MULTI-PARAMETER BIDDING IN HIGHWAY CONSTRUCTION AND REHABILITATION PROJECTS

By

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Abstract:

According to the 2013 ASCE infrastructure report card, roads have been given a grade of D. In addition, the level of federal, state, and local capital investment is insufficient and projected to result in a farther decline in conditions and performance in the long term. Poor highway conditions have caused transportation agencies to shift their focus from expanding road networks to rehabilitation of their existing infrastructures. In response to increasing road user costs caused by rehabilitation or reconstruction projects and limited resources due to insufficient capital investments, State Highway Agencies (SHAs) have started to utilize innovative contracting methods by incorporating construction time and life-cycle cost into the bidding process. In multi-parameter bidding method, a combination of price, construction time, and life-cycle cost is considered the decisive factor in awarding a contract to the successful bidder. The purpose of these bidding methods is to obtain accelerated construction at the lowest possible cost in order to minimize inconvenience to the public. However, unlike conventional bidding, SHAs are required to determine the Unit Time Value (incentive/disincentive rate) and life-cycle cost parameters before the bid process.

This study focuses on the impact of different Unit Time Values on the competitiveness of contractors in the A+B bidding process. A new criterion is introduced to assist SHAs to determine an optimal Unit Time Value to maximize the competition during the bid process. To assist SHAs in determining the value of the life-cycle cost factor, an association analysis method in data mining is applied to historical pavement treatment datasets in order to identify the sequential patterns of various maintenance and rehabilitation activities. Since the newly developed life-cycle cost analysis models are based on the actual treatment strategies, it is expected that the life-cycle cost factor determined by this model is more realistic and closer to actual costs than that of the traditional approach suggested by the Federal Highway Administration. The results of this research will facilitate collaboration among different parties in highway construction contracts. It will advance Integrated Project Delivery (IPD) methods which are a collaborative alliance between SHAs and contractors.

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CHAPTER 1

INTRODUCTION

1.1 Background

Interstate highways in the United States not only have passed their original design life, but also have carried much more traffic volume and weights than what they had been designed. According to the 2013 ASCE infrastructure report card, roads have been given a grade of D. Poor highway conditions have caused transportation agencies to shift their focus from expanding road networks to rehabilitation of their existing infrastructures.

Unlike new highway construction projects, rehabilitation and reconstruction projects affect the traveling public adversely due to delays in traffic flow and safety problems. In response to increasing road user costs caused by rehabilitation or reconstruction projects, State Highway Agencies (SHAs) have started to utilize innovative contracting methods by incorporating construction time and life-cycle cost (LCC) into the bidding process.

Traditionally, SHAs have used bid price as the major criterion in evaluating the contractors' proposals. In alternative procurement methods, such as price-time bi-parameter bidding (A+B bidding) or multi-parameter bidding methods, however, a total combination of price, construction time, and LCC is considered as decisive factors in awarding the contractor. The purpose of these bidding methods is to obtain accelerated construction at the lowest possible LCC in order to minimize the level of inconvenience to the public.

Due to the limited financial resources and the increasing need for accelerating projects, SHAs have started experimenting alternative contracting methods. Since 1990, the Federal Highway Administration (FHWA) has allowed the SHAs to evaluate non-traditional contracting techniques under a program titled “Special Experimental Project (SEP) No. 14 – Alternative Contracting.” Through this program, innovative project delivery, procurement, and contracting techniques that have the potential to accelerate project delivery, reduce initial or life-cycle costs, and improve quality are evaluated to be used as operational practices by SHAs. Until now, cost-plus-time bidding, lane rental, design-build contracting, and warranty clauses have been approved after evaluation. However, alternate pavement type bidding, construction manager at risk, best value contractor selection, and no excuse incentive are among the contracting or project delivery methods that are still under experiment.

Unlike the traditional bidding and contracting systems that take solely one factor (bid price) into consideration while evaluating the contractors, alternative contracting and procurement methods require the agencies to evaluate contractors based not only on initial cost but also on construction time, LCC, and quality. This enables SHAs to gain more control over the procurement and contracting processes. However, alternative contracting and procurement methods require agencies to determine the unit time value, LCCs of different construction methods, and the historical quality of contractors. In other words, the efficiency of these methods is heavily dependent upon the factors that are determined by SHA. Thus, there is an immediate need to develop methods to determine these factors and evaluate the effects of such factors on the bid competition.

1.2 Problem Statement

The conventional bidding models that only stimulate competition over construction costs is not in line with two significant goals of SHAs: 1) accelerating highway maintenance, rehabilitation, or reconstruction projects, and 2) selecting the pavement type with the lowest life-cycle cost. Figure 1.1 indicates the two problems that are the focus of this study.

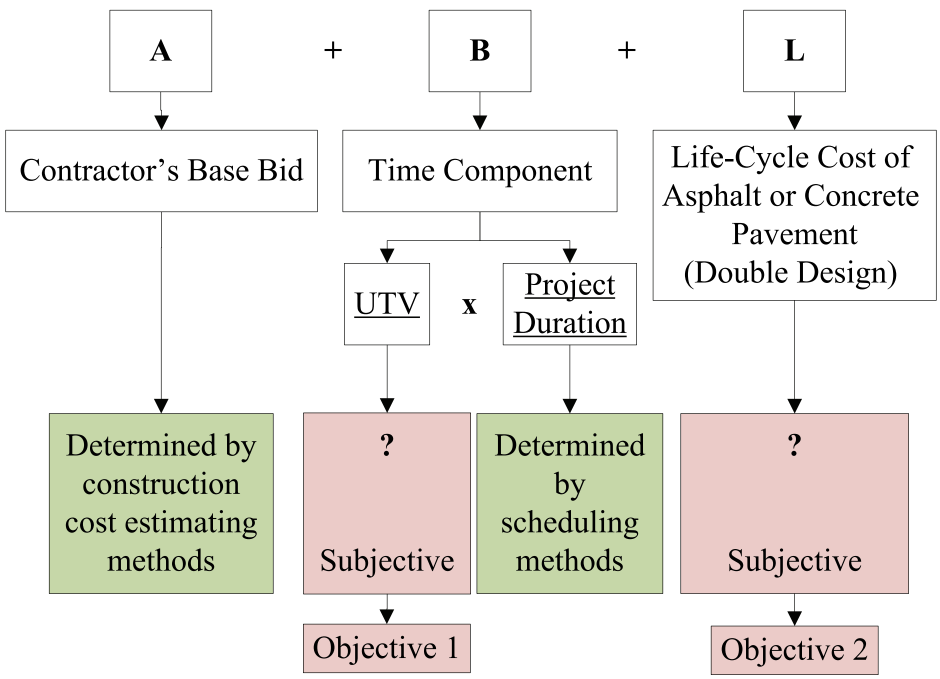


Figure 1.1 Two Research Problems

The FHWA considers inclusion of life-cycle cost during the bid process an suitable approach for determining pavement type when engineering and economic analysis does not indicate a clear choice between different pavement designs (FHWA 2012). However, success of alternate pavement type bidding is heavily dependent on the realistic determination of life-cycle costs of different pavement designs. Previous studies have focused on analyzing historical pavement condition assessment datasets to develop deterioration curves and LCCA models. However, due to resource constraints, pavements have not been rehabilitated based on the schedule dictated by the deterioration curves. Maintenance, rehabilitation, or reconstruction projects have been delayed, while pavement conditions have been in poor condition. Therefore, the LCCA models based on deterioration curves are more idealistic than realistic. In other words, these LCCA models are based on the rehabilitation strategies that are ideal to follow rather than the strategies that have actually been followed by SHAs. The historical pavement treatment datasets in SHAs are valuable sources of data to develop realistic rehabilitation strategies. Therefore, a methodology needs to be developed to assist SHAs to utilize historical treatment datasets in order to develop realistic rehabilitation strategies and LCCA models.

SHAs need to determine the dollar value of project duration if the project duration is considered a factor for evaluating the bid. This value which is also called Unit Time Value (UTV) indicates the dollar value of each day in pavement maintenance, rehabilitation, or reconstruction projects. Previous studies focus on road user cost as the only factor in determining UTV and suggest that UTV has to be more than contractor's additional costs for accelerating construction and be less than a dollar value of total time savings in order to effectively encourage contractors to expedite construction. However, this provides SHAs with a wide range of values which can sometimes vary in the order of magnitude. SHAs have been typically using engineering judgment to determine the

UTVs. Therefore, a computational framework needs to be developed to assist SHAs in determining the optimal UTVs.

1.3 Vision of this Study

Figure 1.2 illustrates the vision of this study which indicates why this research is necessary, how it is conducted, and what can be expected as a result of this study. Project duration and life-cycle cost of alternative designs are critical parameters for SHAs. One approach that accelerates construction projects and at the same time minimizes LCC of alternative designs is to include time and LCC parameters during the bid process so that their values are determined by competition between contractors. To include the project duration in the bid process, the dollar value of project duration needs to be determined. Also the life-cycle cost analysis model of each pavement family needs to be known before including LCC during the bid process.

A pavement family is defined as a group of similar pavement sections that are expected to perform similarly and thus share a common performance or a deterioration curve. However, there is no scientific procedure to assist SHAs in determining the dollar value of construction duration and LCC components. The historical project data provide a base that can be utilized to assist SHAs in determining the optimal time and life-cycle cost parameters. The patterns available in these datasets can be recognized utilizing data mining techniques. Based on these patterns, new computational frameworks can be developed in order to assist SHAs to determine time and LCC components more effectively. The results of this study facilitate implementation of an integrated bidding method where contractors compete not only over initial cost but also over time, and LCC of alternative designs which will result in a more sustainable bidding method.

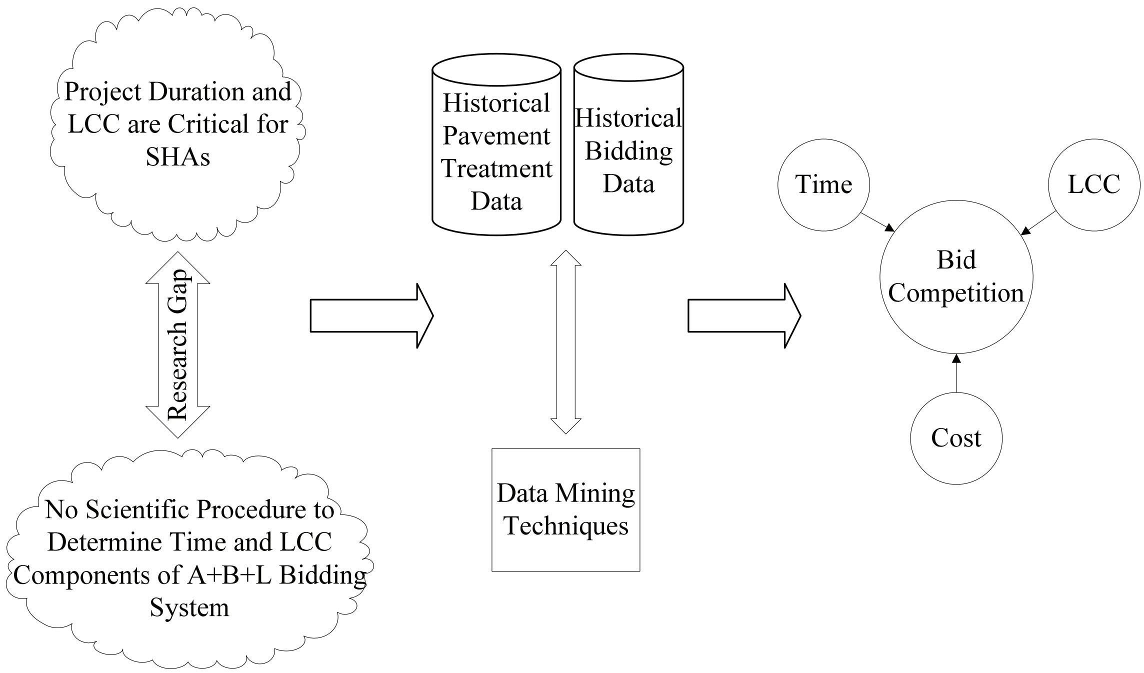


Figure 1.2 Vision of This Study

The A+B+L is a multi-parameter bidding method that combines project duration (B) and the life-cycle costs (L) of different designs with the initial construction cost (A) of projects during the bid process. This bidding method is the main focus of this dissertation. This bidding system is a combination of cost-plus-time and alternate bidding which is known as Alternate Design Alternate Bid (ADAB) model as described by the Louisiana Department of Transportation and Development (LaDOTD) (Temple et al. 2004). Alternate bidding is used when more than one design is deemed to be equal in design life. Alternate designs are provided during the bid process and contractors can select both or between the designs and propose their prices. The factor "A" is contractor's base bid which refers to the traditional bid for the contract items and is the dollar amount for all work to be performed under the contract. The factor "B" incorporates the proposed duration of the project into the bid competition. The factor "L" represents the present value of future rehabilitation and user delay costs associated with a particular alternate. The purpose of this type of procurement method is to reduce the duration and life-cycle cost of the construction project by incorporating these factors into bid competition. The contractor with the lowest Total Combined Bid (*TCB*) would win the bid contract.

$$TCB = A + B + L \quad (1.1)$$

Where TCB = Total Combined Bid

A = Base Bid

B = UTV × Construction Duration

L = life-cycle Cost

1.4 Research Objectives

The goal of this research is to investigate the cost-plus-time-plus LCC bidding model in highway construction industry, and to develop the necessary frameworks that assist SHAs in determining incentives and LCCs more accurately. The following are the specific objectives of this research.

a. To develop a computational framework to adjust Unit Time Value (UTV) for the "B" parameter in A+B+L bidding model based on the competitiveness of participating contractors;

b. To develop realistic LCCA models based on the typical sequential patterns in the historical pavement treatment data set to determine the "L" parameter for A+B+L bidding model.

1.5 Methodology

In this section, the research methodology is explained. Different methodologies that have been adopted for the two objectives of this study are shown in Figure 1.3.

1.5.1 Methodology Used for the First Objective

A literature review was performed to study the practices used by SHAs to determine the dollar value of time in A+B bidding. The methodology utilized for the first objective of this study starts with collecting relevant data from ODOT. The data contains the price and time information of all the completed A+B projects. Then scope-free price and time indices are calculated for each project. The price-time relationship of each contractor is then determined utilizing Analysis of Variance (ANOVA) and Regression analysis by considering price index as a dependent variable and time index as an independent variable. The review of literature shows that both linear and quadratic price-time relationships are possible. Therefore both linear and quadratic equations are investigated during the curve-fitting process. The most competitive bidding strategy of a contractor is determined by calculating the point on the price-time curve that minimizes the total combined bid.

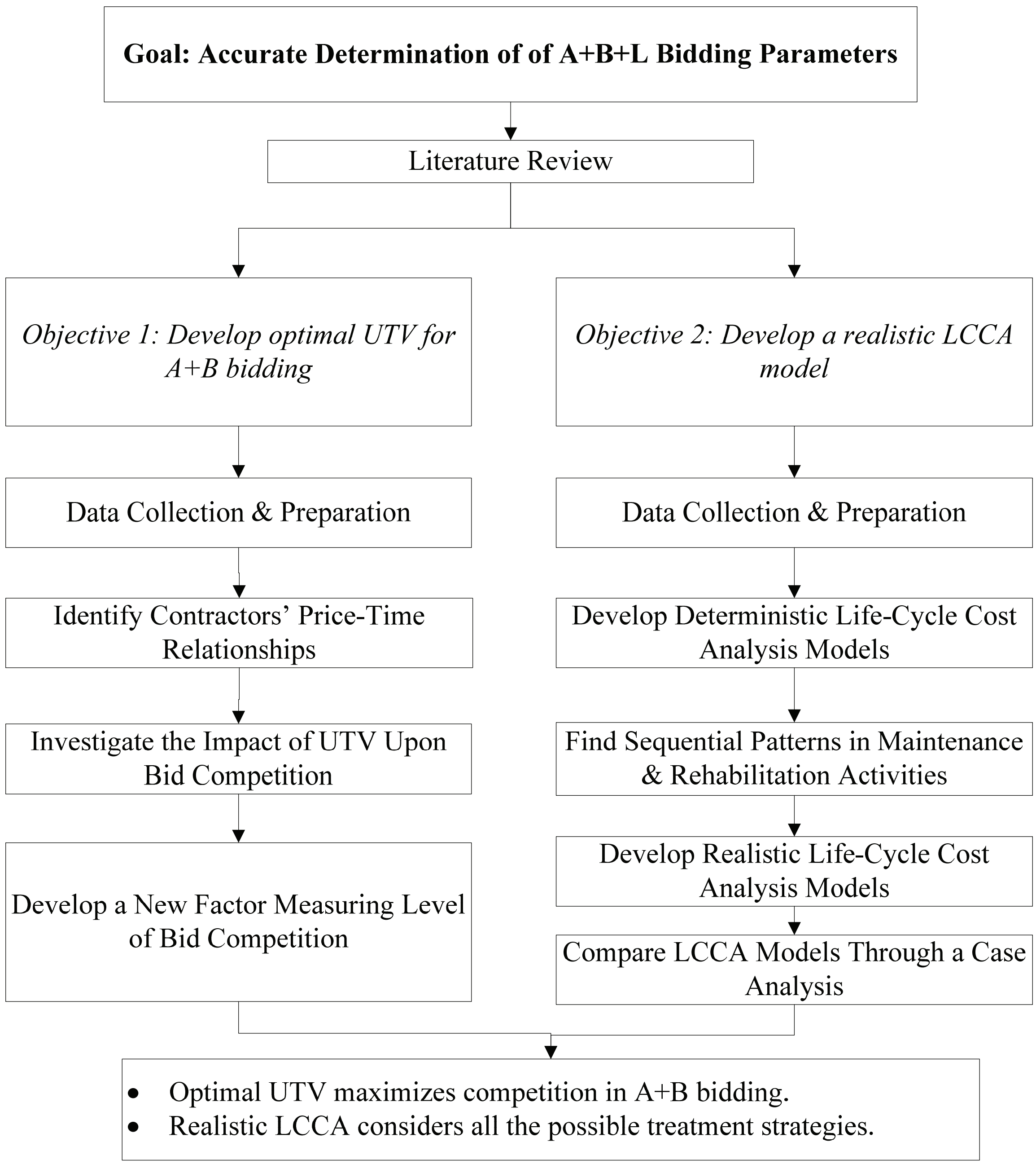


Figure 1.3 Methodology

The impact of UTV upon competitiveness of contractors during an A+B bid competition is investigated through a hypothetical example. Then a bid competition with five participating contractors is investigated under three different scenarios. The impacts of three different UTVs upon the competitiveness of contractors are investigated under these three scenarios. A new factor is developed that measures the competition during the bid process. It is shown how SHAs can determine the optimal UTV that maximizes the bid competition by minimizing this newly developed factor.

1.5.2 Methodology Used for the Second Objective

Literature review is performed to investigate the inclusion of life-cycle cost during the bid process. The review of literature indicates that a realistic determination of life-cycle cost models is the main issue faced in implementation of A+B+L bidding method. This is due to the fact that the value of "L" is critical in determining the winning contractor. The Interstate Structural Pavement History of ODOT in 2010 is collected and prepared for the purpose of analysis. A five-step data preparation is followed to create homogenous pavement sections and prepare data for the purpose of applying a data mining technique.

The data mining technique applied on the data set is called the frequent pattern mining. Frequent patterns are patterns that appear frequently in a data set. The frequent pattern mining technique searches for recurring relationship in a given data set. This technique can be categorized into association rule mining, sequential pattern mining, and market basket analysis. The frequent pattern mining is applied to the Interstate Structural Pavement History of ODOT in 2010 to identify the treatment strategies adopted by ODOT since construction of Interstate Highways. This data mining technique has been widely used in the marketing area to determine which products are being purchased together by the customers. Major grocery stores utilize the association rules in transaction data sets in order to present items in store displays more efficiently. By substituting pavement sections with customers and treatment types with purchase products, the frequent pattern mining technique is applied to pavement treatment data set.

The frequent pattern mining is utilized to find the sequential patterns in the historical treatment activities of Interstate Highway 40. Based on the historical treatment and rehabilitation patterns, two realistic LCCA models are developed for asphalt and concrete pavements separately. Then a spreadsheet tool is developed based on deterministic and realistic LCCA models and a case study is conducted to measure the differences between the calculated “L” parameters utilizing deterministic and realistic LCCA models.

1.6 Expected Contributions

This research will transform the conventional bidding method to an integrated bidding method that considers sustainability aspects of construction during the bid process. The results of this research will also enhance collaboration among different parties in highway construction contracts. It will facilitate moving toward Integrated Project Delivery (IPD) methods which are a collaborative alliance between SHAs and contractors.

The computational frameworks developed in this study will contribute to changes in FHWA policies regarding the implementation of alternate pavement type bidding. It provides SHAs with the necessary tools to implement this type of bidding. It would also enhance the efficiency of guarantee contracting methods by providing SHAs and contractors with a tool to predict the performance of pavement families during their lifecycle more accurately.

The results of this study will eventually reduce the life-cycle cost of projects, while at the same time, minimize project duration and maintain the quality. This will enable SHAs to rehabilitate and reconstruct more highways with the constrained funding for highway infrastructure which translates into substantial savings in taxpayers' money. At the same time, minimized project durations would result in lower social costs by minimizing road user costs, indirect costs to the public, and highway construction accidents. Finally, this study improves sustainability of highway infrastructure design, construction, maintenance, and operation.

1.7 Organization of the Dissertation

A review of literature regarding A+B+L bidding method is discussed in Chapter 2. The rest of dissertation is concentrated on developing innovative approaches to determining B and L parameters in the A+B+L bidding method. In Chapter 3, a computational framework is developed to assist SHAs in adjusting incentive/disincentive rates based on the competitiveness of contractors participating in the bid process. Chapter 4, Chapter 5, Chapter 6, and Chapter 7 are focused on developing a novel approach in determining realistic life-cycle cost models for asphalt and concrete pavements in order to calculate L parameter that is closer to reality. Chapter 4 illustrates the database that is used in the analysis and explains the data preparation stage. The main focus of Chapter 5 is on developing deterministic life-cycle cost models for asphalt and concrete pavements based on the database introduced in Chapter 4. Chapter 6 focuses on two realistic life-cycle cost models that are developed for asphalt and concrete pavements based on the patterns discovered in the historical pavement treatment database. A case study is performed in Chapter 7 to compare the realistic LCCA model developed in this study with the deterministic LCCA models. And finally Chapter 8 discusses the results and findings of this study and provides recommendations for future studies.

CHAPTER 2

LITERATURE REVEIW

This chapter describes the evolution of contracting methods in highway construction, followed by descriptions on the advancement of research studies related to optimal determination of bid parameters in the A+B+L bidding method. Some try to evaluate the impact on the performance of highway construction projects; some others develop guidelines to select appropriate projects and improve the bid parameters.

2.1 Evolution of Contracting Methods

While many advanced technologies have been utilized in highway construction, contracting methods have not advanced much. The traditional contracting method utilized in highway construction is design-bid-build. Under this contracting method, projects are designed by the SHA, awarded to the qualified contractor that proposes the lowest price.

Traditional competitive bidding system is based on the competitive sealed bids with award to the lowest responsive bidder who meets the required conditions. Over the decades, this procurement system has provided taxpayers with an adequate, safe and efficient transportation facility at the lowest price that responsible, competitive bidders can offer. For the most part, it has effectively prevented favoritism in spending public fund while stimulating competition in the private sector.

By 1970s, as the result of this contracting method, claim management became an inseparable part of every highway construction project (Hancher 1999). In the 1980s, with the beginning of total quality management movement in the United States, transportation agencies started to question the cost efficiency and quality orientation of traditional contracting methods (Hancher 1999). While the low bid system is well understood and accepted through the country, the system is slow and does not consider life-cycle cost and duration of construction projects. The resistance to implementation of innovative ideas and the need for large staff to conduct all of the necessary functions are also among the weaknesses of the traditional contracting methods (Hancher 1999).

The evolution of innovative contracting methods can be seen in Table 2.1. In 1987, the Transportation Research Board (TRB) established a Task Force on Innovative Contracting Practices (A2T51). This task force was created for the purpose of identifying promising innovative contracting practices for further evaluation. The task force addressed four major topic areas: bidding procedures, materials control, quality considerations and insurance and surety issues.

The FHWA SEP-14 was initiated on February 13, 1990 to provide a means to evaluate some of the TRB Task Force's more project-specific recommendations. The FHWA SEP-14 is still being used for evaluation of promising alternative contracting techniques.

Table 2.1 Important Milestones in Development of Innovative Contraction Methods

Year	Task
1987 (Hancher 1999)	TRB formed a task force to identify promising innovative contracting practices.
1990 (Hancher 1999)	A team of asphalt concrete pavement specialists from the United States visited six European countries to study advances in highway technology in those nations
1990 (FHWA 1990)	FHWA allowed the State DOTs to evaluate non-traditional contracting techniques under SEP-14.
1992 (Hancher 1999)	Representatives from U.S. transportation agencies and the concrete construction industry conducted a European tour similar to the asphalt study tour of 1990.
1992 (Hancher 1999)	Eight leading highway industry organizations signed a pact for a National Policy on the Quality of Highways.
1993 (Hancher 1999)	FHWA conducted a European Contract Administrative Techniques for Quality Enhancement Study Tour.
1995 (FHWA 2012)	After a five-year evaluation period, A+B bidding was declared operational on May 4, 1995 and is no longer considered to be experimental.
1995 (FHWA 2012)	After a five-year evaluation period, lane rental technique was declared operational on May 4, 1995 and is no longer considered to be experimental.
1995 (FHWA 2012)	Since the implementation of the warranty regulation in 1995, FHWA no longer requires the evaluation of warranties.
1996 (AASHTO 2006)	Chairman of AASHTO Subcommittee on Construction asked Subcommittee members what contracting practices should be available in the year 2000 and to identify institutional obstacles to innovation.
1999 (FHWA 2008)	FHWA does not encourage the use of alternate bids to determine pavement type due to the difficulty in developing truly equivalent designs.
2002 (FHWA 2011)	FWHA published a final rule that allows the use of design-build contracting procedures.
2012 (FHWA 2012)	FHWA considers alternate pavement type bidding a suitable approach for determining pavement type when engineering and economic analysis does not indicate a clear choice between different pavement designs.

2.2 Contracting Methods

As can be seen in Figure 2.1, contracting methods can be categorized into delivery systems, procurement methods, and contract management methods. Project delivery systems refer to the processes by which a project is designed, constructed, and/or maintained. A traditional project delivery system in the public sector is design-bid-build system, involving the separation of design and construction services.

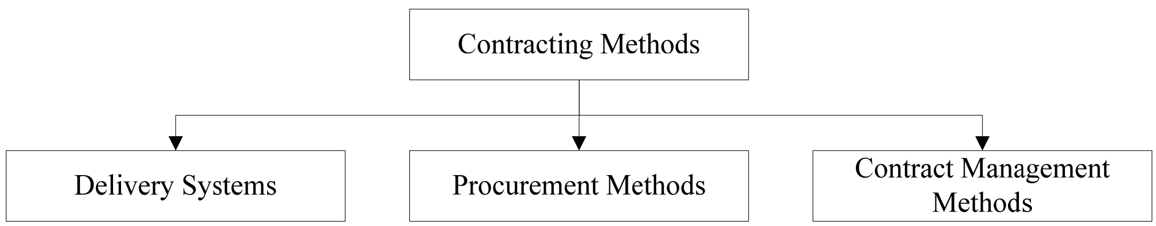


Figure 2.1 Contracting methods

However, in recent years, government agencies and researchers have started experimenting innovative project delivery methods such as construction management at-risk and design-build. Construction management at-risk is one of the innovative delivery methods that are being experimented under "Special Experimental Project No. 14" (SEP-14). Figure 2.2 shows the project delivery methods utilized in the highway construction industry on a continuum, with traditional design-bid-build approach appearing on the left and the more innovative systems arranged from left to right. Delivery systems that are closer to the right shift the risks to the contractor, and have less separation between design and construction services.

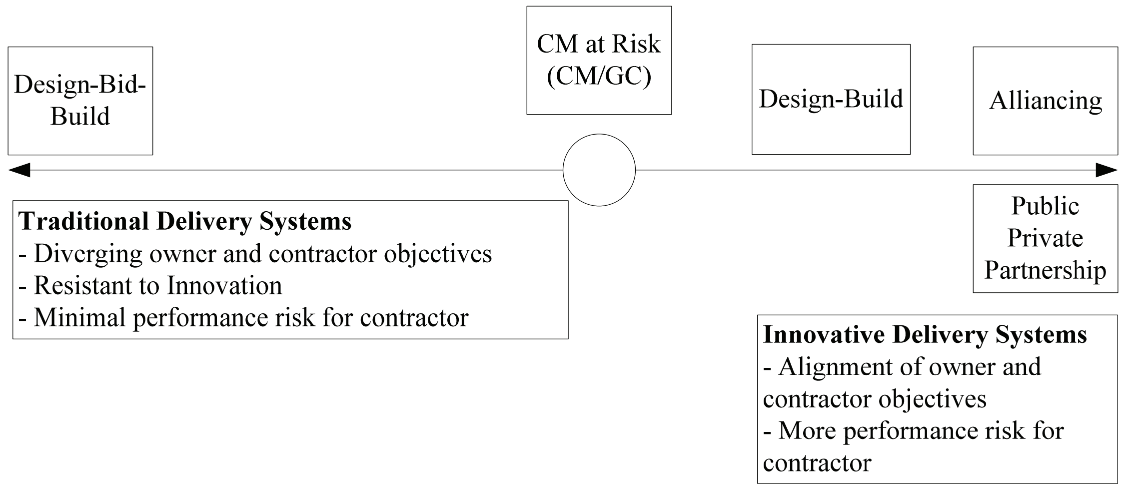


Figure 2.2 Project Delivery Systems on Continuum (Trauner Consulting Services) (2007)

In Design-Bid-Build, the SHA contracts with designer and then uses the design documents to secure competitive bids from contractors. Based on the accepted bid, the SHA contracts with a contractor for construction.

Construction management at risk (CM at Risk) allows a SHA to engage a construction manager during the design process to provide constructability input. Upon the design completion, the SHA and the construction manager negotiate a guaranteed maximum price and execute a contract for construction services, and the construction manager becomes the general contractor. This project delivery method is also called Construction Manager / General Contractor (CM/GC) because the construction entity becomes a general contractor (GC) through the at-risk agreement.

In the design-build approach, the SHA contracts with a single entity for both design and construction. The consolidated entity provides both design and construction services to the SHA. It is observed that by moving from traditional to innovative project delivery methods, there are less distinctions between SHA's, designer's, and contractor's responsibilities.

Procurement practices are the procedures that agencies use to evaluate and select designers, contractors, and consultants. This evaluation can be based only on price, only on technical qualifications, or on a combination of price, technical qualifications, time and other factors. Public sector has traditionally used low bid price to select contractors for highway construction projects.

In 1995, cost-plus-time bidding (A+B) was approved by FHWA for use without SEP-14 approval. Currently, lump sum bidding, multi-parameter bidding, alternate bidding, and best value procurement are among the alternative procurement practices that require FHWA SEP-14 approval. Figure 2.3 shows the procurement systems on a continuum, with the traditional sealed bidding on the very left to long-term partnerships on the right. By moving from traditional bidding to innovative bidding, additional factors, other than cost alone, are considered in the evaluation and selection process to improve the long-term performance and value of construction. An alternative procurement method uses factors other than the traditional fixed-price to award a construction contract.

Contract management methods refer to the contract provisions used to manage construction projects on a daily basis to help the agencies control costs, time, and quality of construction more effectively. Contract management methods such as Incentive/Disincentive (I/D) provisions for early completion, lane rental, and warranties have been approved to be used without FHWA SEP-14 approval. However, methods such as liquidated savings, active management payment mechanism, and no excuse incentives are under experiment and require FHWA SEP-14 approval.

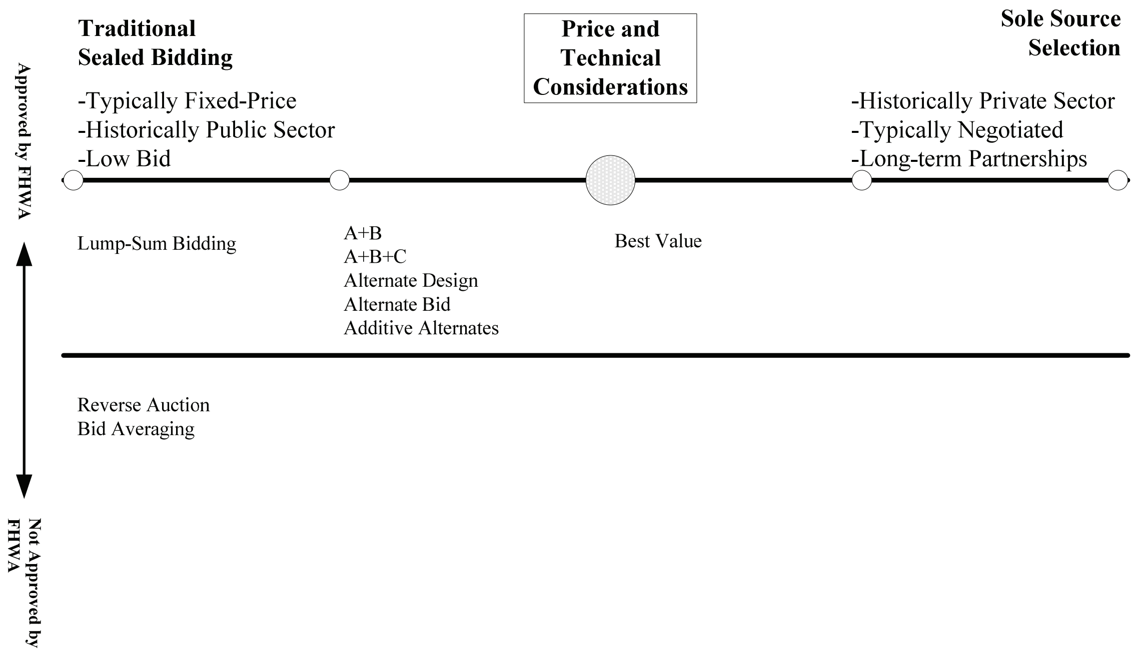


Figure 2.3 Procurement Methods (Trauner Consulting Services) (2007)

2.3 Competitive Bidding

Competitive bidding has an important role in the U.S. economy and is rooted very deeply in the history. Bidding and auctioning are one of the ways that an economy can efficiently allocate its resources (Stark and Rothkopf 1979). Competitive bidding has been in practice in New York state since 1847 (Herbsman and Ellis 1992). Over the years, a few modifications have occurred to the initial concept. However, the original concept from the 19th century remains intact.

In competitive bidding system, the project is awarded to the contractor that proposes the lowest bid. Therefore, it is also called the lowest bidder award system. This protects the public from extravagance, corruption, and other improper practice by public officials (Herbsman and Ellis 1992). Since price is used as the only criterion for evaluation, competitive bidding is independent from any sort of political, social, and economic pressure. However, selection process is based only on one element which is initial cost. This is despite the fact that the success of a construction project is measured in terms of quality, time, and safety which are not accounted for during the conventional competitive bidding process. This might result in awarding the job to a contractor that is not capable of high quality and safe performance. Low bids, bid rigging, and unqualified contractors are among the other problems of competitive bidding during the last decades (Herbsman and Ellis 1992).

2.4 A+B+L Bidding Model

Unlike the conventional competitive bidding method, the A+B+L bidding method creates a situation that other parameters such as project duration and life-cycle cost of an alternative design are also included in the bid competition. When more than one alternate is deemed to be equal over the design life and there is a reasonable possibility that the least costly design approach will depend on competitive circumstances, an alternate bidding procedure can be used. If project is located in a congested urban area where project acceleration is critical, the “B” component is also added to the bid process.

Through the past decades, transportation departments have made numerous decisions about the type of pavements for road construction, reconstruction or rehabilitation activities. Although the decision used to be only based on the availability of materials, equipment, volume of traffic, type of road and initial cost of the pavement, some transportation departments have started considering LCCA by taking user cost, maintenance cost, time to first rehabilitation, salvage value and design life into account (Wimsatt et al. 2009).

Since there is no such thing as truly equivalent pavement designs, the FHWA has allowed states to make some bid adjustments to account for differences in life-cycle costs under FHWA SEP-14 as an "Innovative Contracting." Several SHAs have performed projects utilizing this contracting method and tried to develop a fair environment where asphalt and concrete industries can compete efficiently. This bidding method can be categorized under multi-parameter bidding strategies. The challenges of determining time component will be discussed in the cost-plus-time bidding section. The main challenge in determining L parameter is developing a framework for LCCA that both industries agree upon which will be discussed further in the life-cycle cost analysis component section.

2.4.1 FHWA & AASHTO Recommendations

Changes in pavement materials cost is one of the most important factors that have triggered SHAs to show interest in using alternate pavement type bidding procedures to determine the appropriate pavement. FHWA issued a technical advisory in December 2012 to guide State and local highway agencies that are interested in using alternate bidding procedures to make the pavement type selection on Federal-aid projects on the National Highway System (NHS) (FHWA 2012). It states that "FHWA considers alternate pavement type bidding a suitable approach for determining pavement type when engineering and economic analysis does not indicate a clear choice between different pavement designs." Equivalent design implies that each alternative will be designed to perform equally, and provide the same level of service, over the same performance period, and has similar life-cycle costs (FHWA 2008). The technical advisory indicates several factors that should be considered prior to determining that alternate bidding procedures should be used. These factors include:

- Designs must be equivalent
- Realistic discount rate
- Consideration of uncertainty
- Realistic rehabilitation strategy
- Subjective considerations: considering non-cost related factors such as constructability, type of adjacent pavements, recycling, and conservation of materials.
- Appropriate application: alternate pavement type bidding procedures should only be used where pavement items impacted by the alternate bid are likely to influence the final determination of the lowest responsive bidder for the project. Projects with substantial bridge or earthwork items are generally not suited for alternate bids (FHWA 2012).

AASHTO's guidance on pavement type selection (AASHTO 1993) outlines the pavement selection process, as shown in Figure 2.4. As can be seen in this figure, two lists of factors influence the decision making process:

a) principal factors
b) secondary factors

Principal factors are those factors that have a major influence and may dictate pavement type in some instances. Secondary factors are those factors that have lesser influence and are taken into account when principal factors are not overriding any pavement type or one type is clearly not superior from an economic standpoint. The principal and secondary factors are summarized in Table 2.2.

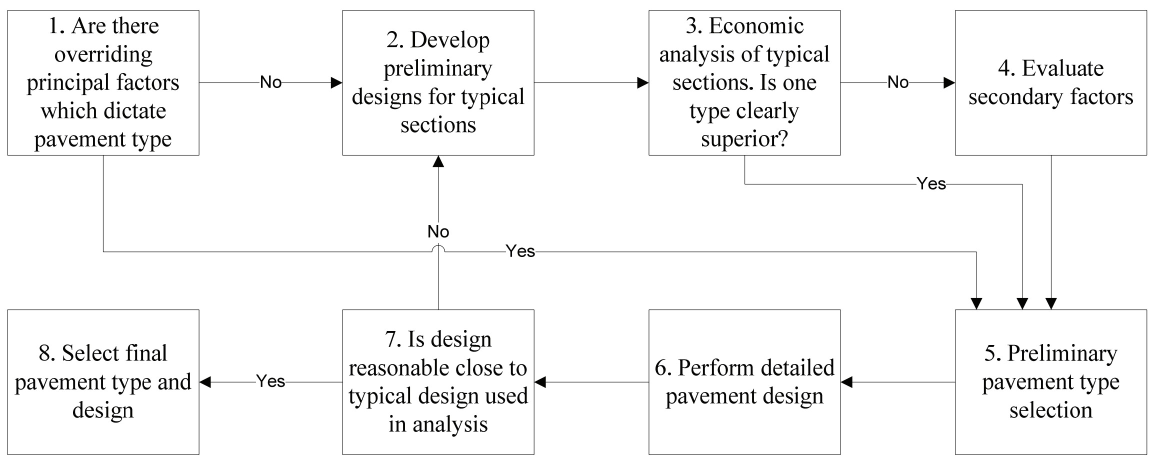


Figure 2.4 Pavement Type Selection Process (AASHTO 1993)

Table 2.2 AASHTO's Principal and Secondary Factors Influencing Pavement Type Selection

Principal Factors	Secondary Factors
• Traffic	• Performance of similar pavements in the area
• Soils characteristics	• Adjacent existing pavements
• Weather	• Conservation of materials and energy
• Construction considerations	• Availability of local materials or contractor capabilities
• Recycling	• Traffic safety
• Cost comparison	• Incorporation of experimental features
	• Stimulation of completion
	• Municipal preferences, participating local government preferences and recognition of local industry

2.4.2 Cost-Plus-Time (A+B) Bidding

Cost-plus-time, price-time biparameter, or A+B bidding is a contract procurement method that incorporates monetary value of construction time into the bid price in evaluating a contractor's total combined bid (TCB). The purpose of this bidding method is to obtain accelerated construction at the lowest possible cost in order to minimize inconvenience to the public. After a five year evaluation period as an FHWA SEP-14 project, A+B bidding was declared operational on May 4, 1995. In price-time bi-parameter bidding (A+B bidding), the contract duration is determined by competition during the bid process. The successful bidder is the contractor who submits the lowest TCB using the following formula:

$$TCB = A + (UTV \times t) \tag{2.1}$$

Where, A is the contractor's bid price, UTV is the unit time value defined by the SHA and *t* is construction time (contract time). Thus, there are theoretically an infinite number of combinations of (*A, t*) that result in the same TCB when the UTV is fixed. Herbsman et al. (Herbsman et al. 1995) reported that A+B bidding has been successful in reducing construction times in almost every case. Also they believe that bidding on cost/time has been more effective and less expensive than Incentive/Disincentive (I/D) provisions alone.

Time Component

The time component in a multi-parameter bidding incorporates the duration of projects into the bid competition. Although it is called the time component of the bidding process, its unit is in dollars. The "B" bid is the product of the calendar days bid by the contractor to achieve the substantial completion of the project multiplied by the unit time value (UTV) specified in the bid proposal. Substantial completion is a milestone that there must be no further lane or shoulder closures after that. The time value is established by the SHA.

According to Herbsman et al. (1995), UTV includes both direct and indirect costs. In the highway construction industry, UTV is commonly referred to as the daily road-user cost. There is not a single method to calculate the time value. Most state highway agencies calculate the UTV and apply this value as their daily I/D fee. However, there are some states using different parameters for establishing I/D fees, such as a percentage of total project cost.

A memorandum issued by the California Department of Transportation (Caltrans) on June 12, 2000 (Caltrans 2000) stated that although exceptions may be allowed, UTV typically ranges from 50 to 100 percent of the calculated daily road user cost. The Caltrans has also issued a guideline on September 30, 2002 which specifies that the time value is a combination of liquidated damages, the lesser of the road user cost (RUC) and 0.1% of the engineer's estimated cost for construction, and costs resulting from delays to adjacent projects, social/economic impacts or business revenue loss. The Oklahoma Department of Transportation (ODOT) divides 5% of project cost estimate by 24% of project time estimate to calculate the daily incentive rate.

Fick et al. (2010) suggest that market influences such as the number of qualified bidders and the availability of other work to contractors should be included as the significant factors in determining I/D rates. Despite the procedural variations in calculating UTV and

I/D rates, SHAs agree that the incentive amount has to be more than contractor's additional costs for accelerating construction and be less than a dollar value of total time savings in order to effectively encourage contractors to expedite construction.

There are different terms in the literature and contracts for referring to the UTV. The UTV shows the worth of time for the SHA. This is related to many factors such as daily road user cost (DRUC), SHA's overhead cost, costs resulting from delays to adjacent projects, social/economic cost for construction, or business revenue loss among others. These costs can be categorized as indirect costs of construction. Although UTV is a function of these costs, a standard procedure that relates unit time value to these indirect costs is yet to be developed.

Among these indirect costs, advanced techniques have been developed to calculate DRUCs. However, DRUC is not a direct cost and is not paid by SHAs' budgets. In other words, for many SHAs a dollar value of DRUC is not equal to a dollar value of agency cost. While, DRUC is highly correlated with public satisfaction, it is not directly deducted from SHA's budget and is not treated with the same level of importance. Now the main challenge is what fraction of these indirect costs is significant by SHAs. Therefore, UTV is not simply the DRUC but a function of the indirect costs caused by the construction activities.

UTV is also referred to by cost per day and I/D rate. This value is multiplied by the proposed durations in cost-plus-time contracts to determine the I/D amounts. UTV is calculated by the SHA for every cost-plus-time bidding project. Although related to the indirect costs of construction, an efficient UTV should also take the other players of a bid competition into account. The UTV should be large enough to compensate added costs and motivate contractors to accelerate construction and less than or equal to the savings made by the SHA. So UTV should not only be related to the indirect costs of construction but also be a function of participating contractors' characteristics.

There are two different A+B contracting methods: 1) A+B without I/D and 2) A+B with I/D. In both methods, the low bidder is determined from the results of the A+B procedure, and the estimated project duration submitted by the successful bidder becomes the contractual project duration. In A+B without I/D contracts, the UTV is only calculated to determine the low bid, and the contractor does not receive any incentive for early completion, nor pays any disincentive for late completion other than normally specified liquidated damages. In A+B with I/D contracts, the winning contractor receives an incentive for early completion, or is charged a disincentive for late completion.

Time-related I/D provisions are frequently used by SHAs to minimize construction duration, especially in urban areas where inconvenience to the traveling public is a matter of importance. This method is an innovative way of reducing construction duration by offering contractors an early completion incentive bonus that can motivate them to apply their ingenuity to completing projects early (Christiansen 1987, Jaraiedi et al. 1995). According to the FHWA (1989), the major area of concern on the use of I/D provisions is the determination of the appropriate dollar amount per day for early completion of projects.

Arditi et al. (1997) suggest that the use of "A+B Bidding" in association with I/D contracts and its likely impact on contract efficiency need to be further explored. They report that contract duration will be more realistic when the project duration is set by the winning bidder, compared to when it is set by the SHA in I/D contracts. They also report that "A+B Bidding" competition results in the elimination of inefficient contractors. Herbsman et al. (1995) also report the need to study the interactions of A+B bidding and I/D provisions.

Several previous studies in this domain have focused on optimizing the incentive/disincentive (I/D) rates with respect to road user costs (Anderson and Damnjanovic 2008, Falk and Horowitz 1972, Fick et al. 2010, Herbsman and Ellis 1992, Herbsman et al. 1995, Moussourakis and Haksever 2010). Although several studies have investigated the optimal UTVs (Arditi et al. 1997, Fick et al. 2010, Shr et al. 2004), studies on the interactions between the UTV and competition between contractors are very limited. Shen et al. (1999) model the most competitive strategy of a single contractor without considering the collective impact of other contractors' competitive strategies on the bid process. Shr and Chen (2004), on the other hand, have assumed that all contractors share a single price-time curve and suggested a methodology to determine a maximum incentive rate for A+B contracts. Thus, no study has investigated the impact of UTV on competitiveness of different contractors in A+B bidding competition.

Price-Time Relationship

In order to investigate the impact of different UTVs upon competitiveness of contractors, price-time relationships of contractors participating in the bid process should be known. Price-time relationships have been used extensively for project compression. With the cost functions for each task in a critical path method (CPM), project managers are able to optimize the compression by minimizing both the duration and cost of a project.

Construction cost and time for undertaking a specific construction project are interrelated (Moussourakis and Haksever 2010, Shen et al. 1999). In identifying the price-time relationship, prior studies show mixed results in terms of the shape of price-time curves (Berman 1964, Falk and Horowitz 1972, Moussourakis and Haksever 2010). Although a vast majority of literature has been generated based on the assumption of a linear price-time relationship, Moussourakis and Haksever (2010) point out that both convex and concave cost curves are possible in practice. Moussourakis et al. (2010) argue that the type of cost function is dependent upon the nature of project activities.

Callahan et al. (1992) report that for a specific construction company, there is an optimum price-time balancing point for every construction contract where construction cost is minimum. In general, the relationship between construction cost and time can be expressed by the curve shown in Figure 2.5 (Shr and Chen 2003). A bid price-time relationship can be developed by adding a certain profit margin to the construction cost.

