12-2006

Life Cycle Cost Analysis of Pavements: State-of-the-Practice

Zeynep Guven
Clemson University, zguven@clemson.edu

LIFE CYCLE COST ANALYSIS OF PAVEMENTS: STATE-OF-THE-PRACTICE

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

---

by
Zeynep Guven
December 2006

Accepted by:
Dr. Prasada Rao Rangaraju, Committee Chair
Dr. Serji N. Amirkhanian
Dr. Bradley J. Putman

ABSTRACT

Life Cycle Cost Analysis (LCCA) is performed by transportation agencies in the design phase of transportation projects in order to be able to implement more economical strategies, to support decision processes in pavement type selection (flexible or rigid) and also to assess the relative costs of different rehabilitation options within each type of pavement. However, most of the input parameters are inherently uncertain. In order to implement the LCCA process in a reliable and trustworthy manner, this uncertainty must be addressed. This thesis summarizes a through research that aims at improving the existing LCCA approach for South Carolina Department of Transportation (SCDOT) by developing a better understanding of the parameters used in the analysis. In order to achieve this, a comprehensive literature review was first conducted to collect information from various academic and industrial sources. After that, two surveys were conducted to survey the state-of-the-practice of LCCA across the 50 U.S. Departments of Transportation (DOTs) and Canada. The questionnaires were designed to gauge the level of LCCA activity in different states as well as to solicit information on specific approaches that each state is taking for pavement type selection. The responses obtained from the web surveys were analyzed to observe the trends regarding the various input parameters that feed into the LCCA process. The results were combined with the additional resources in order to analyze the challenges to implementing the LCCA approach. The survey results showed LCCA is used widely among transportation agencies. However, the extent of the analysis varies widely and is presented here.

DEDICATION

To my mother and father.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Prasada Rao Rangaraju and my committee members, Dr. Serji Amirkhanian and Dr. Bradley Putman for their guidance, interest and overall assistance. I would like to thank Dr. Edward Back for his continuous support.

I would also like to thank all the FHWA and SCDOT officials that provided helpful comments and feedback on the preparation of the survey questions.

In addition, I would like to thank Matt for all his help and support. I would also like to thank Patrick McLaughlin for helping me with the language of my thesis. I would like to thank Bentley for his contribution to the plotting of the statistical data and for always being there for me. I would also like to thank Diana, Inci, Teresa, Patrick Swindler, Basak, Baris, Todd, Uros, Devin, Yeti, Carl, Bridget, Varun, Sahil, Warren, Zeynep, Firat, and all my friends and colleagues at ARTS for their continuous interest, support, and for all the good memories. I would also like to thank all my friends in Turkey.

Finally, I would like to thank my family for their continuous support. Without them this degree would have been too great to achieve.

TABLE OF CONTENTS

LIST OF TABLES

List of Tables (Continued) Page

List of Tables (Continued) Page

LIST OF FIGURES

List of Figures (Continued) Page

ABBREVIATIONS

AADT…………………………………………………....Annual Average Daily Traffic

ACPA………………………………………American Concrete Pavement Association

(B/C)……………………………………………………………………Benefit/Cost Ratio

DOT…………………………………………..………..Department of Transportation

FHWA…………………………………………………...Federal Highway Administration

EUAC……………………………………..……… Equivalent Uniform Annual Cost

HMA ……………………………………………..…………………Hot Mix Asphalt

IRR…………………………………………………………....Internal Rate of Return

ISTEA…………………….………...Intermodal Surface Transportation Efficiency Act

LCCA……………………………………..……………...Life Cycle Cost Analysis

LTPP…………………………...………Long-Term Pavement Performance Program

NHCHRP…………………..…..National Highway Cooperative Highway Research Program

NHS……………………………………………………………National Highway System

NPV……………………………………………………………………..Net Present Value

PCC…………………………………………………………..Portland Cement Concrete

PMS……………………………………………………..Pavement Management Systems

SCDOT……………………………………..South Carolina Department of Transportation

SHA……………………………………………………………..State Highway Agency

SHRP……………………………………………Strategic Highway Research Program

TEA-21……………………………………Transportation Equity Act for the 21st Century

vphpl…………………………………………………………vehicles per hour per lane

VOC…………………………………………………………Vehicle Operating Costs

CHAPTER 1

INTRODUCTION

In the face of scarce funds and limited budgets, transportation officials must constantly choose the most cost effective project alternatives. As transportation agencies consistently rank among the top sectors in public spending, choosing the most cost-effective type and design of pavement while still providing a high quality of service to the traveling public is one of the most important management decisions to be made. Life cycle cost analysis (LCCA) is an essential economic evaluation tool that provides valuable guidance to transportation officials in this process.

1.1 Definition of LCCA

The Federal Highway Administration (FHWA) defines LCCA as follows:

> "LCCA is an analysis technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between competing alternative investment options. It does not address equity issues. It incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments. It attempts to identify the best value (the lowest long-term cost that satisfies the performance objective being sought) for investment expenditures". (Walls and Smith, 1998).

LCCA, as well as being used as a decision support tool when selecting pavement type, is also used to assess different rehabilitation strategies within the same pavement type (Reigle and Zaniewski, 2002). The end result of a successful LCCA is not simply the selection of one alternative over the other, but also the selection of the most cost-effective design strategy for a given situation and a greater understanding of the factors that influence cost effectiveness.

1.2 Historical Background

Transportation agencies using federal funds often must conduct LCCA to justify their planning and design decisions. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) specifically required consideration of “the use of life-cycle costs in the design and engineering of bridges, tunnels, or pavement” in both metropolitan and statewide transportation planning (Walls and Smith 1998).

In addition, the National Highway System Designation Act of 1995 required states to conduct an LCCA for each proposed National Highway System (NHS) project segment costing $25 million or more. The National Cooperative Highway Research Program’s (NCHRP) 2003 report states that Federal Executive Order 12893, signed by President Clinton in January 1994, required all federal agencies to use a “systematic analysis of expected benefits and costs... appropriately discounted over the full life cycle of each project” in making major infrastructure investment decisions (NCHRP, 2003).

The 1998 Transportation Equity Act for the 21st Century, TEA-21, has since removed the requirement to conduct LCCA in transportation investment decision making. However, it is still the intent of FHWA to encourage the use of LCCA for National Highway System (NHS) projects.

1.3 Status of LCCA in South Carolina

The need to conduct LCCA to aid the pavement type selection decisions and analyzing life-cycle costs associated with different pavement repair options is well recognized by South Carolina Department of Transportation (SCDOT) and is routinely adopted on selected projects. However, present procedures are based on simplistic assumptions that do not completely reflect the complexities involved in assessing the true life-cycle costs. The reason for adopting the existing procedure is partly due to lack of appropriate information and partly due to the uncertainty associated with certain analysis parameters.

Presently, SCDOT employs a simple procedure that considers only initial construction costs and future costs of rehabilitation. Often the difference between the net present values of the alternatives is so close that there will be significant uncertainty in the decision-making process. Also, the current procedure employed by SCDOT is deterministic, which does not take into account the uncertainty associated with the input parameters.

1.4 Research Need

Performing LCCA to develop more economical strategies is becoming more important for transportation agencies as traffic volumes increase, highway infrastructure deteriorates, and their budgets tightens. To be able to perform a Life Cycle Cost Analysis, the parameters used in the analysis must be applicable and appropriate. All factors must be considered in the analysis such as user-delay costs and salvage value. Also, regional factors such as types of rehabilitation measures employed for each alternative, or the past performance of pavements must be considered. With these limitations in mind, SCDOT recognized the need to study this issue in a coordinated fashion to see what other states have done or are doing in developing a rational approach for conducting life cycle cost analysis.

1.5 Objectives

This thesis presents research aimed at exploring the use of LCCA in general and in pavement type selection in particular as well as developing a better understanding of the parameters, in terms of their applicability, appropriateness and limitations that influence the analysis procedure for selection of pavement types.

In order to accomplish this objective, a comprehensive literature review was conducted that collected information from various academic and industrial sources in the United States as well as Canada and Europe. The next step in the process was the development of a web survey that was e-mailed to State Highway Officials within the United States and Canada. A final survey was sent to out to individuals that responded to the first survey, in order to gain a better understanding of the input parameters used in the analysis and the procedures employed as well as to find out the concerns or limitations that feed into the process.

.

CHAPTER 2

LITERATURE REVIEW

2.1 General LCCA

LCCA can be performed both at the project and network level. In a project-level analysis, the optimum life cycle strategy for the project under evaluation is determined. This type of analysis does not take into consideration funding availability or other policy considerations (Ozbay et al., 2003). On the other hand, network-level analysis is aimed at finding the best utilization of the network as a whole.

Currently, in the United States, LCCA techniques are commonly used for supporting project-level decisions. Flintsch and Kuttesch report that LCCA tools are also starting to be used at the network-level (Flintsch and Kuttesch, 2004). According to Pantelias (2005) most U.S. transportation officials consider the roadway assets' structural and functional conditions as the most important data in selecting between competing roadway projects. Usage of the assets is the third most influential datum. As can be seen in Figure 2-1, life cycle costs are ranked fifth, after initial agency costs.

2.1.1 Economic Indicators

There are several economic indicators available in the economic evaluation of projects. The most common include benefit/cost ratio (B/C), net present value (NPV), equivalent uniform annual cost (EUAC), and internal rate of return (IRR). The transportation agency's choice of the appropriate indicator depends on several factors such as the level and context of analysis or the economic environment in which the analysis is conducted. For example, the IRR is the preferred economic indicator when projects are evaluated in developing countries where the discount rate is highly uncertain (Ozbay et al., 2003). In general, the most common indicators used are NPV and EUAC (Zimmerman, 2000).

Roadway Asset Data	Average Ranking
Structural condition	3.77
Functional condition	3.67
Usage	3.29
Initial agency costs	3.23
Life Cycle Costs	2.96
Attributes/ characteristics	2.90
Customer/ user feedback and complaints	2.83
Location	2.67
Key: 4 = Very Important, 3 = Somewhat Important, 2 = Not Very Important, 1 = Not Important at All	

Figure 2.1 Ranking of Roadway Asset Data for Project Selection (Pantelias, 2005)

The NPV is the present discounted monetary value of expected net benefits (Walls and Smith, 1998). To compute NPV, values need to be assigned to benefits and costs. These values then need to be discounted to present day costs using an appropriate discount rate. Finally, the sum of total present discounted costs needs to be subtracted from the total present discounted benefits. Since the benefits of keeping the pavement above a certain terminal serviceability level are the same for all alternatives, the benefit component drops out. The resulting equation for NPV is:

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

where: i = discount rate
n = year of expenditure (1.1)

(Walls and Smith, 1998)

Equation (1.1) considers only initial and rehabilitation costs. All other costs that would be added to the analysis such as maintenance costs or user costs would have to be multiplied by the present value component which is the $\left[\frac{1}{(1+i)^{n_k}} \right]$ component of Equation (1.1).

The equivalent uniform annual costs method involves converting all the present and future expenditures to a uniform annual cost. It is the preferred indicator when budgets are established on an annual basis. The formula for EUAC is:

$$\text{EUAC} = \text{NPV} \left[\frac{(1+i)^n}{(1+i)^n - 1} \right]$$

where: i = discount rate
n = year of expenditure (1.2)

2.1.2. LCCA Procedure

The FHWA Technical Bulletin lists the steps involved in conducting a life-cycle cost analysis as follows (Walls and Smith, 1998):

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

Establish alternative pavement design strategies for the analysis period

In the first step of the LCCA process, the competing design alternatives to be compared are identified. "A Pavement Design Strategy" is the combination of initial pavement design and time-dependent rehabilitation and treatment activities necessary (Walls and Smith, 1998).

After the selection of an analysis period, initial pavement design is determined for each alternative. Depending on the initial design, supporting maintenance and rehabilitation strategies are determined.

Determine performance periods and activity timing

Performance periods and activity timing has a major impact on LCCA results. It affects not only agency costs, but user costs as well. State Highway Agencies can determine the performance life for the initial pavement design and subsequent rehabilitation activities based on an analysis of pavement management systems (PMS) and historical experience.

Understanding how pavements perform, and therefore being able to predict performance of pavements is the key to building and maintaining a cost effective highway system. With this in mind, the Long-Term Pavement Performance Program (LTPP) was initiated under the Strategic Highway Research Program (SHRP) and continued under FHWA to understand pavement performance (Simpson et al, 2005). This is an ongoing study of in-service pavements that monitors asphalt and concrete pavement test sections across the United States and Canada with the aim of determining the effects of loading, environment, and material properties on pavement distress and performance. LTPP data collected under this research study is made available to practitioners by the development and wide distribution of the DataPave software program (Walls and Smith, 1998).

Specific pavement performance information is also available in various pavement performance reports or online sources such as the Washington State Department of Transportation's (WSDOT) web based link that assesses the performance data for Superpave and stone matrix asphalt pavements which can be viewed at: http://hotmix.ce.washington.edu/hma/.

Another issue that needs to be considered is preventive maintenance. Preventive maintenance strategies have shown to be more cost-effective compared to conventional maintenance strategies (Wei and Tighe, 2004). Thus tools are needed that allow users to consider the effect of preventive maintenance (Flintch and Kuttesch, 2004). Also, incorporating preventive maintenance into LCCA procedure still remains a question. Flintsch and Kuttesch recommend the incorporation of treatments based on pavement condition thresholds into the LCCA software tool and also the establishment of deterioration functions based on historical PMS. Lamptey et al. also recommend a set of pavement maintenance and rehabilitation strategies using a threshold or a "condition trigger" approach. In this approach treatments are carried out anytime a selected measure of pavement performance reaches a certain threshold value, instead of at a predetermined age (Lamptey et al., 2004).

Work zone arrangements are another important aspect of determining performance periods and activity timing because work zone arrangements directly affect highway user costs. Therefore, it is important that duration of work zones along with frequency and years of work are determined as part of the pavement design strategy.

Estimate agency costs

Determining construction quantities and unit prices is the first step in estimating agency costs. Unit prices can be determined from historical data on previously bid jobs. Tighe proposes a probabilistic approach to determining unit prices of paving materials (Tighe, 2001). The author uses data from the LTPP program to perform a statistical analysis and uses a goodness-of-fit test to find the best-fit-distribution that fits the data. It is reported that based on the nature of the paving industry, a log-normal distribution appears to be the most appropriate for pavement material costs.

Agency costs also include preliminary engineering, contract administration, construction supervision and construction costs, routine and preventive maintenance, resurfacing and rehabilitation costs, the associated administrative cost, maintenance of traffic costs, and in some cases, operating costs such as tunnel lighting and ventilation.

Some agencies also incorporate salvage value as a negative cost. Salvage value is the remaining value of the pavement at the end of the analysis period.

Estimate user costs

User costs are the costs that each driver will incur by using a highway system and the excess costs incurred by the user as a result of many factors (e.g., detour requirements). User costs contain, in general, three components: vehicle operating costs (VOC), crash costs, and user delay costs (Walls and Smith, 1998).

In general, there are user costs associated with both normal and work zone operations. The costs in the normal operations category are costs that are incurred while using a facility during periods free of construction, rehabilitation, and maintenance activities. These costs are a function of pavement condition (Flintch and Kuttesch, 2004). There will be little if any difference between vehicle operating costs of alternatives as long as the pavement performance levels remain relatively high. However, a substantial vehicle operating cost differential will occur if the pavement performance levels differ substantially (Walls and Smith, 1998). There has been a vast amount of research performed on the subject and VOC components are proven to be significant based on years of empirical and theoretical research results (Dewan and Smith, 2002, Berthelot et al., 1996). Berthelot et al. provide a mechanistic-probabilistic model for estimating vehicle operating costs during normal operations.

Several researchers have provided models for estimating user delay costs associated with work zone operations (Daniels et al., 2000, Lindley and Clark, 2004).

FHWA provides in-depth guidance on this subject. Detailed procedures to calculate work zone user cost quantities of alternate pavement design strategies are presented in the Technical Bulletin. The agency's LCCA software RealCost version 2.1 automates the recommended process.

The analyst must have specific knowledge of work zone characteristics to perform an analysis using RealCost. The work zone data that must be acquired for each major construction or rehabilitation activity is:

- Projected year the work zone occurs
- Work zone duration (number of days)
- Specific hours of each day the work zone will be in place
- Work zone length
- Work zone capacity (vehicles per hour per lane)
- Work zone speed limit
- Numbers of lanes open in each direction during construction activity

The analyst must also input specific traffic data such as:

- Annual average daily traffic (AADT) per construction year (total for both directions)
- Cars as percentage of AADT (%)
- Single unit trucks as percentage of AADT (%)
- Combination trucks as percentage of AADT (%)
- Annual growth rate of traffic (%)
- Speed limit under normal operating conditions (mph)
- Lanes open in each direction under normal operating conditions

- Free flow capacity vehicles per hour per lane (vphpl).

Free flow capacity can be calculated by the software if the following parameters are plugged in the free flow capacity calculator: number of lanes in each direction, lane width, proportion of trucks and buses, upgrade, upgrade length, obstruction on two sides or not, distance to obstruction/shoulder width.

Queue dissipation capacity (vphpl) (capacity of each lane during queue dissipation operation conditions)

- Maximum AADT (total for both directions)
- Maximum queue length (miles)
- Rural or urban hourly traffic distribution
- Value of time for passenger cars ($/hour)
- Value of time for single unit trucks ($/hour)
- Value of time for combination trucks ($/hour)

The RealCost program, by performing an hour-by-hour comparison of traffic demand and roadway capacity, determines how many vehicles per hour traverse the work zone and how many vehicles traverse a possible queue. Value of user time rates are then used to calculate user costs resulting from the work zone operations.

Develop expenditure stream diagrams

Expenditure stream diagrams represent expenditures over time as shown in Figure 2-2. These diagrams help visualize the timing and extent of initial construction, rehabilitation activities, and, in some cases, salvage value. Normally, costs are shown with upward arrows and benefits are represented with downward arrows as is the case with salvage value.

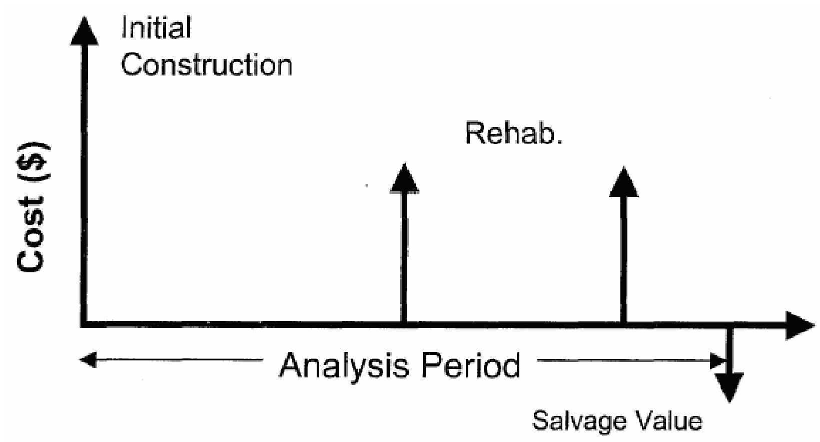


Figure 2.2 Typical Expenditure Stream Diagram for a Project (Walls and Smith, 1998)

Compute net present value

After the expenditure stream diagram is developed, net present value can be calculated using Equation (1.1). Ozbay et al. advise that agency, user, and societal costs are computed separately before the net present value of the total project is computed in order to better understand the components of the total cost (Ozbay, 1998).

Analyze results

The analysis can either be performed deterministically or probabilistically. A detailed discussion of the analysis methods is given in section 2.3. If the deterministic approach is adopted, the LCCA should be subjected to a sensitivity analysis at a minimum. Sensitivity analysis by holding all other inputs constant, allows the analyst to see the independent effect of the variability of one of the inputs. For instance, discount rate might be varied to see the change in NPV and most sensitivity analysis of LCCA evaluate the influence of discount rate since it is a highly disputed variable. According to Ozbay et al, the other most significant parameters that must be evaluated in a sensitivity analysis are:

- Timing of future rehabilitation activities
- Traffic growth rate
- Unit costs of the major construction components
- Analysis periods

Reevaluate design strategy

The designer, after analyzing the results, may choose to alter the design, or develop different rehabilitation strategies, or for instance, might consider different work zone configurations. In the case that traffic levels rise above an expected value so as to increase the user costs to an unacceptably high level, the analyst might consider the design strategies with additional capacity. In short, the information resulting from the LCCA should be interpreted to develop more cost-effective strategies.

The steps explained above are the generally sequential steps developed by FHWA. The sequence of the steps can be altered to meet specific LCCA needs (Walls and Smith, 1998). Also, different authors have added several more steps to the process. For instance, Ozbay et al. recommend that after defining project's alternatives, analysts should decide on the type of approach that would be followed, i.e., deterministic or probabilistic.

Furthermore, DOTs have developed their own procedures, in most cases modeled after the FHWA Technical Bulletin, with some minor customization (Beg et al., 1998; CDOT, 2000; PENNDOT, 2003; Lindley and Clark, 2003; MoDOT, 2004; Zimmerman and Walters, 2004; WSDOT, 2005).

2.2 LCCA Parameters

2.2.1 Analysis Period

Analysis period is the time horizon over which costs are evaluated (Walls and Smith, 1998). According to the FHWA Technical Bulletin, the LCCA analysis period should be sufficiently long to reflect the long-term cost differences associated with the design strategies. The analysis period shall be long enough to incorporate at least one rehabilitation activity for each alternative. Figure 2-3 shows the analysis period for a pavement design alternative.

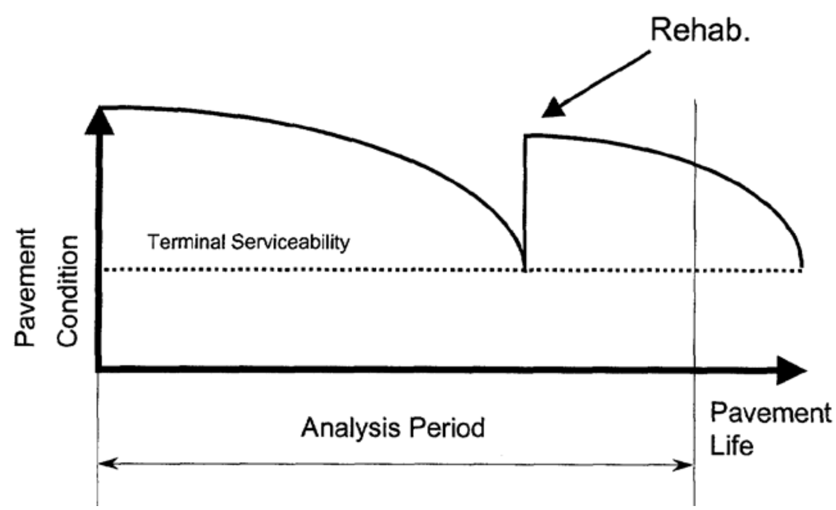


Figure 2.3 Analysis Period for a Pavement Design Alternative (Walls and Smith, 1998)

The FHWA's September, 1996, Final LCCA Policy statement recommends an analysis period of at least 35 years for all pavement projects, including new or total reconstruction projects as well as rehabilitation, restoration, and resurfacing projects. At times, shorter analysis periods may be appropriate, particularly when rehabilitation alternatives are being considered for a certain period of time (e.g., 10 years) until total reconstruction. Deviation from the recommended minimum 35 year analysis period may also be appropriate when slightly shorter periods could simplify the analysis (i.e., no salvage value remaining). Regardless of the analysis period chosen, the analysis period shall be the same for all alternatives (Walls and Smith, 1998).

The 1993 AASHTO Guide for Design of Pavement Structures also provides some guidelines on the selection of an analysis period. The recommended analysis periods, depending on the highway conditions can be seen in Table 2.1 (AASHTO, 1993).

Table 2.1 Recommended Analysis Period

Highway Condition	**Analysis Period (years)**
High Volume Urban	30 to 50
High Volume Rural	20 to 50
Low Volume Paved	15 to 25
Low Volume Aggregate Surface	10 to 20

Another approach for deciding on the analysis period in long-term public projects is to use a "floating" time period (Ozbay et al., 2003). A floating time period is determined as that point in the future where the costs and benefits, discounted to present-day terms, become negligible (i.e., they fall below some extended threshold). The discount rate used is then the prime factor in determining the extent of floating time period.

In addition to selecting the length of the analysis period, an agency must also select a year to be used as the baseline year (Zimmerman et al., 2000). In a present-worth analysis, the base year represents the time to which all of the life-cycle costs are discounted for combining and comparison. Although any base year can be selected, the most common choices for the baseline are a point during the design period, a point halfway through construction, or a point at which construction is completed and the road is opened to traffic. According to the literature, the most realistic baseline costs are obtained from a point during the design period (Zimmerman et al., 2000*)* largely because the analysis can be conducted using contractor quotes or other sources of current costs. As a result, projections of future costs are typically more accurate with this approach.

Recent literature reports that it should be reasonable to include a life cycle analysis (LCA) formulation for pavements that should be capable of incorporating life cycle periods or time horizons of at least 50 years or more (Haas et al., 2006).

2.2.2 Rehabilitation Timings

As noted in section 2.1, rehabilitation timings are highly uncertain and they have a major impact on LCCA results. Figure 2.4 shows the performance curves for two different rehabilitation alternatives. Alternative A represents a traditional longer term strategy with rehabilitation implemented on a 15-year cycle. Alternative B consists of a minimal treatment on a 5-year cycle (Walls and Smith, 1998). As can be seen in Figure 2-4, performance levels vary for different rehabilitation strategies. Differences in pavement performance can produce differences in vehicle operation costs (VOC). Slight differences in VOC rates, when multiplied by several years vehicle mile(s) traveled (VMT), could result in huge VOC differentials over the life of the design strategy (Walls and Smith, 1998).

