schedule chosen and the activities performed during those rehabilitations. All asphalt and concrete pavement rehabilitations were assumed to have an eight-year performance period regardless of the activities performed. Since the end of the pavement performance periods may not coincide with the end of an analysis period, the remaining service life of each alternative was calculated using straight-line depreciation.

To examine the influence of varying analysis periods on the asphalt pavement alternative, three additional rehabilitation measures were assumed at years 28, 36, and 44. The rehabilitation at year 28 (third asphalt rehabilitation) consisted of milling the wearing surface and upper binder layers and replacing with new material. The fourth and fifth asphalt rehabilitations required that the 1.4 inch wearing surface, 2.7 inch upper binder layer, and the top layer (2.7 inch) of the lower binder layer be milled and replaced. The quantity of the top layer of the lower binder needed during the rehabilitation was assumed to be the quantity of material for that layer needed during the initial construction of the asphalt pavement system. Also, since the cost of milling for the fourth and fifth rehabilitations was not provided in the example LCCA, this value was calculated by adding the difference in cost between the 1.4 inch milling in the first rehabilitation and the 4.1 inch milling in the second and third rehabilitations to the $2.90/square yard unit cost for milling 4.1 inches of asphalt. The rehabilitation schedule, a breakdown of cost for each pay item used, and the non-discounted total rehabilitation costs are provided in Table 14.

Table 14. Asphalt rehabilitation schedule

| ASPHALT REHABILITATION #3 (Year 28) | | | | |
|---|---|---|---|---|
| *Activity: Mill and replace wearing surface (1.4") and upper binder layer (2.7")* | | | | |
| **Pay Item Description** | **Unit Cost** | **Unit** | **Quantity** | **COST** |
| Milling (4.1") | $2.90 | sq yd | 183,214 | $531,321 |
| SMA WS, 1/2" Max Agg | $75.69 | ton | 11,334 | $857,870 |
| SMA UB, 1" Max Agg | $55.00 | ton | 22,457 | $1,235,135 |
| SuperPave WS, 1/2" Max Agg | $62.60 | ton | 2,517 | $157,564 |
| SuperPave LB, ESAL-E | $60.00 | ton | 4,998 | $299,880 |
| | | | **TOTAL =** | **$3,081,770** |

| ASPHALT REHABILITATION #4 (Year 36) | | | | |
|---|---|---|---|---|
| *Activity: Mill and replace wearing surface (1.4"), upper binder (2.7"), and top of lower binder (2.7")* | | | | |
| **Pay Item Description** | **Unit Cost** | **Unit** | **Quantity** | **COST** |
| Milling (6.8") | $4.74 | sq yd | 183,214 | $868,434 |
| SMA Wear Surf, 1/2" Max Agg | $75.69 | ton | 11,334 | $857,870 |
| SMA UB, 1" Max Agg | $55.00 | ton | 22,457 | $1,235,135 |
| SuperPave WS, 1/2" Max Agg | $62.60 | ton | 2,517 | $157,564 |
| SuperPave LB, ESAL-E | $60.00 | ton | 28,004 | $1,680,240 |
| SuperPave LB, ESAL-C/D | $56.56 | ton | 4,925 | $278,558 |
| | | | **TOTAL =** | **$5,077,802** |

| ASPHALT REHABILITATION #5 (Year 44) | | | | |
|---|---|---|---|---|
| *Activity: Mill and replace wearing surface (1.4"), upper binder (2.7"), and top of lower binder (2.7")* | | | | |
| **Pay Item Description** | **Unit Cost** | **Unit** | **Quantity** | **COST** |
| Milling (6.8") | $4.74 | sq yd | 183,214 | $868,434 |
| SMA Wear Surf, 1/2" Max Agg | $75.69 | ton | 11,334 | $857,870 |
| SMA UB, 1" Max Agg | $55.00 | ton | 22,457 | $1,235,135 |
| SuperPave WS, 1/2" Max Agg | $62.60 | ton | 2,517 | $157,564 |
| SuperPave LB, ESAL-E | $60.00 | ton | 28,004 | $1,680,240 |
| SuperPave LB, ESAL-C/D | $56.56 | ton | 4,925 | $278,558 |
| | | | **TOTAL =** | **$5,077,802** |

After the first rehabilitation of the concrete pavement alternative at year 20, three additional rehabilitations at year 28, 36, and 44 were created so that the influence the analysis period has on the total life cycle cost of the concrete alternative could be examined. The rehabilitation at year 28 (second concrete rehabilitation) required that the pavement joints be cleaned and refilled, patching, and diamond grinding of the pavement surface. For this rehabilitation, three percent of the pavement surface area was assumed to need patching while the entire surface would require diamond grinding. The third concrete pavement rehabilitation called for the same activities as the second concrete rehabilitation except that this rehabilitation assumed that five percent of the total pavement surface area would require patching instead of three percent. The final concrete rehabilitation at year 44 required that the joints of the pavement be cleaned and filled before an ACOL over the entire pavement surface was constructed.

Several assumptions were made concerning the cost of the concrete pavement rehabilitation activities. Because the LCCA example project had different unit costs for the joint cleaning and filling activity for the different sections of the project, the same cost of the joint cleaning and filling was used for each rehabilitation cycle. Also, since the original LCCA stopped at year 28, unit cost data was not provided in the example project for the concrete patching and diamond grinding activities used in the second and third rehabilitations. Historical data from OMAN Systems, Inc. Bid Tabs Professional cost database was used to determine the cost of these activities. The unit costs of the patching and diamond grinding activities were calculated by averaging the bid costs using data from projects let from 2005 to 2010 and that required a similar number of units. Another assumption was made concerning the quantity of material needed during the ACOL during the fourth concrete pavement rehabilitation. The quantities used in calculating the cost was the same quantity used in the asphalt rehabilitations since the thickness of material needed were equal. A summary of the concrete pavement rehabilitation schedule and the costs of each rehabilitation activity are provided in Table 15.

Table 15. Concrete rehabilitation schedule

| **CONCRETE REHABILITATION #2 (Year 28)** | | | | |
|---|---|---|---|---|
| *Activity: Clean and fill joints, full depth patching (3% of total pavement surface area), and diamond grinding* | | | | |
| **Pay Item Description** | **Unit Cost** | **Unit** | **Quantity** | **COST** |
| Clean and Fill Joints | - | - | - | $732,417 |
| Full Depth Patching (3% Pavement Surface) | $104.66 | sq yd | 5,225 | $546,880 |
| Diamond Grinding (Total Surface) | $2.52 | sq yd | 174,178 | $438,929 |
| | | | **TOTAL =** | **$1,718,226** |

| **CONCRETE REHABILITATION #3 (Year 36)** | | | | |
|---|---|---|---|---|
| *Activity: Clean and fill joints, full depth patching (5% of total pavement surface area), and diamond grinding* | | | | |
| **Pay Item Description** | **Unit Cost** | **Unit** | **Quantity** | **COST** |
| Clean and Fill Joints | - | - | - | $732,417 |
| Full Depth Patching (5% Pavement Surface) | $104.66 | sq yd | 8,709 | $911,505 |
| Diamond Grinding (Total Surface) | $2.52 | sq yd | 174,178 | $438,929 |
| | | | **TOTAL =** | **$2,082,850** |

Table 15. Concrete rehabilitation schedule

| CONCRETE REHABILITATION #4 (Year 44) | | | | |
|---|---|---|---|---|
| *Activity: Clean and fill joints then an asphalt overlay (2.7" binder layer and 1.4" wearing surface layer) for entire pavement surface* | | | | |
| **Pay Item Description** | **Unit Cost** | **Unit** | **Quantity** | **COST** |
| Clean and Fill Joints | - | - | - | $732,417 |
| SMA Wear Surf, 1/2" Max Agg | $75.69 | ton | 11,334 | $857,870 |
| SMA UB, 1" Max Agg | $55.00 | ton | 22,457 | $1,235,135 |
| SuperPave Wear Surf, 1/2" Max Agg | $62.60 | ton | 2,517 | $157,564 |
| SuperPave LB, ESAL-E | $60.00 | ton | 4,998 | $299,880 |
| | | | **TOTAL =** | **$3,282,867** |

The first sensitivity analysis of the analysis period was conducted with the real discount rate set at four percent. The life cycle costs for each pavement alternative were calculated for analysis periods at five-year increments ranging from 20 years to 50 years. A table showing the life cycle cost for each alternative at each analysis period is shown in Table 16 and a graph showing the life cycle cost for each material at a given analysis period is provided in Figure 14. From the graph it can be seen that at a 20-year analysis period, the asphalt alternative is lower than the concrete alternative while with a 50-year analysis period the asphalt alternative is higher than the concrete alternative. With an analysis period of approximately 32 years and the discount rate fixed at four percent the two pavement alternatives are approximately equal. It can be seen that the life cycle cost of the asphalt alternative for this project is more sensitive to a change in analysis period than the concrete alternative.

Table 16. Life cycle cost for varying analysis periods (four percent discount rate

| **Analysis Period** | **ASPHALT LIFE CYCLE COST** | **CONCRETE LIFE CYCLE COST** |
|---|---|---|
| 20 | $10,822,286 | $12,133,212 |
| 25 | $11,795,152 | $12,364,449 |
| 30 | $12,543,656 | $12,643,146 |
| 35 | $13,158,594 | $12,986,039 |
| 40 | $13,964,681 | $13,331,075 |
| 45 | $14,636,943 | $13,640,726 |
| 50 | $15,218,963 | $14,017,010 |

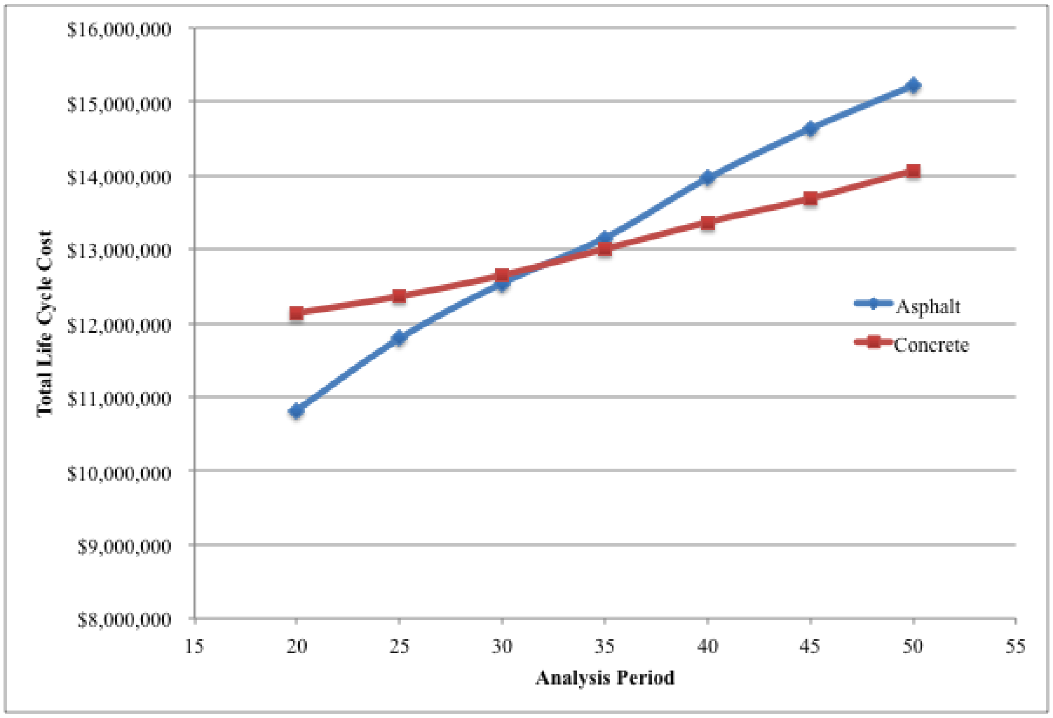


Figure 14. Life cycle costs with various analysis periods (four percent discount rate)

The next step of the sensitivity analysis was to change the discount rate to see how each pavement alternative was influenced by a change in analysis period. For the first run, the discount rate was fixed at two percent and the life cycle cost of each alternative was calculated for each analysis period (values provided in Table 17). From Figure 15, it can be seen that at a 20-year analysis period, the concrete alternative is approximately $1.1 million less than the asphalt alternative. However, using a 50-year analysis period, the concrete pavement alternative is substantially lower than the asphalt alternative; the difference in cost at the 50-year analysis period is approximately $3.3 million. As with the four percent discount rate, the life cycle cost of the asphalt alternative is more sensitive to changing analysis periods when compared to the concrete alternative.

Table 17. Life cycle costs with various analysis periods (two percent discount rate

| Analysis Period | ASPHALT LIFE CYCLE COST | CONCRETE LIFE CYCLE COST |
|---|---|---|
| 20 | $11,025,121 | $12,133,212 |
| 25 | $12,394,504 | $12,458,696 |
| 30 | $13,592,861 | $12,901,576 |
| 35 | $14,676,140 | $13,505,618 |
| 40 | $16,208,152 | $14,162,423 |
| 45 | $17,660,017 | $14,829,334 |
| 50 | $19,010,916 | $15,702,709 |

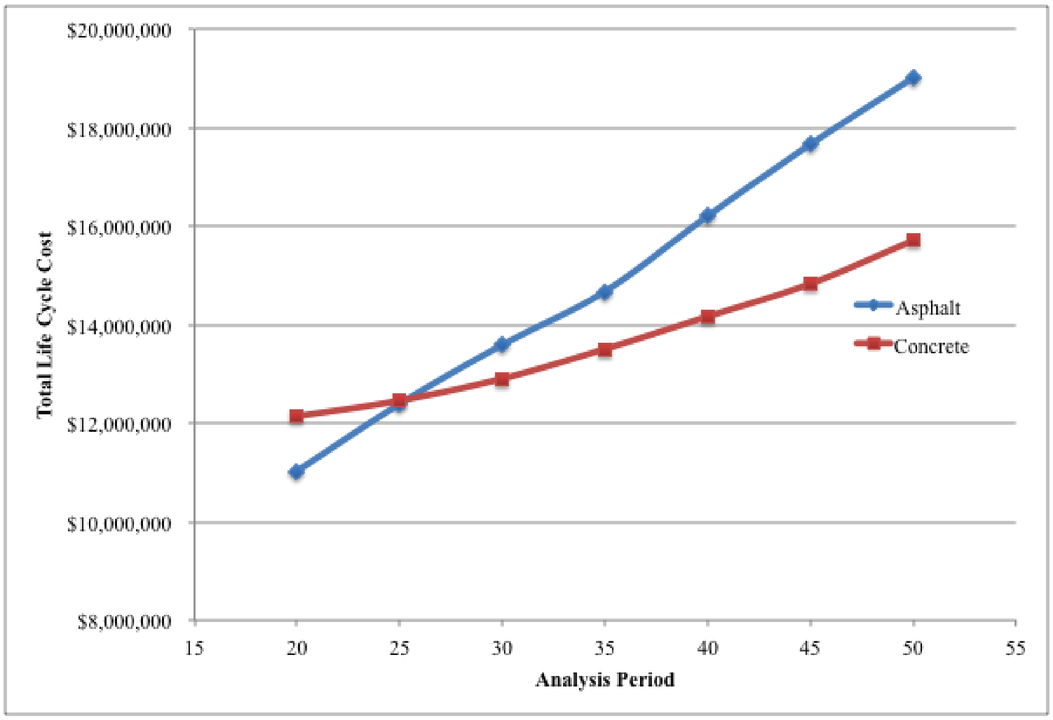



Figure 15. Total life cycle costs with various analysis periods (two percent discount rate)

The final examination of the analysis period sensitivity analysis for both pavement alternatives was run with the discount rate set at six percent. The life cycle costs for both alternatives for analysis periods 20 through 50 years is provided in Table 18. In Figure 16, it can be seen that there is a difference of approximately $1.5 million in the life cycle costs of the asphalt and concrete alternatives when a 20-year analysis period is used in the LCCA calculations. However, as the analysis period is increased, the cost difference between the two alternatives decreases. The life cycle cost of the asphalt and concrete alternatives is nearly equal with an analysis period of 50 years with the slight edge going to the concrete alternative.

Table 18. Life cycle costs with various analysis periods (six percent discount rate

| Analysis Period | ASPHALT LIFE CYCLE COST | CONCRETE LIFE CYCLE COST |
|---|---|---|
| 20 | $10,664,337 | $12,133,212 |
| 25 | $11,355,905 | $12,297,589 |
| 30 | $11,825,584 | $12,473,349 |
| 35 | $12,177,852 | $12,669,776 |
| 40 | $12,604,382 | $12,852,121 |
| 45 | $12,919,466 | $12,997,493 |
| 50 | $13,173,340 | $13,161,626 |

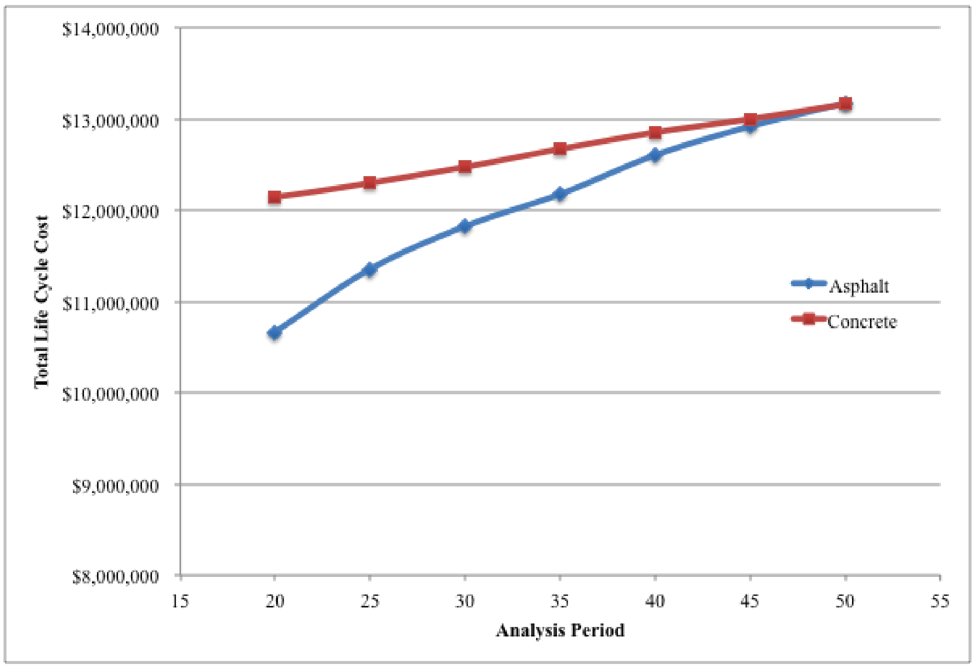



Figure 16. Total life cycle costs with various analysis periods (six percent discount rate)

While the remaining service life was calculated for each alternative in the previous analyses, a sensitivity analysis of the analysis period was also performed without the remaining service life in the LCCA calculations. The life cycle costs for the asphalt and concrete alternatives is provided in Table 19 and graph of the costs are provided in Figure 17.

Table 19. Life cycle costs with various analysis periods without remaining service life (four percent discount rate)

| Analysis Period | ASPHALT LIFE CYCLE COST | CONCRETE LIFE CYCLE COST |
|---|---|---|
| 20 | $10,664,337 | $12,133,212 |
| 25 | $11,355,905 | $12,297,589 |
| 30 | $11,825,584 | $12,473,349 |
| 35 | $12,177,852 | $12,669,776 |
| 40 | $12,604,382 | $12,852,121 |
| 45 | $12,919,466 | $12,997,493 |
| 50 | $13,173,340 | $13,161,626 |

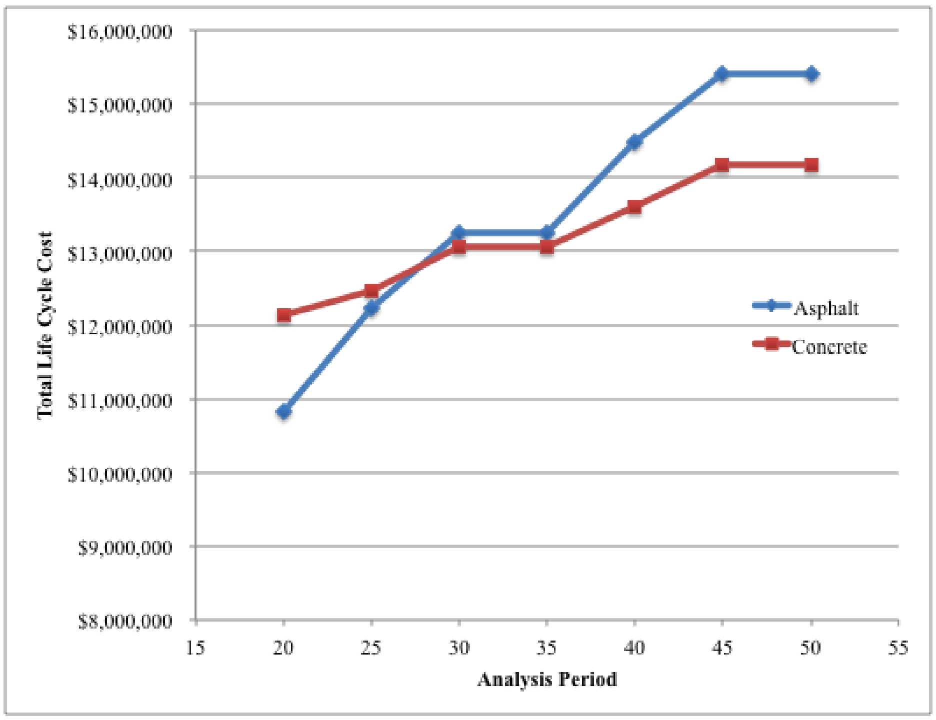



Figure 17. Total life cycle costs with various analysis periods without remaining service life (four percent discount rate)

A sensitivity analysis was also performed to examine the effect that underestimating or overestimating the initial construction cost could potentially have on the example LCCA project using the deterministic approach. To conduct the analysis, the initial construction cost of each alternative was varied while holding the rehabilitation costs constant. The analysis period and discount rate were also initially held constant for the first analysis. The initial construction costs of the asphalt and concrete pavement alternatives were varied by multiplying the initial construction costs of both materials by a range of percentages. To determine the effect of the initial cost estimate being overestimated, the initial costs were varied between 85 to 95 percent in five percent increments. Similarly, to examine an underestimation of the initial construction costs, the initial cost values were varied from 105 percent to 115 percent. The life cycle costs of both alternatives with varying percentages of the initial construction costs is shown in Table 20 and Figure 18.

Table 20. Life cycle costs with various percentages of the initial cost estimate (four percent discount rate)

| Percentage of Initial Construction Cost | ASPHALT LIFE CYCLE COST | CONCRETE LIFE CYCLE COST |
|---|---|---|
| 85% | $10,721,220 | $10,647,496 |
| 90% | $11,223,685 | $11,254,156 |
| 95% | $11,726,150 | $11,860,817 |
| 100% | $12,228,615 | $12,467,478 |
| 105% | $12,731,079 | $13,074,138 |
| 110% | $13,233,544 | $13,680,799 |
| 115% | $13,736,009 | $14,287,459 |

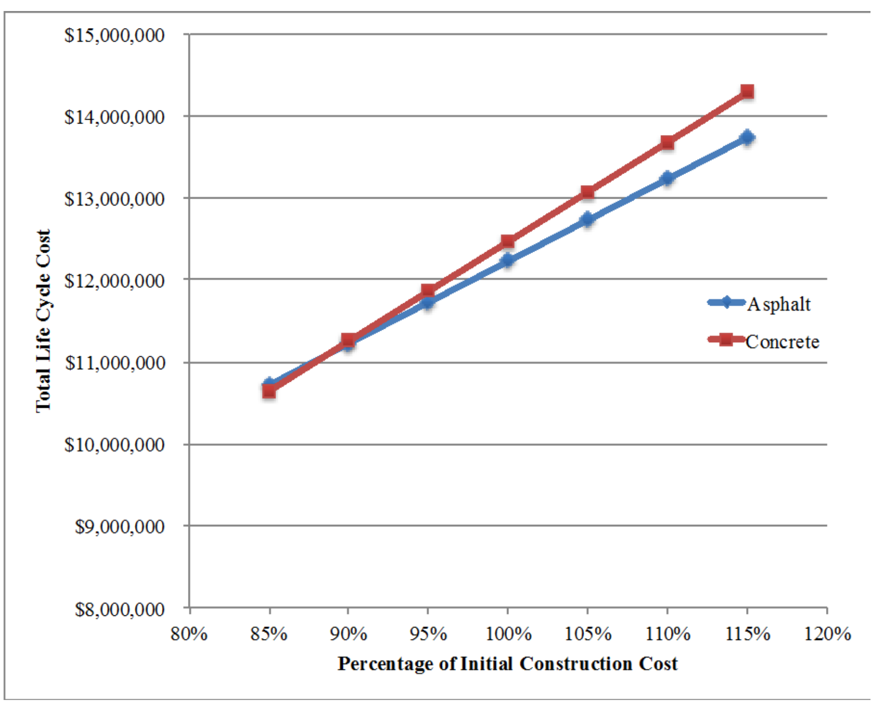



Figure 18. Total life cycle costs at various percentages of initial construction cost (four percent discount rate)

From Table 20 and Figure 18, it can be seen that the accuracy of the initial construction costs have a significant effect on the life cycle costs of both materials, with the asphalt alternative having the lower life cycle costs for a majority of the percentages of initial construction cost. However, if the initial cost estimate of both materials was overestimated by 15 percent, the life cycle cost of the concrete alternative is lower than the asphalt alternative by approximately $0.3 million.

While errors in the estimate of the initial construction costs could be made to both materials, a situation may arise where the initial cost estimate for one material is fairly accurate while the initial construction cost is overestimated or underestimated for the other material. To examine this possibility, a graph was made holding one material's life cycle cost constant while the other material's initial construction cost was varied. These graphs are shown in Figures 19 and 20.

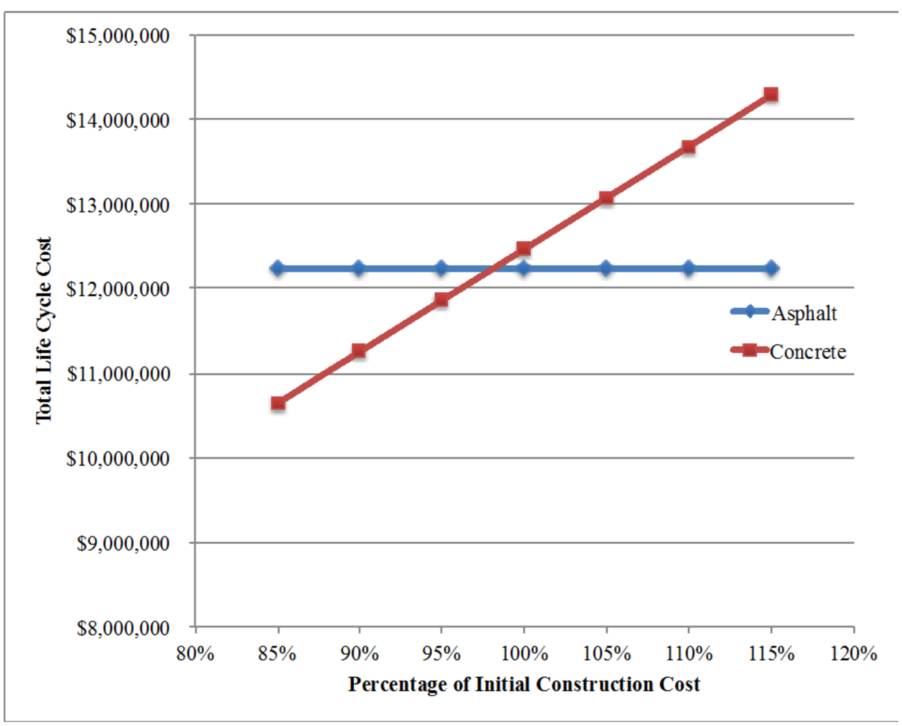


Figure 19. Total life cycle costs at various percentages of concrete initial construction cost

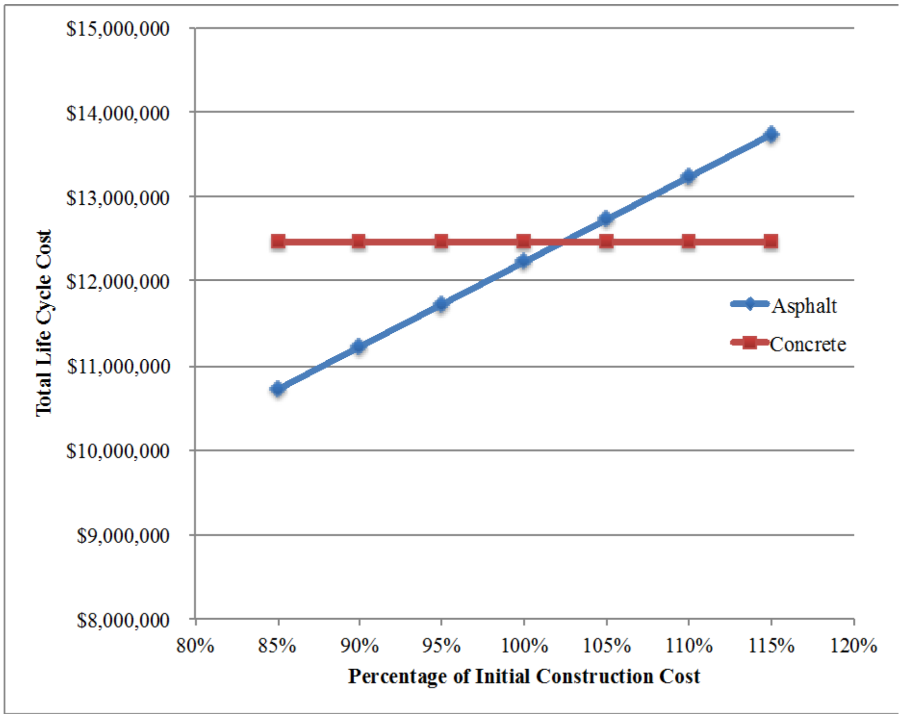



Figure 20. Total life cycle costs at various percentages of asphalt initial construction cost

In Figure 19, the life cycle cost of the asphalt alternative was held constant while the initial cost estimate of the concrete alternative was varied from 85 percent to 115 percent. From this plot of the initial construction cost estimates, if the initial concrete cost estimate was accurate, the asphalt alternative is the better option based on life cycle costs. However, if the initial concrete construction cost was overestimated by just five percent, the concrete alternative would then be the better economic option based on life cycle costs. Figure 20 provides an illustration of varying the asphalt initial construction cost while holding the concrete life cycle cost constant. If the asphalt alternative were underestimated by five percent, the concrete alternative would then be the better pavement alternative based on the economic comparison of the two options.

## 4.4 Sensitivity to Asphalt Alternative Initial Construction Cost

As noted in Chapter III, an attractive feature of probabilistic analysis of the life cycle cost of pavement alternatives is that the evaluator can examine the risk profile of each alternative in addition to the mean of the simulated life cycle costs. The next step for this research objective was to run a probabilistic analysis of the example LCCA project using the recommended pavement LCCA procedure outlined in Chapter III. Before the analysis could be run, a determination must be made as to which factors should be modeled stochastically and which factors should be modeled deterministically. For the given example project, the main source of uncertainty of interest is related to the unit cost of the pay items needed during the construction and rehabilitation of the project. Other sources of uncertainty, such as the discount rate and the timing of the rehabilitation activities, were kept fixed for this analysis so that a direct comparison of total life cycle cost could be made between the two pavement alternatives based solely on the variability of unit costs.

To run the probabilistic models, probability distributions of the unit cost for each pay item is needed to populate the simulation. Ten unique pay items (six asphalt pay items and three concrete pay item) were chosen to model stochastically for the probabilistic analysis of the original LCCA procedure. For this analysis, the deterministic unit cost provided in the example project was used as the mean for the normal probability distribution. Historical data was used to determine the scale parameter of the probability distribution for a given pay item. Bid data for paving projects that were let from 2005 to 2010 and that required a similar quantity of material for each pay item was used to ensure that an accurate distribution of unit cost was obtained. The mean and standard deviations used in the probabilistic LCCA are found in Table 21.