The optimum price-time point represents the construction plan where construction cost is the lowest with a specific construction time. Shortening construction time from the optimum price-time point may require multiple shifts, overtime work, enhanced manpower and equipment, or accelerated material delivery that can increase the project direct cost. On the other hand, by extending time from the optimum price-time point the overhead costs and costs of renting equipment would increase project direct cost. As a result, the price-time curve decreases to a minimum and then increases, which is an indicator of a non-linear equation. Thus any variation in time from the optimum price-time point will result in a corresponding increase in construction cost. Several studies have suggested a quadratic or second-order polynomial function to approximate the relationship between bid price (A) and construction time (t) (Shen et al. 1999, Shr et al. 2004, Shr and Chen 2003, Wu and Lo 2009).

$$A = a + b_1 t + b_2 t^2 \tag{2.2}$$

Equation 2.2 represents the second-order with three unknown constant values where A is bid price; t is construction time; and a, b_1, and b_2 are constant values. Shen et al. (1999) suggests estimating the constants of the quadratic equation of price-time relationship by assuming three feasible bid plans based on the contractor's background and previous experience. One of these points is the shortest time bid plan, which is also called the crash point (Figure 2.5). This is a point where the contractor is not able to further compress the project duration. The next point is the most likely bid plan by which the contractor tends to offer. The third point is the lowest construction cost bid plan, which is also called the normal point. By using these three data points and incorporating them in Equation 2.3, three independent equations are developed. These equations are solved for three unknown constant values (a, b_1, b_2) and the price-time curve can be developed. Shr and Chen (2004), on the other hand, have used the actual completed project performance data and developed a single price-time curve for all contractors and incentive contracting methods (I/D with A+B, I/D without A+B, and Non Excuse Bonus projects) for the Florida Department of Transportation.

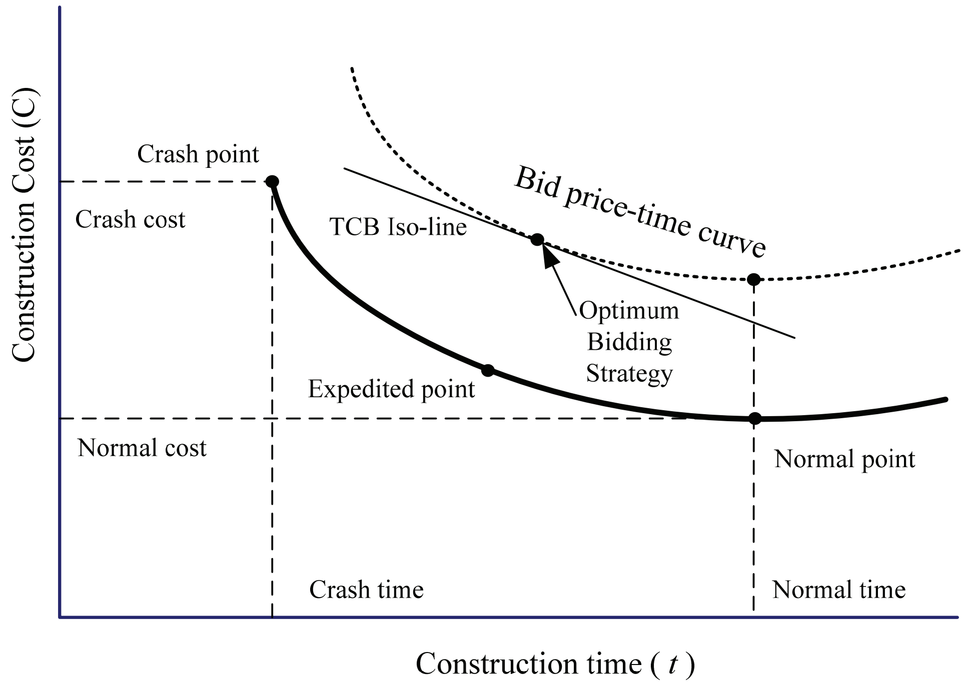


Figure 2.5 Construction Cost and Bid Price Versus Time (Shr and Chen 2003)

2.4.3 Experience of Highway Agencies

The experiences of different transportation departments indicate that using alternate bidding process has been successful in increasing competition by attracting more contractors to participate in the bid process thus lowering construction costs. At the same time, most of the transportation officials have mentioned that this process needs to be assessed in the long run in order to make sure that it selects the most economical alternative pavement type (Temple et al. 2004; MDOT 2001; MoDOT 2004; Gisi 2009; INDOT 2009; KYTC 2009; Wimsatt et al. 2009; Newman 2008).

Table 2.3 shows a summary of alternate bidding process practices in different transportation departments. As can be seen in this table, all of the departments except Kansas DOT and Michigan DOT have reported the application of the alternate bidding in the pavement selection process a successful experience. Michigan DOT reports that the success of the process can only be determined in the future when the actual costs of maintenance and rehabilitation activities and user costs are known. Two states of Louisiana and Kentucky have suggested the use of A+B+C bidding model. In this bidding model "C" stands for the life-cycle cost of alternate pavement design.

Louisiana Department of Transportation and Development

The A+B+L model that is the main focus of this study has first been implemented by the Louisiana Department of Transportation and Development (LADOTD) and is called alternate design, alternate bid (ADAB) that allows the selection of a pavement type through the bid processes. By comparing the lowest bid prices with the estimated costs calculated by LADOTD, Temple et al (2004) have concluded that using the ADAB model suggests a trend toward reduced contract bid prices, possibly because of added competition (Temple et al. 2004).

Michigan Department of Transportation

A comparison of the bid costs versus the increased preliminary engineering costs by Michigan DOT indicates that the alternate pavement type bidding has resulted in significant initial cost savings; however, the cost effectiveness of the alternate pavement type bidding process cannot be determined until an evaluation can be made of the long-term pavement performance and maintenance costs of alternate bid projects versus those of traditional approach (MDOT 2001).

Table 2.3 Summary of the experience of selected transportation departments in applying alternate bidding for pavement type selection process (Continued)

Agency	Features	Method	Constraints	Result
Louisiana DOT	-Trend toward reduced contract bid prices -Selecting the most economical alternative	-LCCA -ADAB Model -"A+B+C"	-AADT -Project length -Minimum required concrete pavement thickness	-Successful
Michigan DOT	-May be able to make savings -Impossible to predict whether savings over engineer's estimate will be realized in future AB projects -Difficult to agree on equivalency of designs for industries	-LCCA -Lowest EUAC -Incentive for extraordinary pavement performance -Letting pavement portion separately	-Not specified	-Cannot be determined
Missouri DOT	-More competition for both industries and ultimately lower cost -Excellent tool for achieving the lowest cost for the longest life -Competition over truer material cost and construction prices -Disagreement by the pavement industries over design-life assumptions -Extra work required to design plans	-LCCA	-Unique working conditions -Very high traffic volumes	-Successful -Constraints can be worked out
Texas DOT	-Is able to attract more contractors -Increases competition -Lower construction costs	-LCCA -Specifying situations that alternate bidding can be applied	-Pavement widening projects -Process does not involve new construction -Pavement is less than 5 miles in length -Concrete pavement thickness is less than 8 inches or 12 inches and greater	-In case applied on right projects helps in selecting a better alternative -Use of LCCA is recommended -Using FHWA RealCost software is recommended for LCCA

Table 2.3 Summary of the experience of selected transportation departments in applying alternate bidding for pavement type selection process

Agency	Features	Method	Constraints	Result
Kansas DOT	-Agency obtained the least cost alternate -Helps eliminate possible biases in the current process -LCCA adjustment did not determine the low bidder	-LCCA -Letting the whole project on one bid	-Not specified	-Not successful -Separate contracts are recommended
Indiana DOT	-More contractors participated in the bid -More competition -Cost saving -Not able to compare whether this process is most economical or promotes more competitive bid prices	-Two distinct sets of bids -LCCA -Present Worth not published before bidding	-Not specified	-Very successful
Kentucky Transportation Center	-Increased numbers of bidders -Increased competition -Lower overall bid prices -Bid adjustment did not affect the award of the project	-LCCA -A+B -A+B+C for projects with initial cost of over $2,000,000	-Can be applied when costs are comparable and there are no overriding engineering factors favoring one alternate	-Successful in select areas in the state
Transportation Association of Canada	-Provide government agencies with better knowledge of the true cost of a roadway -Increases competition -Enables government agencies to pave more roadways	-LCCA	-Not mentioned	-Successful -Concrete pavement structures can be competitive with asphalt pavement structures

Missouri Department of Transportation

The Missouri Department of Transportation (MoDOT) reports that alternate bidding provides an opportunity for both asphalt and concrete contractors to bid on a single project which fosters more competition and ultimately lowers cost to the taxpayers. Two major negative aspects of alternate bidding reported were disagreement by the pavement industries over design-life assumptions and extra work required to design plans and to compute bid quantities for two pavement types. However, MoDOT reports that negative aspects could be resolved and alternate bids on pavement is an excellent tool for achieving the lowest cost for the longest life (MoDOT 2004).

Kansas Department of Transportation

One of the motives of Kansas Department of Transportation (KDOT) in applying the alternative bidding process is to ensure that the agency obtains the least cost alternate where the LCCA shows the surfacing alternates to be very close in cost. Also this process involves both asphalt and concrete industries in deciding about pavement type selection which helps to eliminate possible biases in the current process. However, LCCA adjustment did not determine the low bidder in the alternate pavement type biddings performed by KDOT (Gisi 2009).

Indiana Department of Transportation

Indiana Department of Transportation (INDOT) reports that using their process of alternate bids for pavement type selection has been very successful. The INDOT has observed that the alternate pavement type bidding has attracted more bidders and competition, obtained true cost savings over similar conventional bid projects, and provided a more competitive market (INDOT 2009).

Kentucky Transportation Cabinet

In the Pavement Type Selection Policy prepared by the Kentucky Transportation Cabinet (KYTC), alternate pavement bidding procedure has been recommended in the situations where alternative pavement designs have comparable costs and there are no overriding engineering factors favoring one alternate (KYTC 2009).

Use of alternate pavement bidding in select areas in the state increases the number of bidders. Consequently overall bid prices are reduced through competition creating cost savings. While the bid adjustments did play a role in the process they did not actually determine which contractor was the lower bidder (Newman 2008).

Texas Department of Transportation

Wimsatt et al (2009) developed a protocol for determining when to consider pavement alternates. According to their study, applying alternate pavement type bidding on right projects helps in selecting a better alternative.

Canada

Nine alternate bid tenders across Canada since 2000 have been studied to assess the efficiency of this type of bid process. The results show concrete pavement structures can be competitive with asphalt pavement structures when tendering equivalent pavement designs with LCCA components. Also the research indicates that using alternate bid tenders increase competition and enables government agencies to pave more roadways with the same amount of money (Smith and Fung 2006).

2.4.4 Life-Cycle Cost Analysis Component

The economic assessment of a pavement project over its entire life is an effective approach not only to finding the lowest cost option by evaluating all the expected costs incurred during the service life but also to documenting and predicting the effects of an agency's expected future activities for the project. FHWA and other federal agencies such as the American Association of State Highway and Transportation Officials (AASHTO) have promoted the use of life-cycle based economic evaluation for transportation investment decisions, including pavement projects, since the Intermodal Surface Transportation Equity Act of 1991.

The National Highway System Designation Act of 1995 further imposed a new requirement making LCCA compulsory for National Highway System (NHS) projects costing more than $25 million. The requirement was annulled under the Transportation Equity Act for the 21st Century (TEA-21) in 1998, but FHWA and AASHTO remain active in assisting the states in developing their own LCCA procedures. FHWA is required by TEA-21 to fund research that "expands the knowledge of implementing LCCA" (23 USC 502). Life-cycle costs must still be considered as part of the FHWA's value engineering process for NHS projects costing more than $25 million (23 CFR Part 627) (GPO 2001). Table 2.4 lists all the regulations/policies regarding LCCA and alternate bid in United States.

Clemson University published a comprehensive technical report in April 2008 regarding the life-cycle cost analysis in pavement type selection. This study is based on the analysis of data obtained from a survey of states across the U.S. and provinces across Canada. The goal of this research was to develop a probabilistic-based LCCA approach that is customized for South Carolina utilizing the practices of other states. In the final survey conducted by Clemson University a total of 24 agencies responded. 92% of these agencies (22 agencies) used LCCA for pavement type selection except Maine and British Columbia which indicated that they only have flexible pavements. The specific concerns raised by these states about their LCCA approach are (Rangaraju et al. 2008):

- Unreliable quality of the input data into LCCA models.
- Difficulty in predicting cost of materials in a period of rapidly fluctuating prices to get a reliable and accurate LCCA.

Table 2.4 Regulations/Policies regarding LCCA and alternate bid

Year	Regulation / Policy	Message
1960	An Informational Guide on Project Procedures, produced by AASHO.	Importance of competition between pavement industries.
1981	Pavement Type Selection Policy Statement, FHWA.	Necessity of economic analysis based on LCC of pavements. Where applicable, the use of alternate bids may be permitted.
1990	Intermodal Surface Transportation Equity Act, expired in 1997.	Promoting use of LCC based economic evaluation.
1995	National Highway System Designation Act.	Mandating LCCA for NHS projects costing more than $25 million.
1996	Pavement (Design) Policy, FHWA	No bearing on pavement type selection.
1998	Transportation Equity Act for the 21st Century (TEA-21)	Compulsory LCCA was annulled. Fund research that "expands the knowledge of implementing LCCA".
1999	23 CFR Part 626	Discourage use of alternate bids, difficult in developing truly equivalent pavement designs.
2001	23 CFR Part 627	LCCA must be considered as part of VE process for NHS projects costing more than $25 million.
2008	Clarification of FHWA Policy for Bidding Alternate Pavement Type on the National Highway System	Factors that should be considered prior to utilizing alternate bidding procedures.

- Disagreements with the asphalt and concrete pavement industries about the most appropriate inputs such as the determination of the timing of future rehabilitation, selection of unit costs, and determination of salvage value (Rangaraju et al. 2008).

The summary of principal findings is as below:

- Almost 92% of the survey respondents are using LCCA for pavement type selection.
- Over 50% of the responding agencies use RealCost, DARWin, or some customized software to conduct LCCA.
- Most of the states use a 4% discount rate.
- Majority of state DOTs use historical data from pavement management system to determine their rehabilitation timings.
- About 56% of the respondents include salvage value in their analysis.

2.4.5 Life-Cycle Cost Analysis Software

Over 50% of the SHAs use RealCost, DARWin, or some customized software to conduct LCCA (Rangaraju et al. 2008). RealCost software developed by FHWA is widely used by several state agencies and is recognized as the most comprehensive tool in its treatment of different input parameters (Rangaraju et al. 2008). RealCost automates FHWA's LCCA methodology as it applies to pavements. The software can perform both deterministic and probabilistic modeling of pavement LCCA problems. In addition it supports a deterministic sensitivity analysis and probabilistic risk analyses. The user needs to input agency costs or service lives for individual construction or rehabilitation activities (FHWA 2004).

The DARWin Pavement Design System is a program that automates the AASHTO design equations. The life-cycle cost module of this program accounts for project dimensions, initial construction, up to five preprogrammed rehabilitation strategies, and the salvage value of the pavement. It then discounts all the construction costs and salvage value to the present and reports the net present value of the project (Wilde et al. 1999).

The American Concrete Pavement Association (ACPA) has developed structural design software named “StreePave 12” for concrete pavements. The life cycle cost analysis module allows a detailed cost/benefit analysis and make informed decisions on pavement design project. This software can be used to design equivalent concrete and asphalt sections and evaluate the best possible solution(s) for pavement needs. The Asphalt Pavement Alliance (APA) has developed LCCAEXPRESS software which is a tool for life-cycle cost analysis that follows the guidelines from the FHWA.

Some other SHAs use spreadsheet programs to analyze life-cycle costs of highway pavement projects. The user can provide inputs in the cells of the spreadsheet, and perform calculations using preprogrammed macros that execute calculations.

2.5 Summary

The evolution of contracting methods indicates that procurement methods are moving towards alignment of SHA and contractor’s objectives. The A+B+L bidding method enables SHAs to incorporate project durations and life-cycle cost of designs in the competition. The experiences of different transportation departments indicate that using A+B+L has been successful in increasing competition by attracting more contractors to participate in the bid process and also by stimulating competition over project duration thus lowering construction costs and project durations. However, the review of literature indicates that the main issue that SHAs have faced when implementing A+B+L bidding has been realistic determination of bid parameters.

Determination of incentive/disincentive rates (UTVs) has basically been based on subjective considerations. Most studies have focused on optimal determination of UTV based on the road user costs, whereas the interaction between UTV and competitiveness of contractors which has the same or even more impact on the success of the bidding process has not been investigated. Despite the LCCA guidelines developed by FHWA, each state has followed a different approach in performing LCCA. Lack of certainty in prediction of future maintenance and rehabilitation activities has created a situation where asphalt and concrete industries question the integrity of life-cycle cost models developed for rigid and flexible pavements. Since the result of alternate bidding procedure is dependent on the accuracy of life-cycle costs calculated for rigid and flexible pavements, LCCA is critical in the success of alternate bidding procedure.

CHAPTER 3

UTV IMPACT ON CONTRACTORS' COMPETITIVENESS

The purpose of this chapter is to investigate the impact of UTV on contractors' competitiveness in A+B bidding projects. First the relationships between price and time of A+B bidding projects are determined then a computational framework is introduced that assists SHAs in determining the optimal UTV that maximizes competition in the A+B bidding process.

3.1 Introduction

As was discussed in Chapter 2, price-time relationships have been used extensively for project compression. According to Callahan et al. (1992), for a specific construction company, there is an optimum price-time balancing point for every construction contract where construction cost is minimum. Any variation in time from the optimum price-time point will result in a corresponding increase in construction cost. Several studies have suggested a quadratic or second-order polynomial function to approximate the relationship between bid price (A) and construction time (t) (Shen et al. 1999, Shr et al. 2004, Shr and Chen 2003, Wu and Lo 2009). In this chapter, both linear and non-linear relationships between price and time are investigated to find the most significant price-time curve.

3.2 Price-Time Functions

Completed A+B projects in Oklahoma Department of Transportation (ODOT) are collected and analyzed for each contractor to: 1) identify whether the relationship between price and time is significant and 2) determine the equation that describes the price-time relationship. The price-time equations of each contractor are required to determine the contractors' competitive bidding strategies utilizing maximum/minimum optimization method. Since both linear and quadratic price-time relationships have been suggested by previous literature, both linear and polynomial functions are tested for the price-time data of each contractor and the best model is determined utilizing P-value and R-squared which is a goodness of fit factor.

The entire analysis process is explained using one contractor's data. Figure 3.1 shows the entire procedure of developing price-time relationship model for this contractor. First the historical price and time data of the selected contractor's A+B projects are collected. Then price index and time index are calculated for each project completed by the contractor. These indices, which are explained further in the following section, are the normalized construction costs and durations that creates scope-free data for the curve-fitting process.

After calculating the price and time indices of completed A+B projects, the price index is fit to linear and quadratic functions of time index. The ANOVA and regression analyses are performed for linear and polynomial functions separately. Then the R-squared and P values of the linear and polynomial models are compared and the best model is selected. A quadratic term, DaySq, is created in the analysis since polynomial effects such as

Time*Time cannot be specified in the statistical model. The model is run for both linear and quadratic relationships between price and time indices using SAS® software.

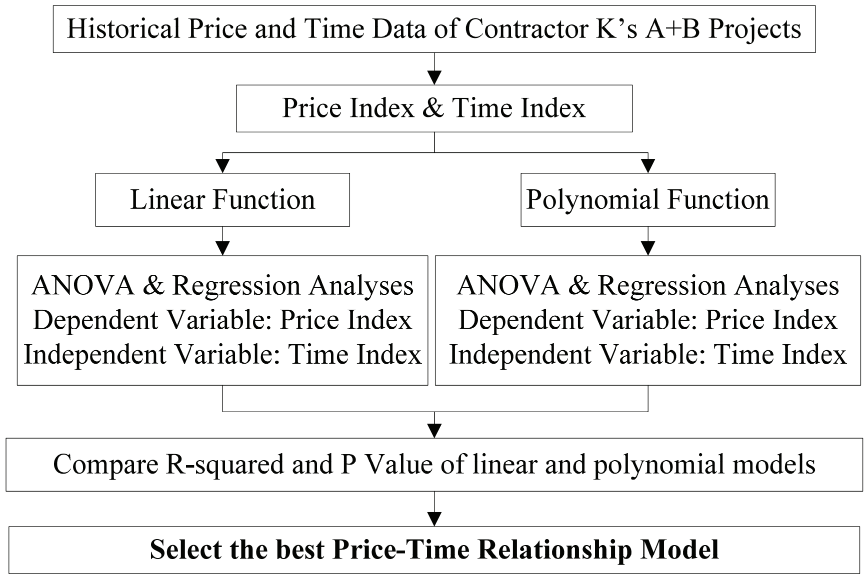


Figure 3.1 Procedure Used to Develop Price-Time Relationship Models

3.2.1 Data Preparation

The data used in this study are obtained from the ODOT. The dataset consists of all the completed price-time bi-parameter bidding projects that ODOT has let. Contractors that had three or more A+B projects with ODOT are selected for further analysis in this study due to the minimum number of data points required in developing a price-time curve. The historical database contains 54 data points for 14 contractors.

Table 3.1 shows the historical A+B bidding data collected for contractor K. The award bid is the bid price of each contractor. The final construction price is the final construction price, excluding incentive/disincentive. The bid days are the duration proposed by the contractor during the A+B bidding process. The final contract time is the bid day that is adjusted for the weather, additional work, or change orders. Days used is the number of days that the contractor used, from the start of project to substantial completion. Also the Incentive/Disincentive rates, Incentive cap, and Incentive paid to the contractor or the Disincentive that the contractor is charged are available for each project.

Table 3.1 Example of Historical A+B Project Information of Contractor K

Contractor	**Award bid (k) ($)**	**Final construction price (k) ($)**	**Bid Days**	**Final contract time (d)**	**Days used**	**Incentive /disincentive ($/d)**	**Incentive cap (k) ($)**	**Incentive paid (k) ($)**
K	4,078	4,257	150	166	174	2,500	100	-20
	2,359	2,402	90	90	87	6,000	360	18
	4,319	4,398	179	179	140	3,250	130	123.5
	4,319	4,434	149	149	113	2,500	87.5	87.5

The completed A+B projects have different budgeted costs and durations. For instance, contractor K completed four A+B projects that are different in terms of award bid, final construction price, final contract time, and days used. In order to develop a contractor's price-time curve for A+B projects using the bid price and time data of previous A+B projects, the scope free time and price measures are necessary because every previous project's scope is different. Two indices are developed to represent the cost and time performance of completed A+B projects: Price Index and Time Index. These concepts have also been used by Shr and Chen (2004) and Pyeon and Lee (2012). The equations utilized to calculate price and time indices are shown in Equation 3.1 and Equation 3.2:

$$\text{Price Index} = \frac{\text{final construction price} - \text{award bid}}{\text{award bid}} \tag{3.1}$$

$$\text{Time Index} = \frac{\text{days used} - \text{final contract time}}{\text{final contract time}} \qquad (3.2)$$

The award bid is the price that the contractor bids. The final construction price is the final construction price excluding incentive/disincentive. The bid days are the duration proposed by the contractor during the A+B bidding process. The final contract time is the bid day that is adjusted for the weather, additional work, or change orders. Days used is the number of days that the contractors used from the start of project to substantial completion.

Price index is measured by dividing the amount of price over-runs by the award bid price. For any project the price index may also be greater than, less than, or equal to zero. If the final construction price of a project is less than the award bid, it means that the contractor has been able to save in construction costs, which results in negative price index. A positive price index, on the other hand, is an indicator of construction cost over-runs. For example, a price index of -0.05 means 5% cost saving and a price index of +0.05 means 5% cost overrun compared to the award bid. A zero price index means the project's final construction price has been equal to award bid.

Time index is measured by dividing the number of days that a project is finished late by the final contract time. For any project the time index may be greater than, less than, or equal to zero. A negative time index indicates time savings, which makes the contractor eligible for monetary incentives while a positive time index is an indicator of schedule overruns, which results in disincentive payments to the contractor. For example, a time index of -0.05 means 5% time saving while a time index of +0.05 means 5% time overrun compared to the contract time. A zero time index means the project's duration has been the same as contract time. Values of price and time indices that are less than zero indicate good project performance, whereas values of time and price indices that are greater than zero indicate poor project performance.

Figure 3.2 shows the scatter plot of price index versus time index for Contractor K. The price and time indices are also shown in Table 3.2. The first row of this table indicates a project that has both cost and schedule overruns. This project was awarded for $4,078,000, but after completion of project the final construction price was $4,257,000, resulting in price index of 4.39%. In addition, the final contract time of this project was 166 days while the final project duration or days used was 174 days, resulting in a time index of 4.82%.

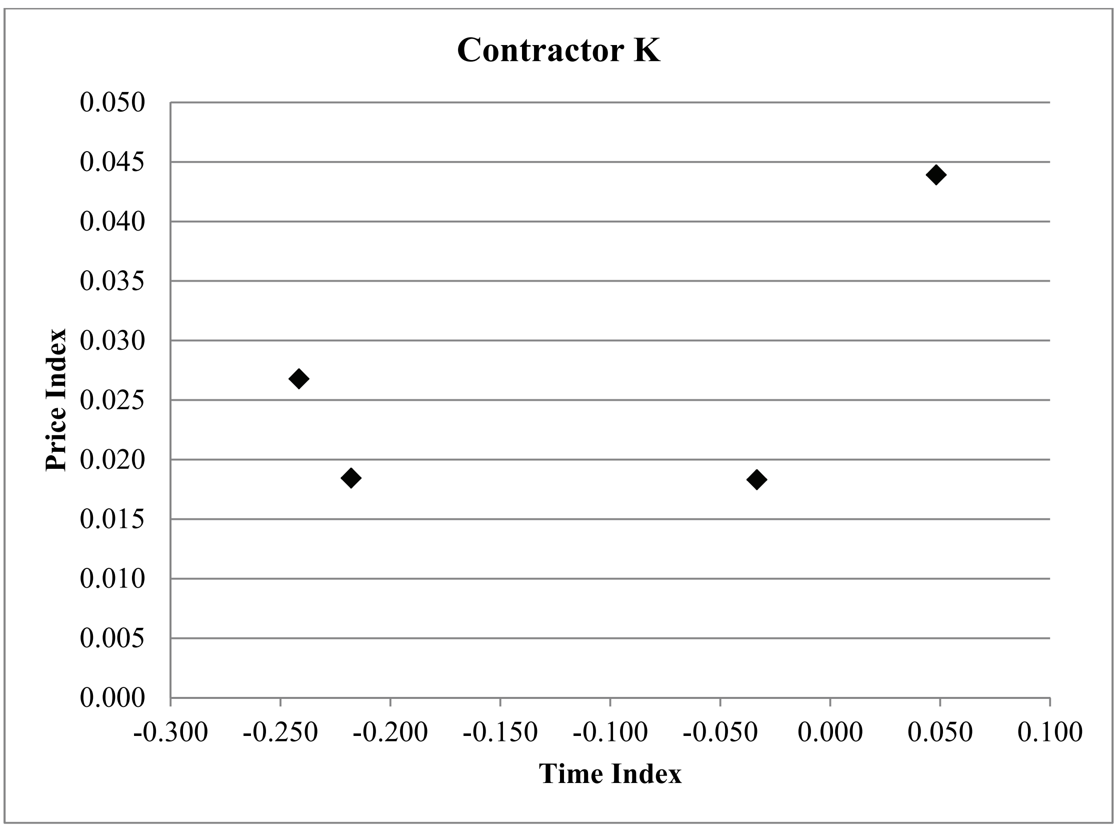


Figure 3.2 Scatter Plot of Price Index vs. Time Index for Contractor K

Table 3.2 Time and Price Indices for Contractor K

Contractor	**Price Index**	**Time Index**
K	0.0439	0.0482
	0.0182	-0.0333
	0.0183	-0.2179
	0.0266	-0.2416

3.2.2 ANOVA and Regression Analysis

The time and price indices are calculated for all projects. Then the analysis of variance (ANOVA) is performed to investigate the relationship between price and time indices.

Linear Regression Model for Contractor K

The F statistic of the linear model is not significant ($F = 1.03$, $p = 0.4168$), indicating that the model is not a good fit for a significant portion of variation in the data. The R-squared value indicates that the model only accounts for 34% of the variation in price index, which is another indicator that this model is not a good fit for the data.

Polynomial Regression Model for Contractor K

Consider a response variable Y that can be predicted by a polynomial function of an independent variable X. The polynomial function shown below is determined after estimating β_0, the intercept; β_1, the slope due to X; and β_2, the slope due to X_2.

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 X_i + \varepsilon_i \qquad (3.3)$$

For the observations $i = 1, 2, \ldots, n$.

Table 3.3 indicates the ANOVA table and parameter estimates for the new model. The overall *F statistic* is significant (F = 102.66, p < 0.1). The R-squared value has increased from 0.3402 to 0.9952, indicating that the model now accounts for 99.5% of the variation in Price Index. All effects are significant with p < 0.06 for each effect in the model. The fitted equation is now

$$Price\ Index = 0.02655 + 0.30414 \times Time + 1.24476 \times TimeSQ \qquad (3.4)$$

Regression Results

The ANOVA and regression analysis is performed for all the contractors individually. The results of the analysis are shown in Table 3.4. For each contractor the ANOVA reveals whether or not the relationships between the dependent and independent variables (Price Index and Time index respectively) are significant. The regression analysis also results in linear and quadratic equations that relate price index to time index combined with the R-squared values, which is a goodness of fit factor.

Table 3.3 Analysis of Variance Procedure for Contractor K's Polynomial Model

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.000437	0.000218	102.66	0.0696
Error	1	0.000002	0.000002		
Corrected Total	3	0.000439			
R-Squared = 0.9952		C.V. = 5.45088	Root mean square error = 0.00146		
Adjusted *R*-Squared = 0.9855		Price Mean = 0.02675	C.V. = Root mean square error/Price Mean		
Variable	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	1	0.02655	0.00110	24.08	0.0264
Time	1	0.30414	0.02267	13.42	0.0474
TimeSQ	1	1.24476	0.10708	11.62	0.0546

Table 3.4 Results of ANOVA and Regression Analyses for ODOT Contractors

Contractor	Selected Regression Model		
	P Value	**Equation**	**R-squared**
A	0.3518	$y = 0.1712\ x^2 + 0.0580\ x - 0.0172$	0.6482
B	0.2044	$y = 2.6500\ x^2 + 0.0360\ x + 0.0450$	0.7956
C		No model selected	
D	0.2739	$y = 3.5154\ x^2 + 0.6018\ x - 0.0972$	0.9250
E	0.2018	$y = -0.3607\ x + 0.0021$	0.6371
F	0.1672	$y = 0.4159\ x - 0.0235$	0.6936
G	0.0171	$y = 0.4702\ x + 0.2974$	0.9993
H		No model selected	
I	0.0773	$y = -0.4238\ x + 0.0980$	0.8513
J	0.0636	$y = -1.4800\ x - 0.2034$	0.8768
K	0.0696	$y = 1.2448\ x^2 + 0.3041\ x + 0.0266$	0.9952
L	0.0636	$y = 0.7991\ x^2 + 0.3095\ x - 0.0194$	0.9364
M	-	$y = -0.2235\ x^2 - 0.0578\ x - 0.0004$	1.0000
N	-	$y = -0.2498\ x^2 - 0.3305\ x - 0.1228$	1.0000

A quadratic regression model performs better for contractors A, B, D, K, L, M, and N. A linear regression model outperforms the quadratic model for contractors E, F, G, I, and J. The regression models are selected based on their P-value as well as R-squared value. A model with a lower P value better explains the variability of the independent variable. If the P values of linear and polynomial regression models are equal, the model with larger R-squared value is selected. Neither linear regression nor polynomial regression is significant for contractors C and H.

3.2.3 Price-Time Curves

In the previous section, the significant regression equations that best explain the relationship between price index and time index for different contractors were identified. Except for contractors C and H that neither linear nor quadratic equations are significant, the price-time curves are developed for other contractors. The process of developing price-time curves from the regression equation is explained for contractor K. The same calculation process is applied to other contractors as well. According to Table 3.4 and after replacing *y* with price index and *x* with time index the fitted model for contractor K is:

$$(A - A_0)/A_0 = 0.0266 + 0.3041(D - D_0)/D_0 + 1.2448[(D - D_0)/D_0]^2 \qquad (3.5)$$

Where A = final construction price

D = days used

A_0 = award bid; and

D_0 = final contract time.

By rearranging the equation we will have the following equation:

$$A = 1.0266\, A_0 + 0.3041\, A_0[(D - D_0)/D_0] + 1.2448\, A_0[(D - D_0)/D_0]^2 \qquad (3.6)$$

This equation illustrates the internal relationship between the bid price and time for contractor K. The functional relationship between bid price and time is determined by deciding (D_0, A_0)D_0, C_0). The (D_0, A_0)D_0, C_0) can be the SHA's or contractors' estimate about the expected duration and price of the project at the normal point. The normal point is the location on the price-time curve where the construction cost is the minimum. Table 3.5 shows the price-time functions for different contractors.

Table 3.5 Price-Time Equations for Contractors

Contractor	Price-Time Equation
A	$A = 0.9828\, A_0 + 0.0580\, A_0[(D - D_0)/D_0] + 0.1712\, A_0[(D - D_0)/D_0]^2$
B	$A = 1.0450\, A_0 + 0.0360\, A_0[(D - D_0)/D_0] + 2.6500\, A_0[(D - D_0)/D_0]^2$
D	$A = 0.9028\, A_0 + 0.6018\, A_0[(D - D_0)/D_0] + 3.5154\, A_0[(D - D_0)/D_0]^2$
E	$A = 1.0021\, A_0 - 0.3607\, A_0[(D - D_0)/D_0]$
F	$A = 0.9765\, A_0 + 0.4159\, A_0[(D - D_0)/D_0]$
G	$A = 1.2974\, A_0 + 0.4702\, A_0[(D - D_0)/D_0]$
I	$A = 1.0980\, A_0 - 0.4238\, A_0[(D - D_0)/D_0]$
J	$A = 0.7966\, A_0 - 1.4800\, A_0[(D - D_0)/D_0]$
K	$A = 1.0266\, A_0 + 0.3041\, A_0[(D - D_0)/D_0] + 1.2448\, A_0[(D - D_0)/D_0]^2$
L	$A = 0.9806\, A_0 + 0.3095\, A_0[(D - D_0)/D_0] + 0.7991\, A_0[(D - D_0)/D_0]^2$
M	$A = 0.9996\, A_0 - 0.0578\, A_0[(D - D_0)/D_0] - 0.2235\, A_0[(D - D_0)/D_0]^2$
N	$A = 0.8772\, A_0 - 0.3305\, A_0[(D - D_0)/D_0] - 0.2498\, A_0[(D - D_0)/D_0]^2$

3.3 Total Combined Bid Iso-Map

In A+B bidding, contractors are allowed to adjust their Total Combined Bid (TCB) by trading-off contract time and bid price. As shown in Equation 2.1 in Chapter 2, contractors can increase the construction duration (t) and keep the TCB constant by decreasing the original bid price (A).

Since TCB is the only factor that defines the winner of an A+B bidding contract, all the bidding strategies that result in the same TCB have the same level of competitiveness. In fact, with a given UTV, there are infinite combinations of bid price (A) and contract time (t) that give the same TCB. In a price-time orthogonal coordinate diagram, these combinations form a straight line, which has been called Iso_Line by Shen et al. (1999) as shown in Figure 3.3. The slope of the Iso-Line is determined by the UTV and since all the points on the line have the same TCB, the line is called TCB Iso-Line. Therefore, A+B bidding can be treated as a single parameter bidding by considering the total combined bid.

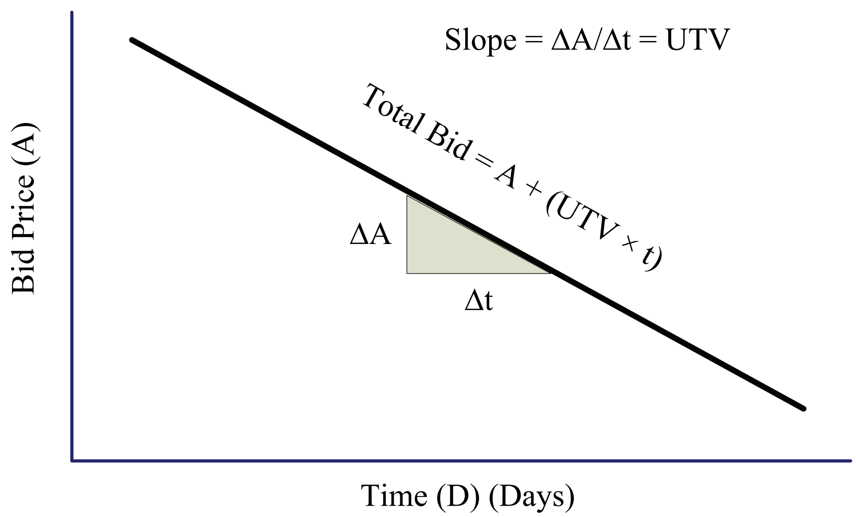
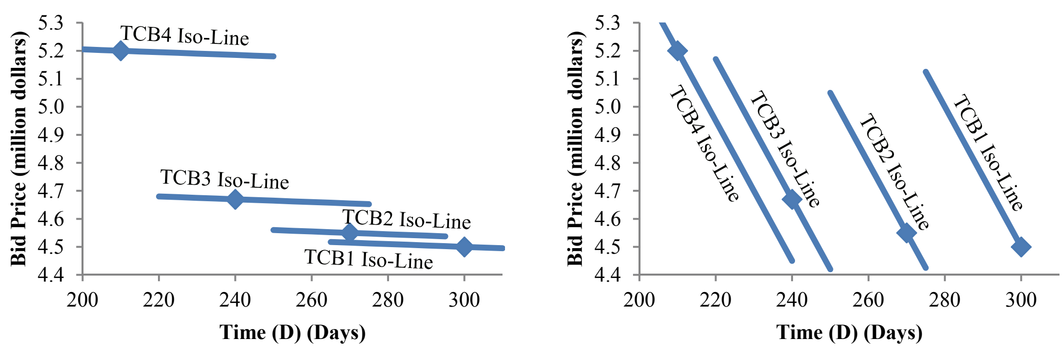


Figure 3.3 Contractor's Overall Competitiveness: TCB Iso-Line (Shen et al. 1999)

3.4 Bid Competition

Assume that four contractors (contractors 1 to 4) are participating in an A+B bidding. Each contractor has different financial and operational strengths; therefore, their most competitive bidding strategies are expected to be different. Two different UTVs (a low value of \$500/day and a high value of \$25,000/day) are assumed to evaluate the impact of the UTV on the competitiveness of each contractor. The TCB Iso-Maps with two different UTVs are shown in Figure 3.4. The TCB Iso-Lines for contractors 1, 2, 3, and 4 are shown with TCB_1 Iso_Line, TCB_2 Iso_Line, TCB_3 Iso_Line, and TCB_4 Iso_Line respectively. For each scenario (low and high UTV), the bid proposals as well as TCB Iso-Lines for each contractor are drawn. UTVs define the slope of each contractor's TCB-Iso line. The TCB of each contractor is the value of the contractor's Iso-line intersecting Y-axis. It is assumed that this value is the lowest TCB that contractor is able to propose.

The situation where the UTV is low is illustrated in Figure 3.4(a). When UTV is low, the contractor 1's TCB Iso-Line intersects Y-axis lower than the other contractors. Therefore, contractor 1 has the most competitive strategy and the following relationship is obtained: $TCB_1 < TCB_2 < TCB_3 < TCB_4$. On the other hand, when the UTV is large, as illustrated in Figure 3.4(b), contractor 4's TCB-Iso line intersects the Y-axis lower than the other contractors and creates the following relationship: $TCB_4 < TCB_3 < TCB_2 < TCB_1$. Therefore, contractor 4 has the most competitive strategy when the UTV is high.



a) Contractor 1's winning situation (Low UTV - $500/day)

b) Contractor 4's winning situation (High UTV - $25,000/day)

Figure 3.4 Iso-Maps for Different UTVs in A+B Bidding

It is very important to note that the UTV is determined by the SHA before contractors participate in the bid process. Therefore, the slope of the TCB Iso-Lines is known before contractors propose their bid price and construction time. The results of this example indicate that the competitiveness of contractors is heavily dependent on the choice of

UTV, which is always determined by SHAs. The next section discusses how contractors can find their optimal strategy in an A+B bid.

3.5 Optimal UTV

After the price-time curve for a contractor is determined, the most competitive strategy is determined by finding the t in Equation 3.7 that minimizes TCB. The objective function is developed by combining Equation 2.1 and Equation 3.1:

$$TCB = A + (UTV \times t) = (a + b_1 t + b_2 t^2) + (UTV \times t) \tag{3.7}$$

$$\text{Objective Function: } \min[TCB] \tag{3.8}$$

Then the derivative of objective function with respect to t is set to zero as follows:

$$TCB'(t) = b_1 + 2b_2 t + UTV = 0 \tag{3.9}$$

so that

$$t = (-UTV - b_1)/2b_2 \tag{3.10}$$

From Equation 2.2, the slope of the price-time curve at construction duration determined in Equation 3.10 is

$$A'(t) = b_1 + 2b_2 t = b_1 + 2b_2(-UTV - b_1)/2b_2 = -UTV \tag{3.11}$$

By referring to Equation 2.1, the bid price equation can be given by

$$A = TCB - (UTV \times t) \tag{3.12}$$

From Equation 3.12, the slope of the TCB Iso-Line can be obtained as

$$A'(t) = -UTV \tag{3.13}$$

From Equation 3.11 and Equation 3.12 it is concluded that the slope of the price-time curve at the duration that minimizes TCB is equal to the slope of the TCB Iso-Line. Therefore, the TCB Iso-Line that is tangent to the price-time curve of the contractor determines the most competitive strategy (see Figure 3.5).

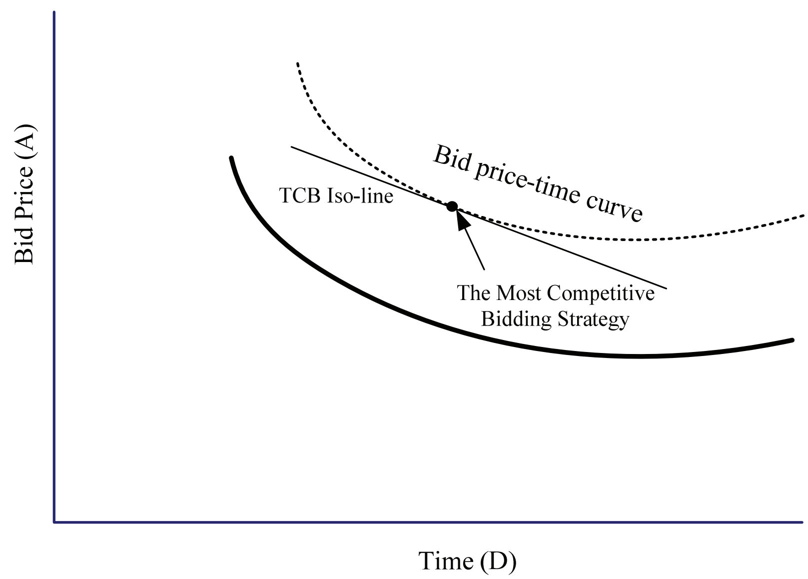


Figure 3.5 The Most Competitive Bidding Strategy

3.6 Application of Price-Time Models

One project is selected to demonstrate how a price-time model can be successfully applied to determine the optimum UTV and I/D rates that maximizes the competition during the bid process. The selected project contract number is 050639 with the bid days of 365 and award bid of $18,464,000. The duration of 365 days is the maximum allowable construction time defined by the SHA prior to letting the project. Contractor L won the A+B bid competition in this project. The competitiveness of contractor L is compared with other contractors under different UTVs in order to study how UTV impacts the competitiveness of contractors during the bid process. By inputting bid days and award bid into the equations developed in Table 3.5, the price-time curves can be determined.

Assume that five contractors (D, J, L, B and K) are participating in the bid process. These contractors have the most significant price-time curves in terms of R-squared and P value. In addition, the contractors have a high number of completed A+B projects (either four or five projects).

The price-time curves of these five contractors are illustrated in Figure 3.6. The bold face line shows the ceiling for competitiveness. The area above the bold face line shows the bid strategies that are noncompetitive for any UTV. The bottom line of the shaded area represents the bidding strategies that have a chance of winning the contract. This competitive line that represents the most competitive strategies in the bid process is made of the price-time curves of contractors D, J, and L. In other words, the entire bidding strategies of the other contractors (B and K) are noncompetitive for any UTV. The competitiveness of contractors is evaluated for different UTVs in order to identify the UTV intervals that make each contractor competitive in the bid process.

Three scenarios are designed to investigate the competitiveness of contractors D, J, and L during A+B bid process. In the first scenario, the UTV is assumed to be equal to zero, meaning that there would be no monetary incentives for early completion. The second scenario investigates a situation where the UTV is equal to $25,000/day. The third scenario is a situation when the UTV is equal to $35,000/day.

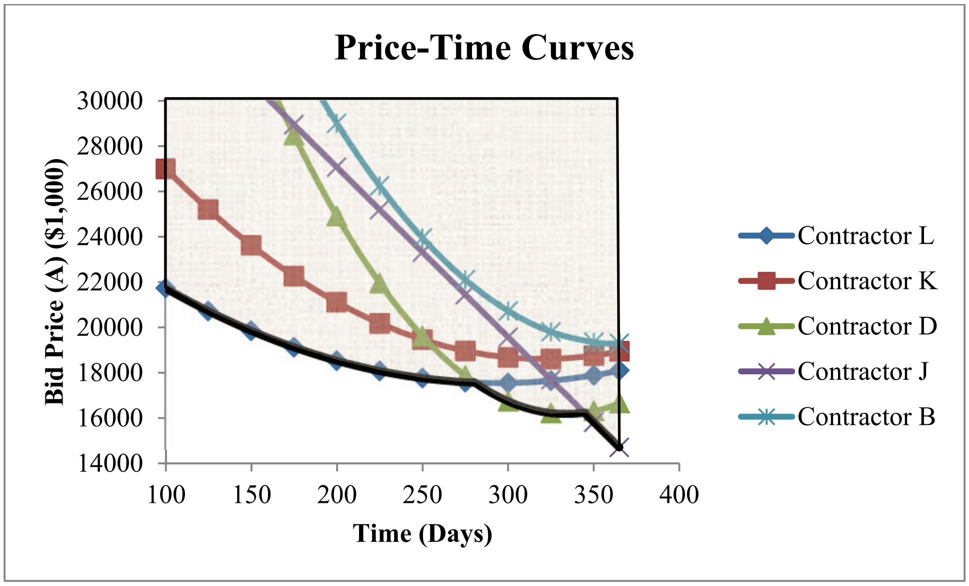


Figure 3.6 Price-Time Curves of Contractors

3.6.1 Scenario- I

In the first scenario the UTV is assumed to be zero, thus in this bid process there would be neither incentive for early completion nor disincentive for late completion. This scenario is illustrated in Figure 3.7. The most competitive strategy of each contractor is the point where a TCB Iso-Line with the slope of zero is tangent to the price-time curve of contractors. Since the price-time relationship for contractor J is linear, the most competitive strategy for this contractor would be the point where TCB Iso-Line passes through the point with the lowest bid price, which occurs at the maximum allowable contract time (365 days). In this scenario, contractor J would be the most competitive contractor due to its ability in proposing the lowest bid price among competing contractors.