There has been extensive research conducted on determining the inputs for rehabilitation activities and determining the expected life of pavements (Cross and Parsons, 2002; CDOT, 2000; Gharaibeh and Darter, 2003).

Project duration of reconstruction and rehabilitation is another key factor involved in calculating user costs. Lindley and Clark focused on collecting data concerning the duration of reconstruction and rehabilitation activities (Lindley and Clark, 2004). Lee et al. presented a computer simulation program that analyzes pavement rehabilitation strategies (Lee et al., 2005).

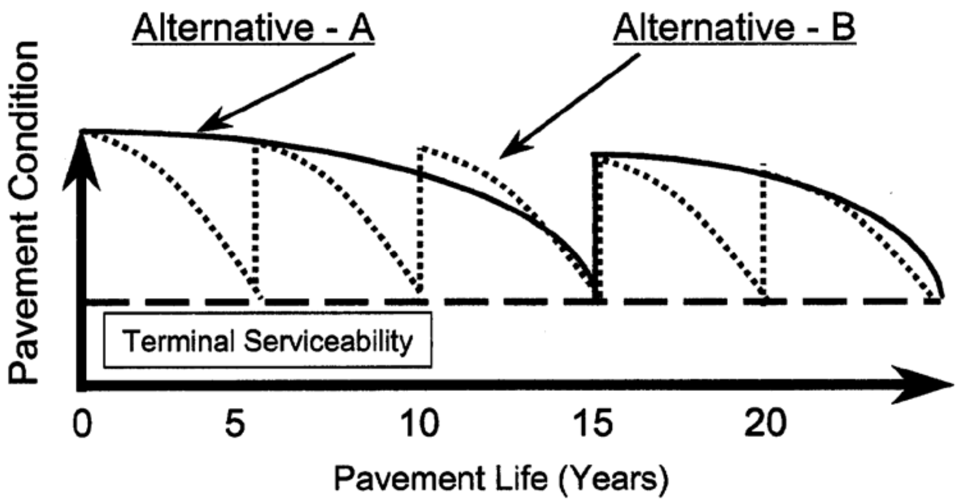


Figure 2.4 Performance curves for Rehabilitation and Maintenance Strategies

2.2.3 Salvage Value

For assets having useful life remaining at the end of the analysis period, a residual value/salvage value should be estimated (Ozbay et al., 2003). Salvage value has two components associated with it. The first one is the residual value that refers to the net value from recycling the pavement (Walls and Smith, 1998). The other component is the serviceable life, which is the remaining life in a pavement alternative at the end of the analysis period. Serviceable life needs to be accounted for in the analysis if, at the end of the analysis period the alternatives have differences in remaining pavement life. For instance, if alternative A had a 10-year remaining life while Alternative B had a 5-year remaining life, not considering salvage value in the life cycle cost analysis process would favor Alternative B unfairly.

In the current procedure outlined in the FHWA Technical Bulletin for calculating serviceable life, the value of the pavement is determined by multiplying the cost of the latest rehabilitation activity by the percent of design life remaining at the end of the analysis period. Revising the procedure by incorporating the cost of initial construction instead of the latest rehabilitation activity is currently being considered by FHWA.

2.2.4 Discount Rate

The discount rate is a highly significant factor in LCCA and can have a major influence on the outcome. When analyzing long-term public investments, discounting is an essential element in comparing costs occurring at different points in time (Jawad and Ozbay, 2006). As time has money value, a dollar spent in the future is worth less than the present dollar. Therefore, the costs and benefits encountered at different points in time need to be converted to costs and benefits that would have been encountered at a common point in time.

The FHWA Technical Bulletin recommends the use of a discount rate that reflects historical trends over long periods of time. The authors report that data collected over a long period of time indicate that the real time value of money is approximately 4 percent. Many state agencies follow this recommendation and report the use of a 4 percent discount rate in their analysis (WSDOT, 2005; Florida DOT, 2005; MoDOT, 2004).

The discount rate, as determined by the Office of Management and Budget, is also widely used among State DOTs Table 2.2 shows the recent trends in real discount rates for various analysis periods published in the OMB Circular A-94 (OMB, 2006).

Wisconsin Department of Transportation's procedure for determining the value of discount rate was determined by a University of Wisconsin Economics Professor, Dr.

Donald Harmatuck in 1984. At the time their Pavement Type Selection Process Report was published (in 1994) they were using a 5 % discount rate. It was concluded by Dr. Harmatuck that when the low cost alternative at the current five percent discount rate was, say, 20 percent lower than competing alternatives, discount rate variations did not affect the choice of the low cost alternative. That is, the low cost alternative remained so over the three to seven percent range. However, if alternative costs were within 15-20 percent, a sensitivity analysis of discount rate was recommended. If the results of the sensitivity analysis were highly dependent upon the discount rate, the analysts were recommended to determine where the resources for the project were coming from. If resources were obtained from increased taxation, a low discount rate was to be justified. If pavement projects were undertaken at the expense of other highway projects, a discount rate above five percent was recommended. Table 2.3 shows the average and standard deviation values for the discount rates published over the last 28 years and Figure 2-5 shows, graphically, the historical and recent trends in real discount rates for a 30-year analysis period.

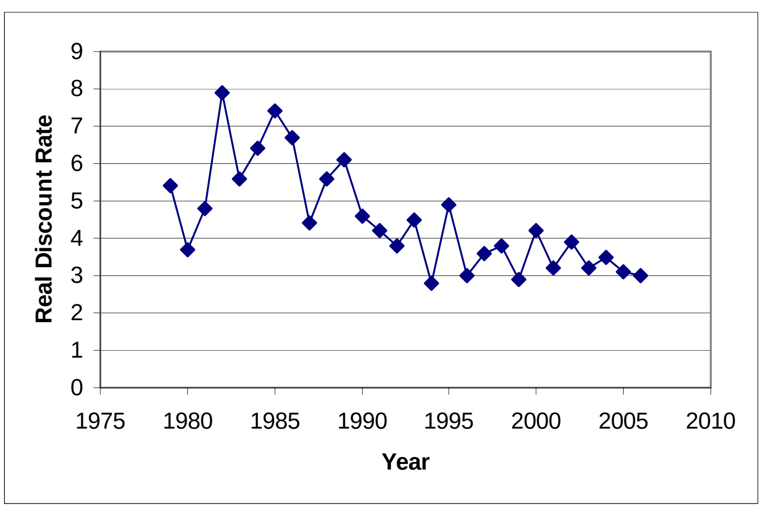


Figure 2.5 Historical Trends in OMB real discount rates for 30 year analysis period

Table 2.2 Recent Trends in OMB real discount rates

Year	3-Year	5-Year	7-Year	10-Year	20-Year	30-Year
1979	2.8	3.4	4.1	4.6	N/A	5.4
1980	2.1	2.4	2.9	3.3	N/A	3.7
1981	3.6	3.9	4.3	4.4	N/A	4.8
1982	6.1	7.1	7.5	7.8	N/A	7.9
1983	4.2	4.7	5.0	5.3	N/A	5.6
1984	5.0	5.4	5.7	6.1	N/A	6.4
1985	5.9	6.5	6.8	7.1	N/A	7.4
1986	4.6	5.1	5.6	5.9	N/A	6.7
1987	2.8	3.1	3.5	3.8	N/A	4.4
1988	3.5	4.2	4.7	5.1	N/A	5.6
1989	4.1	4.8	5.3	5.8	N/A	6.1
1990	3.2	3.6	3.9	4.2	N/A	4.6
1991	3.2	3.5	3.7	3.9	N/A	4.2
1992	2.7	3.1	3.3	3.6	N/A	3.8
1993	3.1	3.6	3.9	4.3	N/A	4.5
1994	2.1	2.3	2.5	2.7	N/A	2.8
1995	4.2	4.5	4.6	4.8	N/A	4.9
1996	2.6	2.7	2.8	2.8	N/A	3.0
1997	3.2	3.3	3.4	3.5	N/A	3.6
1998	3.4	3.5	3.5	3.6	N/A	3.8
1999	2.6	2.7	2.7	2.7	N/A	2.9
2000	3.8	3.9	4.0	4.0	N/A	4.2
2001	3.2	3.2	3.2	3.2	N/A	3.2
2002	2.1	2.8	3.0	3.1	N/A	3.9
2003	1.6	1.9	2.2	2.5	N/A	3.2
2004	1.6	2.1	2.4	2.8	3.4	3.5
2005	1.7	2.0	2.3	2.5	3.0	3.1
2006	2.5	2.6	2.7	2.8	3.0	3.0

Table 2.3 Average and Standard Deviation valued for the published OMB rates

	3-Year	5-Year	7-Year	10-Year	20-Year	30-Year
Average	3.3	3.6	3.9	4.2	3.1	4.5
Standard Deviation	1.2	1.3	1.3	1.4	1.0	1.4

2.3 LCCA Approaches

In general, there are two approaches to LCCA that could be employed: deterministic and probabilistic. In the deterministic approach input variables are treated as discrete fixed values (e.g., design life = 20 years). However, for various reasons, many of the input values used in any LCCA have some level of uncertainty associated with them. In any engineering analysis that involves a prediction, some level of uncertainty will be present and this uncertainty can be expressed as a combination of four major reasons. First, there will be uncertainty associated with randomness (i.e. the observed or measured values will have variation and different frequencies of occurrence). Secondly, there will be uncertainty associated with regional construction variation. That is, a set of data collected at Location A, cannot be used to analyze a situation occurring at Location B. There will also be uncertainty associated with human factors, such as imperfect modeling and estimation. Finally, there will be uncertainty associated with lack of data. For example, the possible omission of a variable because of limited data (Ang and Tang, 1975). It is very important to address this uncertainty in order to predict life cycle costs realistically. There are several methods used to combat these uncertainties including using risk analysis (the probabilistic approach) or by performing sensitivity analysis (Ozbay et al., 2004). In general, a sensitivity analysis is performed to assess the effects of various input parameters when developing a model. However, this analysis does not reveal, in many cases, the areas of uncertainty that may be an important part of the decision-making process (Herbold, 2000). On the other hand, risk analysis utilizes probabilistic approach to the input variables and uses computer simulation to characterize risk associated with the outcome. The LCCA system is much more valid and powerful if all inputs are analyzed probabilistically (Ozbay et al., 2003). Walls and Smith present a risk analysis approach for LCCA using Monte Carlo simulation (Walls and Smith, 1998). The agency's LCCA software RealCost that was released in 2002 enables the analyst to perform a probabilistic approach.

2.3.1 Sensitivity Analysis

In general, a sensitivity analysis is performed to understand what variables make the largest difference in the final result. Christensen et al. report that through this process, analysts can (i) identify the model variables that have a significant influence on model results and/or (ii) determine break-even points that alter the ranking of considered options (Christensen et al., 2005). Some of the factors that can exert significant influence on the model are unit costs of materials, discount rate, and rehabilitation timings. Determining break-even points that alter the ranking of considered options is investigated in Chapter 4.

A statistical approach for investigating the effect of several input parameters on the net present value (NPV) of life-cycle costs predicted by the HDM-III model can be found in Mravira (Mravira et al., 1999).

Sensitivity analysis provides decision-makers some insight regarding the sensitivity of the model. However, it fails to address some very important issues. First, when the ranking of feasible design options are altered due to a change in one model variable (e.g., discount rate), the dominant alternative among considered design options will fail to emerge. Second, since sensitivity analysis typically qualifies the effect of a single model variable on the analysis results, engineers do not gain a sense of the combined and simultaneous influence of several model variables on LCC results and rankings. Finally, without assigning probability distributions to variables, the likelihood that particular values occur is left unexplored. The purpose of risk analysis is to address these shortcomings (Christensen et al., 2005).

2.3.2 Risk Analysis

Risk analysis addresses most of the limitations associated with sensitivity analysis. First, variables are described by probability distributions instead of point values, so the likelihood that particular values occur is not left unexplored. Second, since sampling techniques consider the effect of variability in all of the input parameters, the simultaneous influence of several model variables on the outcome can be seen. Finally, a dominant alternative may still fail to emerge. However, the probabilistic distribution assigned to each variable provides a clearer and more descriptive picture of associated outcomes (Christensen et al., 2005).

Comprehensive introductions to risk analysis, relevant probability and sampling concepts, and related measures of comparison are found in several sources. (Ang and Tang, 1975; Chacko, 1991).

Conducting risk analysis requires the analyst to assign probability distributions to certain input variables. When enough data is available, it is possible to perform a goodness-of-fit test to examine how close the data set distribution is to the hypothesized theoretical distribution (Tighe, 2001). There are also statistical analysis packages that automatically fit the probability distribution to the data (Walls and Smith, 1998).

Tighe reported that a lognormal distribution is better suited to describe most construction variables than the generally presumed normal distribution (Tighe, 2001). It is also shown that both pavement material costs and thickness of pavements follow a lognormal distribution and that using a normal distribution instead of a lognormal distribution alters the results greatly. In fact, it is shown that a cost difference of

$62,000/km is encountered by using a normal distribution instead of a lognormal distribution (Tighe, 2001).

2.3.3 RealCost

RealCost is FHWA's Microsoft Excel based LCCA software package that is based on the FHWA Technical Bulletin of 1998. The software can perform LCCA in either a deterministic or a probabilistic form. For the deterministic approach, discrete values are assigned for each input variable. In contrast, probabilistic LCCA allows the value of individual analysis inputs to be defined by a probability distribution (FHWA, 2004). For a given project alternative, the uncertain input parameters are identified. Then, for each uncertain parameter, a probability distribution needs to be determined. Seven types of probability distributions are available in RealCost. For each probability distribution chosen, the following values in Table 2.4 must be entered.

Table 2.4 Probability distributions and corresponding values

Probability Distribution	**Value**
Uniform	Minimum, maximum
Normal	Mean standard deviation
Log normal	Mean standard deviation
Triangular	Minimum, most likely, maximum
Beta	Alpha, beta
Geometric	Probability
Truncated normal	Mean, standard deviation, minimum, maximum
Truncated log normal	Mean, standard deviation, minimum, maximum

The built-in probabilistic inputs in Real Cost 2.2 software are:

- Discount rate,
- Annual growth rate of traffic
- Free flow capacity

- Value of time for passenger cars
- Value of time for single unit trucks
- Value of time for combination trucks
- Agency construction cost
- User work zone costs
- Maintenance frequency
- Activity service life
- Agency maintenance cost
- Work zone capacity
- Work zone duration

However, the software allows the user to assign probability distributions to other desired inputs as well.

Moreover, when performing a probabilistic analysis, RealCost is able to create reproducible results (i.e., the randomness associated with the simulation numbers can be eliminated). As can be seen in the Figure 2-6, either random or reproducible results can be chosen. If random results are chosen, the computer will generate a seed value (the value that the simulation starts with) from its internal clock. However, when reproducible results are chosen, the analyst specifies a specific seed value. This value is used in all simulations. This causes the same set of random numbers to be generated by the computer allowing the analyst to perform separate simulation runs to compare multiple alternatives.

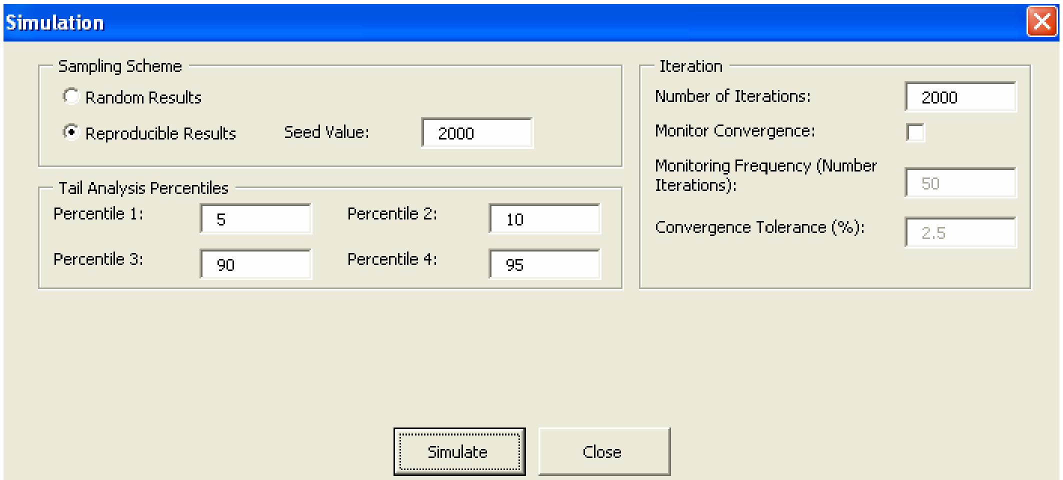


Figure 2.6 Simulation Form

One of the drawbacks of this software is the lack of support for the analyst in the design of work zones (Flintsch and Kuttesch, 2004). The authors report that some assistance in the form of typical work-zone arrangements and production rates for typical maintenance activities would be preferable. Also, some guidance in determination of user cost values that takes into consideration regional factors would prove beneficial.

2.4 State-of-the-Practice

2.4.1 United States

Most states conduct LCCA in their pavement type selection process. However, the degree of implementation varies widely. There have been several efforts to capture the state-of-the-practice in the U.S. and to document the degree of employment of Life Cycle Cost Analysis (Peterson, 1985; AASHTO, 1993; Ozbay et al., 2004) Also, there have been several reports coming from a joint effort of state DOTs and research institutions to promote knowledge exchange and research concerning LCCA principles and methodologies (Beg et al., 1998; Jung et al., 2002; Cross and Parsons, 2002; Ozbay et al., 2003; Temple et al., 2004).

Concerning the various levels of U.S. government, there have been several reports published by state DOTs that present and analyze their current state-of-the-practice (Goldbaum, 2000; VDOT, 2002; PENNDOT, 2003). These reports refer to unit costs used in the analysis, determination of agency and user costs, and rehabilitation data, among others.

Within academia, various universities and university clusters have made significant efforts to promote knowledge exchange and research concerning LCCA principles and methodologies. These include the Southwest Region University Transportation Center and the University of Texas at Austin (Wilde et al., 2001), the University Transportation Center for Alabama and the University of Alabama (Lindley and Clark, 2004), Kentucky Transportation Center and University of Kentucky (Rister and Graves, 2002).

Organizations, such as FHWA and the American Concrete Pavement Association (ACPA) have made significant efforts to enhance the level of knowledge on LCCA. ACPA has published an LCCA bulletin that provides guidelines on LCCA (ACPA, 2002). FHWA supports its implementation by delivering workshops to transportation agencies, providing guidelines (i.e., the publication of the Interim Technical Bulletin on LCCA), offering training in the use of the their RealCost LCCA software, and hosting peer exchange meetings on LCCA.

2.4.2 Europe

In October 1997, the Forum of European National Highway Laboratories officially started a research project aimed at developing economic models for evaluation of life-cycle costs of pavements. The project was called PAV-ECO (Economic

Evaluation of Pavement Maintenance - Life-cycle Cost at Project and Network Level) and ended in October 1999. The PAV-ECO Project was undertaken by a Consortium of Partners consisting of the Danish Road Institute (Denmark), Anders Nyvig A/S (Denmark), Technical Research Center of Finland (Finland), Laboratoire Central des Ponts et Chaussées (France), University of Cologne (Germany), Laboratoire des Voies de Circulation LAVOC - EPFL (Switzerland), Viagroup SA (Switzerland) and Transport Research Laboratory (United Kingdom). The Danish Road Institute managed the Project (Danish Road Institute, 2002).

As part of the PAV-ECO Project, a framework was developed for comparison of life-cycle costs of different maintenance strategies at the project level, which involves calculation of agency and user costs over the length of the selected analysis period. The PAV-ECO project provides a description of the factors that effect traffic forecasts and suggests new traffic simulation models for both network and project level. In the method developed for determining the most cost effective maintenance strategy, not only agency costs, but also user and social costs are considered. The user costs considered are user's lost time, vehicle operation, and crash costs. The social costs considered are, air pollution, and CO_2 emissions. During this project, a range of European VOC models were evaluated to assess their suitability for inclusion in life-cycle cost models for roads in Europe.

2.4.3 Canada

In Canada, an LCCA survey was conducted recently by the University of Saskatchewan Civil Engineering Professor Dr. Gordon Sparks. The survey findings indicate that the use of LCC methods vary widely across agencies, from not using LCC methods at all to using highly sophisticated methods. Most agencies use LCCA in planning, design, and preservation of pavements in the project level. However, some agencies are focusing on using LCCA as part of an asset management approach. The issues raised by the transportation agencies were:

- Lack of standard methods
- Lack of data
- Need for training in LCC methods
- Need for software development, training, and support
- Lack of communication both within departments and between departments and political officials

Nine of the ten provinces in Canada have responded to the survey. The survey responses showed that currently, British Columbia does not use LCCA. Alberta has used LCCA extensively for years in pavement type selection, in the evaluation of different reconstruction alternatives, and selection of materials. Alberta conducts risk and sensitivity analysis to address uncertainty. Saskatchewan has used LCC methods to varying degrees over the years in rehabilitation, reconstruction, and asset management applications. The only component of user costs considered in the analysis is vehicle operating costs. Saskatchewan utilizes both the deterministic and probabilistic approaches. Manitoba has used LCC methods within the asset management system for 8 years. LCCA has been used in planning and design of pavement construction projects (e.g., in pavement type selection), and in asset management (i.e., in preservation, rehabilitation and reconstruction). Manitoba is currently considering the alternative bid process. User costs considered in the analysis are vehicle operating, delay, and driver and passenger value of time costs. External costs such as environmental costs/emissions, right of way costs and socio-economic costs (i.e., benefits of improved infrastructure) are also considered in the analysis. Ontario has used LCC methods extensively for more than 25 years. Approximately 90 percent of pavement designs are subjected to LCCA. Currently the opportunities to incorporate user costs into LCCA are being explored. Ontario conducts both risk and sensitivity analysis. LCCA is currently used in alternate bids. Ontario's guidelines for the use of LCCA can be found online at http://192.75.156.22/sydneyweb/cgi/swebimg.exe?action=Attachments&key=ctcx&ini=splusweb&uid=public (Lane and Kazmierowski, 2005). Quebec has used LCC methods extensively for many years. LCCA has been used for pavement type selection since 2000. The factors considered in the analysis are agency costs and user delay costs. Uncertainty is addressed in the analysis and FHWA's RealCost program is used. The future plans are to include VOC and to have a more uniform usage in all construction and rehabilitation projects. New Brunswick is planning to implement an asset management system by 2007. New Brunswick's criteria used for LCCA are initial costs and ongoing preservation costs. Sensitivity analysis and risk analysis are conducted to address uncertainty. Nova Scotia has used LCC methods in the past in pavement type selection. The past experience has shown the results of LCCA to be highly sensitive to some variables (e.g., discount rate). It was reported that results could be manipulated by varying the discount rate. Newfoundland and Labrador does not typically use LCCA, but have recently hired a consultant to perform LCCA of alternative asphalt surface types for a major project. Almost all of the agencies expressed concerns about the lack of standard guidelines and data, lack of understanding the benefits of using good LCC methods, challenges faced in communication both within departments and between departments and political officials, and challenges with training. Overall, the survey results showed that there is a need for generally accepted LCCA methods that are rational, systematic, and able to handle complexity and uncertainty explicitly and transparently.

2.5 Challenges Surrounding the Implementation of LCCA

FHWA identified the concerns of DOTs regarding the implementation of LCCA (FHWA, 1999):

- Selecting an appropriate discount rate
- Quantifying non-agency costs such as user costs
- Securing credible supporting data, including traffic data
- Projecting costs and travel demand throughout the analysis period
- Estimating salvage value and useful life
- Estimating maintenance costs and effectiveness
- Modeling asset deterioration

CHAPTER 3

SURVEY RESULTS AND ANALYSIS

3.1 Preliminary survey

A web based preliminary survey was formulated and posted on the internet to capture the state-of-the-practice of LCCA. The survey was made available on the server by Zoomerang; an online survey software (www.zoomerang.com).

The questions were as specific as possible in order to gain insight on current practices and also to avoid confusion with regard to the terminology used and the actual information requested from the survey recipients. It contained questions about the general practice of LCCA, such as the length of the analysis period, and assigned initial performance life for rigid and flexible pavements, as well as for different rehabilitation treatments and others. The questionnaire contained 10 questions. The questions were prepared using various formats, such as yes or no boxes and short essay question fields.

For one question the recipients were asked to provide supplementary information on their agency guidelines. Therefore, a prompt and an e-mail link were included to encourage participants to send the survey team helpful documents or other electronic documents they may have had. The contents of the survey were refined several times by the research team for suitability of the contents, the wording of the questions, and the suitability of the format used for the various questions. Complementarily, the survey was also sent for review and commenting to the industry and SCDOT representatives. Various changes were made based on their feedback.

The web survey was launched on the internet in September 2005. An email was sent in order to provide the recipients with the survey's webpage address link and also explain the purpose of the research and its anticipated importance. Reminder emails were sent to the survey recipients who had not yet responded.

A total of 39 completed questionnaires from 33 States and 2 Canadian Provinces were received. The responses were statistically analyzed and charts and tables were created. For four states, more than one transportation official responded to the survey. Since questions were state-specific and required only one valid answer per responding state, the various answers within the same state were compared and discrepancies were resolved so that only one answer would be kept, as complete as possible, based on the following criteria:

- Priority was given to the most complete responses; for example, in the case where one transportation official reported that the state agency used one software program to conduct LCCA and another one reported the use of an additional one, then the final response would contain both of the software programs.

- Priority was given to the responses of transportation officials whose areas of expertise most closely coincided with that of the survey's questions and required input fields.

Answers to essay questions were not considered in the statistical analysis but rather used as a guide for the overall status of the responding state in relation to the researched topics.