Table 21. Asphalt and concrete pay item parameters for probabilistic LCCA

| | Asphalt Alternative Pay Items | | | | | |
|---|---|---|---|---|---|---|
| | **423A003** | **423B001** | **424A360** | **424B581** | **424B651** | **424B681** |
| **Description** | **SMA Wearing Surface** | **SMA Upper Binder** | **SuperPave Wearing Surface** | **SuperPave Lower Binder** | **SuperPave Upper Binder** | **SuperPave Lower Binder** |
| Estimated Unit Cost ($/ton) | 75.69 | 55.00 | 62.60 | 60.00 | 60.00 | 56.56 |
| Sample Standard Deviation ($/ton) | 11.80 | 8.74 | 9.31 | 10.01 | 9.60 | 10.33 |

| | Concrete Alternative Pay Items | | | | |
|---|---|---|---|---|---|
| | **450A023** | **424B681** | **424B651** | **454D000** | **455A000** |
| **Description** | **Concrete Pavement** | **SuperPave Lower Binder** | **SuperPave Upper Binder** | **Concrete Patching** | **Diamond Grinding** |
| Estimated Unit Cost | 50.00 | 62.00 | 47.00 | 104.66 | 2.52 |
| Sample Standard Deviation | 5.65 | 9.41 | 8.41 | 21.91 | 0.54 |

The next step to analyze the probabilistic analysis of the life cycle costs of the two pavement alternatives was to build the cost models for asphalt and concrete using the recommended factors and values described in Chapter III. For this simulation, the analysis period was set at 40 years for both alternatives. Because both the asphalt and concrete pavement industries felt that the current performance periods for their respective pavements were too low and did not reflect advancements in pavement materials, designs, and technology, the recommended initial performance period and rehabilitation periods of both alternatives were extended from the original sensitivity analysis.

The asphalt industry in Alabama, in the LCCA report to ALDOT, recommended that asphalt pavements on an Interstate highway system should have an initial performance period of

19 years and a rehabilitation performance period of 13.5 years (West et al. 2012). Because a rehabilitation schedule of activities was not recommended, the schedule used in the original LCCA was reused in the probabilistic LCCA. At year 19, the asphalt alternative would need a rehabilitation that would require milling and replacing 1.4-inches of the wearing surface layer. At year 32.5, the asphalt pavement would need a rehabilitation that would require milling and replacing 1.4-inches of the wearing surface and 2.7-inches of the upper binder layer.

The concrete pavement industry recommended an initial performance period greater than 20 years and rehabilitation periods greater than eight years. For this analysis, the initial performance period of the concrete pavement alternative was set at 30 years. At year 30, the alternative would need rehabilitative measures. Using the recommendations of the concrete pavement industry, this rehabilitation would require cleaning and resealing the joints, patching approximately three percent of the pavement surface, and diamond grinding the total pavement surface. The performance period of this alternative is estimated to be ten years.

To model the performance periods of the asphalt and concrete pavement alternatives probabilistically, the parameters of probability distribution were needed. Due to a lack of reliable performance data, a survival analysis of pavements using pre-1990 ALDOT Roughometer data was used to populate the distribution parameters for this analysis. In the Auburn University final report, the researchers found that the standard deviations in performance period for asphalt initial construction, asphalt overlays, and JPCP initial construction were 4.3 years, 4.1 years, and 4.3 years, respectively (West et al. 2012). Triangular distributions were chosen to model the performance periods by using the aforementioned recommended performance period lengths as the most likely values and using the standard deviations to calculate the lower and upper limits of the distribution. For example, the initial performance period of the asphalt alternative is estimated to be 19 years. So, using this value as the most likely value, or peak, in the triangular distribution, the lower limit was set at 14.7 years and the upper limit was set at 23.3 years. Because a standard deviation value was not recorded for any concrete rehabilitations, the performance life of the concrete rehabilitation used in this analysis was modeled as a fixed, deterministic value.

Another factor that was selected to model stochastically is the real discount rate. Because predicting the general inflation rate and Treasury interest rates multiple years in the future is improbable, the real discount rate was modeled with a uniform distribution in this analysis. This distribution would allow for an equal probability of a real discount rate being sampled between lower and upper limits. The lower limit of the discount rate chosen for this analysis was one percent and the upper limit was five percent.

The initial and rehabilitation cost equations for both materials were created in one JMP statistical software data tables. The initial construction cost and the rehabilitation costs for each material were calculated by using a form of the general equation:

$$Activity\ Cost = \sum_{i=1}^{n} Unit\ Cost_i * Quantity_i, where\ i = Pay\ Item$$

To run the simulation of the probabilistic initial construction cost and rehabilitation cost models, the Profiler and Simulator modules within the JMP software package were used to populate the location and scale parameters of the unit costs. This module allows for variables within an equation built within a JMP data table to be modeled with a given probability distribution. A screenshot of the Profiler module is shown in Figure 21. The total initial and rehabilitation costs for the asphalt and concrete alternatives were then input into RealCost LCCA software to perform the full analysis of the life cycle costs.

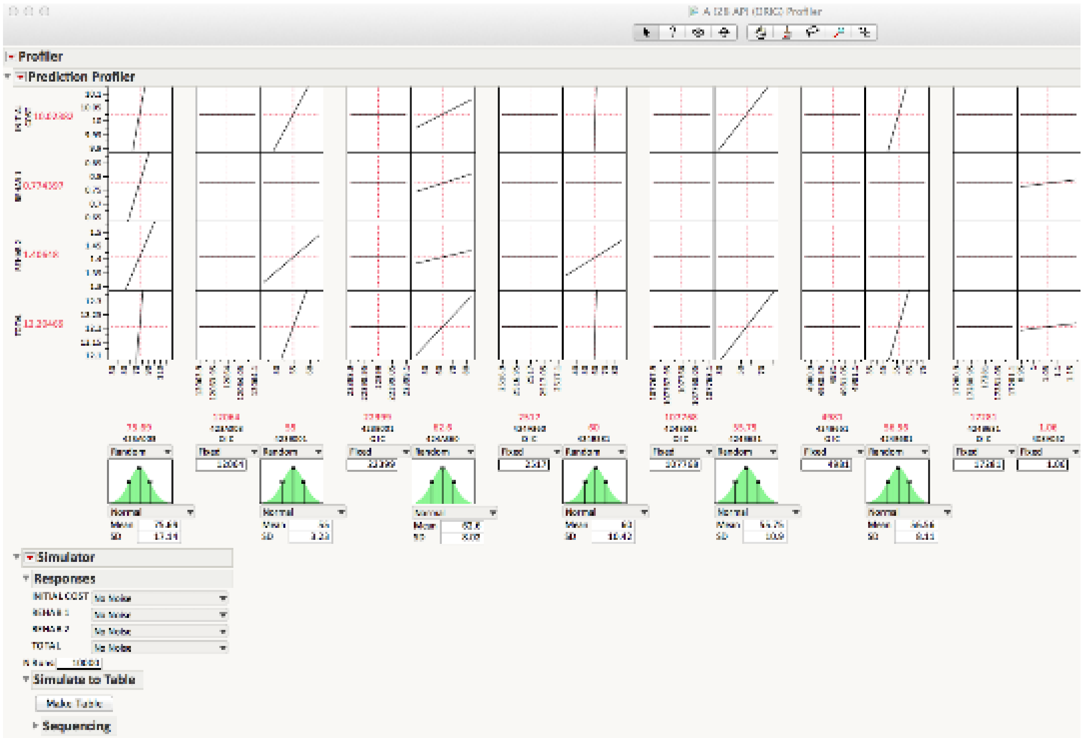


Figure 21. JMP Profiler and Simulator screen shot

The next step in the probabilistic analysis was to simulate the initial construction costs and rehabilitation costs of the asphalt and concrete alternatives. After populating the simulation model with the distribution parameters, 10,000 iterations of the simulated costs were performed and recorded. From the simulation output, the mean initial construction cost of the asphalt alternative was calculated to be $10,019,715 with a standard deviation of $1,132,337. The non-discounted mean cost of the first asphalt rehabilitation was calculated to be $1,238,715 with a standard deviation of $139,678 while the mean and standard deviation of the second asphalt rehabilitation was calculated to be $3,084,930 and $245,194, respectively. The mean of the simulated initial construction cost of the concrete alternative was calculated to be $12,150,272 with a standard deviation of $1,047,590. The non-discounted mean cost of the first concrete pavement rehabilitation was calculated as $1,717,776 with a standard deviation of $146,910.

After these values were obtained from the initial construction and rehabilitation cost simulation models, the mean and standard deviation values were input into RealCost LCCA software. Other factors such as the performance periods of the two alternatives and the discount rate were also entered into the program. For this analysis, only the agency costs were calculated. Also, the remaining service life, if applicable, was calculated for both alternatives. Once all of the program parameters were entered into the program, the simulation was set up to produce 5,000 iterations of the life cycle costs.

From the simulation output, the mean life cycle cost of the asphalt pavement alternative was calculated to be $11,540,082. The standard deviation in the life cycle cost of the asphalt alternative was $1,244,033. The mean life cycle cost of the concrete pavement alternative was calculated to be $12,856,006 with a standard deviation of $1,085,239. The distribution of the life cycle costs of both alternatives is provided in Figure 22.

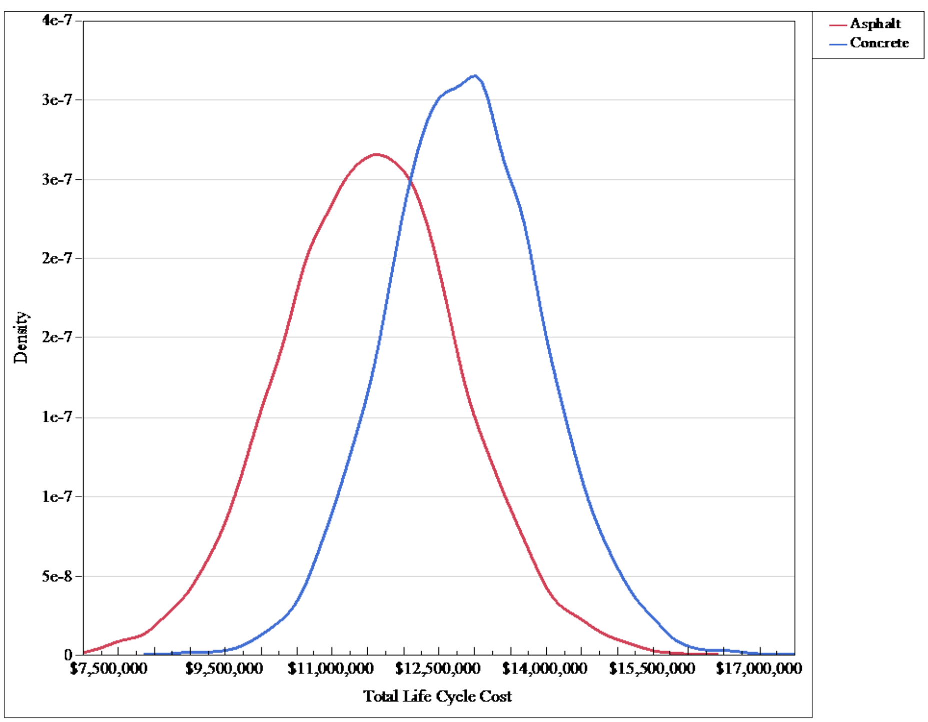



Figure 22. Distribution of asphalt and concrete pavement life cycle costs

A common method of comparison used during a probabilistic LCCA is to compare the cumulative distributions of the asphalt and concrete total life cycle costs. The cumulative distributions are provided in Figure 23. From the RealCost simulation output, the 90-percentile of the asphalt life cycle costs was found to be $13,129,267. From this output, there is a ten percent probability that the total life cycle cost of the asphalt alternative will exceed $13,129,267. The 90-percentile of the concrete life cycle costs was $14,247,704, an increase in $1,118,437 over the 90-percentile value for the asphalt alternative.

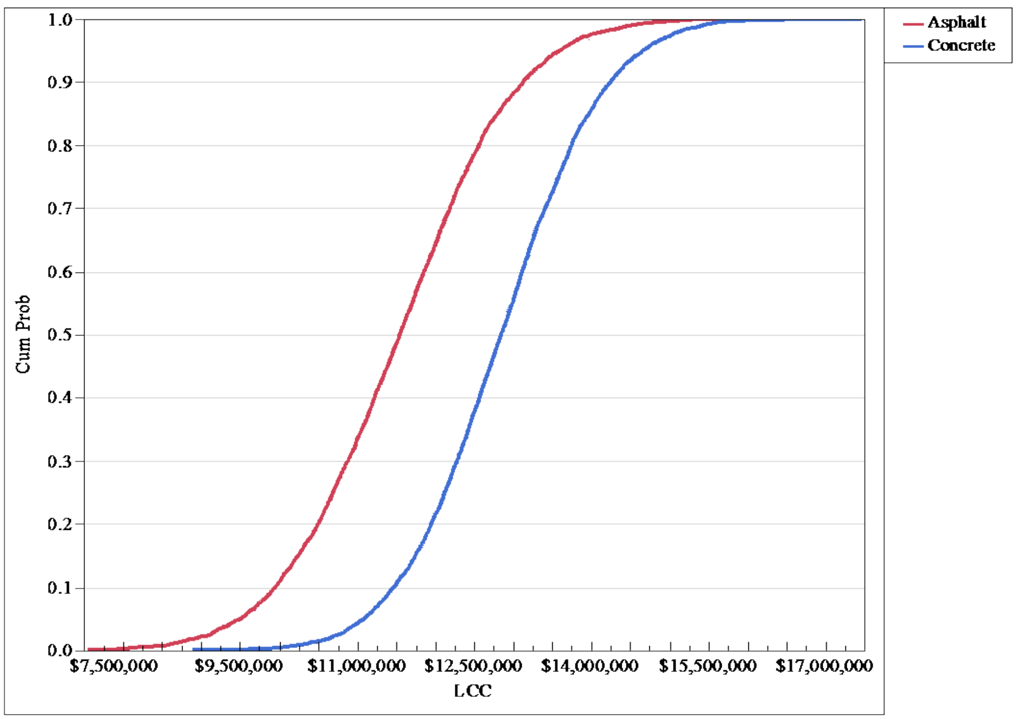


Figure 23. Cumulative distribution of asphalt and concrete pavement life cycle costs

While examining the cumulative distributions of the asphalt and concrete pavement life cycle costs is useful in an assessment of the cost risk associated with the two materials, another informative method of studying the simulation output of the pavement LCCA is by examining the differences between the asphalt and concrete life cycle costs. By storing the simulation output, the difference in the simulated costs is simple to calculate. For this case study, the simulated asphalt life cycle costs were subtracted from the concrete alternative's life cycle costs for each iteration produced by the RealCost simulation. By doing so, a new distribution is created that represents the differences in the life cycle costs of the two pavement materials. If the difference in cost is positive, it indicates that the iteration produced a concrete life cycle cost that is greater than the total life cycle cost of the asphalt alternative.

The cumulative distribution of the differences in costs is shown in Figure 24. The mean of this distribution was calculated to be $1,315,924 with a standard deviation of $1,615,284. The mean value represents the average difference between the simulated life cycle costs of the concrete and asphalt alternative for this project. Another important number from this distribution is the value that corresponds with a difference of $0. From the simulated output for the example LCCA, the cumulative probability when the difference is $0 is approximately 0.206. Based on the inputs in the simulation model and the variability in the model variables, approximately 20.6 percent of the simulated concrete pavement life cycle cost iterations were less than the total asphalt life cycle cost iterations.

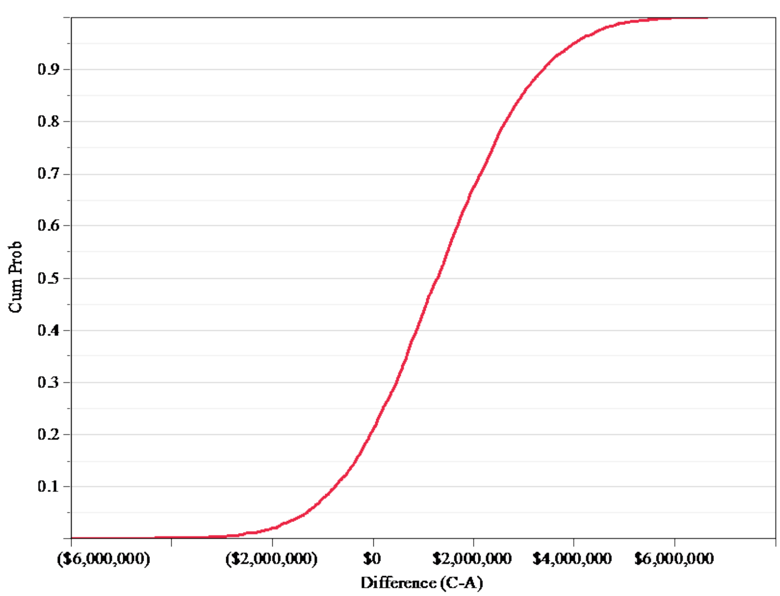



Figure 24. Cumulative distribution of difference between simulated concrete and asphalt pavement life cycle costs

Given what was learned earlier in this chapter about the sensitivity of the life cycle cost to the initial construction costs, the sensitivity of the difference in the asphalt and concrete pavement life cycle costs to any price changes caused by a PAC was the next thrust of this research effort. This analysis would replicate a situation where the initial simulation output was accurately estimated but, due to the variability of asphalt prices after the bid, a PAC was used to offset the difference in the actual cost of the asphalt material and the bid price. To accomplish this task, it was assumed that the LCCA for the Interstate 65 paving project was bid in January 2011. To examine the effect the PAC would have on the difference in life cycle costs between the concrete and asphalt alternatives, the unit cost adjustments found in Table 4 were used to adjust the unit costs of the asphalt pay items for each month after January 2011. For example, the unit cost adjustment for March 2011 was $1.41 per ton of asphalt. To show this increase in price, $1.41 per ton was added to the mean of each asphalt pay item unit cost distribution used in the calculation of the initial construction costs. Using the same standard deviation of each pay item used in the original analysis, a simulation of the initial construction cost with the adjusted unit costs was made and the mean and standard deviation of the cost distribution was then input into RealCost to run the full life cycle cost probabilistic analysis.

During the analysis, the concrete initial construction cost was also adjusted because of the asphalt bond-breaker used in the pavement design; the unit costs of the two asphalt pay items used in the calculation of the concrete pavement initial construction cost were changed based on the increase or decrease in price caused by the PAC for each simulation. Other factors, such as the discount rate and performance periods of the asphalt and concrete pavement alternatives, were kept fixed during the final simulations in RealCost. When performing the simulation in RealCost, the sampling scheme was set to “Reproducible Results” so that the same seed value was used to begin each simulation sequence. This allows the same random numbers to be generated by the computer during the simulation, removing any random variability that could manifest between simulation runs and allowing for a direct comparison based exclusively on actual changes to the distribution of the initial construction cost of the asphalt alternative.

In total, 11 life cycle cost simulations were conducted for the remaining months of 2011. After the initial construction cost simulations for the asphalt and concrete alternative were conducted for a given unit cost adjustment and the new distributions were run in RealCost, the total life cycle cost iterations of the asphalt and concrete pavement alternatives were stored. The asphalt total life cycle cost was then subtracted from the concrete alternative's life cycle cost to create a new distribution of the cost difference. From this distribution, the percentage of iterations that produced a negative cost difference was found. The probabilities that the concrete pavement alternative has a lower life cycle cost than the asphalt alternative for the 12 months of 2011 are provided in Table 22.

Table 22. Percentage of iterations where concrete pavement alternative life cycle cost was less than asphalt life cycle cost

| Date | ALDOT Asphalt Index ($/ton binder) | Unit Cost Adjustment ($/ton AC) | Mean Asphalt Initial Construction Cost | Mean Concrete Initial Construction Cost | Percentage of Iterations where Concrete LCC < Asphalt LCC |
|---|---|---|---|---|---|
| Jan-11 | 458.28 | 0.00 | $10,019,715 | $12,150,272 | 20.6% |
| Feb-11 | 472.39 | 0.71 | $10,132,258 | $12,187,886 | 21.8% |
| Mar-11 | 486.49 | 1.41 | $10,245,136 | $12,232,097 | 23.4% |
| Apr-11 | 514.69 | 2.82 | $10,494,561 | $12,318,361 | 26.5% |
| May-11 | 556.99 | 4.94 | $10,837,226 | $12,446,984 | 31.0% |
| Jun-11 | 601.65 | 7.17 | $11,223,389 | $12,572,884 | 37.9% |
| Jul-11 | 606.35 | 7.40 | $11,261,080 | $12,605,041 | 38.0% |
| Aug-11 | 580.49 | 6.11 | $11,038,521 | $12,510,793 | 34.2% |
| Sep-11 | 571.09 | 5.64 | $10,981,360 | $12,464,729 | 33.9% |
| Oct-11 | 571.09 | 5.64 | $10,981,360 | $12,464,729 | 33.9% |
| Nov-11 | 566.39 | 5.41 | $10,939,686 | $12,463,417 | 33.0% |
| Dec-11 | 559.34 | 5.05 | $10,867,513 | $12,446,965 | 31.7% |

From the table, it can be seen that if the project was bid in January 2011 and the price of asphalt at that time was accurately estimated during the LCCA process, every month following would result in a higher actual initial construction cost for both the asphalt and concrete alternatives due to the unit cost adjustment caused by the PAC. So, if the project was actually constructed in May 2011, the mean initial construction cost of the asphalt alternative was calculated as $10,837,226, an increase of $817,511 from the January 2011 bid, and the mean initial construction cost of the concrete alternative was calculated to be $12,446,984, an increase of $296,712 from the January 2011 bid. The simulation of life cycle costs using these initial construction costs showed that the probability of the concrete life cycle cost being less than the asphalt life cycle cost was 31.0 percent, an increase of 10.4 percent from January 2011. The month of July was found to have the highest increase in the probability that the concrete alternative is less than the asphalt alternative with a probability of 38.0 percent, 17.4 percent higher than the probability calculated for the January 2011 analysis.

From this analysis, it can be seen that the probabilistic LCCA for the example paving project is sensitive to any adjustment in unit cost caused by a PAC in a paving contract. Any increase or decrease in the mean value used in the probabilistic LCCA simulations could increase the percentage of iterations that result in a negative cost difference between the concrete and asphalt pavement alternative by as much as 17 percent. As the unit cost adjustment amount increases for the asphalt pay item unit cost, the probability that the wrong pavement material may be chosen increases if other factors are not fully considered and the decision is based solely on the outcome of the probabilistic analysis. If another form of bond breaker, such as a geotextile fabric interlayer, was used in the concrete pavement design and no asphalt materials were used, the probability the life cycle cost of the concrete pavement alternative is less than the asphalt alternative increases even more.

## 4.5 Summary

The calculation of life cycle costs during the pavement type selection process provides engineers and estimators the ability to compare the costs of each alternative within a given analysis period. An LCCA of each pavement alternative will permit a side-by-side comparison of the options can be made from an economic standpoint. To determine which factors the life cycle costs are sensitive to in the analysis, a sensitivity analysis of the factors used in the analysis can be conducted to see how a change in the value used in the calculations can affect both alternatives.

In the analysis of the discount rate for the example LCCA project, it was found that the life cycle costs of both materials were sensitive to the value used in the calculations. Because the asphalt alternative had more expensive rehabilitations scheduled compared to the concrete alternative it was more sensitive discount rate used in the analysis; higher discount rates favored the asphalt alternative while the lower discount rates favored the concrete alternative. All other factors held constant, the life cycle costs of both alternatives for this project were approximately equal if a discount rate of 3.25 percent was used.

Both alternatives were also sensitive to the analysis period used in the calculation of life cycle costs. Using the assumed rehabilitation schedules and a four percent discount rate, the asphalt alternative had a lower life cycle cost with a 30-year analysis period while the concrete alternative had a lower life cycle cost with a 35-year analysis period. At a two percent discount rate, the concrete alternative had the lower life cycle costs when the analysis period was set at 30 years or greater. However, at a six percent discount rate, the asphalt alternative had the lower total life cycle costs for a majority of analysis periods analyzed in this study except for a 50-year analysis period, where the concrete alternative's life cycle cost was slightly lower than the asphalt alternative's life cycle cost.

While both the discount rate and the analysis period values used in the analysis were found to influence the life cycle costs of the alternatives, it was also found that the life cycle costs of both alternatives were highly sensitive to the accuracy of the initial cost estimate used in the LCCA calculations. For the example LCCA project, an error of five percent in the initial cost estimate of either material changed which material appeared to be the better economic option for this project.

The overestimation or underestimation of the initial construction costs of the pavement alternatives could be caused by numerous factors. While some errors could be made in the estimation of the quantity of paving material needed, most of the inaccuracy of the initial construction cost estimate is attributable to poor unit cost estimates of the pay items. These errors could be the result of a trend in the real price of the paving material that was not foreseen at the time the LCCA was conducted, or a poor unit cost estimate could be made using historical data that is not representative of the project location, time of year the bid is received, or other factors. The unit cost estimate used in the calculations is critically important regardless if a deterministic or probabilistic approach to the LCCA is performed.

In summary, several factors were identified that influenced the life cycle costs of the asphalt and concrete pavement alternatives in the example paving project used in this analysis. While a majority of the pavement LCCA literature emphasizes and encourages a sensitivity analysis to be conducted on key factors such as the discount rate and analysis period, little attention is given to the sensitivity of the initial cost estimate used in the calculations and the effect a PAC could have on the outcome. The difference in life cycle costs of the two alternatives for some projects may be so great that an error made in the initial cost estimates may not change which alternative is the better option. However, as shown in the deterministic analysis of the example paving project used in this study, an error in the estimation of the initial costs as small as five percent could change which project could be considered the best economic option.

# CHAPTER V

# ASPHALT UNIT COST FORECASTING MODELS

## 5.1 Introduction

The main goal of this research was to develop forecasting models for asphalt materials for use in both a deterministic and probabilistic LCCA during the pavement type selection process. As noted in the previous chapters, the use of deterministic LCCA procedures during the pavement type selection process is popular with many state highway agencies across the United States. The deterministic approach provides the analyst with a single calculated life cycle cost value for each pavement material and is a computationally simple method to compare two alternatives. However, any uncertainty, which may be caused by a variety of factors, is ignored with the use of a single fixed value input. To model the uncertainty and risk, some states have adopted a probabilistic approach to the pavement LCCA. However, little guidance is provided for using probabilistic cost estimating techniques when determining the initial construction costs of a paving project when the paving materials may be experiencing volatility in price or upward or downward trend.

How the probabilistic models are calculated with the software that is used to carry out the simulations is another matter of interest. RealCost, LCCA software provided by FHWA, has the capability to perform a probabilistic LCCA but only for certain factors in the analysis. When performing an LCCA with RealCost, the project's initial construction costs, which typically constitute the largest portion of life cycle costs for a project, and rehabilitation costs can be put into the program with a probability distribution and appropriate location and scale parameters for that given distribution. However, calculating the initial construction costs or rehabilitation costs within the program using individual pay item unit costs and quantities is not possible. Therefore, a probabilistic cost model must be created and used to supplement the RealCost program so that any uncertainty associated with the pay item costs associated with the initial construction costs and the rehabilitation costs of the pavement alternatives can be modeled.

### 5.2 Probabilistic LCCA Model Components

Before a probabilistic LCCA model is constructed, the model needs to be broken down into its basic components so that each component can be analyzed separately. The two main components of the LCCA during the pavement type selection process, provided the alternatives provide the same level of benefit, are the initial construction cost and the sum of the discounted rehabilitation costs as shown in the equation,

$$NPV = Initial\ Cost + \sum_{k=1}^{N} Rehab\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right].$$

These main components of the LCCA also need to be decomposed so that the factors and influences on the total initial project cost and subsequent rehabilitation costs can be examined thoroughly. The three main categories of these costs may be broken down into three distinct groups:

1. Construction cost factors
2. Economic factors, and
3. Performance factors.

Each of these groups will contain stochastic factors that will influence the total life cycle cost of the pavement alternatives and may be represented by different probability distributions.

Typically, only construction cost factors will exist in the initial construction cost component of a paving LCCA. When estimating the initial construction cost of a paving project, the estimator will know a majority of the main project details with a fair degree of certainty. These factors include the project location, the estimated bid date of the project, the type of material, and the quantity of material needed to construct the project. The types of materials needed for the construction of the roadway are determined from the thickness design generated by the pavement engineer. An asphalt pavement system, for example, may consist of several asphalt base layers overlain by an open-graded friction course as the wearing surface. The engineer will have determined the specific characteristics of the mixture based on the type of asphalt binder needed, the estimated traffic loading of the roadway, the anticipated performance life of the system, and the climatic characteristics of the project location.

From the thickness design of the pavement system, the engineer can determine with pay line items are necessary for the initial construction of the project. The quantity of paving material needed to construct the pavement system will also be straightforward to calculate from the length and width of the roadway and the thickness of each paving layer. Additional features of the roadway such as shoulders, ramps, and turnaround areas can also be calculated with a fair degree of accuracy for each material being analyzed. After the quantity of each pay line item for the paving materials are determined, the estimator can analyze historical bid cost information to determine an appropriate unit cost for each pay line item.

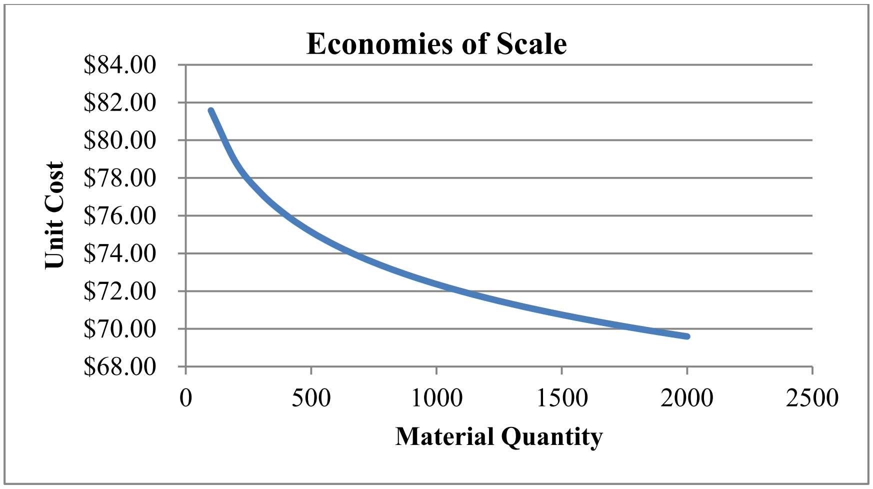
### 5.2.1 Material Unit Cost Estimation for Initial Construction Costs

In an LCCA context, the initial construction costs typically represent the largest portion of the total life cycle cost of a given alternative. The difference between the initial construction costs and subsequent rehabilitation or maintenance costs commonly occurs for two reasons. First, the initial construction of the facility or asset represents a substantial investment in capital, resulting from either constructing an entirely new facility or significantly renovating or restoring an existing asset. These costs typically exceed any costs to perform rehabilitation or maintenance activities that are needed to operate the facility in the future. Second, any rehabilitation or maintenance costs that do occur are brought back to their present value through the use of discount rates during the LCCA calculations. Even if a substantial rehabilitation of the facility is needed in the future, the present value of those costs will be less than the costs to perform the work in the present, especially if the activities are scheduled well into the future or if there is a high discount rate being used in the analysis.

The accuracy of initial construction cost estimates in an LCCA are typically limited by a lack of scope definition of the project and other factors uncontrollable or unforeseen at the time the LCCA is conducted. However, in some situations, this lack of definition is not a hindrance to calculation of project life cycle costs. During the pavement type selection process, for example, an LCCA is typically conducted during the programming or planning stages when the paving project is not fully defined in its entirety. While certain aspects of the project are not yet defined, the thickness designs for asphalt and concrete pavements are necessary to calculate the material quantities needed to complete the project. The quantity of materials needed can be estimated with a fair degree of accuracy at this point in the project development process, and if the paving projects are similar in terms of factors such as earthwork and other costs incidental to the construction of the pavement system, the material costs are the main items for comparison between pavement alternatives in the LCCA.

Several methodologies are available to state highway agencies to estimate the unit costs of the paving materials. Most states have a robust dataset of bid information for both pavement materials, and as a result, historical bid-based cost estimating is a popular method to estimate the initial construction costs of a paving project. Using this method, the engineer can examine past paving projects to estimate the unit costs of the materials to be used in the LCCA in two ways. The first method requires the engineer to categorize the individual line items into major cost groups such as asphalt, base, concrete, earthwork, etc. The engineer can then analyze past projects to determine the percentage of total project cost that each of those price groups represents. While this method is useful for generating estimates of the cost groups that can then be applied to estimate total project costs, this method is not the best choice for estimating initial construction costs for LCCA purposes since it does not permit item level estimates for each pavement material to be made. The second method requires a higher level of detail but it allows the engineer to derive a cost estimate that examines the unit cost of each material at the item level. Like the previous method, the engineer needs to know the length, width, and depth of the pavement, but because more detail about certain factors that will influence the unit cost of the pavement are typically known at the time the estimate is to be made, the engineer can adjust the unit costs of the pavement material line items to increase the accuracy of the estimate.

One of the parameters that can influence the unit cost of the paving materials is the total quantity of material needed to construct the project. The relationship between quantity and unit cost is important to the estimator if the operation is governed by economies or diseconomies of scale. Economies of scale exist when the average cost per unit declines as the number of units increases. This reduction in price may decrease for a number of reasons. The bid unit cost of paving materials, for example, may decrease as the quantity of material needed to build the roadway increases because of discounts offered by the material supplier for a larger material order. If the opposite situation is true, when the average cost per unit increases as the number of units increases, then the operation is influenced by diseconomies of scale. Both economies and diseconomies of scale can be represented by a linear or nonlinear relationship. An illustration of this concept can be seen in Figure 25.