The total combined bid is calculated for these three contractors when UTV is equal to zero dollars per day. For contractors D and L, the most competitive strategies are the points on their price-time curves where the slope is equal to zero. The most competitive strategies of contractors D and L when UTV is equal to zero are calculated as below:

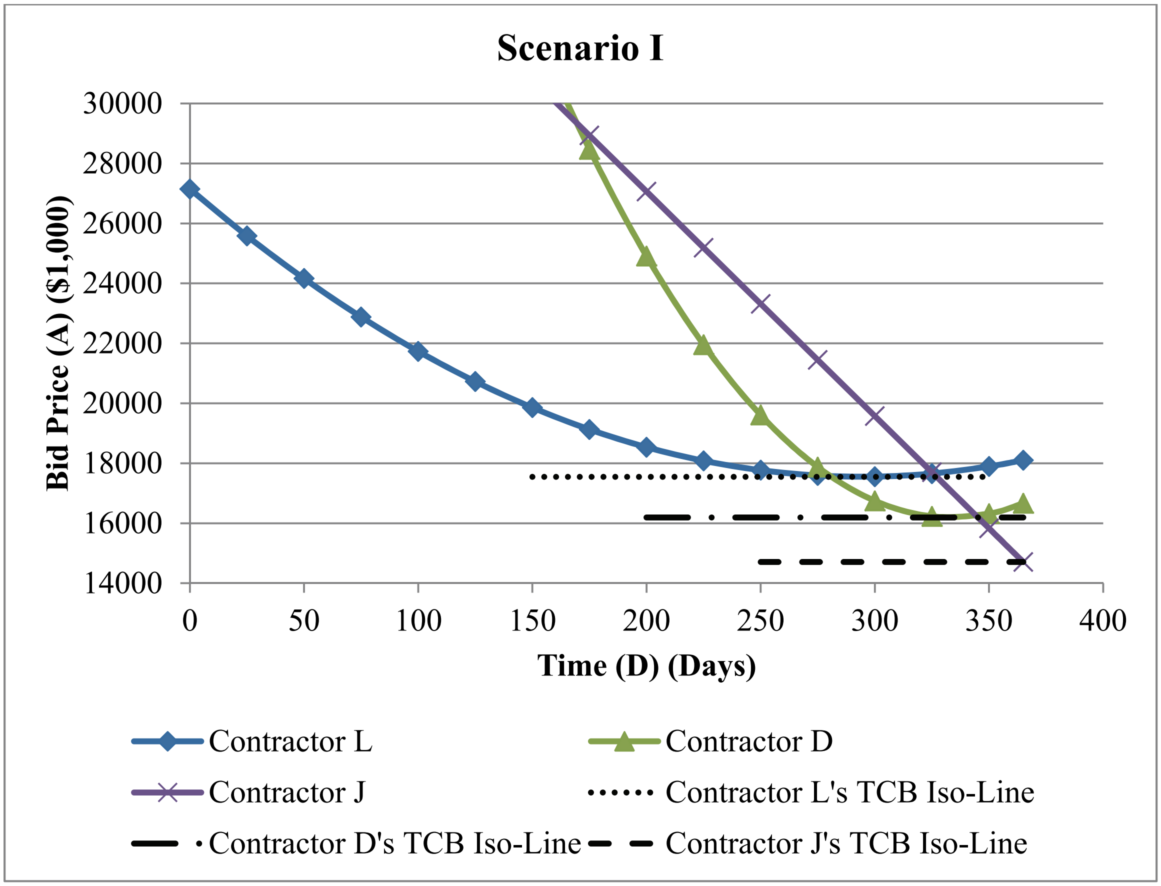


Figure 3.7 A+B Bid Competition when UTV=0

$$A_{Contractor\ D} = 70{,}464.897 - 325.2132\ D + 0.4872\ D^2 \quad (3.14)$$

$$A'_{Contractor\ D}(D) = -UTV \quad (3.15)$$

so that

$$-325.2132 + 0.9744\, D = 0 \tag{3.16}$$

By solving for D, the most competitive duration for contractor D is 334 days. By inserting this duration in Equation 3.14, the most competitive bid price for contractor D is $16,193.74.

$$A_{Contractor\ L} = 27{,}145.77 - 65.191\, D + 0.1107\, D^2 \tag{3.17}$$

$$A'_{Contractor\ L}(D) = -UTV \tag{3.18}$$

so that

$$-65.191 + 0.2214D = 0 \tag{3.19}$$

Solving for D, the most competitive duration for contractor L is 295 days. By inserting this duration in Equation 3.17, the most competitive bid price for contractor L is $17,548.059.

For contractor J, however, the most competitive strategy is the lowest bid price point, which can be calculated by inserting the maximum allowable contract time (365 days) in Equation 3.20.

$$A_{Contractor\ J} = 42{,}035.14 - 74.868\, D \tag{3.20}$$

The most competitive bid price at 365 days is equal to $14,708.42.

Table 3.6 shows the total combined bid comparison of three contractors. Since unit price in the equations is equal to $1,000, the total combined bids in this table have been multiplied by 1,000 to represent the real prices. As shown in this table, contractor J is the contractor with the lowest total combined bid. Therefore, contractor J is the most competitive contractor when project acceleration is not considered a factor in deciding the winning contractor.

Table 3.6 Total Combined Bid Comparison of Contractors for UTV=0

Contractor	Total Combined Bid
L	$16,193,740
J	$14,708,420
D	$17,548,059

3.6.2 Scenario II

In Scenario II, the UTV is equal to $25,000/day, thus in this bid process contractors are paid $25,000/day incentives for early completion of project or charged the same amount for late completion. This scenario is illustrated in Figure 3.8. The most competitive strategy of each contractor is the point where a TCB Iso-Line with the slope of -25 is tangent to the price-time curve of contractors. Since the price-time relationship for contractor J is linear, the most competitive strategy for this contractor would be the point where TCB Iso-Line passes through the point with the lowest bid price, which occurs at the maximum allowable contract time (365 days). In this scenario, contractor L would be the most competitive contractor due to its ability in proposing the lowest TCB among competing contractors.

The total combined bid is calculated for these three contractors when UTV is equal to $25,000/day. For contractors D and L, the most competitive strategies are the points on their price-time curves where the slope is equal to -25. The most competitive strategies of contractors D and L when UTV is equal to 25 are calculated as below:

By inserting UTV in Equation 3.15 the following equation is obtained:

$$-325.2132 + 0.9744\,D = -25 \qquad (3.21)$$

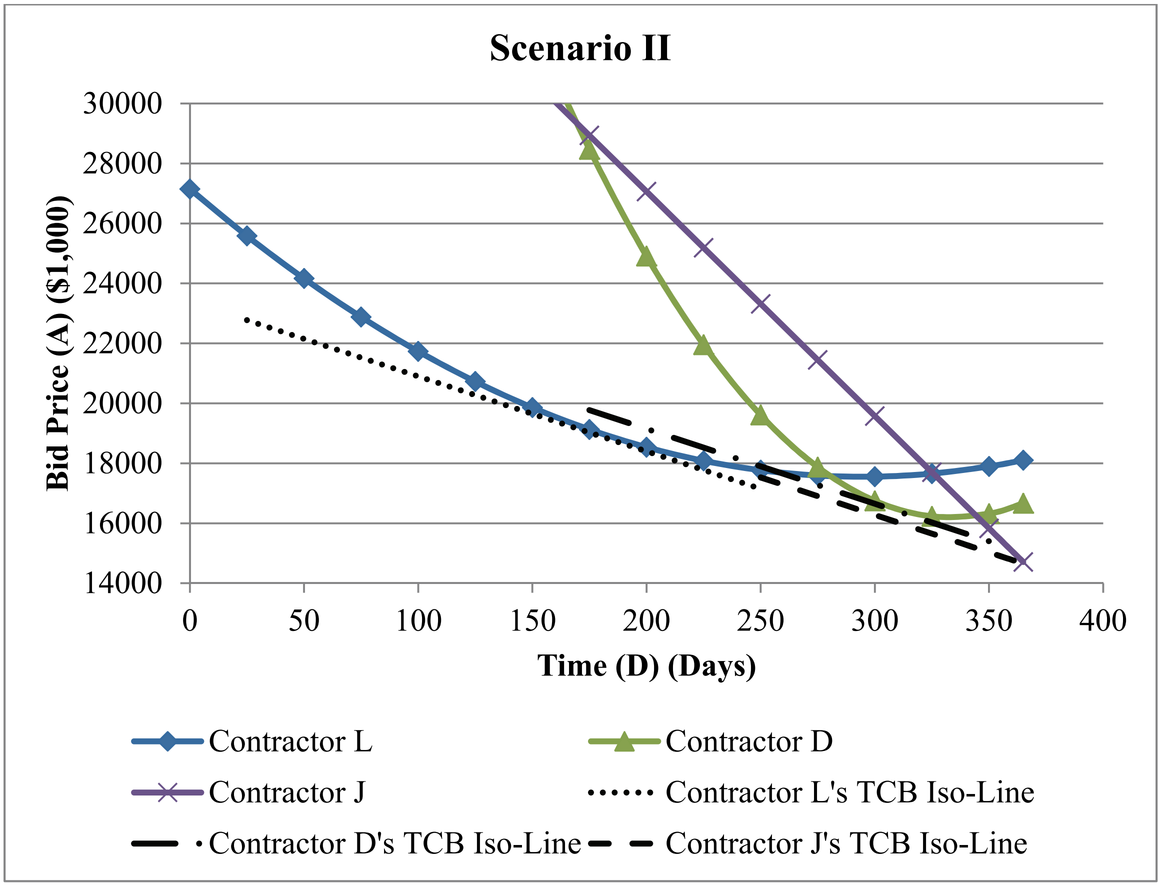


Figure 3.8 A+B Bid Competition when UTV=$25,000/day

By solving for D, the most competitive duration for contractor D is 308 days. By inserting this duration in Equation 3.14, the most competitive bid price for contractor D is $16,514.44.

By inserting UTV in Equation 3.18 the following equation is obtained:

$$-65.191 + 0.2214D = -25 \tag{3.22}$$

Solving for D, the most competitive duration for contractor L is 182 days. By inserting this duration in Equation 3.17, the most competitive bid price for contractor L is \$18,959.54.

For contractor J, however, the most competitive strategy is the lowest bid price point, which can be calculated by inserting the maximum allowable contract time (365 days) in Equation 3.20. The most competitive bid price at 365 days is equal to \$14,708.42.

Table 3.7 shows the total combined bid comparison of three contractors. Since unit price in the equations is equal to \$1,000, the total combined bids in this table have been multiplied by 1,000 to represent the real prices. As shown in this table, contractor L is the contractor with the lowest total combined bid. Therefore, contractor L is the most competitive contractor when UTV is equal to \$25,000/day.

Table 3.7 Total Combined Bid Comparison of Contractors for UTV=\$25,000/day

Contractor	**Total Combined Bid**
L	\$23,497,815
J	\$23,833,420
D	\$24,216,965

3.6.3 Scenario III

In Scenario III, the UTV is equal to \$35,000/day, thus in this bid process contractors are paid \$35,000/day incentives for early completion of project or charged \$35,000/day disincentive for late completion of project. This scenario is illustrated in Figure 3.9. The most competitive strategy of each contractor is the point where a TCB Iso-Line with the slope of -35 is tangent to the price-time curve of contractors. Since the price-time relationship for contractor J is linear, the most competitive strategy for this contractor would be the point where TCB Iso-Line passes through the point with the lowest bid price, which occurs at the maximum allowable contract time (365 days). In this scenario, contractor L would be the most competitive contractor due to its ability in proposing the lowest TCB among competing contractors.

The total combined bid is calculated for these three contractors when UTV is equal to \$35,000/day. For contractors D and L, the most competitive strategies are the points on their price-time curves where the slope is equal to -35. The most competitive strategies of contractors D and L when UTV is equal to 35 are calculated as below:

By inserting UTV in Equation 3.15 the following equation is obtained:

$$-325.2132 + 0.9744\, D = -35 \tag{3.23}$$

By solving for D, the most competitive duration for contractor D is 298 days. By inserting this duration in Equation 3.14, the most competitive bid price for contractor D is \$16,822.335.

By inserting UTV in Equation 3.18 the following equation is obtained:

$$-65.191 + 0.2214D = -35 \tag{3.24}$$

Solving for D, the most competitive duration for contractor L is 136 days. By inserting this duration in Equation 3.18, the most competitive bid price for contractor L is \$20,314.545.

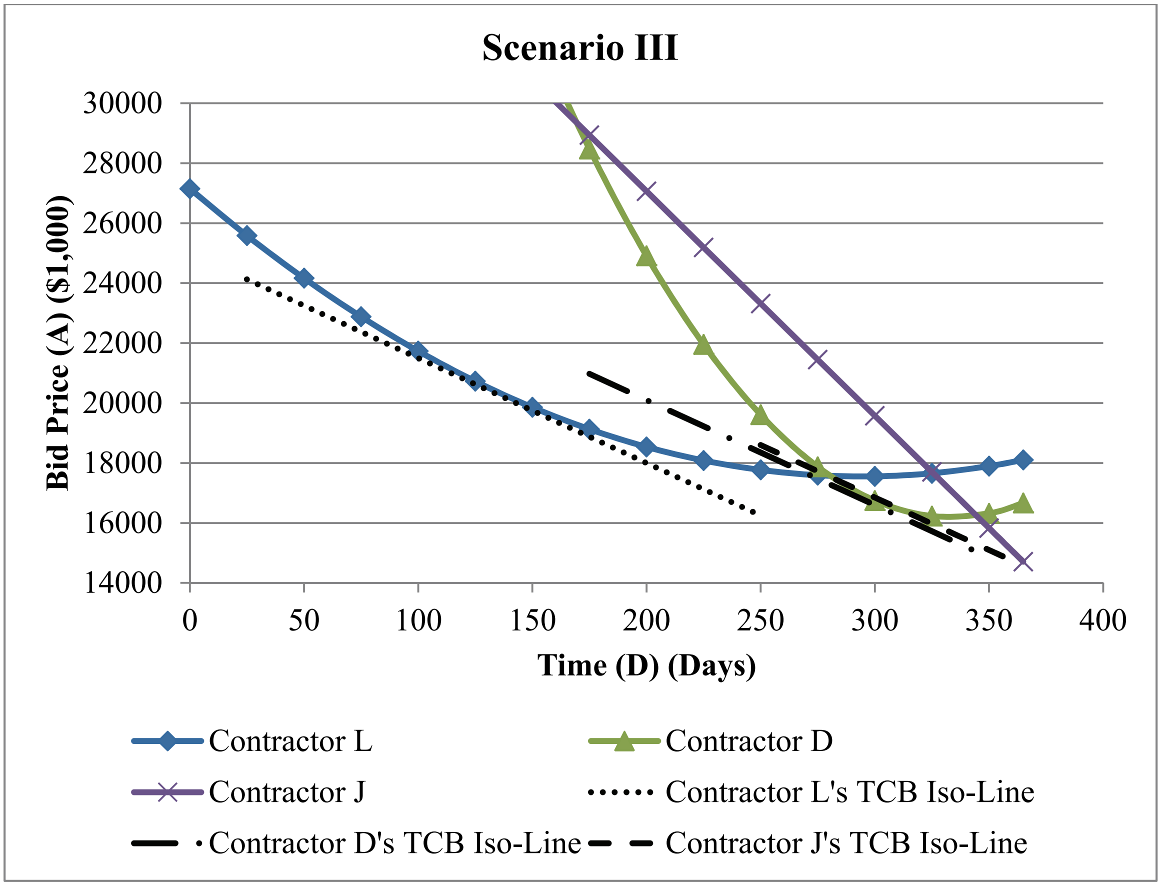


Figure 3.9 A+B Bid Competition when UTV=$35,000/day

For contractor J, however, the most competitive strategy is the lowest bid price point, which can be calculated by inserting the maximum allowable contract time (365 days) in Equation 3.20. The most competitive bid price at 365 days is equal to $14,708.420.

Table 3.8 shows the total combined bid comparison of three contractors. Since unit price in the equations is equal to $1,000, the total combined bids in this table have been multiplied by 1,000 to represent the real prices. As shown in this table, contractor L is the contractor with the lowest total combined bid. Therefore, contractor L is the most competitive contractor when UTV is equal to $35,000/day.

Table 3.8 Total Combined Bid Comparison of Contractors for UTV=$35,000/day

Contractor	Total Combined Bid
L	$25,087,285
J	$27,483,420
D	$27,246,665

3.7 Results

The analysis of these three scenarios clearly indicates that the UTV selected by the SHA can change the competitiveness of contractors participating in the A+B bidding process. When the UTV is equal to zero and contractors do not receive incentives for early completion, contractor J is the most competitive contractor with the following relationship: TCB(J) < TCB(D) < TCB(L). In the second scenario where the UTV is equal to $25,000/day, contractor L becomes the most competitive contractor and the following relationship is obtained: TCB(L) < TCB(J) < TCB(D). And in the third scenario where UTV is equal to $35,000/day contractor L remains the most competitive contractor followed by contractor D and contractor J. Thus the following relationship holds in the third scenario: TCB(L) < TCB(D) < TCB(J).

By gradually increasing UTV from zero, different situations are created in terms of the competitiveness of contractors. These UTVs are determined and named as thresholds in this study. The first situation created after increasing UTV from zero is where the competitiveness of contractor D and contractor L becomes equal. The slope of TCB Iso-Line that is tangent to the price-time curves of contractor D and contractor L is equal to -18.805 meaning that the UTV that equalizes the competitiveness of these contractors is $18,805/day. The second UTV threshold is where the competitiveness of contractor J and contractor L is equal. In this situation the UTV is equal to $23,128/day and both contractor J and contractor L have the most competitive strategy. And finally, by increasing the UTV to $31,366 a situation is developed where the competitiveness of contractor J and contractor D are equal.

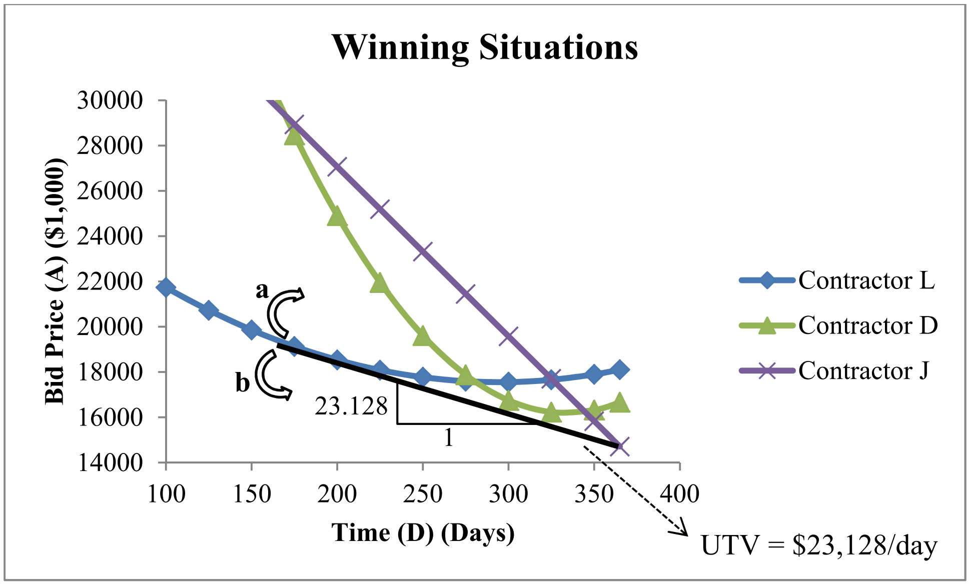
Table 3.9 shows a summary of changes in the competitiveness of contractors by gradually increasing UTV from zero. When the UTV is equal or greater than zero and less than $18,805/day, contractor J has the most competitive strategy followed by contractor D and contractor L. When the UTV is equal to $18,805/day, contractor J still has the most competitive strategy; however, competitiveness of contractors D and L are equal. For UTVs greater than $18,805/day and less than $23,128/day, contractor J has the most competitive strategy followed by contractor L and contractor D. When the UTV is equal to $23,128/day, both contractors J and L are equally competitive for winning the bid competition. For any UTV greater than $23,128/day, contractor L has the most competitive bidding strategy. However, for the UTVs between $23,128/day and $31,366/day, contractor J is more competitive than contractor D and for the UTVs greater than $31,366/day contractor D is more competitive than contractor J.

Table 3.9 Impact of UTV on the Competitiveness of Contractors in A+B Bidding

Scenario	**Competitiveness**
UTV = 0	J > D > L
0 < UTV < $18,805/day	J > D > L
UTV = $18,805/day	J > D = L
$18,805/day < UTV < $23,128/day	J > L > D
UTV = $23,128/day	J = L > D
$23,128/day < UTV < $31,366/day	L > J > D
UTV = $31,366/day	L > J = D
UTV > $31,366/day	L > D > J

Figure 3.10 shows the winning situations for this case analysis. Based on different UTVs and the price-time curves of contractors, two winning situations can be identified in this A+B bid competition. The line that passes through contractor J's price-time line and is tangent to the price-time curve of contractor L is where both contractors have the same level of competitiveness which happens when the slope of the TCB Iso-Line is equal to -23.128 or the UTV is equal to $23,128/day. Region "a" indicates the situation where contractor L has the most competitive strategy. For any UTV greater than $23,128/day or for any steeper TCB Iso-Line, contractor L would be the most competitive contractor. Region "b" is the winning situation for contractor J. Any UTV less than $23,128/day or any shallower TCB Iso-Line makes contractor J the most competitive contractor.

According to the historical data, the real UTV for this project was $4,500/day, which falls into region "b". Contractor J is the most competitive contractor in this situation. However, in the actual A+B bidding process, contractor J did not participate. The results of this chapter suggest that if contractor J had participated in the bid process, this contractor would had a very high possibility to win this project. However, UTV is not high enough to stimulate competition between contractors because contractor L and contractor D are far from having the most competitive strategy. In addition, this encourages contractor J not to offer its most competitive strategy by knowing that they are by far the most competitive contractor in the competition. The actual UTV used in this project does not encourage contractors to propose accelerated bids.



a: UTV > $23,128/day; The most competitive contractor is **L**
b: UTV < $23,128/day; The most competitive contractor is **J**

Figure 3.10 Winning Situations vs. UTV

For each contractor there is only one price-time curve for various types of A+B projects. This is despite the fact that A+B projects can be as varied as a minor surface treatment to a reconstruction project. However, due to limited number of completed A+B projects it was not feasible to study price-time relationship for each project type. Developing multiple price-time models for each contractor based on different types of A+B projects using more comprehensive historical data sets would be a reasonable extension to this study.

3.8 New Factor Measuring Level of Competition

As shown in the results of the case study, when UTV is equal to zero, the total combined bid of contractor J is $1,485,320 less than contractor D and $2,839,639 less than contractor L. When UTV is equal to $18,805/day, the total combined bid of contractor J is $714,262 less than contractors D and L. When UTV is equal to $23,128/day, the total combined bid of both contractors J and L are only $487,800 less than contractor D. For an UTV of $31,366/day the difference between the total combined bid of contractor L and contractors D and J is $1,588,124. In other words, in some situations the competitive strategies of contractors are closer to each other, which create a situation that stimulates contractors to propose accelerated construction durations.

A new factor can be defined in order to measure the level of competition in an A+B bidding project. This factor measures the average of differences between contractors' total combined bids. A lower average of differences between contractors' TCBs indicates a higher level of competition between contractors. This factor can be used by SHAs to maximize the competition during bid process. The following equation is suggested as a measurement of this factor:

$$Average\ Differences\ Between\ Contractors'\ TCB = \sum_{i=1}^{n} \frac{[(n+1)-(2\times i)] \times TCB_i}{\binom{n}{2}} \quad (3.25)$$

Where TCB = Total Combined Bid; n = number of contractors that have a chance to win; and i $=\{1, \ldots, n\}$.

This new factor has been calculated for the contractors in the case study when UTV is equal to $0/day, $18,805/day, $23,128/day, and $31,366/day (Figure 3.11). The average differences between contractors' TCB is equal to $1,893,093 when the UTV is equal to zero. When the UTV is equal to $18,805/day the average differences between contractors' TCB is equal to $714,262. When the UTV is equal to $23,128/day the average differences between contractors' TCB is equal to $314,667. And finally, when the UTV is equal to $31,366/day, the average differences between contractors' TCB is equal to $1,588,669.

It can be clearly seen that the average of differences between contractors' TCB is the lowest when UTV is equal to $23,128/day. If contractor D proposes a TCB that is $314,667 lower than their ideal TCB, their chance of winning the competition increases significantly. In addition, contractors L and J, which have the same level of competitiveness, are also required to propose a lower TCB than their ideal strategy in order to remain competitive. In this situation, all the contractors know their competitors can potentially be the winner and do their best to propose a price and duration that cannot be easily dominated by others. Therefore, $23,128/day would be the UTV that maximizes competition between contractors.

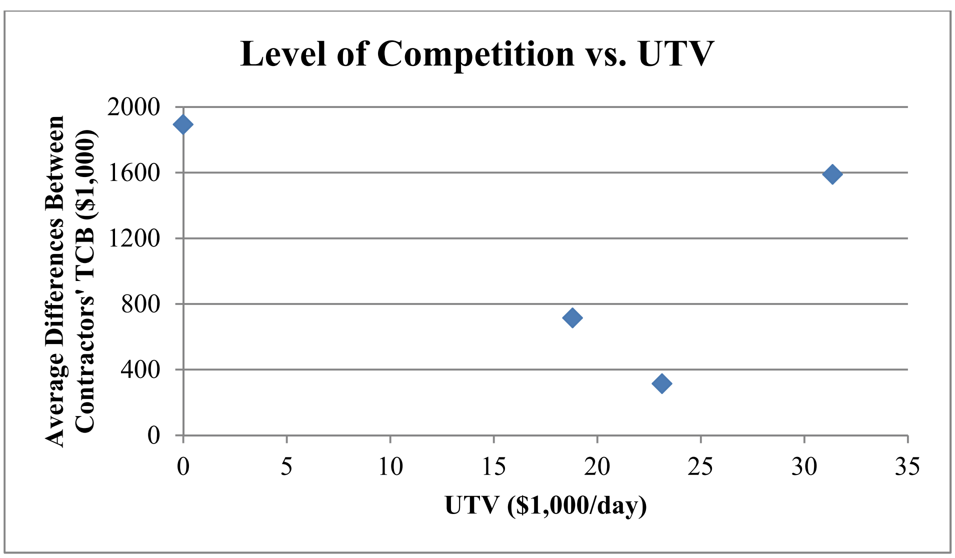


Figure 3.11 Level of Competition for Different UTVs

3.9 Summary

This chapter focused on evaluation of the impact of UTV upon competitiveness of contractors in A+B bidding projects. In order to illustrate the impact of UTV on the A+B bidding competition, TCB Iso-Map, TCB Iso-Line, and a methodology to determine the most competitive bidding strategy for each contractor were illustrated. Through a hypothetical example, it was clearly shown that different UTVs can change the contractor who has the most competitive bidding strategy. The results suggested that the conventional approach that only takes road user costs into account in order to determine the incentive/disincentive rates for A+B bidding projects might result in sub-optimal results.

In the case study, it was clearly shown how different UTVs change the level of competition in A+B bidding and may result in different winning contractors. A new factor was formulated that calculates the average of differences between contractors' TCB which should be minimized in A+B bidding projects to ensure a stimulated competition during the bid process.

This chapter laid a computational foundation that enables SHAs to determine the optimum Incentive/Disincentive rates that maximize the competition among contractors and result in selection of the most efficient contractor in construction acceleration. It also introduces an approach for contractors to study the strategies of their competitors before proposing a bid price utilizing the publically available bid data.

CHAPTER 4

INTERSTATE HIGHWAY STRUCTURAL PAVEMENT HISTORY

This chapter discusses the data collection and data preparation efforts for the purpose of determining deterministic and realistic life-cycle cost parameter for A+B+L bidding projects. The deterministic LCCA models developed in Chapter 5, the realistic LCCA models developed in Chapter 6, and the comparisons between these two LCCA models in Chapter 7 are based on the Interstate highway Structural Pavement History of ODOT in 2010 which has been discussed in this chapter.

4.1 Introduction

The interstate structural history data set for Interstate 40 (in Oklahoma) is used to identify the deterministic and realistic pavement treatment patterns. This data set is a record of the construction and major treatment projects on the Interstate 40 in Oklahoma. Figure 4.1 shows a schematic section of the data set. The ODOT's pavement management branch checks the accuracy of this data set and updates it based on the latest construction activities on a regular basis. This report has been issued on a yearly basis since 1994. In this study the 2010 data set is used. The primary sources of project information include Planning & Research Division log cards, Bureau of Public Roads interstate strip maps, as-built drawings, and the ODOT Oracle database.

For the pavement sections that have not been reconstructed, the construction year indicated in the dataset is the original construction year. The entire interstate highway system at Oklahoma has taken over ten years to be constructed. The traffic on some sections has been rerouted onto existing state highways until construction was complete. For the reconstructed pavement sections, the construction year in the dataset indicates the year that the pavement section has been reconstructed. Therefore, as can be seen in Figure 4.1, the construction year of different pavement sections is not a single year. The pavement types in Interstate 40 can be categorized into four different types: 1) Flexible, 2) Rigid, 3) Composite, and 4) Others. A breakdown of Interstate 40 based on the pavement types can be seen in Figure 4.2. The high percentage of rigid pavement sections in this highway makes it an appropriate choice for the study of alternate pavement type bidding.

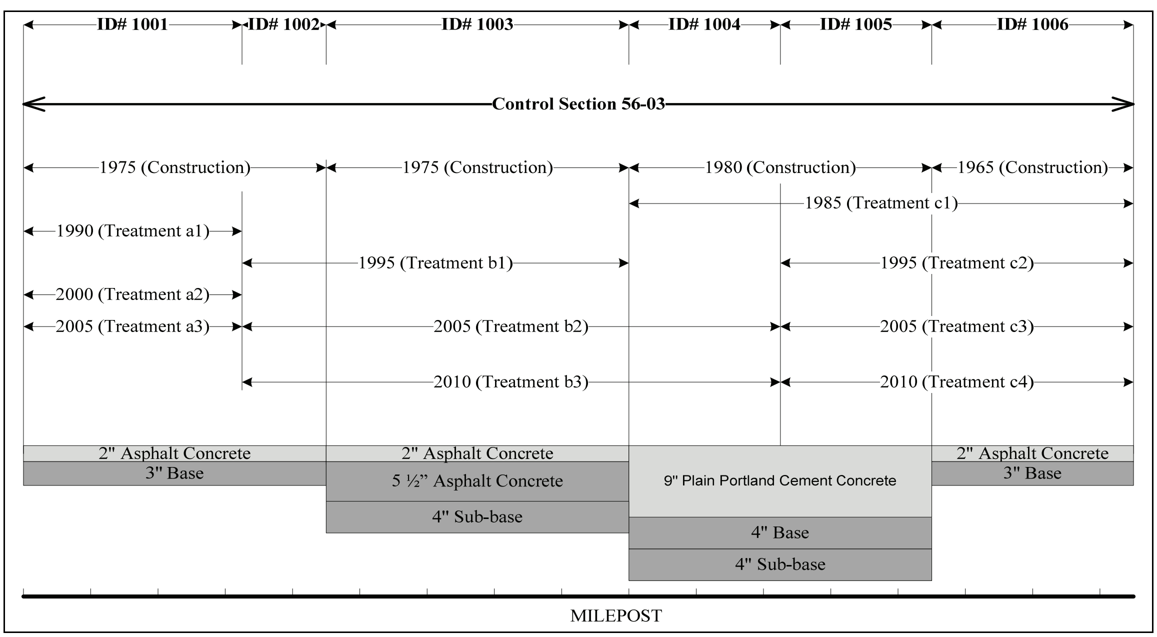


Figure 4.1 Sample of Schematic Section of Interstate Structural History Database

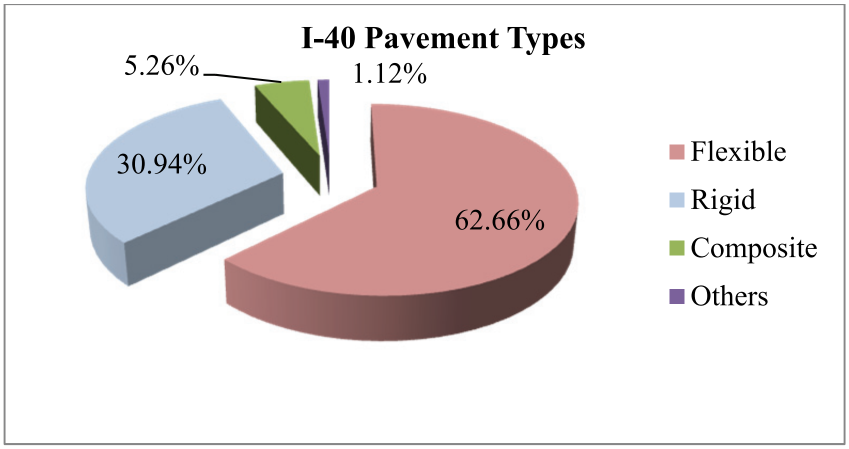


Figure 4.2 Different Pavement Types in I-40

4.2 Log Card

Log cards are being used to keep track of projects performed on each control section. The log card of control section 56-03 in Interstate 40 can be seen in Appendix A. These log cards are stored in the Planning and Research Division in ODOT. Since 2008, an electronic copy of these log cards is also available on the servers of ODOT. The important information on the most log cards have been transformed into spreadsheet formats and the electronic copy of them are available on the servers for future references. However, the entire log cards have been stored in the planning and research division in case the electronic copy cannot be accessed online. The data that can be found in a log card are:

- Control Section Number
- County name
- Start and end of the control section
- List of projects performed on the control section
- Project information:

- Completion date of project
- Project number
- Brief explanation about the type of project, whether a project is reconstruction, overlay, flexible pavement, and rigid pavement among others.
- Width
- Thickness of based and surface
- Length
- Start point and end point

4.3 Control Section

A control section is a specific segment or roadway assigned as a permanent unit for identification and record keeping. Control sections are assigned within a county with termini normally at county lines or major highway junctions. The entire state highway inventory data have been divided into control sections. A code has been assigned to each control section which is made of three different parts. The first part is the numerical portion of the route; the second part is the county code; and the third part is the control number. Figure 4.3 shows a snapshot of the control section map of Okmulgee County. The part of interstate 40 (in blue) that passes through this county is made of only one control section with the number of 40-56-03. The small box containing control section number also shows the length of the section in miles (left side) and kilometers (right side).

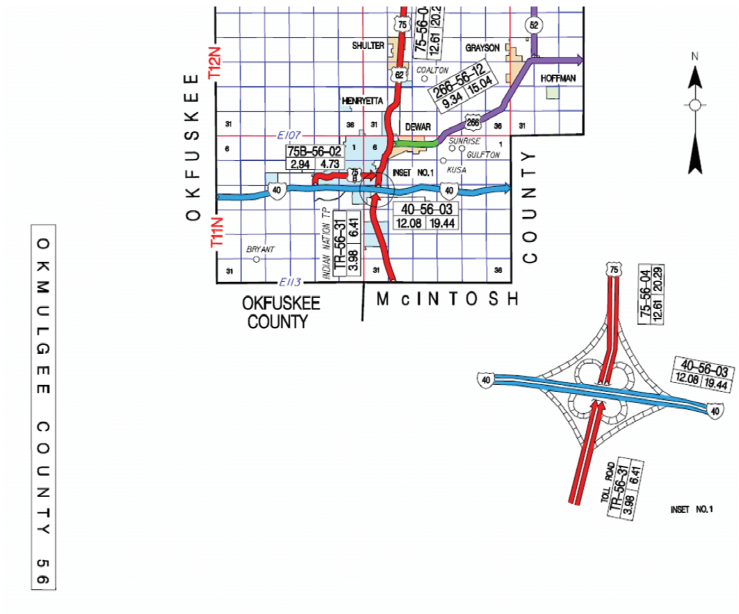


Figure 4.3 Control Section Map of Okmulgee County in Oklahoma

The portion of Interstate 40 passing through the state of Oklahoma is 330.66 miles long starting from the Texas state line and ending in Arkansas state line. It passes through 4 divisions, 13 counties and consists of 18 control sections as shown in Table 4.1.

Table 4.1 Control Sections of Interstate 40

Division	County	County Number	Control Sections
5	Beckham	5	[05-01] [05-04]
7	Caddo	8	[08-48]
4	Canadian	9	[09-05]
5	Custer	20	[20-02] [20-04]
1	Mcintosh	46	[46-07]
1	Muskogee	51	[51-15]
3	Okfuskee	54	[54-22]
4	Oklahoma	55	[55-68] [55-69]
1	Okmulgee	56	[56-03]
3	Pottawatomie	63	[63-40] [63-41]
3	Seminole	67	[67-37]
1	Sequoyah	68	[68-22] [68-23]
5	Washita	75	[75-02]

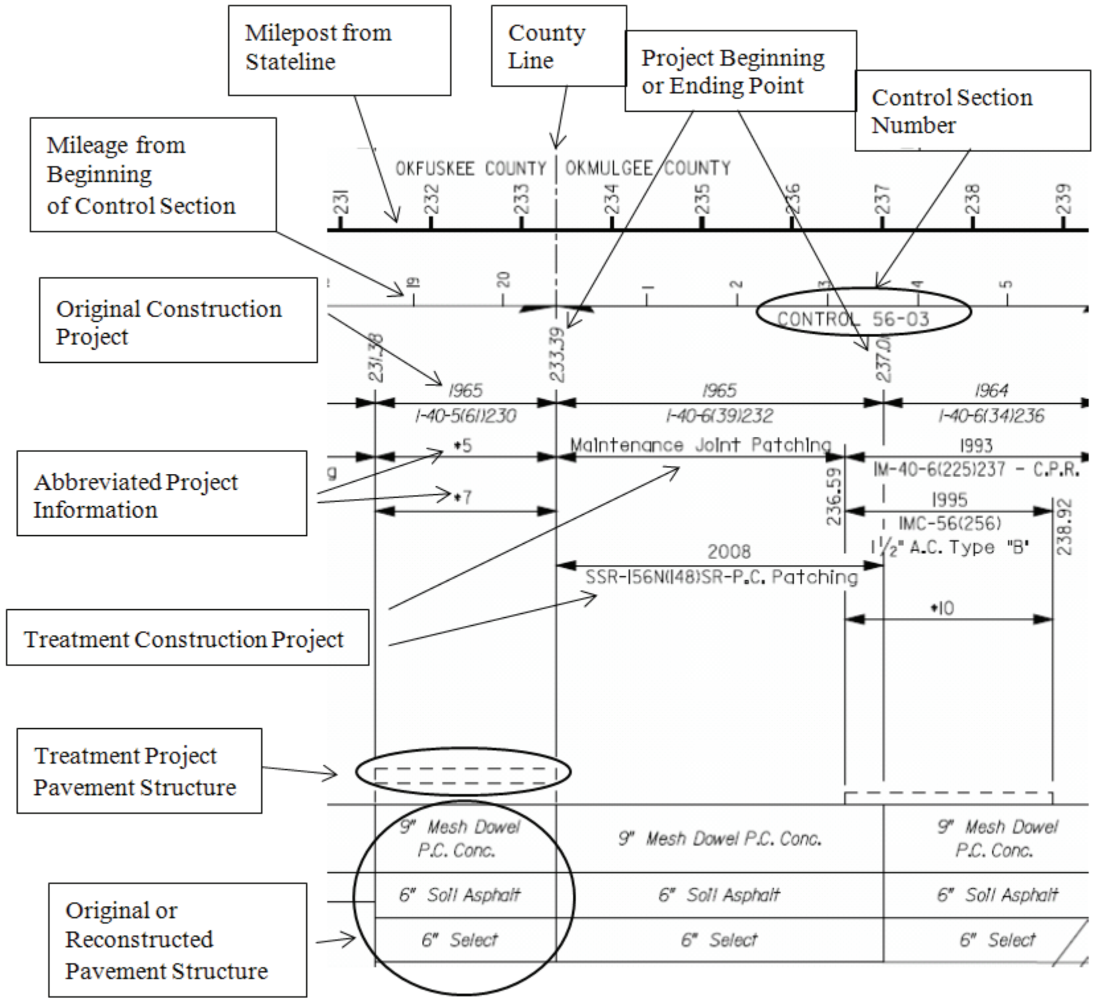


Figure 4.4 Snapshot of Interstate Highway Structural Pavement History

Figure 4.4 shows a snapshot of 2010 Highway Structural Pavement History for Interstate 40 control section 56-03. It illustrates all the components of the data set and identifies where the data is located. As can be seen in this figure this data set is published and maintained in visual format. It specifies time, location and scope of all pavement construction, reconstruction, and treatment projects since Interstate 40 was constructed. It includes the year that projects are opened to traffic, structural layering of the initial pavement and modifications to the initial structural layering through the time, scope of treatment activities, and project numbers for both westbound and eastbound of the Interstate 40. The locations of projects are defined by including the beginning and the end mile posts for all projects that have been performed in Interstate 40.

By looking at Figure 4.4, one can realize that the construction of Interstate 40 from mile post 233.39 to 237.01 has been finished in 1965 by project number I-40-6(39)232; the structural layering of this project is 9” Mesh Dowel P.C. Concrete, 6” Soil Asphalt, and 6” Select material; this project is part of control section number 56-03 in Okmulgee county; a portion of this section with the beginning mile post of 233.39 and ending mile post of 236.59 has undergone a maintenance joint patching project (the time of this project has been pulled out from another source which is discussed in the next section); in 2008 another P.C. Patching project has been performed on this pavement section with project number SSR-156N(148)SR.

4.4 Subsections

The planning and research division in ODOT has broken down control sections into smaller and more manageable subsections. Like the control sections, subsections have different lengths. There are various reasons that trigger the creation of subsection in a control section. A list of break reasons followed by ODOT is available in Appendix B.

Table 4.2 shows the subsections of control section 56-03 and the break reason for each subsection. Control section 56-03 is 12.08 miles and consists of 13 subsections with lengths ranging from 0.09 mile to 4.8 miles. As can be seen in this table reasons for breaking a control section into subsections can be as varied as entering new county, entering city limits, leaving city limits, junctions with other highways, and existence of test sites.

These break rules are not consistent with the objective of evaluating the performance of pavement sections. The performance of a pavement section does not change as it enters a new county or a test site. In addition, the rules defined by ODOT do not capture differences in the directions for divided highways. In dividing highways south to north direction and west to east direction are considered as primary directions. Subsections are defined based on the primary directions. Therefore, different variances in directions cannot be accounted for if ODOT rules are used for dividing control sections. Therefore, finding the performance patterns in the sections that have been divided based on the reasons that are not correlated with their performance can result in performance models that are hard to interpret or not meaningful.

Table 4.2 Break Reasons of Control Section 56-03

Control Section	**Subsection Number**	**Beginning Mile**	**Break Reason**	**Ending Mile**
56-03	5603 00000000	0	Begin control section at County or State line	3.02
56-03	5603 00000302	3.02	Enter urban area boundary	3.2
56-03	5603 00000320	3.2	Surface width or type change	3.52
56-03	5603 00000352	3.52	HPMS break	3.93
56-03	5603 00000393	3.93	State highway junction	4.02
56-03	5603 00000402	4.02	Enter municipal limits	4.2
56-03	5603 00000420	4.2	Leave municipal limits	5.65
56-03	5603 00000565	5.65	Enter municipal limits	6.04
56-03	5603 00000604	6.04	State highway junction	6.6
56-03	5603 00000660	6.6	HPMS break	6.75
56-03	5603 00000675	6.75	HPMS break	7.03
56-03	5603 00000703	7.03	Leave urban area boundary	7.28
56-03	5603 00000728	7.28	HPMS break	12.08

4.5 Data Preparation

The data needs to be cleaned and prepared before performing the analysis. The data preparation process can be categorized into five major steps. In the first step the data is transformed from a graphical format into a spreadsheet format. Then the control sections are broken down into subsections with different break rules than what is followed by planning and research division in ODOT. In the next step, the discrepancies are corrected and missing data are pulled from other data bases available in ODOT. Then the scope of treatment activities are replaced with newly defined treatment types. In the final step, data is transformed into a transactional format in order to be ready for the data mining purposes.

4.5.1 Transforming Data Set

According to the pavement management branch of ODOT, the graphical format of the Interstate Highway Structural Pavement History data set is the most updated format. Therefore it is decided to use the data set in the graphical format and convert it into a spread sheet format. This required a significant amount of time to enter the data into a spreadsheet from a hard copy of the data set. Table 4.3 shows a schematic of the spreadsheet created for data transformation.

Table 4.3 Schematic of Spreadsheet Created to Transform Data

Section ID	Pavement Section Information			1st Treatment Project		2nd Treatment Project		3rd Treatment Project	
	Original Construction Project	Location	Structural Layering	Year	Scope	Year	Scope	Year	Scope
1001									
1002									
1003									
1004									
1005									
1006									
1007									

4.5.2 Breaking Control Sections

The control sections are several miles long and usually consist of pavement sections with different structural layering, construction time, and treatment histories. Figure 4.5 shows control section 54-22 on Interstate 40 in Okfuskee County with beginning milepost of 212.80 and ending mile post of 233.39. This control section consists of three different pavement types:

1) asphalt concrete
2) continuous reinforced concrete pavement
3) mesh dowel Portland Cement concrete pavement.

In addition, the pavement section with beginning mile post of 219.71 and ending mile post of 226.56 has undergone three different treatment strategies since its construction in 1965. In order to study the performance of pavement sections, control sections need to be broken down into smaller sections with homogenous structural layering, construction

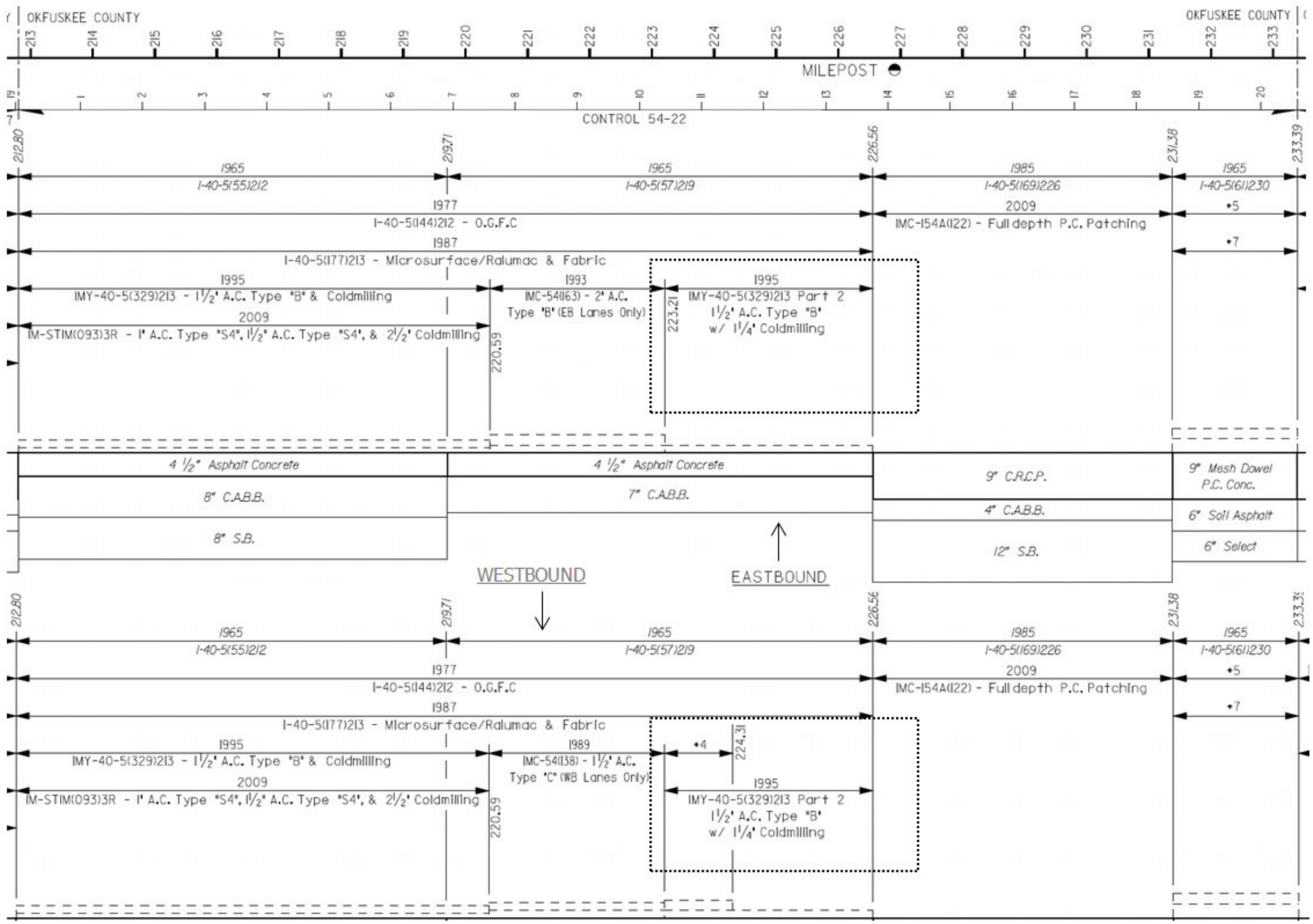


Figure 4.5 Structural Pavement History for Control Section 54-22 (Eastbound and Westbound)

year, and treatment history. As was mentioned earlier, subsections defined by ODOT are not recommended to be used in this study because their break rules are not consistent with the criteria that affect the performance of pavement sections. The difference in treatment history between westbound and eastbound can also be seen in Figure 4.5 from milepost 223.21 to 224.31. Therefore, control section 54-22 is divided into 6 subsections in the eastbound and 7 subsections in the westbound. These subsections are illustrated in Table 4.4. In the restructured data set, each control section is divided into smaller sections based on the following factors: 1) Original pavement type, 2) Original pavement construction year, and 3) Treatment history.