The survey analysis contains, to the extent possible, a comparison to previous surveys conducted in 1984 and in 2001. The survey conducted in 1984 was a comprehensive survey on the practice of LCCA by SHAs and was conducted by the Transportation Research Board as a part of a National Cooperative Highway Research Program (NCHRP) project (Peterson, 1985). This survey collected information from 49 State DOTs (including some Canadian transportation agencies). The survey conducted in 2001 was conducted by K. Ozbay et al. for the New Jersey Department of Transportation (Ozbay et al., 2004). This was a three-stage survey that had obtained information from 39 State DOTs. The response rates were different for each stage and ranged between 14 and 24 responses.

3.1.1 Survey Responses

A total of 33 States and 2 Canadian Provinces have participated in the preliminary survey. Out of these, 94 % of the agencies indicated that they use LCCA as part of the decision process for selecting pavement type. Figure 3-1 shows the responding states. The individual responses are shown in Table B.1.

The responses to the second survey question showed that 50% (16 out of 32) of the responding agencies use RealCost, DARWin, or some customized software to conduct LCCA. Among these states, 6 states use RealCost, 6 states use customized software, and only one state uses DARWin, exclusively. The remaining states use a combination of the available software programs and one state is in the process of adopting RealCost. The individual responses are shown in Table B.1. In comparison, the 2001 survey results showed that 8 out of 16 responding State DOTs used software, predominantly DARWin and customized software, to compute life cycle costs (Ozbay et al., 2003). Based on the results of this survey, it appears that after the release of the RealCost program in 2002 by FHWA (FHWA, 2003), most state agencies have adopted this program for conducting their LCCA calculations.

In the next question, transportation officials were asked if they included user costs in the analysis. Most of the responding States (approximately 60 %, 19 out of 32) do not consider user costs as can be seen in Figure 3-2. However, three states that do not currently include user costs in the analysis, reported that they are planning to include user costs in the future.

Most of the State DOTs incorporating user costs into the analysis, calculate only user delay costs during construction and major rehabilitation activities. One of the respondents indicated the use of a specialized "WorkZone – Road User Costs" software program that could calculate user delay costs encountered by users going through a work zone. Another respondent indicated that user costs are included only when traffic volume is a concern to the analysis. That is, if one of the pavement type alternatives resulted in large queue lengths that would result in high user costs, then the pavement type that would result in lower queue lengths would be chosen. Another respondent indicated that user costs are computed only if an alternate has adverse detour miles. One transportation agency indicated that user costs were analyzed separately from agency costs.

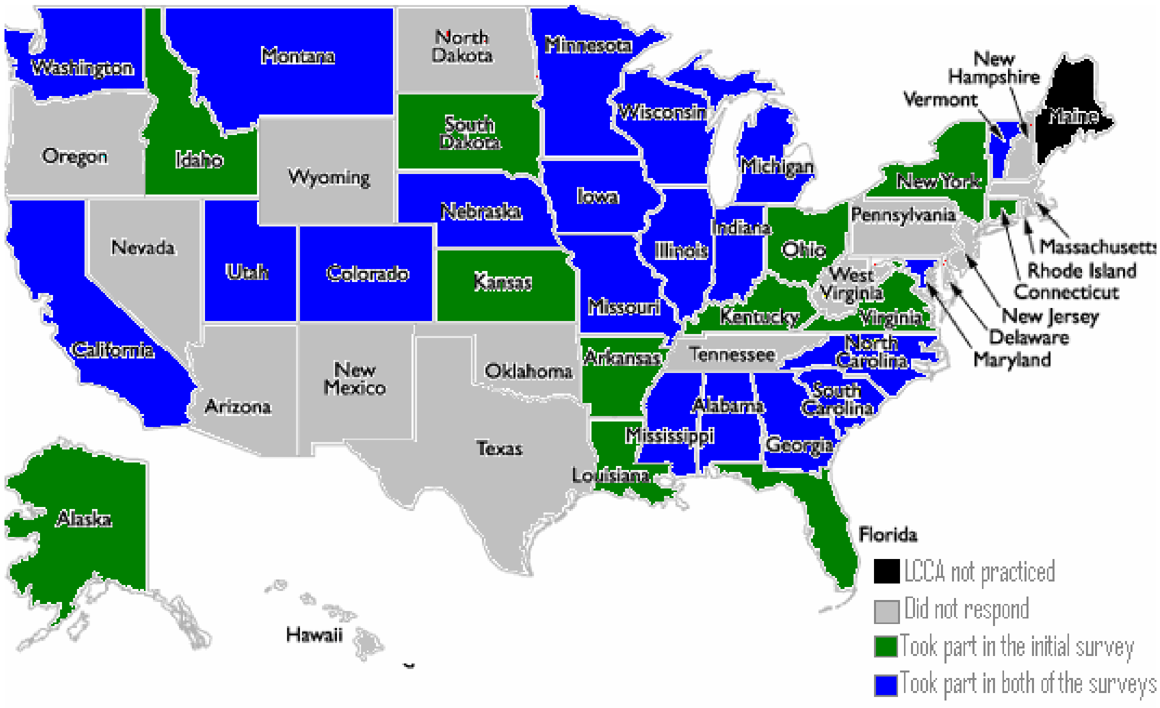


Figure 3.1 Geographical Representation of responses in the 2-stage LCCA survey

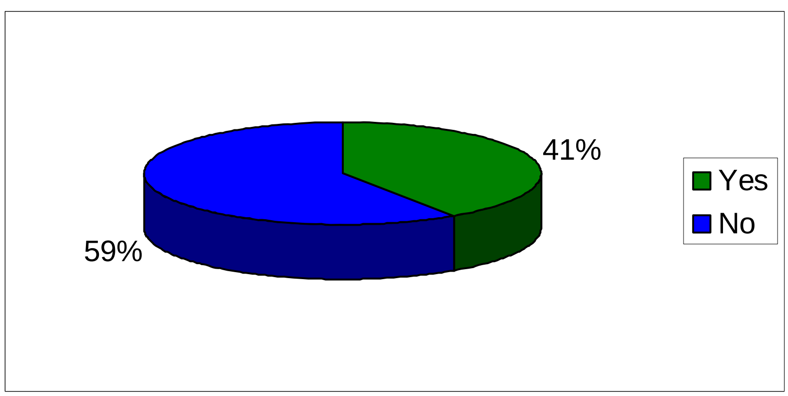


Figure 3.2 Incorporation of User Costs

The survey results showed that almost 6% of the respondents (2 out of 32 states) are currently conducting sensitivity analysis for their discount rates, while 9% (3 out of 32) use the probabilistic approach. The rest of the responding states use discrete values ranging between 3% and 5.3%, and several state DOTs use the Office of Management and Budget (OMB) discount rate as can be seen in Figure 3-3. While some states indicated the use of a fixed discount rate for all analyses, some indicated the use of a variable discount rate value depending upon available current data. The responses are shown in Table B.1.

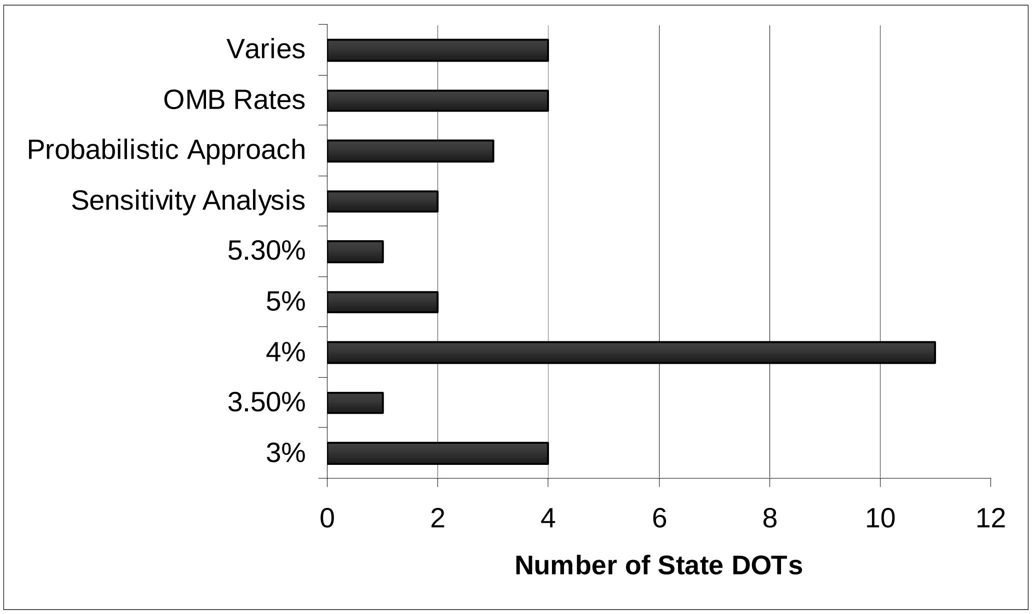


Figure 3.3 Responses of State DOTs on the Discount Rate Used in Most Recent Projects as of 2005

Figure 3-4 illustrates the analysis period used by state agencies based on the results from the surveys in 1984, 2001, and 2005. Comparing the results of the 2005 survey with the two previous surveys, it is evident that State DOTs are moving towards longer analysis periods. Percentage of DOTs using an analysis period of 50 years increased from 7% to 20% in the past four years. In 2005, there was, for the first time, a SHA (NYSDOT) using an analysis period of 65 years for pavement type selection process. NYSDOT indicated that they design their pavements for 50 years and then take into account an additional rehabilitation that will last 15 more years. Some states indicated in the 2005 survey that the analysis period they use depends on the proposed design life or on the network level of the pavement. However, the percentage of these states that determine the analysis period on a project-by-project basis decreased from 43% in 2001 to 22% in 2005.

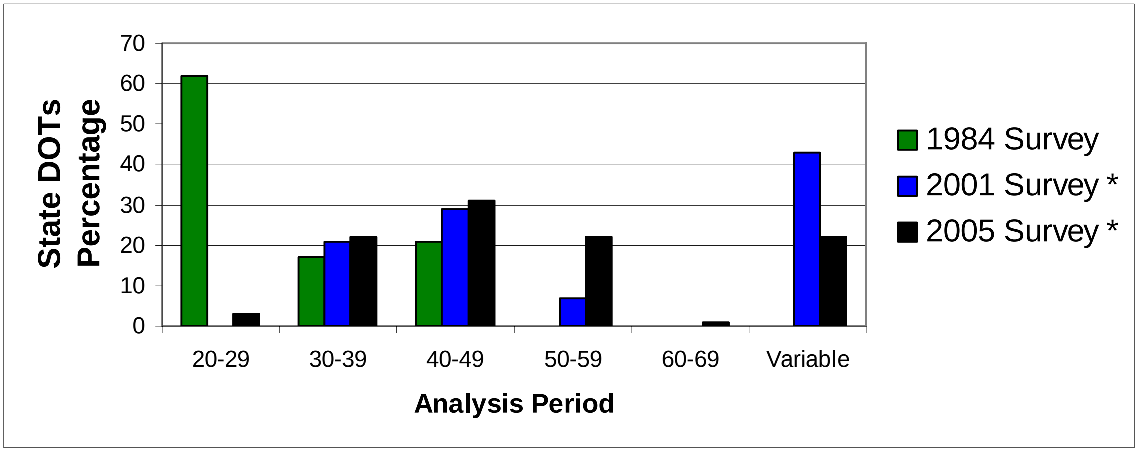
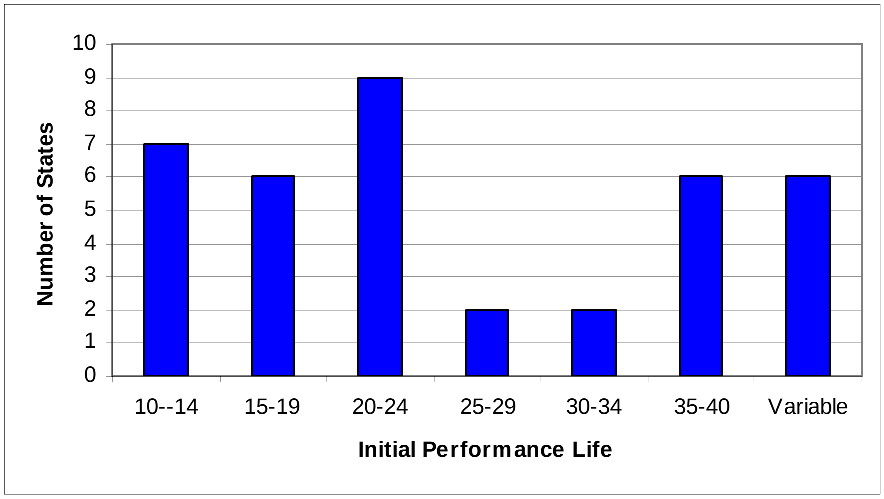


Figure 3.4 Analysis Periods as employed by State Highway Agencies

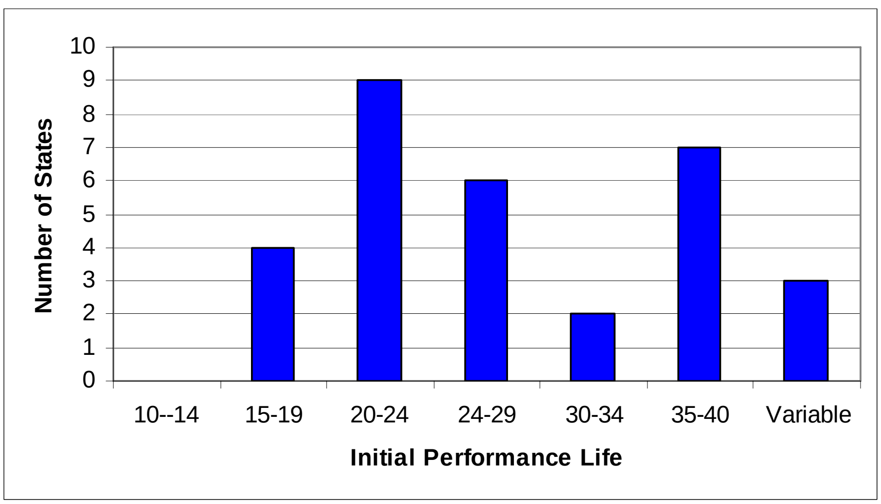
The increase in the length of analysis period over time is likely justified by the advances made in the design, construction and materials used in modern pavements as well as a desire by SHAs to construct longer lasting pavements.

Transportation officials were then asked to report the initial performance life assigned for flexible and rigid pavements. As can be seen in Figure 3-5, the assigned initial performance life ranged between 10 and 34 years for flexible pavements and between 15 and 40 years for rigid pavements. Several states reported the use of different initial performance lives depending on AADT. The individual responses to the analysis period used and initial performance assigned for flexible and rigid pavements are shown in Table B.2.

In the next question, state transportation officials were asked to report the treatments that were defined as maintenance and as rehabilitation. Some agencies do not differentiate between the two and include both maintenance and rehabilitation costs in the analysis. However, most agencies do not include maintenance costs in their LCCA.



(a)



(b)

Figure 3.5 Initial Performance Life Assigned for (a) Flexible Pavements, (b) Rigid Pavements

It is important to differentiate between maintenance and rehabilitation activities to be able to see which activities are not included in the analysis and which are. However, the distinction between the two is not clear and the definitions seem to be agency specific. For instance, one agency reported that an HMA overlay less than

60mm in depth would be considered a maintenance activity while another agency reported that an overlay less than 38mm in depth would be considered a maintenance activity. A third agency reported that 50mm was the depth that determined the distinction between maintenance and rehabilitation. Another example of different definitions by agencies is that of joint cleaning. Some agencies consider it to be a maintenance activity while others consider it to be a rehabilitation activity. However, there seem to be consensus on some of the activities, such as crack sealing; almost all of the agencies listed crack sealing as a maintenance activity. Some other maintenance activities listed were; joint sealing, patching, slab replacement, and thin surface treatments. Rehabilitation activities most commonly listed were; concrete pavement rehabilitation (CPR), diamond grinding and joint repair for rigid pavements, and milling with structural overlay, hot in place recycling, and cold in place recycling for flexible pavements. The detailed responses regarding the maintenance and rehabilitation treatments are shown in Table B.3.

Further on, transportation officials were asked what decision criteria were considered when pavement LCCA values for rigid and flexible pavements are similar. The selection processes differed between DOTs from always selecting the lowest life cycle cost alternative to always having someone in charge (i.e., designer, district engineer, commissioner of highways) making the final decision. However, most DOTs used LCCA costs to decide between the alternatives. Out of the 32 states that have responded to this question, 4 states (12.5 %) indicated that the pavement type selection decision is always based solely on the alternative with the lowest present value. Eight of the states (25%) reported that if the difference between the LCCA costs is greater than 10%, the more economical alternative is selected. One of the respondents indicated that the threshold percentage was 5%, another respondent reported the use of 15%, and yet another agency reported that 20% was used as the decision criteria percentage. If the differences between the alternatives are less than the predetermined percentage values, the regional pavement designer or pavement selection committee formed makes the final decision. Some of the factors considered in making the selection are constructability, availability of materials, design and environmental factors, continuity of pavement type, traffic control costs, availability of qualified constructers as well as public and political influence. Table B.4. shows the individual responses to this question.

In the following question, state transportation officials were asked if they included salvage value or remaining service life in LCCA. Out of the 32 states that have responded, 14 states (44%) do not consider salvage value in their calculations. Seventeen of the State DOTs (53%) always include salvage value in their calculations and one of the DOTs reported that it was included in a probabilistic analysis, but was not calculated in a deterministic analysis. The individual responses are shown in Table B.5.

In the last question of the preliminary survey, the agencies were asked to report any guidelines or policies they may have had regarding their LCCA procedures. 75% of the respondents (24 out of the 32) indicated that they possessed guidelines, while the rest of the agencies currently did not have guidelines or policies for their LCCA process. However, two of these states reported that the guidelines were currently being developed. Most of the agencies provided the research team with links to their online manuals that included the LCCA guidelines or policies. Table B.6. contains the responses provided.

3.2 Final survey

A final survey was formulated and e-mailed to state transportation officials that responded to the preliminary survey. The final survey aimed at soliciting information on specific approaches that each state is taking for pavement type selection process. The survey contained 22 questions and required more specialized and detailed input on current agency practices on LCCA such as the type of LCCA approach followed, the probabilistic inputs used in the analysis, design procedures, rehabilitation timings, the type of rehabilitation and maintenance activities conducted, and parameters used to arrive at user costs. The questionnaire also contained some questions about the general practice of LCCA such as the timing of the last LCCA revision, revisions considered to the LCCA process, and concerns with using LCCA. The questions were again prepared using various formats, such as yes or no boxes, check-all-that-apply boxes and short essay question fields. The contents of the survey were refined several times and sent for review to the industry, SCDOT and FHWA representatives in order to receive comments on the contents and wording of the questions. Various additions/changes were made based on their feedback.

The survey was e-mailed on April 17, 2006 to states that responded to the preliminary survey. The e-mail sent can be found in Appendix C. The survey questionnaire and the summary of results from preliminary survey were sent out as attachments. Reminder emails were sent to the survey recipients who had not yet responded.

3.2.1 Survey Responses

A total of 24 agencies responded to the final survey. 92% of these agencies (22 agencies) used LCCA for pavement type selection. Two of the respondents (i.e. Maine and British Columbia) indicated that they do not use LCCA for pavement type selection process since they only have flexible pavements. However, British Columbia considered alternative bids for LCCA for pavement type selection for a while and they provided responses for most of the questions based on their past experiences. The responses are included in Appendix D along with the other responses and were included in the analysis where applicable such as in questions that were on design procedure and rehabilitation timings.

The responses to the first survey question showed that out of the 22 states that practice LCCA for pavement type selection and responded to the final survey, 68% of the states (15 states) indicated that they were either satisfied or only had minor concerns with their existing LCCA process. However, 32% (7 states) indicated that they had significant concerns about the current practice of LCCA for pavement type selection process. The specific concerns raised by these states include:

- Unreliable quality of the input data into LCCA models
- Lack of adequately trained individuals who understand the importance and implication of the input parameters into LCCA programs such as RealCost.

- Difficulty in predicting cost of materials in a period of rapidly fluctuating prices to get a reliable and accurate LCCA.
- Lack of long-term field performance data for newer asphalt and concrete pavement designs and materials
- Lack of rational and predictable triggers for conducting rehabilitation and maintenance activities
- 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
- Lack of confidence in the LCCA process due to substantial differences between the initial construction costs of asphalt and concrete pavements.

Table D.1. shows the individual responses to this question.

The responses to the next question concerning the revisions considered for the LCCA process for pavement type selection process showed that 59% of the responding states (13 out of 22) are considering revisions to the LCCA process to achieve a more realistic comparison between pavement alternatives. The nature of revisions being considered range from incorporating a probabilistic approach to LCCA to including user costs in the analysis. One of the responding states is considering revisions to the oversight of the selection process by establishing a committee rather than by an individual to ensure a fair selection process. The individual responses are listed in Table D.2.

In the next question, state transportation officials were asked to report the time of the last LCCA revision. Figure 3-6 shows the number of the states and the year in which their LCCA process was updated for pavement type selection. The data indicates that most of the states (61%) revised their LCCA process during the last 3 years. Several DOTs modified their LCCA process to reflect a methodology that is based on FHWA's RealCost software program, while several other States are adjusting their processes constantly to reflect minor changes and clarifications. One of the responding states indicated that their construction pay item unit prices and non-material and labor placement cost percentages are adjusted on a monthly basis in tune with current statewide and regional price averages. This is an important factor to consider in the LCCA for pavement type selection process considering the recent surges in prices of some paving materials. Table D.3. shows the individual responses for the time of the last LCCA revision.

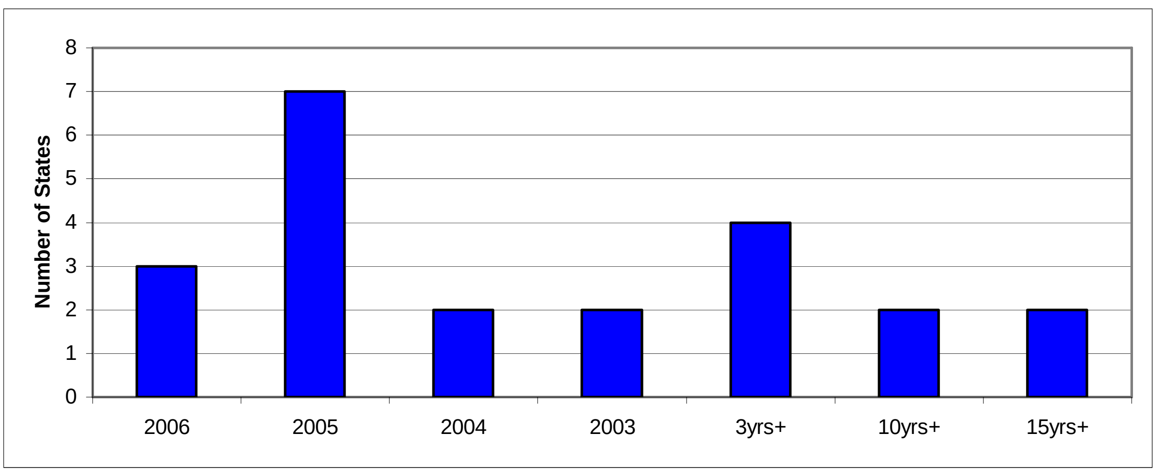


Figure 3.6 Time of the Last LCCA Revision

Another aspect of LCCA that was of interest in this survey was the range of factors that trigger the requirement of LCCA for pavement type selection process. In response to this question, the SHAs were asked to select the criteria (more than one if necessary). Figure 3-7 shows the results of the survey indicating that cost of the project was the most selected criteria, followed by pavement structural considerations and pavement system. Some states base their need to perform an LCCA depending on the pavement structural consideration such as structural number, with a predetermined inclination towards one or the other pavement type.

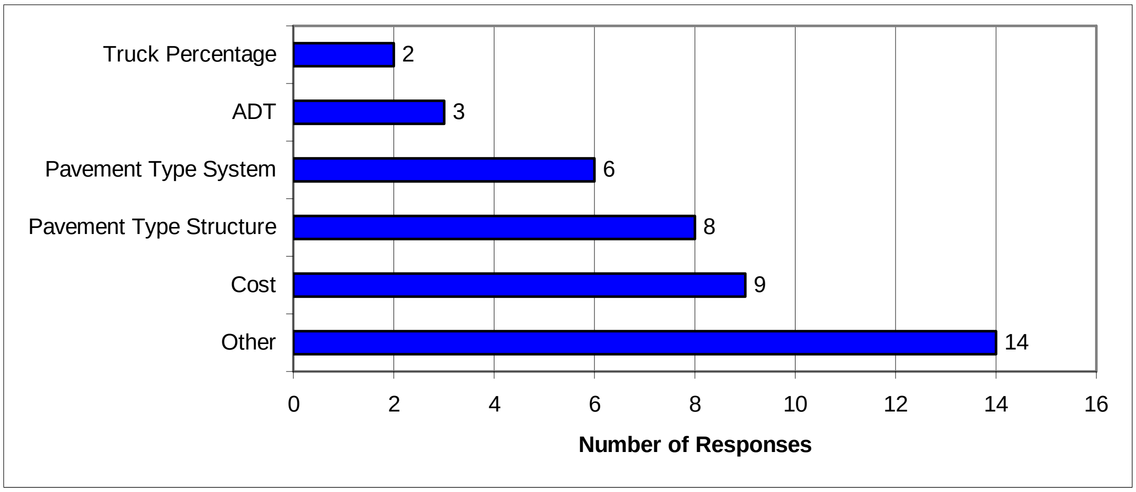


Figure 3.7 Criteria that triggers the requirement to conduct LCCA

The other criteria mentioned by the SHAs that triggered LCCA were as follows: One of the State DOTs indicated that LCCA is conducted for all pavements with design traffic less than 35,000,000 equivalent single axle loads (ESALs). They also reported that pavements with design traffic greater than 35,000,000 ESALs are automatically constructed with continuous reinforced concrete pavement (CRCP) and no LCCA is done. Another State DOT indicated that they use a combination of traffic and subgrade soil strength to determine if a formal pavement selection is needed. When they use the formal pavement selection, LCCA is used to determine pavement design and type. Otherwise an informal process is applied and LCC does not dictate the pavement type. Another transportation official indicated that they perform LCCA on all new construction, re-construction, and rehabilitation projects while another representative indicated that their only consistent use of LCCA is for alternate bidding selection. Another State DOT indicated that they perform LCCA on all new mainline pavement greater than ½ mile in length, ramps with high average daily traffic (ADT) or truck percentage, collector distributors and acceleration-deceleration lanes same as ramps, and intersections with chronic rutting problems. The responses are shown in Table D.4.