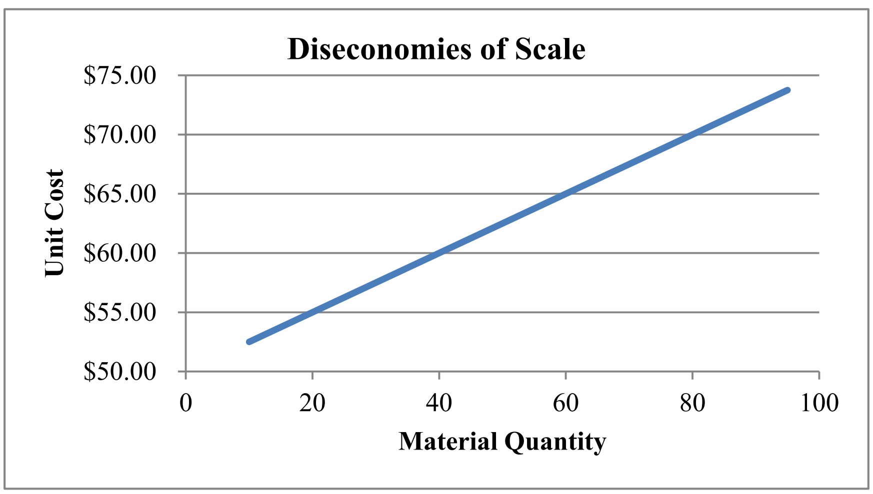




Figure 25. Economies and diseconomies of scale illustration

If a relationship between quantity and unit cost exists, the engineer can model a linear or nonlinear relationship between the quantity of material and unit cost using historical data. A linear relationship between quantity and unit cost can often be modeled using simple linear regression techniques. By doing so, a linear model is created with the form,

$$\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i$$

where $x_i$, the independent variable, represents the quantity of material and $\hat{y}_i$, the dependent variable, represents the fitted value unit cost of the material for quantity $x_i$. The quantities $\hat{\beta}_0$ and $\hat{\beta}_1$ are called the least-squares coefficients. In this form, the coefficient $\hat{\beta}_0$ is the intercept of the least-squares line while $\hat{\beta}_1$ is the slope of the least squares line. These coefficients are estimates of $\beta_0$ and $\beta_1$, the true intercept and slope quantities of the true linear model. When modeling a process with economies of scale, the slope of the least squares line will be negative while a positive slope indicates that the process is influenced by diseconomies of scale.

If the simple linear regression model assumptions are satisfied and the model appears to be the best fit for the data set, the estimator can use the linear model to predict the unit cost of the material for a given quantity. To do so, the estimator can calculate the predicted unit cost by plugging in a quantity value for $x_i$ in the model as long as the quantity used in the prediction of the unit cost is within the range of quantities used to create the regression model. An example of least squares regression line using unit cost as the dependent variable and quantity as the independent variable is shown in Figure 26. Using a quantity outside of the range of data used to create the regression model is known as extrapolation. Extrapolating the least squares line is not recommended to predict the value of the unit costs because it may not properly describe the relationship between quantity and unit cost at quantities below or above the range of quantities used to fit the model.

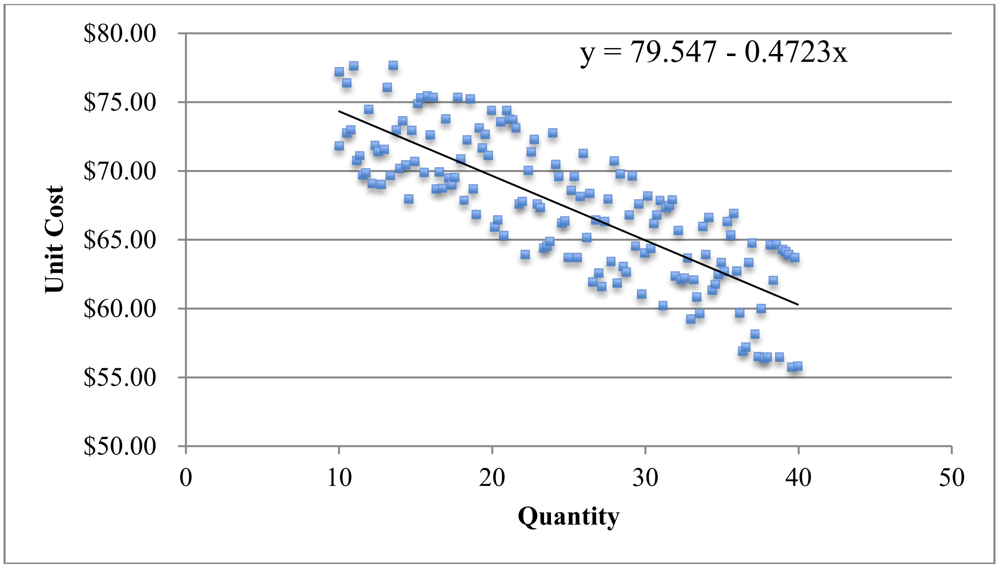


Figure 26. Least squares regression line

The location of the project may also influence the unit cost of a material. Historical bid unit costs in densely populated metropolitan areas may differ significantly from the bid costs on projects that occur in rural areas. These variations in cost can occur for multiple reasons. Increased or decreased costs associated with material availability and transportation, labor availability, and other factors may influence the unit costs of materials depending on project location. Adjusting bid unit costs for estimating purposes may be necessary for projects within a state, such as urban versus rural construction, or when using out of state data. In some instances, historical bid data sets for certain materials, such as portland cement concrete pavements, may be small and may require the estimator to use data from outside of their state to increase the sample size of the data set.

Another important factor in estimating unit costs for construction is time. Depending on the data set, some historical bid data may need to be adjusted for inflation to bring all costs to constant (real) dollars. By adjusting historical construction costs with a common inflation index, such as the CPI, the estimator can thoroughly examine the data set and determine if the historical data is a good representation of the costs for a project to be built in the near future. Figure 27 is a graphical representation of the adjustments made to a historical bid cost data for location and time. In this figure, each data point represents a bid cost data set for five regions at a given point in time. To accurately estimate the cost of the project, the estimator would need to bring all costs to the time the estimate is being made and adjust each data set to correspond to the project location (Region 3 in the figure).

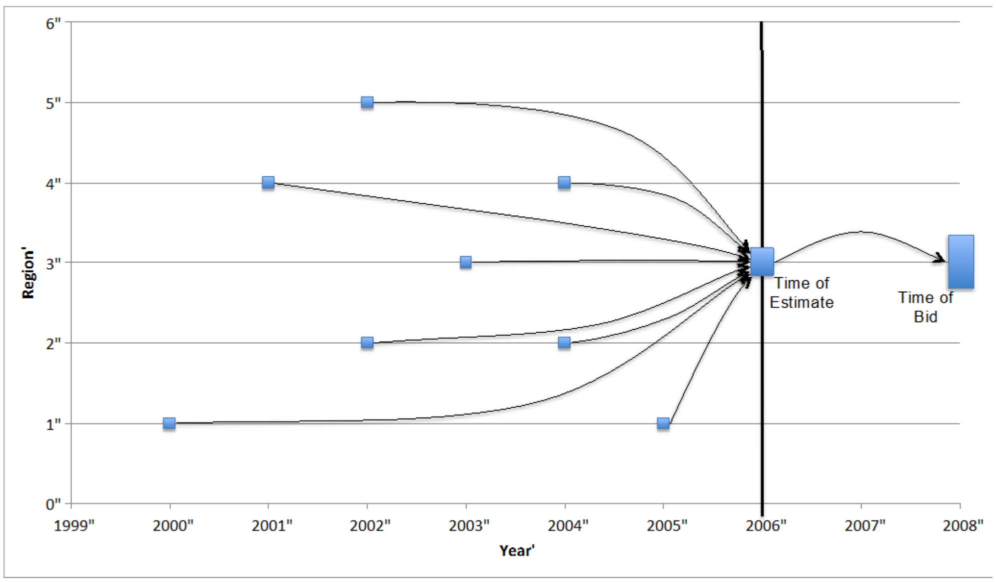



Figure 27. Location adjustment graph

After adjustment the historical data set for inflation, the estimator may notice that the unit cost of certain materials shows certain characteristics through time that may need to be accounted for in the estimate of initial construction costs. Graphing the unit cost in real dollars will provide the estimator with an opportunity to examine how the price of materials behaves over time. One characteristic of the data that can be shown graphically is trending. If the cost of the material, through time, grows with the general rate of inflation, then the graph of the real cost should have zero slope. In this situation, barring any other influences such as quantity on the data, an average value of the data should provide the estimator with a good estimate for the cost of the material. However, if the unit cost of a material may grow at a rate higher or lower than the general rate of inflation. A graphical example of a trend in material prices is shown in Figure 28.

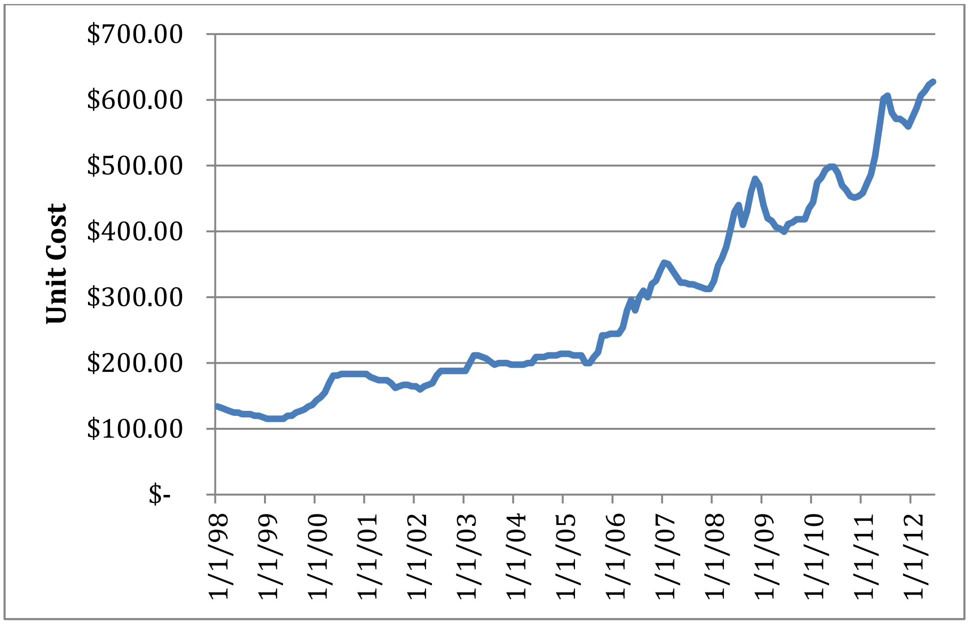



Figure 28. Trend in unit cost through time

Another characteristic that the data may take on through time is seasonality. This is also an important trait that the estimator should be mindful of when preparing the estimate. When graphing the data, the estimator may see that the bid unit costs in January, for example, may differ significantly from the unit costs of a project that was bid during the summer months. When estimating the unit cost for a material that displays seasonal variation, the estimator should account for which the time period the data comes from and when the project will be bid when making an estimate of the unit costs. An example of a data set exhibiting seasonality is shown in Figure 29. In this example, an estimate made using the total historical unit cost data set for all projects will underestimate the bid unit cost of a project to be let in the summer.

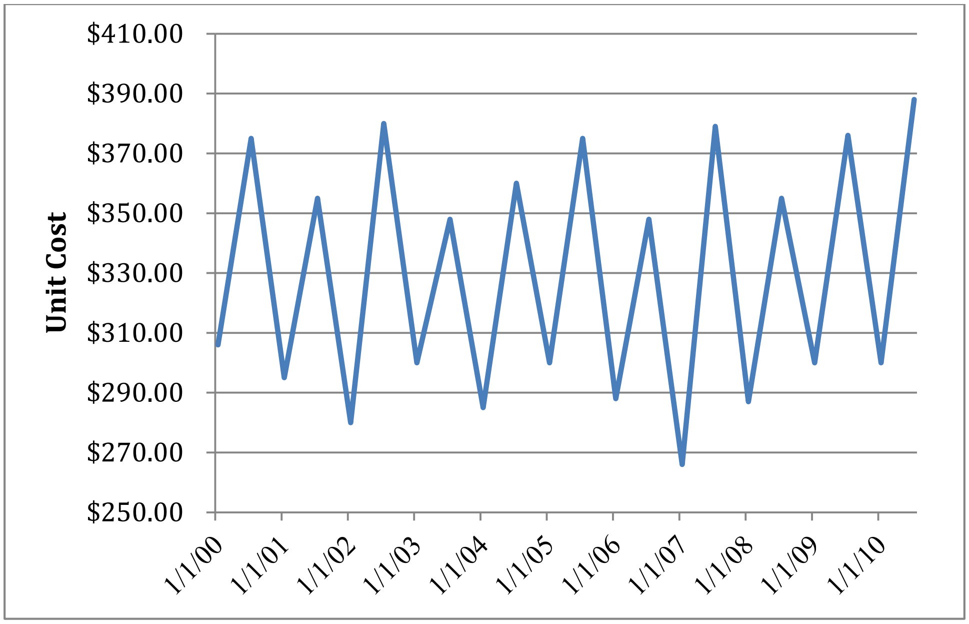


Figure 29. Seasonality in unit cost through time

Macroeconomic effects and other factors outside of seasonal influences may cause the price of the material to fluctuate through time. For example, the price of a given material may have been relatively stable five years ago, but since that time, the price has shown to be increasingly volatile. An example of this occurrence is shown in Figure 30. While trends, seasonality, or volatility shown in the historical unit costs can occur individually within a data set (such as increasing trend with no seasonality or volatility), all or a combination of these characteristics may also exist in the same data set. One or all of these phenomena will increase the difficulty with which a cost estimate can be derived for use in a comparison of life cycle costs during the pavement type selection process.

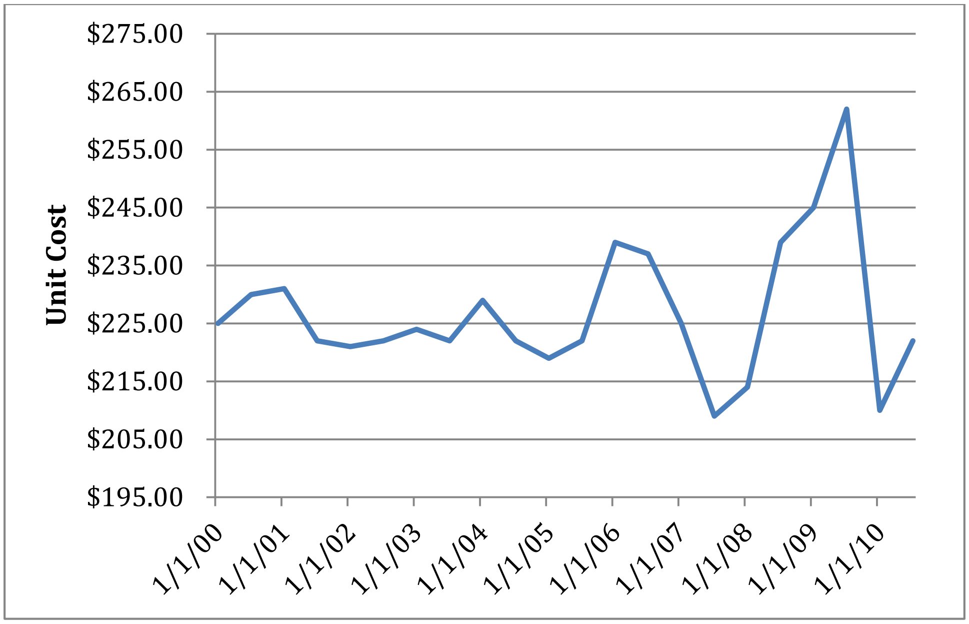


Figure 30. Volatility in unit cost through time

One aspect of the initial construction cost estimate that is important during the calculation of life cycle costs is when the project will be bid. A cost estimate made at the present may not fully represent the conditions at the time of project letting in the future. This is especially true if the cost of materials, labor, and other factors are trending upward or downward or if the costs are influenced by seasonal variations. To predict the cost of materials in the near future, an estimator may develop a model to forecast or predict future values, and one of the most popular methods of statistical forecasting is the use of time series analysis techniques. A time series model uses previously observed values to predict future values and allows the estimator to account for any trends, seasonality (or cyclical behavior), and volatility present in the data set.

An important element of forecasting with time series models is the level of uncertainty associated with the forecasted value in the future. An estimator can use a time series model to obtain a predicted value (or point forecast) in the future and use that value to calculate a deterministic estimate of the future cost of the work. However, if the estimator wanted to model the risk and variability associated with the forecast, a probabilistic cost estimate could also be made using the model.

Several research efforts have been made in estimating future construction costs. Wilmot and Cheng (2003) examined highway construction cost data on highway and bridge projects from 1984 to 1997 to develop cost models that could estimate the future overall highway construction cost in the state of Louisiana. In their models, the researchers including independent variables such as letting date, contract duration, material quantities, and bid volume to create the estimating model and determine how manipulation of these variables influences the overall highway construction cost. While this research strived to estimate the overall construction costs for highway construction, other researchers have attempted to model trends in construction cost indices. Ashuri and Lu (2010) developed five univariate time series models to model the construction cost index (CCI) published monthly by the Engineering News-Record (ENR). In this research, the authors compared the accuracy of each individual time series model for in-sample and out-of-sample forecasting. Similarly, Hwang (2011) developed both univariate and multivariate time series models to forecast the CCI through time.

The adjustments for certain influences on the unit costs of the materials can be made in a number of ways. As shown above, an estimator may use regression techniques to model any relationship that may exist between a material's unit cost and the quantity of material needed to perform the work. Other adjustments can be made by multiplying the unit costs by factors that adjust the cost for influences such as time and location. For example, an estimator can adjust for the time of project bid by multiplying total project costs by the ratio of the construction index at time of bid (derived from a forecast of the index) and the cost index when the estimate is made. Several construction cost indexes are available to the estimator based on the type of project to be executed. Some indexes, such as the ENR CCI and Building Cost Index (BCI), are aggregated indexes that incorporate common construction material and labor components derived from average prices recorded from cities across the country. Indexes are also available for specific industries. Estimators of highway construction, for example, may use the FHWA National Highway Construction Cost Index (NHCCI) or the PPI for Highway and Street Construction Index to adjust their costs. If available, several states have created their own state specific indexes for highway construction using historical material and labor cost data (Wilmot and Cheng 2003).

Adjustments for the project location can be made using similar methods. Location indexes, such as those published by RSMeans, are available to estimators to adjust their estimates to the project's location. To adjust for location, the estimator can adjust all the historical data needed to make the estimate to a common location, such as a major city within their state, and then adjust the cost estimate to apply to the location of the project in relation to their chosen common location. The estimator may also choose to add the location of the data as an explanatory variable in a regression model; modeling the unit cost of a material with location as a categorical variable will also allow the estimator to determine if the differences in cost between locations are statistically significant.

In an LCCA context, several limitations exist that require the estimator to be cautious when adjusting construction costs for influences such as quantity, time, and location. One such limitation is the use of common construction indexes to adjust cost estimates for time. The NHCCI, CCI, and BCI are calculated using aggregated material cost averages for commonly used materials and are best suited for calculating total project costs for screening or order of magnitude estimates. When performing an LCCA, an estimator may be examining the behavior of costs of a specific material through time and an aggregated index may not accurately portray any specific trends or volatility in material cost. This situation is especially true during an LCCA between asphalt and portland cement concrete during the pavement type selection process.

When adjusting for major influences on the costs of a construction project, the estimator will typically have to adjust for each influence one at a time. When analyzing the historical data after adjustment, the estimator should be cognizant of any interaction between influences on the data. An example of this is shown in Figure 32. In this example, three years of bid unit cost data has been adjusted for location and inflation. A simple linear regression model to account for the scale economies present would then be created for the total data set (shown in the top graph). This regression model would provide the estimator with a predicted value of the unit cost of the material based on a given quantity of material needed. However, if the estimator created a linear model for each year of data, they would find that the linear models of each year of data would differ (lower graph in Figure 31). In this example, the slope of the regression models appears to be consistent for all three years but the intercepts of the least squares line are changing significantly each year. If the estimator used the overall regression model to estimate the unit cost and the price of the material continued to follow this trend into the near future, the estimated unit cost of the material would be underestimated. This type of situation would require the estimator to examine more historical data to fully examine any long-term trend in unit cost of the material so that an appropriate estimate could be made.

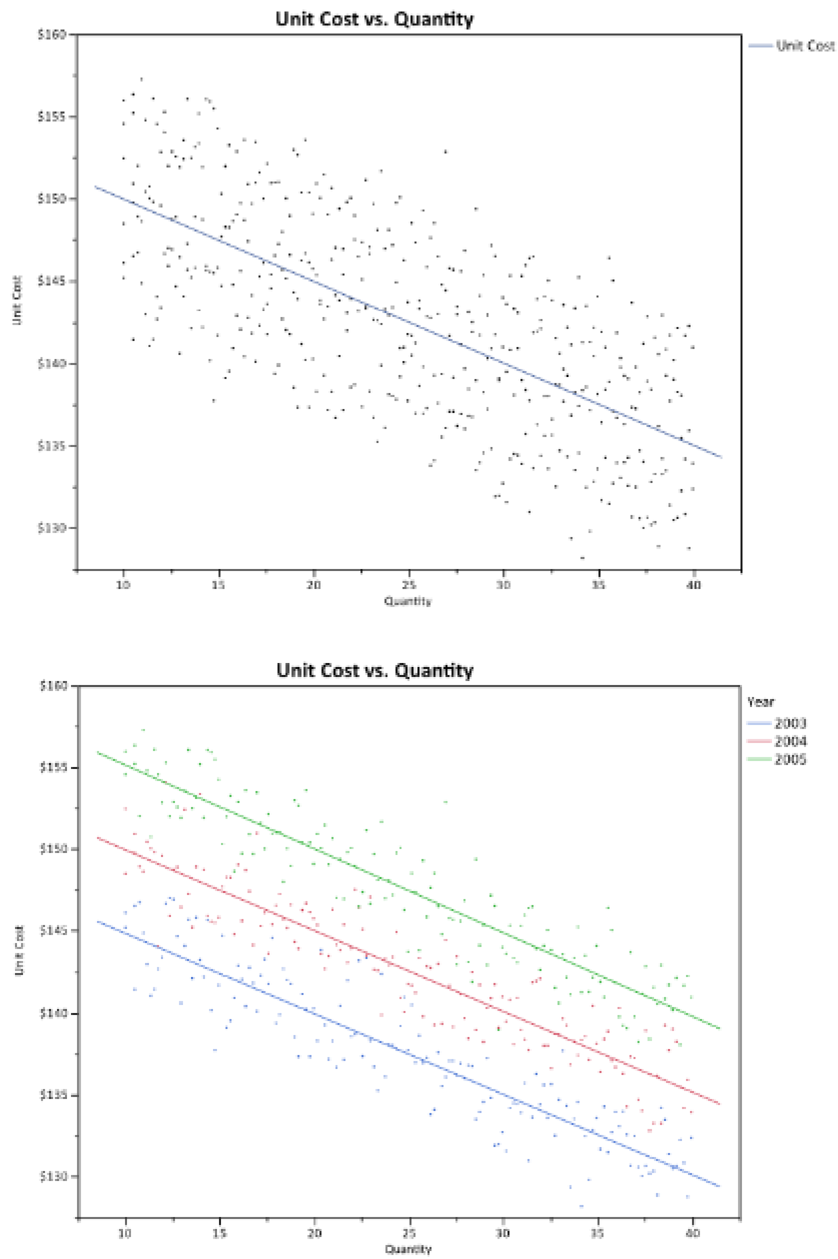



Figure 31. Trend in regression lines through time

In the area of statistical process control (SPC), statisticians and engineers utilize control charts to monitor the quality of a manufactured product or an industrial process. While some products can be monitored by a collection of measurements of a physical dimension or the number of flaws per unit, the quality of certain products and processes may be best represented by a relationship between one or more explanatory variables and a response variable (Woodall et al. 2004; Soleimani et al. 2009). In these situations, collected data is used to create a linear or non-linear model, known as a profile, at each sampling period. Control charts for the *y*-intercept, slope, and variance of the residuals of the regression model are typically created to monitor the process through time. A substantial shift in these charts will signal an out-of-control process and will require any adjustments that are necessary to get the process back in control.

It is hypothesized that a similar profile may exist at each point in time of a historical bid data set for asphalt pavements as a result of influences of quantity, time, location, and other factors on the unit cost of the material. An illustration of these conceptual profiles of material unit cost through time is shown in Figure 32.

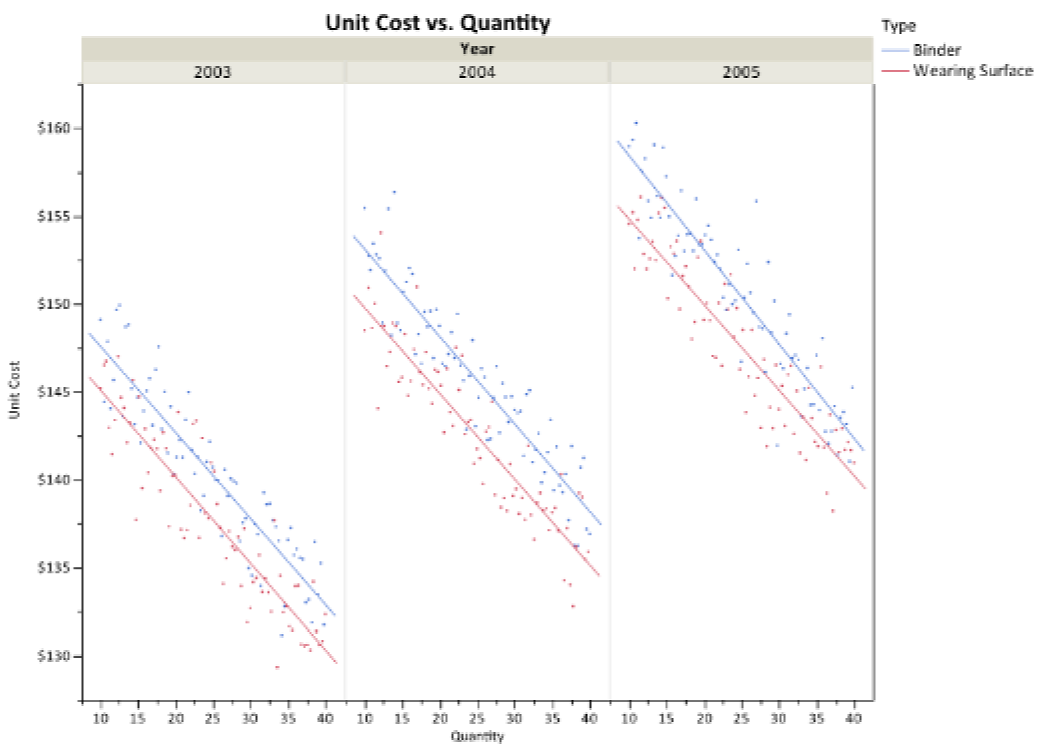


Figure 32. Graph of linear profiles through time

To forecast these linear models into the future, consider a simple linear model with the unit cost as the dependent variable and quantity as the lone explanatory variable so that the estimated regression coefficients can be obtained at each profile. If, for example, the unit cost of the material in question had a positive trend through time, it is hypothesized that the intercept of the models would steadily increase through time while the slope of the model would stay relatively consistent. If the intercepts were serially correlated, a time series model could then be constructed that would allow an estimator to forecast the intercept value at a point in the future. If the slope coefficients of the models at each profile were not serially correlated, the average of the slope coefficients could then be used to with the forecasted intercept term to create a linear model that could predict the unit cost of the material in the future.

To create an initial construction cost-estimating model for use in an LCCA, this research will use variables known to the estimator at the time the LCCA is conducted, including the type of paving material, the quantity of paving material needed, the location of the project, and the estimated point in time the project will be bid. At each time period, a profile will be created using multiple regression techniques with the real unit cost of the material as the dependent variable and the type of material, quantity of material, and other data used as explanatory variables. A time series model (if applicable) of the regression coefficients of each regression model at each profile will then be created; the time series model will be used to forecast values of the regression coefficients into the future to account for when the project will actually be let. This initial cost-estimating model will also allow for both deterministic and probabilistic approaches to the LCCA.

## 5.3 Asphalt Pavement Cost Data

To estimate the initial construction costs of asphalt pavements, historical bid data for both materials is needed to calculate necessary values for use in a probabilistic pavement LCCA. All paving cost data for this research was obtained through the Oman Systems, Inc. Bid Tabs Professional database. This database contains bid data for common highway construction activities including bridge construction, earthwork, paving operations, and signage installation. Cost data from nine states in the Southeast region of the United States was available through the Oman database, including data from the states of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee. Asphalt cost data, on the other hand, was only gathered from the state of Alabama because it is the most commonly used paving material in the state historically and an abundant data set was available.

After the bid data for asphalt pavements was gathered for each of the nine states, the next step in the methodology was to examine the data set to determine what data was needed to perform this research. The Oman database provides the bid data in a tabular format with the following columns of data that was exported into an Excel spreadsheet:

- Pay Item
- Pay Item Description
- Quantity
- Unit
- Unit (Metric)
- Amount
- Extension [Total cost for pay item]
- Job Number
- Bid Date
- County
- Bidders [First three bidders]

- Region
- Position
- Project Description
- Notes
- Total Project Cost

Once the data was collected for each state and the dataset was exported into an Excel spreadsheet, the next step was to create main groups of data for analysis. For this research effort, the main groups were created for asphalt paving projects. To populate the main groups, the pay item descriptions for each data point were analyzed to determine which main group best represents the data point. The asphalt group was populated with bid data from the state of Alabama and contains pay items dealing with all activities associated with asphalt paving.

Within the pay item description column of the pavement cost data set, certain information was provided that identified key characteristics of the data point. These characteristics would later be used as explanatory variables in the multiple regression models at each time profile. For example, ALDOT organizes their asphalt pay items so that they are divided into groups indicating which layer of the asphalt pavement they would be used. For this research, identifiers for the paving mixtures were created for each data point for lower binder layers, upper binder layers, and wearing surface layers. A majority of the asphalt pavement data contained enough information within the pay item description so that the layer identifiers were obtainable. However, some data points did not contain enough information to populate the respective columns for each material and these data points were subsequently withheld from the main data set.

The next step in the research methodology was examining bid dates in the data to determine which data points were needed for the initial construction cost forecast. The start date for the time series model of the linear profiles and the regression coefficients was chosen to be January 2000. While data was available for dates prior to 2000, data was consistently provided by all states starting around the year 2000. Similarly, most bid data was provided until the middle of May 2012. So, for this research, data from January 2000 to April 2012 was used in the analysis.

The next step of the process was determining the length of time to model by each profile. Since the bid day, month, and year was provided for each data point in the Oman data sets, modeling the data at each month was initially chosen as the time period for each profile. However, creating profiles at each month created two problems. Since the asphalt data came solely from the state of Alabama, ALDOT opens a small number of bids (or none at all) during the month of October of each year. By using the monthly time period approach, profiles created at each month of the year would consistently have no data for October of each year. If bid data were available, very few data points would be available to create the regression models. Another critical component of the time periods used in the analysis was the amount of data needed for each profile. To create the linear profiles, sufficient data was needed so that linear models could be created that would provide a reasonable estimation of the regression coefficients at each profile. Given these limitations, the asphalt pavement data was aggregated into bimonthly time periods. For example, the data from the months of January and February of the year 2000 was grouped into time period 1. These time periods were numbered sequentially from the beginning of year 2000 to May 2012. In total, 75 time periods were created for both pavement data sets.

After the main groups were created for each pavement material and the data was categorized by time period, the bid unit cost for each data point needed to be adjusted for the project location and for inflation so that all data could be analyzed at a common location at the same point in time. Since the asphalt pavement data set contained data points from multiple regions of Alabama, the bid unit costs for those projects were adjusted to bring all of the costs to the Birmingham region. To adjust the unit costs for a given project's project original location, the following equation was used:

$$Unit\ Cost_{Alabama} = (Unit\ Cost_k)\frac{Location\ Factor_{Alabama}}{Location\ Factor_k}$$

The location factors and map of Alabama can be seen in Appendix A.

The asphalt data set was adjusted for inflation using the general CPI index. This adjustment was made using a similar formula as the one employed to adjust for the location of the asphalt paving data. Because the last month in the data set was fixed at April 2012, the CPI value at that point in time was used as the base index for adjustment.

### 5.3.1 Asphalt Pavement Cost Data Statistics

In total, 11,062 asphalt bid cost data points were initially identified for the analysis. The average number of data points within a bimonthly time period was 149.5. For all time periods, there were 5,508 wearing surface data points, 4,361 upper binder data points, and 1,193 lower binder layer data points. The average number of data points per time period for the wearing surface, upper binder, and lower binder groups was 74.4, 58.9, and 16.1, respectively. The total number of data points per time period and the statistics of each layer are provided in Appendix B.