4.5.3 Cleaning Data Set

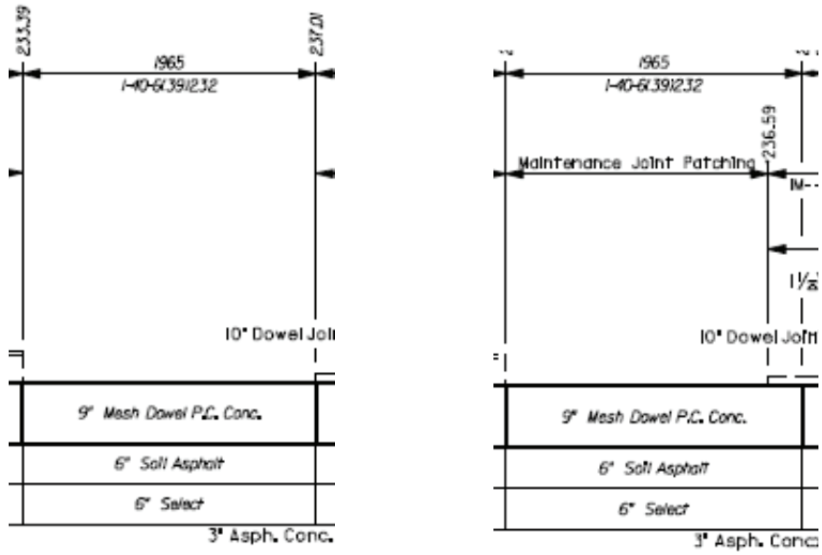
ODOT has started collecting and publishing the Interstate Highway Structural Pavement History data set since 1993. This is despite the fact that the last section of Interstate 40 has been built in 1975. Therefore, the main challenge in developing this data set has been collecting the information of projects that had been constructed years ago. In addition, the amount of data stored in the log cards is so limited and in some cases illegible. The main data cleaning activity was focused on the missing data. Some examples of missing data and the way they have been handled are explained below.

In some cases, the scope of project is not well defined. It required to study the site plan or log card of each project individually to obtain the scope information. For instance, for some projects the thicknesses of overlays are not available in the data set. Or the project scope is not detailed enough to fall under a specific treatment type. For instance, the word resurfacing is not giving enough information regarding the type of material used for treatment, whether or not milling has taken place or the thickness of overlay.

Table 4.4 Subsections of Control Section 54-22 in the Eastbound and Westbound Directions

Subsection	**Direction**	**Beginning Mile Post**	**Ending Mile Post**	**Length (miles)**
1	Eastbound	212.8	219.71	6.91
2	Eastbound	219.71	220.59	0.88
3	Eastbound	220.59	223.21	2.62
4	Eastbound	223.21	226.56	3.35
5	Eastbound	226.56	231.38	4.82
6	Eastbound	231.38	233.39	2.01
1	Westbound	212.8	219.71	6.91
2	Westbound	219.71	220.59	0.88
3	Westbound	220.59	223.21	2.62
4	Westbound	223.21	224.31	1.1
5	Westbound	224.31	226.56	2.25
6	Westbound	226.56	231.38	4.82
7	Westbound	231.38	233.39	2.01

In another case the project number and construction year were missing for a treatment project. In a portion of control section 56-03 in Interstate 40 with the beginning mile post of 233.39 and the ending mile post of 236.59 the construction year and project number are missing for the first treatment that has been applied on the pavement. However, by looking into the data set of previous years it was found out that this treatment activity has been added to the reports since 2003. This helped to estimate the construction year of this treatment activity without having the project number and looking into the project plan. Figure 4.6 shows how a missing construction year has been determined.



2002 Data 2003 Data

Figure 4.6 Strategy to Handle Missing Data

4.5.4 Defining Pavement Treatment Types

The ODOT planning and research division has categorized pavement treatment types based on traffic level, type of material, type of activity, thickness of material, and the existing pavement among others. The data belongs to Interstate 40 and traffic level for all the pavement sections in this highway is considered high traffic level. The pavement treatment types for high traffic level defined by ODOT together with their definitions can be seen in Table 4.5. A brief description of each treatment type is available in Appendix C.

After investigating the data set, it was found out that overlay thicknesses are ranging from 0.75 to 9 inches. Figure 4.7 shows a histogram of AC overlay thicknesses. According to ODOT definitions, thin, medium and thick overlays are called to overlays with thicknesses of 2.25, 3.25 or 7 inches accordingly. After discussing this issue with

ODOT planning and research division, construction division, and roadway design division, it was decided to create intervals to categorize overlays into thin, medium, and thick overlays.

Table 4.5 Treatment Types Defined by ODOT

Name	Treatment Activity
BondedOL_HV	Bonded Overlay on JPCP pavement (include DBR w/o grind) (high volume)
DBR_Grind_HV	Dowel-Bar Retrofit and Grind of JPCP pavement (high volume)
Grind_HV	Grinding of concrete pavement (high volume)
JtRepair_HV	Joint repair project (high volume)
JtSeal_HV	Joint Sealing project (high volume)
MicroSurf_HV	Surface texture of asphalt pavement (high volume)
MillMedOL_HV	Mill & 2" SMA & 1.25" PFC Overlay on AC pavement (high volume)
MillThkOL_HV	Mill & 7" Overlay on AC pavement (high volume)
MillThnOL_HV	Mill & 2.25-inch Overlay (high volume)
ReplaceToAC_HV	Replacing AC pavement with AC (high volume)
ReplaceToCRCP_HV	Replacing existing PC pavement with CRCP (high volume)
ReplaceToDJCP_HV	Replacing any existing pavement with DJCP (high volume)
ReprCRCP	CRCP repair project
SlabRepr_HV	Slab repair project (high volume)
ThnOL_HV	2.25-incb Overlay of asphalt pavement (high volume)
UnBonded_HV	Unbonded overlay
Whitetopping_HV	Whitetopping

All the AC overlays with the thicknesses of less than 3 inches are categorized as thin overlays. Treatment activities with AC overlay thicknesses of 3 inches or more up to 6 inches are considered as medium overlays. All the AC overlays with the thicknesses of 6 inches and more up to 10 inches are categorized as thick overlays. Table 4.6 shows the rules utilized to categorize AC overlays. The frequencies of thin, medium, and thick overlays can be seen after grouping them based on the rules in Figure 4.8.

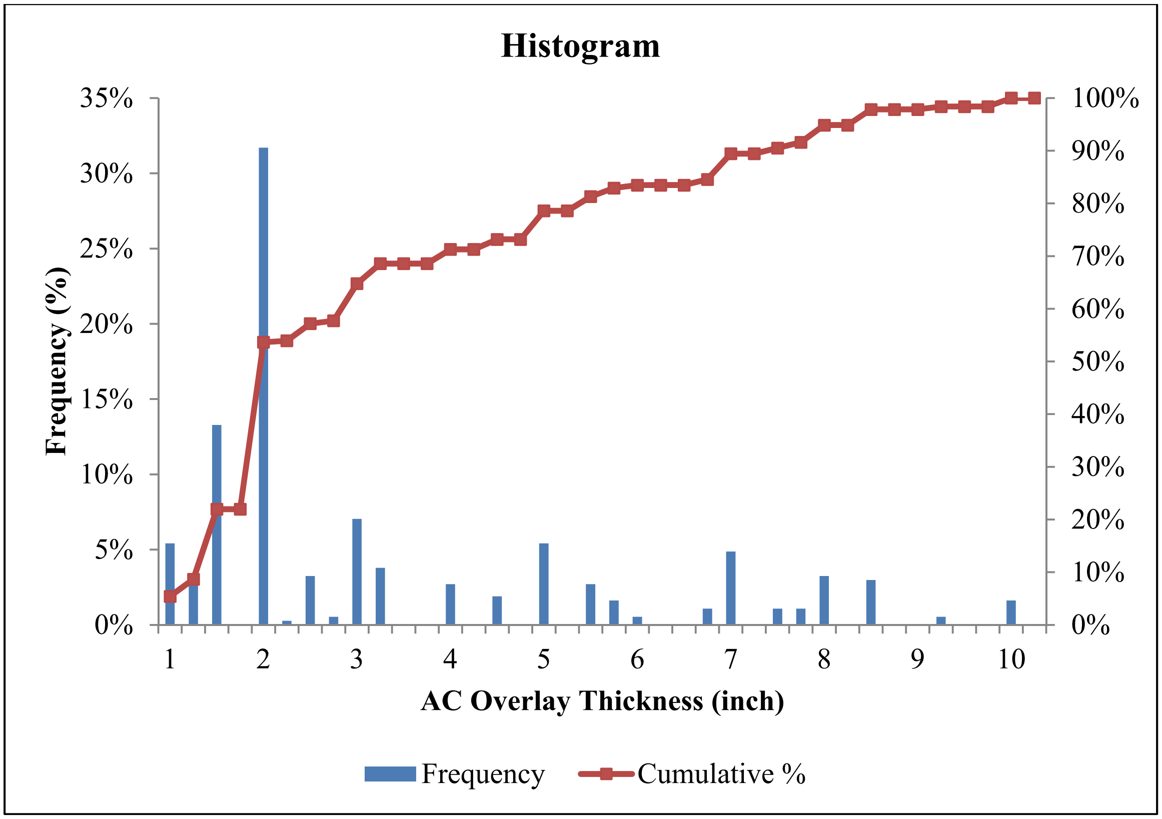


Figure 4.7 Frequency Distribution of AC Overlay Thicknesses

Table 4.6 Rules for Categorizing AC Overlays Based on Thicknesses

AC Overlay Type	Rule
Thin Overlay	Thickness < 3 inches
Medium Overlay	3 inches ≤ Thickness < 6 inches
Thick Overlay	6 inches ≤ Thickness ≤ 10 inches

The treatment activities on Interstate 40 are more diverse than the treatment types defined by ODOT. In many cases, AC overlays are not combined with milling, or they are associated with Fabric, OGFC, both Fabric and OGFC, or Chip Seal. Therefore, more treatment types are defined in order to capture the patterns in treatment activities more accurately. These variances are captured by the following rules:

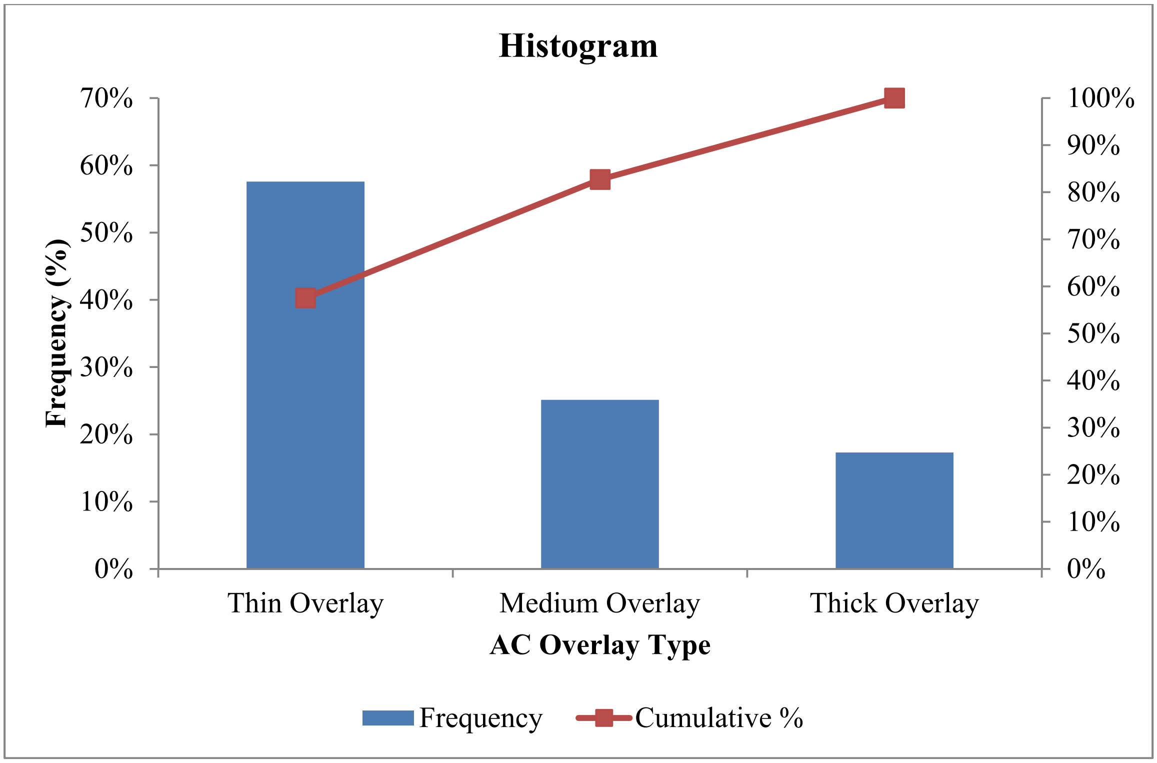


Figure 4.8 Frequency Distribution of AC Overlay Types

a) If an AC overlay is not associated with Fabric, OGFC, or Chip Seal then number 1 is placed on the right hand side of treatment name.
b) If an AC overlay is associated with Fabric, number 2 is placed on the right hand side of treatment name.
c) If an AC overlay is associated with OGFC, number 3 is placed on the right hand side of treatment name.
d) If an AC Overlay is associated with both Fabric and OGFC, number 4 is placed on the right hand side of treatment name.
e) If an AC overlay is associated with Chip Seal, number 5 is placed at the right hand side of treatment name.

The final treatment types defined to categorize treatment activities are illustrated in Table 4.7. The combinations created in AC overlays after considering Fabric, OGFC, and Chip Seal are captured by adding above mentioned numbers to the treatment names.

4.5.5 Restructuring Data Set

This data set should be restructured before the analysis. The appropriate data set structure is available in Table 4.8. In this data set, each row represents a treatment activity on a subsection. A unique ID is allocated to each subsection. The first column shows the ID allocated to each subsection, the second column shows the type of treatment activity, the third column illustrates the sequence, and the fourth column shows the construction year of each treatment activity. The data for Interstate 40 has been collected for both westbound and eastbound directions. For some sections, the treatment activities or pavement structural layering for directions are not identical. Therefore, westbound and eastbound sections have been defined as separate pavement sections in the data set. As mentioned earlier, the control section 54-22 is divided into 13 homogeneous sections in terms of original pavement type, construction year, and treatment history.

The data set is restructured for the entire length of Interstate 40 in Oklahoma. This data set contains 667 rows for a total of 218 subsections where each row represents a treatment activity. As can be seen in Table 4.8, each subsection can have multiple rows in the data set, each row representing one of the treatment activities that has occurred on the section.

Table 4.7 Pavement Treatment Types in Interstate 40

Name	Treatment Activity
OGFC	Open Graded Friction Course
Microsurface	Surface texture of asphalt pavement
Microsurface_Fabric	Surface texture of asphalt pavement with fabric
PC_Patch	Selective PC Patching
Full_PC_Patch	Full depth PC patching
Patch_Level	Patching and type E leveling course
micro_Fabric	Microsurface/Ralumac and Fabric
Level_OGFC	AC leveling course with OGFC
Reconstrct	Reconstruction
BondedOL	Bonded Overlay on JPCP pavement (include DBR w/o grind)
Joint_Rehab	Joint repair project
DBR_Grind	Dowel-Bar Retrofit and Grind of JPCP pavement
Grind	Grinding of concrete pavement
JtSeal	Joint Sealing project
Grind_Seal	Diamond grind and Joint Seal
Chip_Seal	Nova Chip
Grind_Seal_Repair	Diamond grind, joint seal, and slab repair project
Mill_Thin_OL	Mill & AC Overlay of less than 3" on AC pavement
Mill_Med_OL	Mill & AC Overlay of 3" to 6" on AC pavement
Mill_Thick_OL	Mill & AC Overlay of 6" to 10" on AC pavement
Thin_OL	AC Overlay of less than 3" on AC pavement
Med_OL	AC Overlay of 3" to 6" on AC pavement
Thick_OL	AC Overlay of 6" to 10" on AC pavement
HIP_Chip	Hot in place recycling with Nova Chip
ReplaceToAC	Replacing AC pavement with AC
ReplaceToCRCP	Replacing existing PC pavement with CRCP
ReplaceToDJCP	Replacing any existing pavement with DJCP
ReprCRCP	CRCP repair project
SlabRepr	Slab repair project
Unbonded_OL	Unbonded overlay
Whitetopping	Whitetopping

4.6 Summary

In this chapter the five steps of data preparation activities were discussed. The Interstate Highway Structural Pavement History data set is updated for all the interstate highways of Oklahoma by the ODOT planning and research division. The Interstate 40 was selected for this study for three reasons: 1) High percentage of rigid pavement sections compared to other state highways, 2) One of the major interstate highways passing through the whole length of the state of Oklahoma, 3) Divided highway where data is collected for both eastbound and westbound providing more data points for the analysis.

The data preparation approach adopted in this study is unique. The idea behind the data preparation is to divide the pavement sections into homogenous sections where each subsection has the same original construction year, original pavement type and treatment history. This approach minimizes the amount of noise available in the data and provides a base where pavements from the same family can be compared together in terms of their performance and treatment history. The five steps of data preparation can also be followed by other highway agencies to convert their data into a format which is ready to be evaluated for existence of patterns in treatment activities.

Table 4.8 Restructured Data Set for Control Section 54-22

Subsection ID	Pavement Type	Original Construction Year	Treatment Year	Treatment Type	Sequence
1159	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1995	Mill_Thin_OL1	3
	AC	1965	2009	Mill_Thin_OL1	4
1160	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1995	Mill_Thin_OL1	3
	AC	1965	2009	Mill_Thin_OL1	4
1161	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1995	Mill_Thin_OL1	3
	AC	1965	2009	Mill_Thin_OL1	4
1162	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1995	Mill_Thin_OL1	3
	AC	1965	2009	Mill_Thin_OL1	4
1163	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1989	Thin_OL1	3
1164	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1989	Thin_OL1	3
1165	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1993	Thin_OL1	3
	AC	1965	1995	Mill_Thin_OL1	4
1166	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1995	Mill_Thin_OL1	3
1167	AC	1965	1977	OGFC	1
	AC	1965	1987	Microsurface_Fabric	2
	AC	1965	1995	Mill_Thin_OL1	3
1168	CRCP	1985	2009	Full_PC_Patch	1
1169	CRCP	1985	2009	Full_PC_Patch	1
1170	DJCP	1965	1991	Med_OL3	1
	DJCP	1965	2005	Mill_Thin_OL1	2
1171	DJCP	1965	1991	Med_OL3	1
	DJCP	1965	2005	Mill_Thin_OL1	2

CHAPTER 5

DETERMINISTIC LIFE-CYCLE COST ANALYSIS

This chapter discusses the development of deterministic life-cycle cost analysis models for asphalt and concrete pavements. The data collected and prepared in previous chapter is utilized to determine the most likely future maintenance and rehabilitation sequence and timing.

5.1 Introduction

One of the parameters that need to be determined before A+B+L bidding is life-cycle cost of each pavement design. Although the principals of LCCA are fairly uniform, the application of LCCA in design varies considerably among highway agencies. Different policies and priorities in different highway agencies have resulted in including different cost components in performing LCCA. In September 1998, the FHWA published an Interim Technical Bulletin in life-cycle cost analysis in pavement design. This technical bulletin presents technical guidance and recommendations on good/best practices in conducting LCCA in pavement design. It starts with discussions regarding the principals of LCCA and input parameters. It also discusses the variability and uncertainties inherent with input parameters and suggests sensitivity analysis and Monte Carlo simulation analysis. There are two approaches in performing LCCA: 1) Deterministic Approach and 2) Risk Analysis Approach.

A deterministic Approach to LCCA does not consider variability associated with the input parameters which is the main disadvantage of this approach. However, the deterministic approach is straightforward and requires a smaller amount of input parameters, which makes it more practical and easy to adopt. In the risk analysis approach, the input parameters are a range of values with different probabilities of occurrence. Therefore, unlike the deterministic approach the LCCA result is a range of outcomes as well as the likelihood of occurrence. The main disadvantage of this approach is that the true frequency distribution of input parameters is unknown in most highway agencies. This adds to the complexities of the risk analysis approach making it less popular among state highway agencies.

In the deterministic LCCA, all the input variables in the analysis are assigned fixed, discrete value. Based on the historical evidence or professional judgment, a value is determined as most likely and used in the deterministic LCCA. The input values are used to compute a single life-cycle cost estimate for each alternative. This approach is straightforward and is traditionally used in many SHAs. A sensitivity analysis can be done to test input assumptions by varying one input, holding other inputs constant. When enough data is not available to capture the uncertainties in the input variables, the deterministic LCCA combined with sensitivity analysis provides SHAs with a reasonable approach to compare alternative designs. In order to determine input assumptions in the deterministic LCCA, a combination of historical treatment data and professional judgment is utilized.

5.2 Equivalent Pavement Designs

For a project that both asphalt and concrete pavements are feasible, there are two alternatives that need to be compared by LCCA. Therefore the two alternative pavement design strategies would be equivalent asphalt and concrete pavement designs where there is not any technical advantage in using one design over the other design. In the technical advisory issued by FHWA in December 2012 regarding "Use of Alternate Bidding for Pavement Type Selection," the equivalent pavement designs are defined as below (FHWA 2012):

> "Alternate pavements designs should be equivalent to the maximum extent possible. Equivalent designs provide similar level of service over the same performance period, and have similar life-cycle costs. Traditionally it has been difficult for two pavement structures utilizing different materials to be truly equivalent so engineering judgment was needed when determining what is and what is not an equivalent design. However, with the release of AASHTOWare® DARWin-ME™ mechanistic-empirical pavement design guide the process for developing equivalent designs is more rational and mechanistic in its approach. An indicator of similar level of service would be alternates that remain in good condition (<95 inches/mile IRI) and fair condition (<170 inches/mile IRI), based upon historically calibrated models over the performance period. The performance period (analysis period) should be long enough to cover at least one major rehabilitation cycle. Life-cycle costs would be considered similar if the Net Present Value (NPV) for the higher cost alternative is less than 10% higher than the lower cost alternative. This difference is appropriate due to the uncertainty associated with estimating future costs and timing of maintenance and rehabilitation."

5.3 Analysis Period

Analysis period is the time horizon over which future costs are evaluated. It should be sufficiently long to reflect long-term cost differences associated with reasonable design strategies. The FHWA recommends that the analysis period should be long enough to incorporate at least one rehabilitation activity and it should generally always be longer than the pavement design period. According to the FHWA's Final LCCA Policy statement in September 1996, an analysis period of at least 35 years should be considered for all pavement projects, including new or total reconstruction, restoration, and resurfacing projects (GPO 1996) . Slightly shorter periods are also appropriate if it could simplify salvage value computations. For example, if all the alternative strategies would reach terminal serviceability at year 32, then a 32-year analysis would be quite appropriate.

On the other hand, the analysis of historical pavement treatment data set reveals that asphalt pavement sections are treated with cold milling and medium overlays at year 33 and PCC pavement sections are typically treated with unbonded overlay at year 34. This indicates that asphalt and concrete pavements reach to their final serviceability at year 33 and 34 respectively. Therefore, an analysis period of 33 years can simplify salvage value computations and thus can be selected as the analysis period for LCC comparison of asphalt and concrete pavements A+B+L bidding process. By this assumption, the PCC pavement sections have one year serviceability left at the end of year 33 which needs to be incorporated in the LCCA.

5.4 Performance Periods and Activity Timing

Typically, each design alternative will have an expected periodic maintenance treatments and rehabilitation activities. According to FHWA Interim Technical Bulletin regarding LCCA in Pavement Designs (FHWA 1998), depending on the initial pavement design, a variety of rehabilitation strategies need to be employed to keep the highway facilities in functional condition.

The historical pavement treatment information for Interstate 40 is used to determine these rehabilitation strategies. The activity timings are determined by taking the average number of years from the original pavement construction to the time that the treatment is applied. These values are calculated and shown in Table 5.1. The activity timings are calculated separately for asphalt and concrete pavements. Asphalt pavement sections are reconstructed at year 33 and concrete pavement sections are reconstructed at year 34. Thus, asphalt pavement sections are treated two times at years 12 and 28 and concrete pavements are treated once at year 28 before they reach the end of their serviceability lives.

Table 5.1 Deterministic Timing of AC and PCC Pavement Sections

Pavement Type	Time (Years) after Original Construction		
	1st Treatment	2nd Treatment	3rd Treatment
AC	12	28	33
PCC	28	34	

5.5 Rehabilitation Activities

The historical treatment activities applied on asphalt and concrete pavements in Interstate 40 were used to determine the type of rehabilitation activities. The frequency of treatment activities applied on asphalt pavements as the first and the second treatment can be seen in Figure 5.1 and Figure 5.2. As can be seen in Figure 5.1, thin asphalt overlay and OGFC are the most likely treatment types that might occur as the first treatment.

Figure 5.2 reveals that thin asphalt overlay, cold milling and medium asphalt overlay with OGFC and Fabric, or asphalt leveling course with OGFC are treatment activities that are most likely to occur as the second treatment. The frequency distribution of concrete pavements is shown in Figure 5.3. As can be seen in this figure, CPR is the most likely treatment strategy as the first treatment in concrete pavements. This treatment activity consists of partial slab replacement, joint rehabilitation, full-depth patching, sawing, and diamond grinding.

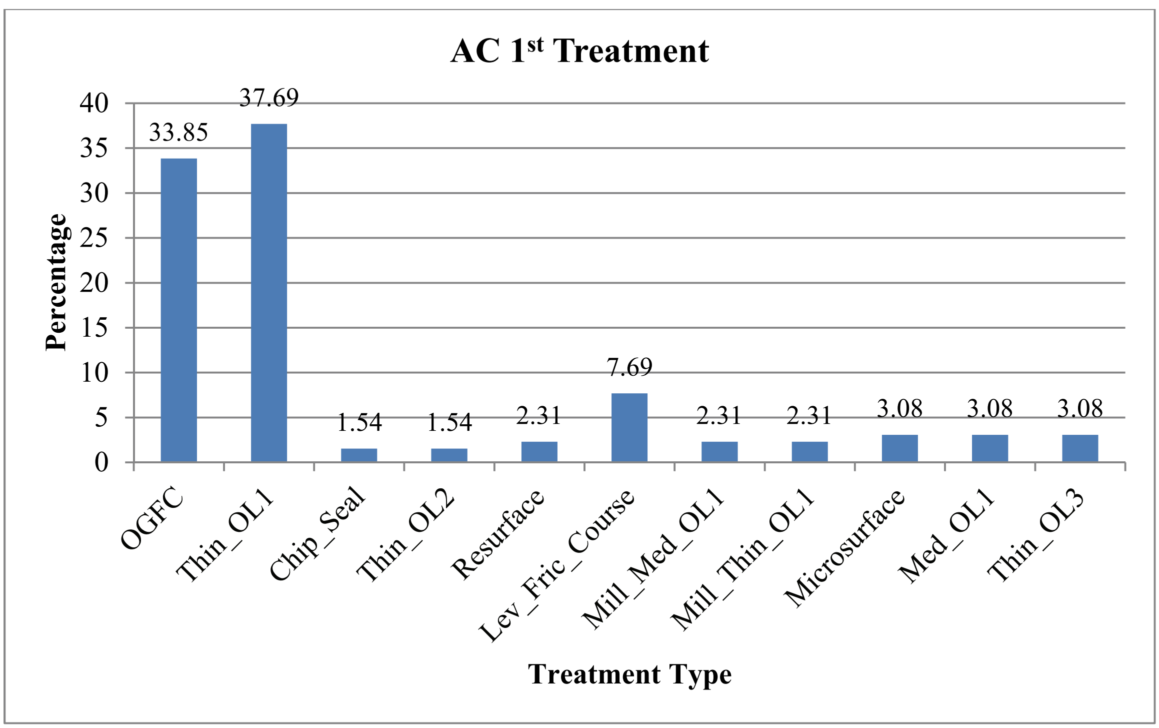


Figure 5.1 Frequency of 1st Treatment Activities on Asphalt Pavements

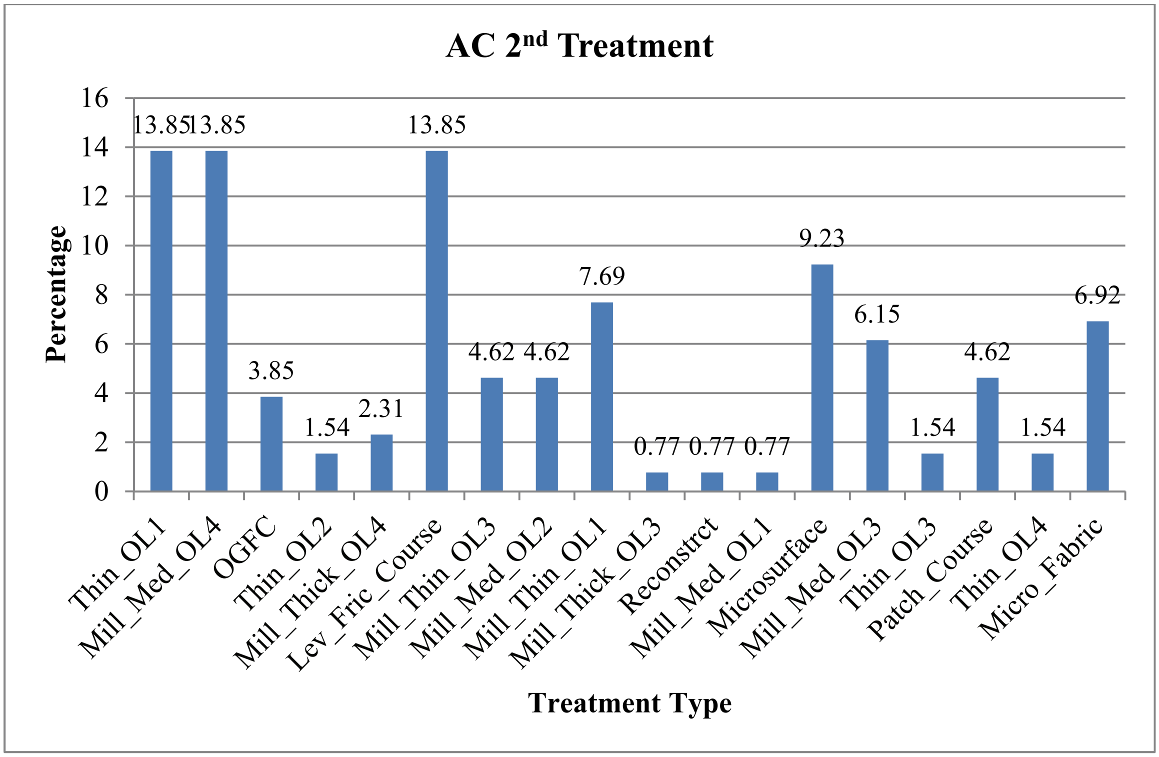


Figure 5.2 Frequency of 2nd Treatment Activities on Asphalt Pavements

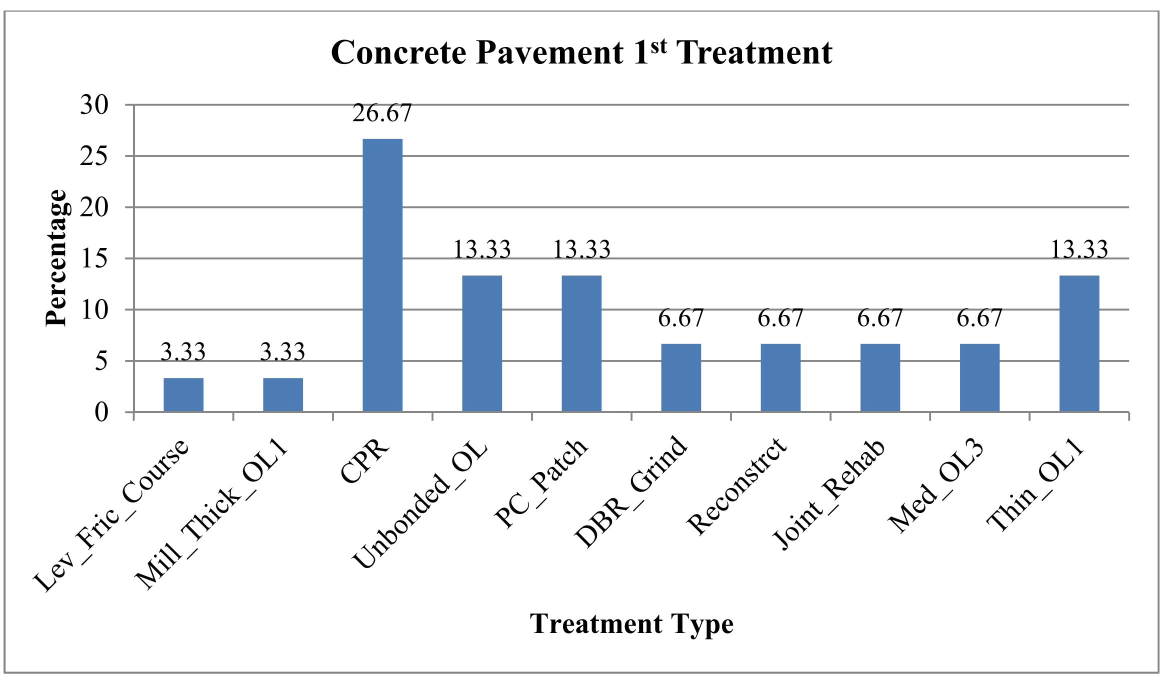


Figure 5.3 Frequency of 1st Treatment Activities on Concrete Pavements

The final deterministic LCC model is shown in Table 5.2. The thicknesses of coldmilling and AC overlays in this table are the averages of those values in the historical data set.

Table 5.2 Deterministic LCCA Model for Asphalt and Concrete Pavements

	Years from pavement original construction				
Pavement Type	**12**	**23**	**28**	**33**	**34**
Asphalt	1.85" AC Overlay (50%) or OGFC (50%)	2.58" Coldmilling + 4.16" AC Overlay + OGFC + Fabric		End of asphalt pavement serviceability	-
PCC	-	-	CPR	-	End of concrete pavement serviceability

5.6 Rehabilitation Costs

Rehabilitation costs can be estimated by determining construction quantities and unit prices. Construction quantities are directly related to the initial design and subsequent rehabilitation strategies as shown in Table 5.2. Unit prices can be determined from ODOT historical data on previously bid jobs of comparable scale. Based on FHWA recommendations, LCCA need only consider differential cots between alternatives. Costs common to all alternatives will not change the outcome of LCCA and cancel out. However, the associated administrative, mobilization, and construction service costs are included in the LCCA. To estimate the rehabilitation costs, the following sources in ODOT are used:

- Cost estimations per square yard for different treatments, developed by Planning & Research Division. The Pavement Management Branch in Planning & Research

Division utilizes these estimates to determine the funding levels needed to preserve or improve the condition of the state's highway routes.

- Weighted average item price report by item, region, and quarter which include a price history for selected items. The Construction Division utilizes this unit price history to estimate the costs of projects before letting process.

The Pavement Management Branch has estimated the treatment costs for low volume (less than 2,000 average annual daily traffic), moderate volume (2,000-10,000 average annual daily traffic) and high volume (over 10,000 average annual daily traffic). The traffic in interstate 40 is more than 10,000 average annual daily traffic and thus can be categorized as high volume. The estimated unit prices for high volume traffic can be seen in Table 5.3.

5.7 Discount Rate

The LCCA can be performed using either real or nominal discount rates. Real discount rate reflects the true time value of money with no inflation premium and should be used with non-inflated dollar cost estimates of future investments. Nominal discount rates include an inflation component and should only be used in conjunction with inflated future dollar cost estimates of future investments. The result of LCCA can significantly be influenced by discount rates. Therefore, selecting a reasonable discount rate utilizing historical trends is critical in the success of LCCA.

Table 5.3 Pavement Treatment Price Estimations for High Traffic

Treatment Activity	Price ($/SY)
Calculate Cost for Bonded Overlay on JPCP pavement (include DBR w/o grind)	50.00
Cost for Dowel-Bar Retrofit and Grind of JPCP pavement	14.20
Calculate Cost for grinding of concrete pavement	7.10
Cost for a joint repair project	7.10
Cost for Joint Sealing project	2.41
Cost for surface tx of asphalt pavement	8.52
Cost for a Mill & 2" SMA & 1.25" PFC Overlay on AC pavement	21.31
Cost for Mill & 7" Overlay on AC pavement	56.82
Cost for Mill & 5" Overlay on AC pavement	24.86
Cost for Mill & 2.25-inch Overlay	13.66
Cost for PFC on asphalt pavement	6.39
Cost for replacing AC pavement with AC	142.05
Cost for replacing existing PC pavement with CRCP	198.86
Cost for replacing any existing pavement with DJCP	170.45
Cost for a CRCP repair project	9.23
Cost for a slab repair project	9.23
Cost for 2.25-incb Overlay of asphalt pavement	18.47
Cost for Unbonded overlay	142.05
Cost for Whitetopping	113.64

Table 5.4 shows recent trends in real discount rates for various analysis periods published over the last several years in annual updates to Office of Management and Budget (OMB) Cricular A-94 (OMB 2011). Table 5.5 shows trends in nominal discount rates from the same source as mentioned for Table 5.4. Figure 5.4 reflects the historical trend of 10-year interest rates on treasury notes and bonds. The upper curve reflects the nominal rate of return while the lower curve represents the inflation adjusted real rate of return. For the last 10 years (since year 2003), the real rate of return ranges somewhere between 1- to 3-percent and the average close to 2.3 percent.

Table 5.4 Recent Trends in OMB Real Discount Rates

Year	Analysis Period					
	3	**5**	**7**	**10**	**20**	**30**
2003	1.6	1.9	2.2	2.5	-	3.2
2004	1.6	2.1	2.4	2.8	3.4	3.5
2005	1.7	2	2.3	2.5	3.0	3.1
2006	2.5	2.6	2.7	2.8	3.0	3.0
2007	2.5	2.6	2.7	2.8	3.0	3.0
2008	2.1	2.3	2.4	2.6	2.8	2.8
2009	0.9	1.6	1.9	2.4	2.9	2.7
2010	0.9	1.6	1.9	2.2	2.7	2.7
2011	0.0	0.4	0.8	1.3	2.1	2.3
2012	0.0	0.4	0.7	1.1	1.7	2.0
Average	**1.38**	**1.75**	**2.00**	**2.30**	**2.73**	**2.83**
Standard Deviation	0.91	0.79	0.71	0.61	0.52	0.44

Table 5.5 Recent Trends in OMB Nominal Discount Rates

Year	Analysis Period					
	3	**5**	**7**	**10**	**20**	**30**
2003	3.1	3.6	3.9	4.2	-	5.1
2004	3.0	3.7	4.2	4.6	5.4	5.5
2005	3.7	4.1	4.4	4.6	5.2	5.2
2006	4.7	4.8	4.9	5.0	5.3	5.2
2007	4.9	4.9	4.9	5.0	5.1	5.1
2008	4.1	4.3	4.4	4.6	4.9	4.9
2009	2.7	3.3	3.7	4.2	4.7	4.5
2010	2.3	3.1	3.5	3.9	4.4	4.5
2011	1.4	1.9	2.4	3.0	3.9	4.2
2012	1.6	2.1	2.5	2.8	3.5	3.8
Average	3.15	3.58	3.88	4.19	4.71	4.80
Standard Deviation	1.21	1.02	0.88	0.76	0.66	0.53

In the report published in 1998, the FHWA has suggested using a real discount rate, one that does not reflect an inflation premium, of 3 to 5 percent in conjunction with real/constant dollar cost estimates. By following the same procedure, real discount rate of

1 to 3 percent in conjunction with real/constant dollar cost estimates is utilized for LCCA.

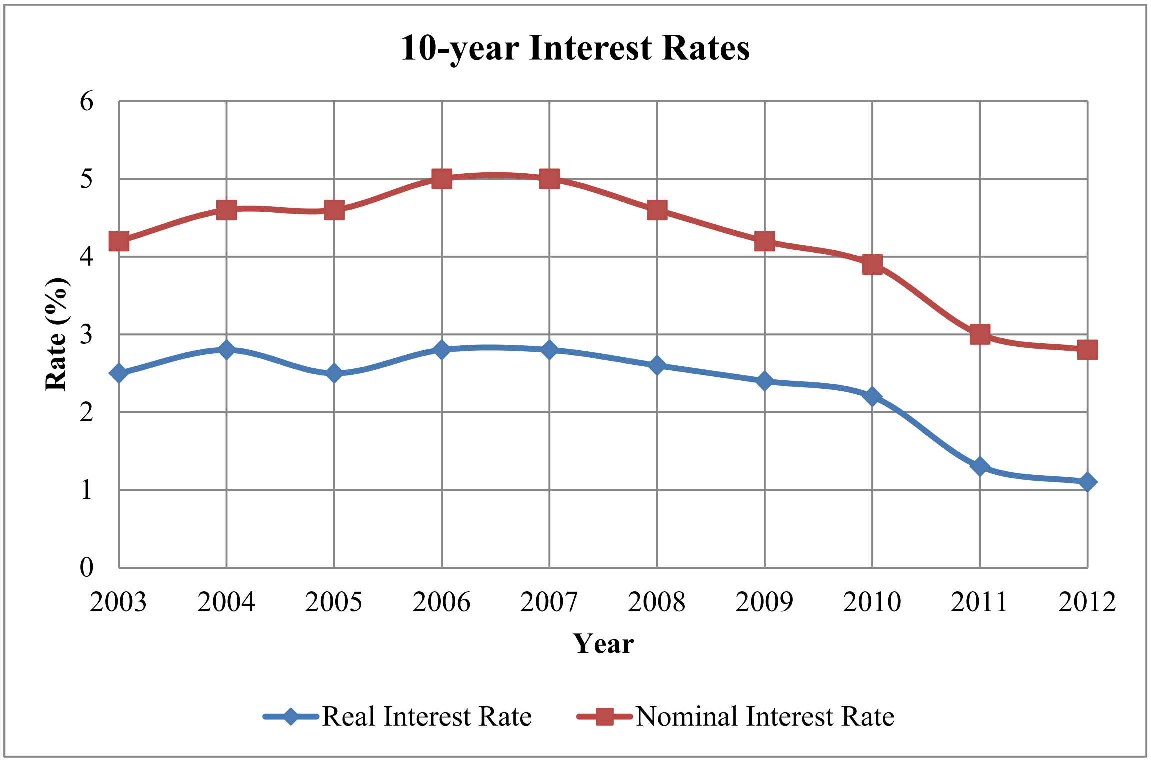


Figure 5.4 Historical Trends on 10-Year Interest Rates on Treasury Notes and Bonds

5.8 Deterministic LCCA

Future costs are discounted to the base year and added to the initial cost to determine the Net Present Value (NPV) for the LCCA alternative. The NPV is the economic indicator and the basic NPV formula for discounting discrete future amounts at various points in time back to same base year is:

$$NPV = Initial\ Cost + \sum_{k=1}^{N} Rehab\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] \quad (5.1)$$

where i = discount rate

n = year of expenditure

5.9 Summary

The deterministic life-cycle cost models were developed for asphalt and concrete pavements of Interstate 40 in Oklahoma (see Table 5.2). The details of Net Present Value calculations are available in section 8.2.2. The Interstate Highway Structural Pavement History was used to estimate the analysis period, treatment activity timing, and type of rehabilitation activities.

Two deterministic LCCA models were developed for asphalt and concrete pavements. The treatment types in the models are the rehabilitation activities that have repeated the most in the data set. The timing of treatment activities are determined based on the average time to the first and the second rehabilitation activities in the historical data set. Rehabilitation costs were determined utilizing historical data of pavement management branch and construction division of ODOT. Also, the historical trend of 10-years interest rates on treasury notes and bonds were used to determine a realistic interest rate for LCCA.

CHAPTER 6

REALISTIC LIFE-CYCLE COST ANALYSIS

In this chapter, a data mining technique is applied to the historical pavement treatment dataset of Oklahoma Department of Transportation (ODOT) to determine the typical sequential patterns in treatment activities.

6.1 Introduction

The review of literature indicated that there is no consensus between industries on the life-cycle cost analysis models of different pavement families. It was also indicated in previous chapter that pavement sections have been treated differently during their lifecycle. Association analysis technique has extensively been used in the marketing area in order to identify the purchasing behavior of customers by determining the products that are purchased together as well as the sequence of purchases. This chapter illustrates how this popular technique in the marketing area can be applied to the pavement management databases in order to determine realistic LCCA models for asphalt and concrete pavements.

6.2 Assumption

It has been assumed that the future performance of different pavement families can be predicted by analyzing their past behavior. In other words, the past performance of pavements would be a valid indicator of their future performance.

6.3 Data Mining

Data mining can be defined as a non-trivial extraction of implicit, previously unknown, interesting, and potentially useful information from data (Chen 2001). Fayyad et al (Fayyad et al. 1996) distinguishes between data mining and KDD by mentioning that the KDD process is the process of using data mining methods (algorithms) to extract (identify) what is deemed knowledge according to the specifications of measures and thresholds. In other words, data mining is mainly concerned with means by which patterns are extracted from data while KDD involves the evaluation and possible interpretation of the patterns to make the decision of what constitutes knowledge and what does not (Fayyad et al. 1996). On the other hand, some research has used data mining and KDD interchangeably because both concentrate on harvesting information from data (Kennedy et al. 1997, Zhou et al. 2010).

Data mining consists of four major techniques utilized depending on the objectives: (a) classification; (b) clustering; (c) numeric prediction; and (d) association. Classification is learning a function that maps a data item into one of several predefined classes.

Classification methods have been applied to pavement condition assessment databases in order to classify deteriorations (Hand 1981, Weiss and Kulikowski 1990). Numeric prediction is referred to as a combination of techniques such as decision tree, neural network, regression, and ensemble prediction among others. Clustering is a common descriptive task where one seeks to identify a finite set of categories or clusters to describe the data (Jain and Dubes 1988). This technique has been applied to pavement management data sets to identify patterns in deterioration of different types of pavement (Amado and Bernhardt 2002).

Predictive modeling techniques have been utilized extensively in developing pavement deterioration models and treatment type prediction (Amado and Bernhardt 2002, Kaur and Pulugurta 2008, Zhou et al. 2010). The purpose of association analysis is to find useful associations and/or correlation relationships among large sets of data items. Association rules, expressed by "if-then" statements, show the attributed value conditions that occur frequently together in a given data set (Amado and Bernhardt 2002, Zhou et al. 2010). Although this technique has been applied on pavement condition databases (Hunter 2003, Zhang et al. 2008), its application on the pavement treatment data set has not been reported.

Data mining has mostly been used by statisticians, data analysts, and the management information system (MIS) communities. Even though this new data analysis process has not been actively employed in the engineering disciplines, the concept of finding hidden patterns from data is not new because many statistical analysis tools have been actively used to solve problems in the engineering domain.