In the next question state transportation officials were asked the type of LCCA approach followed. The responses to this question revealed that in 2006, 4 years after the introduction of the FHWA Probabilistic LCCA Software – RealCost, only 5% of the responding states (1 state) used a probabilistic approach for all projects. Approximately 81% (17 out of 21) of the agencies responding to the survey still used a deterministic approach, while 14% used a combination of probabilistic and deterministic approaches for different aspects of LCCA as can be seen in Figure 3-8. Three of the responding agencies indicated that the use of probabilistic approach is currently being considered. The state-by-state responses for the LCCA approach followed are listed in Table D.5.

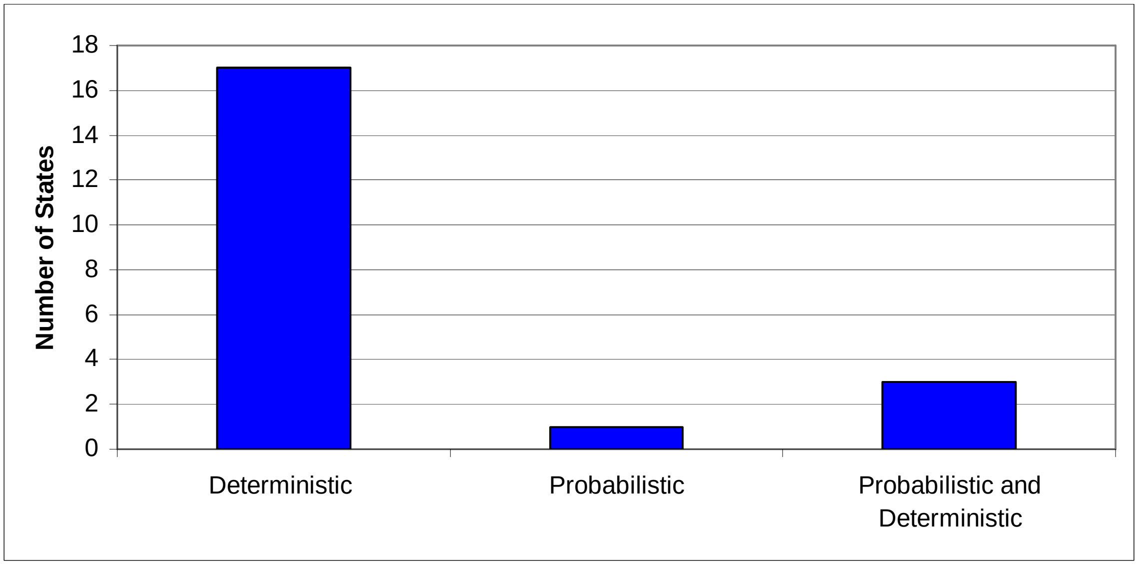


Figure 3.8 The type of LCCA Approach Followed

The responses regarding the use of sensitivity analysis showed that 25% of the SHAs utilizing a deterministic approach perform sensitivity analysis on several parameters to address the uncertainty in LCCA. Currently, discount rate, analysis period, timing of rehabilitations, and unit costs of materials in both initial construction and future rehabilitation projects are the parameters considered in sensitivity analysis by different states. Table D.6. shows the responses to this question.

Table D.7. shows responses from four SHAs who conduct a probabilistic approach to LCCA on some typical input values in their probabilistic approach and the associated probability distributions. Out of these four SHAs, Indiana DOT indicated that their probabilistic approach is currently on a trial basis.

Out of the states that use a probabilistic approach, three states provided the research team with the probabilistic values used for their discount rates. The responses are shown in Table 3.1. Discount rate probability density functions of these reported values were plotted and are shown in Figure 3-9.

The results showed that the distributions used are very different and that there is no consensus on the use of probability distributions and values used regarding the discount rate among the states.

Table 3.1 Typical Discount Rate Values

	Colorado DOT	**Maryland DOT**	**Washington DOT**
INPUT	Typical Values Used	Typical Values Used	Typical Values Used
Discount rate	Log Normal Distribution Mean 4.5 Std. Dev. 3.1	Truncated Normal Distribution Mean 3, Std Dev.0.25, Minimum: 2.5, Maximum: 3.5	Triangular Distribution, Min 3, Max 5, Most Likely 4

In the next question, transportation officials were asked to list the data sources used in selecting the input parameters for conducting an LCCA. The responses are summarized in Figure 3-10 and listed in Table D.8.

The following two questions collected information on the design procedures used for flexible and rigid pavements. The results showed that the 1993 AASHTO guidelines were most commonly practiced (by 50% of the respondents) in the design phase of flexible pavements. In the design of rigid pavements, again the1993 AASHTO procedure was the most commonly practiced procedure by 32% in this case. The second most common procedure practiced by state DOTs was combining AASHTO guidelines with State Design which was followed by AASHTO 1972 design procedure. The individual responses are listed in Table D.9. and Table D.10, respectively.

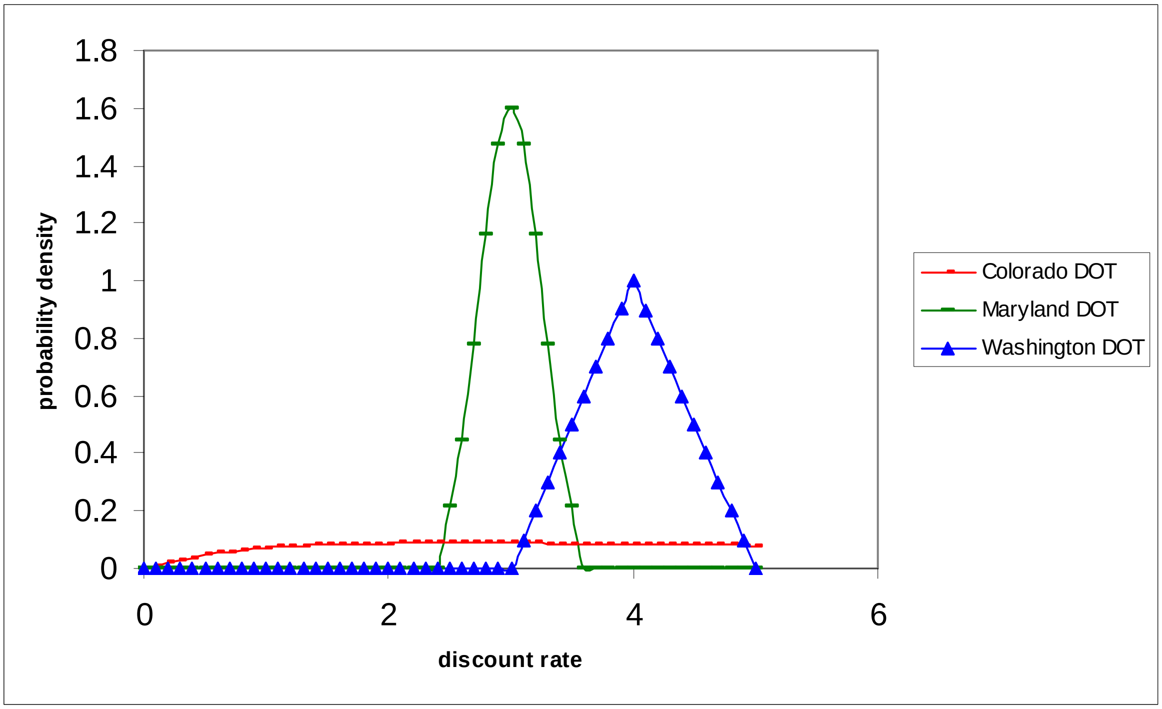


Figure 3.9 Discount Rate Probability Density Functions

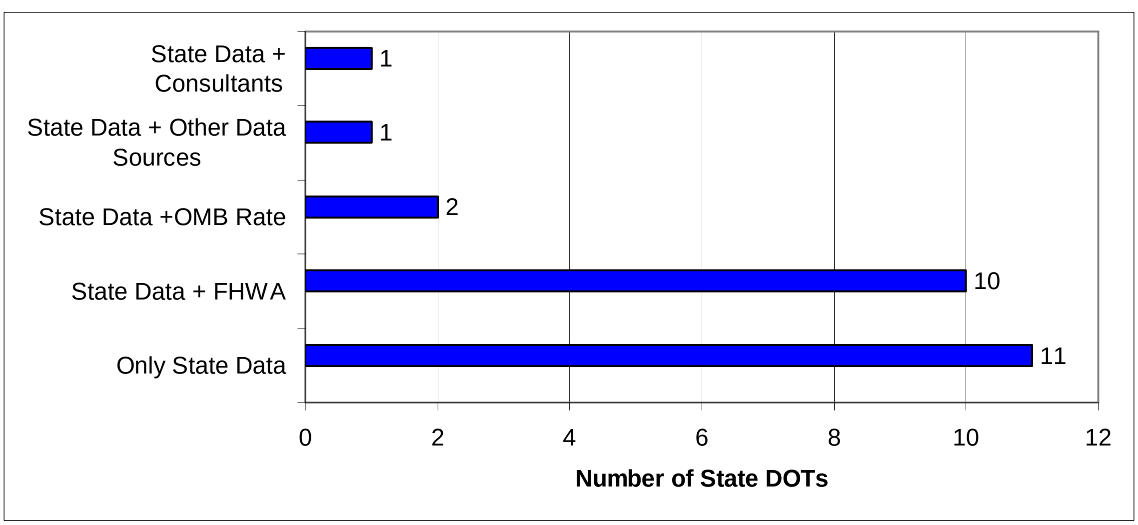


Figure 3.10 Data sources used in selecting the input parameters

In the next two questions, transportation officials were requested to provide information on the basis for arriving at the performance life of initial pavement design and the life of subsequent rehabilitation activities for rigid and flexible pavements. The practices varied between using historic data from Pavement Management Systems (PMS) to basing the decisions on visual inspection and available funding and are listed in Table D.11 through Table D.13.

Table D.14 summarizes the responses for different states on the performance life of initial pavement design, the life of subsequent rehabilitation activities for both flexible and rigid pavements.

Table D.15 through Table D.25 include the individual responses regarding the timing of initial and subsequent rehabilitation activities as well as frequency of maintenance activities during a given cycle of rehabilitation, rehabilitation options considered, and maintenance activities performed, and the unit costs of these activities for both flexible and rigid pavements.

The next question attempted to capture the costs included in the analysis when calculating agency costs. Figure 3-11 shows the results. All of the states surveyed indicated that construction costs were included in the analysis along with resurfacing and rehabilitation costs. However, there is a lack of consensus on the inclusion of other agency cost elements such as traffic maintenance, engineering, and construction management, for example, that are incurred by the agency over the analysis period. The individual responses to this question are shown in Table D.26

Table 3.2 Analysis Period and Rehabilitation Timings

State DOT	Analysis Period	Time to first rehabilitation		Rehabilitation Service Life	
		Flexible Pavements :	**Rigid Pavements:**	**Flexible Pavements :**	**Rigid Pavements:**
AL	28 yrs	12 yrs	20 Yrs, type not a consideration	8 yrs	8yrs
CA	Varies, from 20 to 55 years,	18-20 yrs Preventive maintenance before	JPCP 20-40 Yrs Preventive maintenance before	10 yrs	At least 10 yrs
CO	40 yrs	10 yrs	JPCP, 22 Yrs	10 yrs	18 yrs
GA	40 yrs	10 yrs	CRC - 25 years, JPCP - 20 years	10 yrs	20 yrs
IL	40 yrs	Depends on traffic	CPR of JPCP at 20 yrs CRCP: constructed for high-volume traffic routes and no LCCA is done.	Depends on the traffic factor	20 yrs
IN	40 yrs	25 yrs	JPCP, 30 Yrs	15 yrs	12 yrs
KS	30 yrs, but moving to 40 yrs	10 yrs	JPCP, 20 Yrs	Approximately 10 yrs	7-10 yrs
MD	40 yrs	15 yrs	JPCP, 20 yrs based on a 25 –yr initial structural life	12 yrs	Varies depending on which rehabilitation cycle
MI	Depends on the pavement/fix type	26 yrs	JPCP, 26 Yrs	10-15 yrs	21 yrs for unbonded overlay, 20 yrs for rubblizing & overlay
MN	50 yrs	For 7 million ESAL or less, route and seal cracks at year 6, for high ESAL do a crack fill at year 7.	JPCP, 17 Yrs	Depends on traffic	1st rehab:Joint reseal and minor CPR that lasts 10 yrs 2nd rehab: partial and some full depth repairs to last 13 yrs 3rd rehab:major CPR to last 15 yrs (which gives a 33% residual life at the end of the analysis period)
MS	40 yrs	12 yrs	JPCP, 1st rehab @ year 16	9 yrs	16 yrs
MO	45 yrs	20 yrs	25 Yrs	13 yrs for first mill and overlay, 12 yrs for 2nd mill & overlay	20 yrs
MT	35 yrs	19 yrs	JPCP, 20 yrs	12 yrs	20 yrs
NE	50 yrs	15-20	overlay at 35 Yrs unless performing exceptional	4" overlay for 12-15 yrs, then additional 4" overlay to give a total life of 50 Yrs	15 yrs for a total life of 50 Yrs

Table 3.2 (Continued)

State DOT	Analysis Period	Time to first rehabilitation		Rehabilitation Service Life	
		Flexible Pavements :	Rigid Pavements:	Flexible Pavements :	Rigid Pavements:
NC	20 yrs for SN<6.0 and 30 years for SN>6.0., looking at 40 yrs for SN>6.0	Typically 12-15 yrs	JPCP, 15 Yrs	12 Yrs	10 Yrs
SC	30 yrs	12 yrs for conventional mixes, 15 yrs for polymer-modified	JPCP, 20 Yrs	10 Yrs for conventional, 15 Yrs for polymer-modified	10 Yrs
UT	-	12-15 yrs	JPCP, 10 yrs for minor, 20 Yrs for major	OGSC* is at 7 to 8 yrs, rest is variable	Varies
VT	-	Varies	20 Yrs	10-12 yrs	10-15 yrs
WA	50 yrs	10-17 yrs	JPCP 20-30 yrs	10-17 yrs	Diamond grind 15-20 yrs, DBR** 15 yrs
WI	50 yrs	18 yrs over dense graded bse and 23 yrs over open-graded base	25 Yrs (undrained base) if placed over dense graded base and 31 Yrs if over open-graded base	Mill and overlay to give 12 yrs of service life	8 yrs if the initial rehab is repair 15 yrs if the initial rehab is an HMA overlay
Ontario	50 yrs	19 yrs for dense friction course, 21 yrs for SMA	JPCP, 18 yrs to first rehab, which is minor CPR and diamond grinding	13 yrs, then 12 yrs, then 11 yrs, then 10 yrs	10 yrs

*Dowel Bar Retrofit, **Open Graded Surface Course

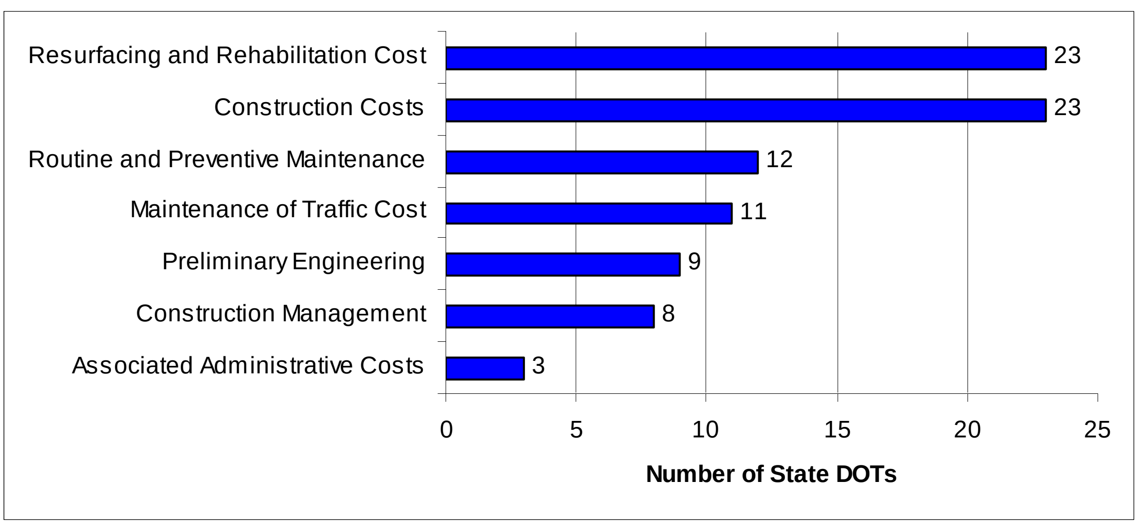


Figure 3.11 Calculations of Agency Costs

In the following question, the transportation officials were asked if typical construction cost values used in LCCA, were open for industry discussion to ensure that they were representative of field applications. The results showed that 8 out of 22 responding state DOT agencies do not have their cost values open for industry discussion as can be seen in Table D.27.

The next question attempted to capture information about the design options considered in the pavement type selection process. State DOT representatives were asked if they used a single initial construction cost based on optimal design of the pavement type, or if they considered different design criteria within each pavement type. The responses showed that 12 out of 21 responding states considered a single optimal design, while the other 9 states considered different design criteria within each pavement type. The responses are shown in Table D.28.

The next question investigated the parameters used in arriving at user costs. Only 8 states responded to this question and only 5 of these states provided values for the different parameters. Table D.29 shows the parameters each responding state is using to arrive at user costs. Table D.30 lists the typical values used for the parameters.

Table D.31 summarizes the responses regarding the use of salvage value. The responses showed that, out of the 23 state DOTs that responded to this question, 10 state DOTs always include salvage value in their calculations. The last question of the survey attempted to clarify how salvage value was calculated. Of the 10 state agencies that calculate salvage value, 8 indicated that serviceable life was calculated, while one agency indicated that both residual value of the pavement and serviceable life were included in the analysis. One DOT reported that the benefit of using any recycled bituminous or concrete material was incorporated into the initial cost estimate, instead of assigning a salvage value at the end of the analysis period. Table D.32 lists the responses to this question.

3.3 Conclusions

Based on the information gathered from the preliminary and final LCCA surveys conducted in this study, the following conclusions are drawn:

- Approximately 92% of the survey respondents are using LCCA for pavement type selection and almost 70% of the participating agencies do not have any concerns with using LCCA.
- Over 61% of the states that responded indicated that they had updated their LCCA process during the last three years.
- Cost, pavement structure (e.g., structural number), and pavement type system (e.g., interstate, secondary roads, etc.) were reported, by many states, to be the major criteria that would trigger the requirement to conduct LCCA.
- So far, 4 states have implemented the probabilistic approach and several others are conducting research to start implementing it.
- Over 50% of the responding agencies use RealCost, DARWin, or some customized software to conduct LCCA. Over one half of the respondents indicated that they use RealCost software.
- Majority of the states (approximately 59%) do not consider any type of user cost in their approach to life cycle cost analysis. Those states that incorporate user costs into the analysis, consider only work zone user delay costs.

- Most of the states use a 4% discount rate. Approximately 15 % of the respondents address the uncertainty in the discount rate by using a range of values, 3 to 5.3%, instead of using discrete input values. Some states use the OMB discount rate.
- State DOTs are moving towards using longer analysis periods. The majority of the respondents use a 40 year analysis period. However, more than 20% of the responding agencies use an analysis period of 50 years and one state DOT uses an analysis period of 65 years.
- Majority of state DOTs use historical data from pavement management systems to determine their rehabilitation timings.
- Approximately 56% of the respondents include salvage value in their analysis.
- Out of these, 80% calculate only remaining serviceable life, and the rest calculate both residual value and remaining serviceable life.

CHAPTER 4

RECOMMENDATIONS

4.1 Discount Rate Determination

The current practices showed that there is no consensus on the probability distributions and values used for discount rate in a probabilistic analysis as shown in Figure 3.9. More research needs to be done in this area to determine distributions estimated using historical data. Jawad and Ozbay make the following suggestions for developing probability distributions for discount rate (Jawad and Ozbay, 2006):

- A probability distribution constructed from the recorded real treasury discount rates published in the OMB circular, corresponding to a 30-year maturity. However, the authors note that special attention must be given to distribution bounds.
- A triangular distribution constructed with the mean value being the OMB discount rate in the evaluation year with +/- 2% as the minimum and maximum boundaries of the distribution.

If a probabilistic distribution cannot be developed, the analyst will need to use a deterministic value. In this case, the procedure used by Wisconsin DOT (WisDOT) can be followed. The basis of the procedure is explained in Chapter 2 and will be elaborated here. The procedure involves the use of a set value for all analysis which is 5%. When the low cost alternative at this current discount rate is at least 20 percent lower than competing alternatives, it is assumed that discount rate variations do not affect the choice of the low cost alternative. That is, the low cost alternative remains so over the three to seven percent range in this case. However, if alternative costs are within 15-20 percent, a sensitivity analysis of discount rate is recommended. If the results of the sensitivity analysis are highly dependent upon the discount rate, the analysts are recommended to determine where the resources for the project are coming from.

However, the set value that is being used by WisDOT, which is 5% was determined in 1984. The OMB rates at the time ranged between 5 and 6.4% for different analysis periods. The FHWA's Technical Bulletin recommends the use of 4%. The Technical Bulletin was published in 1998 when the OMB rates ranged between 3.4% and 3.8%. The 2006 values for real discount rate range between 2.5% and 3% and Figure 2-5 shows the trends in discount rate values over time. To determine a reasonable discount rate that reflects historical trends, the past and current rates can be obtained from the OMB Circular A-94 which is annually updated (OMB, 2006).

4.2 Analysis Period

The survey responses showed that state DOTs are moving towards longer analysis periods. The majority of the state DOTs are using a 40 year analysis period. However, 20% of the responding agencies use an analysis period of 50 years and one state DOT uses an analysis period of 65 years. Analysis period must be selected with caution, since it is also one of the parameters that can change the ranking of the alternatives. In Chapter 5, case studies of altering analysis period are provided.

4.3 Rehabilitation Timings

With the presence of a historic database, strategies can be based on statistical analysis of the information gathered on the location, type, and timing of the past rehabilitation and maintenance activities. Probability distributions can be developed for each type of pavement and for each type of rehabilitation activity. Several DOTs (CDOT, WSDOT) use their Pavement Management Systems to construct probability distributions representing possible values for timing of future rehabilitation activities. However, in the absence of such data, establishing rehabilitation strategies that are representative of the actual practice in the agency and judged by an expert opinion are recommended.

Also, the LTTP pavement performance database can be accessed online at http://www.datapave.com/Login.asp. Even though it is yet to be completed; the current data might be helpful in the development of empirical models for pavement conditions.

4.4 Salvage Value

There are two components associated with salvage value: the value of the recycled materials, and the value of the remaining service life of the pavement. Most of the agencies that incorporate salvage value into their analysis include remaining service life. The procedure for this process is outlined in the FHWA Technical Bulletin. However, the residual value from recycling the pavement should also be calculated. Minnesota DOT's approach can be followed in this process: The benefit of reusing any in-place bituminous or concrete material, which can be recycled back into the new pavement structure, is incorporated into the initial cost estimate. This results in separate cost estimates for designs using virgin material and designs using the recycle material. This way, the uncertainty associated with discounting the residual value component is eliminated.

4.5 User Costs

Even if user costs are not included in the total costs by assigning a distinct dollar value to user costs, addressing excessive queues and user delays is recommended. For addressing these components, determining the length of the work zone queue that results during a rehabilitation or construction activity is necessary. RealCost by performing an hour-by-hour comparison of roadway capacity and traffic demand calculates the length of a possible queue. The analysis of queue lengths can then be used to compare different alternatives. It can also be used to schedule lane closures.

4.6 Sensitivity Analysis

Conducting sensitivity analysis on input parameters especially on discount rate, and rehabilitation timings is recommended to be able to understand which inputs make the largest impact on the results. Sensitivity analysis may also be conducted to determine break-even points that alter the ranking of the alternatives. An example of this type of analysis is provided in Chapter 5.

4.7 Risk Analysis

The key element in a risk analysis is defining the probability density distributions for each of the input parameters that carry inherent variability in their values. These distributions can be developed by either using subjective or objective methods (Ozbay et al, 2003). Subjective methods use expert opinion and are used in the absence of real data. In this method, the subject expert defines a probability distribution that can best fit the variability of the parameter according to his expertise and experience. In the presence of real data, objective methods can be employed which involve determining the distribution that best fits the data. In the past this would involve rigorous calculations. However, today this can easily be accomplished by the help of software programs such as BestFit. This program will determine the distribution that best fits the data.

After determining the probability distributions for all uncertain parameters, the final result can be calculated easily by computer simulation. The survey results showed that the most commonly used software for this purpose is FHWA's RealCost.