To provide a validation period for the time series models of the regression coefficients, the last ten time periods of data were withheld from the initial construction of the regression models. Summary statistics and a graphical analysis of the variables for the first 65 time periods of data are provided below. The first variable examined was the quantity of asphalt material used in each project. From the data, the mean quantity was calculated to be 4,309.5 tons with a standard deviation of 9,768.6 tons. The median quantity value was determined to be 1,007.5 tons. The quantity variable also displayed a fairly sizeable range, with a minimum value of one ton and a maximum value of 295,416 tons. A histogram of the quantity variable for the first 65 time periods of data is shown in Figures 33.

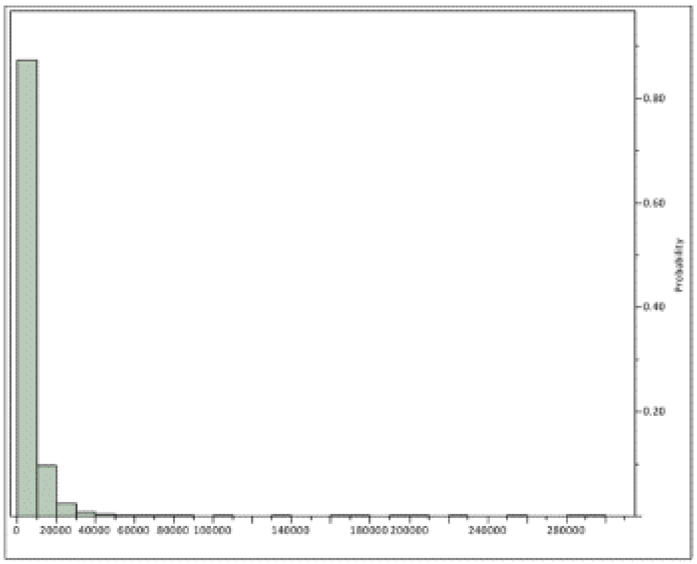



Figure 33. Histogram of asphalt quantity variable

Similar statistics were calculated for the unit cost of the asphalt pavement data for the first 65 bimonthly time periods of data. The mean cost per ton of asphalt material was calculated to be \$68.77 per ton of asphalt with a standard deviation of \$28.74 per ton of material. The median unit cost was determined to be \$63.30 per ton. The range of the asphalt unit cost data was \$391.20 per ton, with a minimum value of \$2.23 per ton and a maximum unit cost of \$393.40 per ton. A histogram of the unit costs is shown in Figure 34.

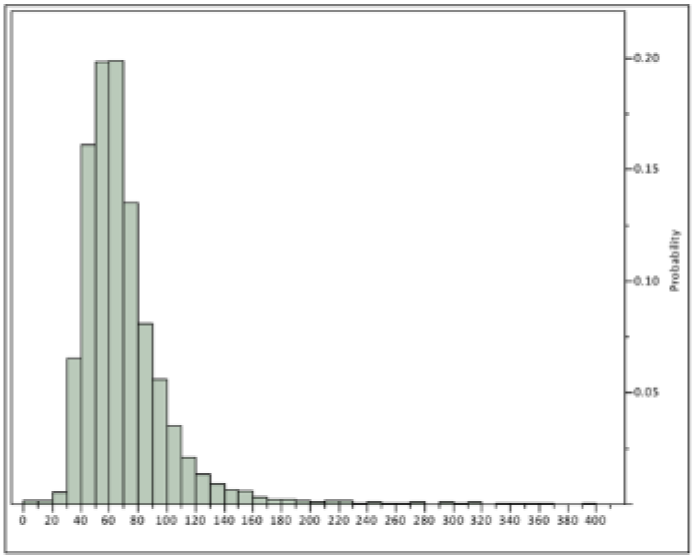


Figure 34. Histogram of asphalt unit cost variable

## 5.3.2 Asphalt Regression Models

After the pavement cost data asphalt was prepared for analysis, the next step in the methodology was creating the regression models for the first 65 time periods of data. Since multiple explanatory variables were available that would also be available for an estimator at the time the initial construction cost estimate was to be made, a multiple regression model was chosen as the starting point for this research effort. The dependent variable in the model was the unit cost of the asphalt and the explanatory variables were chosen to be the quantity of asphalt needed for the project and the type of asphalt. These variables would allow an estimator to predict the unit cost of the material based on information available at the time the LCCA is conducted.

The regression model used to fit the data is as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3$$

where $y$ is the unit cost of the asphalt (dollars per ton), $x_1$ is the quantity of asphalt (tons), and the $x_2$ and $x_3$ is the type of asphalt (wearing surface, upper binder layer, or lower binder layer).

Dummy coding was used for variables $x_2$ and $x_3$ since they are categorical variables and their direct inclusion into the regression model would not provide a meaningful interpretation. The coding for this analysis is provided in Table 23. An interaction between the quantity of asphalt and the type of asphalt was included in the model to determine if there is a difference in the slope on the quantity variable for the three types of asphalt.

Table 23. Regression dummy variables

| | $x_2$ | $x_3$ |
|---|---|---|
| Wearing Surface | 0 | 0 |
| Upper Binder | 1 | 0 |
| Lower Binder | 0 | 1 |

Once the dependent variable and the explanatory variables were defined, the next step in building the multiple regression models was to visually inspect the data as a whole for the entire data for the first 65 periods. A regression model for the entire data set would determine the applicability of the model in general and variables chosen for this study. The overall model will also serve as a baseline for the individual models built for each time period. From Figure 35, it can be seen that the plot of unit cost versus quantity does not appear to exhibit a strong linear pattern in the data, with a majority of the data points clustered at the low values of both quantity and unit cost. The relatively weak linear relationship for unit cost and quantity was confirmed with a correlation coefficient that was calculated to be equal to -0.2448. A correlation matrix for the two variables is shown in Figure 36.

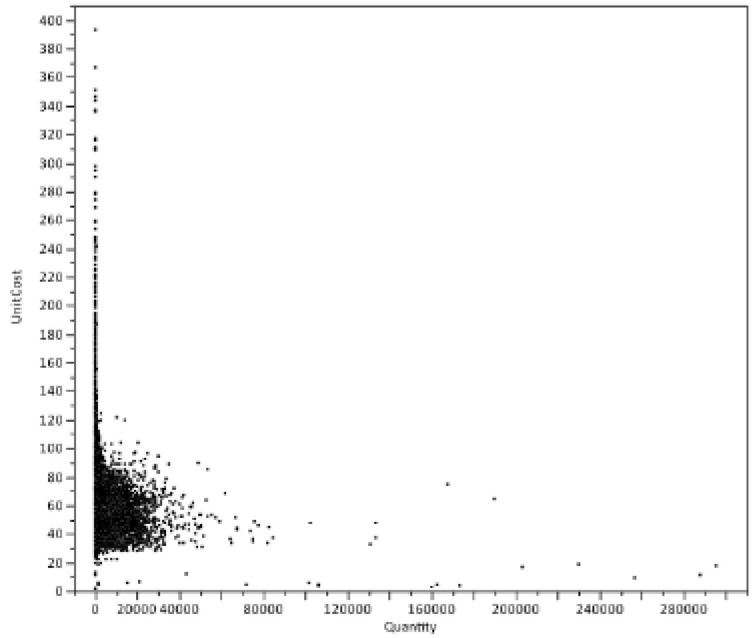


Figure 35. Asphalt unit cost versus quantity

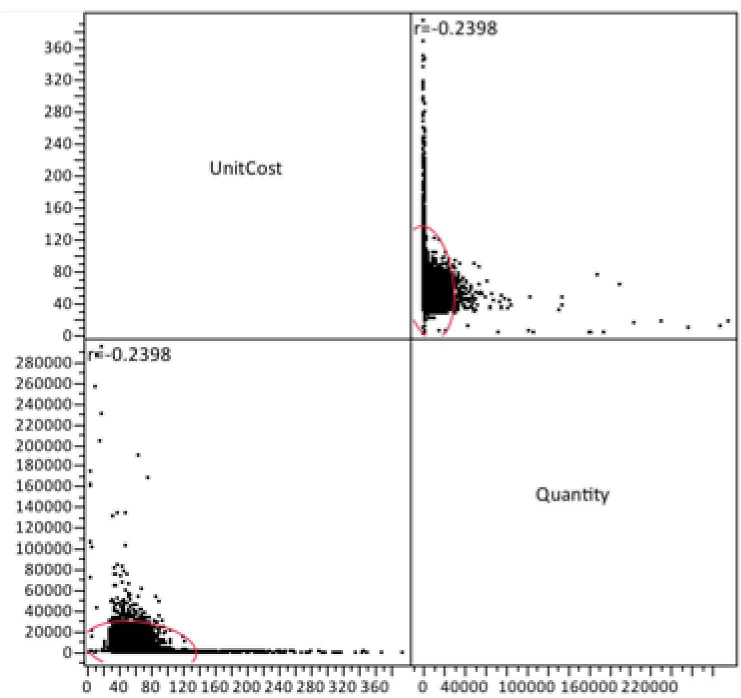


Figure 36. Unit cost and quantity scatterplot matrix

Given that the distributions of the unit cost variable and the quantity variable were heavily skewed to the right, these variables were transformed by taking the natural logarithm of both variables before fitting the regression model. The correlation coefficient between the natural logarithm of unit cost and the natural logarithm of quantity was calculated to be -0.5381, indicating that the transformed variables have a moderate linear relationship. The scatterplot matrix for the transformed variables is provided in Figure 37.

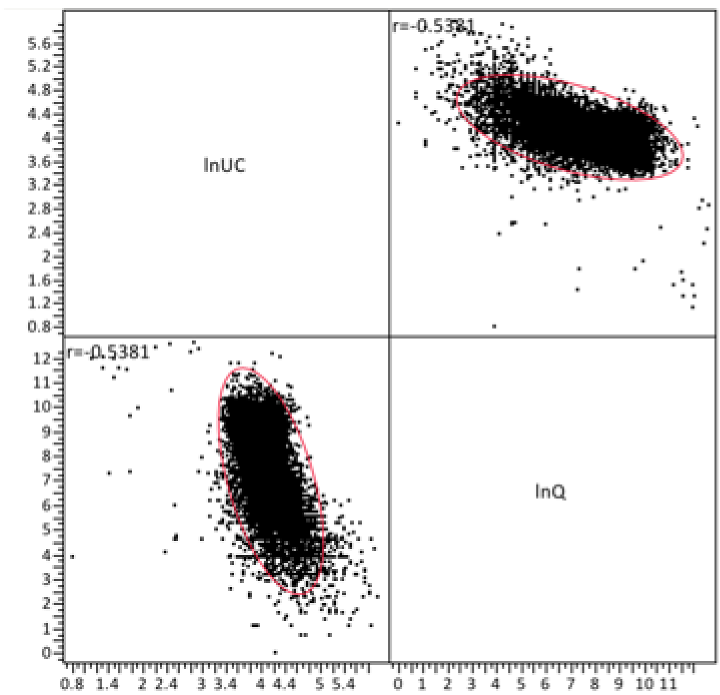


Figure 37. Transformed unit cost and quantity scatterplot matrix

Since the transformations of unit cost and quantity appeared to improve the linear relationship between the two variables the regression model of the form

$$lny = \beta_0 + \beta_1 lnx_1 + \beta_2 x_2 + \beta_{12}(lnx_1)x_2 + \beta_{13}(lnx_1)x_3$$

was used to model the data set. The JMP output results of the regression fit for the first 65 periods are shown in Table 24.

Table 24. Full regression model summary statistics

| Summary of Fit | |
|---|---|
| $R^2$ | 0.311234 |
| $R^2$ Adjusted | 0.310878 |
| Root Mean Square Error | 0.306503 |
| Mean of Response | 4.138004 |
| Observations (or Sum Weights) | 9,661 |

**Analysis of Variance**

| Source | DF | Sum of Squares | Mean Square | F Ratio |
|---|---|---|---|---|
| Model | 5 | 409.861 | 81.9722 | 872.5659 |
| Error | 9,655 | 907.0278 | 0.0939 | **Prob > F** |
| C. Total | 9,660 | 1,316.8888 | | <.0001* |

**Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 4.7675191 | 0.017607 | 270.78 | <.0001* |
| lnx1 | -0.088243 | 0.002403 | -36.72 | <.0001* |
| x2 | 0.2046586 | 0.02566 | 7.98 | <.0001* |
| x3 | 0.3201562 | 0.038473 | 8.32 | <.0001* |
| lnx1*x2 | -0.03464 | 0.003574 | -9.69 | <.0001* |
| lnx1*x3 | -0.049309 | 0.005282 | -9.33 | <.0001* |

From the output, it was shown that all least-squares coefficients were found to be significantly different than zero at a five percent significance level. The $R^2$ value, or the proportion of the variance in the dependent variable explained by the regression model, was calculated to be 0.3112.

The next step after fitting the regression model is to examine the residuals and determine if the model is adequate or if the assumptions pertaining to least-squares regression were violated. The assumptions of the linear regression model are:

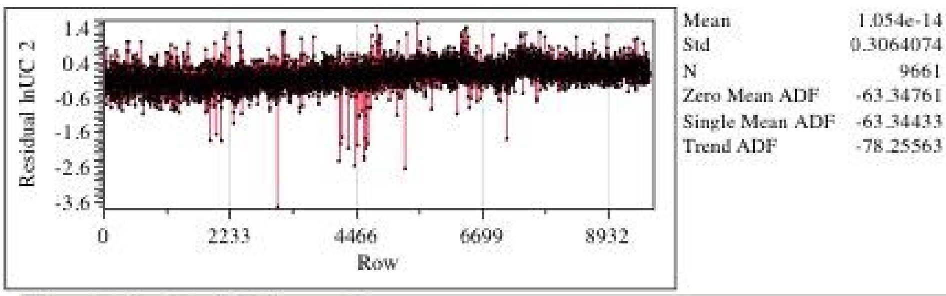
1. The errors of the model are random and independent, and the magnitude of an error does not influence the value of the next error,

2. The errors all have mean 0,

3. The errors are homoscedastic (all have the same variance, $\sigma^2$),

4. The errors are normally distributed (Navidi 2008).

The first check of the residuals was to determine if there was any autocorrelation present. Since the data set was in chronological order, examining the autocorrelation plot and the partial autocorrelation plot of the residuals performed the check for autocorrelation. A plot of the residuals by row number and the autocorrelation (ACF) and partial autocorrelation (PACF) plots are shown in Figure 38.




**Time Series Basic Diagnostics**

| Lag | AutoCorr | -.8-.6-.4-.2 0 .2 .4 .6 .8 | Ljung-Box Q | p-Value | Lag | Partial | -.8-.6-.4-.2 0 .2 .4 .6 .8 |
|---|---|---|---|---|---|---|---|
| 0 | 1.0000 | | . | . | 0 | 1.0000 | |
| 1 | 0.4130 | | 1648.10 | <.0001* | 1 | 0.4130 | |
| 2 | 0.3396 | | 2762.90 | <.0001* | 2 | 0.2038 | |
| 3 | 0.2996 | | 3630.27 | <.0001* | 3 | 0.1305 | |
| 4 | 0.2907 | | 4447.27 | <.0001* | 4 | 0.1173 | |
| 5 | 0.2874 | | 5245.96 | <.0001* | 5 | 0.1048 | |
| 6 | 0.3054 | | 6147.84 | <.0001* | 6 | 0.1196 | |
| 7 | 0.3045 | | 7044.37 | <.0001* | 7 | 0.0981 | |
| 8 | 0.3117 | | 7984.02 | <.0001* | 8 | 0.0982 | |
| 9 | 0.3038 | | 8876.52 | <.0001* | 9 | 0.0765 | |
| 10 | 0.2949 | | 9717.81 | <.0001* | 10 | 0.0623 | |

Figure 38. Residuals by row with autocorrelation and partial autocorrelation plots

From the plot of the residuals by row scatterplot in Figure 38, it can be seen that there appears to be an upward trend in the residuals through time. The significant autocorrelations in the ACF plot and partial autocorrelations in the PACF plot also show that a trend in the residuals through time is present.

In addition to the autocorrelation of the model residuals, the check for equal variances of the residuals also provided an area for concern. The diagnostic tool used for this check was the residual versus the predicted value of *lny* scatterplot (shown in Figure 39). From the graph, it appears that the variability in the residuals is not consistent throughout the range of the predicted values, with smaller variability at smaller predicted values (larger quantities of material) and larger variability at larger predicted values (smaller quantities of asphalt). Given the lack of independence in the residuals and the heteroscedastic nature of the residuals, it was determined that this model is not a good fit for the first 65 periods of asphalt pavement data.

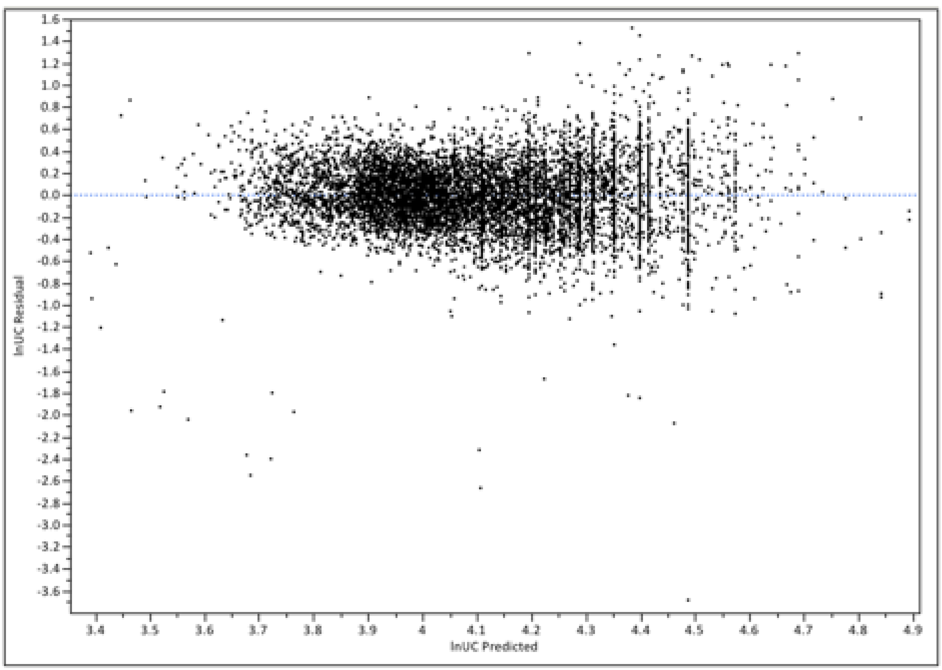


Figure 39. Residuals by predicted values plot

Since the regression models were to be fit to each bimonthly time period of data and a trend in the real unit cost of asphalt was anticipated, which would explain the trend in the residuals, the baseline regression model for the entire first 65 bimonthly time periods of data may or may not provide a good representation of the regression models fit to each individual time period. To verify, a regression model was fit for each period of data and the residuals were examined to determine the adequacy of the regression models at each period based on the assumptions of linear regression.

From the regression fit at each time period, several of the regression coefficients were not significant at a five percent significance level for each time period. Only time periods 25, 59, 60 and 65 had all significant regression coefficients. To determine the adequacy of each model at every period, the residuals for each time period were examined to see if the assumptions were violated. The autocorrelation and partial autocorrelation plots for the residuals at each time period did not show as severe a violation of the independence assumption as the regression model fit to the entire data set. However, significant first lag autocorrelation were found for the residuals in several periods, including periods 7, 29, 33, 43, 45, 46, and 53. Overall, the residuals for each bimonthly time period also violated the equal variances assumption, with a "fan" pattern similar to the residuals of the overall regression model shown above. An example of the typical pattern shown in the residuals by predicted value plot is shown in Figure 40.

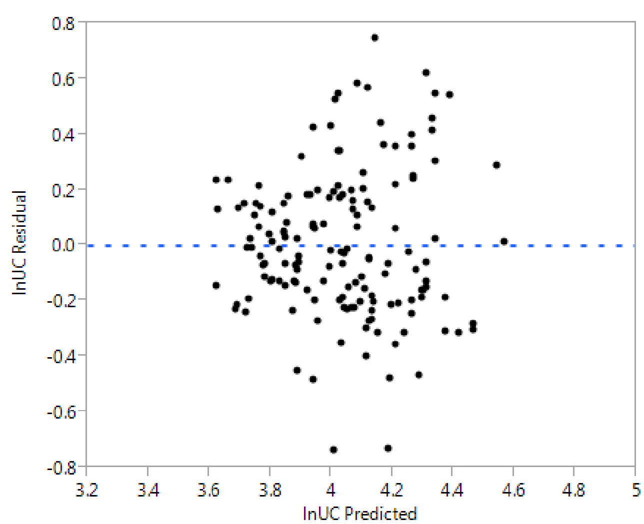



Figure 40. Time period #5 residuals by predicted values plot

While regression analysis is moderately robust to violations of equal variance, it is not very robust to violating the independent residuals assumption. Correlated residuals can have a significant effect on the inferences made on the regression coefficients. The ordinary least squares estimates of the standard errors of the coefficients will be inconsistent and will typically underestimate the true standard error, resulting in higher *t*-values. The higher t-values will cause coefficients to appear more significant. Due to violation of assumptions in both the overall regression model and the models fit to each time period of data, it was determined that the models were not adequate and would not provide a good representation of the data set and that another methodology was needed to forecast the unit cost of asphalt.

### 5.3.3 Time Series Model of Asphalt Unit Cost

Since the multiple regression models at each time period were not adequate, the next approach considered was to build a time series model using the average and standard deviation values of the asphalt unit cost calculated for each time period. Given what was learned about the higher variability of the asphalt unit costs at lower quantities and lower variability in unit cost at larger quantities when fitting the regression models at each time period, the data set was separated into two groups based on the quantity variable to determine any differences in the average unit cost and standard deviation of the unit cost. The cut-off point between the groups was chosen to be 1,000 tons from an examination of the scatterplot of the unit costs versus quantity. For this quantity of asphalt and greater, the variability of the unit costs became more consistent. This cut-off point was also approximately equal to the median quantity. Group A was comprised of data that required less than a 1,000 tons of material while Group B represented quantities equal to or greater than 1,000 tons of material. The mean unit cost and standard deviation for both groups A and B, respectively, at each time period can be found in Appendix C. A plot of the mean unit costs for each layer for quantity groups A and B are shown in Figures 41 and 42, respectively.

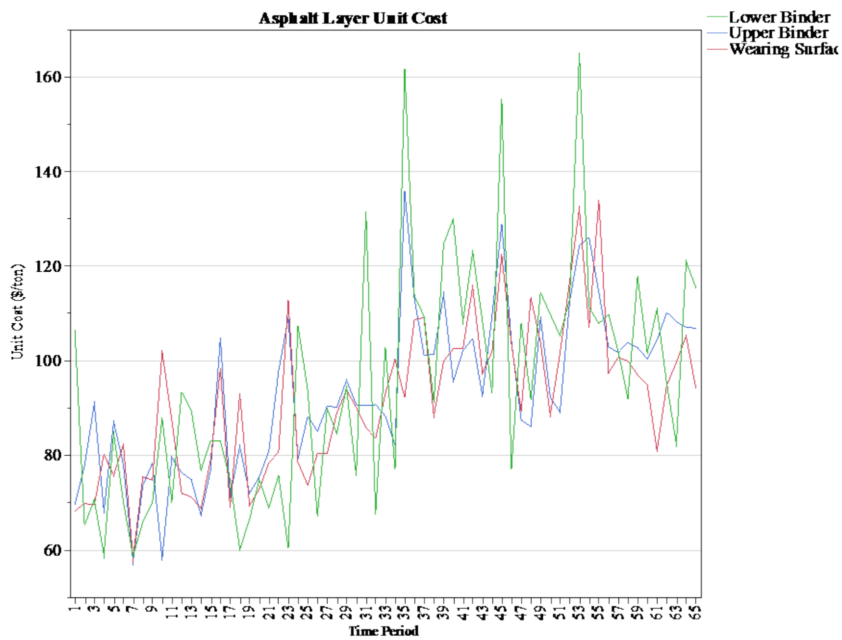



Figure 41. Mean unit cost by layer for first 65 periods (quantity group A)

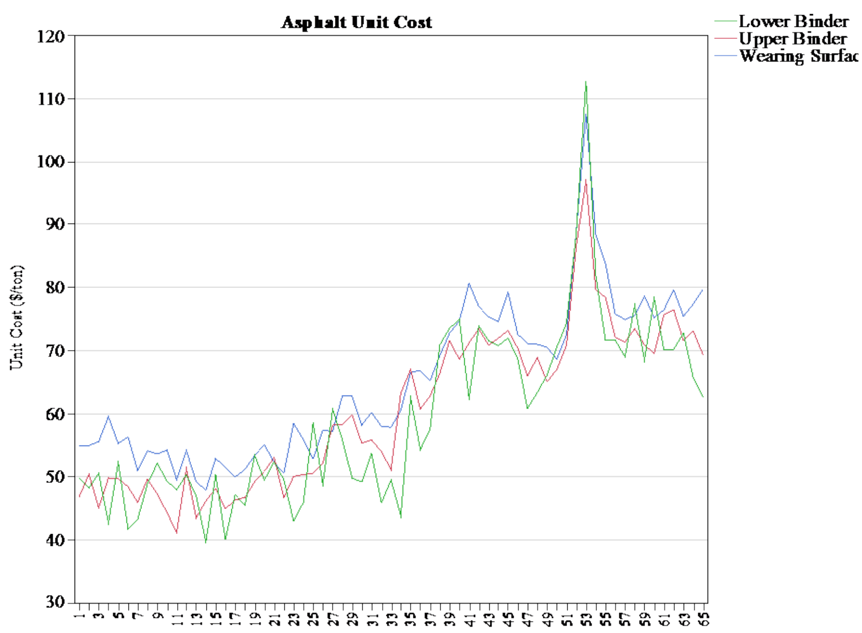



Figure 42. Mean unit cost by layer for first 65 periods (quantity group B)

The goal of the first approach for creating prediction models for the unit costs of the three asphalt layers was to build the time series models for the mean unit cost for both groups. Time series models are used to model historical data and to forecast future observations of the series of interest. A general class of time series models for stationary data is classified as autoregressive-moving-average (ARMA) models. These mixed models expresses a time series as a linear function of its past values. An autoregressive-moving average process of order (*p, q*) is represented by

$$Y_t = \mu + \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{t-p} + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} \cdots \theta_q a_{t-q}$$

where $Y_t$ is the observable time series, $\mu$ is the mean of the series, and $a_t$ is a white noise process independently distributed as $N(0, \sigma^2)$.

If the time series is not stationary, however, the data may need to be processed first to remove any long-term trends or evidence of seasonality. One method that may remove a trend in the data is known as differencing. By differencing a time series, the first observation is subtracted from the second observation, the second observation in the series is subtracted from the third observation, and so on. If differencing is necessary to make the original time series stationary, the process can be defined as an autoregressive-integrated-moving-average (ARIMA) model of order (*p, d, q*), where *d* equals the degree of differencing. For example, if *d* is equal to one, then an ARIMA (*p, 1, q*) process can be represented by the equation

$$Y_t - Y_{t-1} = \phi_1(Y_{t-2} - Y_{t-1}) + \phi_2(Y_{t-3} - Y_{t-2}) + \cdots + \phi_p(Y_{t-p} - Y_{t-p-1}) + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} \cdots \theta_q a_{t-q}$$

For the lower binder data for quantity group A, a plot of the data for the first 65 time periods and the ACF and PACF plots for the series are provided in Figures 43 and 44, respectively.

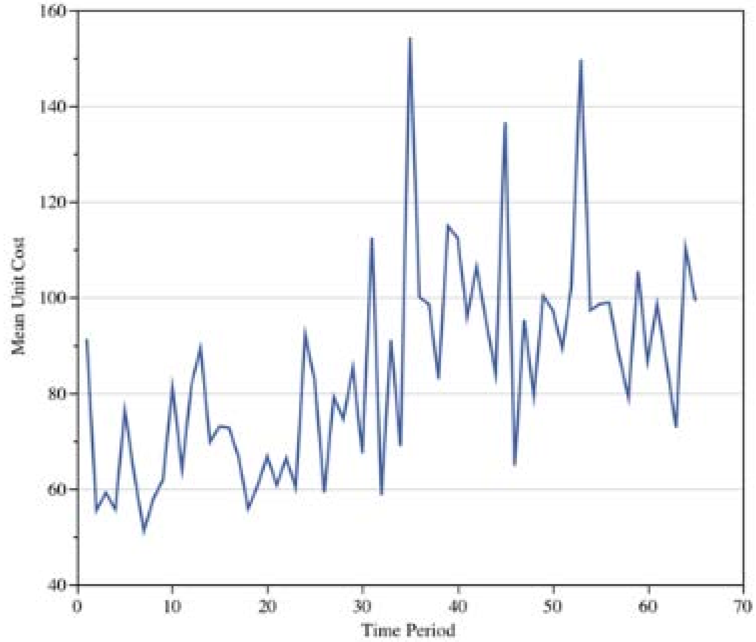
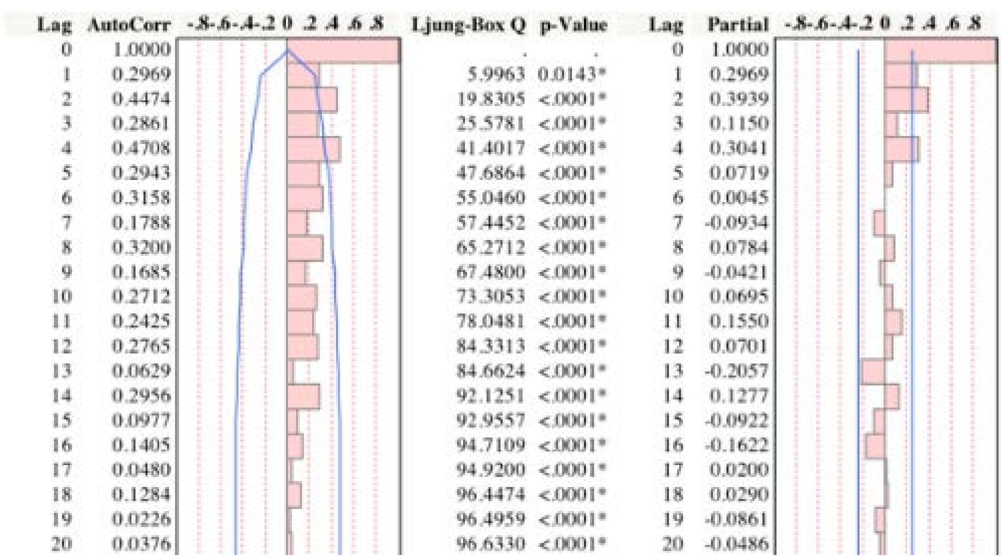


Figure 43. Mean unit cost of lower binder layer for first 65 periods (quantity group A)



| Lag | AutoCorr | Ljung-Box Q | p-Value | Lag | Partial |
|---|---|---|---|---|---|
| 0 | 1.0000 | . | . | 0 | 1.0000 |
| 1 | 0.2969 | 5.9963 | 0.0143* | 1 | 0.2969 |
| 2 | 0.4474 | 19.8305 | <.0001* | 2 | 0.3939 |
| 3 | 0.2861 | 25.5781 | <.0001* | 3 | 0.1150 |
| 4 | 0.4708 | 41.4017 | <.0001* | 4 | 0.3041 |
| 5 | 0.2943 | 47.6864 | <.0001* | 5 | 0.0719 |
| 6 | 0.3158 | 55.0460 | <.0001* | 6 | 0.0045 |
| 7 | 0.1788 | 57.4452 | <.0001* | 7 | -0.0934 |
| 8 | 0.3200 | 65.2712 | <.0001* | 8 | 0.0784 |
| 9 | 0.1685 | 67.4800 | <.0001* | 9 | -0.0421 |
| 10 | 0.2712 | 73.3053 | <.0001* | 10 | 0.0695 |
| 11 | 0.2425 | 78.0481 | <.0001* | 11 | 0.1550 |
| 12 | 0.2765 | 84.3313 | <.0001* | 12 | 0.0701 |
| 13 | 0.0629 | 84.6624 | <.0001* | 13 | -0.2057 |
| 14 | 0.2956 | 92.1251 | <.0001* | 14 | 0.1277 |
| 15 | 0.0977 | 92.9557 | <.0001* | 15 | -0.0922 |
| 16 | 0.1405 | 94.7109 | <.0001* | 16 | -0.1622 |
| 17 | 0.0480 | 94.9200 | <.0001* | 17 | 0.0200 |
| 18 | 0.1284 | 96.4474 | <.0001* | 18 | 0.0290 |
| 19 | 0.0226 | 96.4959 | <.0001* | 19 | -0.0861 |
| 20 | 0.0376 | 96.6330 | <.0001* | 20 | -0.0486 |

Figure 44. ACF and PACF for lower binder (quantity group A)

After examining the ACF and PACF plots and fitting several models to the lower binder series, an IMA (1, 1) model without a constant term was chosen as it provided the best fit to the data set. The model summary statistics and parameter estimates for the model are provided in

Table 25. The standard deviation of the fitted model was estimated to be 18.8377 with an $R^2$ value of 0.2526. The estimated MA (1) coefficient was significant at a five percent significance level.