Statistical analysis starts with an establishment of a hypothesis, then collects and analyzes data to accept or annul the hypothesis. However, the data mining starts with available data first and then uses the data to solve a problem by selecting and using the most appropriate statistical or artificial intelligence-based prediction models. Data mining is not a simple modeling and prediction process but is a framework for the whole problem solving cycle or process. It is a combination of many algorithms that is chosen based on available data and the problem.

A typical data mining process involves six distinct states as shown in Figure 6.1. These six phases are integrated with each other to make a cycle of the data mining process and the arrows indicate the frequent dependencies between phases.

In the problem understanding and data understanding stages, a clear and specific problem is defined. The required and available dataset are identified. The data preparation phase covers all activities to construct the final dataset, which is then fed into the modeling tools from the initial raw data. This phase is a critical stage because the performance of the developed models is highly dependent upon the quality of input data. In this stage, the collected data goes through a data cleaning process to identify any possible mistakes or irregularity in the data and eliminate any outliers.

Then, the cleaned dataset goes through the data construction stage in which the dataset is clustered through some techniques such as K-means clustering with principal component analysis (PCA). The key issue in the data construction stage is to discover the true dimensionality of the data. Not all variables are critical and some variables may be highly correlated with each other. The data construction technique will determine the possible number of uncorrelated clusters in the dataset, which can explain most of the variability of the data.

In the modeling phase, the actual search for knowledge in the data is performed. In the evaluation phase, the most appropriate model for each cluster can be selected through testing and evaluating all competing models. In the deployment phase, the developed models are actually used for problem solving.

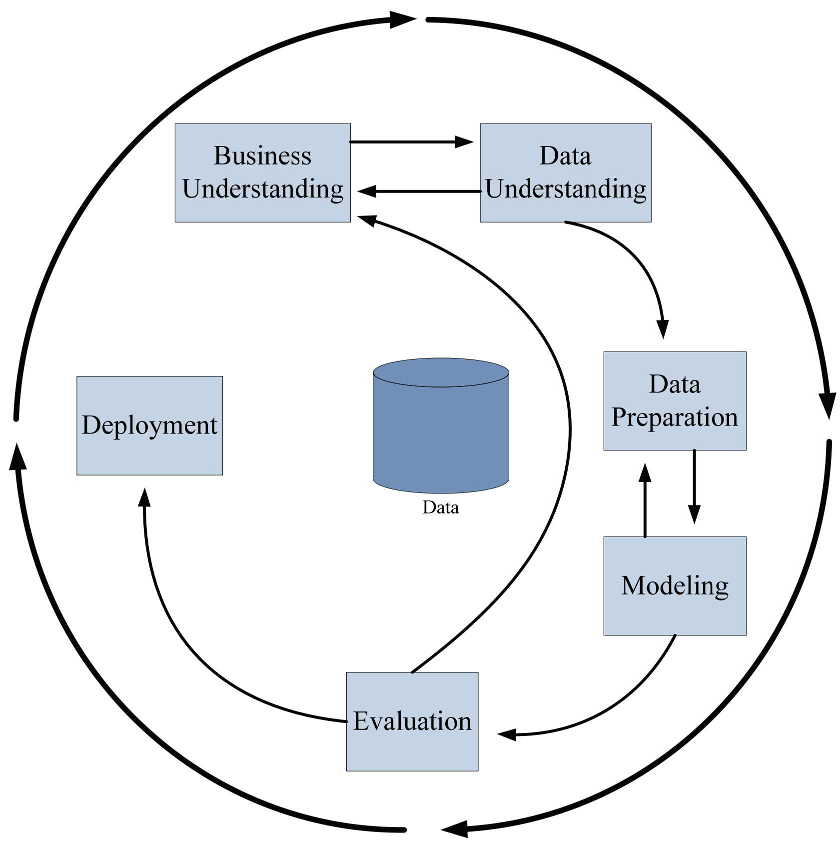


Figure 6.1 Data Mining Process (SAS 1999)

6.3.1 Frequent Pattern Mining

Frequent patterns are patterns that appear frequently in a data set. This technique searches for recurring relationships in a given data set. As illustrated in Figure 6.2, this technique can be categorized into association rule mining, sequential pattern mining, and market basket analysis. This section introduces the basic concepts of frequent pattern mining for the discovery of interesting associations and correlations between item sets.

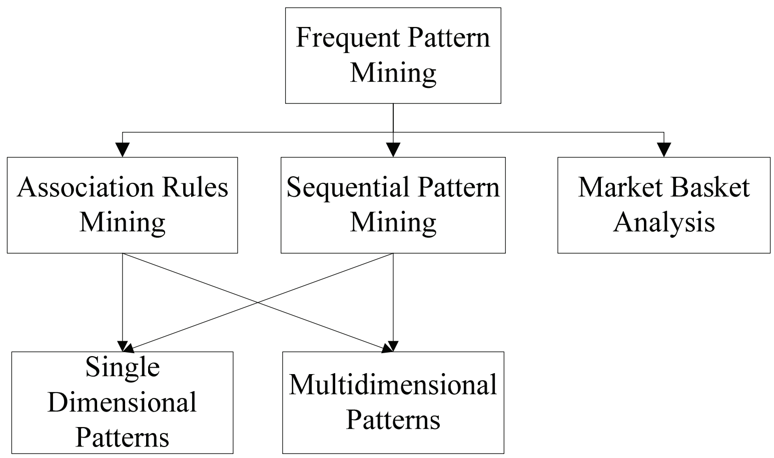


Figure 6.2 Frequent Pattern Mining Techniques

6.3.2 Market Basket Analysis

Progress in bar code technology has not only helped businesses to handle their products more efficiently, but also enabled agencies to store data that do not necessarily consist of items bought together at the same point of time but it may consist of items bought by a customer over a period of time. This type of data is called basket data.

Market basket analysis is a more general term for retail analysis. Consider a supermarket with a large collection of items. Typical business decisions that the manager of the supermarket has to make include what to put on sale, how to design coupons, how to place merchandise on shelves, and which products to bundle in order to maximize the profit. Market basket analysis analyzes customer habits by finding associations between different items that customers place on their shopping basket. This analysis provides the decision makers with the insight that what items are purchased together by customers.

For instance, if customers are buying chips, how likely are they to also buy salsa on the same trip to the supermarket? This information can lead to increased sales by helping retailers design marketing strategies and plan their shelf space accordingly. Items that are frequently purchased together can be placed in proximity to further encourage the combined sale of such items. In an alternative strategy, the associated items can be placed at opposite ends of store in order to expose customers who purchase such items to other items along the way. These two items can also be purchased as a package of chips with salsa or they can be packaged together with poorly selling items in order to increase the sale. As another strategy, price on one can be raised and on the other one can be lowered. This association rule will also necessitate that the manager should not to advertise these products together.

Table 6.1 shows a small transaction data where customers with their purchased products are shown. Item A has been purchased four times, Item B has been purchased three times, item C has been purchased one time, item D has been purchased two times, and item E has been purchased two times. Visual inspection of the example data might reveal the regularity that all four transactions involving item E also involved item A and the two of the four transactions that involved item A also involved item B.

Table 6.1 Hypothetical Market Basket Data

Customer	Purchased Items
1	A,B
2	C, A, D
3	A, E
4	A, E, B
5	D,B

6.3.3 Association Rule Mining

Agrawal et al. (1993) developed the earliest form of the association rules mining in order to perform market basket analysis. They introduced a methodology for mining a large collection of basket data type transactions for association rules. The association rules are expressed by "if-then" statements, show attributed value conditions that occur frequently together in a given data set. If the number of possible patterns is small, the set of all possible patterns can be tried in turn and see whether it occurs in data and/or whether it is significant in some sense. But typically it is completely infeasible since for 1,000 items in the data set there are at least 2^{1000} patterns/rules in the data set.

Association rule mining finds relationship between item sets. An item set is a set of items. Each transaction is an item set. For example, in the hypothetical basket data shown in Table 6.1, [A, B], [C, A, D] or even combinations that do not occur in the data, such as [B, E] are item sets. Association rule is composed of two item sets called an antecedent and consequent. In the statement that 67% of transactions that purchase B also purchase A, the antecedent item set is [B], and the consequent item set is [A]. The rules are typically displayed with an arrow leading from the antecedent to the consequent: [B] => [A].

Association rules mining start with developing a co-occurrence matrix for pairs of products as shown in Table 6.2. The numbers placed on the diagonal are the number of times a particular item is purchased. As expected, this matrix is symmetric because the number of times that for example item A is purchased together with item B is equal to the number of times that item B is purchased together with Item A. The following simple rules can be generated from this co-occurrence matrix:

- Item A, B and A, E are more likely to be purchased together than any other pair.
- Item C is never purchased with Item B.
- Item E is never purchased with item C or D.

Table 6.2 Co-occurrence Matrix for Pairs of Products

	A	**B**	**C**	**D**	**E**
A	4	2	1	1	2
B	2	3	0	1	1
C	1	0	1	1	0
D	1	1	1	2	0
E	2	1	0	0	2

6.3.4 Sequential Pattern Mining

The frequent pattern mining that takes the order of events into consideration is called sequential pattern mining. Sequential patterns are frequent subsequences in a sequence of ordered events. It reveals the sequence and structure in the patterns. For example, by studying the order in which items are frequently purchased, we may find that customers tend to first buy a Laptop, followed by a webcam, and then a memory card.

6.4 Applications of Data Mining on Pavement Management Data

Association analysis is the identification of items that occur together in a given event or record. This technique is also known as market basket analysis. Association rules are based on the number of times items occur alone and in combination in the transaction records. An association rule can be expressed as “if item A is part of an event, then item B is also part of the event” with a probability value.

In the marketing area, association analysis is utilized extensively to determine which products are being purchased together by the customers. Major grocery stores utilize the association rules in transaction data sets in order to present items in store displays more efficiently. An example of an association rule might be, “if shoppers buy a jar of salsa, then they buy a bag of tortilla chips.” In this example, the antecedent is, “buy a jar of salsa,” and the consequent is, “buy a bag of tortilla chips.” By substituting pavement sections with customers and treatment types with purchased products, the concept of association can be applied to the historical pavement treatment data set. The goal of this analysis is to identify the treatment types that are associated together and the sequence of their occurrence. This analysis can assist in discovering rehabilitation strategies embedded in historical pavement treatment data sets.

6.4.1 Data Preparation

The interstate structural history data set for Interstate 40 (in Oklahoma) was utilized for the purpose of association analysis. This data set is a record of the construction and major treatment projects on the Interstate 40 in Oklahoma.

All the real-world databases are highly susceptible to noisy, missing, and inconsistent data due to errors in collecting and storing a huge amount of data that needs to be collected in a daily basis. Since low quality data leads to low quality mining, the quality of data is critically important in a data mining process. Therefore, the datasets used for the data mining are preprocessed in order to improve the efficiency and ease of mining process. As indicated in Figure 6.3, the data preprocessing can be categorized into four techniques:

a) Data cleaning (data cleansing)
b) Data integration
c) Data reduction
d) Data transformation

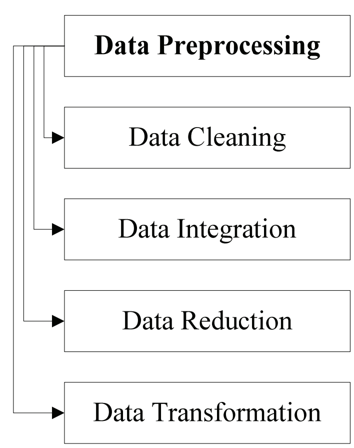


Figure 6.3 Data Preprocessing

The application details of data preparation steps have been discussed in Chapter 4 of this dissertation.

6.4.2 Performance Measures

The statistical significance of association rules is measured by certain performance measures. An association rule is accompanied by frequency-based statistics that describe that relationship. The two statistics that are used initially to describe these relationships are support and confidence (Agrawal et al. 1993).

Support

Let D be the database of transactions and N be the number of transactions in D. Each transaction D_i is an item set. Support(A=> B) is the proportion of transactions that contain both item sets A and B. In other words, the support of an association rule is the proportion of transactions that contain both the antecedent and the consequent. This performance measure indicates how often the association occurs within the treatment data set. Support is symmetric, meaning that the support of the rule A => B is the same as the support of B => A.

$$Support\ (A => B) = \frac{Support\ (A \cup B)}{All\ Transactions} = P(A \cup B) \qquad (6.1)$$

where; *Support* ($A \cup B$): Transactions that contain both items *A* and *B*

Confidence

The confidence of an association rule is the proportion of transactions containing the antecedent that also contains the consequent. This performance measure indicates the strength of an association. Confidence(A=> B) is the conditional probability that a transaction contains item B, given that it already contains treatment type A. Confidence is not symmetric.

$$Confidence(A => B) = \frac{Support\ (A \cup B)}{Support\ (A)} = P(B|A) \qquad (6.2)$$

Where; *Support* ($A \cup B$): Transactions that contain both items *A* and *B*

Support (A): Transactions that contain item *A*

The association rules mining starts with finding all frequent item sets in the data. Each of these item sets will occur at least as frequently as a predetermined minimum support count. Then strong association rules are generated from the frequent item sets. Therefore, these rules satisfy minimum support and minimum confidence. There are also additional significance measures that can be applied for the discovery of correlation relationships between associated items.

A correlation rules is measured not only by its support and confidence but also by the correlation between item sets A and B. There are many different correlation measures from which to choose that are discussed here.

Lift

This performance measure is defined as the ratio of the rule's confidence to the rule's expected confidence. Larger lift ratios tend to indicate more interesting association rules. The occurrence of item set A is independent of the occurrence of item set B if $P(A \cup B) = P(A)P(B)$; otherwise, item sets A and B are dependent and correlated as events. This definition can also be extended to more than two item sets. The lift between the occurrence of A and B can be measured by computing

$$Lift(A => B) = \frac{P(A \cup B)}{P(A)P(B)} = \frac{Confidence(A => B)}{Support(B)} \quad (6.3)$$

where; *Support* (B): Transactions that contain item B

Lift is symmetric, meaning that the lift of the rule A => B is the same as the lift of B => A. If the value of lift is less than 1, then the occurrence of A is negatively correlated with the occurrence of B, meaning that the occurrence of one likely leads to the absence of the other one. If the resulting value is greater than 1, then A and B are positively correlated, meaning that the occurrence of one infers the occurrence of the other. If the resulting value is equal to 1, then A and B are independent and there is no correlation between the events. Lift measures the degree that the occurrence of an event lifts the occurrence of the other.

A creditable rule satisfies the minimum support and confidence, and has a value of lift greater than one.

6.5 Pavement Families

The restructured historical pavement treatment data set of Interstate 40 is analyzed by data mining software (SAS® Enterprise Miner*TM*). The association analysis is performed for different pavement families separately. This is based on the assumption that the performances of pavement families are different during the lifecycle of a pavement section. A pavement family is defined as a group of similar pavement sections that are expected to perform similarly and thus share a common performance or a deterioration curve. The current classification of fourteen different pavement families is based on pavement type, traffic volume, and presence of "D" cracking (for JCP only) as shown in Table 6.3 (ODOT 2005).

The entire sections of Interstate 40 is under a traffic level of more than 10,000 AADT, thus categorized as high traffic volume. As can be seen in Table 6.3 the pavement types are categorized into four different groups based on the pavement material: 1) Asphalt Concrete (AC), 2) Dowel Jointed Concrete Pavement (DJCP), 3) Jointed Plain Concrete Pavement (JPCP), 3) Dowel Mesh Jointed Concrete Pavement (DMJCP), 4) Continuously Reinforced Concrete Pavement (CRCP), and 5) Composite Pavement. The main focus of this study is on asphalt and concrete pavements. Among concrete pavements, association rule mining is performed for DJCP sections only. Both association and sequence analyses are done for each pavement type and a LCCA model is developed for each of them accordingly.

Table 6.3 Classification of Pavements

Asphalt Pavements (AC)	Concrete Pavements	Composite pavements
a) AC Low Volume – AC with less than 2,000 AADT b) AC Moderate Volume – AC with 2,000 – 10,000 AADT c) AC High Volume – AC with 10,000 – 40,000 AADT d) AC Very High Volume – AC with over 40,000 AADT	e) CRCP Low volume – CRCP with less than 10,000 AADT f) CRCP High volume – CRCP with over 10,000 AADT g) DJCP – Dowel Jointed Concrete Pavement h) DMJCP – Mesh Dowel Jointed Concrete Pavement i) Jointed Plain Concrete Pavement (JPCP) Low Volume – JPCP with less than 10,000 AADT j) JPCP High Volume – with over 10,000 AADT k) JPCP "D" – D cracked JPCP	l) Composite Low Volume – AC over PC with less than 10,000 AADT m) Composite Moderate Volume – with 2,000-10,000 AADT n) Composite High Volume – with 10,000 AADT

6.6 Asphalt Concrete (AC) Pavement

6.6.1 Association Analysis

The results of association analysis are illustrated in Table 6.4. Only the rules that have a lift value of greater than 1 have been shown in this table. The rules in this table have been sorted based on the support value. The support in the first rule indicates the proportion of pavement sections that contain both treatments Mill_Thin_OL1 and Thin_OL1. A strong rule has a high support and confidence level with a lift value of greater than 1. For this pavement type, there are 20 association rules that have a lift value of greater than 1. However, not all of them are considered creditable rules.

Larger lift ratios tend to indicate more interesting association rules. Rule no. 12 has the largest lift value. If the lift value is greater than 1, then both sides of the rule are positively correlated, meaning that the occurrence of one infers the occurrence of the other. Lift measures the degree that the occurrence of one treatment lifts the occurrence of the other.

Table 6.4 Association Rules for Asphalt Concrete Pavement

No.	Expected Confidence (%)	Confidence (%)	Support (%)	Lift	Transaction Count	Rule
1	44.87	60.38	20.51	1.35	32	Mill_Thin_OL1 <=> Thin_OL1
2	40.38	66.67	12.82	1.65	20	Mill_Med_OL4 <=> OGFC
3	40.38	89.47	10.90	2.22	17	Mill_Thick_OL1 <=> OGFC
4	44.87	75.00	9.62	1.67	15	Level_OGFC <=> Thin_OL1
5	44.87	77.78	8.97	1.73	14	Mill_Med_OL3 <=> Thin_OL1
6	44.87	46.43	8.33	1.03	13	Mill_Med_OL1 <=> Thin_OL1
7	44.87	60.00	7.69	1.34	12	Mill_Thick_OL3 <=> Thin_OL1
8	44.87	54.55	7.69	1.22	12	Mill_Thin_OL3 <=> Thin_OL1
9	40.38	42.86	7.69	1.06	12	Mill_Med_OL1 <==> OGFC
10	40.38	42.86	7.69	1.06	12	Microsurface <=> OGFC
11	33.97	55.00	7.05	1.62	11	Mill_Thick_OL3 <=> Mill_Thin_OL1
12	11.54	83.33	6.41	7.22	10	Thin_OL1 & Mill_Thin_OL3 <=> Mill_Med_OL3
13	14.10	71.43	6.41	5.06	10	Thin_OL1 & Mill_Med_OL3 <=> Mill_Thin_OL3
14	12.82	62.50	6.41	4.88	10	UTBWC <=> Thin_OL3
15	12.82	52.63	6.41	4.11	10	Mill_Thick_OL1 <=> OGFC & Mill_Med_OL4
16	14.10	55.56	6.41	3.94	10	Mill_Med_OL3 <=> Mill_Thin_OL3
17	19.23	58.82	6.41	3.06	10	OGFC & Mill_Thick_OL1 <=> Mill_Med_OL4
18	19.23	52.63	6.41	2.74	10	Mill_Thick_OL1 <=> Mill_Med_OL4
19	40.38	100.00	6.41	2.48	10	Mill_Thick_OL1 & Mill_Med_OL4 <=> OGFC
20	44.87	100.00	6.41	2.23	10	Mill_Thin_OL3 & Mill_Med_OL3 <=> Thin_OL1

The rule, “if Mill_Thin_OL1 is performed, then Thin_OL1 is more likely to occur,” has confidence value of 60.38%. The confidence of 60.38% means that if a section is treated by Mill_Thin_OL1, there is a 60.38% chance that the section will also be treated by Thin_OL1. The expected confidence of 44.87% means that 44.87% of all sections are treated by Thin_OL1, regardless of what other treatments are applied. The lift value of 1.35 means that sections treated by Mill_Thin_OL1 are 1.35 times more likely to also be treated by Thin_OL1 as compared to sections that are not treated by Mill_Thin_OL1. This rule is considered as one of the creditable rules because it has a large confidence (60.38%), a large level of support (20.51%), and a value of lift greater than one (1.35).

6.6.2 Sequence Analysis

The sequence analysis reveals the order that treatments are applied on the pavement sections. The goal of sequence analysis is to determine common sequences in time-ordered data. The results of this analysis are utilized to determine the life-cycle cost (LCC) model for the purpose of LCCA. Unlike association analysis, the sequences of events become important by defining the sequence as an input variable in the analysis.

The results of the analysis and generated rules are shown in Table 6.5. The rules are sorted based on the confidence value. Rules have been separated based on the number of treatments that are included in them. The first 12 rules have 2 treatments and the rest of the rules have 3 treatments. For the 2 treatment rules only rules with support value of greater than 7% are shown in this table. For 3 treatment rules only rules with support value of greater than 5% are shown in this table. This is based on the assumption that rules with support percentage of less than 7% for two treatment rules and 5% for three treatment rules are not creditable. Since all the rules with more than 3 treatments have support value of less than 5% they are not included in this table. The definition of support and confidence are the same as in association analysis except the fact that the sequence of events makes a difference in the analysis.

Table 6.5 Summary of the Sequence Analysis Results

No.	Transaction Count	Support (%)	Confidence (%)	Rule
1	32	20.92	45.71	Thin_OL1 ==> Mill_Thin_OL1
2	20	13.07	31.75	OGFC ==> Mill_Med_OL4
3	17	11.11	26.98	OGFC ==> Mill_Thick_OL1
4	14	9.15	26.42	Mill_Thin_OL1 ==> Mill_Thin_OL1
5	15	9.80	21.43	Thin_OL1 ==> Level_OGFC
6	11	7.19	20.75	Mill_Thin_OL1 ==> Mill_Thick_OL3
7	13	8.50	20.63	OGFC ==> Mill_Thin_OL1
8	14	9.15	20.00	Thin_OL1 ==> Mill_Med_OL3
9	12	7.84	19.05	OGFC ==> Microsurface
10	12	7.84	19.05	OGFC ==> Mill_Med_OL1
11	13	8.50	18.57	Thin_OL1 ==> Mill_Med_OL1
12	11	7.19	17.46	OGFC ==> Thin_OL1
13	12	7.84	17.14	Thin_OL1 ==> Mill_Thick_OL3
14	12	7.84	17.14	Thin_OL1 ==> Mill_Thin_OL3
15	10	6.54	83.33	OGFC ==> Microsurface ==> Microsurface
16	10	6.54	50.00	OGFC ==> Mill_Med_OL4 ==> Mill_Thick_OL1
17	8	5.23	40.00	OGFC ==> Mill_Med_OL4 ==> Mill_Med_OL1
18	8	5.23	25.00	Thin_OL1 ==> Mill_Thin_OL1 ==> Mill_Thin_OL1
19	8	5.23	57.14	Thin_OL1 ==> Mill_Med_OL3 ==> Mill_Thin_OL3

The rules with both large support and confidence values are considered creditable rules. The rule, “if Thin_OL1, then Mill_Thin_OL1,” is the most creditable rule due to its large confidence (45.71%) and level of support (20.92%). Figure 6.4 shows a scatter plot of rules identified in Table 6.5. In this figure rules are plotted against support and confidence values. Rules that are closer to the upper right corner of the plot are stronger.

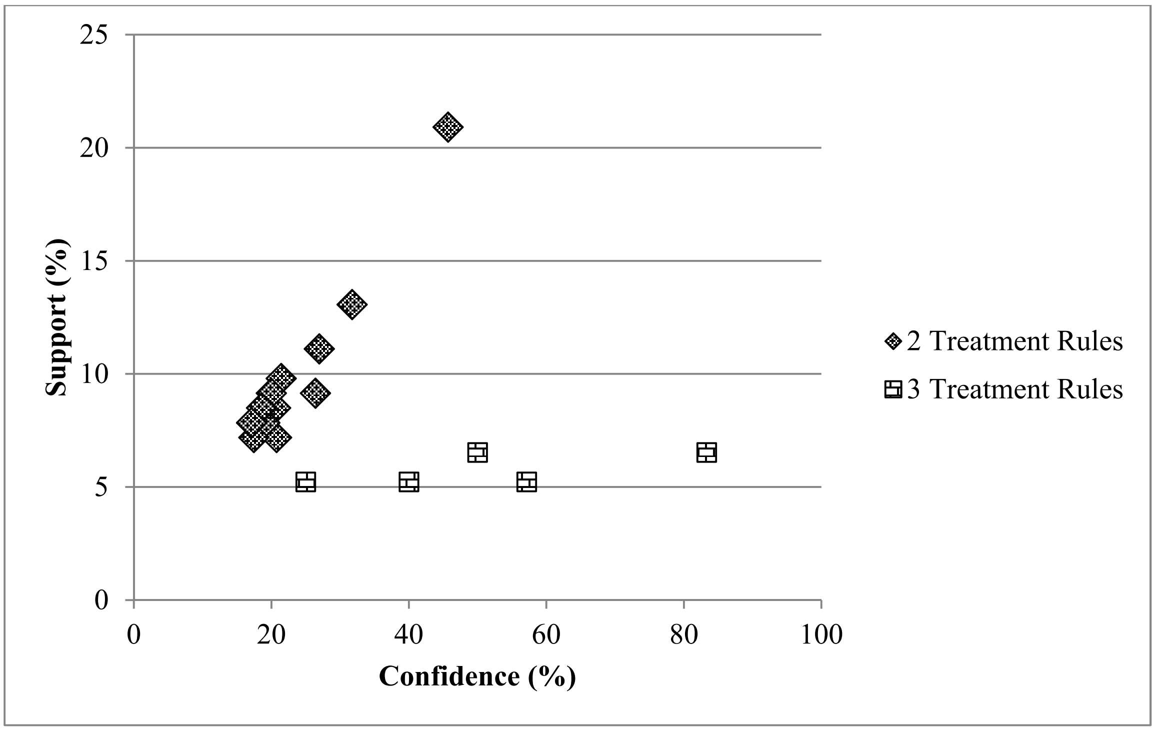


Figure 6.4 Scatter Plot of Rules Based on Support vs. Confidence Values

A graphic representation of the sequence analysis can be seen in Figure 6.5. The nodes in this graph indicate treatment activities. The diameter of the nodes is correlated with the number of times that the treatment activities have occurred in the data set. For AC pavement sections in Interstate 40, Thin_OL1, OGFC, and Mill_Thin_OL1 are the major treatment activities that have occurred the most in the data set. The thickness of links between nodes identifies the strength of association between treatment activities.

As can be seen in this figure, there is a strong association between Thin_OL1 and Mill_Thin_OL1. The direction of the arrow head between Thin_OL1 and Mill_Thin_OL1 indicates that Thin_OL1 occur as the first treatment activity. By looking at the direction of all the links between treatment activities, it can be inferred that Thin_OL1 and OGFC are the two treatment activities that are very likely to occur as the first treatment.

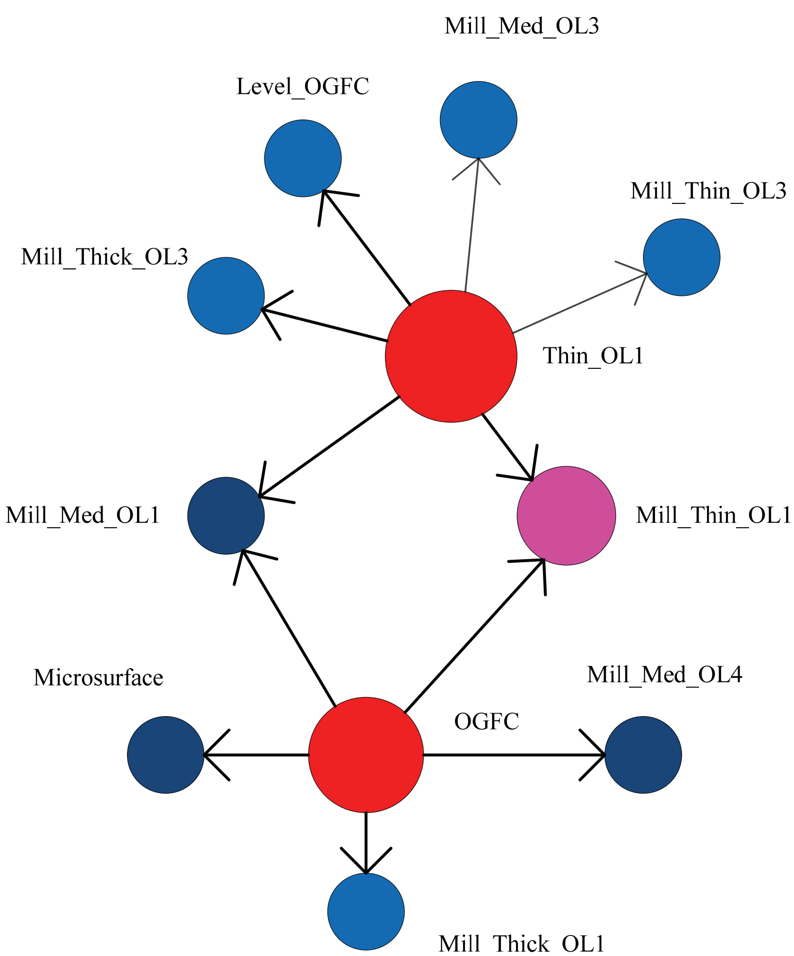


Figure 6.5 Summary of the Association Analysis Results

6.6.3 Frequency Analysis

The relationships between different treatment types were studied, and strong sequences were identified. For instance, it was revealed from the sequence analysis that "if Thin_OL1, then Mill_Thin_OL1," is a strong rule. But whether OGFC is likely to occur as the first, second, third, fourth, or fifth treatment on AC pavement has not been discovered yet. In addition, the confidence is a conditional probability which identifies the probability of occurrence of Mill_Thin_OL1 if Thin_OL1 is known to occur as the first treatment. Whereas, we are interested in calculating the probability that A and B occur together. For the rule "if A, then B" the confidence is as follows:

$$Confidence(A => B) = \frac{transactions\ that\ contain\ both\ items\ A\ and\ B}{transactions\ that\ contain\ item\ A}$$

$$= P(B|A) \qquad (6.4)$$

According to general multiplication rule for dependent events in probability theory we have

$$P(A \cap B) = P(A) * P(B|A) \qquad (6.5)$$

Therefore, we first need to determine the probability of occurrence of event A. In the previous example event A would be Thin_OL1.

In order to address this issue, frequencies of each treatment type are broken down based on the order of treatment. For instance, the number of times that Thin_OL1 occurs as the first, second, third, fourth, and fifth treatment are counted and plotted with other treatment types.

Figure 6.6 shows the frequency distributions of treatment types based on their time of occurrence. The major treatment types for AC pavement are listed on the horizontal axis of this figure.

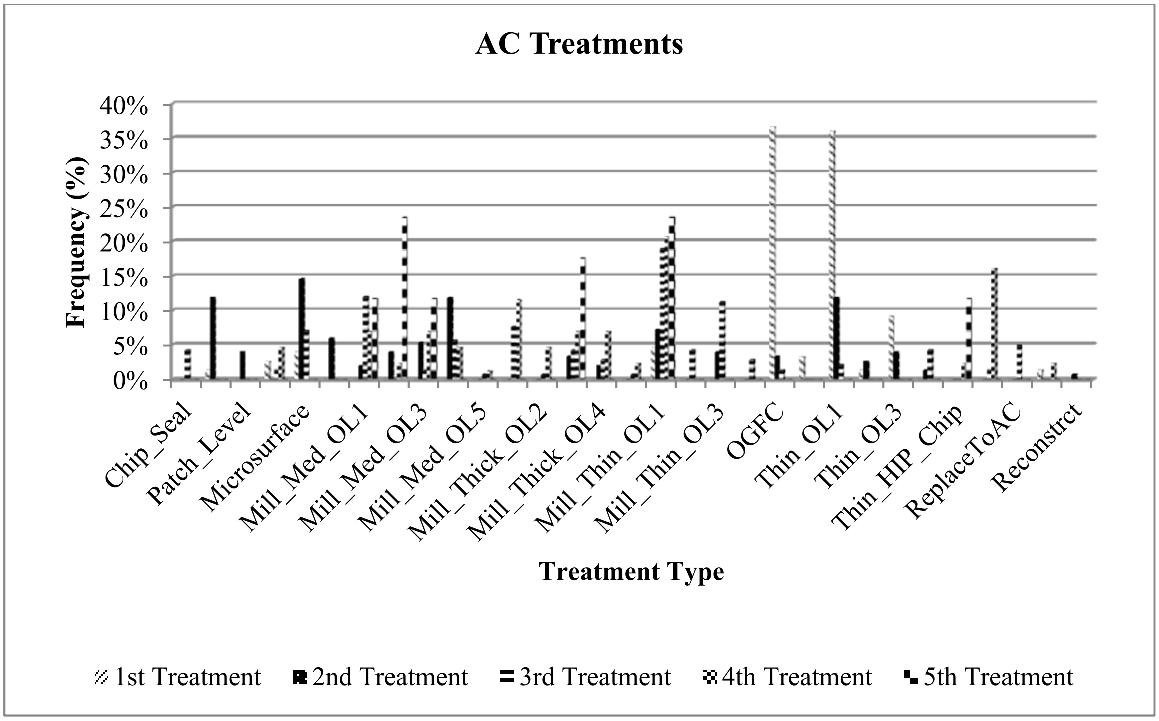


Figure 6.6 Frequency Distributions of AC Pavement Treatment Types Based on Time of Occurrence

A tabular illustration of this figure is also available in Table 6.6. For the first treatment, OGFC (36.6%) and Thin_OL1 (35.9%) are the most common treatment activities. Microsurface (14.6%), Level_OGFC (11.9%), Mill_Med_OL4 (11.9%), and Thin_OL1 (11.9%) are the treatment types that have mostly occurred as the second treatment. Mill_Thin_OL1 (19.0%), Mill_Med_OL1 (12.0%), and Mill_Thin_OL3 (11.3%) are the most common treatments in the third order. The treatments that are likely to occur as the fourth treatment are Mill_Thin_OL1 (20.7%), UTBWC (16.1%), and Mill_Thick_OL1

(11.5%). And finally, Mill_Thin_OL1 (23.5%), Mill_Med_OL2 (23.5%) and Mill_Thick_OL3 (17.6%) tend to be used as the fifth treatment on AC pavements.

Table 6.6 Frequency of AC Pavement Treatment Types

Treatments	**1st Treatment**		**2nd Treatment**		**3rd Treatment**		**4th Treatment**		**5th Treatment**	
		%		**%**		**%**		**%**		**%**
Chip_Seal	0	0.0	0	0.0	6	4.2	0	0.0	0	0.0
Level_OGFC	2	1.3	18	**11.9**	0	0.0	0	0.0	0	0.0
Patch_Level	0	0.0	6	4.0	0	0.0	0	0.0	0	0.0
Med_OL1	4	2.6	0	0.0	2	1.4	4	4.6	0	0.0
Microsurface	6	3.9	22	**14.6**	10	7.0	0	0.0	0	0.0
Microsurface_Fabric	0	0.0	9	6.0	0	0.0	0	0.0	0	0.0
Mill_Med_OL1	0	0.0	3	2.0	17	**12.0**	6	6.9	2	11.8
Mill_Med_OL2	0	0.0	6	4.0	0	0.0	2	2.3	4	**23.5**
Mill_Med_OL3	0	0.0	8	5.3	2	1.4	6	6.9	2	11.8
Mill_Med_OL4	0	0.0	18	**11.9**	8	5.6	4	4.6	0	0.0
Mill_Med_OL5	0	0.0	0	0.0	1	0.7	1	1.1	0	0.0
Mill_Thick_OL1	0	0.0	0	0.0	11	7.7	10	**11.5**	0	0.0
Mill_Thick_OL2	0	0.0	0	0.0	1	0.7	4	4.6	0	0.0
Mill_Thick_OL3	0	0.0	5	3.3	6	4.2	6	6.9	3	17.6
Mill_Thick_OL4	0	0.0	3	2.0	4	2.8	6	6.9	0	0.0
Mill_Thick_OL5	0	0.0	0	0.0	1	0.7	2	2.3	0	0.0
Mill_Thin_OL1	7	4.6	11	7.3	27	**19.0**	18	**20.7**	4	**23.5**
Mill_Thin_OL2	0	0.0	0	0.0	6	4.2	0	0.0	0	0.0
Mill_Thin_OL3	0	0.0	6	4.0	16	**11.3**	0	0.0	0	0.0
Mill_Thin_OL4	0	0.0	0	0.0	4	2.8	0	0.0	0	0.0
OGFC	56	**36.6**	5	3.3	2	1.4	0	0.0	0	0.0
Thick_OL1	5	3.3	0	0.0	0	0.0	0	0.0	0	0.0
Thin_OL1	55	**35.9**	18	**11.9**	3	2.1	0	0.0	0	0.0
Thin_OL2	2	1.3	4	2.6	0	0.0	0	0.0	0	0.0
Thin_OL3	14	9.2	6	4.0	0	0.0	0	0.0	0	0.0
Thin_OL4	0	0.0	2	1.3	6	4.2	0	0.0	0	0.0
Thin_HIP_Chip	0	0.0	0	0.0	0	0.0	2	2.3	2	11.8
UTBWC	0	0.0	0	0.0	2	1.4	14	**16.1**	0	0.0
ReplaceToAC	0	0.0	0	0.0	7	4.9	0	0.0	0	0.0
Whitetopping	2	1.3	0	0.0	0	0.0	2	2.3	0	0.0
Reconstrct	0	0.0	1	0.7	0	0.0	0	0.0	0	0.0
Total	**153**	**100.0**	**151**	**100.0**	**142**	**100.0**	**87**	**100.0**	**17**	**100.0**

By combining the results of the association and sequence analyses with frequency analysis, the treatment strategies embedded in the data set for AC pavements are revealed as illustrated in Figure 6.7. Treatment types are linked together based on the rules identified during the sequence analysis. The numbers shown in the figure refer to the rule numbers identified in Table 6.5.

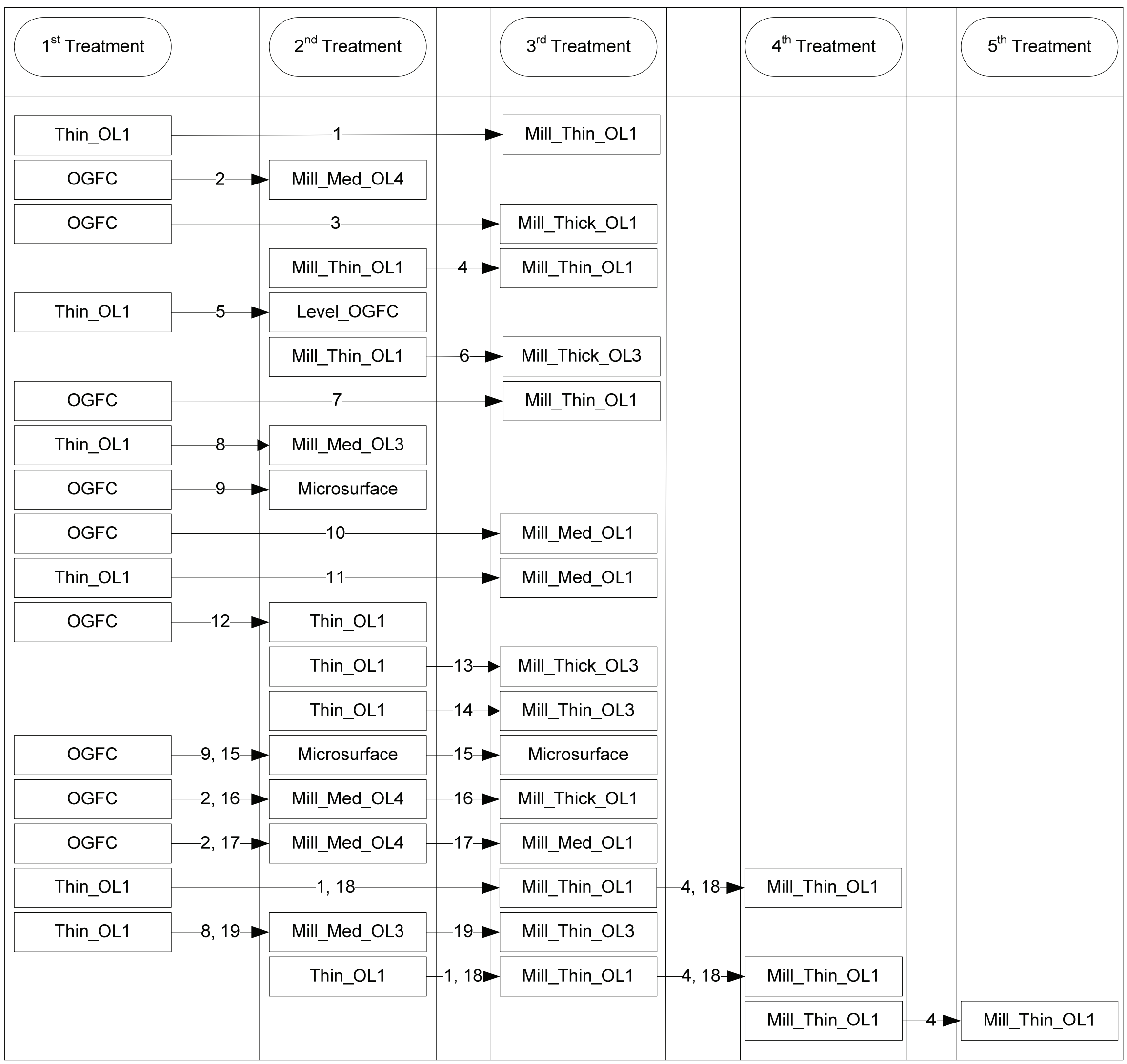


Figure 6.7 AC Pavement Treatment Strategies

Some of the rules developed in the sequence analysis are two treatment rules and some of them are three treatment rules. The two treatment rules do not necessarily start from the first treatment. For instance, rules no. 4, no. 13, and no. 14 indicate a relationship between the second and the third treatments. Other rules such as rule no. 3, no. 10, and no. 11 indicate a relationship between the first and the third treatments. In addition, the majority of rules belong to the first three treatment activities because the number of pavement sections that have undergone four or five treatment activities in their life-cycle is few and these relationships have been filtered out from the results.

The data used in the analysis consist of all the AC pavement sections of Interstate 40 which have been under very high traffic volume during their life-cycle (i.e. the same pavement family). However, it was found out that many pavement sections that belong to the same pavement family have undergone different treatment strategies during their life-cycles. The results of this analysis indicate that the traditional approach of the SHAs, by assuming one LCC model for each pavement type, needs to be revised.

6.6.4 Realistic LCCA Model

The rules identified in Figure 6.7 are summarized into 9 rules as indicated in Figure 6.8. Only the rules that indicate a relationship between the first three treatment activities are considered in the final LCCA model. Rules such as no. 3 that relates first treatment to the third treatment and rules such as no. 4 that relates the second treatment to the third treatment are ignored. It should be noted that summarizing rules do not mean that these rules are not considered in the model. For instance, rule no. 4 is part of rule no. 18 or rule no. 10 is part of rule no. 17.

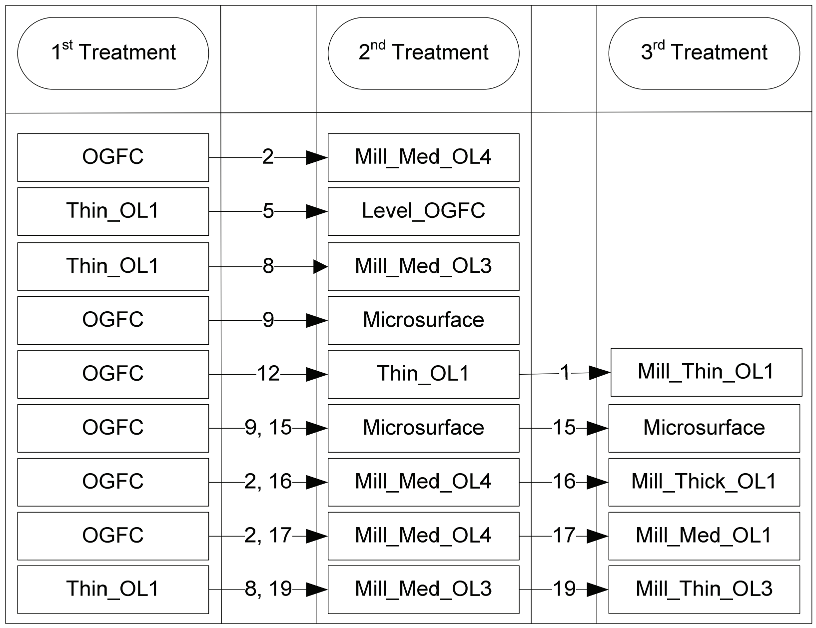


Figure 6.8 Summarized Realistic LCCA Model for AC Pavements

Realistic LCCA model is based upon the realistic LCC models developed during the association and sequence analyses. In realistic LCCA model, possible treatment strategies are assigned a probability of occurrence, and the final LCC is the weighted summation of individual net present values (NPVs). We are interested in calculating the probability that A and B occur together.

The probability of occurrence is obtained by multiplying the confidence level by the probability of event A. For the rules generated for AC pavement sections, OGFC and Thin_OL1 are the only possible treatment options as the first treatment and their likelihood of occurrence is the same. In other words, there is 50% chance that each one of these treatments is applied on AC pavement section as the first treatment. Therefore the probability of occurrence is calculated by multiplying confidence by 0.5 for each rule in Figure 6.8. Then these probabilities are normalized in order to have summation of equal to 100%. Probabilities of occurrence can be seen in Table 6.7. It should be noted that some of two treatment rules are not considered in the final LCCA model because they are accounted for in three treatment rules. For example rule no. 8 is part of rule no. 19 or rule no. 9 is part of rule no. 15 or rule no. 2 is part of rule no. 16.

Table 6.7 Final Realistic LCCA Model for AC Pavement

Rule No.	Rule	Support (%)	Confidence (%)	Probability
15	OGFC=>Microsurface=>Microsurface	6.54	83.33	30.94%
19	Thin_OL1=>Mill_Med_OL3=>Mill_Thin_OL3	5.23	57.14	21.21%
16	OGFC=>Mill_Med_OL4=>Mill_Thick_OL1	6.54	50	18.56%
17	OGFC=>Mill_Med_OL4=>Mill_Med_OL1	5.23	40	14.85%
5	Thin_OL1=>Level_OGFC	9.8	21.43	7.96%
12	OGFC=>Thin_OL1=>Mill_Thin_OL1	7.19	17.46	6.48%

Table 6.8 shows the timing of treatment strategies developed for AC pavement sections. As can be seen in this table, regardless of the type of first treatment (OGFC or Thin_OL1), the average time to the first treatment is 10.8 years. However, the average time to the second treatment depends upon the type of that treatment. For instance, in rule no. 15 the first treatment is applied 10.8 years after construction of the section. This is the same for all the treatment strategies starting with OGFC. However, based on the type of the second and the third treatments, average time to the second and the third treatments vary. According to rule no. 15 the section is treated with Microsurface 6.5 years later than

the first treatment. Finally Microsurface is applied again as the third treatment 9 years after the second treatment. For rule no. 16 the second treatment which is Mill_Med_OL4 is applied 14 years later than the first treatment activity.

Table 6.8 Timing of Realistic LCCA Model for AC Pavement

Rule No.	Rule	Time to the 1st Treatment (years)	Time to the 2nd Treatment (years)	Time to the 3rd Treatment (years)
15	OGFC=>Microsurface=>Microsurface	10.8	6.5	9.0
19	Thin_OL1=>Mill_Med_OL3=>Mill_Thin_OL3	10.8	12	10.0
16	OGFC=>Mill_Med_OL4=>Mill_Thick_OL1	10.8	14	16.0
17	OGFC=>Mill_Med_OL4=>Mill_Med_OL1	10.8	14	14.3
5	Thin_OL1=>Level_OGFC	10.8	7	-
12	OGFC=>Thin_OL1=>Mill_Thin_OL1	10.8	7.3	-
	Average	10.8	10.4	12.3

6.7 Dowel Jointed Concrete Pavement (DJCP)

6.7.1 Association Analysis

The results of association analysis are illustrated in Table 6.9. This table shows all the rules generated by association analysis. The rules in this table have been sorted based on the support value. The support in the first rule indicates the proportion of pavement sections that contain both treatments Joint_Rehab and Unbonded_Overlay. A strong rule has a high support and confidence level with a lift value of greater than 1. For this pavement type, there are 32 association rules with a lift value of greater than 1. However, not all of them are considered creditable rules.