Probabilistic results of an LCCA provide the analyst with NPVs that are normally distributed. The standard deviation of the normal distribution determines the spread of the distribution and, therefore, determines the risk associated. The agency, depending on its willingness to take risk, then makes the choice. However, in this process, comparing the distributions by a single value is simpler than comparing them by the mean, standard deviation, minimum, and maximum values and is practiced by agencies that are using the probabilistic approach. The agencies identify NPVs for an alternative, at a specified level of probability. For example, an analyst using the probabilistic approach to an LCCA might find that there is a 90% probability that the NPV for alternative 1 is $5 million or less, and that there is a 90% probability that the NPV for alternative 2 is $4 million or less.

Using the the 100^{th} percentile value incorporates all of the risk associated with the outcome; however the choice made by looking at the 100^{th} percentile value might, in many cases, not end up being the most economical choice. Using a lower percentile value in the decision making process increases the risk associated, however may enable the agency to choose an alternative that is more economical. For instance, Colorado DOT uses the 75^{th} percentile value. When making a comparison of probabilistic NPV distributions, it is important for the decision maker to define the level of risk the organization can tolerate. Based on the willingness of the organization to take risks, the percentile value to be compared can be chosen.

CHAPTER 5

CASE STUDIES

Sensitivity analysis shows the independent effect of the variability of one of the inputs. For instance, discount rate might be varied to see the change in NPV and most sensitivity analysis of LCCA evaluate the influence of discount rate. In the following case studies, the effects of the variation in discount rate and analysis period on NPV were investigated.

The LCCA consisted of comparing a hot mix alternative (HMA) versus Portland cement concrete (PCC) alternative. The data was provided by Colorado DOT. It evaluates the life cycle costs of keeping a one mile section of State Highway 119 in Boulder County of Colorado, over a certain serviceability index. The initial service life assigned for the HMA alternative had a mean value of 10 years with a standard deviation of 3.1 years. Each of the HMA rehabilitation activities also had a mean value of 10 years of assigned service life with a standard deviation of 3.1 years. The PCC alternative had an assigned initial service life with a mean value of 22 years and a standard deviation of 6.6 years. Each of the PCC rehabilitation activities had an assigned service life of 18 years with a standard deviation of 4 years. User costs were included in the analysis and economic variables used to calculate user costs were as follows:

- Value of time for passenger cars ($/hour): $17.00
- Value of time for single unit trucks ($/hour): $35.00
- Value of time for combination trucks ($/hour): $36.50

The sensitivity analyses were conducted by keeping the initial input parameters constant and varying discount rate and analysis period.

5.1 Finding the discount rate that changes the lowest cost alternative

In this sensitivity analysis, the effect of the change in discount rate on NPV was investigated. Discount rates were varied between 2% and 8% and incremented by 0.5%.

A break-even point was observed in the results. Figure 5.1 shows that the change in the discount rate alters the ranking of the alternatives in terms of the agency costs around a value of approximately 6%. For this example, user costs do not seem to differentiate between the alternatives for different discount rates. As can be seen in Figure 5-2, above a discount rate of approximately 6%, the ranking of the alternatives change and alternative 1 becomes the lowest cost alternative.

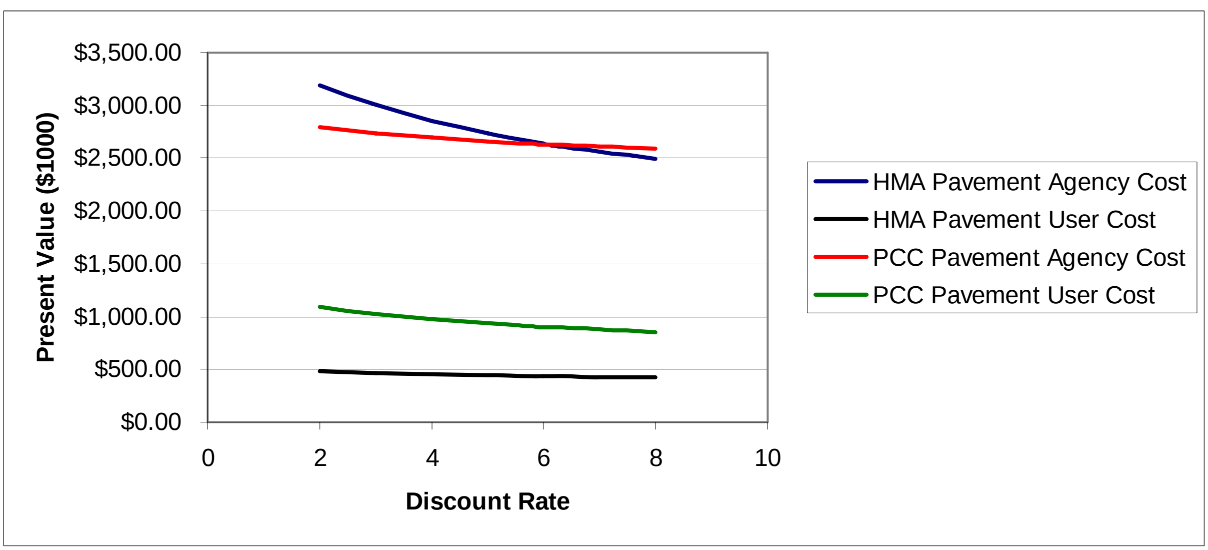


Figure 5.1 The effect of Discount Rate on Agency and User Costs

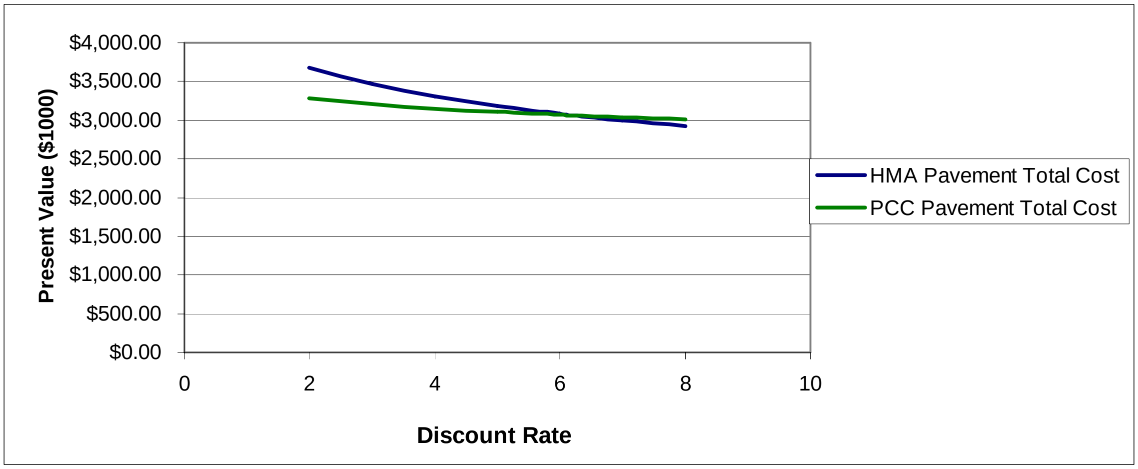


Figure 5.2 The effect of Discount Rate on Total Cost

5.2 Altering analysis period - remaining service life and using a 4% discount rate

Analysis period was altered between 10 years and 70 years. In this analysis, the analysis period was limited with 70 years, because the input data for Alternative 1, covered a period of 70 years; an initial construction with a service life of 10 years, followed by 6 rehabilitation activities, each with a service life of 10 years. RealCost allows the user to enter data for 6 rehabilitation activities following initial construction. RealCost is currently being modified by FHWA to allow for an analysis containing more rehabilitation activities. As the Figure 5.3 shows, alternative 2 agency costs always remain less than alternative 1 agency costs. However, around an analysis period of 20, the agency costs become very close. It is also worth noting that, in terms of agency costs, alternative 2 is the lower cost option, while in terms of user costs, alternative 1 is the lowest cost option. The change in analysis period, does not alter the ranking of the alternatives in terms of agency and user costs. However, the ranking is changed when total costs are considered. As Figure 5.4 displays, for analysis periods less than approximately 15 years, alternative 2 is the lowest cost option. For longer analysis periods, alternative 1 is the lowest cost alternative.

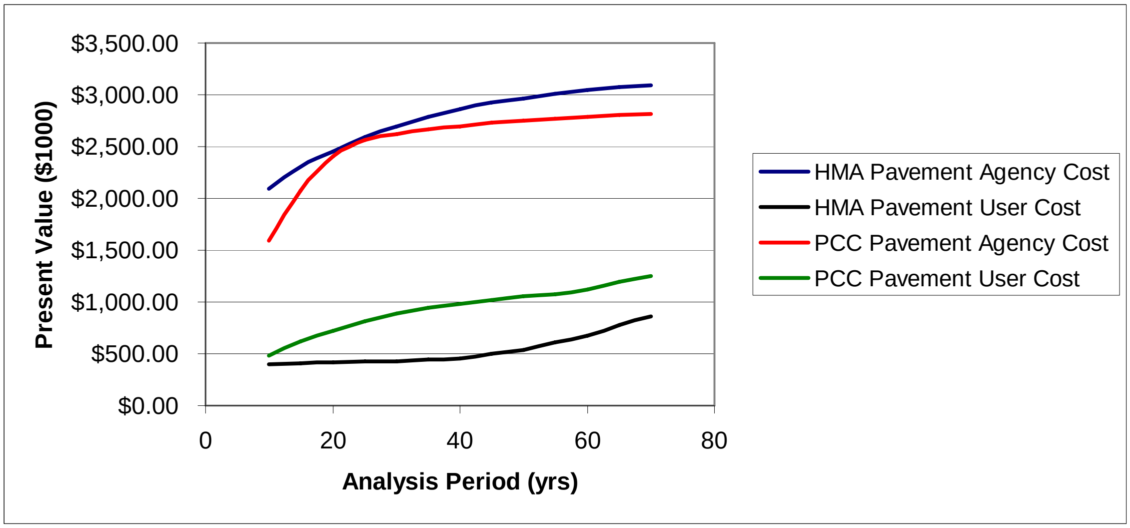


Figure 5.3 The effect of Analysis period on Agency and User Costs

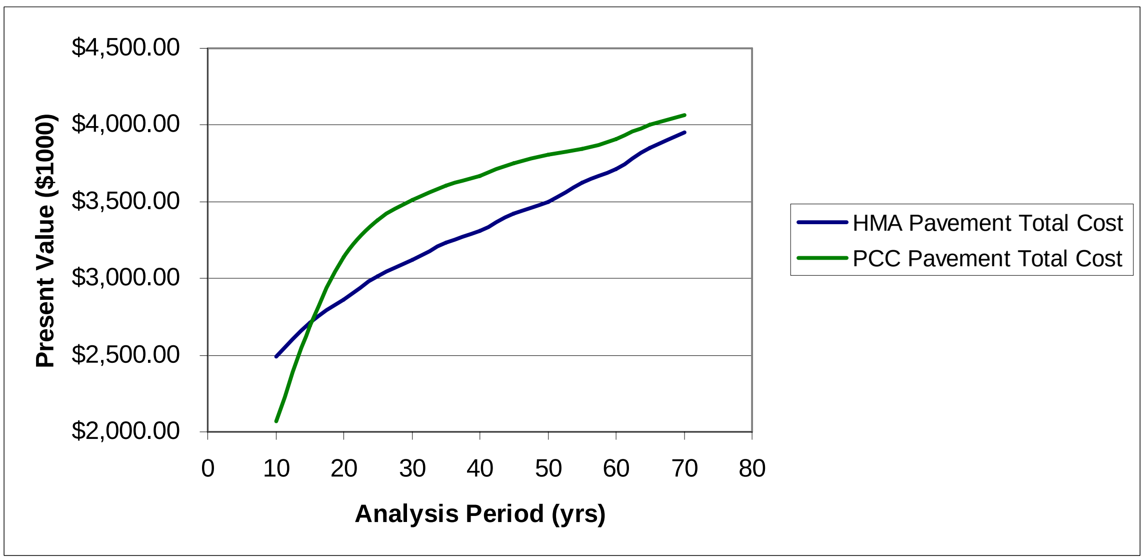


Figure 5.4 The effect of Analysis Period on Total Cost

5.3 Altering analysis period – remaining service life and 3% discount rate

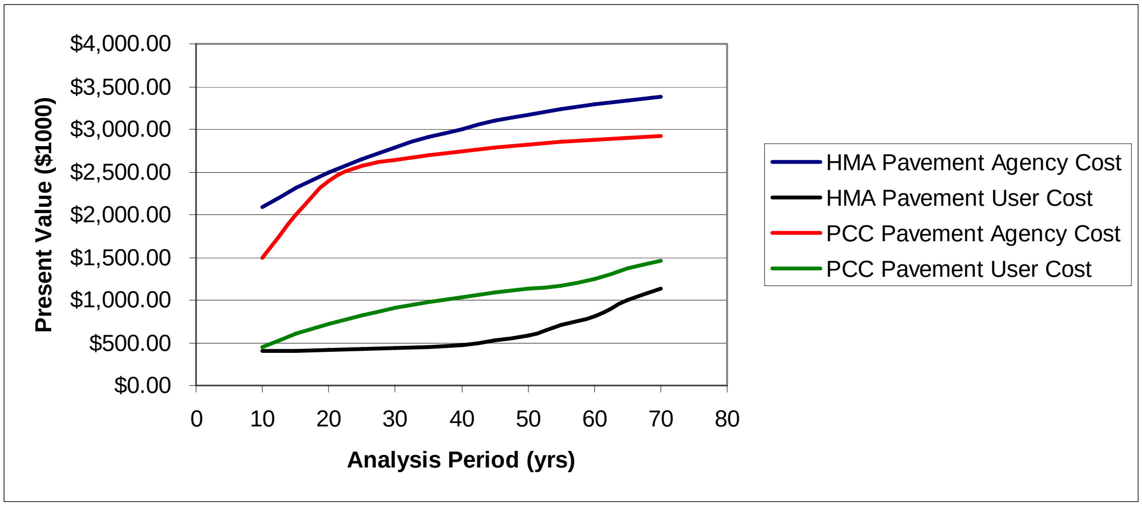


Figure 5.5 The effect of analysis period on agency and user costs – remaining service life and 3% discount rate

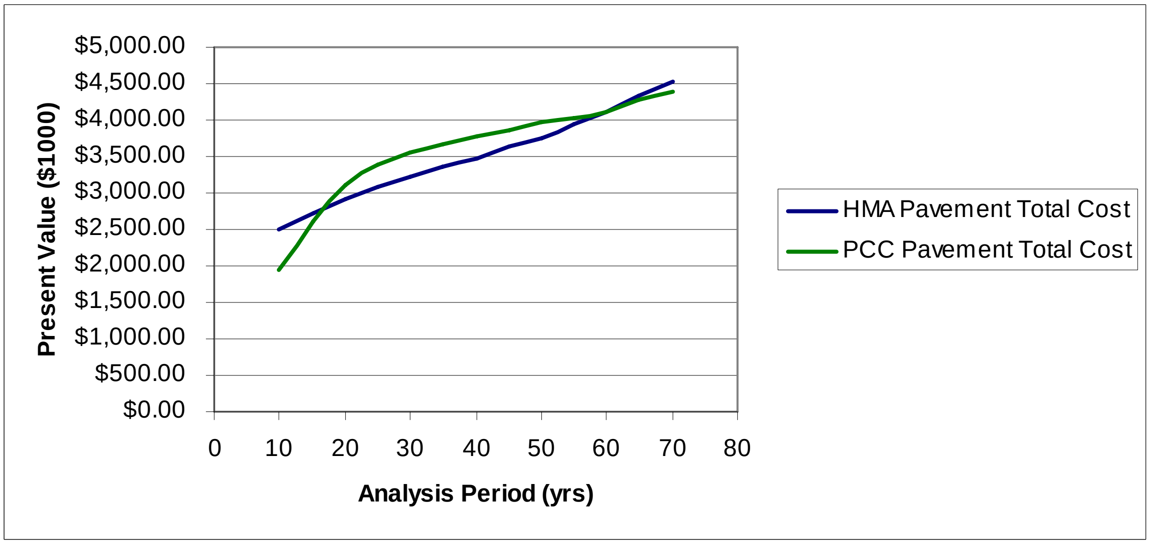


Figure 5.6 The effect of analysis period on total cost – remaining service life and 3% discount rate

As expected, a lower discount rate increases the present value of the alternatives. Figure 5.5 shows that the decrease in the discount rate also increased the difference between the alternatives in terms of agency costs. When discount rate is 4% the agency cost lines intersect at a certain analysis period value. However, with a

3% discount rate, the lines never intersect, which shows that the present value difference between the alternatives in terms of agency costs increased. Total cost of the alternatives graph has two break even points. As Figure 5.6 shows alternative 2 is the lowest cost alternative for analysis periods between 10 years and approximately 15 years and also for analysis periods longer than 60 years and less than 70 years.

5.4 Altering analysis period - no remaining service life and 4% discount rate

The previous analysis was repeated; this time with no remaining service life included in the analysis. Again, a discount rate of 4% was used. As Figure 5.5 shows, lowest cost alternative in terms of agency costs changes around approximately 30 years. At analysis periods longer than 30 years, alternative 2 is the lowest cost alternative in terms of agency costs. There isn't a cross over with user costs. However, there is a change in user costs with change in the analysis period. This reflects to the total cost (a combination of agency and user costs) as is shown in Figure 5.6 It is showed that the lowest cost alternative is approaching the higher cost alternative as analysis period increases. So, it is shown that present value of alternatives is a function of analysis period and that the ranking of alternatives might change when the analysis period is changed.

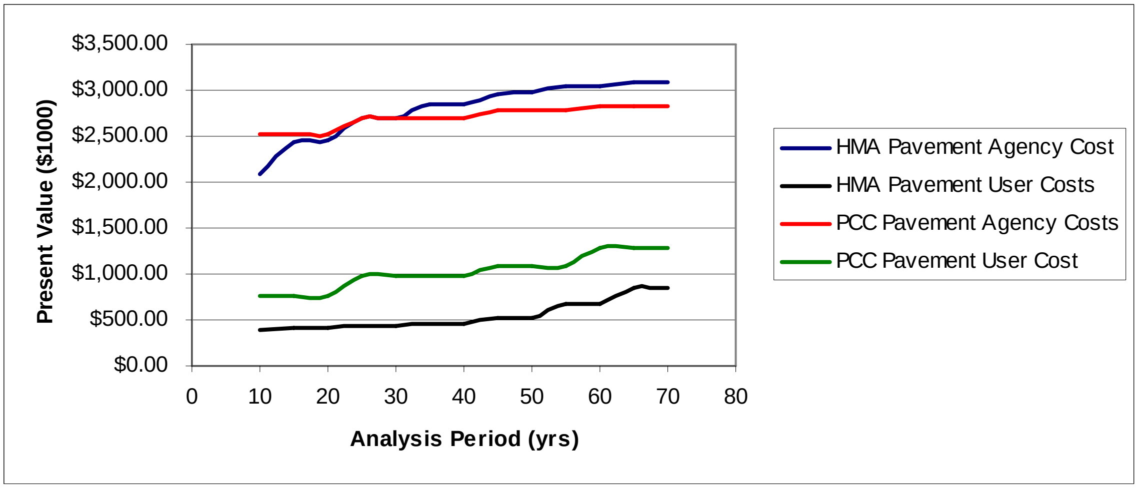


Figure 5.7 The effect of analysis period in agency and user costs – no remaining service life and 4% discount rate

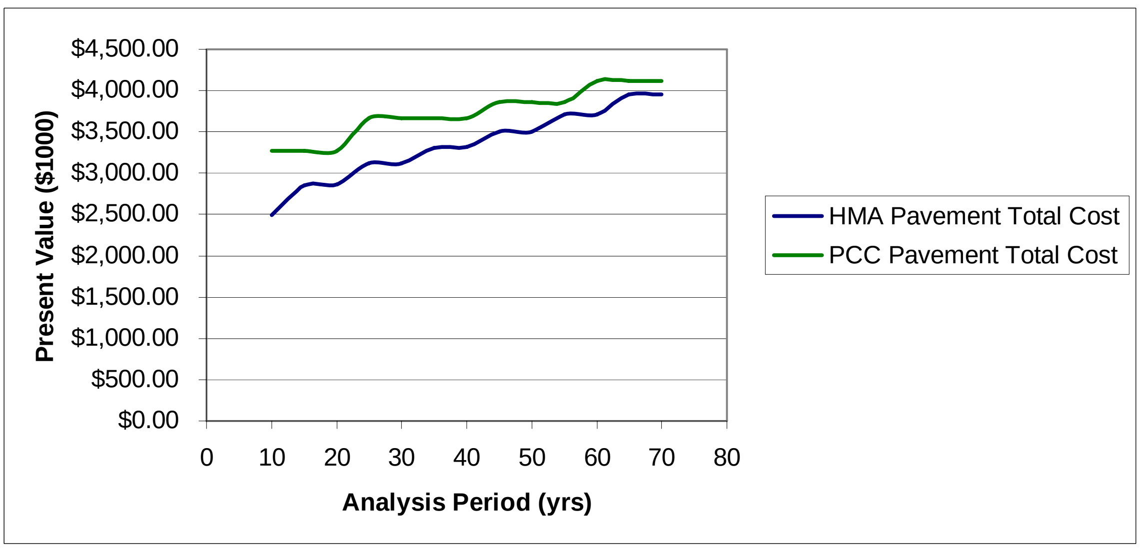


Figure 5.8 The effect of analysis period on total cost – no remaining service life and 4% discount rate

5.5 Altering analysis period - no remaining service life and 3% discount rate

In this analysis, remaining service life was not included and a 3% discount rate was used. Holding everything constant, the sensitivity of the results on analysis period was investigated. The only difference between this analysis and the previous one is the change in the discount rate. It can be seen from Figure 5.7 that the break even point occurs earlier with a lower discount rate, i.e. the analysis period value where the ranking of the alternatives change is lower. Also, the break even point is observed in total costs as Figure 5.8 shows.

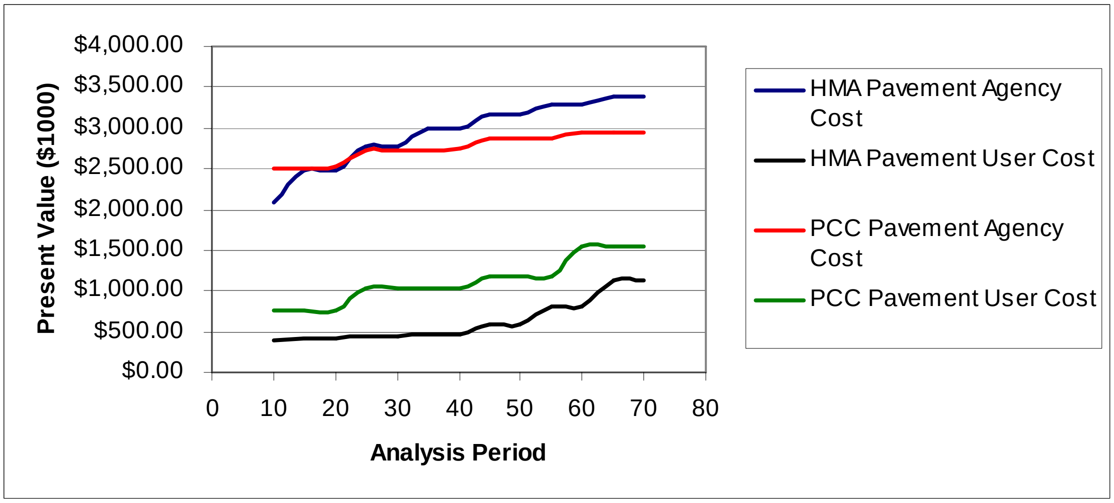


Figure 5.9 The effect of analysis period on agency and user costs – no remaining service life and 3% discount rate

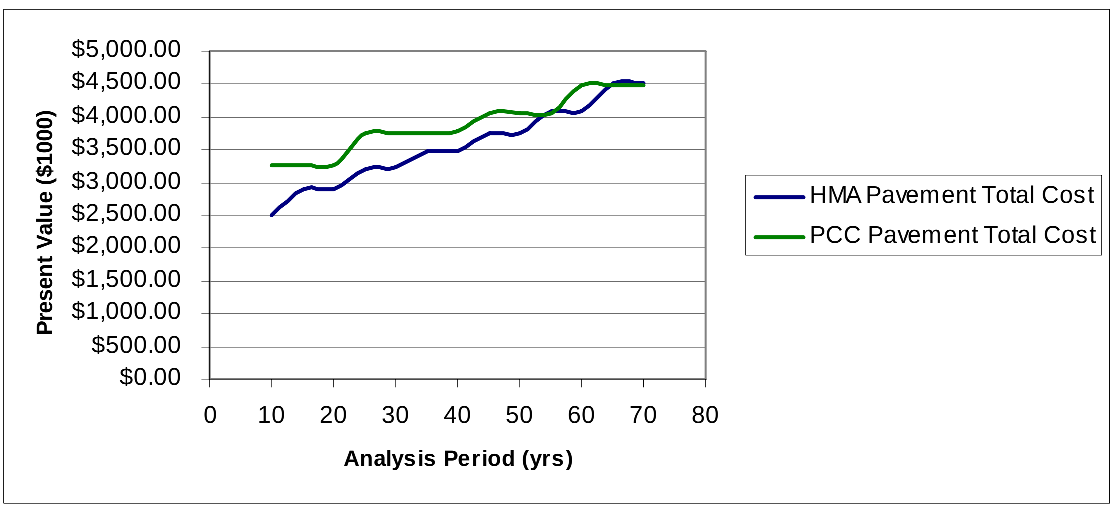


Figure 5.10 The effect of analysis period on total costs – no remaining service life and 3% discount rate

APPENDICES

Appendix A

Life Cycle Cost Analysis Preliminary Survey Questionnaire

Life-Cycle Cost Analysis Questionnaire

1.