Table 25. IMA (1, 1) without constant model statistics for lower binder (quantity group A)

| **Model Summary** | |
|---|---|
| Degrees of Freedom | 63 |
| Sum of Squared Errors | 22,356.1646 |
| Variance Estimate | 354.8598 |
| Standard Deviation | 18.8377 |
| Akaike's 'A' Information Criterion | 559.5307 |
| $R^2$ | 0.2526 |
| MAPE | 15.5267 |
| MAE | 13.3269 |
| -2LogLikelihood | 557.5307 |

| **Parameter Estimates** | | | | | |
|---|---|---|---|---|---|
| **Term** | **Lag** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| MA1 | 1 | 0.821644 | 0.063277 | 12.98 | <.0001 |

To check the adequacy of the IMA (1, 1) model, the residuals of the fitted model were examined for autocorrelation and normality. The ACF and PACF plots of the residuals are provided in Figure 46. The ACF plot of the residuals does not indicate any significant autocorrelation. Assessing the normality of the residuals was accomplished by examining the normal probability plot of the residuals shown in Figure 45. While there is some departure from normality in the tails of the residual distribution, there is nothing unusual about this plot.

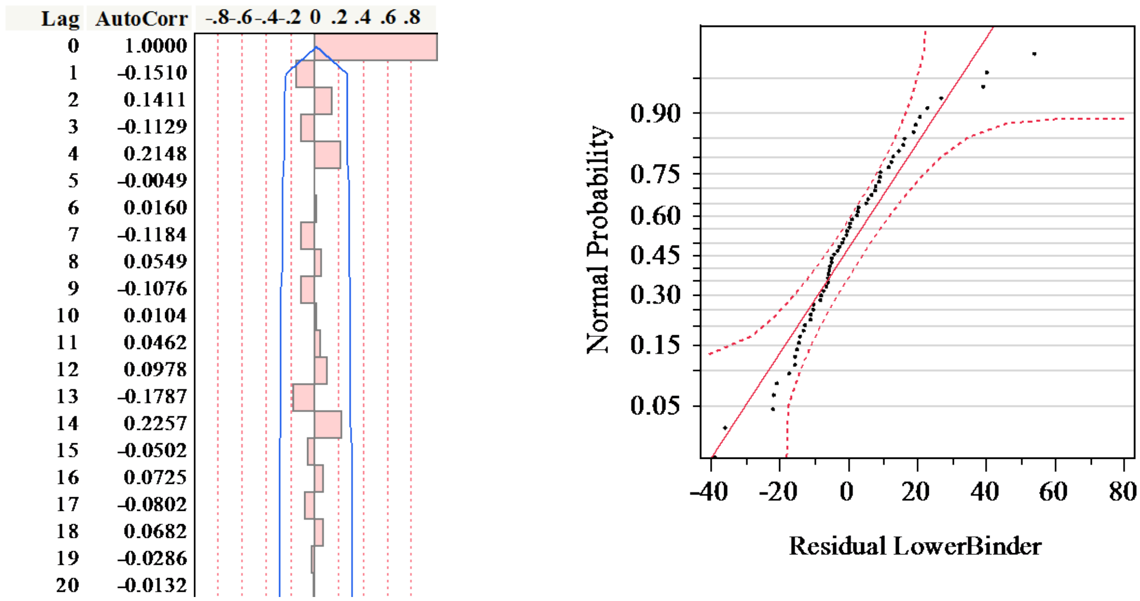



Figure 45. Residual plots of IMA (1, 1) residuals for lower binder (quantity group A)

The next layer to be analyzed for quantity group A was the upper binder layer. A plot of the mean unit cost data for the upper binder by bimonthly time period is provided in Figure 46. The ACF and PACF plots are shown in Figure 47.

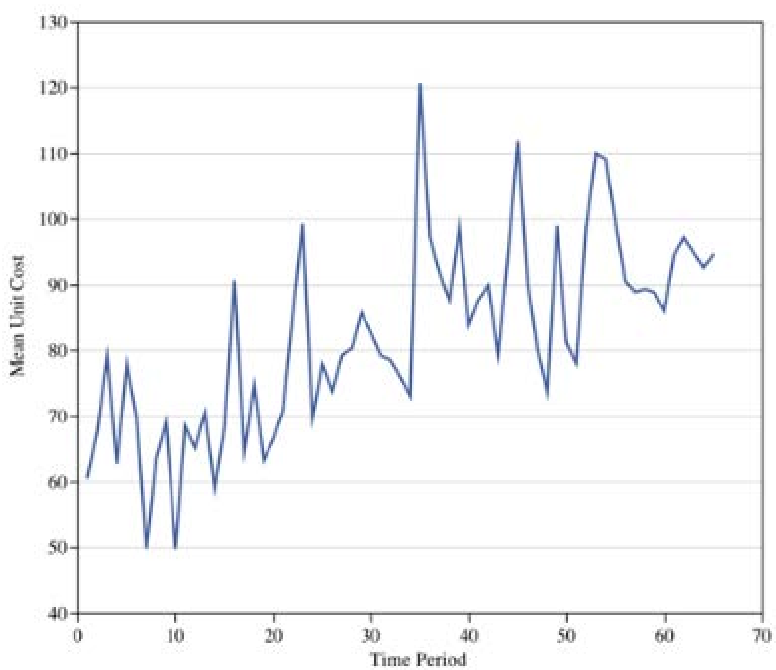



Figure 46. Mean unit cost of upper binder layer for first 65 periods (quantity group A)

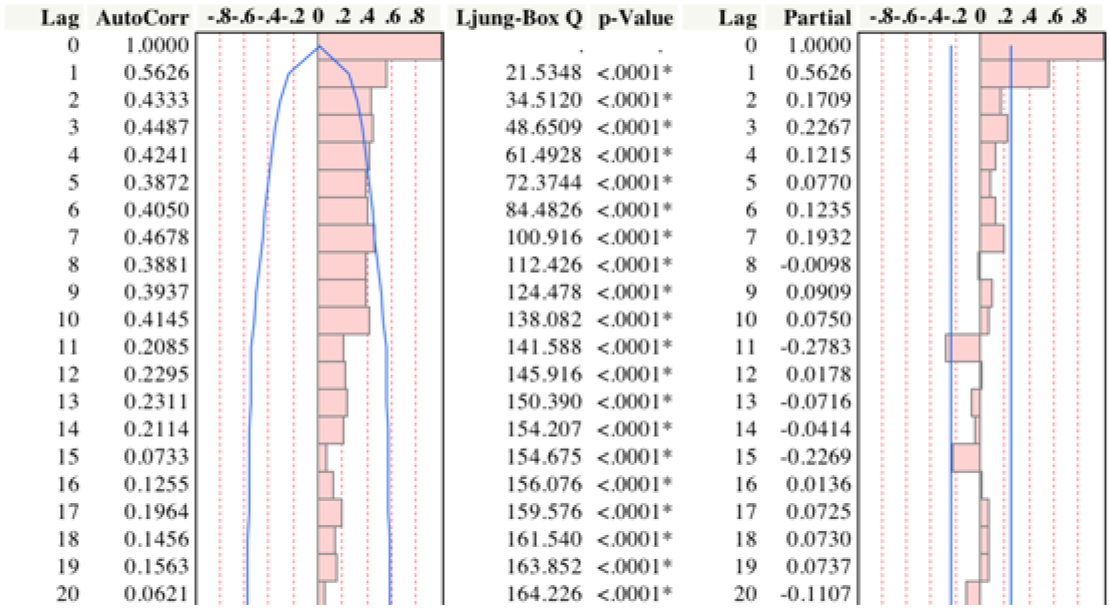


Figure 47. ACF and PACF of upper binder layer for first 65 periods (quantity group A)

After examining the ACF and PACF plots and fitting several models, it was determined that an IMA (1, 1) model without a constant term provided the best fit for the upper binder time series data. The statistics and parameter estimates for the model are provided in Table 26. The MA (1) coefficient was significant at a five percent significance level.

Table 26. IMA (1, 1) without constant model statistics for upper binder (quantity group A)

| **Model Summary** | |
|---|---|
| Degrees of Freedom | 63 |
| Sum of Squared Errors | 7,881.6613 |
| Variance Estimate | 125.1057 |
| Standard Deviation | 11.1851 |
| Akaike's 'A' Information Criterion | 492.6683 |
| $R^2$ | 0.4051 |
| MAPE | 9.7825 |
| MAE | 8.0947 |
| -2LogLikelihood | 490.6683 |

**Parameter Estimates**

| Term | Lag | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|---|
| MA1 | 1 | 0.791764 | 0.070438 | 11.24 | <.0001 |

From the ACF plot in Figure 48, it can be seen that there are no significant autocorrelations in the residuals of the IMA (1, 1) model for the upper binder layer data. The normal quantile plot, shown in Figure 48, does not indicate that there is a violation of the normality assumption. The IMA (1, 1) model with a constant was determined to be an adequate model for the first 65 time periods of the mean unit cost for the upper binder data.

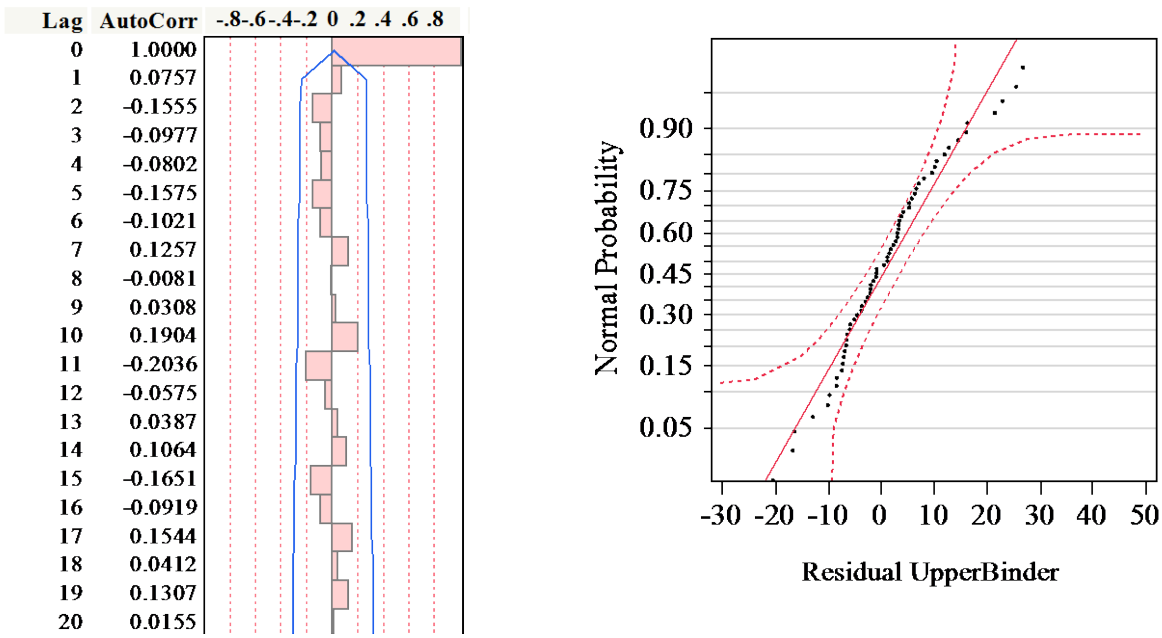


Figure 48. Residual plots of IMA (1, 1) residuals for upper binder (quantity group A)

The last layer to be analyzed for quantity group A was the wearing surface data set. A plot of the mean unit cost data for the wearing surface is provided in Figure 49. The ACF and PACF plots are shown in Figure 50.

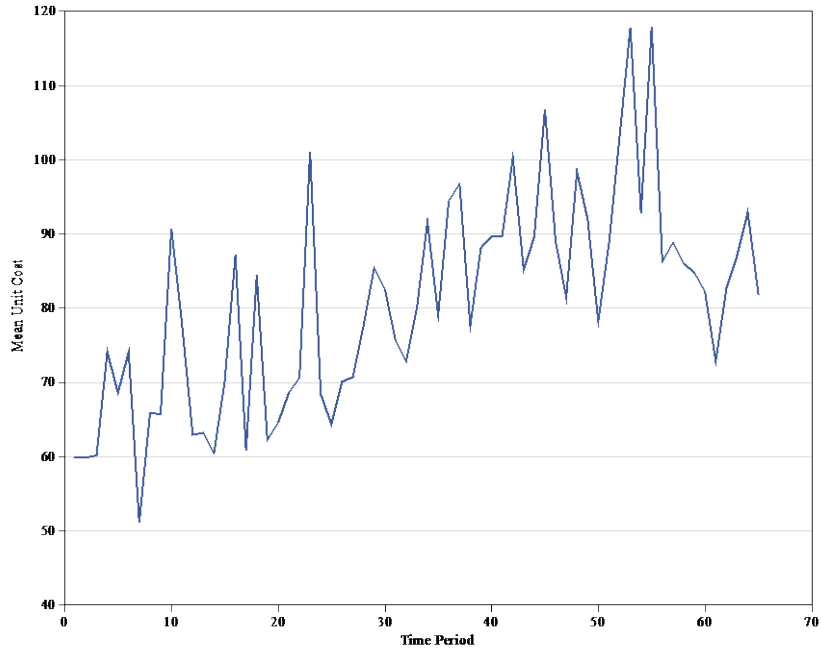


Figure 49. Mean unit cost of wearing surface layer for first 65 periods (quantity group A)

| Lag | AutoCorr | Ljung-Box Q | p-Value | Lag | Partial |
|---|---|---|---|---|---|
| 0 | 1.0000 | . | . | 0 | 1.0000 |
| 1 | 0.5115 | 17.8051 | <.0001* | 1 | 0.5115 |
| 2 | 0.4559 | 32.1744 | <.0001* | 2 | 0.2631 |
| 3 | 0.3790 | 42.2644 | <.0001* | 3 | 0.1056 |
| 4 | 0.3698 | 52.0292 | <.0001* | 4 | 0.1202 |
| 5 | 0.4623 | 67.5409 | <.0001* | 5 | 0.2582 |
| 6 | 0.4406 | 81.8685 | <.0001* | 6 | 0.1290 |
| 7 | 0.4358 | 96.1268 | <.0001* | 7 | 0.0991 |
| 8 | 0.3453 | 105.234 | <.0001* | 8 | -0.0283 |
| 9 | 0.2090 | 108.630 | <.0001* | 9 | -0.1812 |
| 10 | 0.3132 | 116.399 | <.0001* | 10 | 0.1047 |
| 11 | 0.3614 | 126.933 | <.0001* | 11 | 0.1381 |
| 12 | 0.3398 | 136.421 | <.0001* | 12 | -0.0122 |
| 13 | 0.3053 | 144.227 | <.0001* | 13 | -0.0255 |
| 14 | 0.1745 | 146.829 | <.0001* | 14 | -0.1182 |
| 15 | 0.0934 | 147.588 | <.0001* | 15 | -0.1707 |
| 16 | 0.1102 | 148.667 | <.0001* | 16 | -0.0368 |
| 17 | 0.0789 | 149.232 | <.0001* | 17 | -0.1241 |
| 18 | 0.1860 | 152.437 | <.0001* | 18 | 0.0536 |
| 19 | 0.1760 | 155.370 | <.0001* | 19 | 0.1330 |
| 20 | -0.0412 | 155.534 | <.0001* | 20 | -0.2407 |

Figure 50. ACF and PACF of wearing surface layer for first 65 periods (quantity group A)

After fitting several models, it was determined that an IMA (1, 1) without a constant term model provided the best fit for the wearing surface time series data for quantity group A. The model statistics and parameter estimates are shown in Table 27. The estimated MA (1) coefficient was significant at a five percent significance level.

Table 27. IMA (1, 1) without constant model statistics for wearing surface (quantity group A)

| **Model Summary** | | | | | |
|---|---|---|---|---|---|
| Degrees of Freedom | 63 | | | | |
| Sum of Squared Errors | 7,791.2369 | | | | |
| Variance Estimate | 123.6704 | | | | |
| Standard Deviation | 11.1207 | | | | |
| Akaike's 'A' Information Criterion | 491.8732 | | | | |
| $R^2$ | 0.3733 | | | | |
| MAPE | 10.4570 | | | | |
| MAE | 8.6513 | | | | |
| -2LogLikelihood | 489.8732 | | | | |
| **Parameter Estimates** | | | | | |
| **Term** | **Lag** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| MA1 | 1 | 0.777924 | 0.074125 | 10.49 | <.0001 |

The residuals of the IMA (1, 1) model were checked to assess the adequacy of the model. From the ACF plot in Figure 51, it can be seen that there are no significant autocorrelations in the residuals of the IMA (1, 1) model for the wearing surface data. The normal probability plot, shown in Figure 51, does not indicate that there is a severe violation of the normality assumption. After checking the adequacy of the model, the IMA (1, 1) without a constant was determined to be an adequate model for the wearing surface data.

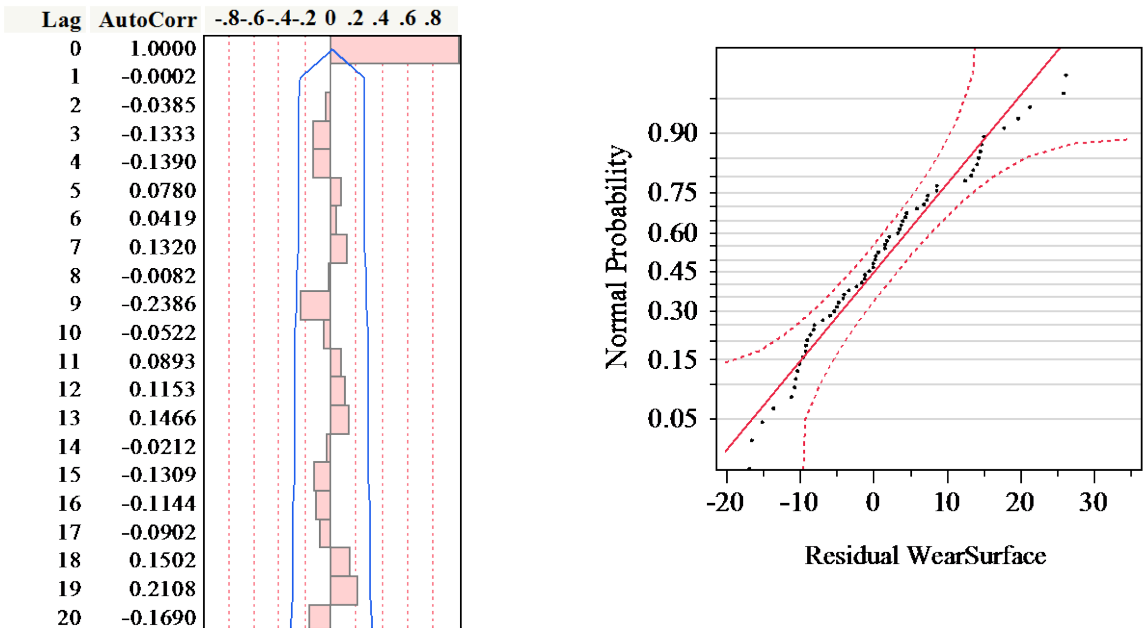


Figure 51. ACF of IMA (1, 1) residuals for wearing surface (quantity group A)

### 5.3.4 Time Series Models for Asphalt Group B

A plot of the mean unit costs can be seen in Figure 52 while the ACF and PACF plots of the lower binder data can be found in Figure 53.

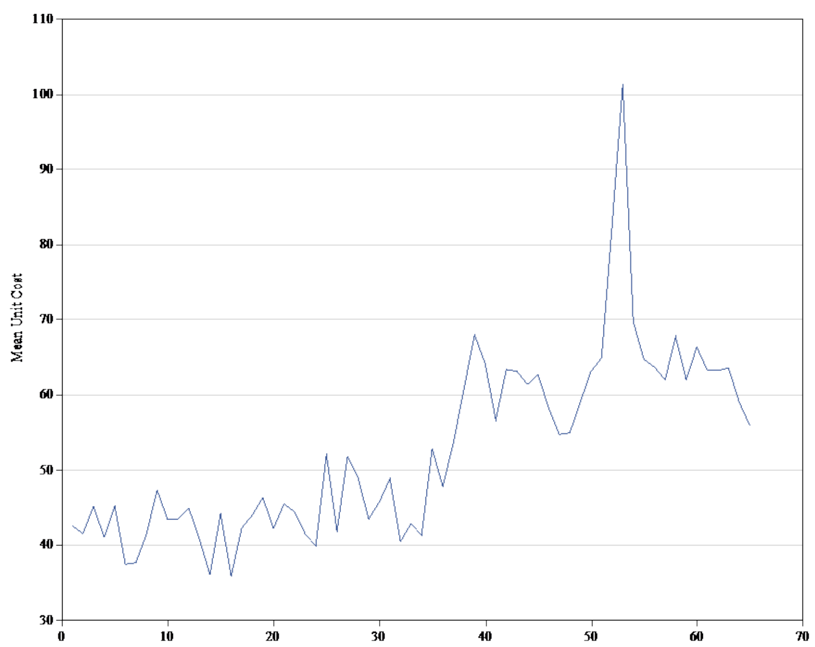


Figure 52. Mean unit cost of lower binder layer for first 65 periods (quantity group B)

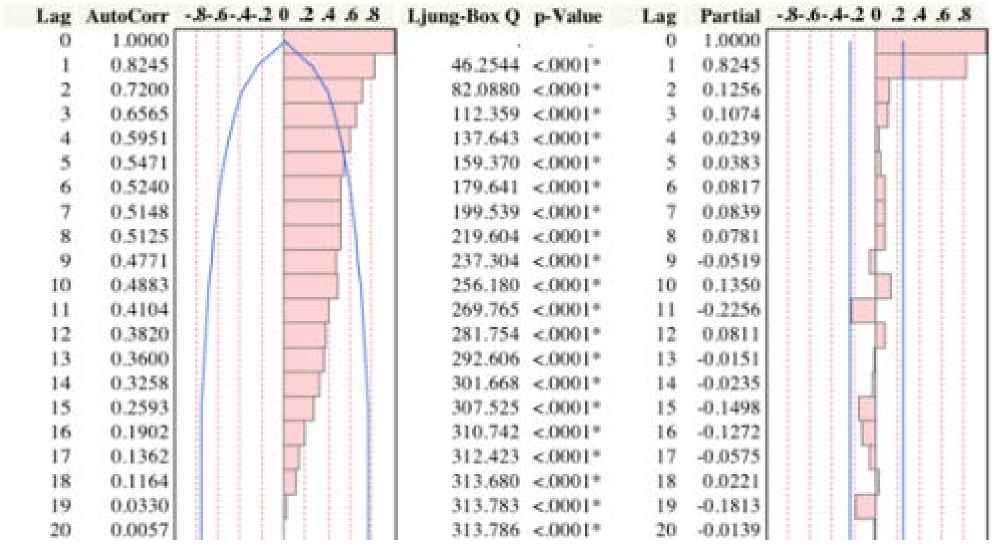


Figure 53. ACF and PACF for lower binder (quantity group B)

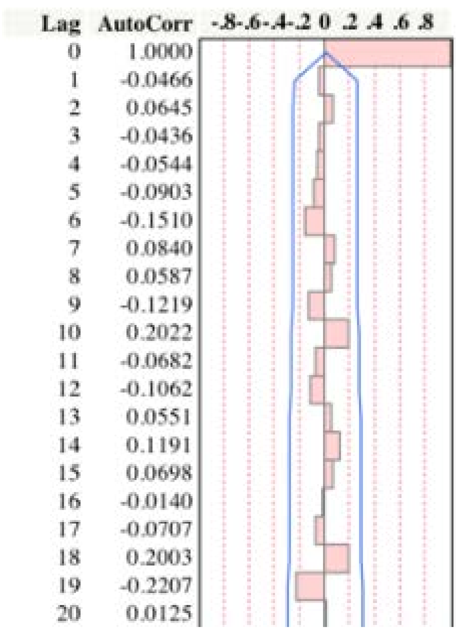
After fitting and testing several models, it was determined that an ARIMA (1, 1, 1) model without a constant term provided the best fit for the lower binder data set. The model statistics are provided in Table 28. Both the estimated AR (1) coefficient and MA (1) coefficient are significant at a five percent significance level.

Table 28. ARIMA (1, 1, 1) model statistics for lower binder (quantity group B)

| **Model Summary** | |
|---|---|
| Degrees of Freedom | 62 |
| Sum of Squared Errors | 3,918.9654 |
| Variance Estimate | 63.2091 |
| Standard Deviation | 7.9504 |
| Akaike's 'A' Information Criterion | 449.3545 |
| $R^2$ | 0.6752 |
| MAPE | 9.4891 |
| MAE | 5.8279 |
| -2LogLikelihood | 445.3545 |

| **Parameter Estimates** | | | | | |
|---|---|---|---|---|---|
| **Term** | **Lag** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| AR1 | 1 | 0.391690 | 0.185828 | 2.11 | 0.0391 |
| MA1 | 1 | 0.785043 | 0.122162 | 6.43 | <0.0001 |

The next step after fitting the ARIMA (1, 1, 1) model to the lower binder data for quantity group B was to check the model's adequacy. The ACF plot of the model residuals is provided in Figure 54. As shown in the plot, the residuals of the model are not significantly correlated. The normal probability plot of the model residuals is also shown in Figure 55. While there is some departure from normality in the tails of the residual distribution, there is nothing unusual about this plot. Therefore, the ARIMA (1, 1, 1) model without a constant is adequate for the lower binder unit cost data.



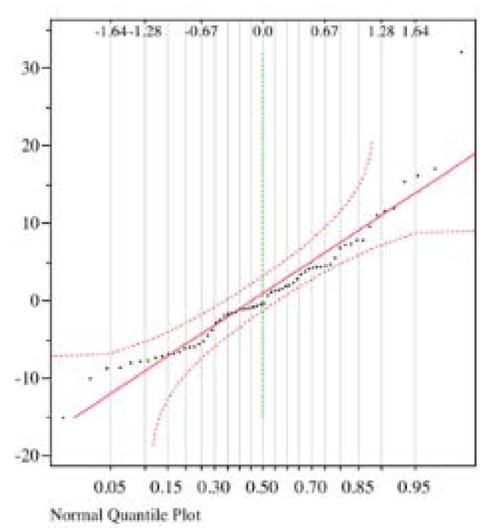




Figure 54. Residuals plots of ARIMA (1, 1, 1) for lower binder (quantity group B)

The next data set to be analyzed is the upper binder layer data in quantity group B. The plot of the mean unit cost data for the upper binder is shown in Figure 55. The ACF and PACF plots for the upper binder layer are shown in Figure 56.

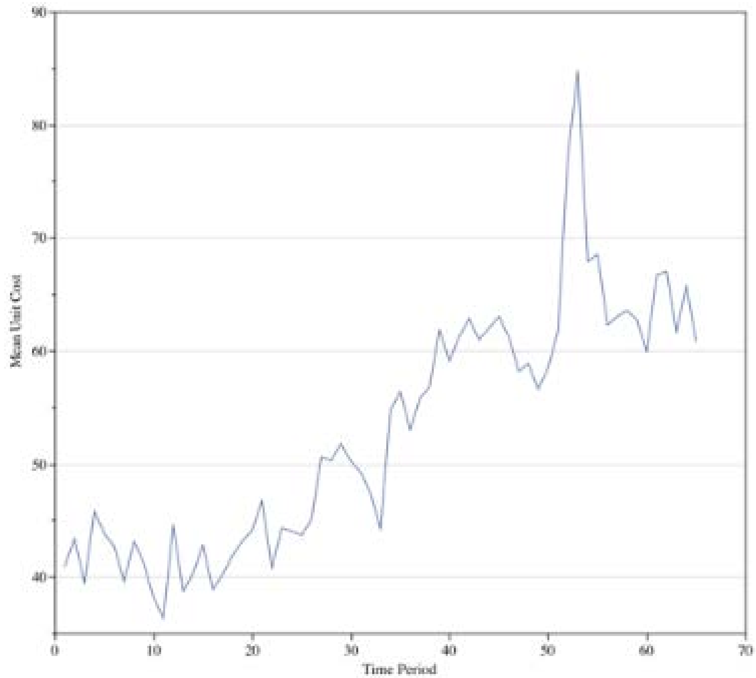
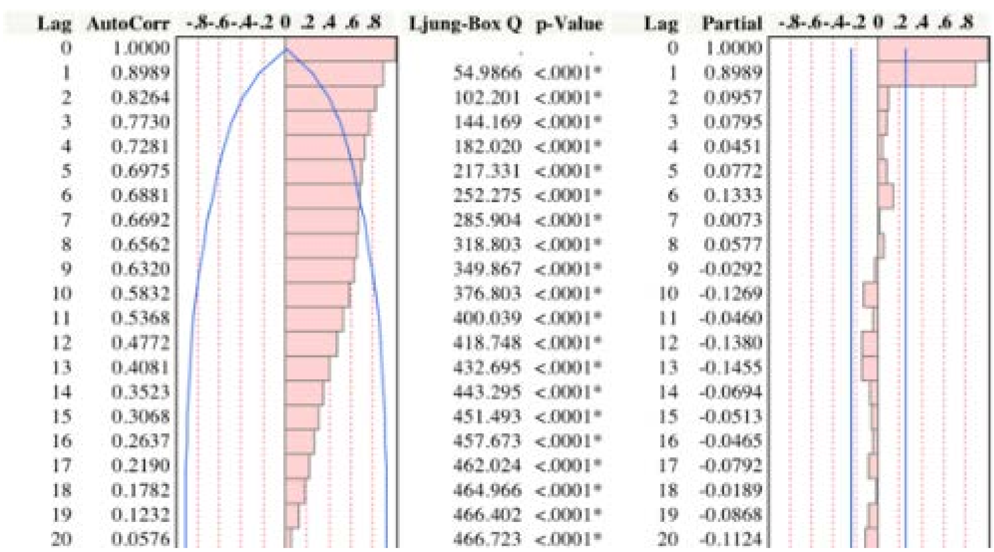


Figure 55. Mean unit cost of upper binder layer for first 65 periods (quantity group B)



| Lag | AutoCorr | Ljung-Box Q | p-Value | Lag | Partial |
|---|---|---|---|---|---|
| 0 | 1.0000 | . | . | 0 | 1.0000 |
| 1 | 0.8989 | 54.9866 | <.0001* | 1 | 0.8989 |
| 2 | 0.8264 | 102.201 | <.0001* | 2 | 0.0957 |
| 3 | 0.7730 | 144.169 | <.0001* | 3 | 0.0795 |
| 4 | 0.7281 | 182.020 | <.0001* | 4 | 0.0451 |
| 5 | 0.6975 | 217.331 | <.0001* | 5 | 0.0772 |
| 6 | 0.6881 | 252.275 | <.0001* | 6 | 0.1333 |
| 7 | 0.6692 | 285.904 | <.0001* | 7 | 0.0073 |
| 8 | 0.6562 | 318.803 | <.0001* | 8 | 0.0577 |
| 9 | 0.6320 | 349.867 | <.0001* | 9 | -0.0292 |
| 10 | 0.5832 | 376.803 | <.0001* | 10 | -0.1269 |
| 11 | 0.5368 | 400.039 | <.0001* | 11 | -0.0460 |
| 12 | 0.4772 | 418.748 | <.0001* | 12 | -0.1380 |
| 13 | 0.4081 | 432.695 | <.0001* | 13 | -0.1455 |
| 14 | 0.3523 | 443.295 | <.0001* | 14 | -0.0694 |
| 15 | 0.3068 | 451.493 | <.0001* | 15 | -0.0513 |
| 16 | 0.2637 | 457.673 | <.0001* | 16 | -0.0465 |
| 17 | 0.2190 | 462.024 | <.0001* | 17 | -0.0792 |
| 18 | 0.1782 | 464.966 | <.0001* | 18 | -0.0189 |
| 19 | 0.1232 | 466.402 | <.0001* | 19 | -0.0868 |
| 20 | 0.0576 | 466.723 | <.0001* | 20 | -0.1124 |

Figure 56. ACF and PACF of upper binder layer for first 65 periods (quantity group B)

After examining the ACF and PACF plots and fitting several candidate models, an ARIMA (1, 1, 1) model without a constant term was chosen as the best fit for the upper binder data set. The model statistics for the model are provided in Table 29. Both the estimate of the AR coefficient and MA coefficient are significant at a five percent significance level.

Table 29. ARIMA (1, 1, 1) model statistics for upper binder (quantity group B)

| **Model Summary** | |
|---|---|
| Degrees of Freedom | 62 |
| Sum of Squared Errors | 1,439.7644 |
| Variance Estimate | 23.2220 |
| Standard Deviation | 4.8189 |
| Akaike's 'A' Information Criterion | 385.0565 |
| $R^2$ | 0.8514 |
| MAPE | 5.7891 |
| MAE | 3.5630 |
| -2LogLikelihood | 381.0565 |

| **Parameter Estimates** | | | | | |
|---|---|---|---|---|---|
| **Term** | **Lag** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| AR1 | 1 | 0.53414 | 0.1813 | 2.95 | 0.0045 |
| MA1 | 1 | 0.77147 | 0.1216 | 6.34 | <0.0001 |

To determine the model's adequacy, the residuals were checked for serial correlation and normality. From Figure 57, it can be seen from the ACF plot that there are no significant autocorrelation in the residuals. Since there is not a severe violation of the normality of the residuals it is determined that the ARIMA (1, 1, 1) model without a constant term is an adequate representation of the upper binder layer data in quantity group B.