Table 6.9 Association Rules for DJCP

No	Expected Confidence (%)	Confidence (%)	Support (%)	Lift	Transaction Count	Rule
1	11.76	33.33	11.76	2.8	4	Joint_Rehab <=> Unbonded_Overlay
2	5.88	100.00	5.88	17.0	2	Med_OL3 <=> Mill_Thin_OL1
3	5.88	100.00	5.88	17.0	2	ReplacetoDJCP <=> Reconstruction & Grind
4	5.88	100.00	5.88	17.0	2	Joint_Seal <=> Reconstruction & Grind_Seal
5	5.88	100.00	5.88	17.0	2	ReplacetoDJCP <=> Reconstruction & Joint_Rehab
6	5.88	100.00	5.88	17.0	2	Grind <=> Reconstruction & Joint_Rehab
7	5.88	100.00	5.88	17.0	2	Grind <=> ReplacetoDJCP
8	5.88	100.00	5.88	17.0	2	Reconstruction & Joint_Rehab <=> ReplacetoDJCP
9	5.88	100.00	5.88	17.0	2	Reconstruction & Grind <=> ReplacetoDJCP
10	5.88	100.00	5.88	17.0	2	Joint_Rehab & Grind <=> ReplacetoDJCP
11	5.88	100.00	5.88	17.0	2	Grind <=> ReplacetoDJCP & Joint_Rehab
12	5.88	100.00	5.88	17.0	2	Grind <=> ReplacetoDJCP & Reconstruction
13	5.88	50.00	5.88	8.5	2	Grind_Seal <=> Joint_Seal
14	11.76	100.00	5.88	8.5	2	ReplacetoDJCP <=> Reconstruction
15	11.76	100.00	5.88	8.5	2	Joint_Seal <=> Reconstruction
16	11.76	100.00	5.88	8.5	2	Grind <=> Reconstruction
17	11.76	100.00	5.88	8.5	2	ReplacetoDJCP & Joint_Rehab <=> Reconstruction
18	11.76	100.00	5.88	8.5	2	ReplacetoDJCP & Grind <=> Reconstruction
19	11.76	100.00	5.88	8.5	2	Joint_Seal & Grind_Seal <=> Reconstruction
20	11.76	100.00	5.88	8.5	2	Joint_Rehab & Grind <=> Reconstruction
21	5.88	50.00	5.88	8.5	2	Grind_Seal <=> Reconstruction & Joint_Seal
22	11.76	50.00	5.88	4.3	2	Grind_Seal <=> Reconstruction
23	11.76	50.00	5.88	4.3	2	PC_Patch <=> Thin_OL1
24	35.29	100.00	5.88	2.8	2	Grind <=> Joint_Rehab
25	5.88	16.67	5.88	2.8	2	Joint_Rehab <=> Reconstruction & Grind
26	5.88	16.67	5.88	2.8	2	Joint_Rehab <=> ReplacetoDJCP
27	5.88	16.67	5.88	2.8	2	Joint_Rehab <=> ReplacetoDJCP & Grind
28	5.88	16.67	5.88	2.8	2	Joint_Rehab <=> ReplacetoDJCP & Reconstruction
29	11.76	16.67	5.88	1.4	2	Joint_Rehab <=> Grind_Seal
30	35.29	50.00	5.88	1.4	2	Grind_Seal <=> Joint_Rehab
31	11.76	16.67	5.88	1.4	2	Joint_Rehab <=> Reconstruction

Larger lift ratios tend to indicate more interesting association rules. Rules from no.2 to no.12 have the largest lift value. If the lift value is greater than 1, then both sides of the rule are positively correlated, meaning that the occurrence of one infers the occurrence of the other. Lift measures the degree that the occurrence of one treatment lifts the occurrence of the other.

The rule, "if Joint_Rehab is performed, then Unbonded_Overlay is more likely to occur," has confidence value of 33.33%. The confidence of 33.33% means that if a section is treated by Joint_Rehab, there is 33.33% chance that the section will also be treated by Unbonded_Overlay. The expected confidence of 11.76% means that 11.76% of all sections are treated by Unbonded_Overlay, regardless of what other treatments are applied. The lift value of 2.8 means that sections treated by Joint_Rehab are 2.8 times more likely to also be treated by Unbonded_Overlay as compared to sections that are not treated by Joint_Rehab. This rule is considered as the most creditable rule for DJCP sections because it has a large confidence (33.33%), a large level of support (11.76%), and a value of lift greater than one (2.8).

6.7.2 Sequence Analysis

The results of the sequence analysis and generated rules are shown in Table 6.10. The rules are sorted based on the confidence value. The number of rules generated in the analysis is 24. Not all of these 24 rules are considered creditable. As can be seen in the table, the first two rules have large support and confidence values. The other rules are only based on two pavement sections which might decrease their creditability. Although the confidence of rule no. 5 is 100%, it has only occurred in two pavement sections.

The rules with both large support and confidence values are considered creditable rules. The rule, “if Thin_OL1, then Thin_OL1,” is the most creditable rule due to its large confidence (100%) and level of support (16.67%). Figure 6.9 shows a scatter plot of rules identified in Table 6.10. In this figure rules are plotted against support and confidence values. Rules that are closer to the upper right corner of the plot are stronger.

Table 6.10 Summary of the Sequence Analysis Results for DJCP Sections

Rule No.	Transaction Count	Support (%)	Confidence (%)	Rule
1	4	16.67	100	Thin_OL1 => Thin_OL1
2	4	16.67	33.33	Joint_Rehab => Unbonded_Overlay
3	2	8.33	16.67	Joint_Rehab => Grind
4	2	8.33	16.67	Joint_Rehab => Grind_Seal
5	2	8.33	100	Joint_Seal => Grind_Seal
6	2	8.33	16.67	Joint_Rehab => Joint_Rehab
7	2	8.33	100	Med_OL3 => Mill_Thin_OL1
8	2	8.33	50	Thin_OL1 => PC_Patch
9	2	8.33	100	Grind => Reconstruction
10	2	8.33	50	Grind_Seal => Reconstruction
11	2	8.33	16.67	Joint_Rehab => Reconstruction
12	2	8.33	100	Joint_Seal => Reconstruction
13	2	8.33	100	ReplacetoDJCP => Reconstruction
14	2	8.33	100	Grind => ReplacetoDJCP
15	2	8.33	16.67	Joint_Rehab => ReplacetoDJCP
16	2	8.33	100	Joint_Rehab => Joint_Rehab => Grind
17	2	8.33	50	Thin_OL1 => Thin_OL1 => PC_Patch
18	2	8.33	100	Joint_Rehab => Grind => Reconstruction
19	2	8.33	100	Joint_Seal => Grind_Seal => Reconstruction
20	2	8.33	100	Joint_Rehab => Joint_Rehab => Reconstruction
21	2	8.33	100	Grind => ReplacetoDJCP => Reconstruction
22	2	8.33	100	Joint_Rehab => ReplacetoDJCP => Reconstruction
23	2	8.33	100	Joint_Rehab => Grind => ReplacetoDJCP
24	2	8.33	100	Joint_Rehab => Joint_Rehab => ReplacetoDJCP

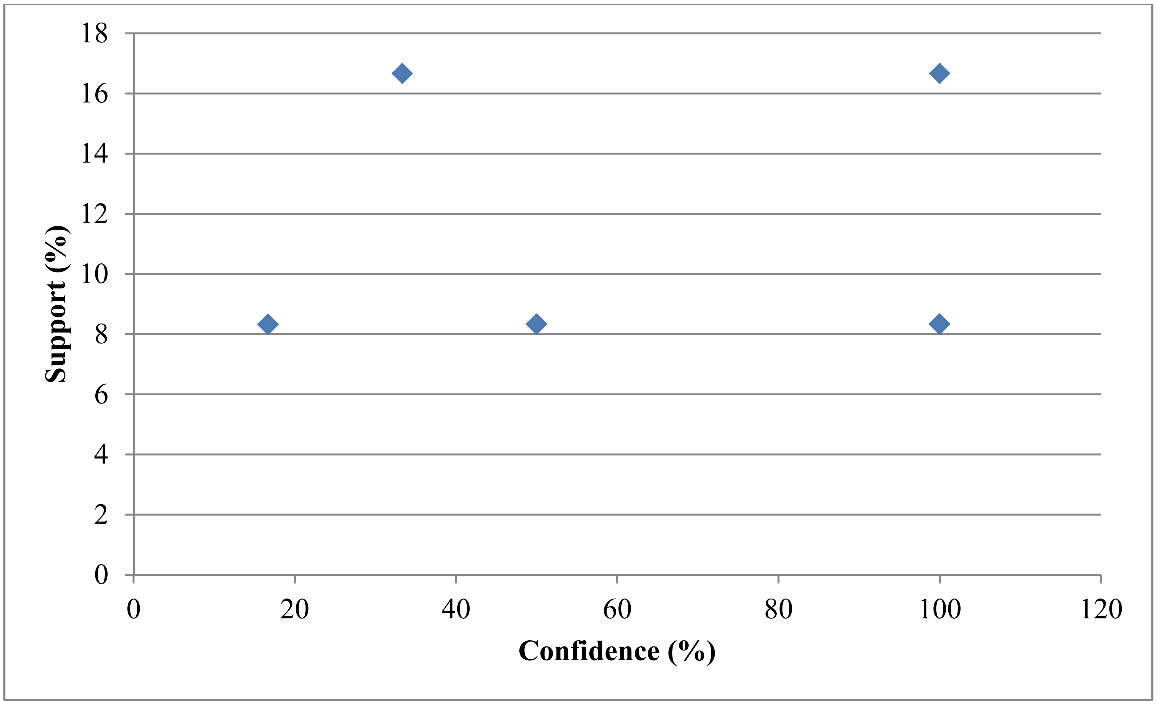


Figure 6.9 Scatter Plot of Rules Based on Support vs. Confidence Values for DJCP

A graphic representation of the sequence analysis can be seen in Figure 6.10. The nodes in this graph indicate treatment activities. The diameter of the nodes is correlated with the number of times that the treatment activities have occurred in the data set. For DJCP sections in Interstate 40, Joint_Rehab is the major treatment activity that has occurred the most in the data set. The thickness of links between nodes identifies the strength of association between treatment activities.

As can be seen in this figure, there is a strong association between Joint_Rehab and ReplacetoDJCP. The direction of the arrow head between Med_OL3 and Mill_Thin_OL1 indicates that Med_OL3 occurs as the first treatment activity. By looking at the direction of all the links between treatment activities, it can be inferred that the treatment strategies are more diverse than AC pavements. Also some flexible treatment has also been applied on DJCP sections such as Med_OL3, Mill_Thin_OL1 and Thin_OL1. As can be seen in this figure, Joint_Rehab, Joint_Seal, Med_OL3, and Thin_OL1 are always the preceding treatment activity. On the other hand Unbonded_Overlay, Reconstruction, Mill_thin_OL1, and PC_Patch tend to be the last chain of treatment activities on the DJCP sections.

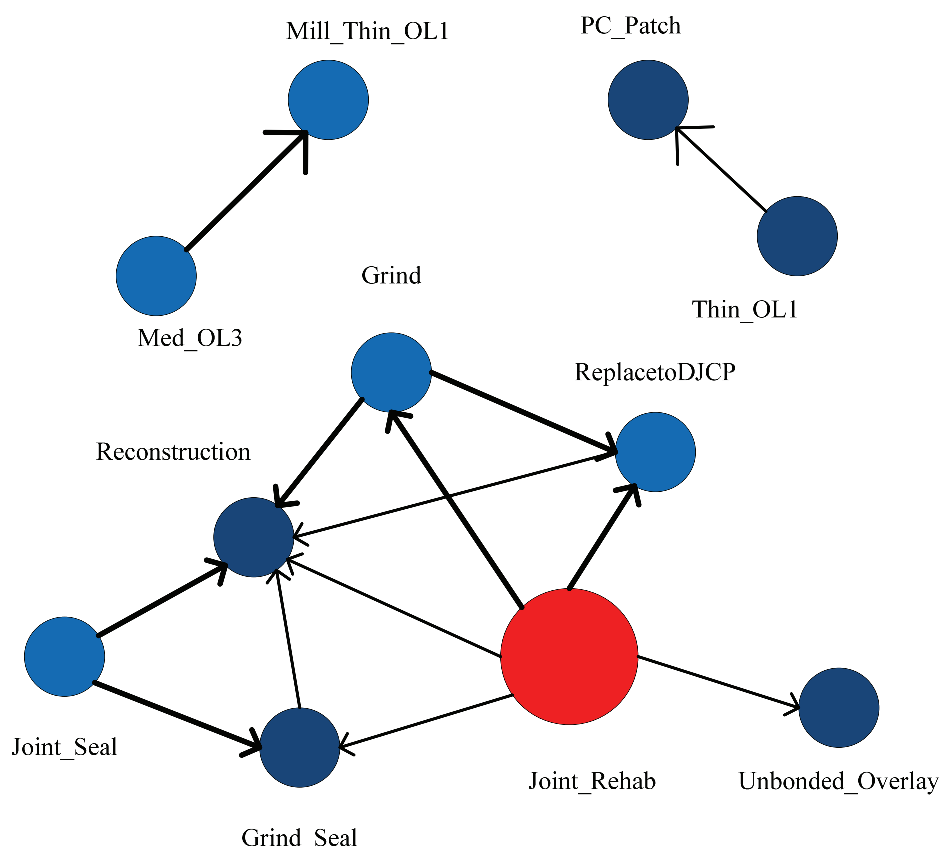


Figure 6.10 Link Graph of Sequence Analysis for DJCP

6.7.3 Frequency Analysis

The relationships between different treatment types were studied, and strong sequences were identified. For instance, it was revealed from the sequence analysis that "if Joint_Rehab, then Unbonded_Overlay," is a strong rule. But whether Joint_Rehab is likely to occur as the first, second, third, or fourth treatment on DJPC sections has not been discovered yet. In addition, the confidence is a conditional probability which identifies the probability of occurrence of Unbonded_Overlay if Joint_Rehab is known to occur as the first treatment.

Since we are interested in calculating the probability that both treatments occur together, we first need to determine the probability of occurrence of event A. In the previous example event A would be Joint_Rehab. In order to address this issue, frequencies of each treatment type are broken down based on the order of treatment. For instance, the number of times that Joint_Rehab occurs as the first, second, third, fourth, and fifth treatment are counted and plotted with other treatment types.

Figure 6.11 shows the frequency distributions of treatment types based on their time of occurrence. The major treatment types for DJCP sections are listed on the horizontal axis of this figure. A tabular illustration of this figure is also available in Table 6.11. For the first treatment, Joint_Rehab (50.0%) and Thin_OL1 (16.7%) are the most common treatment activities. Thin_OL1 (25.0%), Unbonded_OL (25.0%), and Grind_Seal (25.0%) are the treatment types that have mostly occurred as the second treatment. Reconstruction (40.0%) is the most common treatment in the third order. The treatments that are likely to occur as the fourth treatment are Reconstruction (50.0%) and ReplaceToDJCP (50.0%). And finally, Reconstruction (100%) tends to be used as the fifth treatment on DJCP sections.

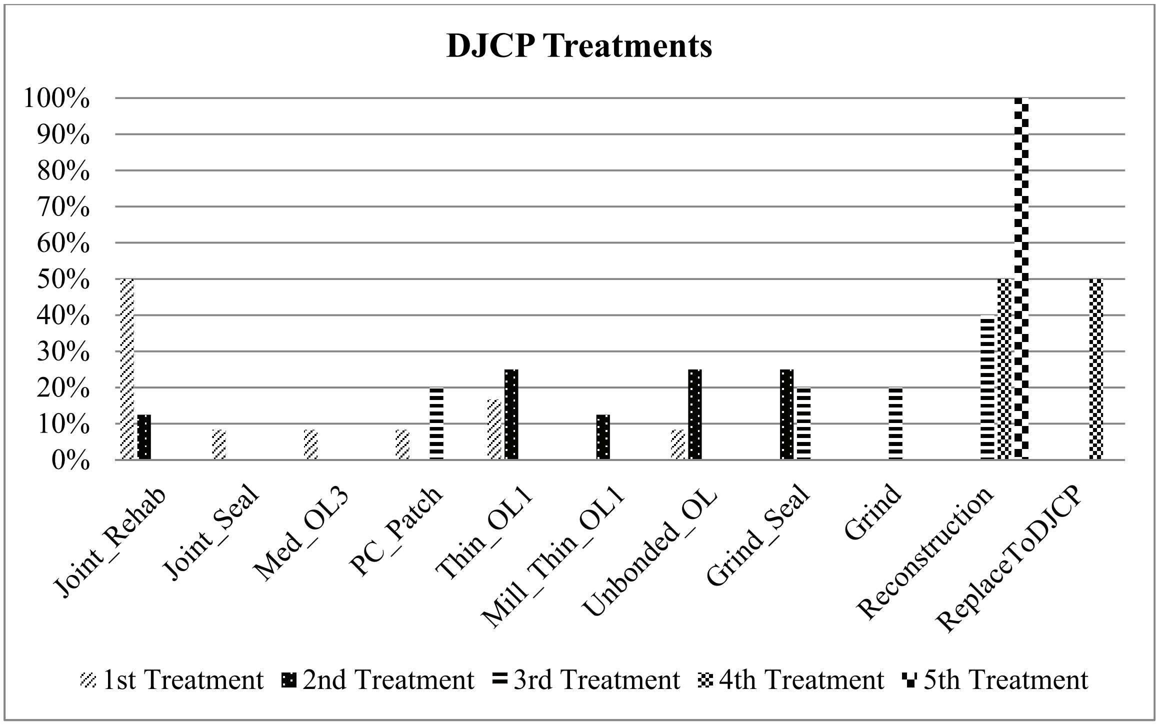


Figure 6.11 Frequency Distributions of DJCP Pavement Treatment Types Based on Time of Occurrence

Table 6.11 Frequency of DJCP Treatment Types

Treatment	1st Treatment		2nd Treatment		3rd Treatment		4th Treatment		5th Treatment	
Joint_Rehab	12	**50.0%**	2	12.5%	0	0.0%	0	0.0%	0	0.0%
Joint_Seal	2	8.3%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Med_OL3	2	8.3%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
PC_Patch	2	8.3%	0	0.0%	2	20.0%	0	0.0%	0	0.0%
Thin_OL1	4	**16.7%**	4	**25.0%**	0	0.0%	0	0.0%	0	0.0%
Mill_Thin_OL1	0	0.0%	2	12.5%	0	0.0%	0	0.0%	0	0.0%
Unbonded_OL	2	8.3%	4	**25.0%**	0	0.0%	0	0.0%	0	0.0%
Grind_Seal	0	0.0%	4	**25.0%**	2	20.0%	0	0.0%	0	0.0%
Grind	0	0.0%	0	0.0%	2	20.0%	0	0.0%	0	0.0%
Reconstruction	0	0.0%	0	0.0%	4	**40.0%**	2	**50.0%**	2	**100.0%**
ReplaceToDJCP	0	0.0%	0	0.0%	0	0.0%	2	**50.0%**	0	0.0%
Total	**24**	**100.0%**	**16**	**100.0%**	**10**	**100.0%**	**4**	**100.0%**	**2**	**100.0%**

By combining the results of the association and sequence analyses with frequency analysis, the treatment strategies embedded in the data set for DJCP sections are revealed as illustrated in Figure 6.12. Treatment types are linked together based on the rules identified during the sequence analysis. The numbers shown in the figure refer to the rule numbers identified in Table 6.10.

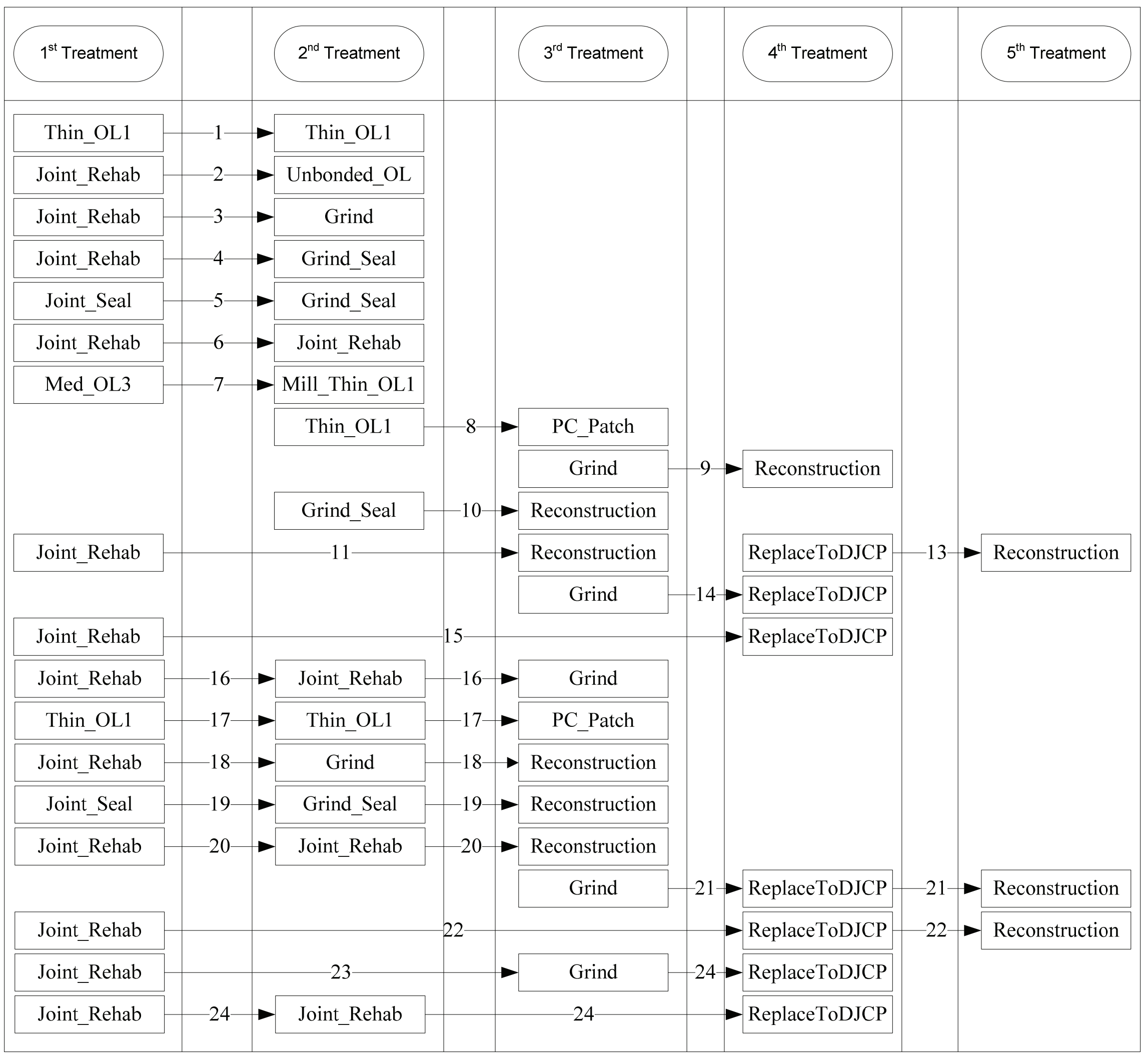


Figure 6.12 Treatment Strategies of DJCP Sections

Some of the rules developed in the sequence analysis are two treatment rules and some of them are three treatment rules. The two treatment rules do not necessarily start from the first treatment. For instance, rules no. 8 and no. 10 indicate a relationship between the second and the third treatments. Other rules such as rule no. 11 and no. 23 indicate a relationship between the first and the third treatments. In addition, the majority of rules belong to the first two treatment activities because pavement sections that have undergone three, four or five treatment activities in their life-cycle are few and these relationships have been filtered out from the results.

The data used in the analysis consist of all the DJCP sections of Interstate 40 which have been under very high traffic volume during their life-cycle (i.e. the same pavement family). However, it was found out that many pavement sections that belong to the same pavement family have undergone different treatment strategies during their life-cycles. The results of this analysis indicate that the traditional approach of the SHAs, by assuming one LCC model for each pavement type, needs to be revised.

6.7.4 Realistic LCCA Model

The rules identified in Figure 6.12 are summarized into 12 rules as indicated in Figure 6.13. Only the rules that indicate a relationship between the first three treatment activities are considered in the final LCCA model. Rules such as no. 11 that relates first treatment to the third treatment and rules such as no. 9 that relates the second treatment to the third treatment are ignored. It should be noted that summarizing rules do not mean that these rules are not considered in the model. For instance, rule no. 8 is part of rule no. 17 or rule no. 10 is part of rule no. 19.

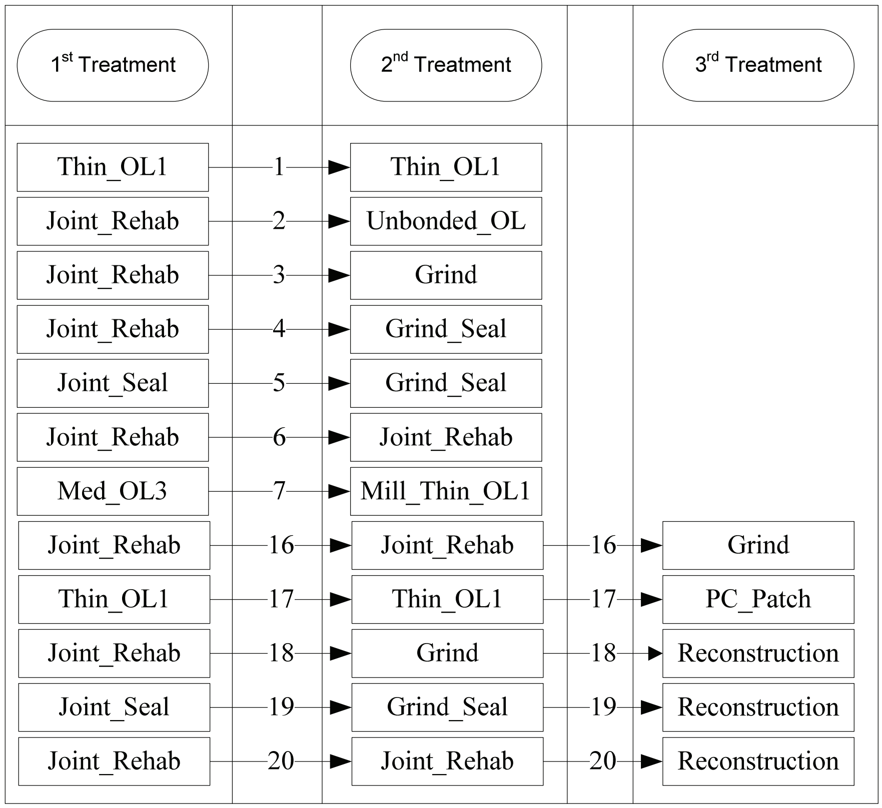


Figure 6.13 Summary of Realistic LCCA Model for DJCP Sections

Realistic LCCA model is based upon the realistic LCC models developed during the association and sequence analyses. In realistic LCCA model, possible treatment strategies are assigned a probability of occurrence, and the final LCC is the weighted summation of individual net present values (NPVs). We are interested in calculating the probability that A and B occur together.

The probability of occurrence is obtained by multiplying the confidence level by the probability of event A. For the rules generated for DJCP sections, Joint_Reahb, Thin_OL1, Joint_Seal, and Med_OL3 are the possible treatment options as the first treatment and their likelihoods of occurrence are 50%, 16.7%, 8.3%, and 8.3% respectively. Therefore the probability of occurrence is calculated by multiplying confidence by the likelihoods of first treatment occurrence for each rule in Figure 6.13. Then these probabilities are normalized in order to have summation of equal to 100%. Probabilities of occurrence can be seen in Table 6.12. Those two treatment rules that are incorporated in three treatment rules are eliminated from the final LCCA model. These rules are no. 1, no. 3, no. 6, no. 5 which are represented by rules no. 9, no. 10, no.8, and no. 11 respectively.

Table 6.12 Final Realistic LCCA Model for DJCP

Rule No.	**Rule**	**Support (%)**	**Confidence (%)**	**Probability**
8	Joint_Rehab ==> Joint_Rehab ==> Grind	8.33	100.00	25.01%
10	Joint_Rehab ==> Grind ==> Reconstruction	8.33	100.00	25.01%
12	Joint_Rehab ==> Joint_Rehab ==> Reconstruction	8.33	100.00	25.01%
2	Joint_Rehab ==> Unbonded_Overlay	16.67	33.33	8.34%
9	Thin_OL1 ==> Thin_OL1 ==> PC_Patch	8.33	50.00	4.18%
4	Joint_Rehab ==> Grind_Seal	8.33	16.67	4.17%
7	Med_OL3 ==> Mill_Thin_OL1	8.33	100.00	4.15%
11	Joint_Seal ==> Grind_Seal ==> Reconstruction	8.33	100.00	4.15%

The timings of treatment strategies are illustrated in Table 6.13. The average times to the first, the second, and the third treatments are based on the type of treatments and would be different for each strategy. For instance, rule no. 8 starts with Joint_Rehab after 23.2 years of pavement construction. Then it is followed by another Joint_Rehab after 17 years and Grinding after 1 year. Rule no. 10 has started with the same treatment as rule no. 8 but the difference is that Grinding has been performed as the second treatment. This has changed the time to the second treatment to 11 years compared to 17 years in rule no. 8. In treatment strategy no. 9, ODOT has not treated the pavement section for 29 years and then applied Thin_OL1. After two years they are required to apply another Thin_OL1 followed by PC_Patch 13 years later. This is an indicator of the strategies that are dictated due to lack of budget.

Table 6.13 Final Realistic LCCA Model for DJCP

Rule No.	Rule	Time to the 1st Treatment (years)	Time to the 2nd Treatment (years)	Time to the 3rd Treatment (years)
8	Joint_Rehab ==> Joint_Rehab ==> Grind	23.20	17.00	1.00
10	Joint_Rehab ==> Grind ==> Reconstruction	23.20	11.00	9.00
12	Joint_Rehab ==> Joint_Rehab ==> Reconstruction	23.20	17.00	9.00
2	Joint_Rehab ==> Unbonded_Overlay	23.20	15.00	-
9	Thin_OL1 ==> Thin_OL1 ==> PC_Patch	29.00	2.00	13.00
4	Joint_Rehab ==> Grind_Seal	23.20	11.00	-
7	Med_OL3 ==> Mill_Thin_OL1	26.00	14.00	-
11	Joint_Seal ==> Grind_Seal ==> Reconstruction	14.00	14.00	10.00
	Average	**23.1**	**12.6**	**8.4**

6.8 Realistic LCCA Formulation

The NPV for each strategy is calculated by the formula below:

$$NPV = \sum_{j=1}^{J} P_j = \sum_{j=1}^{J} F_j \left[\frac{1}{(1+i)^{n_j}}\right] \qquad (6.6)$$

where;

i = the annual rate of interest

j = the treatment sequence

J = the total number of treatment activities during the analysis period

n_j = the number of interest periods (usually annual)

NPV = the net present value

P_j = the amount at a time assumed to be the present

F_j = the amount n interest periods, hence equal to the compound amount P_j

Then, the realistic LCC is obtained by the following equation:

$$Realistic\ LCC = \sum_{k=1}^{K}((Probability)_k * NPV_k) \tag{6.7}$$

where;

k = the number of the treatment strategy

K = the total number of possible treatment strategies

NPV_k = the net present value of treatment strategy k, calculated by Equation 6.6

$(Probability)_k$ = the occurrence probability of treatment strategy k

$$and\ \sum_{k=1}^{K}(Probability)_k = 1 \tag{6.8}$$

Based on this approach, all the possible treatment strategies affect the final LCC based on their probability of occurrence.

6.9 Summary

In this chapter a novel approach in performing LCCA was introduced and formulated. An intensive data mining analysis was applied on the data set to reveal the typical sequential patterns in the historical pavement treatment projects. Two realistic LCCA models were developed for AC and DJCP sections of Interstate 40. Unlike the deterministic model that assumed each pavement family performs the same and is treated with a single strategy, the realistic LCCA consists of all the possible treatment strategies with different probabilities of occurrence. The results of this novel approach would be closer to actual costs because the uncertainties in adopting treatment strategies have been taken into consideration. It was clearly shown in this chapter that uncertainty in the future rehabilitation scenarios need to be taken into consideration for the results of LCCA to be closer to actual costs.

CHAPTER 7

CASE STUDY OF LIFE-CYCLE COST ANALYSIS

The LCC models developed in Chapter 5 and Chapter 6 are utilized to conduct a case study. As mentioned earlier, ODOT Roadway Design Division and Field Division evaluate both flexible and rigid pavement designs in terms of a range of factors such as initial construction cost and engineering factors among others. A completed project is selected for further investigation and analysis. The purpose of this analysis is to determine the LCC difference between pavement design alternatives. Finally an A+B+L bid model is constructed based on the findings of this study.

7.1 Project Information

Project number IM-STIM(001) has been awarded to a contractor in March 2009 and opened to traffic in 2011. The scope of project is 12.83 lane miles full depth reconstruction of I-40 with DJPCC from milepost 281.67 to milepost 288.22. The project is located in Muskogee County on control section 51-15 with annual average daily traffic of 17,500.

During the inception phase, two pavement designs were available for this project which can be summarized to:

1) 11” of DJPCC and 4” cement treated base on top of 8” aggregate base and

2) 13” HMA plus 2” SMA plus 1.25” PFC on top of 8” aggregate base.

Figures 7.1 and 7.2 show rigid and flexible pavement designs suggested for this project. The pay items with the unit prices and the initial pavement construction cost analysis can be seen in Table 7.1 for rigid pavement and Table 7.2 for flexible pavement.

Table 7.1 Flexible Surfacing Cost of Project No. IM-STIM(001)

Item	Unit	Total Quantity	Unit Price	Subtotal Price
Fly Ash (12% over 100%)	Ton	16,261	$50.00	$813,050.00
Lime (5% over 35%)	Ton	2,304	$120.00	$276,480.00
Cementitious Stabilized Subgrade	S.Y.	368,582	$1.75	$645,018.50
Lime Stabilized Subgrade	S.Y.	129,410	$2.50	$323,525.00
TBSC Type E	Ton	44,718	$25.00	$1,117,950.00
Aggregate Base	C.Y.	75,207	$29.00	$2,181,003.00
Separator Fabric	S.Y.	368,582	$1.00	$368,582.00
Prime Coat	Gal.	136,863	$1.75	$239,510.25
Tack Coat	Gal.	69,787	$1.50	$104,680.50
HMA S3 (PG 65-22)	Ton	170,130	$70.00	$11,909,100.00
HMA S3 (PG 76-28)	Ton	36,316	$80.00	$2,905,280.00
SMA (PG 76-28)	Ton	23,850	$90.00	$2,146,500.00
PFC	Ton	13,275	$100.00	$1,327,500.00
HMAS4 (OG 64-22)	Ton	8,400	$75.00	$630,000.00
Total				**$24,988,179.25**

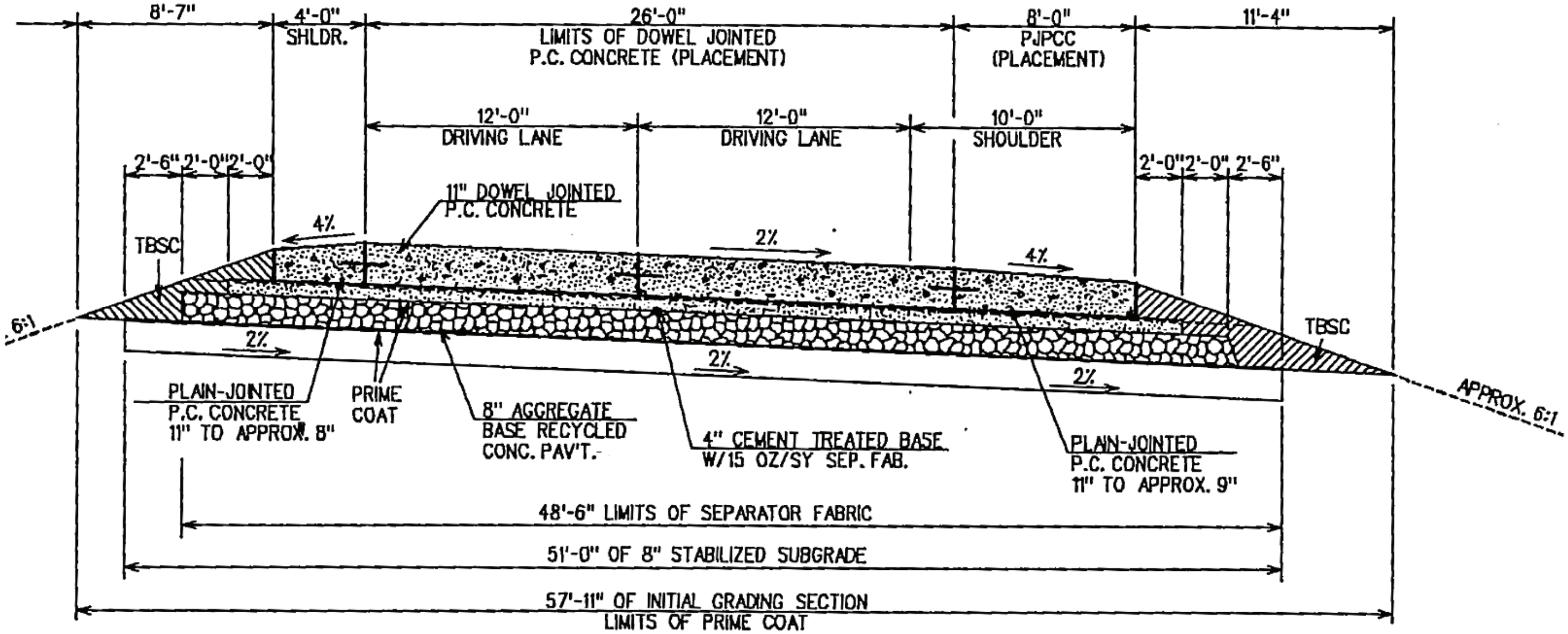


Figure 7.1 Rigid Section of I-40 Pavement Rehabilitation Project (Eastbound)

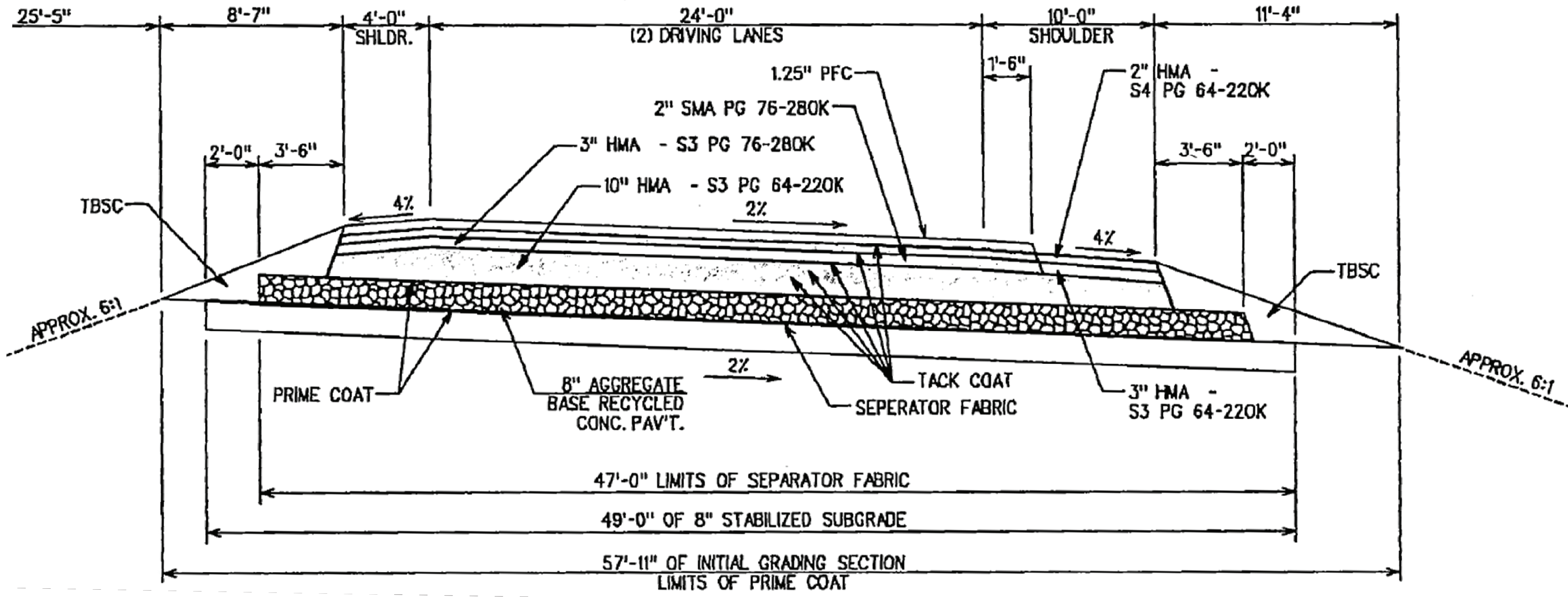


Figure 7.2 Flexible Section of I-40 Pavement Rehabilitation Project (Eastbound)

Table 7.2 Rigid Surfacing Cost of Project No. IM-STIM(001)

Item	Unit	Total Quantity	Unit Price	Subtotal Price
Fly Ash (12% over 100%)	Ton	16,261	$50.00	$813,050.00
Lime (5% over 35%)	Ton	2,439	$120.00	$292,680.00
Cementitious Stabilized Subgrade	S.Y.	384,165	$1.75	$672,288.75
Lime Stabilized Subgrade	S.Y.	134,153	$2.50	$335,382.50
TBSC Type E	Ton	42,007	$25.00	$1,050,175.00
Aggregate Base	C.Y.	76,562	$29.00	$2,220,298.00
Cement Treated Base	S.Y.	316,411	$9.00	$2,847,699.00
Separator Fabric	S.Y.	400,426	$1.00	$400,426.00
Prime Coat	Gal.	138,218	$1.75	$241,881.50
P.C. Concrete Pavement (Placement)	S.Y.	90,113	$8.00	$720,904.00
Dowel Jointed P.C. Concrete Pavement (Placement)	S.Y.	195,809	$10.00	$1,958,090.00
P.C. Concrete for Pavement (Only)	C.Y.	84,015	$80.00	$6,721,200.00
Total				**$18,274,074.75**

7.2 Life Cycle Cost Analysis

Both deterministic and realistic LCCA models are used in this case study to calculate the LCC of rigid and flexible pavement projects. Table 5.1 in Chapter 5 determines the deterministic LCCA model developed for flexible and rigid pavement sections of Interstate 40. According to this model, flexible pavement sections are treated two times during their lifecycle. Rigid pavement sections, on the other hand, are treated once before the end of their service life.

7.2.1 Salvage Value

Salvage value represents the value of an investment alternative at the end of the analysis period. This cost is included as negative cost in LCCA. The two fundamental components associated with salvage value are residual value and serviceable life. Residual value refers to the net value obtained from recycling the pavement. The difference between residual values of AC pavement and DJCP sections is generally not very large, and when discounted over 33 years, tends to have little effect on LCCA results. Serviceable life represents the more significant salvage value component and is the remaining life in a pavement alternative at the end of the analysis period.

For example, over a 33-year analysis, AC pavement section reaches terminal serviceability at year 33, while DJCP section requires a 6-year design rehabilitation at year 28. In this case, the serviceable life of AC pavement section at year 33 would be 0, as it has reached its terminal serviceability. Conversely, DJCP section receives a 6-year design rehabilitation at year 28 and will have 1 year of serviceable life at year 33, the year the analysis terminates. The value of the serviceable life of DJCP section at year 33 is calculated as a percent of design life remaining at the end of the analysis period (1 of 6 years or 16.67%) multiplied by the cost of DJCP section's rehabilitation at year 33. So the salvage value for pavement alternatives is prorated-based on the cost of final rehabilitation activity, expected life of rehabilitation, and time since last rehabilitation activity as shown below:

$$SV = \left(1 - \frac{L_A}{L_E}\right) C \qquad (7.1)$$

Where

L_E = the expected life of the rehabilitation

L_A = portion of expected life consumed

C = cost of the rehabilitation activity

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	A	B	C	D
1	**Life-Cycle Cost Adjustment Worksheet**			
2				
3	Job Piece No.		20900(05)	
4	Federal Project No.		IM-STIM(001)	
5	County		Muskogee	
6	Route		I-40	
7	Letting Date			
8	Project Length (mi)			
9				
10				
11	Total Area of Paving		286,072.0	SY
12	Area of Traveled Way		195,809.0	SY
13	Area of Shoulders		90,338.7	SY
14				
15	Asphalt Weight Factor		1.97	Tons/CY
16	OGFC Weight Factor		1.97	Tons/CY
17				
18	Analysis Period		33.00	yrs
19				
20	Estimated Unit Price for Asphalt		$70.00	/Ton
21	Estimated Unit Price for Shoulders		$65.00	/Ton
22	Estimated Unit Price for Cold Milling		$2.82	/SY
23	Estimated Unit Price for Diamond Grinding		$2.50	/SY
24				
25	Estimated Unit Price for Open Graded Friction Surface Course		$105.00	/Ton
26	Estimated Unit Price for Fabric Reinforcement		$0.70	/SY
27	Estimated Unit Price for Partial Depth PCC Patching		$125.00	/SY
28	Estimated Unit Price for Sawing		$4.80	/LF
29	Estimated Unit Price for Slab Repair Project		$9.23	/SY
30	Estimated Unit Price for Joint Rehabilitation		$7.10	/SY
31	Estimated Unit Price for Microsurface		$8.52	/SY
32	Estimated Unit Price for Thin_OL1		$18.47	/SY
33	Estimated Unit Price for Mill_Med_OL1		$21.31	/SY
34	Estimated Unit Price for Med_OL1		$21.31	/SY
35	Estimated Unit Price for Mill_Thin_OL1		$13.66	/SY
36	Estimated Unit Price for Grinding		$7.10	/SY
37	Estimated Unit Price for AC Leveling Course		$160.00	/CY
38				
39				
40	Miscellaneous for Asphalt		11.70%	
41	Mobilization for Asphalt		4.60%	
42	Construction added costs for Asphalt		10.10%	
43				
44	Miscellaneous for Concrete		23.00%	
45	Mobilization for Concrete		4.90%	
46	Construction added costs for Concrete		9.60%	

Figure 7.3 Deterministic LCCA Spreadsheet (General Project Information)

7.2.2 Deterministic LCCA

A spreadsheet is developed to perform deterministic LCCA. Figure 7.3 shows a snapshot of this spreadsheet software. Project information, scope of project, asphalt weight factor, and estimated unit price for material is indicated in this part of the LCCA spreadsheet. Asphalt and OGFC weight factors are required because the unit prices of these items are available in Tons while quantities are estimated based on the geometry of pavement sections in terms of square yard.

The LCC is calculated for both flexible and rigid pavement projects. The deterministic LCC model illustrated in Table 5.1 is utilized to determine the timing and scope of treatment activities. As can be seen in Table 7.3, the averages of OMB real interest rates from 2003 to 2012 are calculated to be used in the LCCA. The average of real interest rates for years 12, 23, and 28 are straight line interpolation from the published rates.

Table 7.3 Average of OMB Real Interest Rates From 2003 to 2012

Year	5-Year	10-Year	12-Year*	20-Year	23-Year*	28-Year*	30-Year +
Real Interest Rate	1.750%	2.300%	2.380%	2.730%	2.760%	2.810%	2.830%

*Straight Line Interpolation From Published Rates

The expenditure stream diagrams for both AC pavement and DJCP sections are shown in Figure 7.4. It is assumed that the AC pavement sections reach the end of their service lives after 33 years and DJCP sections after 34 years. Therefore, the analysis period is assumed to be 33 years in order to facilitate the calculation of salvage values. The salvage value for AC pavement sections is equal to zero while DJCP sections have a salvage value remaining at the end of the analysis period.