State:
Department:
Unit:
Name of person filling out questionnaire:
Job title:
Contact Phone:
Email:

2. Does your department use Life-Cycle Cost Analysis (LCCA) as part of the decision process for selecting pavement type? If yes, please answer questions 3 – 10.

YES NO

3. Do you use any specialized software for LCCA?

YES NO

If yes, name of software:

4. Does your DOT include User Costs in the analysis? If yes, in what ways does it consider it?

YES NO

5. What discount rate is used and how is it determined?

6. What analysis period is used? (If not a fixed value, please explain briefly)

7. What is the initial performance life assigned for:

(a) Flexible pavements

(b) Rigid pavements

8. What treatments do you define as maintenance, as rehabilitation?

9. What are your DOT's decision criteria when pavement LCCA values for asphalt and concrete are very similar?

10. Does your DOT use salvage value or remaining service life value in its LCCA calculations?

11. Does your DOT have any agency guidelines or policies regarding the pavement selection process?

YES NO

If yes, please let us know how to access the information, or please send the information to prangar@clemson.edu

Appendix B

Life-Cycle Cost Analysis Preliminary Survey Results

Table B.1 Practice of LCCA and LCCA Parameters

State	Practice of LCCA	Software	User Costs	Discount Rate
Alabama	Yes	Darwin	No	4%
Alaska	Yes	Yes	Work zone user delay costs	3-5%
Arkansas	Yes	No	No	Used 3.8% recently, Current data is checked constantly
California	Yes	Yes, in process of adopting RealCost	Yes	4%
Colorado	Yes	DARWin 3.1 and RealCost 2.2.1	Yes during construction and rehab In-house developed software program for user costs	DARWin: 4% RealCost:4.5% mean with a standard deviation of 1.65 for a lognormal probability distribution
Connecticut	Yes	RealCost	Work zone user delay costs	4%
Florida	Yes	No	No	5% (relates to national values)
Georgia	Yes	No	Delay costs and VOC Queue lengths are calculated.	3% and sensitivity analysis
Idaho	Yes	Yes, in-house developed spreadsheet	No, it is being considered as a future program enhancement	4%
Illinois	Yes	No	No, considering using user costs	3%; set by policy
Indiana	Yes	INDOT LCCA software,RealCost 2.2	Yes, if traffic volume is a concern to the analysis	4%
Iowa	Yes	No	No	3% (Average difference between the interest on the State pooled money and the inflation rate over the last 40 years)
Kansas	Yes	No	Used only if an alternate has adverse detour miles	3% (Set by the Secretary of Transportation)
Kentucky	Yes	No	Yes, user costs are analyzed separately from agency costs.	Sensitivity of rates from 0 to 10% is analyzed
Louisiana	Yes	In-house program based on FHWA-SA-98-079	Yes, all user cost components outlined in the FHWA manual are included	4%

State	Practice of LCCA	Software	User Costs	Discount Rate
Maine	No	-	-	-
Maryland	Yes	FHWA developed software based on RealCost	Yes	Probabilistic approach with a 3%mean and 0.5% range. It is based on the current and projected market values.
Michigan	Yes	Custom, in Microsoft Excel spreadsheet	For initial construction and maintenance. University of Michigan's software "Construction Cost Congestion" is used.	OMB Discount Rate, the 30-year rate is used.
Minnesota	Yes	No	No	30-year OMB rate
Mississippi	Yes	No	No	4%
Missouri	Yes	No	No	OMB Discount Rate
Montana	Yes	FHWA RealCost Software	No	3%
Nebraska	Yes	DNPS86 or Darwin	No	Currently 3.08 (Average annual interest rate – consumer price index = discount rate)
New York	Yes	No, currently developing software	No, new LCCA software will include user costs	4% (The yield on a 10 year treasury note minus the amount lost to inflation was determined to be approximately 4%)
North Carolina	Yes	No	No	4%
Ohio	Yes	No	No	OMB 30-year real interest rate
South Carolina	Yes	No	No	3.5%
South Dakota	Yes	No	No	Currently 4.6%
Utah	Yes	RealCost	Yes	4%
Vermont	No	-	-	-
Virginia	Yes	No	No	4% (Based on historical information and in line with FHWA data)
Washington	Yes	FHWA Real Cost & WSDOT designed and built software	Yes, consider both day and night construction scenarios. User delay costs are considered.	4%, as based on the OMB 30 year discount rate
Wisconsin	Yes	WisPave	No	5% (It's been 5% for many years and is determined by WisDOT's investment management division)
British Columbia	No	-	-	-
Ontario	Yes	No	No	5.3% set by the Ministry of Finance

B.2 Analysis Period and Rehabilitation Timings

State	Analysis Period	Initial Performance Life Assigned for:	
		Flexible Pavements	Rigid Pavements
Alabama	28 Yrs	12 Yrs	20 Yrs
Alaska	35 Yrs	15 Yrs	No rigid pavements
Arkansas	35 Yrs	20 Yrs	20 Yrs
California	Depends on the design life of the project	5-40 Yrs	5-40 Yrs
Colorado	40 Yrs	10-12 Yrs depending upon traffic	22 Yrs
Connecticut	Depends on facility, 30-40 Yrs	18 Yrs until functional or structural overlay	27-28 Yrs until repair
Florida	40 Yrs	20 Yrs	20 Yrs
Georgia	40 Yrs	10 Yrs	20-25 Yrs
Idaho	36 Yrs	20 Yrs	40 Yrs
Illinois	40 Yrs	20 Yrs until structural overlay, surface corrections before	40 Yrs for jointed PCC until 1st overlay: CPR at 20
Indiana	40 Yrs	25 Yrs	30 Yrs
Iowa	40 Yrs	20 Yrs	40 Yrs
Kansas	30 Yrs, but moving to 40 Yrs	10 Yrs	20 Yrs
Kentucky	40 Yrs	20/40 Yrs	20/40Yrs
Louisiana	New Construction 40 Yrs Overlays 30 Yrs	15 Yrs	20 Yrs
Maryland	40 Yrs	15 Yrs with a std dev. of 6 (probabilistic)	25 Yrs with a std dev. of 6 (probabilistic)
Michigan	Depends on the pavement/fix type	26 Yrs for full depth reconstructed HMA pavements	26 Yrs for full depth reconstructed concrete pavements
Minnesota	50 Yrs	15-20 Yrs depending upon traffic volume	17 Yrs
Mississippi	40 Yrs	12 Yrs	16 Yrs
Missouri	45 Yrs	20 Yrs	25 Yrs
Montana	35 Yrs	30 Yrs	35 Yrs
Nebraska	50 Yrs	20 Yrs	35 Yrs
New York	65 Yrs, design life of 50 plus one rehabilitation lasting 15yrs	12-15 Yrs	25 Yrs
North Carolina	20 years for SN<6.0 and 30 years for SN>6.0. Looking at 40 years for SN>6.0.	10 Yrs	15 Yrs
Ohio	35 Yrs	12 Yrs	22 Yrs
South Carolina	30 Yrs	15 Yrs	20 Yrs
South Dakota	20 Year Design Life, 40 Year Service Life	16 Yrs	18 Yrs- 1st minor joint/spall treatment
Utah	-	20Yrs	40 Yrs
Virginia	50 Yrs	30 Yrs	30 Yrs
Washington	50 Yrs	8-15	20-30
Wisconsin	50 Yrs	18 Yrs (undrained base)	25 Yrs (undrained base)
Ontario	50 Yrs	19-21 yrs depending on the surface course	28 years for doweled JPC

B.3. Maintenance and Rehabilitation Treatments

State	Maintenance and Rehabilitation Treatments
Alabama	Routine maintenance costs are not included in the LCCA. Flexible alternative: overlay at year 12 and at year 20. Rehabilitation treatment is mill and placing a binder and wearing layer. Rigid alternative: perform CPR at year 20. CPR includes slab removal and replacement, full depth spall repair, diamond grinding, joint and crack clean and seal and maybe undersealing.
Alaska	Maintenance: asphalt surface treatments, crack sealing. Rehabilitation: structural enhancements that extend pavement life &/or improve its load bearing capacity.
Arkansas	No differentiation between maintenance and rehabilitation treatments. All anticipative maintenance and rehabilitation costs are included in the analysis.
California	Maintenance: overlay, mill and replace, seals, etc. Rehabilitation: slab replacement, mill and replace, grinding, etc.
Colorado	Maintenance: work undertaken that preserves the existing pavement, retards future deterioration, and improves the functional life without substantially increasing the structural capacity. Rehabilitation: everything in between maintenance and reconstruction. Maintenance activities are traditionally done by CDOT maintenance forces (crack sealing, patching, etc.) and rehabilitation activities are done by contractors (2-inch overlays, diamond grinding).
Connecticut	Maintenance activities for flexible pavements: crack sealing (routine), thin surface treatment (preservation). Maintenance activities for rigid pavements: joint and crack sealing (routine), diamond grinding (preservation). Rehabilitation activities for flexible pavements: functional or structural overlay (and joint repair in composite pavements, cold-in-place recycling. Rehabilitation activities for rigid pavements: CPR, diamond grinding with joint repair.
Florida	Rehabilitation activities for rigid pavements: CPR for 3-5% slab replacement Rehabilitation activities for flexible pavements: milling with structural overlay
Georgia	Maintenance costs are generally not considered in LCCA. Rehabilitation activities for flexible pavements: milling, overlay/inlay, seal and full depth patching. Rehabilitation activities for rigid pavements: full depth slab replacement, punch-out repair
Idaho	Maintenance activities for flexible pavements: chip seals and crack sealing. Maintenance activities for rigid pavements: joint and crack seal. Rehabilitation activities for flexible pavements: hot in place recycling, cold in place recycling, inlay/overlays. Rehabilitation activities for rigid pavements: Slab replacement, dowel bar retrofit, diamond grinding.
Illinois	Maintenance activities: joint and crack sealing and patching Rehabilitation activities: HMA Overlays
Indiana	Maintenance activities: Crack sealing; re-seal joints, cleaning joints, etc. Rehabilitation activities: Mill and fill, asphalt overlay, CPR, diamond grinding, etc.

State	Maintenance and Rehabilitation Treatments
Iowa	No maintenance treatments are included. No rehabilitation is included for PCC in the 40 year analysis. Rehabilitation activities: overlays. HMA pavements receive an overlay in year 20.
Kansas	Actions equivalent to 1 1/2" overlay and less are considered as maintenance. Actions greater than 1 1/2" overlay are used for resurfacing, rehabilitation, and reconstruction.
Kentucky	Maintenance activities: fixing potholes, and minor joint repairs. Rehabilitation activities for flexible pavements: milling and resurfacing. Rehabilitation activities for rigid pavements: grinding, patching, slab replacement.
Louisiana	All treatments analyzed in the analysis are considered rehabilitation i.e. cold plane, overlay, patching, joint cleaning and sealing.
Maryland	Maintenance is reactive and unscheduled treatments like patching and possibly crack sealing. Rehabilitation is a planned treatment and may include CPR for rigid pavements and pre-overlay repairs and overlays for all pavement types.
Michigan	Rehabilitation: Unbonded concrete overlays, HMA over rubblized concrete, HMA crush and shape, white-topping, multiple courses HMA overlay, HMA mill & resurface. Maintenance: joint/crack sealing/resealing, thin HMA overlays, full depth concrete, joint repairs, surface seals, crack filling, diamond grinding, dowel bar retrofit. When it comes to a major rehabilitation (i.e. unbonded overlay, HMA over rubblized concrete, etc) they are life-cycled as well.
Minnesota	Maintenance: route and seal cracks, crack fill, surface treatment (chip seal), joint reseal. Rehabilitation: Mill and overlay, concrete full and partial depth rehabilitation, diamond grinding.
Mississippi	No differentiation between maintenance and rehabilitation
Missouri	Rigid and flexible pavement maintenance costs are assumed to be the same over the entire design lives so they are not input into the LCCA. Flexible pavement rehabilitation: Mill and fill 1.75" wearing course at 20 and 33 years. Rigid pavement rehabilitation: Diamond grind 1.5% full depth repair at 25 years.
Montana	Maintenance activities for flexible pavements: crack seals, asphalt overlays, mill and fill (less than 60 mm in depth) Rehabilitation activities for flexible pavements: mill and fill (greater than 60mm in depth), partial and full depth reclamation with and without PCC treatment. Maintenance activities for rigid pavements: crack seal, slab replacement. Rehabilitation activities for rigid pavements: dowel bar retrofit with diamond grind, crack and seal with overlay
Nebraska	Maintenance: Crack sealing, fog seals, armor/chip seal, micro-surfacing Rehabilitation: Milling and overlay and several types of in-place recycling
New York	Maintenance treatments: crack sealing, thin HMA overlays, and spall repairs Rehabilitation treatment is meant to add additional service life to the original pavement.

State	Maintenance and Rehabilitation Treatments
North Carolina	Maintenance: sealing cracks, patching, thin resurfacing, micro-surfacing or surface treatments. Rehabilitation: mill and fill, overlays with more than one layer, spall repair, slab replacement, diamond grinding
Ohio	These terms are not defined as part of LCCA
South Carolina	Maintenance activities for flexible pavements: crack sealing, pavement marking, bituminous surface treatments for Maintenance activities for rigid pavements: patching with asphalt Rehabilitation activities for flexible pavements: milling and overlay Rehabilitation activities for rigid pavements: patching with PCC and joint sealing
South Dakota	Maintenance: crack sealing, asphalt surface treatments, etc. Rehabilitation: overlays including milling, full depth reclamation and cold recycling, joint and spall treatments.
Utah	Maintenance is preventative, rehab is reactive. An HMA overlay of > 1.5 inches would be considered rehab, even if it were preventative.
Virginia	Maintenance: surface treatments, patching, and less than 2 inch milling and overlay Rehabilitation: thicker overlays (≥ 2 inches), grinding, dowel bar retrofit
Washington	Maintenance costs are not considered in LCCA. Rehabilitation includes HMA overlays, inlays, or diamond grinding with resealing joints for PCCP.
Wisconsin	Maintenance activities for flexible pavements: Crack sealing, seal coats, patching, and some “super” patches. Maintenance activities for rigid pavements: minor joint repair, possibly crack or joint sealing, however joints are not initially sealed. Rehabilitation activities for flexible pavements: overlays, whitetopping, pulverizing. Rehabilitation activities for rigid pavements: joint repair, retrofit dowel bars, HMA overlays, concrete overlays, diamond grinding, rubblizing.
Ontario	Flexible pavement maintenance: mill & patching small areas, and crack sealing. Rigid pavement maintenance: joint and crack sealing, and diamond grinding. Flexible pavement rehabilitation: mill & resurface. Rigid pavement rehabilitation: Major CPR, overlay with asphalt.

Table B.4 Decision Criteria

State	Decision Criteria when pavement LCCA values for rigid and flexible pavements are similar
Alabama	If the LCCA difference is less than 10 % then both of the alternate pavement types are considered. The HMA alternate has a dollar amount added to the bid that accounts for the difference in the initial performance period of the two pavement types. Other Considerations: Construction time Traffic Control Plan, frictional properties of pavement, noise in urban areas, budget limitations, historical performance of adjacent pavement, constructability, minimizing maintenance. If the LCCA difference is greater than 10 % then the lower cost alternate is chosen.
Alaska	Alaska does not have rigid pavements. LCCA is used to choose between asphalt pavement alternative designs.
Arkansas	The alternative with lowest present value is selected.
California	It is up to the designer since he/she is familiar with the local situation/material but a written approval from the District Director is required.
Colorado	If the LCCA difference is less than 10 %, pavement type selection committee is formed and proceeds as outlined in the Pavement Design Manual.
Connecticut	Done on a case-by-case basis, constructability issues are considered.
Florida	The District Engineer makes the decision on pavement type selection on all instances.
Georgia	Decision factors such as the rehabilitation costs, number of days for initial construction, number of rehabilitations in the analysis period and salvage value is considered.
Idaho	Several factors are considered: past performance of ach pavement type in the area, surrounding pavement and continuity of maintenance operations, availability of aggregates in the area, preferences of the individuals involved, and construction considerations.
Illinois	Alternatives within 10 % of each other go to Pavement Selection Committee. The Committee considers costs (initial and life cycle), constructability, high accident locations, high stress intersections, adjacent sections, public and political influence.
Indiana	+/- 10% difference can go either way.
Iowa	Type of work and constructability (i.e. urban w/curb and paved median may favor PCC pavement), type of adjacent pavement sections and amount of work of each pavement type for that year are considered.
Kansas	A selection committee consisting of the Division of Operations, District Engineer, Chief of Construction & Maintenance, Chief of Design, and Chief of Materials & Research make the selection regardless of how similar or different the costs are. The committee also follows the guidelines published in Appendix B in the 1993 AASHTO Guide for Design of Pavement Structures.
Kentucky	The Commissioner of Highways makes all final determination on pavement type.
Louisiana	If the percentage difference in total net present value of alternate pavement types is less than 20%, alternate typical sections are placed in the plans. If the percentage is greater than 20%, the pavement type with the lowest life cycle cost is placed in the plans.
Maryland	If LCCA costs (Agency costs + User Costs) are within 10 % of one another, additional data is collected (constructability, design and environmental factors) and presented with the LCCA data to pavement type selection team (Senior Management) for final decision about pavement type. If difference is greater than 10%, the more economical alternative is continued with in the design process.

State	Decision Criteria when pavement LCCA values for rigid and flexible pavements are similar
Michigan	Decision is based solely on the lowest cost alternative.
Minnesota	Decision is based solely on the lowest cost alternative.
Mississippi	Currently looking at alternate pavement type bidding.
Missouri	LCCA is used only to supplement the alternate pavement design process. The future rehab costs for both AC and PCC over a 45-year design life are brought back to present worth value. During evaluation of the bids, the difference between the two, which can be called the correction factor, is added to any asphalt bids, because future asphalt rehab costs would always exceed PCC costs, and compared to PCC bids. The lowest bidder under these circumstances is usually awarded the contract.
Montana	If the LCCA was similar between rigid and flexible pavements, would probably use a flexible pavement because of familiarity with building flexible pavements.
Nebraska	1.Construction issues 2.Location of project (supply issues) 3.Budget requirements
New York	Typically upfront costs will decide which is selected.
North Carolina	Constructability, traffic control, long term vision for a corridor, division preferences
Ohio	Transverse uniformity of cross section, longitudinal uniformity of cross section, drainage, recycle ability/reusability, risk of design, risk of construction/constructability, availability of local materials, user delay days, noise, district/local concerns.
South Carolina	A committee consisting of members from maintenance, state construction, program management, materials and research, district construction, and FHWA considers a variety of factors, including LCCA for pavement type selection.
South Dakota	If the 40 year analysis shows a difference of 10% or less, then other variables such as first cost savings, traffic control, and availability of materials and continuity of pavement type are considered.
Utah	Based on initial costs and politics, asphalt alternative is chosen. The engineers would normally choose PCC if they had the choice.
Virginia	If estimates are within 10 %, other factors are evaluated. Initial constructability, constructability of future improvements, volume of traffic, availability of materials, availability of qualified contractors, and location of project.
Washington	If the difference is greater than 15% then the lowest cost alternative is chosen. If the difference is less than 15% then a detailed engineering analysis is performed that provides the engineering decisions for the selection.
Wisconsin	If the results are within 5%, the regional pavement designer (or consultant) can decide which pavement type it will be (something other than the lowest cost would only be chosen, typically, if all surrounding pavement is that type, or if the locals prefer it, but it’s almost never done). If greater than 5%, a different pavement type can be requested, but it must go before a committee for final decision (and if a local entity is willing to pay the cost difference over the lowest cost option, they are usually given that opportunity).
Ontario	The lower cost alternative gets selected in the Alternative Bid Process after applying LCC adjustment factor to the tender bid.

Table B.5 Usage of Salvage Value

State	Usage of Salvage Value or Remaining Service Life
Alabama	No
Alaska	Yes. Salvage Value is determined by multiplying the cost of the most recent rehabilitation activity by the proportion of its life that remains.
Arkansas	Yes
California	Yes
Colorado	No for deterministic, yes for RealCost
Connecticut	Yes
Florida	No
Georgia	Yes
Idaho	Yes
Illinois	No
Indiana	Yes
Iowa	No, salvage values are considered the same for each pavement type at the end of the analysis period.
Kansas	Yes, only when alternates of unequal periods of performance are considered.
Kentucky	No
Louisiana	No
Maryland	Yes. The present worth cost of the last treatment in the analysis period is calculated as a salvage value based on the percentage of the remaining life in that particular treatment.
Michigan	No, but discussing it's use more
Minnesota	Yes, a 60 year life for concrete is used. 33% residual value is used.
Mississippi	No, but at year 40 both alternatives are returned to the same condition, i.e. rubblize and overlay the concrete alternate, and overlay flexible alternate.
Missouri	No
Montana	Yes
Nebraska	Yes
New York	Yes
North Carolina	No
Ohio	No
South Carolina	No, it is assumed at 30 years either pavement type can be rehabilitated with an asphalt overlay and that their performance will be the same afterwards.
South Dakota	No
Utah	No
Virginia	Yes
Washington	Yes
Wisconsin	Yes
Ontario	Yes

Table B.6 Guidelines

State	Guidelines or Policies
Alabama	No
Alaska	Yes. Have guidelines regarding the choice between an asphalt pavement and surface treatment.
Arkansas	No. Pavement selection is made by the Assistant Chief Engineer for Design based on recommendations submitted by the Engineer for Roadway Design. LCCA is used only on major projects.
California	Yes. Currently being updated but current guidelines found at: http://www.dot.ca.gov/hq/oppd/hdm/pdf/chp0600.pdf
Colorado	Yes. Section 9.9 Pavement Selection Committee in Chapter 9 of CDOT 2006 Pavement Design Manual.
Connecticut	Yes
Florida	Yes. http://www.dot.state.fl.us/pavementmanagement/pcs/pcs_pub.htm (Reference # 18).
Georgia	Yes. Guidelines are being formulated through the use of several decision factors that include initial costs, rehab costs, salvage value, user costs, and constructability. These decision factors are included in a matrix and each is given a percentage of performance. The values calculated in the LCCA for each decision factor is used to calculate a score for each alternative.
Idaho	Yes. Section 540 and 541 of the ITD Materials Manual. Link: http://itd.idaho.gov/manuals/ManualsOnline.htm
Illinois	Yes http://www.dot.il.gov/desenv/BDE%20Manual/BDE/pdf/chap54.pdf - pp. 87-98
Indiana	No
Iowa	No
Kansas	Yes
Kentucky	No, currently in the process of developing a revised pavement type selection policy.
Louisiana	Yes. An article written for TRB titled “Agency Process for Alternate Design and Alternate Bid of Pavements”. (Reference # 42).
Maine	-
Maryland	Yes. Pavement Type Selection Team, Final Report
Michigan	Yes
Minnesota	Yes, http://www.dot.state.mn.us/tecsup/tmemo/active/tm04/19mat02.pdf
Mississippi	No
Missouri	Yes, http://www.modot.mo.gov/newsandinfo/PavementTypeSelection.htm
Montana	Yes, LCCA is used only on large projects with total costs greater than $10 Million.
Nebraska	Yes
New York	Yes, VOLUMES I and II (http://dot.state.ny.us/cmb/consult/cpdmfiles/cpdm.html)
North Carolina	Yes
Ohio	No, policies for the current process have yet to be written.
South Carolina	Yes

State	Guidelines or Policies
South Dakota	Yes
Utah	No, currently being developed.
Virginia	Yes, http://www.virginiadot.org/business/resources/bu-mat-MOI-6.pdf
Washington	Yes, http://www.wsdot.wa.gov/biz/mats/Apps/EPG.htm http://www.wsdot.wa.gov/biz/mats/pavement/Technotes/PTSP_Jan2005.pdf
Wisconsin	Yes, http://www.dot.state.wi.us/business/engrserv/cauextranet.htm Need to register as a consultant to access the on-line Facilities Development Manual and other manuals.
Ontario	Yes, http://192.75.156.22/sydneyweb/cgi/swebimg.exe?action=Attachments&key=ctcx&ini=splusweb&uid=public (Reference # 25).

Appendix C

Life-Cycle Cost Analysis Final Survey Questionnaire

Clemson University is conducting a research study on Life-Cycle Cost Analysis (LCCA) for pavement type selection. The research study involves identifying and quantifying factors that need to be considered in developing realistic life cycle cost analysis. This research is sponsored by South Carolina Department of Transportation (SCDOT).

As part of this research study, you had received a preliminary survey that was sent out on September 26, 2005. Please find attached a summary of the responses received from 33 states in the U.S.A and 2 provinces from Canada. I hope you find this summary useful in your own efforts to improve on your states LCCA process.

In order to develop a more complete understanding of the status quo on the LCCA process, a Final Survey has been prepared as part of the on-going research study that is more comprehensive in nature. I would appreciate if you can respond to the Final Survey within next four weeks. One of the questions (#5) in the survey requests you to attach additional information (typical examples of LCCA process for pavement type selection). I would appreciate if you can attach the response to this questionnaire using separate sheets of paper, or as an attachment in your email response.

At the conclusion of the survey you can submit your responses either through email or through regular mail. If you wish to submit your responses to the survey using email, please send it to prangar@clemson.edu.

I really appreciate your time in completing the survey. I will provide you a copy of the synthesized results at the conclusion of this survey.

Sincerely,

Prasad Rangaraju, Ph.D., P.E.
Assistant Professor of Civil Engineering
220, Lowry Hall
Department of Civil Engineering
Clemson University
Clemson, SC, 29634-0911
(864) 656-1241 (p)
(864) 656-2670 (f)
prangar@clemson.edu

Life-Cycle Cost Analysis for Pavement Type Selection: *Final LCCA Survey*

Please put an X mark next to the answer(s) that is (are) applicable.