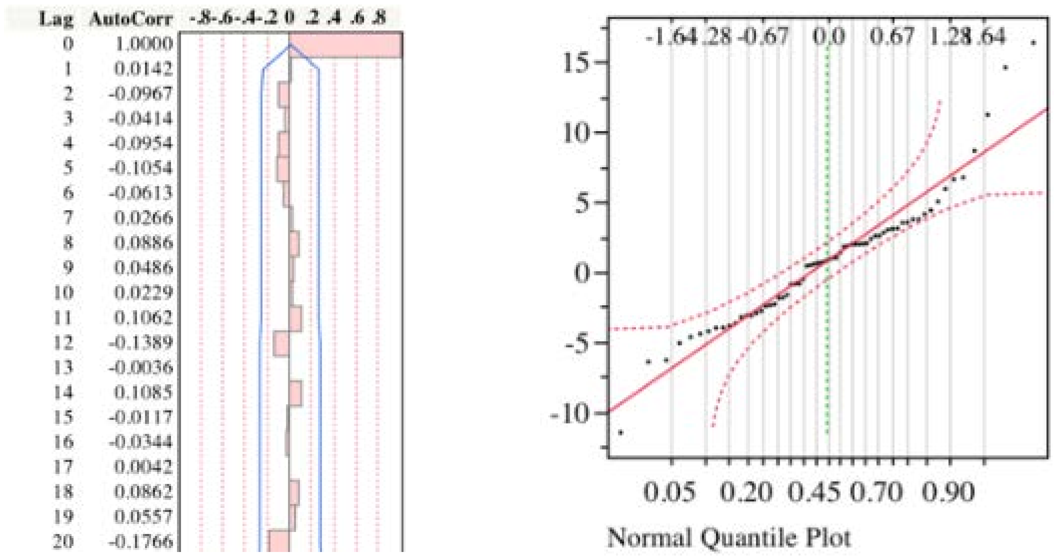


Figure 57. Residual plots of ARIMA (1, 1, 1) for upper binder (quantity group B)

The next group of data to analyze was the wearing surface layer in quantity group B. A plot of the wearing surface mean unit costs by the bimonthly time period is provided in Figure 58. The ACF and PACF plots of the wearing surface layer data are shown in Figure 59.

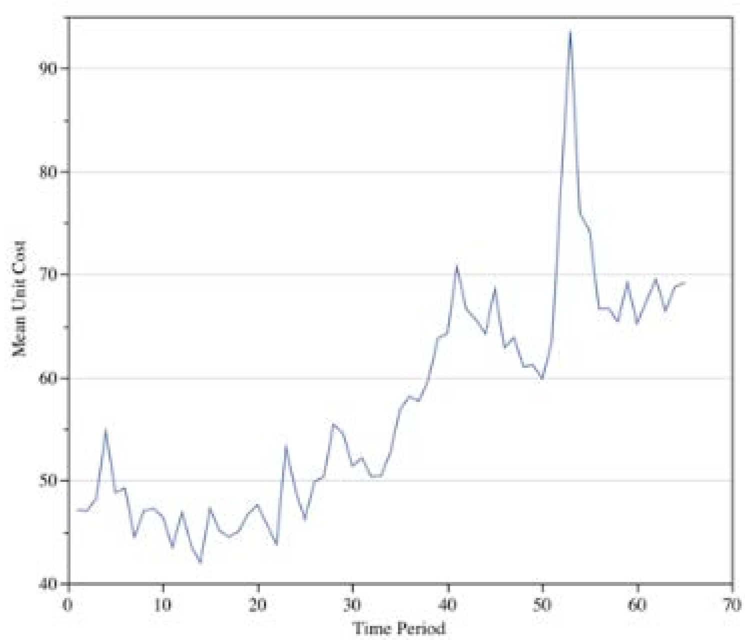


Figure 58. Mean unit cost of wearing surface layer for first 65 periods (quantity group B)

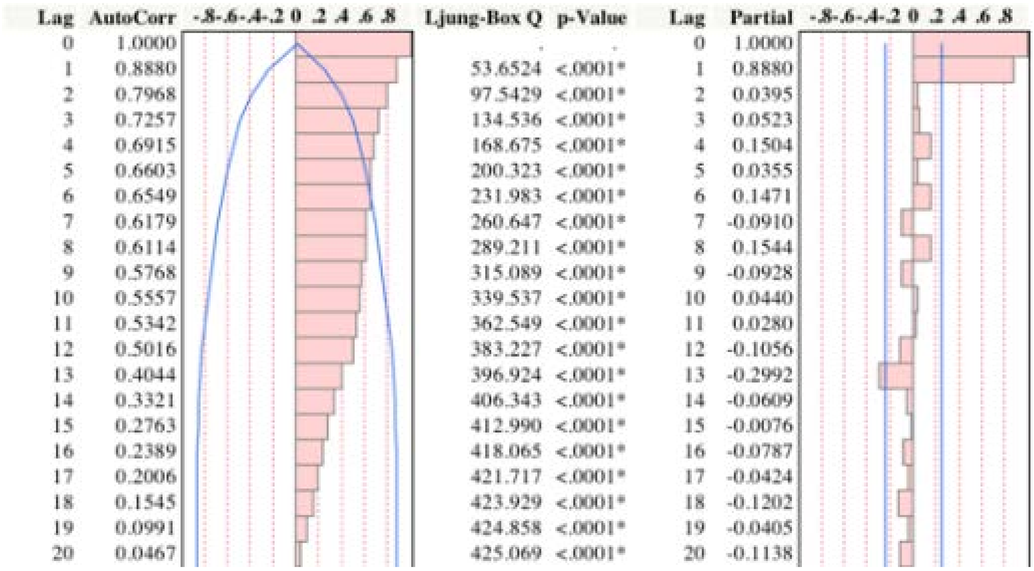


Figure 59. ACF and PACF of wearing surface layer for first 65 periods (quantity group B)

After fitting several time series models, the best model for the wearing surface layer data for quantity group B was determined to be an ARIMA (1, 1, 1) model without a constant term. The model statistics for this model are provided in Table 30.

Table 30. ARIMA (1, 1, 1) model statistics for wearing surface (quantity group B)

| **Model Summary** | |
|---|---|
| Degrees of Freedom | 62 |
| Sum of Squared Errors | 1,598.0779 |
| Variance Estimate | 25.7754 |
| Standard Deviation | 5.0770 |
| Akaike's 'A' Information Criterion | 391.7221 |
| $R^2$ | 0.8347 |
| MAPE | 4.8884 |
| MAE | 3.3534 |
| -2LogLikelihood | 387.7221 |

| **Parameter Estimates** | | | | | |
|---|---|---|---|---|---|
| **Term** | **Lag** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| AR1 | 1 | 0.636937 | 0.163799 | 3.89 | 0.0002 |
| MA1 | 1 | 0.823371 | 0.106591 | 7.72 | <0.0001 |

The ACF plot and the distribution of the residuals are provided in Figure 60. The ACF plot of the ARIMA (1, 1, 1) model residuals does not indicate any significant autocorrelation. While there is a slight departure from normality of the residuals it does not appear severe enough to validate the normality assumption.

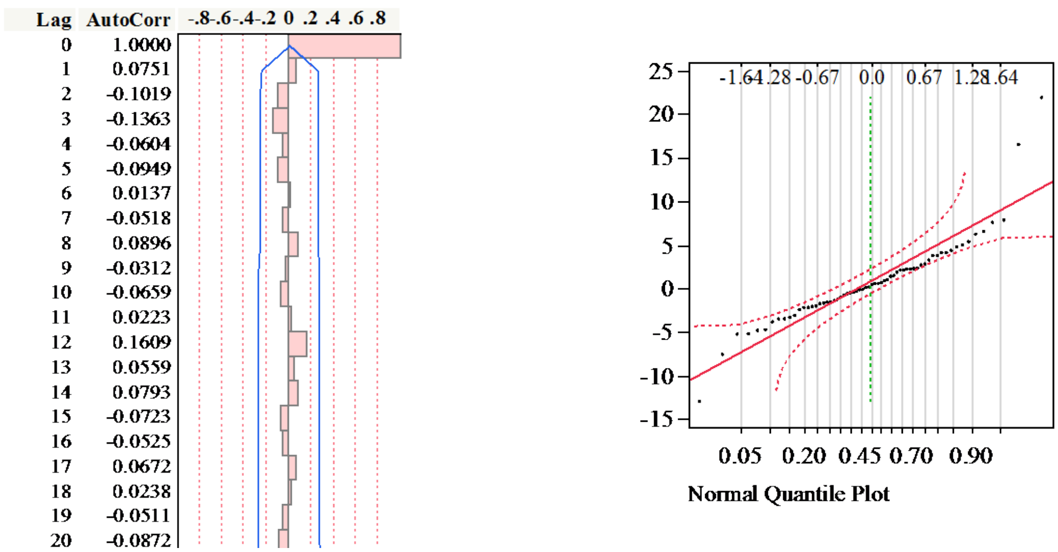


Figure 60. Residual plots of ARIMA (1, 1, 1) for wearing surface (quantity group B)

### 5.3.5 Regression Models of Asphalt Unit Costs

From the plots of the mean unit costs of the three layers for both quantity groups A and B, it was noticed that a shift in the mean unit cost occurred between time periods 30 and 40 for all layers in both quantity groups. To model this shift, regression models were created for all layers using dummy variables as the independent variable to demarcate the shift in the mean unit costs. For example, if the shift in the mean unit cost occurred between time periods 31 and 32, the independent variable for time periods less than 32 would be indicated by a “0” while time periods 32 or greater would be represented by a “1” in the model.

Since the regression models were fit to time series data, the violation of the independence of the residuals was anticipated. If the model residuals were not independent and there was autocorrelation present in the residual set, the estimates of the coefficients generated from the ordinary least squares regression may no longer be reliable (Montgomery 2012). Autocorrelation in the residuals would also make the standard error estimates for the coefficients, *t* statistics, and *p*-values biased.

For example, assuming a simple linear model such that,

$$y_t = \beta_0 + \beta_1 x_t + r_t$$

where $y_t$ is the unit cost, $x_t$ is the independent variable associated with the time period, and $r_t$ is the residuals of the regression model. If the residuals are autocorrelated and represent a stationary first-order autoregressive process, then the residuals will take on the following structure,

$$r_t = \emptyset r_{t-1} + \varepsilon_t$$

where $\emptyset$ is the autoregressive coefficient and $\varepsilon_t$ represents the "random shocks" and are assumed to be independent $N(0, \sigma^2)$. If it was determined that the residuals of the regression models fit to the lower binder, upper binder, and wearing surface layers of both quantity groups were autocorrelated and resembled the above structure, the Cochrane-Orcutt method was used to account for this situation. The Cochrane-Orcutt method consists of the following steps:

1. Develop ordinary regression model and store the residuals,
2. If the residuals are autocorrelated, estimate $\emptyset$ using

$$\widehat{\emptyset} = \frac{\sum_{t=2}^{T} r_t r_{t-1}}{\sum_{t=1}^{T} r_t^2}$$

3. Transform the variables $y_t$ and $x_t$ to

$$y_t' = y_t - \widehat{\emptyset} y_{t-1}$$
$$x_t' = x_t - \widehat{\emptyset} x_{t-1}$$

4. Regress $y_t'$ on $x_t'$ for t = 2, 3… to estimate the transformed intercept $\hat{\beta}_0'$ and transformed slope $\hat{\beta}_1'$ and to obtain a new set of residuals. If the new residuals are not serially correlated, then no additional analysis is required (Bowerman 2005).

To complete the second step in the Cochrane-Orcutt method, the Durbin-Watson test was employed to test if the residuals are first-order autocorrelated. The Durbin-Watson statistic is calculated as

$$d = \frac{\sum_{t=2}^{n}(r_t - r_{t-1})^2}{\sum_{t=1}^{n}(r_t)^2}$$

where $r_1, r_2, \ldots, r_n$ are the time-ordered residuals. The null hypothesis is expressed as $H_0$: the residuals are not autocorrelated while the alternative hypothesis is $H_1$: the error terms are positively autocorrelated. The decision criteria is:

1. If $d < d_{L,\alpha}$ reject $H_0$
2. If $d > d_{U,\alpha}$ do not reject $H_0$
3. If $d_{L,\alpha} \leq d \leq d_{U,\alpha}$ the test is inconclusive

where $d_{L,\alpha}$ represents the lower bound, $d_{U,\alpha}$ represents the upper bound, and α is the type I error rate (Panik 2009). If the test is conclusive and the null hypothesis is rejected, then an estimate of the first-order autoregressive term could then be made.

The coefficients obtained from the regression of the transformed variables can be used to estimate the original model. The slope and the standard error of the transformed model are equal to the estimate for the slope and standard error of the slope coefficient for the original model parameters. The correct estimate for the intercept, $\hat{\beta}_0$, for the original model $y$ versus $x$ relationship is calculated as:

$$\hat{\beta}_0 = \frac{\hat{\beta}_0'}{1 - \hat{\phi}}$$

The standard error of the intercept is similarly calculated by:

$$s.e.(\hat{\beta}_0) = \frac{s.e.(\hat{\beta}_0')}{1 - \hat{\phi}}$$

To use the model to predict the unit cost of a specific asphalt layer, the structural portion of the regression model, $\hat{y}_t = \hat{\beta}_0 + \hat{\beta}_1 x_t$, is used to estimate the mean unit cost at time *t* is in conjunction with the autoregressive error process, $r_t = \widehat{\emptyset} r_{t-1} + \varepsilon_t$. Combining the two portions creates the full prediction model, $\hat{y}_t = \hat{\beta}_0 + \hat{\beta}_1 x_t + \widehat{\emptyset} r_{t-1}$.

The first regression model was constructed for the lower binder layer of quantity group A. By examining the graph of the average unit costs for the lower binder layer through time, it was determined that the shift in the unit costs occurred between time periods 34 and 35. Therefore, the independent variable was set to “0” for all time periods less than 34 and “1” for all time periods after time period 35. A summary of the model statistics is provided in Table 31. From the regression fit, both the regression coefficients were found to be significant at a five percent significance level. The Durbin-Watson statistic was calculated to be 2.22. Since the upper bound of *d* for α equal to 0.05 is 1.63, the null hypothesis is rejected and it is concluded that there is no problem with autocorrelated residuals. An examination of the normal probability plot of the model residuals (found in Figure 61) indicates that the residuals are approximately normally distributed.

Table 31. Regression model statistics for lower binder layer (quantity group A)

| Model Summary | |
|---|---|
| Sum of Squared Errors | 20,961.33 |
| Variance Estimate | 327.52 |
| $R^2$ | 0.4470 |
| RMSE | 17.958 |
| MAPE | 0.142 |
| MAE | 13.212 |

| Parameter Estimates | | | | |
|---|---|---|---|---|
| **Term** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| $\beta_0$ | 79.5646 | 3.1282 | 25.43 | <0.0001 |
| $\beta_1$ | 32.3237 | 4.5297 | 7.14 | <0.0001 |

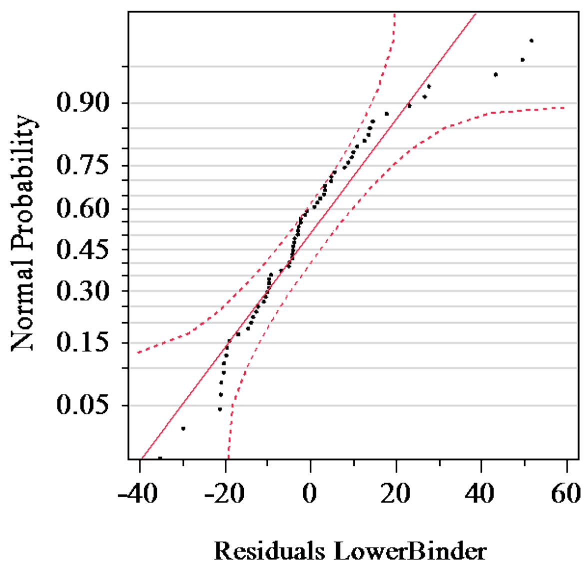


Figure 61. Normal probability plot of regression model for lower binder (quantity group A)

The upper binder layer for quantity group A was the next layer to be analyzed. From the graph of upper binder unit costs through time, it appears that the mean shift occurs between time periods 34 and 35, so the value of “0” was used for all $x_t$ used for time period 34 and all time periods prior while a value of “1” was used for all $x_t$ used for all time period 35 and all subsequent time periods. From the initial regression fit of the model, the Durbin-Watson statistic was calculated to be 1.43. The lower bound for the *d* statistic is 1.57 so the null hypothesis is rejected, and it is concluded that the residuals of the regression model are positively autocorrelated. An estimate of $\emptyset$ was calculated to be 0.2785. Using this estimated value, the intercept and slope of the transformed model were estimated to be 58.9614 and 24.9353, respectively. The Durbin-Watson statistic ($d$ = 1.96) did not indicate that the residuals of the transformed model were positively autocorrelated. After converting the transformed coefficient estimates back to the original units, the full prediction model for the upper binder layer is $\hat{y}_t = 81.7219 + 24.9353x_t + 0.2785r_{t-1}$. The statistics of the full prediction model are provided in Table 32. The normal probability plot (shown in Figure 62) shows that the residuals are approximately normally distributed.

Table 32. Regression model statistics for upper binder layer (quantity group A)

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 7,880.839 |
| Variance Estimate | 123.1381 |
| $R^2$ | 0.5685 |
| RMSE | 11.011 |
| MAPE | 9.492 |
| MAE | 8.471 |

| **Parameter Estimates** | | | | |
|---|---|---|---|---|
| **Term** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| $\beta_0$ | 81.7219 | 2.6888 | 30.39 | <0.0001 |
| $\beta_1$ | 24.9353 | 3.8073 | 6.55 | <0.0001 |

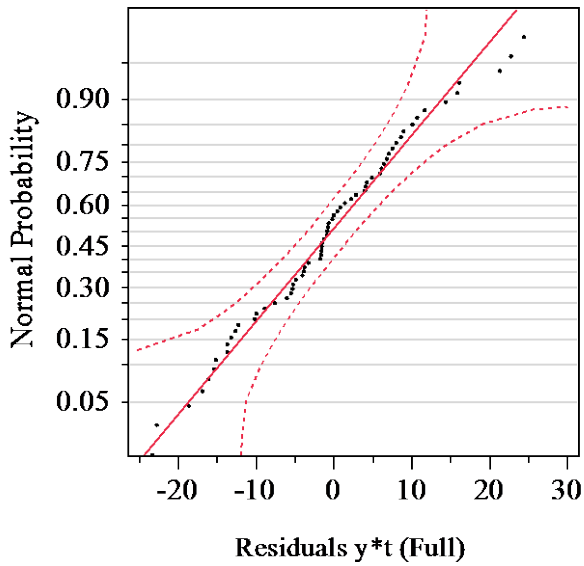


Figure 62. Normal probability plot of regression model for upper binder (quantity group A)

The next regression model was constructed for the wearing surface layer of quantity group A. From the graph of the average unit costs through time, it was determined that the shift in the unit costs occurred between time periods 32 and 33. Therefore, the independent variable was set to "0" for all time periods less than 32 and "1" for all time periods after time period 33. The Durbin-Watson statistic, *d*, calculated from the model residuals was 1.74, which is greater than the upper bound of 1.63. Therefore, the null hypothesis is not rejected and it is concluded that the residuals are not autocorrelated. A summary of the regression model statistics is provided in Table 33. Both of the regression coefficients were found to be significant at a five percent significance level.

Table 33. Regression model statistics for wearing surface layer (quantity group A)

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 8,434.671 |
| Variance Estimate | 131.792 |
| $R^2$ | 0.4948 |
| RMSE | 11.391 |
| MAPE | 9.386 |
| MAE | 8.527 |

**Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| $\beta_0$ | 80.0680 | 2.0454 | 39.15 | <0.0001 |
| $\beta_1$ | 22.5523 | 2.8706 | 7.86 | <0.0001 |

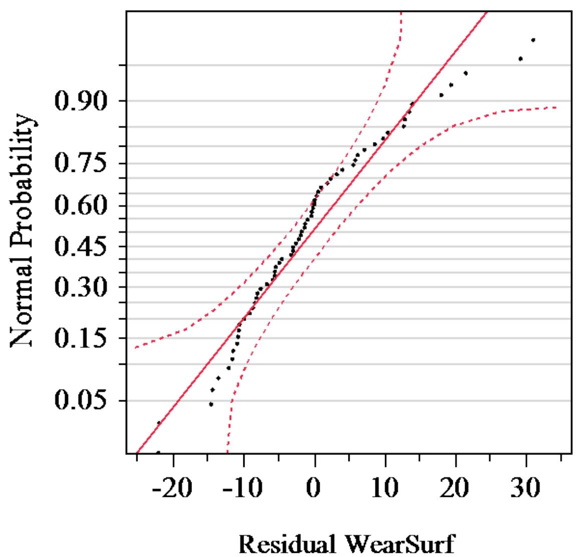


Figure 63. Normal probability plot of regression model for wearing surface (quantity group A)

The first regression model built from quantity group B was for the lower binder layer data. The graph of the mean unit costs of the lower binder layer data through time was examined and it was determined that the shift in the unit costs appears to have occurred between time periods 37 and 38. After fitting the initial regression model, the Durbin-Watson statistic was calculated to be 1.25, which is less than the lower bound of 1.57, indicating that the null hypothesis is rejected and that the residuals of the model are serially correlated. Using the model residuals, an estimate of $\emptyset$ was determined to be 0.3613 and was used to transform the initial data set. The residuals of the transformed regression model fit to the transformed data did not display any autocorrelation within the residuals with a *d* statistic of 2.00. Converting the transformed coefficient estimates back to the original model produces the full prediction model $\hat{y}_t = 49.6738 + 22.4691x_t + 0.3613r_{t-1}$. The full regression model statistics can be seen in Table 34.

Table 34. Regression model statistics for lower binder layer (quantity group B)

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 3149.23 |
| Variance Estimate | 49.988 |
| $R^2$ | 0.7416 |
| RMSE | 6.961 |
| MAPE | 7.877 |
| MAE | 4.722 |

| **Parameter Estimates** | | | | |
|---|---|---|---|---|
| **Term** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| $\beta_0$ | 49.6738 | 1.8522 | 26.82 | <0.0001 |
| $\beta_1$ | 22.4691 | 1.1830 | 18.99 | <0.0001 |

The normal probability of the residuals of the full regression model is provided in Figure 64. From this plot, a potential outlier was identified at time period 53 (located at the top right hand corner of the plot); this point had a standardized residual value of 4.94. This time period corresponds with the months of September and October 2008 when there was a noticeable spike in the price of liquid asphalt binder. This spike in price can be seen in Figure 8. Several factors were identified by NAPA as being responsible for the abnormally high liquid binder prices. Higher than average oil prices in the beginning of 2008, less asphalt produced per barrel of crude oil due to refiners utilizing coker technology to produce more gasoline and diesel fuel, and

Hurricane Ike striking the Gulf Coast in September 2008 were all found to be contributing factors. However, the price of the asphalt binder began to return to normal in the months following the spike. Because the spike in the mean unit cost in the lower binder layer for quantity group B at time period 53 is explainable from the spike in the liquid asphalt binder prices and is not representational of the asphalt prices during normal market conditions, the lower binder data was reanalyzed with time period 53 removed.

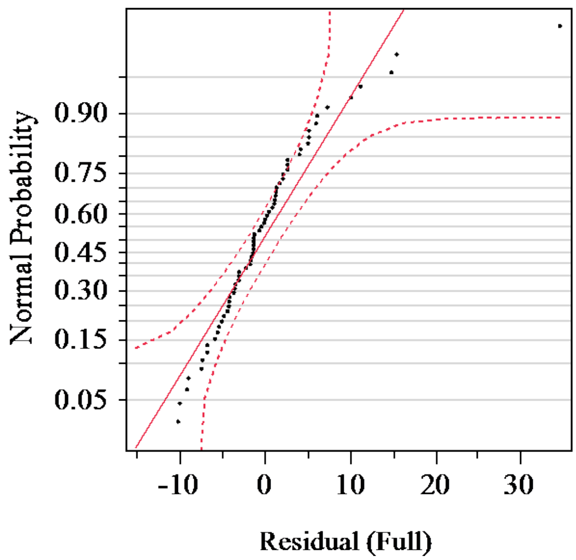


Figure 64. Normal probability plot of regression model for lower binder (quantity group B)

After removing time period 53, the regression model was refit to the data set using the same mean shift point used in the previous analysis. Both the intercept and slope estimates (49.4812 and 21.4658, respectively) were significant at a five percent level and the Durbin-Watson statistic was calculated to be 1.55. Since this value is less than the lower bound of 1.57, it was concluded that the residuals of the model were positively autocorrelated, albeit the autocorrelation between residuals was rather weak. The residuals of the model were used to calculate the estimate of *Ø* as 0.1116, and this estimated value was used to transform the original model. The new estimates of the intercept and slope from the transformed model were calculated to be 43.9574 and 21.4658, respectively. The Durbin-Watson statistic of the residuals of the transformed model was calculated to be 1.85, failing to reject the null hypothesis. Converting back to the original model produces the full prediction model $\hat{y}_t = 49.4812 + 21.4658x_t + 0.1116r_{t-1}$. The model summary statistics are provided in Table 35. From this table, it can be seen that the model without time period 53 has a higher $R^2$ value and lower variance estimate, indicating that it fits the lower binder unit cost data better than the model fit to all time periods. The normal probability plot shown in Figure 65 also indicates that the residuals of the full model are approximately normally distributed.

Table 35. Regression model statistics for lower binder layer (quantity group B) with time period 53 removed

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 1,935.433 |
| Variance Estimate | 30.7212 |
| $R^2$ | 0.7929 |
| RMSE | 5.444 |
| MAPE | 7.093 |
| MAE | 4.025 |

**Parameter Estimates**

| **Term** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
|---|---|---|---|---|
| $\beta_0$ | 49.4812 | 1.0345 | 47.83 | <0.0001 |
| $\beta_1$ | 21.4658 | 1.5724 | 13.65 | <0.0001 |

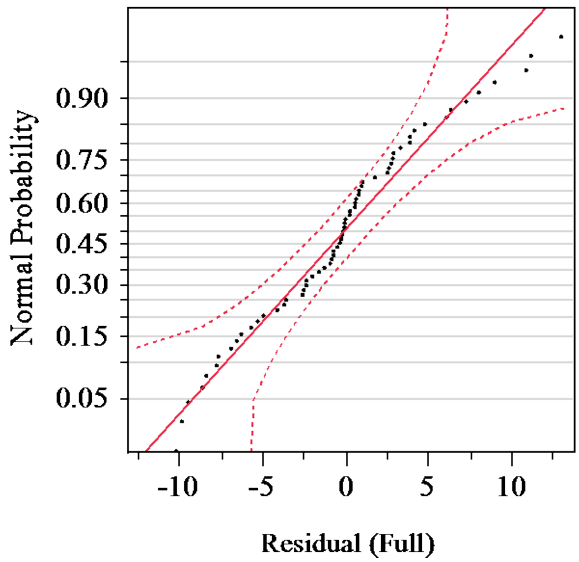


Figure 65. Normal probability plot of regression model for lower binder (quantity group B) with time period 53 removed

By examining the plot of the mean unit costs for the upper binder layer versus time, it was determined that a shift in the mean unit costs occurred between time periods 33 and 34. The initial regression model produced statistically significant intercept and slope coefficients of 49.7199 and 21.9350, respectively, and a Durbin-Watson statistic of 0.73. The estimate of $\emptyset$, which was calculated to be 0.6288, was used to transform the original model. By fitting the transformed model, the intercept was calculated to be 22.5951 and the slope coefficient was calculated to be 18.5263. The Durbin-Watson statistic of 1.88 indicated that there was no significant serial correlation in the transformed model residuals. After converting back to the original model, the full prediction model for the upper binder layer is $\hat{y}_t = 51.0814 + 19.4638x_t + 0.6288r_{t-1}$.

Table 36. Regression model statistics for upper binder layer (quantity group B)

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 1,232.178 |
| Variance Estimate | 19.5584 |
| $R^2$ | 0.8755 |
| RMSE | 4.354 |
| MAPE | 5.112 |
| MAE | 3.093 |

**Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| $\beta_0$ | 51.0814 | 2.0348 | 25.10 | <0.0001 |
| $\beta_1$ | 19.4638 | 2.6318 | 7.40 | <0.0001 |

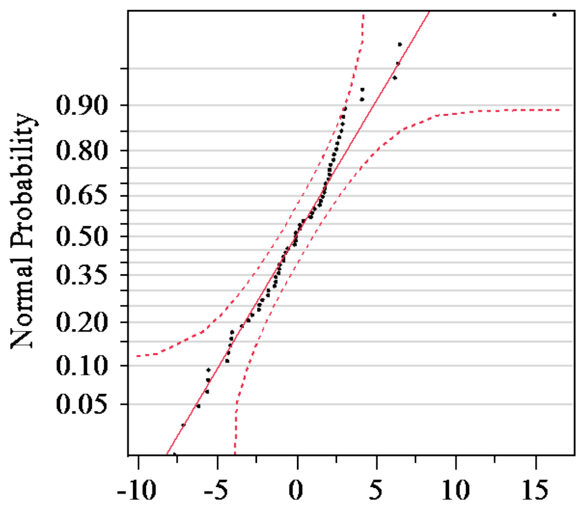



Figure 66. Normal probability plot of regression model for upper binder (quantity group B)

After the initial regression model for the upper binder layer was fit to the data, the mean unit cost at time period 53 was also identified as a potential outlier. With the mean unit cost at time period 53 excluded from the analysis, the estimates for the intercept and slope coefficients were calculated to be 49.7199 and 21.1235, respectively. However, the Durbin-Watson statistic calculated from the model resulted was found to be 0.80, significantly less than the lower bound of 1.57. This indicates that the residuals are positively autocorrelated. The residuals were used to produce an estimate of $\emptyset$ equal to 0.6385. Regressing the transformed model produced an estimate of the intercept equal to 18.4282 and a slope estimate of 18.3015. The Durbin-Watson statistic for the residuals of the transformed model was calculated to be 2.39, indicating that we do not reject the null hypothesis and consider that the residuals are not positively autocorrelated. Converting back to the original model produces the full prediction model $\hat{y}_t = 50.9825 + 18.3015x_t + 0.6385r_{t-1}$. Table 37 features the summary statistics for the full prediction model for the upper binder layer. The normal probability plot provided in Figure 67 show a slight departure from normality at the tails but it does not appear to be severe enough to invalidate the model.

Table 37. Regression model statistics for upper binder layer (quantity group B) with time period 53 removed

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 911.032 |
| Variance Estimate | 14.461 |
| $R^2$ | 0.8938 |
| RMSE | 3.773 |
| MAPE | 4.791 |
| MAE | 2.789 |

**Parameter Estimates**

| **Term** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
|---|---|---|---|---|
| $\beta_0$ | 50.9825 | 1.8554 | 27.48 | <0.0001 |
| $\beta_1$ | 18.3015 | 2.4000 | 7.63 | <0.0001 |

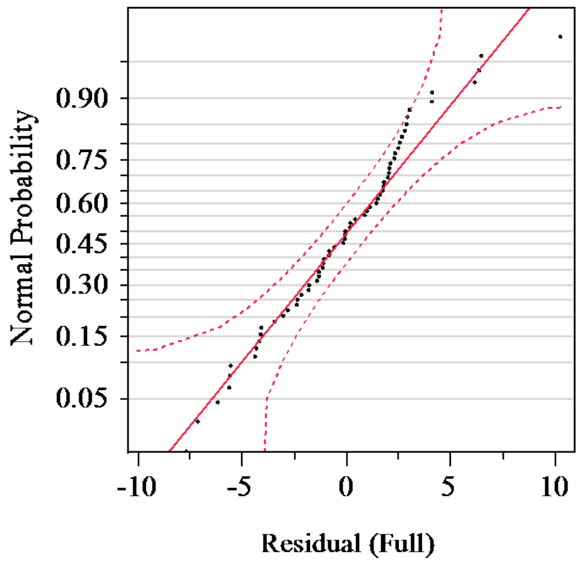


Figure 67. Normal probability plot of regression model for upper binder (quantity group B) with time period 53 removed

The last data set to analyze was the wearing surface layer for quantity group B. The shift in the mean unit cost of the wearing surface layer was determined to be between time periods 34 and 35. The initial estimates of the intercept and mean shift coefficients were calculated to be 54.9543 and 21.3067, respectively. Using the residuals of the original model, the Durbin-Watson statistic was estimated as 0.78, implying that the residual set is autocorrelated. The residuals were also used to estimate $\varnothing$, which was calculated to be 0.5997. Regressing the transformed model using the estimated value resulted in an estimated intercept of 22.5951 and an estimated mean shift of 18.5263. A Durbin-Watson statistic of 1.72 did not indicate any problem with serial correlation in the residuals of the transformed model. The new prediction model for the wearing surface layer is $\hat{y}_t = 56.4484 + 18.5263x_t + 0.5997r_{t-1}$. A summary of the model statistics is shown in Table 38 and the normal probability plot in Figure 68 does not indicate a severe violation of the normality assumption.