Figure 7.5 shows the process of LCCA for AC pavement. As can be seen there are two treatment activities which are performed at years 12 and 23. The treatment activities are based on the LCC models developed in Table 5.1. For each treatment activity, miscellaneous, mobilization, and construction costs are also added to the LCC. The percentages associated with these items are adopted from Missouri DOT LCCA models. These percentages can also be modified by SHAs based on project characteristics and historical information. The thickness of treatment activities are based on the average thickness of treatments in the historical data base.

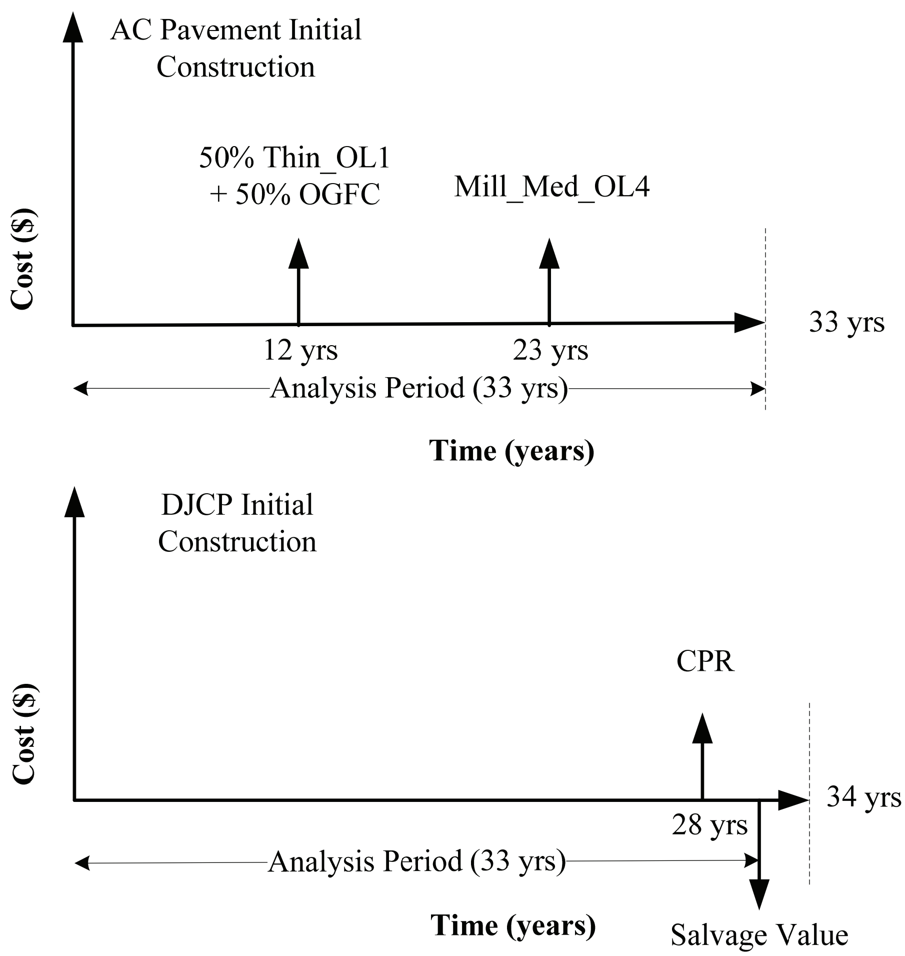


Figure 7.4 Expenditure Stream Diagrams for Deterministic AC Pavement and DJCP Sections LCCA

The quantity of material used for the treatment is calculated using the area of paving, area of traveled way, and area of shoulders. For OGFC and AC overlays the weight of material is calculated using the weight factors provided in general information. The unit price of materials is based on the unit prices provided in the general project information section.

Cost of material is the product of quantity and unit price. In this case study, the miscellaneous cost is 11.7% of the total treatment costs. Mobilization cost is 4.6% of total treatment costs plus miscellaneous costs. Construction added cost is 10.1% of total treatment costs plus miscellaneous cost plus mobilization cost. Then the cost is discounted using the real interest rate and year of treatment activity. The cost and present worth of both treatment activities are added and reported as total cost and total present worth of AC pavement treatment activities. The total present worth of future treatment activities is calculated with the OMB average discount rate and the analysis period of 33 years. The total LCC of AC pavement project is $7,299,879.

Figure 7.6 shows the LCCA analysis for DJCP project. According to the deterministic LCC model, only one treatment is applied on the section which is going to be at year 28. The end of serviceability of DJCP sections is one year more than AC pavement sections. Therefore, the LCC of DJCP sections are adjusted for salvage value. The adjusting factor is approximately 97% which is obtained by dividing the entire life of AC pavement sections by the entire life of DJCP sections. The CPR or concrete pavement restoration is a combination of different treatment activities with different weighting factors. Based on the historical pavement treatment data set of Interstate 40, CPR is a combination of 10%

Traveled Way Full Depth PCC Patching, 20% Slab Repair of Traveled Way, 30% Joint-Rehabilitation of Traveled Way, and 40% Diamond Grinding of Traveled Way.

	A	B	C	D	E	F	G	H	I
1									
2	**ODOT AC Projection**								
3			% or				Unit		Present
4			Thick. (in.)	Year	Quantity	Unit	Price	Cost	Worth
5									
6	**12 Year Maintenance**	12							
7	Discount Rate:	2.380%							
8									
9	Open Graded Friction Course Traveled Way	50.0%	1.25	12	13,394	TON	$105.00	$703,179	$530,254
10	Thin AC Overlay of Traveled Way	50.0%	1.85	12	195,809	SY	$18.47	$1,808,296	$1,363,603
11	Miscellaneous		11.7%	12	1	Price	$293,842.55	$293,843	$221,581
12	Mobilization		4.6%	12	1	Price	$129,044.60	$129,045	$97,310
13	Construction added costs		10.1%	12	1	Price	$296,370.56	$296,371	$223,488
14									
15									
16	**23 Year Maintenance**	23							
17	Discount Rate:	2.760%							
18									
19	Mill and Medium AC Overlay of Traveled Way		4.16	23	195,809	SY	$21.31	$4,172,690	$2,230,806
20	Open Graded Friction Course Traveled Way		1.25	23	13,394	TON	$105.00	$1,406,357	$751,868
21	Fabric Reinforcement	x2		23	391,618	SY	$0.70	$274,133	$146,557
22	Resurfacing Shoulders		1.75	23	18,751	TON	$65.00	$1,218,843	$651,619
23	Miscellaneous		11.7%	23	1	Price	$827,426.66	$827,427	$442,359
24	Mobilization		4.6%	23	1	Price	$363,374.67	$363,375	$194,268
25	Construction added costs		10.1%	23	1	Price	$834,545.24	$834,545	$446,165
26									
27									
28	**Years in analysis:**		**Total Cost:**					**$12,328,102**	**$7,299,879**
29	33.00		End of service life	33	yrs				
30	Discount Rate:	2.830%							
31			**Equivalent Uniform Annual Cost:**						**$343,252**
32									

Figure 7.5 Deterministic LCCA Spreadsheet for AC Pavement Sections

	A	B	C	D	E	F	G	H	I
34	**ODOT DJCP Projection**								
35			% or				Unit		Present
36			Thick. (in.)	Year	Quantity	Unit	Price	Cost	Worth
37	**28 Year Maintenance**	28							
38	Discount Rate:	2.810%							
39	**Treatment**	**Scope**							
40	Traveled Way Full Depth PCC Patching	10.00%		28	19,581	SY	$125.00	$2,447,613	$1,126,556
41	Slab Repair Traveled Way	20.00%		28	39,162	SY	$9.23	$361,463	$166,370
42	Joint Rehabilitation Traveled Way	30.00%		28	58,743	SY	$7.10	$417,073	$191,965
43	Diamond Grinding of Traveled Way	40.00%		28	78,324	SY	$2.50	$195,809	$90,124
44	Miscellaneous		23.0%	28	1	Price	$787,050.36	$787,050	$362,253
45	Mobilization		4.9%	28	1	Price	$206,241.41	$206,241	$94,926
46	Construction added costs		9.6%	28	1	Price	$423,863.99	$423,864	$195,091
47									
48	**Salvage Value**	33							
49	Discount Rate:	2.830%							
50									
51				33			Treatment 1	$806,518.97	-$321,115
52									
53	**Years in analysis:**				**Total Cost:**			**$4,839,114**	**$1,906,170**
54	33.00								
55	Discount Rate:	2.830%	End of service life	34	yrs				
56			**Equivalent Uniform Annual Cost:**						**$89,631**
57									

Figure 7.6 Deterministic LCCA for DJCP Pavement Sections

The Miscellaneous, Mobilization, and Construction added cost factors for DJCP sections are assumed to be 23%, 4.9%, and 9.6% accordingly. Using the same equations and procedure as AC pavement sections, the total present worth cost for DJCP project would be $1,906,170.

Deterministic LCCA Results

The results of the deterministic LCCA analysis indicate that the present worth of treatment costs for AC pavement project would be $5,393,709 more than that of DJCP pavement project. Table 7.4 shows the breakdown of LCCA of both projects. According to the results of LCCA, rigid pavement is clearly the superior pavement type. The rigid pavement is not only $6,715,100 lower in initial cost, but also the present worth of its future treatments is $5,393,709 less than flexible pavement sections. Therefore, the LCC of DJCP for this project is in total $12,108,809 lower than AC pavement.

Table 7.4 Summary of Deterministic LCCA Results for Asphalt and Concrete Pavement Sections

Project	Initial Pavement Cost ($)	Present Worth of Treatment Costs ($)	Total LCCA ($)
AC Pavement	24,989,000	7,299,879	32,288,879
DJCP	18,273,900	1,906,170	20,180,070

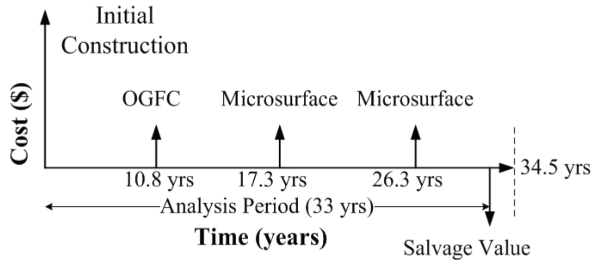
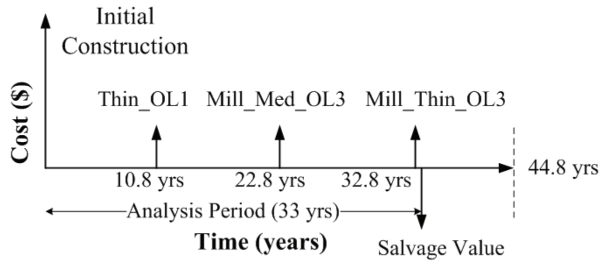
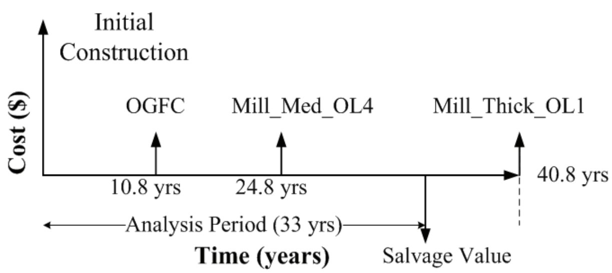
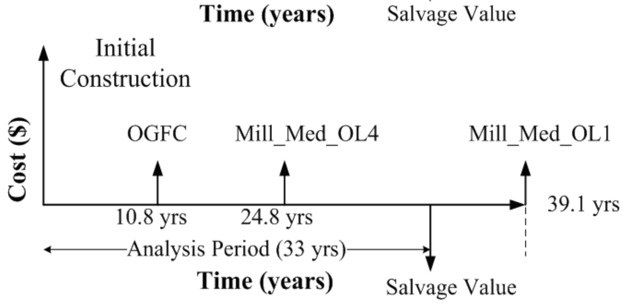
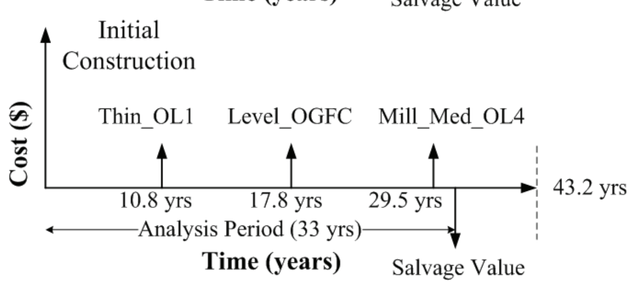
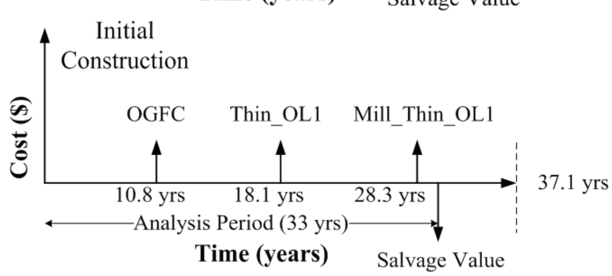
7.2.3 Realistic LCCA

The realistic LCCA is based on the models developed for AC pavement and DJCP sections in Chapter 6. Unlike the traditional LCCA, pavement sections are treated with different treatment types with different probabilities of occurrence during their lifecycle. The spreadsheet developed for deterministic LCCA is used for the realistic LCCA tool. The only difference is that instead of determining one LCC for each pavement type, multiple LCC's are developed and weighted average of those costs are considered as the total LCC of that pavement type. Table 6.7 in Chapter 6 shows the realistic LCCA model for AC pavement sections. The expenditure stream diagrams are developed based on the realistic LCCA models. An Excel-based spreadsheet is developed to calculate LCC for each treatment scenario. The details of calculations can be seen in Appendix D.

Table 7.5 shows the realistic LCCA model for AC pavement sections together with their associated expenditure stream diagrams, probability and net present worth. Each treatment scenario in the model has a unique expenditure stream diagram with different treatment activities, treatment timing, and end of serviceable life. The analysis periods for all the diagrams have been assumed to be 33 years. In all the treatment scenarios, AC pavement sections are treated at least two times during the analysis period which satisfies FHWA recommendations for LCCA. In addition, adopting the same analysis period as the deterministic analysis would enable a better comparison between realistic and deterministic approaches.

In the first treatment scenario, all the treatment costs at years 10.8, 17.3, and 26.3 are discounted to the present year. There is remaining service life at the end of analysis period which is calculated by the equation introduced in salvage value section. The last Microsurface applied on the pavement at year 26.3 extends the service life of pavement for 8.2 years. However, the analysis period ends 6.7 years after the treatment activity. Therefore the section has a remaining life of equal to 1.5 years at the end of the analysis period.

Table 7.5 Realistic LCCA for AC Pavement Sections

No.	Expenditure Stream Diagram	Probability	Present Worth
1		30.94 %	$3,666,254
2		21.21 %	$7,533,845
3		18.56 %	$3,760,930
4		14.85 %	$3,943,578
5		7.96 %	$13,456,222
6		6.48 %	$5,227,307

The salvage value calculations for the second, the fifth, and the sixth scenarios would be the same as the first scenario. In the third and the fourth scenarios, the treatment activities in years 10.8 and 24.8 are discounted to the present time. The third treatment is applied at the end of the service life of pavement. Therefore, this treatment is not considered during the LCCA and the salvage value would be calculated by considering the remaining service life of pavement due to the second treatment activity.

The net present worth for each treatment scenario is multiplied by its associated probability and added together to obtain realistic LCC for AC pavement sections. This process has been illustrated in Table 7.6 which results in realistic LCCA of $5,425,520.29.

Table 7.6 Realistic LCCA Results for AC Pavement

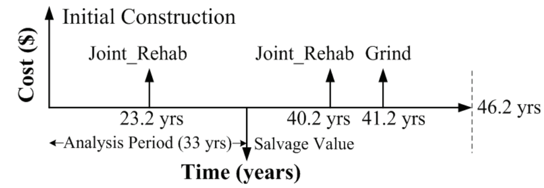
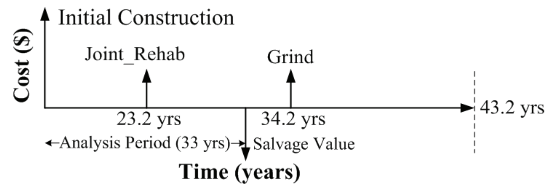
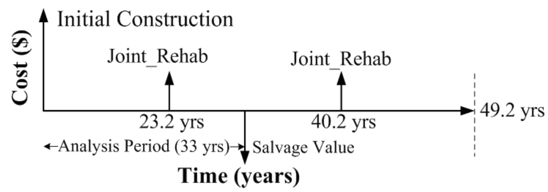
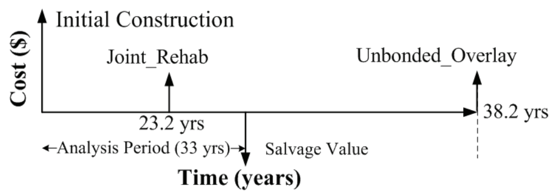
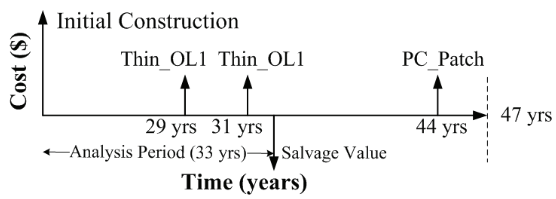
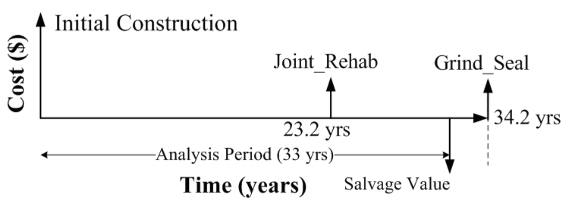
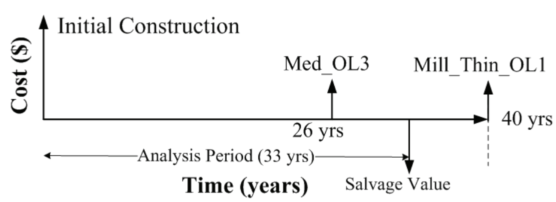
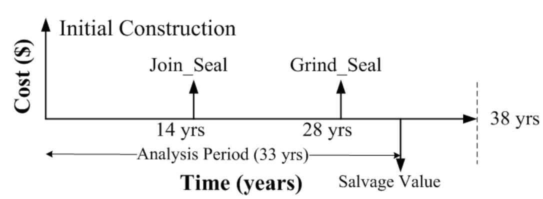
ODOT Realistic AC LCCA				
Rule No.	**Rule**	**Probability (%)**	**Present Worth**	**Probability × Present Worth**
1	OGFC=>Microsurface=>Microsurface	30.94	3,666,254	1,134,203
2	Thin_OL1=>Mill_Med_OL3=>Mill_Thin_OL3	21.21	7,533,845	1,598,173
3	OGFC=>Mill_Med_OL4=>Mill_Thick_OL1	18.56	3,760,930	698,123
4	OGFC=>Mill_Med_OL4=>Mill_Med_OL1	14.85	3,943,578	585,622
5	Thin_OL1=>Level_OGFC=>Mill_Med_OL4	7.96	13,456,222	1,070,563
6	OGFC=>Thin_OL1=>Mill_Thin_OL1	6.48	5,227,307	338,836
Weighted Average Present Worth				**$5,425,520.29**

The realistic LCCA for DJCP sections utilizes the LCCA models developed in Chapter 6. A net present worth is calculated for each treatment scenario in the realistic model. A spreadsheet is developed and used to perform the LCCA. Table 7.7 shows the expenditure stream diagrams for possible DJCP section treatment scenario together with their associated probability and net present worth. The realistic LCCA model for DJCP sections consists of eight different treatment scenarios. Each treatment scenario has unique treatment types, treatment timing, service life, and probability of occurrence.

The treatment activities within the analysis period are discounted to present year utilizing the average OMB real interest rates. The analysis period for all the scenarios is assumed to be 33 years in order to be consistent and comparable with other analyses in this chapter. All the treatment scenarios have at least one treatment during the analysis period which is in conformance with FHWA recommendations.

The salvage value is a negative cost calculated at the end of the analysis period representing the remaining life of pavement section. The salvage value is calculated by determining the remaining service life of the last treatment activity before the end of the analysis period. In the first treatment scenario, Joint_Rehab which is applied in year 23.2 extends the service life of pavement for 17 years. This implies that the remaining service life associated with the treatment at the end of the analysis period would be 7.2 years. Using the equation introduced in the salvage value section (Equation 7.1), a portion of Joint_Rehab cost (7.2 divided by 17) is added as the salvage value. The details of analysis are available in Appendix E.

Table 7.7 Realistic LCCA for DJCP Sections

No.	Expenditure Stream Diagram	Probability	Present Worth
1		25.01 %	$713,360
2		25.01 %	$959,490
3		25.01 %	$713,360
4		8.34 %	$773,525
5		4.18 %	$2,713,338
6		4.17 %	$959,490
7		4.15 %	$3,022,760
8		4.15 %	$1,907,554

The final results of realistic LCCA for DJCP sections are illustrated in Table 7.8. The present worth of each treatment scenario is multiplied by the probability of occurrence of that scenario and added together resulting in the realistic LCCA. As can be seen in this table, the present worth of treatment scenarios range from $713,360 to $2,713,338. However, the weighted average of these present values is $1,019,136.47. This would be the realistic LCC for DJCP sections in Interstate 40.

Table 7.8 Final Results of LCCA for DJCP Sections

ODOT Realistic DJCP LCCA				
Rule No.	**Rule**	**Probability**	**Present Worth ($)**	**Probability × Present Worth**
1	Joint_Rehab ==> Joint_Rehab ==> Grind	25.01%	713,360	$178,384.70
2	Joint_Rehab ==> Grind ==> Reconstruction	25.01%	959,490	$239,932.41
3	Joint_Rehab ==> Joint_Rehab ==> Reconstruction	25.01%	713,360	$178,384.70
4	Joint_Rehab ==> Unbonded_Overlay	8.34%	773,525	$64,476.56
5	Thin_OL1 ==> Thin_OL1 ==> PC_Patch	4.18%	2,713,338	$113,310.17
6	Joint_Rehab ==> Grind_Seal	4.17%	959,490	$39,988.73
7	Med_OL3 ==> Mill_Thin_OL1	4.15%	3,022,760	$125,475.91
8	Joint_Seal ==> Grind_Seal ==> Reconstruction	4.15%	1,907,554	$79,183.28
	Realistic LCCA			**$1,019,136.47**

Realistic LCCA Results

The results of realistic LCCA indicate that the present worth of treatment costs for AC pavement project would be $5,229,793 more than that of DJCP pavement project. Table 7.9 shows the breakdown of LCCA of both projects. According to the results of LCCA, rigid pavement is clearly the superior pavement type. The rigid pavement is not only $6,715,100 lower in initial construction cost, but also the present worth of its future treatments is $5,229,793 less than flexible pavement sections. Therefore, the LCC of DJCP for this project is in total $11,944,893 lower than AC pavement. Therefore, this project is not suitable for alternate bidding and the pavement with the lower total LCC should be selected.

Table 7.9 Summary of Realistic LCCA Results for Asphalt and Concrete Pavement Sections

Project	Initial Pavement Cost ($)	Present Worth of Treatment Costs ($)	Total LCC ($)
AC Pavement	24,989,000	5,425,520	30,414,520
DJCP	18,273,900	1,019,136	19,293,036

7.3 Construction of A+B+L Bidding Model

Unlike traditional bidding models, SHAs are required to determine two factors before letting A+B+L bidding projects. One of these factors is the UTV which is multiplied by the number of days proposed by each contractor to determine the "B" parameter. According to the computational framework developed in Chapter 3, SHAs should determine the UTV that maximizes the competition during the bid process. It was determined in Chapter 3 that $23,128/day would be the UTV that maximizes competition between contractors. The other parameter that needs to be determined by SHAs is "L" which is the difference between LCCs of the alternative pavement designs. Based on the realistic LCCA models, the "L" parameter would be equal to $4,406,384 which is only added to the total combined bid of asphalt contractors. This is due to the fact that the LCC of asphalt pavement is more than the LCC of concrete pavement. Based on the models developed in this dissertation, the following would be the optimal bid model provided to contractors.

$$Total\ bid\ for\ Asphalt\ Contractors: A + (\$23{,}128/day \times Duration) + \$4{,}406{,}384 \quad (7.2)$$

$$Total\ bid\ for\ Concrete\ Contractors: A + (\$23{,}128/day \times Duration) \quad (7.3)$$

Where A is the base bid or the price proposed by each contractor and Duration is the project duration (typically for substantial completion) proposed by each contractor. Each contractor that proposes the lowest total combined bid would win the project. As can be seen in this bid model, asphalt contractors should either adjust their proposed base bid price or duration or a combination of these two in order to compete with concrete contractors because concrete pavements requires less future maintenance and rehabilitation costs in this case.

Figure 7.7 shows an A+B+L bid competition between the three contractors participated in the case analysis in Chapter 3 when UTV is equal to $23,128/day. Each contractor can either propose an asphalt or concrete pavement. The solid lines indicate the most competitive bid strategies of contractors if they propose concrete pavement. The dotted lines indicate the most competitive bid strategies of contractors when they propose asphalt pavement. The dotted lines are bid strategies that are $4,406,384 more than the solid lines due to the LCC difference between asphalt and concrete pavement.

In the A+B+L bid model, competitiveness of a contractor is heavily dependent on the pavement type that they propose. Three contractors are competing in this bid competition and each contractor has two pavement options to select, therefore eight scenarios need to be investigated to exhaust every possible option in the competition. These eight scenarios are shown in Table 7.10. For instance, in scenario 1, all the contractors propose concrete pavement and in scenario 2 contractor L and contractor D propose concrete pavement while contractor J proposes asphalt pavement.

The total combined bids are calculated for each scenario based on the price-time equations as well as Equations 7.2 and 7.3. The average differences between contractors' TCBs are calculated utilizing Equation 3.25 for each scenario. As can be seen in this table, the differences between contractors' TCBs are minimal when all the contractors are proposing the same type of pavement. Unlike A+B bidding that contractor D's bidding strategies is always noncompetitive, in one of the A+B+L bidding scenarios this contractor has the lowest TCB and is very likely to win the bid competition. This happens in scenario 7 when both contractor L and contractor J propose asphalt pavement and contractor D proposes concrete pavement. Contractor L and contractor J have the same level of competitiveness when they propose the same type of pavement and their competitiveness can be different when their proposed pavement types are different.

If we assume that all the contractors have the ability to propose both asphalt and concrete pavements, then the following situations exist. Both contractor L and contractor J know that if they propose asphalt pavement, they are significantly increasing other contractors' chances of winning the competition. For instance, if contractor L selects asphalt pavement, contractor J or contractor D can easily win the competition by selecting concrete pavement. On the other hand, contractor D will always select the concrete pavement because this would be the only situation that provides them with a chance of winning the competition. Therefore, when all the contractors have the ability to propose both asphalt and concrete pavements, all of them select concrete pavement and UTV of equal to $23,128/day creates the highest level of competition.

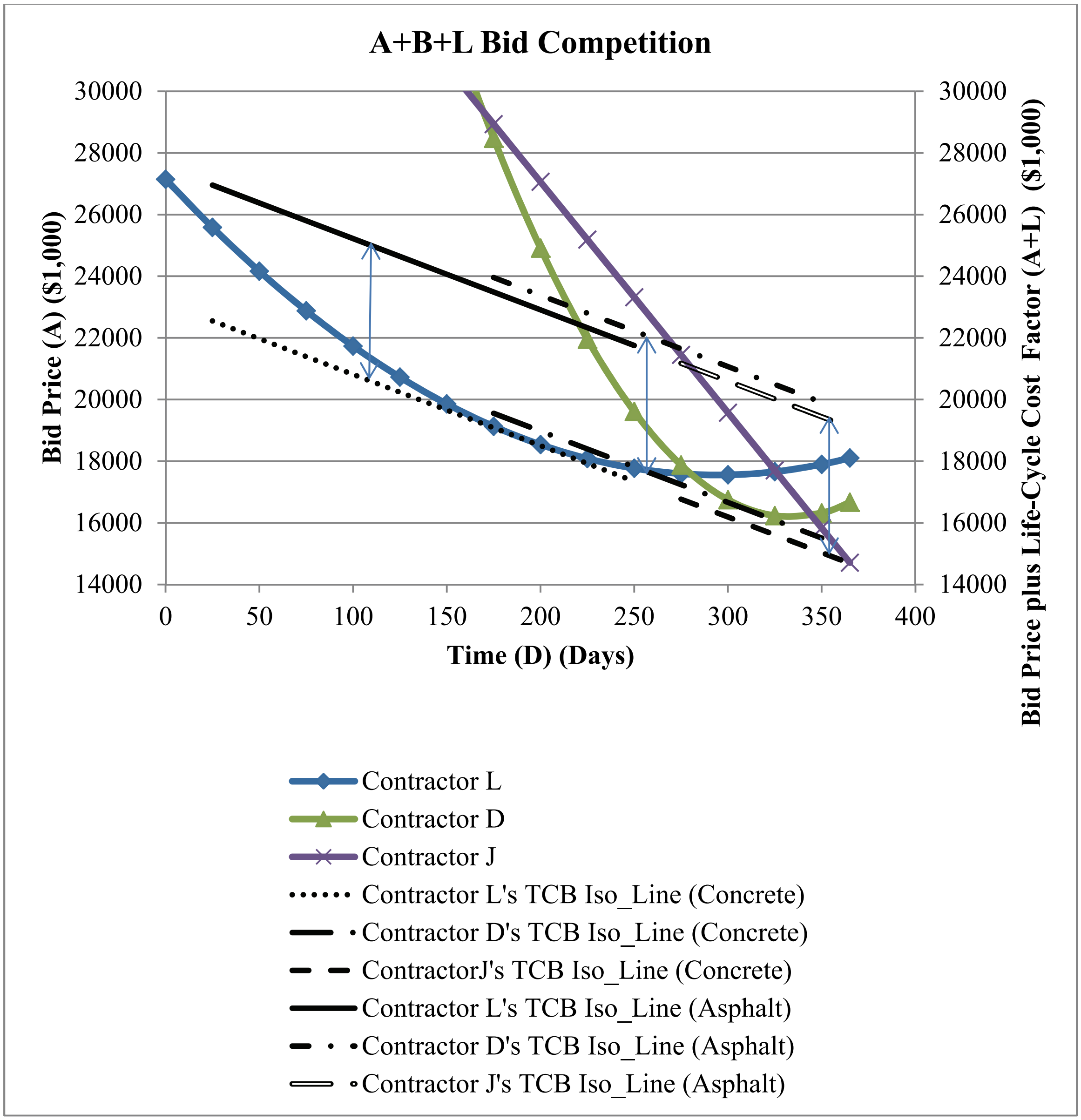


Figure 7.7 A+B+L Bid Competition

It can be inferred from this case study that inclusion of "L" in the bid model can decrease the level of competition during the bid process if contractors do not propose the same type of pavement. However, A+B+L bid model stimulates contractors to either select a pavement type with lower LCC or propose lower bid price and/or duration to stay competitive in the bid competition. Alternate pavement type bidding can attract more contractors to the bid process because it creates a situation where both asphalt and concrete industries can participate. More participation during the bid process means more competition between contractors. However, this case study cannot measure the impact of the number of contractors on the level of competition.

Table 7.10 Possible Scenarios in A+B+L Bid Competition

Scenario	Contractor	Pavement Type	Total Combined Bid	Winning Contractor	Average Differences Between Contractors' TCB
1	L	Concrete	$23,128,000	L & J	$314,667
	D	Concrete	$23,600,000		
	J	Concrete	$23,128,000		
2	L	Concrete	$23,128,000	L	$2,937,589
	D	Concrete	$23,600,000		
	J	Asphalt	$27,534,384		
3	L	Concrete	$23,128,000	L	$3,252,256
	D	Asphalt	$28,006,384		
	J	Asphalt	$27,534,384		
4	L	Asphalt	$27,534,384	L & J	$314,667
	D	Asphalt	$28,006,384		
	J	Asphalt	$27,534,384		
5	L	Concrete	$23,128,000	L & J	$3,252,256
	D	Asphalt	$28,006,384		
	J	Concrete	$23,128,000		
6	L	Asphalt	$27,534,384	J	$2,937,589
	D	Concrete	$23,600,000		
	J	Concrete	$23,128,000		
7	L	Asphalt	$27,534,384	D	$2,622,923
	D	Concrete	$23,600,000		
	J	Asphalt	$27,534,384		
8	L	Asphalt	$27,534,384	J	$3,252,256
	D	Asphalt	$28,006,384		
	J	Concrete	$23,128,000		

When all the contractors are capable of proposing both types of pavement or there is no information about contractors' preferred pavement types, the UTV of equal to $23,128 is the optimal UTV that maximizes the competition during the bid process. In three scenarios (scenario 1, scenario 4, and scenario 5) contractor L and contractor J have the same levels of competitiveness. In these scenarios both contractors are proposing the same pavement type. In scenario 2 and scenario 3 contractor L is the most competitive contractor and in scenario 6 and scenario 8 contractor J is the most competitive contractor. Therefore, both contractor L and contractor J can win the bid competition in five out of 8 scenarios.

7.4 Summary

By comparing the results of deterministic and realistic LCCA, it is inferred that realistic approach has resulted in lower LCCs. Table 7.11 shows the results of LCCA for AC pavement and DJCP sections with two different approaches. The realistic LCCA approach has resulted in 26% lower LCC in AC pavement sections and 47% lower LCC in DJCP sections. The difference between LCCs of rigid and flexible pavement sections is 18.3% more in deterministic approach. The difference between LCC of rigid and flexible pavement is the L factor which is used in the alternate bidding.

Figure 7.8 shows the bar chart of LCCA results for deterministic and realistic approaches. Although this case study revealed that this project is not suitable for alternate bidding, the LCC factors were calculated to determine the difference between these two approaches. Figure 7.9 shows the bar chart of LCC factors calculated by two different approaches.

The results of this analysis indicate that the realistic LCCA approach can be different from the traditional LCCA. The results of the realistic LCCA approach are closer to the actual costs because all the possible treatment strategies have been considered during the analysis.

Table 7.11 Comparison Between Deterministic and Realistic LCCA Approaches

	Deterministic LCCA	Realistic LCCA	Percentage of Difference
AC	$7,299,879	$5,425,520	26%
DJCP	$1,906,170	$1,019,136	47%
Difference Between AC and DJCP	5,393,709	4,406,400	18.3%

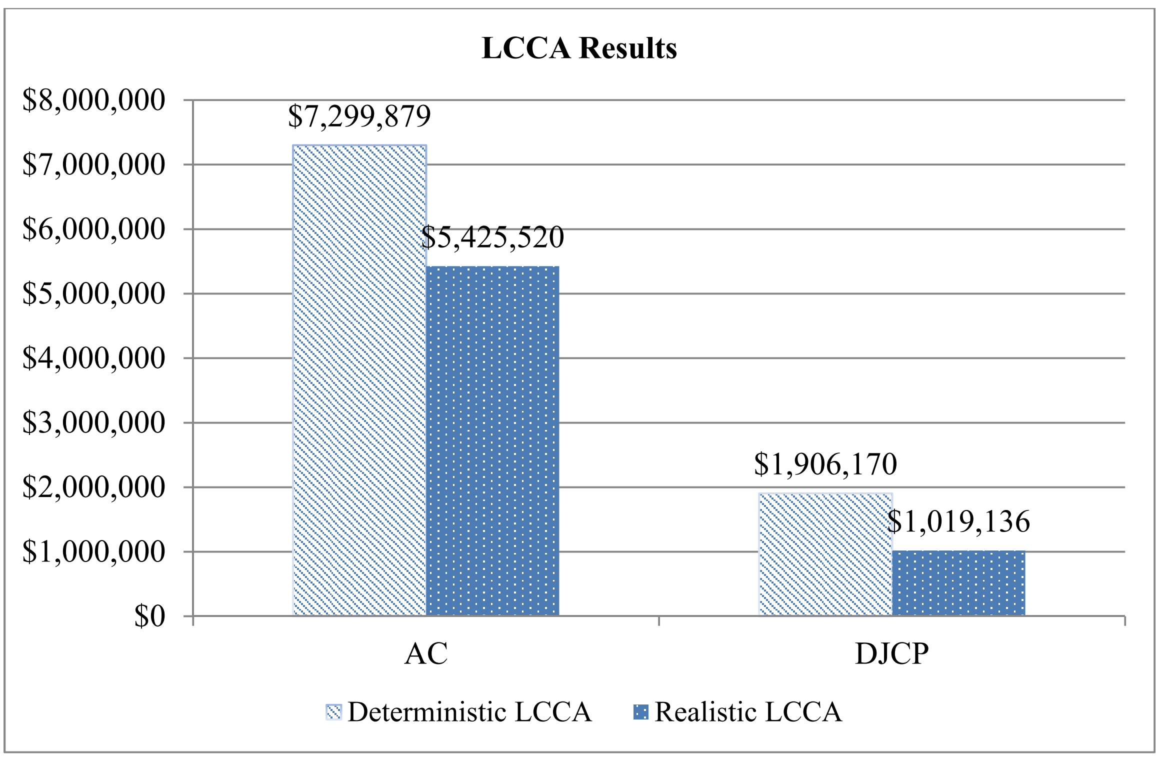


Figure 7.8 The LCCA Results for Deterministic and Realistic Approaches

An A+B+L bid model was constructed based on the bid parameters developed in this chapter and Chapter 3. The analysis of competition between contractors indicated that asphalt contractors need to decrease their proposed bid price and/or duration by a value of $4,406,384 in order to be able to compete with concrete contractors. Different scenarios were investigated in the A+B+L competition and it was concluded that the UTV of $23,128/day is still optimal when the preferred pavement type of contractors is not known during the bid competition.

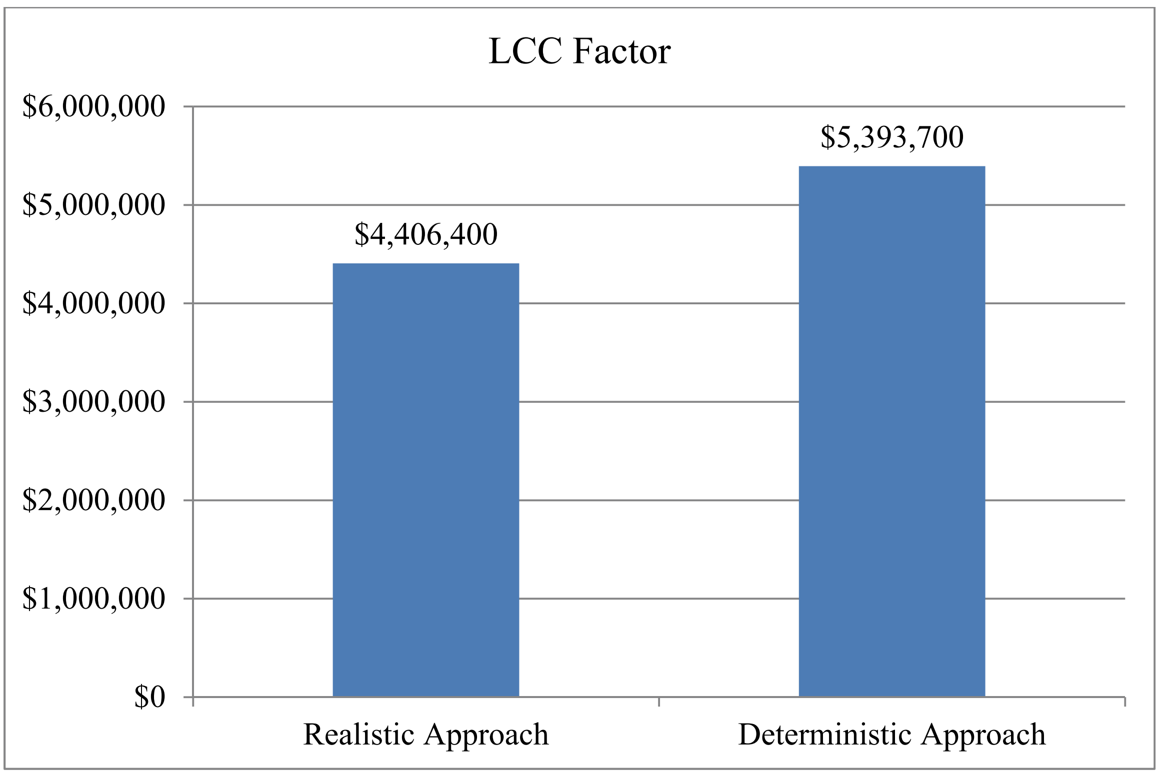


Figure 7.9 LCC Factors for Case Project Based on Realistic and Deterministic Approaches

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Two computational frameworks were developed in this study in order to determine time and life-cycle cost parameters for A+B+L bidding. Conventionally, the UTV or time parameter is determined based on the amount of road user cost in a reconstruction or rehabilitation project. The result of this research provides SHAs with a computational framework to determine the UTV that maximizes competition during the bid process. Conventionally SHAs consider one future treatment scenario when determining LCC of various pavement designs whereas it was determined in this study that even the same type of pavement sections that fall into one pavement family have been treated differently in their lifecycles. This study introduces a computational framework that enables SHAs to utilize their currently available historical treatment databases in order to find the patterns in the rehabilitation activities. The realistic LCCA models for asphalt and concrete pavements consider all the possible treatment strategies. This chapter summarizes the main conclusions drawn in this study and also provides recommendations for future studies.

8.1 Optimal UTV Determination

This part of the dissertation focused on evaluation of the impact of UTV upon competitiveness of contractors in A+B bidding projects. First the cost-time relationships for different contractors in ODOT were determined utilizing ANOVA and Regression analysis. In order to illustrate the impact of UTV on the A+B bidding competition, TCB Iso-Map, TCB Iso-Line, and a methodology to determine the most competitive bidding strategy for each contractor were illustrated. Through a hypothetical example, it was clearly shown that different UTVs can change the contractor who has the most competitive bidding strategy. The results suggested that the conventional approach that only takes road user costs into account in order to determine the incentive/disincentive rates for A+B bidding projects might result in sub-optimal results.

The results of ANOVA and regression analysis indicated that for the majority of contractors there is a significant relationship between time and bid price. The price-time models for contractors of ODOT were developed utilizing the historical A+B bidding data. In the case study, it was clearly shown how different UTVs change the level of competition in A+B bidding and may result in different winning contractors. A new factor was formulated that calculates the average of differences between contractors' TCB which should be minimized in A+B bidding projects to ensure a stimulated competition during the bid process.

This study laid a computational foundation that enables SHAs to determine the optimal Incentive/Disincentive rates that maximize the competition among contractors and result in selection of the most efficient contractor in construction acceleration. It also introduces an approach for contractors to study the strategies of their competitors before proposing a bid price utilizing the publically available bid data.

There are also significant implications in the findings of this study for the SHA's practice in implementing an A+B contracting method. Usually SHAs have two goals in using an A+B bidding method: 1) to encourage contractors to compete over the original bid price (A), and 2) to compete with each other to propose lower bid days in order to minimize the negative impact on the traveling public (B).

The SHAs should realize the full impact of selecting the UTV for bidding projects. If the UTV is very low, only contractors that are able to propose the lowest bid price will likely have a chance to win the project and those that are capable of accelerating construction are not competitive. If the UTV is very high, contractors that are capable of reducing the project duration are very likely to win the competition; whereas, those that can reduce the bid prices, but not the duration, are less competitive. In addition, contractors may adjust their bid proposal and propose a lower price and/or duration, if their most competitive strategy is very close to other contractors' competitive strategies and they are convinced that they are likely to win if they slightly change their strategies. When the vast majority of contractors are strictly noncompetitive, contractors are discouraged to propose lower bid prices and/or durations.

The computational framework developed in this study assist SHAs in determining the UTV that minimizes the difference between competitiveness of contractors. Therefore, contractors are encouraged to modify their bidding strategies and propose lower bid prices and/or durations to win the contract.

8.2 Realistic LCCA

The LCCA models developed in this study enables SHAs to calculate the life-cycle costs that are closer to actual costs. The life-cycle cost analysis has long been investigated; however, this study is not providing another LCCA model for asphalt and concrete pavements. This study introduces the framework to consider uncertainty in sequence and timing of treatment strategies in LCCA. Unlike the conventional LCCA models that assume a unique sequence and timing of treatment activities for pavement sections of the same family this study introduces a novel approach that enables SHAs to identify and consider all the possible sequences and timings of treatment activities for each pavement family.

The importance of accurate calculation of LCC of pavement type alternatives is two folds. First it results in accurate selection of projects for alternate pavement type bidding. In addition, the LCC factor which is the difference between the LCC of two pavement alternatives would be closer to actual cost which results in selection of a more cost-effective pavement alternative during the bid process.

The historical pavement treatment activities on Interstate 40 were utilized to extract treatment patterns adopted by ODOT. While this data set indicates the actual treatment strategies adopted by ODOT since the construction of Interstate Highways, a review of literature indicated that this data set has not been used for the purpose of developing LCC models.

Data preparation is one of the main challenges in applying the new process introduced in this study. The historical pavement treatment data are usually collected on a project basis.

Therefore, the pavement management datasets need to be restructured in a section-based format that association rules mining or sequence analysis can be applied. A unique five-step data preparation approach was adopted to restructure the data set and transform it into a format that is suitable for knowledge discovery and data mining purposes. These steps are transforming data set, breaking control sections, cleaning data set, defining pavement treatment types, and restructuring data set.

Two different approaches were used to create LCC models for different types of pavement: 1) Deterministic and 2) Realistic. In the deterministic approach the historical pavement treatment data set of Interstate 40 were used and the LCC model was developed based on statistics such as median and mean. Based on the deterministic model, the treatment activities that occur on each pavement type are the activities that has occurred the most in the data set. Also the time to these activities would be the average of the times that it has taken in the past. Therefore, if different treatment strategies have been applied on a pavement family during its lifecycle, the deterministic approach assumes that the strategy that has occurred the most is the LCC of that pavement family.

In contrast, realistic approach is based on the significant sequential pavement treatment patterns that are extracted from the data set utilizing a data mining technique called association rules mining. Therefore, the LCC models developed for pavement families consist of different treatment strategies with different probabilities of occurrence associated with them. In realistic LCCA model, a probability of occurrence is defined for each treatment strategy, and the final LCC is the weighted summation of individual NPVs. It was indicated that the results of these two approaches can be significantly different. The case study analysis indicated that the realistic LCCA approach resulted in 26% lower LCC in AC pavement sections and 47% lower LCC in DJCP sections.

Identifying the sequence of treatment activities is beneficial for several decisions made by SHAs. It assists in developing LCC models for different types of pavement. A realistic LCC model is critically important for pavement type selection or alternate bidding procedures such as A+B+L bidding method. This enables ODOT to do more with fewer amounts of tax dollars in the long run. By identifying the treatment strategies occurred during the last 50 years, ODOT would be able to plan more efficiently for future maintenance and rehabilitation projects. Contractors may also apply the same methodology on the data collected from their previous performance guarantee contracts in order to forecast pavement treatment activities for the purpose of improving their bid proposals.

One challenge SHAs faced while adopting the alternate pavement type bidding process has been lack of consensus between asphalt and concrete industries in the approach of calculating life-cycle cost adjustment factor. The realistic LCCA models based on historical pavement treatment data set is an unbiased approach that both asphalt and concrete industries can agree on the results. This approach is based on the treatment strategies that have actually occurred during the past.

An Excel-based spreadsheet was created to calculate LCC for flexible and rigid pavement alternatives. This spreadsheet enables SHAs to enter project information such as project scope, analysis period, estimated unit prices, miscellaneous, mobilization, and construction added costs for asphalt and concrete pavement projects and obtain deterministic and realistic LCCs of rigid and flexible pavement sections as well as the "L" parameter which is used in the A+B+L bidding.