1. Do you have any concerns with using LCCA as part of your pavement type selection process?

(a)YES ☐

(b)NO ☐

If yes, please explain:

2. Are you considering revisions to your LCCA process for pavement type selection? (If you need additional space, please continue your response at the end of the document.)

(a)YES ☐

(b)NO ☐

If yes, please explain:

3. When was the last time your LCCA was revised?

4. What criteria would trigger the requirement to conduct LCCA for pavement type selection? (Select more than one, if necessary)

(a) ADT ☐

(b) Cost ☐

(c) Pavement Structure ☐

(d) Truck Percentage ☐

(e) Pavement Type System ☐

(e.g., Interstate, Secondary Roads, etc.)

(f) Other ☐

If other, please specify:

5. Can you provide examples of recent project LCCA calculations?

6. Which type of LCCA approach does your agency follow?

(a) Probabilistic ☐

(b) Deterministic ☐

(c) Combination of both for different aspects of LCCA ☐

(d) Other ☐

If other, please specify:

7. a. If you are using a deterministic approach, do you perform risk or sensitivity analysis on different input parameters for LCCA?

(a)YES ☐

(b) NO ☐

7. b. What are the typical parameters used in a sensitivity analysis? (e.g., discount rate, analysis period, etc.)

8. If you are using probabilistic approach:

a. What parameters are evaluated in the analysis? **(Type your response in Table 1)**

b. Which probability distribution is used? (Uniform, normal, log normal, triangular, beta, geometric, truncated normal, truncated log normal) **(Select your response in Table 1)**

c. What are the corresponding values used? (Ex: log normal distribution requires mean and standards deviation values) **(Type your response in Table 1)**

- ***For example:*** **(for discount rate)**: *Table 1 shall be filled in the following manner*

Input	Probability Distribution Type	Values
Discount rate	Triangular	Minimum 3 Maximum 5 Most Likely 4

Table 1 – RESPONSES TO QUESTION '8'

INPUT	YES	NO	PROBABILITY DISTRIBUTION TYPE	TYPICAL VALUES USED
(a) **Discount rate**	☐	☐	Select Here	
(b) **Timing of future rehab activities**	☐	☐	Select Here	
(c) **Free flow capacity**	☐	☐	Select Here	
(d) **Annual traffic growth rate**	☐	☐	Select Here	
(e) **Analysis period**	☐	☐	Select Here	
(f) **Value of time for passenger cars**	☐	☐	Select Here	
(g) **Value of time for single unit trucks**	☐	☐	Select Here	
(h) **Value of time for combination trucks**	☐	☐	Select Here	
(i) **Agency construction cost**	☐	☐	Select Here	
(j) **User work zone**	☐	☐	Select Here	

costs				
(k) **Agency maintenance cost**	☐	☐	Select Here	
(l) **Work zone capacity**	☐	☐	Select Here	
(m) **Work zone duration**	☐	☐	Select Here	
(n) **Other**	☐	☐	Select Here	

9. Which of the following data sources do you use in selecting the input parameters such as analysis period, etc. for conducting an LCCA?

(a) State Data ☐

(b) FHWA ☐

(c) Consultants ☐

(d) Other ☐

If other, please specify:

---

10. What design procedure does your DOT currently use for flexible pavements?

(a) AASHTO 1972 ☐

(b) AASHTO 1986 ☐

(c) AASHTO 1993 ☐

(d) AASHTO 1998 ☐

(e) Individual State design procedure ☐

(f) Combination of AASHTO & State procedure ☐

(g) Other

If other, please specify:

---

11. What design procedure does your DOT currently use for rigid pavements?

a. AASHTO 1972 ☐

b. AASHTO 1986 ☐

c. AASHTO 1993 ☐

d. AASHTO 1998 ☐
e. Individual State design procedure ☐
f. Combination of AASHTO & State procedure ☐
g. Other ☐

If other, please specify:

---

12. What is the basis (e.g., visual inspection etc.,) for arriving at the time to first-rehabilitation in case of:

(a) Rigid Pavements:

(b) Flexible Pavements:

13. What is the basis on which the nature and timing for subsequent rehabilitation activities are made in case of :

(a) Rigid Pavements:

(b) Flexible Pavements:

RIGID PAVEMENTS

☐

☐

14. Which of the following options do you consider for the first rehabilitation of rigid pavements? What are typical unit costs involved?

Rehabilitation Option	YES	NO	Unit Cost

Partial Depth Repair	☐	☐	
Full Depth Repair	☐	☐	
Joint and Crack sealing	☐	☐	
Diamond grinding	☐	☐	
HMA Overlay	☐	☐	
Unbonded Overlay	☐	☐	
Rubblizing + Overlay	☐	☐	
Other	☐	☐	

If other, please specify:

14. a. What is the time to first rehabilitation? Please indicate the type of concrete pavement (e.g. CRC vs Jointed dowled) and the corresponding rehabilitation timing.

14. b. What is the typical rehabilitation service life?

14. c. What constitutes typical maintenance/preservation activities during a given cycle of rehabilitation?

14. d. What is the frequency of maintenance/preservation activity within a given cycle of rehabilitation?

FLEXIBLE PAVEMENTS

15. Which of the following options do you consider for the first rehabilitation of HMA pavements? What are typical unit costs involved?

Rehabilitation Option	YES	NO	Unit Cost
Milling & overlay	☐	☐	
Pulverizing (Full-depth reclamation)	☐	☐	
Cold-in place recycling	☐	☐	
Hot-in place recycling	☐	☐	
Whitetopping	☐	☐	
Ultrathin Whitetopping	☐	☐	
Other	☐	☐	

If other, please specify:

---

15. a. What is the time to first rehabilitation?

---

15. b. What is the rehabilitation service life?

---

15. c. What constitutes typical maintenance/preservation activities during a given cycle of rehabilitation?

---

15. d. What is the maintenance/preservation activity frequency within a given cycle of rehabilitation?

---

16. Which of the following are included in your analysis when arriving at your agency costs?

(a) Preliminary engineering ☐
(b) Construction management ☐
(c) Construction costs ☐
(d) Routine and preventive maintenance ☐
(e) Resurfacing and rehabilitation cost ☐
(f) Maintenance of traffic cost ☐
(g) Associated administrative costs ☐
(h) Other ☐

If other, please specify:

---

17. Are the typical construction costs values used in LCCA, open for industry discussion to ensure they are representative of field applications?

(a) YES ☐
(b) NO ☐

18. In your pavement type selection process, does your agency consider:

(a) A single 'initial construction cost' based on optimal design of the pavement type
(b) Different design criteria within each pavement type ☐

19. What parameters are used to arrive at your user costs? Please check the applicable from Table 2. Where appropriate provide typical value or range for your Interstate pavements.

Table 2: Parameters used to arrive at User Costs

	Yes	No	Typical Value or range
Annual Average Daily Traffic (AADT) construction year (total for both directions)	☐	☐	
Cars as percentage of AADT (%)	☐	☐	
Single unit trucks as percentage of AADT (%)	☐	☐	
Combination trucks as percentage of AADT (%)	☐	☐	
Annual growth rate of traffic (%)	☐	☐	
Speed limit under normal operating conditions (mph)	☐	☐	
Lanes open in each direction under normal operating conditions	☐	☐	
Free flow capacity vehicles per hour per lane (vphpl)	☐	☐	
Queue dissipation capacity (vphpl) (capacity of each lane during queue dissipation operation conditions)	☐	☐	
Maximum AADT (total for both directions)	☐	☐	
Maximum queue length (miles)	☐	☐	
Rural or urban hourly traffic distribution	☐	☐	
Value of time for passenger cars ($/hour)	☐	☐	
Value of time for single unit trucks ($/hour)	☐	☐	
Value of time for combination trucks ($/hour)	☐	☐	

20. Do you use salvage value in your LCCA calculations?

(a)YES

(b)NO

If no, please explain:

---

21. How do you calculate salvage value?

(a)Calculate residual value (net value from recycling the pavement)

(b) Calculate serviceable life (remaining life in a pavement alternative at the end of the analysis period

(c) Calculate both residual value and serviceable life

(d) Other

If other, please explain:

22. General Comments (If you have comments about any question, you are welcome to address it here.)

Appendix D

Life-Cycle Cost Analysis Final Survey Results

Table D.1 Concerns with using LCCA

Question 1	
Concerns with using LCCA as part of the pavement type selection process	
State	**Concerns with LCCA process**
Alabama	No concerns
California	Lack of adequately trained individuals who understand the importance and implication of input parameters into RealCost
Colorado	No concerns
Georgia	No concerns
Illinois	No concerns
Indiana	Have concerns, but did not specify.
Iowa	No concerns
Kansas	Difficulty in predicting cost in a period where petroleum prices are escalating rapidly with no history to predict future
Maine	Maine DOT does not use LCCA for pavement type selection. Mainly due to upfront costs of PCC pavements, only HMA pavements were constructed over the past 30 years. Because of very scarce funding the upfront cost dictates pavement type. As asphalt prices continue to increase, PCC pavements and LCCA may become more viable.
Maryland	No concerns
Michigan	No concerns
Minnesota	No concerns
Mississippi	No concerns
Missouri	Future rehabilitation assumptions for newer asphalt and concrete pavement designs have not been verified from field data because of their short performance histories. Also, do not have a good grasp of actual maintenance.
Montana	No concerns
Nebraska	No concerns
North Carolina	Debate with industries over most appropriate inputs
South Carolina	Concerns with regard to determining the timing of future rehabilitation, selection of unit costs, and determination of salvage value
Utah	Concerns come from a political/market standpoint, i.e., LCCA is not popular.
Vermont	No concerns
Washington	No concerns
Wisconsin	No concerns
British Columbia	Only initial costs are considered
Ontario	No concerns

Table D.2 Revisions considered for LCCA

Question 2	
Revisions considered for the LCCA process for pavement type selection	
State	**Revisions considered**
Alabama	No revisions considered.
California	Including the probabilistic approach and continuing revision as new information and data arrive.
Colorado	No revisions considered.
Georgia	Generally satisfied with the current process but continually looking for ways to improve process and/or incorporate efficient methods.
Illinois	Illinois is in the process of meeting with industry to collaborate on changes to the maintenance and activity schedules that are part of the LCCA analysis. In addition, a model is being developed for user delay, as currently user delay costs are not considered.
Indiana	The process should be fair to both the concrete and asphalt industries. The procedure has to include an oversight of the selection process by a committee, not solely by the pavement engineer. The meaning of "fair" should include "a realistic unit price" and not an artificial one, and also no special treatment for either of the pavement type.
Iowa	No revisions considered.
Kansas	Considering alternate bids to offset problems of estimating costs during inflationary periods.
Maryland	Only planning on improvements to inputs and constraints where they are appropriate.
Michigan	No revisions considered.
Minnesota	No revisions considered.
Mississippi	LCCA rehab life is revised periodically to reflect current performance in the Pavement Management database.
Missouri	No revisions considered.
Montana	Considering including user costs in LCCA as the roads in Montana are becoming increasingly congested and User Costs are becoming more important.
Nebraska	No revisions considered.
North Carolina	Including longer design period for highest volume roadways.
South Carolina	A research project is being conducted by Clemson University to study potential revisions to the LCCA procedure.
Utah	No revisions considered.
Vermont	No revisions considered.
Washington	Potentially, if the LCCA difference is greater than 30 %, a full analysis will not be required. Instead a simple letter will be placed in the project file stating the results based on a preliminary analysis.
Wisconsin	For some time incorporating probabilistic LCCA have been considered. At this time it is not on the horizon, however.
British Columbia	No revisions considered.
Ontario	Looking at incorporating life expectancy of Superpave mixes, whereas Marshall mixes were used in the past.

Table D.3 The time of the last LCCA Revision

Question 3	
The time of the last LCCA revision	
State	**Time of the Last Revision**
Alabama	2003
California	The "Living Document" of RealCost Procedures Manual which is based on deterministic approach is currently being finalized and will be continuously updated thereafter.
Colorado	The LCCA process was revised in July 2005. CDOT currently uses the deterministic approach using AASHTO's DarWin software along with user cost software Workzone. Also a second approach was added using FHWA's probabilistic RealCost software as a tool to familiarize with the probabilistic approach.
Georgia	March 2006
Illinois	More than 10 years ago
Indiana	2005
Iowa	1998
Kansas	2004
Maryland	Fall of 2005
Michigan	October 2002 March 2005: minor updates/clarifications, converted to English units
Minnesota	2004
Mississippi	2005
Missouri	The current LCCA for alternate bidding has not been fundamentally revised since it was developed approximately three years ago. The construction pay item unit prices and non-material and labor placement cost percentages (P.E., mobilization, miscellaneous) are adjusted on a monthly basis in tune with current statewide and regional price averages. The discount rate used for converting future costs to present worth values is based on OMB data and adjusted accordingly with time.
Montana	Not specified
Nebraska	The DSNP-86 has been used for quite some time, 15yrs+
North Carolina	1998
South Carolina	Although the method has been adjusted to reflect minor changes, the general methodology itself has not changed in over ten years.
Utah	2005
Vermont	It was revised after a LCCA training course circa 1999-2000
Washington	May 2005
Wisconsin	The same procedure had been used for at least 15 years
British Columbia	Never revised. Lowest initial cost determines the pavement type. Alternative bids with LCCA for concrete versus asphalt were considered but was not continued as the initial costs were prohibitive.
Ontario	2000

Table D.4 Criteria that would trigger the Requirement to conduct LCCA

Question 4						
Criteria that would trigger the requirement to conduct LCCA for pavement type selection						
State	**ADT**	**Cost**	**Pavement Structure**	**Truck Percentage**	**Pavement Type System**	**Other**
Alabama			X			
California	X	X	X			
Colorado		X	X			
Georgia		X	X		X	X
Illinois						X
Indiana		X			X	X
Iowa						X
Kansas						X
Maryland		X				X
Michigan		X				
Minnesota						X
Mississippi				X		X
Missouri						X
Montana		X			X	
Nebraska	X	X	X	X	X	X
North Carolina			X		X	
South Carolina			X			
Utah			X			X
Vermont	X	X				
Washington						X
Wisconsin					X	X
British Columbia						X
Total Responses:	**3**	**9**	**8**	**2**	**6**	**14**

Question 4 - Continued	
Criteria that would trigger the requirement to conduct LCCA for pavement type selection	
State	**Other Criteria that would trigger the requirement to conduct LCCA**
Illinois	LCCA is conducted for all new or reconstructed pavements with design traffic less than 35,000,000 ESALs. Pavements with design traffic greater than 35,000,000 ESALs are automatically constructed with CRCP and no LCCA is done.
Indiana	Scope of the project
Iowa	Project size: If more than ~ 5,000 tons or 5,000 s.y. then a LCCA is conducted.
Georgia	Projects with full FHWA oversight
Kansas	LCCA is performed on all new construction, re-construction, and rehabilitation projects
Maryland	Any project going through the Project Planning Division
Minnesota	A combination of traffic and Subgrade soil strength (Design R-Value) is used to determine if a formal pavement selection is needed. Formal pavement selections use LCC to determine pavement design and type. Otherwise LCC is still applied but does not dictate the pavement type.
Mississippi	Federal funding being utilized
Missouri	Only consistent use of LCCA is for alternate pavement bidding selection
Nebraska	LCCA is used for all new construction and some of the higher volume roadways or those with complicated needs
Utah	Required for all projects that are not programmatic preservation
Washington	New mainline pavement greater than 1/2 mile in length, ramps with high ADT or Truck %, collector distributors and accel-decel lanes same as ramps, and intersections with chronic rutting problems
Wisconsin	Almost all projects require a LCCA. Only very few local projects do not require it.
British Columbia	Only if the cost of asphalt rises to the point that would make concrete competitive as to initial cost

Table D.5 Type of LCCA Approach followed

Question 6	
The type of LCCA approach followed	
State	**Type of LCCA Approach**
Alabama	Deterministic
California	Deterministic, planning to incorporate probabilistic approach
Colorado	Deterministic and Probabilistic. A second approach using RealCost software was added in order to move away from deterministic so that probabilistic approach could be used in the near future.
Georgia	Deterministic. Currently deterministic LCCA approach is used but have used probabilistic in the past. With FHWA's completion of the RealCost software, the probabilistic approach will be incorporated more.
Illinois	Deterministic
Indiana	Deterministic
Iowa	Deterministic
Kansas	Deterministic
Maryland	Probabilistic
Michigan	Deterministic
Minnesota	Deterministic
Mississippi	Deterministic
Missouri	Deterministic
Montana	Deterministic
Nebraska	Deterministic
North Carolina	Deterministic
South Carolina	Deterministic
Utah	Deterministic
Vermont	Combination of both for different aspects of LCCA
Washington	Combination of both for different aspects of LCCA
Wisconsin	Deterministic
British Columbia	Not specified
Ontario	Not specified

Table D.6 The Usage of Sensitivity Analysis

Questions 7a & 7b		
The usage of sensitivity analysis		
State	**Sensitivity Analysis**	**Typical Parameters used**
Alabama	No	
California	No	Sensitivity analysis will be considered later and some of the parameters considered will be discount rate, value of user time, and annual growth rate of traffic.
Colorado	No	
Georgia	Yes	Discount rate, Analysis Period
Illinois	No	
Indiana	Yes	Discount rate, analysis period, and type and timing of rehabilitations
Iowa	Yes	The sensitivity of discount rate and various maintenance costs were reviewed in the past.
Kansas	No	
Michigan	No	
Minnesota	No	
Mississippi	No	
Missouri	No	
Montana	No	
Nebraska	No	
North Carolina	No	
South Carolina	Yes	A variety of unit costs for PCC are looked at to determine the break-even points in both first cost and life-cycle cost when compared to asphalt because the asphalt prices are better defined.
Utah	No	
Vermont	No	
Washington	Yes	Rehab intervals
Wisconsin	No	
British Columbia	Not specified	
Ontario	Not specified	

Table D.7 Typical Responses from States on Probabilistic Approach Inputs

Question 8				
The parameters evaluated in a probabilistic approach, the probability distribution used, and the corresponding values used				
	Colorado DOT	**Indiana DOT**	**Maryland DOT**	**Washington DOT**
INPUT	**Typical Values Used**	**Typical Values Used**	**Typical Values Used**	**Typical Values Used**
Discount rate	Log Normal Distribution Mean 4.5 Std. Dev. 3.1	Deterministic: 4	Truncated Normal Distribution Mean 3, Std Dev.0.25, Minimum: 2.5, Maximum: 3.5	Triangular Distribution, Min 3, Max 5, Most Likely 4
Timing of future rehab activities	HMA* =10 Std. Dev 3.1 PCCP**= 22 Std. Dev. 6	Normal Distribution 30 yrs for PCCP 25 yrs for HMA	For initial construction: HMA = 14.8 Std. Dev. 5.8 PCCP = 20.0 Std. Dev. 5.7	Triangular Distribution Varies according to location
Agency construction cost	Triangular Distribution Project Specific	Normal Distribution Project specific Std. Dev. is 10% of the cost	Normal Distribution Project specific	Normal Distribution Deterministic Value, + or – 10%
Agency maintenance cost	Not specified	Normal Distribution Project specific Std. Dev. is 10% of the cost	Maintenance is not included in the analysis	Assumed equal

*Hot mix asphalt, ** Portland Cement Concrete Pavement

Table D.8 The Data Sources used in selecting the Input Parameters

Question 9				
The data sources used in selecting the input parameters for conducting an LCCA				
State	**State Data**	**FHWA**	**Consultants**	**Other**
Alabama	X			
California	X	X		
Colorado	X	X		
Georgia	X	X		
Illinois	X	X		X
Indiana	X	X		
Iowa	X			
Kansas	X			
Maryland	X	X		
Michigan	X	X	X	
Minnesota	X			OMB discount rate forecast
Mississippi	X			
Missouri	X			OMB discount rate forecast
Montana	X	X		
Nebraska	X	X		
North Carolina	X	X		
South Carolina	X			
Utah	X			
Vermont	X			
Washington	X			
Wisconsin	X			
British Columbia	X			
Ontario	X			
Total Responses	**23**	**10**	**1**	**3**

Table D.9 Design Procedure used for Flexible Pavements

Question 10							
Design Procedure used for flexible pavements							
State	**AASHTO 1972**	**AASHTO 1986**	**AASHTO 1993**	**AASHTO 1998**	**State design**	**AASHTO & State Design**	**Other**
Alabama			X				
California					X		
Colorado			X				
Georgia	X						
Illinois					X		
Indiana			X				
Iowa			X				
Kansas				X			
Maine			X				
Maryland						X	
Michigan			X				
Minnesota						X	
Mississippi	X						
Missouri							NCHRP 1-37 Guide
Montana			X				
Nebraska		X	X				
North Carolina	X						
South Carolina	X						
Utah			X				
Vermont			X				
Washington			X				
Wisconsin	X						
British Columbia						X	
Ontario			X				

Table D.10 Design Procedure used for Flexible Pavements

Question 11							
Design Procedure used for rigid pavements							
State	**AASHTO 1972**	**AASHTO 1986**	**AASHTO 1993**	**AASHTO 1998**	**State design**	**AASHTO & State Design**	**Other**
Alabama			X				
California					X		
Colorado				X			X*
Georgia			X				
Illinois						X	
Indiana			X				
Iowa							PCA
Kansas	X						
Maryland						X	
Michigan			X				
Minnesota						X	
Mississippi				X			
Missouri							NCHRP 1-37 Guide
Montana			X				X
Nebraska		X	X				
North Carolina	X						
South Carolina			X				
Utah						X	
Vermont				X			
Washington			X				
Wisconsin	X						
Ontario						X	
Total Responses	**3**	**1**	**8**	**3**	**1**	**5**	**4**

Table D.11 Timing of the first Rehabilitation of Rigid Pavements

Question 12a	
The basis for arriving at the time to first rehabilitation in case of rigid pavements	
State	**Basis for arriving at the time to first-rehabilitation**
Alabama	Visual inspection and available funding
California	Maintenance treatment decision trees produced by the districts
Colorado	CDOT pavement management program using cost/benefit with regional analysis for individual cases
Georgia	The past performance data of the rigid pavements in the state obtained from the state maintenance department.
Illinois	Selection of actual timing and subsequent rehabilitations are made in the basis of Condition Rating Survey (CRS) history. The CRS takes into account a visual inspection, maintenance, ride (smoothness), and faulting. Capacity concerns, safety issues, and poor friction may also trigger rehabilitation.
Indiana	Pavement management system data, based on PQI (Pavement Quality Index) and PCR (Pavement Condition Rating).
Iowa	For the LCCA model the timing is based on historical pavement data. For actual project selection, field reviews and Pavement Management data are used.
Kansas	Input to the design methodology and pavement performance measures
Maine	No rigid pavements
Maryland	Historical performance from data in PMS
Michigan	Historical performance data in time to 50 distress points. The distress scale used starts at zero and goes up from there.
Minnesota	Historical data from PMS
Mississippi	Historical data
Missouri	Average historical time of first rehab based on older JRCP designs Actual planning of pavement rehabs: visual inspection, FWD, and pavement management data
Montana	Engineering judgment due to relative inexperience
Nebraska	Distresses such as cracking and past history
North Carolina	PCR, history performance from PMS, site visit
South Carolina	Anecdotal observation of previous pavement performance combined with estimates of the effect of implemented design changes
Utah	Scheduled - Past research has defined a 10 year cycle, with the option to delay
Vermont	Combination of visual inspection and assessment of pavement condition survey.
Washington	State wide performance experience (WSDOT is currently working on performance models for rigid pavements)
Wisconsin	Projected initial service life of our current (JPCP w/dowels) design - this is the same for all designs.
British Columbia	No rigid pavements
Ontario	Friction (diamond grinding at year 18)

Table D.12 Timing of the first Rehabilitation of Flexible Pavements

Question 12b	
The basis for arriving at the time to first rehabilitation in case of flexible pavements	
State	**Basis for arriving at the time to first-rehabilitation**
Alabama	Same as 12a
California	Same as 12a
Colorado	Same as 12a
Georgia	Same as 12a
Illinois	Same as 12a
Indiana	Same as 12a
Iowa	Same as 12a
Kansas	Same as 12a
Maine	Combination of rutting, ride and cracking
Maryland	Same as 12a
Michigan	Same as 12a
Minnesota	Same as 12a
Mississippi	Same as 12a
Missouri	Average historical time of first rehab based on older mix designs and additional performance assumption with polymer-modified asphalts
Montana	Historical performance data obtained from PMS
Nebraska	Distresses such as rutting or cracking, and past history
North Carolina	Same as 12a
South Carolina	Same as 12a
Utah	Scheduled - Based on preservation strategy, modified by semi-annual inspection
Vermont	System-wide analysis of pavement condition (from annual survey), benefit-cost analysis of potential treatment(s), and amount of funding
Washington	Washington State Pavement Management System - rehab intervals for similar project ADT in the area of the analysis)
Wisconsin	Projected initial service life for our HMA pavements - the same for all designs.
British Columbia	Smoothness and distress surveys
Ontario	Surface course distresses