Table 38. Regression model statistics for wearing surface layer (quantity group B)

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 1,503.73 |
| Variance Estimate | 23.869 |
| $R^2$ | 0.8462 |
| RMSE | 4.810 |
| MAPE | 4.663 |
| MAE | 3.137 |

| **Parameter Estimates** | | | | |
|---|---|---|---|---|
| **Term** | **Estimate** | **Std Error** | **t Ratio** | **Prob>\|t\|** |
| $\beta_0$ | 56.4484 | 2.0822 | 27.11 | <0.0001 |
| $\beta_1$ | 18.5263 | 2.7670 | 6.70 | <0.0001 |

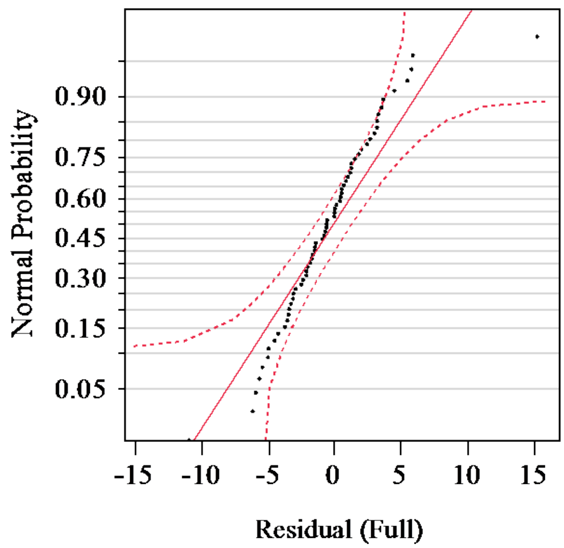


Figure 68. Normal probability plot of regression model for wearing surface (quantity group B)

Similar to the lower binder and upper binder layers in quantity group B, once the initial regression model was built, it was noticed that the residual at time period 53 was a possible outlying point with a standardized residual of 5.07. The regression model was refit with this point excluded from the data set and the estimates of the intercept and slope were calculated to be 54.9543 and 20.2680, respectively. The Durbin-Watson statistic was calculated to be 0.81, indicating that the residuals of the original model are autocorrelated. Using the estimated $\emptyset$ value of 0.6340, the estimated intercept of the transformed model was calculated to be 20.6918 and the estimated slope coefficient was calculated to be 16.3695. The residuals of the transformed model produced a Durbin-Watson statistic of 2.26, which is greater than the upper bound of 1.63. After converting back to the original model, the full prediction model for the wearing surface layer unit costs is $\hat{y}_t = 56.5294 + 16.3695x_t + 0.6340r_{t-1}$. The model summary is shown in Table 39.

Table 39. Regression model statistics for wearing surface layer (quantity group B) with time period 53 removed

| **Model Summary** | |
|---|---|
| Sum of Squared Errors | 902.409 |
| Variance Estimate | 14.324 |
| $R^2$ | 0.8870 |
| RMSE | 3.755 |
| MAPE | 4.331 |
| MAE | 2.782 |

**Parameter Estimates**

| **Term** | **Estimate** | **Std Error** | ***t* Ratio** | **Prob>\|t\|** |
|---|---|---|---|---|
| $\beta_0$ | 56.5294 | 1.7767 | 31.82 | <0.0001 |
| $\beta_1$ | 16.3695 | 2.3354 | 7.01 | <0.0001 |

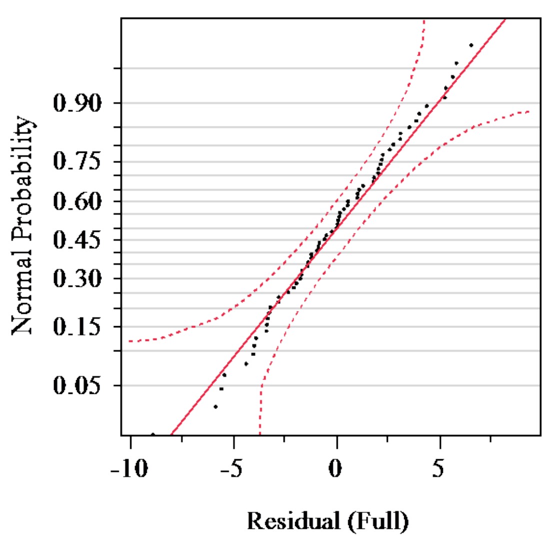



Figure 69. Normal probability plot of regression model for wearing surface (quantity group B) with time period 53 removed

After fitting a regression model to the lower binder, upper binder, and wearing surface layers in quantity groups A and B, it was noticed that the mean unit cost of each layer did undergo a significant shift in cost between time periods 30 and 40. For example, in quantity group A, the increase in cost shifted upwards by $22.55 per ton for the wearing surface layer after time period 32 while the mean unit cost of the lower binder layer increased by $32.32 per ton after time period 34. The shift in mean unit costs for quantity group B was also found to be significant for each of the three layers. It is interesting to note that for both quantity groups the shift in the lower binder mean unit costs was the highest of the three layers while the shift in the unit costs of the wearing surface layers was the lowest of the three asphalt layers.

### 5.3.6 Model Comparison and Selection

For each layer in each quantity group, a time series model and a regression model were constructed for the mean unit costs from time period 1 to time period 65. To compare the time series models and regression models, several key considerations were used to select the final model. The first criterion considered was the measurement of the error between the fitted model and the data from the estimation or training period. The next criterion involved comparing the two types of models based on their performance in the validation period; this consideration would evaluate the models based on their ability to forecast future values of the unit cost of each asphalt layer through the use of multiple step ahead forecasts. The three measures used to compare the models during the estimation and validation periods were the root mean square error (RMSE), the mean absolute percentage error (MAPE), and the mean absolute error (MAE). The final criterion used when comparing the time series models and the regression models for each layer in each quantity group was qualitative considerations. This involved scrutinizing each model based on the reasonableness of the model as well as the simplicity of the model.

Table 40 provides the measures of each time series and regression model for the lower binder layer in quantity group A during the model estimation period. From the table, it can be seen that the regression model provided a better fit to the mean unit cost data for the first 65 time periods.

Table 40. Summary of estimating models for lower binder layer for quantity group A

| **Model Comparison for Estimation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 20.58 | 15.71 | 14.95 |
| Regression | 17.96 | 14.20 | 13.21 |

The next step was to evaluate the models based on their accuracy during the validation period. Table 41 provides the calculated RMSE, MAPE, and MAE of the forecasts for the lower binder layer in quantity group A. From the table, it can be seen that the IMA (1, 1) time series model prediction for time periods 66 through 74 had the lower values of all three measures.

Table 41. Summary of estimating models for lower binder layer for quantity group A during validation period

| **Model Comparison for Validation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 14.70 | 13.55 | 12.34 |
| Regression | 17.93 | 17.31 | 15.77 |

Based on the comparison of the time series model and the regression model during the estimation and validation periods, it was determined that the IMA (1, 1) time series model was the best estimating model for the lower binder layer data in quantity group A.

The next set of models to evaluate was the time series and regression models constructed for the upper binder layer in quantity group A. From Table 42, it is shown that the regression model performed slightly better in terms of RMSE and MAE while the time series model has a slightly better MAPE value. Both models appear to be similar in terms of their average error for the estimation period data.

Table 42. Summary of estimating models for upper binder layer for quantity group A

| **Model Comparison for Estimation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 12.55 | 9.33 | 8.81 |
| Regression | 11.01 | 9.49 | 8.47 |

Table 43 provides a summary of the three measures of the forecasted error. As with the estimation period, the time series model and regression model are very similar in terms of the errors measures. The time series model did perform slightly better than the regression model but this difference is slight; for example, the difference in MAE between the time series model and the regression model was $0.03 per ton of upper binder.

Table 43. Summary of estimating models for upper binder layer for quantity group A during validation period

| **Model Comparison for Validation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 12.75 | 10.14 | 8.87 |
| Regression | 12.81 | 10.19 | 8.90 |

Both the IMA (1, 1) time series model and the regression model performed similar during the estimation and validation periods. However, due to the autocorrelation structure in the regression model residuals and the need to potentially perform the Cochrane-Orcutt method to obtain the best reliable estimates of the regression model coefficients when new data is available, it was determined that the IMA (1, 1) time series model is the best forecasting model for the upper binder data in quantity group A.

The last set of models to evaluate for quantity group A was for the wearing surface layer. The error measures for the time series and regression models for the estimation period are found in Table 44. From the comparison of the error measures, the regression model performed better in terms of RMSE and MAE while the time series model performed better in terms of the MAPE. The RMSE of the regression model is approximately 6.8 percent lower than the RMSE of the time series model for the data in the first 65 time periods.

Table 44. Summary of estimating models for wearing surface layer for quantity group A

| Model Comparison for Estimation Period | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 12.17 | 10.16 | 9.49 |
| Regression | 11.39 | 9.39 | 8.53 |

The error measures of the time series model and regression model for the wearing surface layer during the validation period are provided in Table 45. Neither the time series nor regression model performed as well in the validation period as they did during the estimation period. Both of the models had RMSE values greater than $20 per ton. This poor performance is most likely attributed to the high mean unit cost of the wearing surface material experienced during time periods 66 and 68. For the forecasted unit costs, the regression model did perform better than the time series model.

Table 45. Summary of estimating models for wearing surface layer for quantity group A during validation period

| Model Comparison for Validation Period | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 23.86 | 12.67 | 16.18 |
| Regression | 21.46 | 9.90 | 12.89 |

Because the regression model for the shift in the mean unit cost of the wearing surface layer data did not showcase any autocorrelation in the residual set, this model was chosen as the best model for the wearing surface layer in quantity group A. This simple model also had better performance in terms of the error measures during the validation period.

The first set of models to compare for quantity group B was the lower binder layer. Table 46 provides the summary of the error measures of the time series model, the regression model, and the regression model with time period 53 omitted for the lower binder layer during the estimation period. Both regression models performed better than the ARIMA model across all three measures of error. The regression model with time period 53 removed did provide a better fit to the data for the estimation period data than the regression model with all time periods.

Table 46. Summary of estimating models for lower binder layer for quantity group B

| **Model Comparison for Estimation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 7.83 | 9.49 | 5.83 |
| Regression | 6.96 | 7.88 | 4.72 |
| Regression (*t*=53 removed) | 5.44 | 7.09 | 4.03 |

The comparison of error measures for the three models during the validation period are shown in Table 47. All three models performed better during the validation period than the estimation period. It can also be seen that the time series model and the regression model without time period 53 performed slightly better than the regression model with time period 53. The percent difference in RMSE between the time series model and the regression model without time period 53 was just 0.5 percent.

Table 47. Summary of estimating models for lower binder layer for quantity group B during validation period

| **Model Comparison for Validation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 3.35 | 3.64 | 2.57 |
| Regression | 3.58 | 4.47 | 3.04 |
| Regression (*t*=53 removed) | 3.37 | 4.25 | 2.91 |

While the regression models performed better during the estimation period, the time series model performed the best overall during the validation period. Due to the increase in time needed to perform the Cochrane-Orcutt method for the regression models, the ARIMA (1, 1, 1) time series model was chosen as the best model for the lower binder layer data in quantity group B.

The next set of models to compare for quantity group B was the upper binder layer, and Table 48 provides the summary of the error measures of the time series model, the regression model, and the regression model with time period 53 omitted for the unit cost data during the estimation period. As with the lower binder layer in quantity group B, both regression models performed better than the ARIMA model across all three measures of error. The regression model with time period 53 removed provided the best fit for the estimation period data than the regression model with all time periods. The RMSE of the regression model with time period 53 omitted was approximately 26 percent less than the RMSE of the time series model and 15 percent less than the regression model with all time periods.

Table 48. Summary of estimating models for upper binder layer for quantity group B

| **Model Comparison for Estimation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 4.75 | 5.79 | 3.56 |
| Regression | 4.35 | 5.11 | 3.09 |
| Regression (*t*=53 removed) | 3.77 | 4.79 | 2.79 |

The next step in the model comparison process for the upper binder layer in quantity group B was the performance of the models during the validation period. As shown in Table 49, all three models forecasted the mean unit cost of the upper binder layer all of the models had a RMSE values less than $6 per ton and had MAE values of less than $5 per ton. Out of the three models, the time series model did have the lower error measures values.

Table 49. Summary of estimating models for upper binder layer for quantity group B during validation period

| Model Comparison for Validation Period | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 4.72 | 4.99 | 3.74 |
| Regression | 5.17 | 5.48 | 4.13 |
| Regression (*t*=53 removed) | 5.89 | 6.16 | 4.67 |

Similar to the lower binder group data in quantity group B, the regression models for the upper binder layer performed better in terms of the measures of error during the validation period. However, the time series model performed the best during the validation period. Because of the autocorrelation structure in the regression model residuals, the ARIMA (1, 1, 1) time series model was chosen as the best model for the upper binder layer.

The last set of models to compare for quantity group B were the three models constructed for the wearing surface layer, and a summary of the three models and their error measures can be found in Table 50. The regression model without time period 53 was shown to provide the lowest measures of error out of the three models.

Table 50. Summary of estimating models for wearing surface layer for quantity group B

| Model Comparison for Estimation Period | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 5.00 | 4.89 | 3.35 |
| Regression | 4.81 | 4.66 | 3.14 |
| Regression (*t*=53 removed) | 3.76 | 4.33 | 2.78 |

The error measures for the wearing surface layer during the validation period are found in Table 51. While the regression model without time period 53 was found have the lowest error measures during the estimation period, the time series model had the lowest error measures during the validation period. The regression model with omitted time period 53 was shown to underestimate the unit cost for time periods 67 through 74.

Table 51. Summary of estimating models for wearing surface layer for quantity group B during validation period

| **Model Comparison for Validation Period** | | | |
|---|---|---|---|
| **Model Type** | **RMSE** | **MAPE** | **MAE** |
| Time Series | 3.61 | 3.78 | 3.00 |
| Regression | 5.41 | 5.58 | 4.52 |
| Regression (*t*=53 removed) | 6.77 | 7.22 | 5.85 |

Both regression models performed the best in terms of the error measures during the model estimation or training period for the wearing surface layer while the time series performed better during the validation period. Due to the complexity of developing new regression models as new data comes online because of the autocorrelated errors, the ARIMA (1, 1, 1) time series model was chosen as the best cost-estimating model for the wearing surface layer.

After the best models were selected for each layer for both quantity groups, the models were refit to the full 74 time periods of data. A review of the model assumptions for each model confirmed that all of the models built for the full 74 time periods were acceptable. Table 52 provides the full estimating models for each layer for quantity groups A and B.

Table 52. Asphalt cost-estimating models for full 74 time periods

| Quantity Group | Layer | Estimating Model |
|---|---|---|
| A | Lower Binder | $Y_{t-1} - 0.82086r_{t-1}$ |
| | Upper Binder | $Y_{t-1} - 0.79145r_{t-1}$ |
| | Wearing Surface | $80.0680 + 24.5667x_t \text{ where } \begin{cases} x_t = 0 \text{ for } t < 33 \\ x_t = 1 \text{ for } t \geq 33 \end{cases}$ |
| B | Lower Binder | $Y_{t-1} + 0.38531(Y_{t-1} - Y_{t-2}) - 0.78618r_{t-1}$ |
| | Upper Binder | $Y_{t-1} + 0.55017(Y_{t-1} - Y_{t-2}) - 0.78780r_{t-1}$ |
| | Wearing Surface | $Y_{t-1} + 0.63892(Y_{t-1} - Y_{t-2}) - 0.82890r_{t-1}$ |

## 5.4 Variability in Forecasting Models

The models for the three asphalt layers for quantity groups A and B constructed for this research objective will provide a point forecast for the unit cost at a point in the future. While this point will provide the analyst with an estimated unit cost for the asphalt material, his value is not enough for a probabilistic approach to an LCCA during the pavement type selection process. For a probabilistic analysis, the analyst must have some estimate of the distribution and its parameters for the asphalt pay items so that a simulation model for the initial construction cost may be populated.

An important consideration for the probability distributions is the type of distribution and ability of the parameters to change with the forecasted asphalt layer unit cost. For example, assigning a triangular distribution would not be practical if the upper and lower limits of the distribution were fixed and not allowed to change. If a layer's unit cost was experiencing an upward trend, for example, the unit cost could potentially exceed the fixed upper limit of the distribution after a number of time periods in the future. A triangular distribution could be used, however, if the upper and lower limits were allowed to change with any trend in the layer's unit cost. To determine the type of distribution present within the three layers, the individual data points for the lower binder, upper binder, and wearing surface layer for each quantity group were analyzed graphically and with goodness-of-fit tests, to determine if the data fit a given distribution was statistically significant, at each of the 74 time periods.

The first data sets to analyze were for the lower binder layer in quantity group A. After reviewing the lower binder data of quantity group A at each time period and performing Shapiro-Wilk *W* goodness-of-fit tests on the data, it was found that approximately 68.9 percent (51 of the total 74 time periods) of the cost data sets failed to reject the null hypothesis that the data is from a normal distribution. From this, it was determined that that lower binder layer data should be modeled as a normal distribution. To determine the standard deviation value that would be used to populate the simulation model, the standard deviation of the data for the lower binder layer was calculated at each time period. The mean of these standard deviations was then calculated to replicate the average amount of variability in lower binder unit costs at each time period.

After viewing the histograms of the upper binder and wearing surface layer unit cost for quantity group A, it was found that many of the data sets within each time period for the two layers were positively skewed. Because of the skew, the unit cost data at each time period were fit to a lognormal distribution using a Kolmogorov's *D* goodness-of-fit test. A total of 54 time periods, or 73.0 percent, were found to be lognormally distributed in the upper binder layer and 55 of the time periods, or 74.3 percent, of the wearing surface layer were found to be lognormally distributed. To obtain the parameters of the lognormal distribution for use in a simulation model, the shape parameter for the lognormal distribution fit at each time period was recorded. These values were averaged for the upper binder and wearing surface layers to acquire the parameter values that would be used in the simulation. The distribution scale parameters for the three layers are provided in Table 53.

Table 53. Distribution parameters for asphalt layers for quantity groups A

| Layer | Distribution | Parameter |
|---|---|---|
| Lower Binder | Normal | 32.74 |
| Upper Binder | Lognormal | 0.3466 |
| Wearing Surface | Lognormal | 0.3028 |

After analyzing the distribution of the unit cost data for the three layers, it was determined that a majority of the time periods of data for quantity group B were normally distributed. For example, for the lower binder layer in quantity group B, it was found that 64 time periods out of the total 74 time periods, or 86.5 percent, had unit cost data that was normally distributed. Forty-six time periods, or 62.2 percent, of the upper binder unit cost data sets were normally distributed while 50, or 67.6 percent, of the 74 total time periods of the wearing surface unit cost data were normally distributed. By analyzing the plots of the distributions, it was found that several of the upper binder and wearing surface unit cost data sets at each time period were approximately normally distributed save for a smaller or larger data value or heavier tails of the distribution. Because a majority of the data sets at each time period were normally distributed, it was decided that the best way to model the forecasted unit cost data for quantity group B for a probabilistic analysis of the initial construction cost was using a normal distribution of the asphalt pay item unit costs. The average standard deviation values of the three asphalt layers for quantity group B for the 74 time periods can be found in Table 54.

Table 54. Distribution parameters for asphalt layers for quantity groups B

| Layer | Distribution | Parameter |
|---|---|---|
| Lower Binder | Normal | 11.60 |
| Upper Binder | Normal | 11.90 |
| Wearing Surface | Normal | 10.57 |

Because of the lag time between when an LCCA is conducted during the project timeline and when the project will actually be bid or constructed, it is recommended that the following steps be taken when estimating the initial construction costs of asphalt paving:

1. Estimate quantity of materials - Based on preliminary pavement design, calculate the quantity of lower binder, upper binder, and wearing surface material needed for the project. If the total quantity of each layer is less than 1,000 tons of material, use the models generated for quantity group A. If more than 1,000 tons of material is needed for a given layer, use quantity group B models.
2. Determine when estimated unit costs are needed:
    a. If a PAC is not used in the paving contract, estimate the month the project will be bid.
    b. However, if a PAC is used, estimate when the paving project will begin and estimate the duration of the project. Also estimate the quantity of material that will be place in two-month periods for the entire project duration.
3. Use models to forecast the unit cost of the three layers:
    a. If a PAC is not used, the unit costs of the three layers should be forecasted to the time the project will be bid.
    b. If a PAC is used, forecast the unit cost of the material for each two-month period of construction.
4. Adjust forecasted unit costs for project location within the state of Alabama
5. Populate simulation model with material quantities and the distribution parameters of the forecasted unit costs and run simulation. Use simulated cost distribution in RealCost to calculate asphalt total life cycle cost.

## 5.5 Forecasting Models Exercised in Example Project

The example LCCA project chosen to execute the asphalt cost forecasting models was for a pavement reconstruction project on Interstate 20/59 in Jefferson County, Alabama. The current pavement system on this section of the roadway is an 8.25-inch CRCP. The project will require an HMA overlay over the rubblized CRCP. The project length is 1.05 miles. Because this project requires an overlay of the existing pavement system, transitions are required at the beginning and end of the project limits. The transitions were designed to be 1,200-feet in length on both ends of the project.

The asphalt design calls for a total HMA thickness of approximately 12 inches, which includes a wearing surface thickness of 1.40-inches, an upper binder layer thickness of 2.25-inches, and a lower binder layer thickness of 8.37-inches. This project will require 24,324 tons of lower binder, 6,078 tons of upper binder, and 3,638 tons of wearing surface material for the overlay of the existing CRCP system. The transition areas at the beginning and end of the project will require 5,258 tons of lower binder, 1,314 tons of upper binder, and 784 tons of wearing surface.

Assume that the LCCA for the paving project is conducted in April 2012. The anticipated bid date for this project is scheduled for December 2012. Since ALDOT utilizes PACs during the construction of asphalt roadways, it is estimated that the overlay will be constructed in May 2013 and it will take one month to complete the paving operations. Therefore, all paving material will be purchased and installed in the month of May in the year 2013. A forecast of the lower binder, upper binder, and wearing surface unit costs for quantity group B will be needed to estimate the paving cost in May 2013 by using the prediction models created earlier in this objective because the project LCCA is conducted in time period 74 and the overlay is scheduled to begin time period 81 (May of 2013).

Using the forecasting models for quantity group B generated earlier in this research objective, the forecasted unit cost of the lower binder layer for time period 81 is $68.69 per ton. At time period 81, the forecasted unit cost of the upper binder layer is $74.93 per ton while the estimate for the wearing surface layer $79.10 per ton of material. Because the forecasted costs were made for the Birmingham region and the project is within the Birmingham region, no location adjustments to the unit cost estimates are necessary. The next step in the cost estimating process is populating the simulation model with these forecasted values, the standard deviation values for the three layers, and the material quantities. Once the simulation model was populated with the necessary values, 10,000 simulated runs were generated using JMP statistical software.

From the cost simulation output, the mean initial construction cost for the asphalt alternative was calculated to be $2,928,095 with a standard deviation of $358,438. These values could then be entered into the initial construction cost section for the asphalt pavement alternative in the RealCost LCCA software package so that a full probabilistic assessment of the life cycle cost could be executed.

## 5.6 Summary

The uncertainty associated with paving costs, especially asphalt paving costs, has increased in recent times. The volatility and rise in asphalt liquid binder costs has increased the difficulty associated with estimating the initial construction cost of asphalt paving operations that will be used in an LCCA during the pavement type selection process. Literature concerning pavement LCCAs provides little guidance on how to forecast the initial construction cost of asphalt paving. Pavement LCCA literature also does not provide any supportive methods on how to manage the use of PAC in the contracts and any ramifications the use of these instruments could have on the actual cost of asphalt pavement construction. These factors could ultimately lead an analyst to make a poor decision on which pavement to use for the project.

Given the lack of formal instruction on how to accommodate such factors, the main goal of this research objective was to develop and exercise a methodology to forecast the initial construction cost of asphalt paving materials. This methodology presented techniques that an analyst performing a pavement LCCA could use to produce an estimate of the asphalt paving cost in Alabama that is supported by historical bid data. This method also factors in the location of the paving project within the state of Alabama and provides guidance on how to use the forecasting models when a PAC is used in the paving contract.

# CHAPTER VI

# SUMMARY, CONCLUSION, AND RECOMMENDATIONS

## 6.1 Summary

During this research effort, the first objective was to examine the LCCA procedure currently used in the pavement type selection process in Alabama and compare the current procedure with state-of-the-practice techniques and methods used throughout the country. After reviewing LCCA procedures from other state highway agencies and other literature pertaining to economic analyses during the pavement type selection process, key issues and factors were identified and examined. Once the most important LCCA factors were identified, meetings between the asphalt and concrete pavement industries within the state of Alabama and ALDOT representatives allowed both industries to voice their opinions on the LCCA factors and values. After reviewing the state-of-the-practice literature and hearing the arguments from both pavement industries on the key LCCA factors, recommendations for the application of an LCCA during the pavement type selection process were provided.

The second objective of this dissertation used a major paving project on Interstate 65 in Birmingham as a case study to assess the LCCA procedure currently used by ALDOT and to examine the sensitivity of changes to various factors used in the analysis. Using the details provided by ALDOT in the case study, which included material quantities, pay item unit costs, and rehabilitation schedules and activities, factors such as the analysis period, discount rate, and remaining service life were analyzed to determine the sensitivity that changes to these factors had on the total life cycle costs of both alternatives. From the sensitivity analysis of the deterministic LCCA, several factors, such as discount rate and analysis period were found to influence on the total life cycle costs of both asphalt and concrete pavement alternatives. However, one of the most significant factors in the deterministic LCCA was the initial construction cost of the alternatives. For the paving case study, a slight deviation in the initial construction cost of either the asphalt or concrete alternative could potential change which alternative is the most attractive based on the total life cycle cost.

The second portion of the second research objective examined the effect that a PAC could have on the outcome of a probabilistic LCCA of the example project. To examine the sensitivity of the asphalt initial construction cost, the means of the asphalt unit cost distributions used in the calculation of the initial cost distribution of the asphalt and concrete alternatives were varied and the impact on the cost difference between the concrete and asphalt distributions was evaluated. From this analysis of the paving case study, the effect of PACs on the initial construction costs could increase the probability that the wrong material would be chosen by as much as 17 percent for the example paving project.

The third and final objective of this research effort was to develop and exercise a new methodology for estimating the initial construction cost of asphalt pavements for use in both deterministic and probabilistic LCCAs. To accomplish this objective, forecasting models were created to account for the time difference between when the LCCA is conducted during the project life cycle and when the project would actually be bid or constructed. Asphalt unit cost data within the state of Alabama was used to develop time series and regression models to create the forecasting models for the lower binder, upper binder, and wearing surface layers based on the quantity of material needed to construct the project and the location of the asphalt paving project.

## 6.2 Limitations

There were several limitations encountered during the research project. The main limitation was the concrete pavement data set that was used to create forecasting models for concrete pavements. Similar to asphalt pavements, there is a potential for the price of concrete to rise or fall in the time period between when the LCCA is conducted and when the project is put out for bid. Forecasting models were attempted for concrete pavements but several problems were encountered. The first problem was the lack of concrete paving unit cost data in the state of Alabama. Because ALDOT uses asphalt as the main paving material, concrete paving costs are not as available as asphalt cost data. Due to this fact, concrete pavement cost data from nine states in the Southeast was used to increase the sample size as much as possible. However, the sample size of the data was still small even after supplementation with out-of-state cost data. The main problem encountered when constructing the forecasting models for concrete pavements was noticed when partitioning the concrete data into different groups based on the quantity of material required and into time periods. Separating the data into quantity groups and time periods decreased the number of data points to even lower levels. There were several instances when some time periods within a quantity group did not have any data available or just one or two data points.

The concrete data set is also different from the asphalt unit cost data because of how the two materials are estimated and bid. Because a majority of the concrete unit cost data was provided on a cost per square area basis, such as dollars per square yard, another problem was encountered when attempting to account for the thickness of the concrete pavements in the data set. In the pay item description column from the Oman database, the thickness of the concrete pavement was typically provided and a new variable was created based on this information. The thicknesses of the concrete pavements from the nine Southeastern states ranged from six inches thick up to 14.5 inches thick. Because dividing the data set even further and grouping the data based on quantity and thickness was not feasible based on the already small concrete cost data sample size at each time period, the thickness of the pavement in the forecast models was initially omitted. However, this approach does not make sense because increasing the thickness of a concrete pavement will require more concrete needed to complete the pavement, thus increasing the total amount of the work. Manipulation of the unit cost variable, such as dividing the cost per square yard of a data point by the thickness of the pavement, was attempted but this falsely assumes that a pure linear relationship between thickness and unit cost exists.

While the concrete cost data sets from the Oman database provides a significant amount of supporting information, other key information needed to explain some of the variability in the models, such as joint spacing, dowel bar types, and dowel spacing, was not provided in the dataset. This information is valuable because it helps determine the costs associated with the cost of the dowel bars, a material cost, as well as construction activities such as joint sawing, which constitutes material, labor, and equipment costs. Building an estimating model for the concrete pavements that made assumptions about these factors would be unreasonable and would not provide the analyst with a reliable estimate of the concrete pavement cost.

Another problem with the concrete data set is attributable to using bid data from other states. Since the location of the paving projects was provided, it was not difficult to adjust the unit cost data based on the geographic location of the project. However, because the cost data came from nine different states, differing design standards and concrete mix specification issues does not provide an opportunity to equally compare the unit costs in the concrete pavement data set. For example, constructing a concrete pavement in Alabama will have a different cost than a similar pavement constructed in North Carolina because of variations in project scope, location, and other factors. However, a portion of the cost to construct the pavement in Alabama is negatively impacted by the disallowance of limestone aggregate in the concrete mix used to construct the travel lanes. Another factor that may alter the unit cost of the concrete pavement includes the incentive and disincentive policies at the state highway agencies. The penalty for failing to meet a certain requirement in one state may be more severe than other states, prompting one paving contractor in a state to increase the unit cost of the pavement to cover the risk of not meeting the specifications. A combination of all of these factors greatly reduced the reliability of the concrete pavement unit cost forecasting models when using the same methods employed to build the asphalt pavement forecasting models.

Another limitation of this research effort was made apparent during the sensitivity analysis of the ALDOT paving project on Interstate 65 used in Chapter IV. Because ALDOT does not conduct pavement LCCAs with analysis periods greater than 28 years and due to a lack of detailed performance information and traffic projections, the timing of both asphalt and concrete pavement rehabilitation activities were assumed. Other assumptions were made about the severity of the pavement distress at the time rehabilitations were scheduled and what rehabilitation would be necessary to remediate the pavement system. Another limitation of this study was the small sample of historical data for some of the paving pay items used during the sensitivity analysis of the example project LCCA.

## 6.3 Conclusion

The main goal of this dissertation was to develop a framework to estimate the initial construction costs of asphalt pavements when used in an LCCA during the pavement type selection process. This goal was accomplished by dividing the goal into three distinct research objectives.

The first objective of this research was to identify the key issues and factors used in an LCCA when comparing two pavement alternatives and provide recommendations on the state-of-the-practice usage of these factors and values. This objective was addressed in Chapter III. In this chapter, the factors commonly used in an LCCA were discussed and the current use of these factors in other states around the country was examined. Input from the asphalt pavement industry and concrete pavement industry within the state of Alabama was also considered when providing the factor and value recommendations. While reviewing LCCA literature and listening to the input from the asphalt pavement industry, concrete pavement industry, and DOT personnel, it became apparent that there was no straightforward method for forecasting the cost of asphalt materials during the estimation of the initial construction cost for the pavement type selection and how an error in the cost estimate could impact which pavement type is chosen during the analysis.

The second research objective for this dissertation required an examination of the effect that PACs have on the initial construction costs when used in a probabilistic LCCA. This objective was addressed in Chapter IV. To examine how PACs could influence the initial construction costs, a probabilistic analysis was constructed using an existing deterministic LCCA conducted for a paving project in Alabama as an example that provided pavement quantities and unit costs. The sensitivity to the asphalt price adjustments was performed by adjusting the means of the asphalt pay item unit costs by the unit cost adjustments caused by changes in the price of asphalt liquid binder in the probabilistic life cycle cost models. Using the example paving project and the asphalt price adjustments in Alabama for the year 2011, it was found that the price adjustments of the asphalt binder could increase the probability that the wrong pavement type is chosen during the analysis by over 18 percent. This finding was important because it illustrates the importance of estimating the actual costs the agency will pay during the construction of the pavement, not just the bid prices, and this finding also created the basis for developing a framework for estimating the initial construction costs for asphalt pavements and the creation of the asphalt cost estimating models.