8.3 A+B+L Bid Model

Based on the UTV and "L" parameter developed in Chapter 3 and Chapter 7 an A+B+L bidding model was constructed. The UTV for this model was $23,128/day and the "L" parameter for the model was equal to $4,406,384 which is equal to the difference between the LCC of asphalt and concrete pavements. The analysis of competition in this bod model indicated that inclusion of "L" in the bid model can decrease the level of competition during the bid process if contractors do not propose the same type of pavement. However, A+B+L bid model stimulates contractors to either select a pavement type with lower LCC or propose lower bid price and/or duration to stay competitive in the bid competition.

Alternate pavement type bidding can attract more contractors to the bid process because it creates a situation where both asphalt and concrete industries can participate. More participation during the bid process means more competition between contractors. However, this study is not measuring the impact of number of contractors on the level of competition.

An A+B+L bid model was constructed based on the bid parameters developed in this study. The analysis of competition between contractors indicated that asphalt contractors need to decrease their proposed bid price and/or duration by a value of $4,406,384 in order to be able to compete with concrete contractors. Different scenarios were investigated in the A+B+L competition and it was concluded that the UTV of $23,128/day is still optimal when the preferred pavement type of contractors is not known during the bid competition.

8.4 Recommendations for Future Studies

It has been assumed that for each contractor there is only one price-time curve for various types of A+B projects. This is despite the fact that A+B projects can be as varied as a minor surface treatment to a reconstruction project. However, due to limited number of completed A+B projects it was not feasible to study price-time relationship for each project type. Developing multiple price-time models for each contractor based on different types of A+B projects using more comprehensive historical data sets would be a reasonable extension to this study.

It has also been assumed that the future performance of different pavement families can be predicted by analyzing their past behavior. In other words, it has been assumed that past behavior of pavements would be a valid indicator of their future performance. While some of the past treatment strategies have improved the performance of pavements, some of them have not been applied on the pavements at the right time and sequence. Therefore, the treatment strategies need to be investigated in order to differentiate between the successful sequence of treatments that lead to lowest life-cycle costs and unsuccessful sequences that cause higher life-cycle costs.

The developed LCCA models provide SHAs with the most realistic prediction of the future treatment activities where both asphalt and concrete industries have consensus on.

The LCCA models in this study have been developed for two pavement families of Interstate 40 in the state of Oklahoma. Since the realistic LCCA models are dependent on the historical pavement treatment activities, there is no universal model that fits all the situations. Therefore, each SHA should apply the same approach introduced in this study to their historical databases in order to develop realistic LCCA models for their own highways.

A potential improvement area of the process developed in this study is the application of rigorous classification methods to various pavement types. This study is based on the current classification of Pavement families of ODOT. However, with rich pavement performance data available, pavements can be further classified based on other factors such as foundation materials and thicknesses, environmental conditions, and serviceability that may lead to different life-cycle performance. This new set of classification of pavements may result in more accurate LCCA models by reducing the variability in pavement performance over time.

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APPENDICES

APPENDIX A

LOG CARD OF CONTROL SECTION 56-03 IN INTERSTATE 40

FORM RL-3
Revised 1956

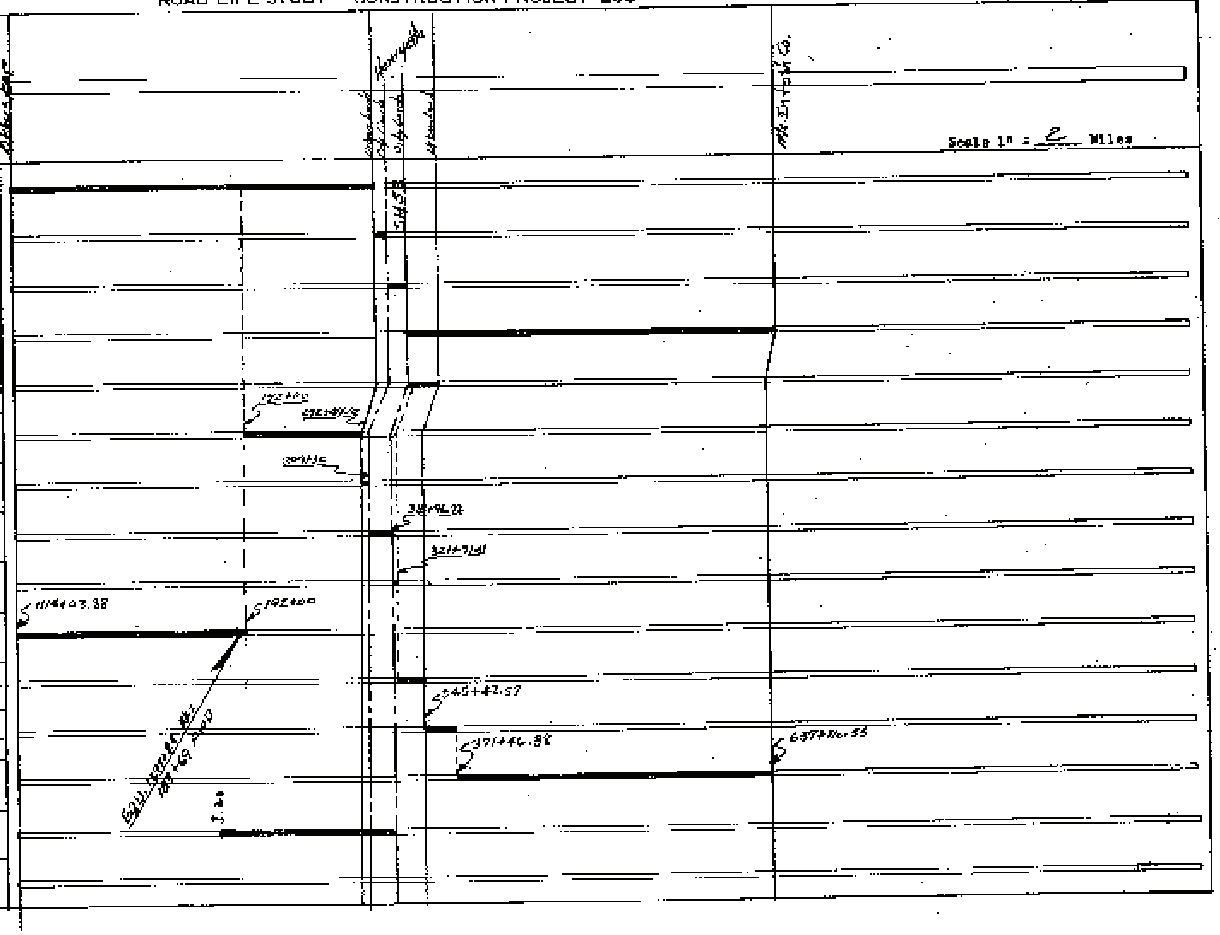
STATE OF OKLAHOMA
DEPARTMENT OF HIGHWAYS
DEPARTMENT OF STATISTICS
U.S. BUREAU OF PUBLIC ROADS

ROAD LIFE STUDY CONSTRUCTION PROJECT LOG

Sheet 1 of 1
Control Section Okmulgee Co. # 56
40-56-03

Location and Termini
Fr: Okfuskee County Line
East
To: McIntosh County Line

RL-1 Code No.	Date Comp.	Proj	Type of work	Width	Thick Surf. Base	Miles
183			Projected		—	5.800
227			Projected			0.200
228			Projected			0.300
229			Projected			6.900
245			Projected			0.500
246	12/64	I-40 6(98) 236	P.C. Conc.	48'	9 / —	1.903
247	12/64	I-40 6(98) 236	P.C. Conc.	48'	9 / —	0.129
248	12/64	I-40 6(98) 236	P.C. Conc.	48'	9 / —	0.372
249	12/64	I-40 6(98) 236	P.C. Conc.	48	9 / —	0.056
250	/65	I-40 6(99) 232	P.C. Conc.	48	9" / —	3.839
251	/65	I-40 6(99) 232	P.C. Conc.	48	9" / —	0.444
252	/65	I-40 6(99) 233	P.C. Conc.	48'	9" / —	0.494
253	/65	I-40 6(98) 239	P.C. Conc.	48'	9" / —	5.045
[illegible]	[illegible]	Cnt. 56 (216)	1½" Asph. Conc. Pres. "B" Q[illegible]	48	1 / 6	2.84



FORM R-L-7

CONSTRUCTION LOG

ROAD LIFE AND INVESTMENT STUDY

STATE OF OKLAHOMA
DEPARTMENT OF HIGHWAYS
PLANNING DIVISION

COUNTY Okmulgee
CONTROL SECTION 40-56-03
SHEET 2 OF 2

LOCATION AND SEGMENT
FR Okfuskee County Line
TO McIntosh County Line

YEAR BUILT	CONTRACT NUMBER	WIDTH	THICKNESS SURF.	THICKNESS BASE	TYPE OF WORK	LENGTH	
06 27 00	Jmy-40 -6 (216) 290	48	10	3	x" AC Concrete over 3" Type "B" over 6" Agg Base over 8" [illegible]	1.24	1
06 27 00	Jmy-40 -6 (216) 290	48	10"	3	10" AC Concrete over 3" Type B over 9" [illegible] RC [illegible] 6" [illegible]	4.80	2
							3
							4
							5
							6
							7
							8
							9
							10

Okfuskee C/L — McIntosh C/L

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

O.S.

Overl Sealed

REMARKS

APPENDIX B

ODOT BREAK REASONS FOR CONTROL SECTIONS

Break Reason: (Column Name: BREAK_REASON)

- Code this item to indicate the reason a subsection break is necessary. When more than one reason occurs at the same time; use the lowest numbered reason. When making subsection breaks for ramps / interchanges see page 24 for more information.

Roadway Codes:

1) State Highway Junction #1
2) Enter Municipal Limits #2
3) Leave Municipal Limits #2
4) Enter Urban Area Boundary #2
5) Leave Urban Area Boundary #2
6) Surface width, or Type Change #3
7) Shoulder width, or Type Change
8) N.H.S. Change
9) Other
10) Terrain Area Type
11) Begin Control Section at County or State Line
12) Centroid Break Point only
13) HPMS Break
14) Maintenance Division Break
15) Project Break
16) Enter Oklahoma Test Section
17) Leave Oklahoma Test Section
18) Last Maintenance Date
19) Maintenance Responsibility
20) Junction of Proposed Highway or Old Highway
21) Under Construction or Improvement Type change
22) Programming Break, on 8.00 Mile Contract Length Project

Interchange Codes:

23) Diamond 1-side
24) Trumpet 3-leg
25) Fully Directional 3-leg
26) Modified Cloverleaf with Collector
27) Modified Trumpet
28) Full Cloverleaf
29) Full Diamond
30) Full Diamond 1-Quadrant Cloverleaf
31) Half Diamond
32) 3-Leg Directional Loop
33) 3-Leg Directional
34) 2-Quadrant Cloverleaf
35) Modified Diamond
36) No Interchange Involved

(See pages 13, 26, and 74 for additional Break Reason Notes)

Break Reason Notes **(Continued from previous page)**

- Junctions with another RFC control section.
- Junctions with a State Highway.
- Junctions with County Commissioner Districts (Mileage is split between district boundaries).
- See UFC or RFC control section books for junction break point criteria, and coding direction.
- Municipal and urban limits are defined as the point at which the limits occur on both sides of the roadway facility.
- On **open type sections** a surface width break shall be made when the normal width of the section changes 2 feet or more. On **curbed sections** when the curb-to-curb width changes by 1 foot or more. The **break point** for changing from 2 to 4 lanes, 4 to 6 lanes, etc, shall be where the standard construction of the greater lanes section width begins or ends. The transition areas will be included in the subsection with the lessor number of lanes.
- Surface type breaks will be made where the exposed surface type of the inventory changes.
- Do not break subsections for surface type or width change at channelized intersections, transitions from 2 to 4 lanes, or maintenance improvements to correct base failures or alignment problems unless the length is over 0.50 mile long.
- Do not break surface type or width subsections for short extents of short sections of standard construction at bridge locations, intersection improvements, or alignment correction where the construction design meet Oklahoma design standard; i.e. 24' surface with paved shoulders.

Subsection Length: (Column Name: LENGTH_3D_MI)

- Record the length of the inventoried subsection to the nearest hundredth **(00.01)** mile. For divided roadway subsection, the subsection length for both sides will be the same.

Number of Lanes: (Column Name: NO_LANES)

- Code the number of through traffic lanes for the type of facility:
  0 -Zero One Lane, One-Way Facility (Ramp & Frontage Roads Only)
  1 Two Lanes, One-Way Facility (Ramp & Frontage Roads Only)
  2 Two or Three Lanes Two-Way Facility
  3 Two or Three Lanes One-Way Facility (City One-Way Pairs Only)
  4 Four Lane Facility
  6 Six Lane Facility
  8 Eight Lane Facility
- Do not include acceleration / deceleration lanes, exit only, merging, climbing, left or right turn only lanes. Lanes should be stripped off or otherwise evident on the roadway surface.
- For **multilane sections** enter the **total** number of lanes for **both sides.**

Surface Type:

(Column Names: SURFACE_TYPE_CD, SURF_PRIMARY, SURF_ORIGINAL, BASE_TYPE, SURF_THICKNESS)

- **(See the Base and Surface Chart on page 27)**

Surface Width: (Column Name: SURFACE_WIDTH)

- Record the width of through lane driving surface from inside shoulder to inside shoulder or face to face of curb. **Do not include** medians, turn lanes or climbing lanes. For **open type sections** record the width to the nearest even foot (18, 20, 22, 24). For **2 lane facilities** do not exceed 24 feet. Any excess surface over 24 feet shall be included in shoulder width.

“Rules of the Road”

I. Additional Guidance for Break Reasons

- Always break for a new subsection when the inventory route crosses or changes:
    - State or U.S. numbered highway with a grade crossing.
    - Major or minor collector.
    - County Commissioner district boundaries.
    - Municipal limits.
    - Urban Area Boundaries.
    - Change in reservation (Col. 33), i.e. State Parks, National Forests, Indian Agencies, etc.
    - Number of lanes.
    - Surface width.
    - Surface type.
    - Right-of-way width.

II. Split Mileages

- When an inventory route lies along the boundary of either the county itself or the county commissioner districts, it is necessary to split the mileage between both administrative units. If the boundary is a county commissioner district, record one-half in one district and the other half in the adjacent district. Do code the road as one continuous piece, i.e., do not make the second entries subsection **0000.** If the boundary is a county line, code the entire subsection as one-half of its actual length. The other half will be posted in the adjacent county’s file, so do not be concerned with it. The exception to split mileages is State line roads. Record these roads in the normal manner.

III. City Codes

- Remember to record the appropriate city code when a road goes inside **EITHER** municipal limits **OR** an Urban Area.
- If the road is in an urban area but not in the city limits, Rural / Municipal code will be **1** AND the Population Group code will be **0** but **the City code cannot be 00.**

IV. County Line Collectors

- Before coding a county, be sure to check the surrounding county’s collector map for any collectors. This avoids duplication of mileage.

V. Local City Streets

- When coding local city streets, first label all municipal county roads and collectors (or **F.A.U.’s** in Urban Areas). Also note the alignments of any highways. The above is necessary to avoid duplication of mileage. Do not color the collectors (or F.A.U.’s),since this may lead to confusion with city streets that are Portland Cement.

- Instead, label the route by its respective number and place arrows on its termini, if applicable. Remember that city street mileages are cumulative, so there should be relatively few entries in most city’s files.

APPENDIX C

BRIEF DESCRIPTIONS OF PAVEMENT TREATMENTS

Chip Seal

This technique involves applying an asphalt binder followed by a layer of aggregate, which is rolled into the binder. It is used to provide a surface seal or skid-resistant surface to structurally sound pavement. This treatment is best suited to low-volume roads. Multiple treatments may be applied up to 1 in. thick. The cost, however, approaches that of a thin hot mix overlay. Some agencies consider applying a thin overlay as surface treatment (Shahin 1994).

NovaChip®

Originally developed in France in 1986, NovaChip® is a paving process that places a thin (3/8 to 3/4 inch), gap graded coarse aggregate hot mix asphalt over a Novabond® membrane (polymer modified asphalt emulsion seal coat). NovaChip® is marketed as a pavement rehabilitation, preventive maintenance or surface treatment that has an extremely durable surface with improved skid resistance and is resistant to rutting and wear. Based on the United States and European experience, SemMaterials, the licensed applicator of NovaChip®, anticipates that NovaChip® will provide a service life of approximately 10 to 12 years (Russel et al. 2008).

Diamond Grinding

Diamond grinding is the process of removing a thin layer of the existing concrete surface by grinding it with a series of closely spaced rotating diamond saw blades. This method is used to reprofile jointed concrete pavements that have developed a rough ride because of faulting or slab warping. It is also used to restore transverse drainage and to provide a textured pavement surface. (Shahin 1994)

Dowel Bar Retrofit (DBR)

DBR is a concrete pavement restoration procedure that involves cutting slots in the pavement across the joint or crack, cleaning the slots, placing the dowel bars and then backfilling the slots with new concrete. The method links slabs together at transverse cracks and joints to evenly distribute the load across the crack or joint. Such load transfer across transverse joints of jointed plain concrete pavements is essential for long-term performance, especially when the roadway carries heavy truck loads (IGGA 2010).

Joint Sealing, Joint Repair, and Joint Rehabilitation

Joint sealing is the process of cleaning and sealing or resealing PCC joints. This technique is used to stop surface water infiltration into the pavement foundation and to stop the accumulation of incompressibles in the joints. Water infiltration results in weakened support and eventual pumping, corner breaks, and slab shattering. Accumulation of incompressibles in joints leads to spalling of the concrete and is a source of foreign object damage (Shahin 1994).

Bonded Concrete Overlay

A bonded concrete overlay (BCO) consists of a new concrete overlay placed directly on top of an existing concrete pavement. The overlay bonds to the existing concrete to create a monolithic slab. Saw cuts are placed in the overlay at locations of underlying joints, patches, and working cracks in order to accommodate movements and prevent reflective cracking. A BCO is a technique intended for use on a good-performing pavement to extend its life. It is not intended for use on a pavement at the end of its service life. A proper application for a BCO may be to increase the structural capacity of a relatively new concrete pavement that was under-designed for in-service loading. Another application may be to restore the riding surface of a severely spalled pavement, or one with high steel, that shows otherwise good performance (IDOT 2005).

Unbonded Concrete Overlay

An unbonded concrete overlay is essentially a new concrete pavement constructed over an existing concrete pavement. A flexible interlayer, typically constructed of hot-mix asphalt (HMA), separates the concrete layers. The flexible interlayer acts as a shear zone, allowing the concrete layers to move independently of each other, and preventing reflective cracking in the concrete overlay. For this reason, the term "unbonded" is used, although the layers do bond in the sense of adhering together.

An unbonded concrete overlay is a viable option for structural rehabilitation of deteriorated HMA-overlaid concrete pavements, and is particularly effective in controlling reflective cracking over unpatched D-cracked pavements. The overlay pavement can be jointed-plain concrete, jointed-reinforced concrete, or continuously-reinforced concrete (IDOT 2005).

Whitetopping

A whitetopping overlay is constructed when a new portland cement concrete layer is placed on top of an existing HMA pavement system. Coined "whitetopping" by the industry, these overlays have been used on airports; Interstate, primary, and secondary highways; local roads and streets; and parking lots to improve the performance, durability, and riding quality of deteriorated HMA surfaces (Rasmussen and Rozycki 2004).

AC Leveling Course

A layer of an asphalt aggregate mixture of variable thickness used to eliminate irregularities in the contour of an existing surface prior to placement of an overlay.

AC Overlay

This technique involves adding one or more AC layers to an existing AC or PCC pavement. It is used to correct or improve structural capacity of functional requirements such as skid resistance and ride quality. The use of an AC overlay is usually more economic when the existing pavement is still in good condition. An overlay may be combined with other maintenance and rehabilitation methods (Shahin 1994).

Hot in place recycling

This technique involves using reclaimed asphalt pavement from a cold milling operation, new aggregate, new asphalt cement, and a recycling agent, if needed, to produce recycled hot mix. It is used for any application for which conventional hot mix can be used (Shahin 1994).

Open Graded Friction Course (OGFC)

An OGFC is a sacrificial wearing course. OGFC consists of an aggregate with relatively uniform grading and little or no fine aggregate and mineral filler. It is designed to have a large number of void spaces in the compacted mix.

The most important benefit of OGFC is the increase in roadway safety during wet weather by providing maximum tire to surface contact and strong contrast in pavement markings. Studies have shown that its open void structure aids in the drainage of water and preservation of the surface friction. Once water contacts the OGFC surface, the void structure allows it to drain below the contact point between the tire and pavement to reduce the potential for hydroplaning and splash and spray. Thus, it reduces skid and hydroplaning-related accidents (Caltrans 2006).

Cold Milling

Cold milling is the removal of a given thickness of the surface layer using a machine containing a rotary drum with teeth. It is used in asphalt pavement to bring the pavement grade to an acceptable level, remove a deteriorated layer, and to provide good bonding with the overlay (Shahin 1994).

Reconstruction

Reconstruction is the removal and replacement of existing pavement structure. It is used when the existing pavement is badly deteriorated and is based on economic analysis justification (Shahin 1994).

Selective PC Patching

Selective PC patching involves removing localized areas of deteriorated or spalled PCC pavement and replacing it with a suitable patch material such as cement concrete or epoxy concrete (Shahin 1994).

Full-Depth PC Patching

This type of maintenance and rehabilitation involves full-depth replacement of part or all of a PCC slab. When the entire slab is replaced, it is called “slab replacement.” Full-depth patching is used to repair a variety of distresses, most of which occur near joints or cracks. Such distresses include corner breaks and “D” cracking. When a full-depth patch is performed adjacent to a joint or crack, the load transfer across the joint or crack should be restored. Deterioration of a reflected joint or crack in an asphalt concrete overlay is also a candidate for full-depth patching of the underlying concrete pavement (Shahin 1994).

Slurry Seal (AC Pavement)

This technique involves applying a thin layer of a specially prepared mixture of asphalt emulsion, well-graded find aggregate, water, and mineral filler. It is used to provide a surface seal or skid-resistant surface to structurally sound pavement. Slurry seal will fill small cracks (less than 1/8 in. wide). Larger cracks need to be individually treated before application of slurry seal. The use of slurry seals is best suited to pavements subjected to low to moderate volumes of traffic. (Shahin 1994).

Microsurfacing

Micro-surfacing is a mixture of asphalt emulsion, graded aggregates, mineral filler, water and other additives. The mixture is made and placed on a continuous basis using a travel paver (Slurry Surfacing Machine). The travel paver meters the mix components in a predetermined order into a pug mill. The typical mixing order is aggregate followed by cement, water, the additive and the emulsion.

The resulting slurry material is a free flowing composite material that is spread via a spreader box over the existing road surface. The consistency of the slurry material allows it to spread over the pavement, wetting it, and forming an adhesive bond to the pavement. The slurry mixture contains asphalt emulsion that breaks onto the pavement surface through heterogeneous or homogenous flocculation. The asphalt particles coalesce into films, creating a cohesive mixture. The mixture then cures, by loss of water, into a hardwearing, dense-graded asphalt/aggregate mixture that is bonded to the existing pavement. A slurry surfacing does not add any structural capacity to an existing pavement; they are applied as a maintenance treatment to improve the functional characteristics of the pavement surface.

APPENDIX D

REALISTIC LCCA FOR AC PAVEMENT

O7

	A	B	C	D	E	F	G	H	I	J
1										
2	**ODOT AC Projection (#1)**									
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5										
6	**10.8 Year Maintenance**	10.8								
7	Discount Rate:	2.330%								
8										
9	Open Graded Friction Course Traveled Way		1.25	10.8		13,394	TON	$105.00	$1,406,357	$1,096,639
10	Miscellaneous		11.7%	10.8		1	Price	$164,543.81	$164,544	$128,307
11	Mobilization		4.6%	10.8		1	Price	$72,261.45	$72,261	$56,347
12	Construction added costs		10.1%	10.8		1	Price	$165,959.42	$165,959	$129,411
13										
14										
15	**17.3 Year Maintenance**	17.3								
16	Discount Rate:	2.620%								
17										
18	Microsurface		1	17.3		195,809	SY	$8.52	$1,668,293	$1,066,494
19	Miscellaneous		11.7%	17.3		1	Price	$195,190.24	$195,190	$124,780
20	Mobilization		4.6%	17.3		1	Price	$85,720.21	$85,720	$54,799
21	Construction added costs		10.1%	17.3		1	Price	$196,869.52	$196,870	$125,853
22										
23	**26.3 Year Maintenance**	26.3								
24	Discount Rate:	2.793%								
25										
26	Microsurface		1	26.3		195,809	SY	$8.52	$1,668,293	$808,409
27	Miscellaneous		11.7%	26.3		1	Price	$195,190.24	$195,190	$94,584
28	Mobilization		4.6%	26.3		1	Price	$85,720.21	$85,720	$41,538
29	Construction added costs		10.1%	26.3		1	Price	$196,869.52	$196,870	$95,398
30										
31	**Salvage Value**	33								
32	Discount Rate:	2.830%								
33										
34				33				Treatment 3	$392,574.27	-$156,303
35										
36										
37										
38										
39	**Years in analysis:**		**Total Cost:**						**$6,493,842**	**$3,666,254**
40	33		End of service life	**34.5**	yrs					
41	Discount Rate:	2.830%								
42			**Equivalent Uniform Annual Cost:**							**$172,393**
43										

M20

	A	B	C	D	E	F	G	H	I	J
1										
2	**ODOT AC Projection (#2)**									
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5										
6	**10.8 Year Maintenance**	10.8								
7	Discount Rate:	2.330%								
8										
9	Thin_OL1			10.8		195,809	TON	$18.47	$3,616,592	$2,820,119
10	Miscellaneous		11.7%	10.8		1	Price	$423,141.29	$423,141	$329,954
11	Mobilization		4.6%	10.8		1	Price	$185,827.74	$185,828	$144,903
12	Construction added costs		10.1%	10.8		1	Price	$426,781.69	$426,782	$332,793
13										
14										
15	**22.8 Year Maintenance**	22.8								
16	Discount Rate:	2.758%								
17										
18	Mill_Med_OL1			22.8		195,809	SY	$21.31	$4,172,690	$2,243,982
19	OGFC		1.25	22.8		13,394	TON	$105.00	$1,406,357	$756,309
20	Miscellaneous		11.7%	22.8		1	Price	$652,748.52	$652,749	$351,034
21	Mobilization		4.6%	22.8		1	Price	$286,662.60	$286,663	$154,161
22	Construction added costs		10.1%	22.8		1	Price	$658,364.28	$658,364	$354,054
23										
24	**32.8 Year Maintenance**	32.8								
25	Discount Rate:	2.830%								
26										
27	Mill_Thin_OL1			32.8		195,809	SY	$13.66	$2,674,751	$1,070,909
28	OGFC		1.25	32.8		13,394	TON	$105.00	$1,406,357	$563,073
29	Miscellaneous		11.7%	32.8		1	Price	$477,489.67	$477,490	$191,176
30	Mobilization		4.6%	32.8		1	Price	$209,695.51	$209,696	$83,957
31	Construction added costs		10.1%	32.8		1	Price	$481,597.64	$481,598	$192,821
32										
33	**Salvage Value**	33								
34	Discount Rate:	2.830%								
35										
36				33				Treatment 3	$5,162,392.92	-$2,055,401
37										
38										
39	**Years in analysis:**		**Total Cost:**						**$22,241,450**	**$7,533,845**
40	33		End of service life	**44.8**	yrs					
41	Discount Rate:	2.830%								
42			**Equivalent Uniform Annual Cost:**							**$354,253**
43										

L2

	A	B	C	D	E	F	G	H	I	J
1										
2	**ODOT AC Projection (#3)**									
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5										
6	**10.8 Year Maintenance**	10.8								
7	Discount Rate:	2.330%								
8										
9	OGFC	100.0%	1.25	10.8		13,394	TON	$105.00	$1,406,357	$1,096,639
10	Miscellaneous		11.7%	10.8		1	Price	$164,543.81	$164,544	$128,307
11	Mobilization		4.6%	10.8		1	Price	$72,261.45	$72,261	$56,347
12	Construction added costs		10.1%	10.8		1	Price	$165,959.42	$165,959	$129,411
13										
14										
15	**24.8 Year Maintenance**	24.8								
16	Discount Rate:	2.783%								
17										
18	Mill_Med_OL1			24.8		195,809	SY	$21.31	$4,172,690	$2,112,361
19	OGFC		1.25	24.8		13,394	TON	$105.00	$1,406,357	$711,947
20	Fabric Reinforcement	x2		24.8		391,618	SY	$0.70	$274,133	$138,775
21	Miscellaneous		11.7%	24.8		1	Price	$684,822.03	$684,822	$346,681
22	Mobilization		4.6%	24.8		1	Price	$300,748.08	$300,748	$152,249
23	Construction added costs		10.1%	24.8		1	Price	$690,713.73	$690,714	$349,663
24										
25	**Salvage Value**	33								
26	Discount Rate:	2.830%								
27										
28				33				Treatment 2	$3,670,613.50	-$1,461,450
29										
30										
31	**Years in analysis:**		**Total Cost:**						**$13,009,199**	**$3,760,930**
32	33		End of service life	**40.8**	yrs					
33	Discount Rate:	2.830%								
34			**Equivalent Uniform Annual Cost:**							**$176,845**
35										

L2

	A	B	C	D	E	F	G	H	I	J
1										
2	**ODOT AC Projection (#4)**									
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5										
6	**10.8 Year Maintenance**	10.8								
7	Discount Rate:	2.330%								
8										
9	OGFC	100.0%	1.25	10.8		13,394	TON	$105.00	$1,406,357	$1,096,639
10	Miscellaneous		11.7%	10.8		1	Price	$164,543.81	$164,544	$128,307
11	Mobilization		4.6%	10.8		1	Price	$72,261.45	$72,261	$56,347
12	Construction added costs		10.1%	10.8		1	Price	$165,959.42	$165,959	$129,411
13										
14										
15	**24.8 Year Maintenance**	24.8								
16	Discount Rate:	2.783%								
17										
18	Mill_Med_OL1			24.8		195,809	SY	$21.31	$4,172,690	$2,112,361
19	OGFC		1.25	24.8		13,394	TON	$105.00	$1,406,357	$711,947
20	Fabric Reinforcement	x2		24.8		391,618	SY	$0.70	$274,133	$138,775
21	Miscellaneous		11.7%	24.8		1	Price	$684,822.03	$684,822	$346,681
22	Mobilization		4.6%	24.8		1	Price	$300,748.08	$300,748	$152,249
23	Construction added costs		10.1%	24.8		1	Price	$690,713.73	$690,714	$349,663
24										
25	**Salvage Value**	33								
26	Discount Rate:	2.830%								
27										
28				33				Treatment 2	$3,211,869.08	-$1,278,802
29										
30										
31	**Years in analysis:**		**Total Cost:**						**$12,550,455**	**$3,943,578**
32	33		End of service life	**39.1**	yrs					
33	Discount Rate:	2.830%								
34			**Equivalent Uniform Annual Cost:**							**$185,433**
35										

ODOT AC Projection (#5)

Row	A	B	C	D	E	F	G	H	I	J
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
6	**10.8 Year Maintenance**	10.8								
7	Discount Rate:	2.330%								
9	Thin_OL1			10.8		195,809	TON	$18.47	$3,616,592	$2,820,119
10	Miscellaneous		11.7%	10.8		1	Price	$423,141.29	$423,141	$329,954
11	Mobilization		4.6%	10.8		1	Price	$185,827.74	$185,828	$144,903
12	Construction added costs		10.1%	10.8		1	Price	$426,781.69	$426,782	$332,793
15	**17.8 Year Maintenance**	17.8								
16	Discount Rate:	2.634%								
18	AC Leveling Course	20.0%	1.5	17.8		58,743	CY	$160.00	$9,398,832	$5,916,836
19	OGFC		1.25	17.8		13,394	TON	$105.00	$1,406,357	$885,343
20	Miscellaneous		11.7%	17.8		1	Price	$1,264,207.15	$1,264,207	$795,855
21	Mobilization		4.6%	17.8		1	Price	$555,192.24	$555,192	$349,510
22	Construction added costs		10.1%	17.8		1	Price	$1,275,083.46	$1,275,083	$802,702
24	**29.5 Year Maintenance**	29.5								
25	Discount Rate:	2.825%								
27	Mill_Med_OL1			29.5		195,809	SY	$21.31	$4,172,690	$1,834,442
28	OGFC		1.25	29.5		13,394	TON	$105.00	$1,406,357	$618,278
29	Fabric Reinforcement	x2		29.5		391,618	SY	$0.70	$274,133	$120,517
30	Miscellaneous		11.7%	29.5		1	Price	$684,822.03	$684,822	$301,069
31	Mobilization		4.6%	29.5		1	Price	$300,748.08	$300,748	$132,218
32	Construction added costs		10.1%	29.5		1	Price	$690,713.73	$690,714	$303,659
34	**Salvage Value**	33								
35	Discount Rate:	2.830%								
37				33				Treatment 3	$5,605,878.00	-$2,231,974
39	**Years in analysis:**		**Total Cost:**						**$31,687,357**	**$13,456,222**
40	33		End of service life	**43.2**	yrs					
41	Discount Rate:	2.830%								
42			**Equivalent Uniform Annual Cost:**							**$632,733**

ODOT AC Projection (#6)

		% or Thick. (in.)	Year	Adjustment	Quantity	Unit	Unit Price	Cost	Present Worth
10.8 Year Maintenance	10.8								
Discount Rate:	2.330%								
OGFC		1.25	10.8		13,394	TON	$105.00	$1,406,357	$1,096,639
Miscellaneous		11.7%	10.8		1	Price	$164,543.81	$164,544	$128,307
Mobilization		4.6%	10.8		1	Price	$72,261.45	$72,261	$56,347
Construction added costs		10.1%	10.8		1	Price	$165,959.42	$165,959	$129,411
18.1 Year Maintenance	18.1								
Discount Rate:	2.674%								
Thin_OL1			18.1		195,809	CY	$18.47	$3,616,592	$2,243,184
Miscellaneous		11.7%	18.1		1	Price	$423,141.29	$423,141	$262,452
Mobilization		4.6%	18.1		1	Price	$185,827.74	$185,828	$115,259
Construction added costs		10.1%	18.1		1	Price	$426,781.69	$426,782	$264,710
28.3 Year Maintenance	28.3								
Discount Rate:	2.813%								
Mill_Thin_OL1			28.3		195,809	SY	$13.66	$2,674,751	$1,219,899
Miscellaneous		11.7%	28.3		1	Price	$312,945.86	$312,946	$142,728
Mobilization		4.6%	28.3		1	Price	$137,434.05	$137,434	$62,681
Construction added costs		10.1%	28.3		1	Price	$315,638.22	$315,638	$143,956
Salvage Value	33								
Discount Rate:	2.830%								
			33				Treatment 3	$1,603,085.59	-$638,267
Years in analysis:		**Total Cost:**						**$11,505,320**	**$5,227,307**
33		End of service life	**37.1**	yrs					
Discount Rate:	2.830%								
		Equivalent Uniform Annual Cost:							**$245,796**

APPENDIX E

REALISTIC LCCA OF DJCP SECTIONS

ODOT DJCP Projection (#1)

		% or Thick. (in.)	Year	Adjustment	Quantity	Unit	Unit Price	Cost	Present Worth
23.2 Year Maintenance	23.2								
Discount Rate:	2.762%								
Treatment	**Scope**								
Joint Rehabilitation Traveled Way			23.2		195,809	SY	$7.10	$1,390,244	$738,883
Miscellaneous		23.0%	23.2		1	Price	$319,756.10	$319,756	$169,943
Mobilization		4.9%	23.2		1	Price	$83,790.00	$83,790	$44,532
Construction added costs		9.6%	23.2		1	Price	$172,203.84	$172,204	$91,522
40.2 Year Maintenance	40.2								
Discount Rate:	1.992%								
Treatment	**Scope**								
Grind			7.2		195,809	SY	$7.10	$1,390,244	$1,206,188
Miscellaneous		23.0%	7.2		1	Price	$319,756.10	$319,756	$277,423
Mobilization		4.9%	7.2		1	Price	$83,790.00	$83,790	$72,697
Construction added costs		9.6%	7.2		1	Price	$172,203.84	$172,204	$149,406
41.2 Year Maintenance	41.2								
Discount Rate:	2.102%								
Treatment	**Scope**								
Grind			8.2		195,809	SY	$7.10	$1,390,244	$1,172,223
Miscellaneous		23.0%	8.2		1	Price	$319,756.10	$319,756	$269,611
Mobilization		4.9%	8.2		1	Price	$83,790.00	$83,790	$70,650
Construction added costs		9.6%	8.2		1	Price	$172,203.84	$172,204	$145,198
Salvage Value	33								
Discount Rate:	2.830%								
			33				Treatment 1	$832,656.21	-$331,521
Years in analysis:					**Total Cost:**			**$832,656**	**$713,360**
33		End of service life	**46.2**	yrs					
Discount Rate:	2.830%								
		Equivalent Uniform Annual Cost:							**$33,543**

ODOT DJCP Projection (#2)

	A	B	C	D	E	F	G	H	I	J
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5	**23.2 Year Maintenance**	23.2								
6	Discount Rate:	2.762%								
7	**Treatment**	**Scope**								
8	Joint Rehabilitation Traveled Way			23.2		195,809	SY	$7.10	$1,390,244	$738,883
9	Miscellaneous		23.0%	23.2		1	Price	$319,756.10	$319,756	$169,943
10	Mobilization		4.9%	23.2		1	Price	$83,790.00	$83,790	$44,532
11	Construction added costs		9.6%	23.2		1	Price	$172,203.84	$172,204	$91,522
13	**34.2 Year Maintenance**	34.2								
14	Discount Rate:	1.750%								
15	**Treatment**	**Scope**								
16	Grind			1.2		195,809	SY	$7.10	$1,390,244	$1,361,600
17	Miscellaneous		23.0%	1.2		1	Price	$319,756.10	$319,756	$313,168
18	Mobilization		4.9%	1.2		1	Price	$83,790.00	$83,790	$82,064
19	Construction added costs		9.6%	1.2		1	Price	$172,203.84	$172,204	$168,656
22	**Salvage Value**	33								
23	Discount Rate:	2.830%								
26				33				Treatment 1	$214,472.05	-$85,392
30	**Years in analysis:**					**Total Cost:**			**$214,472**	**$959,490**
31	33		End of service life	**43.2**	yrs					
32	Discount Rate:	2.830%								
33			**Equivalent Uniform Annual Cost:**							**$45,117**

	A	B	C	D	E	F	G	H	I	J
1										
2	**ODOT DJCP Projection (#3)**									
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5	**23.2 Year Maintenance**	23.2								
6	Discount Rate:	2.762%								
7	**Treatment**	**Scope**								
8	Joint Rehabilitation Traveled Way			23.2		195,809	SY	$7.10	$1,390,244	$738,883
9	Miscellaneous		23.0%	23.2		1	Price	$319,756.10	$319,756	$169,943
10	Mobilization		4.9%	23.2		1	Price	$83,790.00	$83,790	$44,532
11	Construction added costs		9.6%	23.2		1	Price	$172,203.84	$172,204	$91,522
12										
13	**40.2 Year Maintenance**	40.2								
14	Discount Rate:	1.992%								
15	**Treatment**	**Scope**								
16	Joint Rehabilitation Traveled Way			7.2		195,809	SY	$7.10	$1,390,244	$1,206,188
17	Miscellaneous		23.0%	7.2		1	Price	$319,756.10	$319,756	$277,423
18	Mobilization		4.9%	7.2		1	Price	$83,790.00	$83,790	$72,697
19	Construction added costs		9.6%	7.2		1	Price	$172,203.84	$172,204	$149,406
20										
21										
22	**Salvage Value**	33								
23	Discount Rate:	2.830%								
24										
25										
26				33				Treatment 1	$832,656.21	-$331,521
27										
28										
29										
30	**Years in analysis:**					**Total Cost:**			**$832,656**	**$713,360**
31	33		End of service life	**49.2**	yrs					
32	Discount Rate:	2.830%								
33			**Equivalent Uniform Annual Cost:**							**$33,543**
34										

L2

	A	B	C	D	E	F	G	H	I	J
1										
2	**ODOT DJCP Projection (#4)**									
3			% or					Unit		Present
4			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
5	**23.2 Year Maintenance**	23.2								
6	Discount Rate:	2.762%								
7	**Treatment**	**Scope**								
8	Joint Rehabilitation Traveled Way			23.2		195,809	SY	$7.10	$1,390,244	$738,883
9	Miscellaneous		23.0%	23.2		1	Price	$319,756.10	$319,756	$169,943
10	Mobilization		4.9%	23.2		1	Price	$83,790.00	$83,790	$44,532
11	Construction added costs		9.6%	23.2		1	Price	$172,203.84	$172,204	$91,522
12										
13										
14	**Salvage Value**	33								
15	Discount Rate:	2.830%								
16										
17										
18				33				Treatment 1	$681,544.53	-$271,356
19										
20										
21										
22	**Years in analysis:**					**Total Cost:**			**$681,545**	**$773,525**
23	33		End of service life	**38.2**	yrs					
24	Discount Rate:	2.830%								
25			**Equivalent Uniform Annual Cost:**							**$36,372**
26										

L2 fx

ODOT DJCP Projection (#5)

A	B	C	D	E	F	G	H	I	J
		% or Thick. (in.)	Year	Adjustment	Quantity	Unit	Unit Price	Cost	Present Worth
29 Year Maintenance	29								
Discount Rate:	2.820%								
Treatment	**Scope**								
Thin_OL1			29		195,809	SY	$18.47	$3,616,592	$1,614,541
Miscellaneous		23.0%	29		1	Price	$831,816.21	$831,816	$371,344
Mobilization		4.9%	29		1	Price	$217,972.01	$217,972	$97,308
Construction added costs		9.6%	29		1	Price	$447,972.52	$447,973	$199,987
31 Year Maintenance	31								
Discount Rate:	2.830%								
Treatment	**Scope**								
Thin_OL1			31		195,809	SY	$18.47	$3,616,592	$1,522,596
Miscellaneous		23.0%	31		1	Price	$831,816.21	$831,816	$350,197
Mobilization		4.9%	31		1	Price	$217,972.01	$217,972	$91,767
Construction added costs		9.6%	31		1	Price	$447,972.52	$447,973	$188,598
44 Year Maintenance	44								
Discount Rate:	1.750%								
Treatment	**Scope**								
PC_Patch	30.00%		11		195,809	SY	$125.00	$7,342,838	$5,401,890
Miscellaneous		23.0%	11		1	Price	$1,688,852.63	$1,688,853	$1,242,435
Mobilization		4.9%	11		1	Price	$442,552.82	$442,553	$325,572
Construction added costs		9.6%	11		1	Price	$909,527.32	$909,527	$669,110
Salvage Value	33								
Discount Rate:	2.830%								
			33				Treatment 2	$4,327,529.44	-$1,723,001
Years in analysis:					**Total Cost:**			**$4,327,529**	**$2,713,338**
33		End of service life	**47**	yrs					
Discount Rate:	2.830%								
		Equivalent Uniform Annual Cost:							**$127,585**

ODOT DJCP Projection (#6)

		% or Thick. (in.)	Year	Adjustment	Quantity	Unit	Unit Price	Cost	Present Worth
23.2 Year Maintenance	23.2								
Discount Rate:	2.762%								
Treatment	**Scope**								
Joint Rehabilitation Traveled Way			23.2		195,809	SY	$7.10	$1,390,244	$738,883
Miscellaneous		23.0%	23.2		1	Price	$319,756.10	$319,756	$169,943
Mobilization		4.9%	23.2		1	Price	$83,790.00	$83,790	$44,532
Construction added costs		9.6%	23.2		1	Price	$172,203.84	$172,204	$91,522
Salvage Value	33								
Discount Rate:	2.830%								
			33				Treatment 1	$214,472.05	-$85,392
Years in analysis:					**Total Cost:**			**$214,472**	**$959,490**
33		End of service life	**34.2**	yrs					
Discount Rate:	2.830%								
		Equivalent Uniform Annual Cost:							**$45,117**

ODOT DJCP Projection (#7)

		% or Thick. (in.)	Year	Adjustment	Quantity	Unit	Unit Price	Cost	Present Worth
23.2 Year Maintenance	23.2								
Discount Rate:	2.762%								
Treatment	**Scope**								
Med_OL1			23.2		195,809	SY	$21.31	$4,172,690	$2,217,691
OGFC		1.3	23.2		13,394	TON	$125.00	$1,674,235	$889,818
Miscellaneous		23.0%	23.2		1	Price	$1,344,792.69	$1,344,793	$714,727
Mobilization		4.9%	23.2		1	Price	$352,394.15	$352,394	$187,290
Construction added costs		9.6%	23.2		1	Price	$724,234.71	$724,235	$384,914
Salvage Value	33								
Discount Rate:	2.830%								
			33				Treatment 1	$3,445,144.28	-$1,371,680
Years in analysis:					**Total Cost:**			**$3,445,144**	**$3,022,760**
33		End of service life	**40**	yrs					
Discount Rate:	2.830%								
		Equivalent Uniform Annual Cost:							**$142,135**

	A	B	C	D	E	F	G	H	I	J
1	**ODOT DJCP Projection (#8)**									
2			% or					Unit		Present
3			Thick. (in.)	Year	Adjustment	Quantity	Unit	Price	Cost	Worth
4	**14 Year Maintenance**	14								
5	Discount Rate:	2.486%								
6	**Treatment**	**Scope**								
7	Joint Rehabilitation Traveled Way			14		195,809	SY	$7.10	$1,390,244	$985,797
8	Miscellaneous		23.0%	14		1	Price	$319,756.10	$319,756	$226,733
9	Mobilization		4.9%	14		1	Price	$83,790.00	$83,790	$59,414
10	Construction added costs		9.6%	14		1	Price	$172,203.84	$172,204	$122,107
11										
12	**28 Year Maintenance**	28								
13	Discount Rate:	2.810%								
14	**Treatment**	**Scope**								
15	Joint Rehabilitation Traveled Way			28		195,809	SY	$7.10	$1,390,244	$639,884
16	Miscellaneous		23.0%	28		1	Price	$319,756.10	$319,756	$147,173
17	Mobilization		4.9%	28		1	Price	$83,790.00	$83,790	$38,566
18	Construction added costs		9.6%	28		1	Price	$172,203.84	$172,204	$79,260
19										
20										
21	**Salvage Value**	33								
22	Discount Rate:	2.830%								
23										
24										
25				33				Treatment 1	$982,996.92	-$391,379
26										
27										
28	**Years in analysis:**					**Total Cost:**			**$982,997**	**$1,907,554**
29	33		End of service life	**38**	yrs					
30	Discount Rate:	2.830%								
31			**Equivalent Uniform Annual Cost:**							**$89,696**
32										

VITA

Saeed Abdollahipour

Candidate for the Degree of

Doctor of Philosophy

Thesis: MULTI-PARAMETER BIDDING IN HIGHWAY CONSTRUCTION AND REHABILITATION PROJECTS

Major Field: Civil & Environmental Engineering

Biographical:

Personal: Born in Tehran, Iran on February 26, 1983.

Education: Completed the requirements for the Doctor of Philosophy in Civil & Environmental Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2013.
Completed the requirements for the Master of Science in Civil & Environmental Engineering at Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran in July 2008.
Completed the requirements for the Bachelor of Science in Civil & Environmental Engineering at Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran in February 2005.

Experience: Served as Construction Manager and Site Design Manager at Nokia Siemens Networks Company in Tehran, Iran (2005-2009). Got involved in several Telecommunications Infrastructure construction projects. Worked as Graduate Research Assistant at Oklahoma State University (2009-2013). Authored and co-authored several journal and conference papers in the area of Pavement Management, Infrastructure Asset Management, Horizontal Directional Drilling, Project Delivery Methods, Alternate Pavement Type Bidding, and Life-Cycle Cost Analysis. Worked as Intern in Pavement Management Branch of Oklahoma Department of Transportation (ODOT) in Oklahoma City, OK (Summer 2012).

Professional Memberships: Chi Epsilon, ASCE, CI of ASCE, and AISC.