The third and final objective of this research was to develop models for forecasting the unit costs of asphalt materials in a LCCA. To accomplish this objective, the forecasted values would need to provide an estimate of the pay item unit cost as well as a means to estimate the uncertainty in that value for use in a probabilistic analysis. The forecasting models were constructed using both time series analysis and regression methods. For a majority of the asphalt layers and quantity groups, the time series models were chosen because they provided the greatest accuracy with the multiple step ahead forecasts and the simplicity of the models when compared to the autoregressive nature of the regression model residuals. From the data, it appears that the asphalt unit costs did undergo a shift in cost in the year 2008, but recently, the volatility in the mean unit costs of the asphalt paving materials has subsided in recent years.

## 6.4 Research Contributions

This research has made the following contributions to the current body of knowledge pertaining to the use of LCCAs as an economic comparison tool during the pavement type selection process:

- Identified key issues that the asphalt and concrete pavement industries currently have with the LCCA process and made recommendations based on collaborative meetings, expert opinion, and review of pertinent literature.
- Examined the use of probabilistic LCCA that incorporate state-of-the-practice factors and values and evaluated the effect changes in the initial construction cost due to PACs could have on the probabilistic LCCA outcome.
- Developed a probabilistic cost estimating process for asphalt pavements for use in the pavement type selection LCCA procedure that accounts for the point in time the project will be bid and/or constructed, the quantity of paving material required, and trends and variability associated with asphalt pavement costs through the use of short term forecasts of the unit costs.

## 6.5 Recommendations

While the analysis of the life cycle costs is a useful tool for decision making during the pavement type selection process, it should be noted that in the end, it is just a tool and that other factors should be considered in addition to the life cycle costs of the alternatives. While this research focused solely on the agency costs borne by the sponsoring agency, the user costs associated with the construction, maintenance, rehabilitation, and normal operation of the roadway should also be considered when selecting between asphalt and concrete pavement types.

A pavement LCCA is a perfect example of the GIGO (garbage in, garbage out) principle commonly used in the field of computer science and technology. The results of the LCCA are only as good as the quality of the input values and factors used to calculate the life cycle costs of asphalt and concrete pavements. While a probabilistic approach to a pavement LCCA can provide decision makers with a better understanding of the risk and uncertainty associated with the alternatives, the simulated output is worthless if the input distributions are not realistic. As shown in Chapter IV (second research objective), a slight deviation in the mean of the initial construction cost distribution of the asphalt alternative can significantly increase or decrease the probability that the wrong pavement may be chosen if agency cost is the sole criteria.

Great care and study should be given to the input values and distribution parameters used in a probabilistic LCCA. The need for reliable and accurate estimates of factors such as initial performance periods and rehabilitation performance periods advocates strongly for a properly designed and maintained pavement management system (PMS). This system can provide the analyst with a wealth of performance data, allowing them to predict the performance of the pavement and determine the point in time rehabilitation activities are necessary and predict the severity of future rehabilitative activities. This information will then allow for realistic probability distributions of the performance of the pavements to be generated for use in a probabilistic LCCA.

While non-cost factors inputs are important in an LCCA between pavement types, the main driver of the total life cycle costs of the asphalt and concrete pavement alternatives is typically the initial construction cost of the pavement. Accurate documentation of pavement project bids would greatly benefit the analyst conducting the LCCA while developing the estimate of the initial construction cost. While this historical data is beneficial, the need for an accurate estimate of the unit cost of the asphalt and concrete pay items when the project is actually bid or constructed is of the greatest value. Special care should be given when PACs are used in the paving contract because the actual cost paid for the asphalt alternative is the most important aspect when calculating the initial construction costs of the two alternatives, not the asphalt bid price. If a PAC is used in the contract, the bid amount is not what is actually paid and the actual cost is likely to be higher than the bid amount, especially if the real price of asphalt is increasing through time. By using the recommended factors and values outlined in Chapter V and by following the framework for forecasting asphalt unit costs by layer and quantity to compensate for PAC used in paving contracts, an analyst will be able to compare the life cycle costs of the two pavement materials reasonably and without bias toward one material.

## 6.6 Future Research

Several future research efforts became apparent while working on this project. One of the main future research efforts will examine the applicability of the cost forecasting models provided in Chapter V to other areas of infrastructure construction, industrial, and commercial construction. Because other commonly used construction materials such as steel and lumber may experience trends in price, the need for an accurate forecast based on any changes in the real cost of these materials is crucial during the planning stages of a project. Another research endeavor is the application of LCCA to growing areas of construction such as the construction of sustainable facilities. The use of LCCA for sustainable construction projects is an interesting application because the use of new, energy-efficient materials and systems now allow architects and engineers to design facilities that minimize their environmental impact. However, due to the relative newness of these materials and designs, the long-term benefits and costs of these systems may not be known until they have been in use for a period of time and data is gathered on their performance.

An interesting topic that became apparent during this research effort was the correlation between pay items during the execution of a probabilistic LCCA. When conducting a Monte Carlo simulation of life cycle costs for asphalt and concrete pavement alternatives, several decisions must be made to ensure that an accurate portrayal of cost risk can be generated for a given paving project. One choice made when building the cost model is determining which variables in the model have the potential for variability and should be modeled as a random variable. Another decision is the type of distribution the random variable should be modeled after as well as determining the parameters of that distribution. One assumption that is not explicitly discussed in the LCCA for pavement type selection literature is the possible correlation between the unit costs of the pavement pay items.

When the assumption is made that there is independence between the pay items, this assumption also assumes that the pay items are uncorrelated. While this approach provides a straightforward method to simulating the life cycle costs, failure to account for positive correlation between the pay item unit costs will underestimate the variance of the simulated life cycle costs. If the two unit costs are assumed to be independent and uncorrelated in the simulations, the covariance term in the calculation of the total variance is equal to zero because the correlation between the two unit costs is equal to zero. However, if the two unit costs are positively correlated, the variance of the sum of costs $X$ and $Y$, for example, will be higher than if the costs were assumed uncorrelated. Larger projects that require more material will also increase the total variance of the total construction cost of the paving project more so than a project with similar pay item unit cost variances but with smaller quantities of material.

It must be mentioned that any correlation between pay items does not necessarily imply that the rise in the unit cost of one item causes a rise in the cost of a similar pay item. The increase or decrease in unit cost of two similar materials may be attributable to a confounding factor that is not included in the analysis, thus causing a spurious relationship between the two pay items. For example, the average unit costs of an asphalt wearing surface layer and a binder layer may rise and fall together and the correlation in unit costs of the two may be high, but this does not mean that the rise in cost of the wearing surface layer was the direct cause of the rise in the binder layer unit cost. The covariance relationship between the two pay items is most likely attributable to a rise or fall in the price of an outside factor, and in the case of asphalt pavements, the outside factor that would have the greatest influence on the unit cost of the paving mix is the price of the liquid asphalt binder. Because of this, an area of future research is to examine any possible correlation structure between pavement pay items as well as any correlation that may exist between other materials commonly used in the construction industry.

The assumption of independence between asphalt and concrete pavement costs when using RealCost LCCA software or other simulation software packages is also an important consideration. In the example LCCA project used in Chapter IV, the concrete pavement design required an asphalt bond-breaker layer to be placed between the existing pavement system and the new concrete pavement during the initial construction phase of the project. Because both alternatives would require an asphaltic material during construction, it is not reasonable to assume that the initial construction costs between the two alternatives would be completely independent. In other words, a simulation iteration that produces a low asphalt cost for the asphalt alternative could not be viewed as a realistic outcome if the asphalt unit cost used in the calculation of the concrete pavement initial construction costs was much higher because the two costs were assumed to be independent. Another example of this situation would occur if both the asphalt and concrete pavement alternatives were scheduled to receive an ACOL at the same period in the future.

An additional research endeavor involves determining when an analysis of user costs would be necessary during a probabilistic LCCA of the agency costs. Both the asphalt and concrete pavement industries in Alabama recommended that the user costs of both pavement materials be analyzed when the deterministic agency costs were within ten percent of each other. This approach could easily be transferred to a probabilistic analysis when the mean or median of the simulation output is within ten percent. However, certain cases may arise where the means, for example, of the asphalt and concrete simulated life cycle costs may not be within ten percent of each other but the probability of choosing the wrong material is greater than 20 percent or 30 percent. Determining what probability the cost difference between the two alternatives is less than zero would be valuable to an analyst to determine when an examination of the user costs is needed to support the decision making process.

Another interesting research endeavor spawned by this project concerns the spatial relationship of highway infrastructure construction costs. Factors such as proximity to material suppliers, population density, and other factors can positively or negatively influence the cost of an infrastructure project. The use of Geographic Information Systems (GIS) has grown in popularity with civil engineering research in recent years. Future research will use the tools in GIS such as Kriging and other spatial interpolation techniques to develop GIS based cost estimating systems for infrastructure projects.

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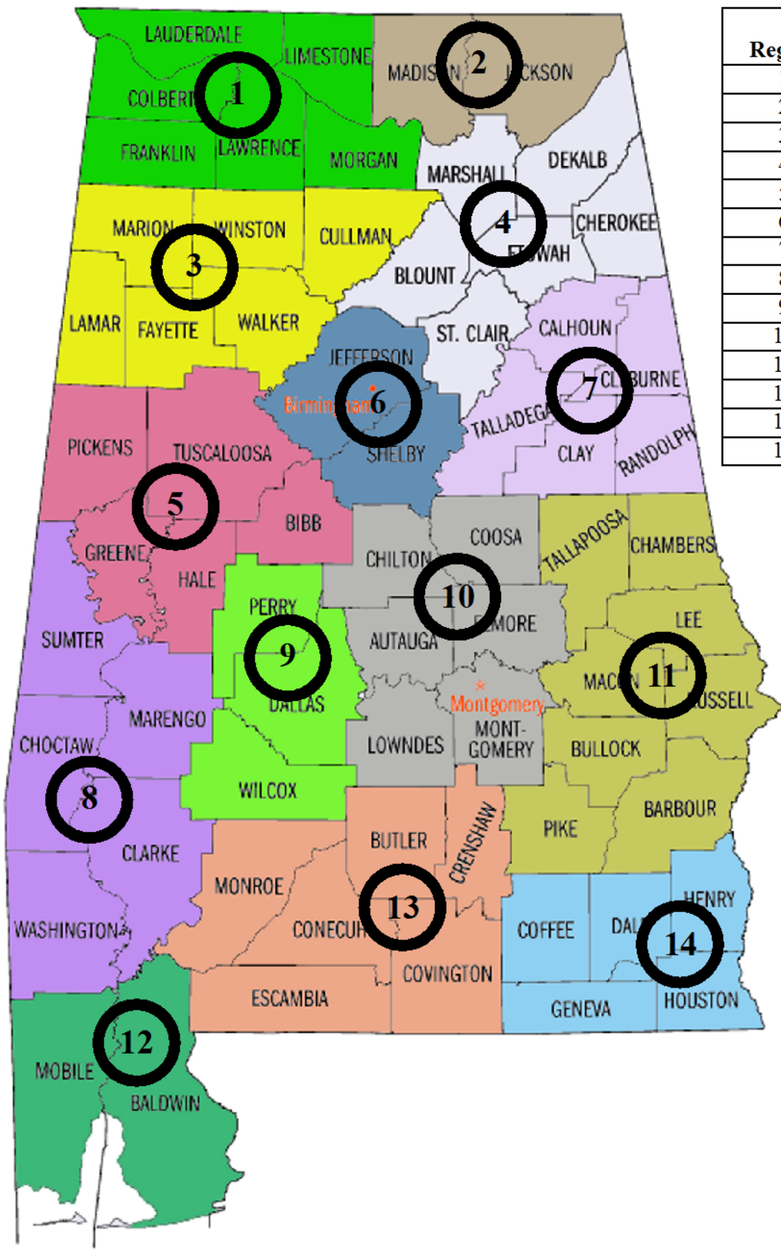
APPENDIX A




| Region | Location Index |
|---|---|
| 1 | 0.77 |
| 2 | 0.83 |
| 3 | 0.73 |
| 4 | 0.74 |
| 5 | 0.77 |
| 6 | 0.87 |
| 7 | 0.77 |
| 8 | 0.73 |
| 9 | 0.73 |
| 10 | 0.76 |
| 11 | 0.73 |
| 12 | 0.82 |
| 13 | 0.73 |
| 14 | 0.75 |

Figure A.1. Alabama location factor map

APPENDIX B

Table B.1. Number of data points per time period

| Time Period | Lower Binder | Upper Binder | Wearing Surface | | Time Period | Lower Binder | Upper Binder | Wearing Surface |
|---|---|---|---|---|---|---|---|---|
| 1 | 15 | 46 | 61 | | 38 | 31 | 94 | 140 |
| 2 | 22 | 82 | 109 | | 39 | 19 | 71 | 125 |
| 3 | 6 | 51 | 58 | | 40 | 9 | 34 | 57 |
| 4 | 6 | 23 | 22 | | 41 | 15 | 43 | 53 |
| 5 | 16 | 38 | 50 | | 42 | 11 | 26 | 39 |
| 6 | 17 | 56 | 47 | | 43 | 18 | 54 | 119 |
| 7 | 9 | 37 | 54 | | 44 | 25 | 98 | 123 |
| 8 | 19 | 95 | 110 | | 45 | 15 | 52 | 73 |
| 9 | 21 | 81 | 104 | | 46 | 8 | 25 | 35 |
| 10 | 11 | 14 | 15 | | 47 | 19 | 18 | 31 |
| 11 | 7 | 21 | 26 | | 48 | 20 | 53 | 65 |
| 12 | 16 | 45 | 47 | | 49 | 20 | 53 | 78 |
| 13 | 12 | 31 | 46 | | 50 | 18 | 88 | 96 |
| 14 | 32 | 167 | 216 | | 51 | 20 | 69 | 81 |
| 15 | 28 | 76 | 82 | | 52 | 13 | 34 | 53 |
| 16 | 7 | 39 | 50 | | 53 | 21 | 39 | 31 |
| 17 | 13 | 69 | 61 | | 54 | 12 | 62 | 76 |
| 18 | 9 | 40 | 47 | | 55 | 14 | 46 | 55 |
| 19 | 18 | 63 | 73 | | 56 | 16 | 88 | 114 |
| 20 | 24 | 98 | 113 | | 57 | 20 | 140 | 161 |
| 21 | 12 | 85 | 113 | | 58 | 20 | 77 | 110 |
| 22 | 12 | 35 | 60 | | 59 | 26 | 85 | 85 |
| 23 | 3 | 13 | 7 | | 60 | 9 | 50 | 85 |
| 24 | 17 | 60 | 51 | | 61 | 11 | 49 | 79 |
| 25 | 25 | 91 | 105 | | 62 | 17 | 101 | 119 |
| 26 | 14 | 62 | 75 | | 63 | 16 | 105 | 114 |
| 27 | 17 | 104 | 124 | | 64 | 20 | 34 | 58 |
| 28 | 20 | 41 | 50 | | 65 | 19 | 43 | 54 |
| 29 | 16 | 48 | 47 | | 66 | 20 | 35 | 40 |
| 30 | 23 | 56 | 48 | | 67 | 19 | 125 | 149 |
| 31 | 9 | 53 | 72 | | 68 | 0 | 9 | 12 |
| 32 | 21 | 58 | 83 | | 69 | 28 | 113 | 117 |
| 33 | 25 | 44 | 57 | | 70 | 11 | 43 | 68 |
| 34 | 12 | 33 | 34 | | 71 | 22 | 58 | 66 |
| 35 | 4 | 19 | 27 | | 72 | 21 | 48 | 61 |
| 36 | 17 | 55 | 67 | | 73 | 5 | 19 | 45 |
| 37 | 16 | 38 | 90 | | 74 | 14 | 113 | 140 |

APPENDIX C

Table C.1. Lower binder mean unit cost and standard deviation for quantity groups A and B

| Time Period | Lower Binder Quantity Group A | | Lower Binder Quantity Group B | |
|---|---|---|---|---|
| | **Mean** | **Standard Deviation** | **Mean** | **Standard Deviation** |
| 1 | 106.43 | 111.16 | 49.78 | 11.08 |
| 2 | 65.17 | 30.71 | 48.24 | 6.84 |
| 3 | 70.51 | - | 50.55 | 11.66 |
| 4 | 58.90 | 11.38 | 42.64 | 2.50 |
| 5 | 84.57 | 32.22 | 52.28 | 18.90 |
| 6 | 70.08 | 29.31 | 41.75 | 9.59 |
| 7 | 58.57 | 1.55 | 43.25 | 7.58 |
| 8 | 65.88 | 17.60 | 48.80 | 5.91 |
| 9 | 70.07 | 32.72 | 52.12 | 10.50 |
| 10 | 87.74 | 43.39 | 49.31 | 11.78 |
| 11 | 70.09 | 7.70 | 47.92 | 17.10 |
| 12 | 93.31 | 57.48 | 50.32 | 7.05 |
| 13 | 89.38 | 29.46 | 46.93 | 10.89 |
| 14 | 76.76 | 29.42 | 39.66 | 8.45 |
| 15 | 83.08 | 27.72 | 50.33 | 15.53 |
| 16 | 82.91 | 35.59 | 40.04 | 7.67 |
| 17 | 74.66 | 26.77 | 47.16 | 9.08 |
| 18 | 60.06 | 18.03 | 45.41 | 13.69 |
| 19 | 66.35 | 10.95 | 53.39 | 16.06 |
| 20 | 74.82 | 15.20 | 49.45 | 5.71 |
| 21 | 68.83 | 37.27 | 52.36 | 14.49 |
| 22 | 75.72 | 27.04 | 49.51 | 8.11 |
| 23 | 60.27 | - | 42.97 | 14.95 |
| 24 | 107.39 | 44.43 | 45.94 | 7.25 |
| 25 | 93.62 | 55.28 | 58.50 | 23.43 |
| 26 | 67.06 | 9.33 | 48.80 | 9.30 |
| 27 | 89.77 | 36.52 | 60.68 | 14.30 |
| 28 | 84.60 | 21.44 | 55.86 | 6.55 |
| 29 | 94.30 | 39.09 | 49.76 | 12.39 |
| 30 | 75.64 | 13.31 | 49.17 | 16.65 |
| 31 | 131.43 | 64.68 | 53.65 | 15.46 |
| 32 | 67.48 | 13.79 | 45.83 | 17.73 |
| 33 | 102.88 | 57.98 | 49.47 | 19.08 |

Table C.1. Lower binder mean unit cost and standard deviation for quantity groups A and B

| | | | | |
|---|---|---|---|---|
| 34 | 76.88 | 14.71 | 43.84 | 4.03 |
| 35 | 161.59 | 90.24 | 62.50 | 7.57 |
| 36 | 113.64 | 48.14 | 54.29 | 7.76 |
| 37 | 109.30 | 39.43 | 57.54 | 14.24 |
| 38 | 91.09 | 17.88 | 70.85 | 9.30 |
| 39 | 124.65 | 73.38 | 73.51 | 8.48 |
| 40 | 129.85 | 47.59 | 74.85 | 9.52 |
| 41 | 108.22 | 27.46 | 62.38 | 22.12 |
| 42 | 123.01 | 21.62 | 73.87 | 16.29 |
| 43 | 108.36 | 46.98 | 71.54 | 12.28 |
| 44 | 93.09 | 31.59 | 70.73 | 15.89 |
| 45 | 155.33 | 67.67 | 71.95 | 16.78 |
| 46 | 76.93 | 19.35 | 68.63 | 5.69 |
| 47 | 107.88 | 26.16 | 60.79 | 11.34 |
| 48 | 91.79 | 23.70 | 63.32 | 7.66 |
| 49 | 114.36 | 15.06 | 66.04 | 11.14 |
| 50 | 109.75 | 41.85 | 70.50 | 7.63 |
| 51 | 105.22 | 38.41 | 74.29 | 10.34 |
| 52 | 112.96 | 19.41 | 88.45 | 21.06 |
| 53 | 165.13 | 103.62 | 112.69 | 13.22 |
| 54 | 111.24 | 31.62 | 81.86 | 5.82 |
| 55 | 107.78 | 31.95 | 71.56 | 14.55 |
| 56 | 109.76 | 20.31 | 71.62 | 7.46 |
| 57 | 101.94 | 34.02 | 68.99 | 10.45 |
| 58 | 91.82 | 17.68 | 77.08 | 13.18 |
| 59 | 117.69 | 38.34 | 68.48 | 13.12 |
| 60 | 101.58 | 30.81 | 78.24 | 19.33 |
| 61 | 110.78 | 50.53 | 70.06 | 9.44 |
| 62 | 95.18 | 18.90 | 70.16 | 8.15 |
| 63 | 82.30 | 10.48 | 72.76 | 12.28 |
| 64 | 120.92 | 32.51 | 65.70 | 15.52 |
| 65 | 115.42 | 36.97 | 62.60 | 14.76 |
| 66 | 119.60 | 28.16 | 67.11 | 12.64 |
| 67 | 77.83 | 6.28 | 67.30 | 15.09 |
| 68 | - | - | - | - |
| 69 | 97.21 | 31.92 | 69.49 | 10.42 |
| 70 | 99.46 | 8.97 | 73.71 | 9.53 |
| 71 | 105.86 | 23.78 | 69.05 | 9.57 |
| 72 | 99.99 | 30.86 | 74.56 | 12.94 |
| 73 | 88.20 | - | 70.38 | 7.46 |
| 74 | 96.25 | 37.92 | 64.40 | 5.18 |

Table C.2. Upper binder mean unit cost and standard deviation for quantity groups A and B

| Time Period | Upper Binder Quantity Group A | | Upper Binder Quantity Group B | |
|---|---|---|---|---|
| | Mean | Standard Deviation | Mean | Standard Deviation |
| 1 | 69.55 | 23.37 | 46.85 | 8.15 |
| 2 | 77.75 | 33.91 | 50.37 | 11.21 |
| 3 | 90.80 | 56.99 | 45.07 | 13.03 |
| 4 | 68.23 | 22.08 | 49.81 | 9.32 |
| 5 | 87.02 | 35.36 | 49.70 | 15.54 |
| 6 | 78.04 | 24.81 | 48.41 | 11.39 |
| 7 | 57.48 | 22.63 | 45.94 | 12.12 |
| 8 | 73.56 | 30.32 | 49.60 | 11.67 |
| 9 | 78.25 | 33.12 | 47.33 | 11.44 |
| 10 | 58.12 | 22.23 | 44.31 | 7.19 |
| 11 | 79.48 | 33.38 | 41.17 | 14.06 |
| 12 | 76.31 | 33.17 | 51.23 | 8.92 |
| 13 | 74.81 | 45.11 | 43.49 | 7.07 |
| 14 | 67.26 | 27.59 | 46.18 | 12.10 |
| 15 | 76.87 | 31.72 | 48.15 | 9.34 |
| 16 | 104.89 | 77.85 | 44.90 | 6.09 |
| 17 | 71.38 | 22.06 | 46.31 | 5.54 |
| 18 | 81.78 | 35.86 | 46.71 | 7.05 |
| 19 | 71.89 | 25.54 | 49.18 | 11.61 |
| 20 | 75.30 | 27.37 | 50.85 | 7.82 |
| 21 | 80.86 | 31.33 | 53.00 | 15.62 |
| 22 | 97.71 | 70.14 | 46.68 | 7.43 |
| 23 | 109.00 | 64.69 | 50.05 | 2.08 |
| 24 | 79.24 | 32.52 | 50.34 | 6.73 |
| 25 | 88.17 | 42.43 | 50.54 | 13.34 |
| 26 | 85.02 | 30.33 | 52.18 | 11.77 |
| 27 | 90.27 | 29.73 | 58.15 | 14.95 |
| 28 | 90.16 | 33.53 | 58.27 | 12.12 |
| 29 | 95.82 | 36.10 | 59.77 | 11.33 |
| 30 | 90.62 | 27.34 | 55.31 | 12.67 |
| 31 | 90.41 | 37.50 | 55.83 | 8.80 |
| 32 | 90.63 | 28.95 | 53.97 | 12.53 |
| 33 | 88.28 | 24.17 | 51.12 | 22.86 |
| 34 | 82.08 | 41.89 | 63.24 | 18.85 |
| 35 | 135.75 | 91.94 | 66.97 | 13.09 |
| 36 | 113.13 | 50.88 | 60.71 | 9.39 |
| 37 | 101.00 | 38.51 | 62.78 | 14.22 |
| 38 | 101.33 | 61.38 | 66.30 | 14.12 |
| 39 | 113.88 | 30.90 | 71.53 | 11.61 |
| 40 | 95.57 | 26.17 | 68.59 | 10.46 |
| 41 | 102.03 | 26.24 | 71.19 | 8.65 |
| 42 | 104.62 | 38.22 | 73.42 | 9.81 |

Table C.2. Upper binder mean unit cost and standard deviation for quantity groups A and B

| | | | | |
|---|---|---|---|---|
| 43 | 92.50 | 25.52 | 70.82 | 13.52 |
| 44 | 109.59 | 35.96 | 71.92 | 14.22 |
| 45 | 128.89 | 66.06 | 73.12 | 19.70 |
| 46 | 104.05 | 27.94 | 70.36 | 12.43 |
| 47 | 87.38 | 40.86 | 65.90 | 11.89 |
| 48 | 86.00 | 18.26 | 68.89 | 9.20 |
| 49 | 109.01 | 64.41 | 64.99 | 11.94 |
| 50 | 92.25 | 29.59 | 67.00 | 15.92 |
| 51 | 89.05 | 29.97 | 70.78 | 13.51 |
| 52 | 112.55 | 25.66 | 86.47 | 17.33 |
| 53 | 124.26 | 30.82 | 96.81 | 12.91 |
| 54 | 126.01 | 42.11 | 79.60 | 12.96 |
| 55 | 114.34 | 47.83 | 78.40 | 17.19 |
| 56 | 102.86 | 35.13 | 72.11 | 12.57 |
| 57 | 101.67 | 28.20 | 71.31 | 14.05 |
| 58 | 103.78 | 44.08 | 73.43 | 16.22 |
| 59 | 102.70 | 30.74 | 70.85 | 8.62 |
| 60 | 100.34 | 23.80 | 69.49 | 10.33 |
| 61 | 104.26 | 56.58 | 75.62 | 11.55 |
| 62 | 110.16 | 35.27 | 76.41 | 11.79 |
| 63 | 108.18 | 32.75 | 71.52 | 13.89 |
| 64 | 106.98 | 19.93 | 73.09 | 13.31 |
| 65 | 106.83 | 38.39 | 69.37 | 12.04 |
| 66 | 109.07 | 22.01 | 66.11 | 11.92 |
| 67 | 96.05 | 27.78 | 69.27 | 12.99 |
| 68 | 73.99 | 21.23 | 67.71 | 6.99 |
| 69 | 98.92 | 31.46 | 71.45 | 8.33 |
| 70 | 106.69 | 44.74 | 79.73 | 20.68 |
| 71 | 104.12 | 30.41 | 79.83 | 13.23 |
| 72 | 113.59 | 44.50 | 72.70 | 9.95 |
| 73 | 94.21 | 31.95 | 72.75 | 11.31 |
| 74 | 101.89 | 40.51 | 76.46 | 15.42 |

Table C.3. Wearing surface mean unit cost and standard deviation for quantity groups A and B

| Time Period | Wearing Surface Quantity Group A | | Wearing Surface Quantity Group B | |
|---|---|---|---|---|
| | Mean | Standard Deviation | Mean | Standard Deviation |
| 1 | 68.18 | 21.60 | 54.86 | 6.53 |
| 2 | 69.73 | 26.63 | 54.93 | 8.26 |
| 3 | 69.48 | 20.08 | 55.56 | 11.77 |
| 4 | 80.11 | 15.65 | 59.50 | 8.88 |
| 5 | 75.67 | 27.84 | 55.23 | 8.47 |

Table C.3. Wearing surface mean unit cost and standard deviation for quantity groups A and B

| | | | | |
|---|---|---|---|---|
| 6 | 82.15 | 32.20 | 56.30 | 12.23 |
| 7 | 58.20 | 17.73 | 50.98 | 8.62 |
| 8 | 75.35 | 27.43 | 54.08 | 9.79 |
| 9 | 74.70 | 33.65 | 53.60 | 11.34 |
| 10 | 101.78 | 64.77 | 54.21 | 13.14 |
| 11 | 87.41 | 24.07 | 49.51 | 16.75 |
| 12 | 71.92 | 15.42 | 54.14 | 7.90 |
| 13 | 71.13 | 44.74 | 49.18 | 7.33 |
| 14 | 68.70 | 25.97 | 47.91 | 7.74 |
| 15 | 79.00 | 34.12 | 52.91 | 8.64 |
| 16 | 98.29 | 62.38 | 51.44 | 7.91 |
| 17 | 68.79 | 21.86 | 49.94 | 8.55 |
| 18 | 92.96 | 68.00 | 51.17 | 6.18 |
| 19 | 69.36 | 18.96 | 53.34 | 9.57 |
| 20 | 72.71 | 22.89 | 55.08 | 6.37 |
| 21 | 78.37 | 33.98 | 52.27 | 9.93 |
| 22 | 80.64 | 57.60 | 50.53 | 10.62 |
| 23 | 112.80 | 40.76 | 58.43 | 6.91 |
| 24 | 78.51 | 25.06 | 55.82 | 5.44 |
| 25 | 73.59 | 16.30 | 52.85 | 8.80 |
| 26 | 80.36 | 21.91 | 57.34 | 8.80 |
| 27 | 80.32 | 36.25 | 57.17 | 9.75 |
| 28 | 88.85 | 28.45 | 62.80 | 9.64 |
| 29 | 93.75 | 39.63 | 62.74 | 9.23 |
| 30 | 90.06 | 19.18 | 58.16 | 14.82 |
| 31 | 85.82 | 27.99 | 60.20 | 7.72 |
| 32 | 83.50 | 30.20 | 57.95 | 11.42 |
| 33 | 92.92 | 29.11 | 57.83 | 16.30 |
| 34 | 100.26 | 62.31 | 60.51 | 7.57 |
| 35 | 92.15 | 23.13 | 66.52 | 4.60 |
| 36 | 108.67 | 53.01 | 66.82 | 7.79 |
| 37 | 109.02 | 28.62 | 65.18 | 9.00 |
| 38 | 88.21 | 28.72 | 69.15 | 13.97 |
| 39 | 99.82 | 42.38 | 72.71 | 13.43 |
| 40 | 102.50 | 25.65 | 74.65 | 12.84 |
| 41 | 102.45 | 34.51 | 80.61 | 13.13 |
| 42 | 115.68 | 30.41 | 76.95 | 8.76 |
| 43 | 97.29 | 20.49 | 75.28 | 14.49 |
| 44 | 101.88 | 32.47 | 74.50 | 11.42 |
| 45 | 122.21 | 68.75 | 79.23 | 15.87 |
| 46 | 103.41 | 34.08 | 72.56 | 10.68 |
| 47 | 89.25 | 21.44 | 71.06 | 11.18 |
| 48 | 113.29 | 57.87 | 70.95 | 8.89 |
| 49 | 103.83 | 24.00 | 70.48 | 12.05 |
| 50 | 88.44 | 24.16 | 68.59 | 10.08 |
| 51 | 101.46 | 33.53 | 72.46 | 11.50 |

Table C.3. Wearing surface mean unit cost and standard deviation for quantity groups A and B

| | | | | |
|---|---|---|---|---|
| 52 | 116.72 | 25.29 | 88.75 | 14.36 |
| 53 | 132.07 | 39.50 | 107.42 | 11.31 |
| 54 | 106.84 | 20.20 | 88.30 | 14.28 |
| 55 | 133.89 | 73.38 | 83.71 | 18.31 |
| 56 | 97.38 | 30.45 | 75.75 | 12.26 |
| 57 | 100.64 | 29.36 | 74.89 | 11.51 |
| 58 | 99.87 | 27.48 | 75.50 | 12.36 |
| 59 | 96.99 | 27.87 | 78.62 | 8.75 |
| 60 | 94.82 | 20.97 | 75.18 | 10.47 |
| 61 | 80.92 | 17.92 | 76.42 | 12.12 |
| 62 | 94.69 | 18.19 | 79.56 | 9.71 |
| 63 | 99.58 | 25.11 | 75.40 | 8.60 |
| 64 | 105.17 | 42.31 | 77.29 | 15.37 |
| 65 | 94.16 | 22.52 | 79.61 | 10.71 |
| 66 | 144.48 | 59.24 | 78.02 | 11.73 |
| 67 | 88.35 | 24.89 | 72.80 | 10.42 |
| 68 | 148.81 | 99.06 | 76.22 | 11.08 |
| 69 | 102.84 | 30.53 | 81.94 | 11.76 |
| 70 | 101.45 | 21.63 | 84.07 | 10.40 |
| 71 | 106.69 | 34.72 | 83.52 | 12.57 |
| 72 | 102.35 | 30.29 | 81.51 | 8.73 |
| 73 | 108.18 | 26.47 | 77.99 | 10.73 |
| 74 | 105.04 | 51.30 | 78.54 | 12.17 |