Table D.13 The Basis for Subsequent Rehabilitations for Rigid Pavements

Question 13a	
The basis for arriving at the time to subsequent rehabilitation in case of rigid pavements	
State	**Basis for arriving at the time to subsequent rehabilitation**
Alabama	Same as 12a
California	Same as 12a
Colorado	CDOT default values obtained by analysis of historical data
Georgia	Same as 12a
Illinois	Same as 12a
Indiana	Same as 12a
Iowa	Field reviews and Pavement Management data
Kansas	Pavement Management measure of performance history
Maine	No rigid pavements
Maryland	Same as 12a
Michigan	Same as 12a
Minnesota	Same as 12a
Mississippi	Same as 12a
Missouri	None other assumed for 45-year design period
Montana	Same as 12a
Nebraska	35 yrs before a structural overlay is performed. Based on visual distresses and past history
North Carolina	Historic maintenance and rehab records
South Carolina	Same as 12a
Utah	Preventative Schedule based on past system performance
Vermont	Required maintenance, treatment, and available funding
Washington	Same as 12a
Wisconsin	The timing for a first rehabilitation is based on the standard initial service life for standard concrete pavements. Subsequent rehabilitations are based on the standard service lives of each projected rehabilitation.
British Columbia	No rigid pavements
Ontario	Major concrete pavement restoration (full depth and partial depth patching)

Table D.14 The Basis for Subsequent Rehabilitations for Flexible Pavements

Question 13b	
The basis for arriving at the time to subsequent rehabilitation in case of flexible pavements	
State	**Basis for arriving at the time to subsequent rehabilitation**
Alabama	Same as 12a
California	Same as 12a
Colorado	Same as 13a
Georgia	Same as 12a
Illinois	Same as 12a
Indiana	Same as 12a
Iowa	Same as 13a
Kansas	Same as 13a
Maryland	Same as 12a
Michigan	Same as 12a
Minnesota	Same as 12a
Mississippi	Same as 12a
Missouri	Same as 12b
Montana	Same as 12b
Nebraska	20 yrs before an initial structural overlay based on visual distresses and past history.
North Carolina	Same as 13a
South Carolina	Same as 12a
Utah	Same as 13a
Vermont	Ideally right treatment at the right time supported by PMS. However, network needs often prevent full application of this philosophy
Washington	Same as 12b
Wisconsin	The timing for a first rehabilitation is based on the standard initial service life for standard HMA pavements. Subsequent rehabilitations are based on the standard service lives of each projected rehabilitation.
British Columbia	Same as 12b
Ontario	Surface course distresses and structural improvement (mill and 2-lift overlay)

Table D.15 Rehab Options for Rigid Pavements and Typical Unit Costs Considered

Question 14		
The rehabilitation options considered for the first rehabilitation of rigid pavements and the typical unit costs involved		
State	**Rehabilitation Options Considered**	**Unit Cost**
Alabama	Full Depth Repair	$900/SY
	Joint and Crack Sealing	$3.50/LF
	Diamond grinding	$2.50/SY
California	Full Depth Repair	$10,000/slab
	Joint and Crack Sealing	$2,000/linear mile
	Diamond grinding	$50,000/lane mile,$50/bar
Colorado*	Full Depth Repair	$90.38/SY
	Joint and Crack Sealing	$1.43/LF
	Diamond grinding	$8.81/SY
Georgia	Full Depth Repair	$450 per CY
	Joint and Crack Sealing	$0.67/LF
	Diamond grinding	$3.50/SY
	CRC Punch-out Repair	$600 per CY
Illinois**	Partial Depth Repair	$50/SY
	Full Depth Repair	$125/SY
	Joint and Crack Sealing	0.40$/LF
	Diamond grinding	$7.5/SY
	HMA Overlay	$45-50/ton
Indiana	Partial Depth Repair	Total unit cost of first rehab is $139,334/Lane Mile
	Full Depth Repair	
	HMA Overlay	
Iowa	HMA Overlay	$76.00/inch/mile for primary
	Interstate resurfacing	$96.00/inch/mile
	Rubblize	$80.00/inch/mile for primary
	Unbonded overlay	$ 1M/mile Interstate, $750,000/mile Primary
Kansas	Partial Depth Repair Full Depth Repair Joint and Crack Sealing Diamond grinding HMA Overlay	Unit costs not specified
Maryland***	Partial Depth Repair	Unit costs not specified
	Full Depth Repair	
	Diamond grinding	$6.70, standard deviation: $2.60
Michigan	Unbonded Overlay	$17.40/SY
	Rubblizing + Overlay	$16.57/SY
Minnesota	Partial Depth Repair	$15/SF
	Joint and Crack Sealing	2$/LF

Question 14 - continued		
The rehabilitation options considered for the first rehabilitation of rigid pavements and the typical unit costs involved		
State	**Rehabilitation Options Considered**	**Unit Cost**
Mississippi	Full Depth Repair Mill&Fill HMA Shoulder	Unit costs not specified.
Missouri	Full Depth Repair Diamond grinding	Unit costs not specified.
Montana	Full Depth Repair Joint and Crack Sealing Diamond grinding	Unit costs not specified.
Nebraska	Partial Depth Repair	$85/SY
	Full Depth Repair	$100/SY
	HMA Overlay	$45/ton
	Unbonded Overlay: min 6” concrete	Unit cost not specified
	Rubblizing + Overlay	Rubblize for $2/sy & min 8" HMA
North Carolina	Joint and Crack Sealing Diamond grinding	Unit costs not specified.
South Carolina	Full Depth Repair	$110/SY
	Joint and Crack Sealing	$1.25/LF
Utah	Partial Depth Repair Full Depth Repair Diamond grinding Unbonded Overlay Rubblizing + Overlay	Unit costs not specified.
Vermont	Joint and Crack Sealing: $30/lf	
Washington	Partial Depth Repair	Unit costs not specified.
	Full Depth Repair	
	Joint and Crack Sealing	$1/LF
	Diamond grinding	$6-$12/SY
	Dowel Bar Retrofit	$350,000 / Lane Mile (typically one lane DBR and one lane grind)
Wisconsin	Partial Depth Repair	Unit cost not specified
	Full Depth Repair	$160-200/CY
	HMA Overlay: 3" overlay	$15-$25/ton for mix and $150-$250/ton for AC
Ontario	Partial Depth Repair Full Depth Repair Joint and Crack Sealing Diamond grinding HMA Overlay	Unit costs not specified
*The above values are default LCCA calculations only. CDOT currently has 6regions and each region has the option to select the appropriate cost. ** The above values are the most common rehabilitation activities used on jointed pavements for a first rehabilitation. *** The process and data resources are explained in Maryland DOT’s report.		

Table D. 16 Rehabilitation Timings for Rigid Pavements

Question 14a	
The type of rigid pavement and the corresponding rehabilitation timing (time to first rehabilitation)	
State	**Time to first rehabilitation**
Alabama	20 years, type not a consideration
California	Jointed doweled 20-year for 20-year life, 40-year for 40-year life
Colorado	JPCP with dowels and tie bars, first rehab is at year 22
Georgia	CRC: 25 years, JPCP: 20 years
Illinois	IDOT's current maintenance and activity schedules call for CPR of jointed doweled pavement at year 20. CPR activities include full-depth patching, undersealing, grinding, and joint routing and sealing. Currently, no maintenance and activity schedules exist for CRCP. CRCP is constructed for high-volume traffic routes based on policy, and no LCCA is done.
Indiana	30years for JPCP. The next rehabilitation is 12 years, which constitutes a reconstruction.
Iowa	JPCP 40 years
Kansas	Non-reinforced, dowel jointed : Time to first rehab 20 years, subsequent rehabs on 10 year cycle
Maryland	Jointed plain concrete pavement (JPCP) is used by MDSHA. Time to first rehabilitation is planned at year 20 based on a 25-yr initial structural design life.
Michigan	Jointed plain concrete, with a 26 year life for new concrete pavements.
Minnesota	JPCP: 17years
Mississippi	JPCP: 16years
Missouri	25 years
Montana	Doweled jointed plain concrete pavement. 20 years
Nebraska	4" min overlay at 35 yrs unless performing exceptional
North Carolina	15 years (CRC is not build, all existing CRC is more than 20 years old)
South Carolina	JPCP: 20years
Utah	JPCP: 10 years for minor, 20 years for major
Vermont	20 years
Washington	JPCP: 20-30 years
Wisconsin	JPCP with dowels (15 or 18 foot joint spacing, depending on thickness), initial service life 25 years if placed over dense-graded base, 31 years if placed over open-graded base
Ontario	JPCP with dowels, 18 years to first rehab which is minor CPR and diamond grinding

Table D.17 Typical Rehabilitation Service Lives for Rigid Pavements

Question 14b	
Typical rehabilitation service lives for rigid pavements	
State	**Rehabilitation service life**
Alabama	8 years
California	At least 10 years
Colorado	18 years
Georgia	20 years
Illinois	20 years
Indiana	First time rehab which is a combination of Partial depth, Full depth patching, and HMA structural overlay is 12 years
Iowa	20 years
Kansas	7-10 years
Maryland	Varies depending on which rehabilitation cycle
Michigan	21 Years for unbonded overlay, and 20 years for rubblizing & overlay
Minnesota	10 years
Mississippi	16 years
Missouri	20 years
Montana	20 years
Nebraska	15 years
North Carolina	10 years
South Carolina	10 years
Utah	Varies based on treatment
Vermont	10-15 years
Washington	Diamond Grind 15-20 yrs, DBR 15 yrs
Wisconsin	If the initial rehabilitation is repair, it gets an 8-year service life; if the initial rehabilitation is an HMA overlay, it gets a 15-year service life
Ontario	10 years

Table D.18 Typical Maintenance Activities for Rigid Pavements

Question 14c	
Typical maintenance/preservation activities during a given cycle of rehabilitation for rigid pavements	
State	**Typical maintenance/preservation activities**
Alabama	Punch-outs/Corner Breaks repaired w/HMA
California	Crack sealing, diamond grinding for surface friction.
Colorado	Partial and full depth patching, crack sealing, and cross stitching.
Georgia	Because maintenance / preservation activities (such as guard rail repair, striping, etc) are minimal costs when compared with rehabilitation costs and because these activities are the same regardless of pavement type, maintenance / preservation activities are not incorporated into the LCCA
Illinois	Joint sealing, pothole repair, paint striping
Indiana	Cleaning and sealing joints (from year 0 to year 30) Crack sealing (from year 31 to 42 after patching and HMA overlay)
Iowa	Maintenance costs not included in LCCA since accurate cost data from actual activities is currently not present.
Kansas	Crack and joint sealing
Maryland	Typical reactive maintenance operations are not significant factors to impact the LCCA costs. Therefore, routine maintenance not included as part of LCCA.
Michigan	Michigan defines partial depth repairs, full depth repairs, joint & crack sealing and diamond grinding, as regular maintenance/preservation work items.
Minnesota	Joint clean, minor spot repair
Mississippi	None assumed in LCCA
Missouri	None assumed in LCCA, but would probably consist of occasional full-depth and partial-depth repairs.
Montana	Typical maintenance is not included in Rigid Pavement LCCA. Typically, little to no maintenance performed on PCCP between rehabs.
Nebraska	Joint or crack sealing. Some diamond grinding if faulting on non-dowelled concrete. However, all of the concrete pavements since 2000 are joint doweled.
North Carolina	Crack sealing, maintenance of shoulders, spall repair, overlay with high quality ultra thin wearing course
South Carolina	Maintenance between rehabilitation is not included, primarily because it is not done.
Utah	Crack sealing, some slab replacement due to blowups or spot failures
Vermont	2inch HMA overlay
Washington	Diamond Grinding, DBR, and Panel Replacement
Wisconsin	Minor/minimal repairs
Ontario	Full and partial depth concrete repairs, joint sealing

Table D.19 Frequency of Maintenance Activities for Rigid Pavements

Question 14d	
Frequency of maintenance/preservation activities during a given cycle of rehabilitation for rigid pavements	
State	**Frequency of maintenance/preservation activity**
Alabama	No set frequency, repaired as needed
California	Acquired from the districts' decision trees
Colorado	Annual maintenance cost is the average for the life of the initial construction or rehabilitation strategy.
Georgia	Same as 14c
Illinois	Maintenance is done on an as-needed basis by local IDOT field crews. IDOT does not use any scheduled preservation activities.
Indiana	Cleaning and sealing joints is 8 years, crack sealing is 3 years.
Iowa	Same as 14c
Kansas	Eight to twelve years
Maryland	Not specified
Michigan	For Unbonded Overlays, one cycle at year 11. For rubblized pavements, three cycles at years 6, 8 & 12. These are based on historical, and some predicted, information
Minnesota	Maintenance costs are not included in the LCCA
Mississippi	None assumed in LCCA
Missouri	None assumed in LCCA
Montana	Not specified
Nebraska	Joint seal 5-7 yrs. If diamond grind is performed: 10-12yrs
North Carolina	10 years
South Carolina	Not specified
Utah	Varies
Vermont	8-10 years on HMA overlays
Washington	20-30 yrs for Diamond Grinding
Wisconsin	Maintenance is considered at 10 and 15 years
Ontario	Year 12, then 18, then 28

Table D.20 Rehab Options of Flexible Pavements and Typical Unit Costs Involved

Question 15		
The options considered for the rehabilitation of flexible pavements and the typical unit costs involved		
State	**Rehabilitation Option Considered**	**Unit Cost**
Alabama	Milling & overlay	$9.00/SY
California	Milling & overlay	$300,000 per lane mile
	Cold-in place recycling	$200,000 per lane mile
	Hot-in place recycling	$100,000 per lane mile
	Thin overlay with 3 inches or less	$300,000 per lane mile
Colorado*	Milling & overlay	
	2" Milling	$7.84/SY
	2" Overlay	$43.27 ton
Georgia	Milling & overlay	
	Milling	$0.72- $7.50 / SY
	Overlay	$40 to $90 per ton based on pavement type
Illinois	Milling & overlay	$45-$50/ton
Indiana	Milling & overlay	$121,185/Lane Mile
Iowa	Milling & overlay	$78,000/in/mile for Primary, $98,000/inch/mile for interstate resurfacing
Kansas	Milling & Overlay Hot-in place recycling	Unit costs not specified
Maine	Milling & overlay Pulverizing (Full-depth reclamation)	Unit costs not specified
Maryland	Milling & overlay	Unit costs not specified
Michigan	Milling & overlay	$4.45/SY
	Pulverizing (Full-depth reclamation)	$14.97/SY
Minnesota	If low volume (7 million ESAL or less), a route and seal at age 6 is performed. If high ESAL, crack fill at age 7 is performed	Unit costs not specified
Mississippi	Milling & overlay : First rehab is a single lift overlay of lanes and shoulders	Unit costs not specified
Missouri	Milling & overlay	Unit costs not specified
Montana	Milling & overlay	Unit costs not specified

Question 15 - continued		
The options considered for the rehabilitation of flexible pavements and the typical unit costs involved		
State	**Rehabilitation Option Considered**	**Unit Cost**
Nebraska	Milling & overlay	$200,000/mi
	Pulverizing (Full-depth reclamation)	$256,000/mi with HMA overlay
	Cold-in place recycling	$190,000/mi with HMA overlay
	Hot-in place recycling was tried but currently not used	
North Carolina	Milling & overlay Hot-in place recycling	Unit costs not specified
South Carolina**	Milling & overlay	$23.75/SY
Utah	Milling & overlay Pulverizing (Full-depth reclamation) Hot-in place recycling	Unit costs not specified
Vermont	Milling & overlay : Level with HMA and less than 2 inch overlay	Unit costs not specified
Washington	Milling & Overlay	$40/ton, $2/SY
Wisconsin	Milling & Overlay: Milling	 $4-$7/ton
	3" Overlay	$15-$25/ton for mix and $150-$250/ton for AC
	Overlay- no milling	
British Columbia	Milling & overlay	$12 per meter sq
	Hot-in place recycling	$6 per sq meter
	Just overlay	$8 per sq meter
Ontario	Milling & overlay	Unit costs not specified
* The above values are default LCCA calculations only. CDOT currently has 6 regions and each region has the option to select the appropriate cost. **Please note that "Milling & overlay" is actually several unit cost items, the price included here is the estimated total unit cost (including maintenance of traffic) for a project of that type. The costs given for PCC are not total unit costs, but specific unit costs.		

Table D.21 Timing of the first Rehabilitation of Flexible Pavements

Question 15a	
Time to first rehabilitation of flexible pavements	
State	**Time to first rehabilitation**
Alabama	12 years
California	18-20 years
Colorado	10 years
Georgia	10 years
Illinois*	Depends on the traffic factor
Indiana	25 years
Iowa	20 years
Kansas	10 years
Maine	12-15 years (usual treatment is medium HMA overlay)
Maryland	15 years
Michigan	26 years
Minnesota	If low volume (7 million ESAL or less), a route and seal at age 6 is performed. If high ESAL, crack fill at age 7 is performed
Mississippi	12 years
Missouri	20 years
Montana	19 years
Nebraska	Design for 20 years, but usually a rehab is performed around 15 years
North Carolina	Typically 12-15 years
South Carolina	12 years for conventional mixes, 15 years for polymer-modified
Utah	12-15 years
Vermont	Varies
Washington	10-17 yrs - depending on eastern or western Washington
Wisconsin	Standard service life for HMA pavements is 18 years (over dense-graded base) and 23 years over open-graded base
British Columbia	Average 15 years
Ontario	19 years for dense friction course, 21 years for SMA
* In IDOT's current maintenance and activity schedules, time to first rehabilitation and rehabilitation service life depend on the traffic factor. The current maintenance and activity schedules assume that rutting drives rehabilitation.	

Table D.22 Rehabilitation Service Lives of Flexible Pavements

Question 15b	
The rehabilitation service lives of flexible pavements	
State	**Rehabilitation Service Life**
Alabama	8 years
California	10 years
Colorado	10 years
Georgia	10 years
Illinois	Same as 15a
Indiana	15 years
Iowa	20 years
Kansas	Approximately 10 years
Maine	10 years for overlay
Maryland	Every 12 years
Michigan	10 to 15 years, depending on the fix
Minnesota	See Table D.23
Mississippi	9 years
Missouri	13 years for first mill and overlay, 12 years for second mill and overlay.
Montana	12 years
Nebraska	A 20yr initial design, then structural overlay of 4" is about 12-15 yrs, and then additional 4" overlay to give a total life of the roadway of 50 years.
North Carolina	12 years
South Carolina	10 year for conventional, 15 years for polymer-modified
Utah	10 years
Vermont	10-12 years
Washington	10-17 years
Wisconsin	The standard rehabilitation is an overlay (or mill and overlay). It is given a 12-year service life.
British Columbia	Average of 15 years for overlay and mill and fill average of 13 years for hot in place
Ontario	13 years, then 12, then 11, then 10

Table D.23 Minnesota DOT Rehabilitation and Maintenance Activities for Flexible Pavements

(a)

Minnesota DOT Rehabilitation and Maintenance Activities for Bituminous Pavement with Low ESALs (7 Million or less)	
Pavement Age	Treatment
0	Initial Construction
6	Route & Seal Cracks
10	Surface Treatment
20	Mill & Overlay
23	Route & Seal Cracks
27	Surface Treatment
35	Mill & Overlay
38	Route & Seal Cracks
43	Surface Treatment
50	End of Analysis Period (no residual value)

(b)

Minnesota DOT Rehabilitation and Maintenance Activities for Bituminous Pavement with High ESALs (>7 Million)	
Pavement Age	Treatment
0	Initial Construction
7	Crack Fill
15	Mill & Overlay
20	Crack Fill
27	Mill & Overlay
32	Crack Fill
40	Mill & Overlay
45	Crack Fill
50	End of Analysis Period (no residual value)

`

Table D.24 Typical Maintenance Activities for Flexible Pavements

Question 15c	
Typical maintenance/preservation activities during a given cycle of rehabilitation for flexible pavements	
State	**Rehabilitation Service Life**
Alabama	Localized HMA patching (spot patching); Skin patch wheel paths; Crack sealing
California	Crack sealing, seal coats, fog seals, and remove and replace open-graded friction course.
Colorado	Crack sealing and patching
Georgia	Same as 14c
Illinois	Crack and joint routing and sealing, pothole patching, paint striping
Indiana	Crack sealing (from year 0 to 25) Crack sealing (from year 26 to 40, after the first rehab)
Iowa	Same as 14c
Kansas	Crack sealing, fog seals, chip or slurry seals
Maine	Crack sealing, light 3/4" overlay
Maryland	Not specified
Michigan	Crack sealing, surface sealing, microsurfacing
Minnesota	Not specified
Mississippi	None
Missouri	None assumed in LCCA, but would probably consist of patching and crack sealing.
Montana	Chip seals, asphalt overlays
Nebraska	Crack sealing, Fog sealing, armor/chip coats, profile milling (<1")
North Carolina	Patching, surface treatment, crack sealing, skin patch
South Carolina	No maintenance between rehabilitation.
Utah	Crack sealing, rut filling (rare), pot-hole patching, replace OGSC
Vermont	Level and overlay, mill and fill
Washington	Prelevel and Overlay, Overlay, Mill and Fill, Bituminous Surface Treatment
Wisconsin	Crack sealing, seal coats
British Columbia	Crack sealing and minor patching
Ontario	Mill and overlay, hot mix patching, crack sealing

Table D.25 Frequency of Maintenance Activities for Flexible Pavements

Question 15d	
The maintenance/preservation activity frequency within a given cycle of rehabilitation for flexible pavements	
State	**Rehabilitation Service Life**
Alabama	No set frequency, repaired as needed
California	3-7 years
Colorado	Annual maintenance cost is the average for the life of the initial construction or rehabilitation strategy.
Georgia	Same as 14c
Illinois	Maintenance is done on an as-needed basis by local IDOT field crews. IDOT does not use any scheduled preservation activities.
Indiana	Crack sealing is 3 years.
Iowa	Same as 14c
Kansas	5-7 years
Maine	Crack seal at about 5 years after construction.
Maryland	Not specified
Michigan	For a mill & overlay: 2 cycles of maintenance, and for pulverizing: 2 cycles of maintenance. These are not yet based on historical performance information.
Minnesota	See Table ?
Mississippi	None assumed in LCCA.
Missouri	None assumed in LCCA.
Montana	7 years - chip seal, 12 years - overlay with chip seal, 19 years - mill & fill w/ chip seal, 26 years - chip seal, 31-years reconstruction.
Nebraska	Crack sealing 3yrs, Fog Sealing about 5yr after construction and then as needed, armor coat 8-10 yrs after construction, profile milling only when necessary.
North Carolina	5 years
South Carolina	Not specified
Utah	OGSC is at 7 to 8 years. Rest is variable.
Vermont	Varies depending upon funding
Washington	Prelevel and Overlay, Overlay, Mill and Fill, Bituminous Surface Treatment
Wisconsin	First maintenance is considered at 3 years with second after another 5 years. This same scenario is used after each rehabilitation
British Columbia	One time of crack sealing if required, minor patch if required
Ontario	3,7,12 years for crack sealing 9,12,15 years for hot mix patching

Table D.26 Agency Costs

Question 16							
The costs that are included in the analysis when calculating agency costs							
State	Preliminary engineering	Const. management.	Const. costs	Routine & preventive maintenance	Resurfacing and rehab. cost	Maint. of traffic cost	Adm. Costs
Alabama			X		X	X	
California	X	X	X	X	X	X	X
Colorado	X	X	X	X	X	X	
Georgia			X	X	X		
Illinois			X	X	X		
Indiana			X	X	X		
Iowa			X		X		
Kansas			X		X		
Maryland			X		X	X	
Michigan			X	X	X	X	
Minnesota			X		X		
Mississippi	X	X	X		X	X	X
Missouri	X	X	X		X		
Montana			X	X	X		
Nebraska	X	X	X	X	X		
North Carolina	X	X	X		X	X	
South Carolina			X		X	X	
Utah			X	X	X	X	
Vermont	X		X		X	X	
Washington	X	X	X		X	X	X
Wisconsin			X	X	X		
British Columbia	X	X	X	X	X		
Ontario			X	X	X		
Total Responses	**9**	**8**	**23**	**12**	**23**	**11**	**3**

Table D.27 Openness for Industry Discussion

Question 17	
Are the typical construction costs values used in LCCA, open for industry discussion to ensure they are representative of field applications?	
State	**Are construction costs open for industry discussion?**
Alabama	Yes
California	Yes
Colorado	Yes
Georgia	Yes
Illinois	No
Indiana	No
Iowa	No
Kansas	Yes
Maryland	Yes
Michigan	Yes
Minnesota	An estimate is performed each time for formal pavements so typical values are not used. The industries are informed of the selection and given the opportunity to inform Minnesota DOT of aggregate sources.
Mississippi	No
Missouri	Yes
Montana	No
Nebraska	No
North Carolina	No, they are based on most recent bid tabs
South Carolina	Yes
Utah	Yes
Vermont	Not specified
Washington	Yes
Wisconsin	Yes
British Columbia	Yes
Ontario	No

Table D.28 Design Options Considered

Question 18		
Design options considered in the pavement type selection process		
State	**A single 'initial construction cost' based on optimal design of the pavement type**	**Different design criteria within each pavement type**
Alabama		X
California		X
Colorado	X	
Georgia	X	
Illinois	X	
Indiana		X
Iowa	X	
Kansas	X	
Maryland		X
Michigan*		
Minnesota		X
Mississippi	X	
Missouri		X
Montana		X
Nebraska	X	
North Carolina	X	
South Carolina	X	
Utah		X
Vermont	Not specified	
Washington	X	
Wisconsin		X
British Columbia	X	
Ontario	X	
Total Responses	**12**	**9**
* Other: both alternatives must be designed to carry equivalent traffic. Initial construction costs are based on recent as-bid prices.		

Table D.29 User Cost Parameters

Question 19								
Parameters used to arrive at user costs								
Parameters	**CA**	**CO**	**GA**	**IN**	**MI**	**UT**	**VT**	**WA**
AADT construction year (total for both directions)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cars as percentage of AADT (%)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Single unit trucks as percentage of AADT (%)	Yes	Yes	Yes	Yes	All trucks are lumped together	Yes	Yes	Yes
Combination trucks as percentage of AADT (%)	Yes	Yes	Yes	Yes		Yes	Yes	Yes
Annual growth rate of traffic (%)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Speed limit under normal operating conditions (mph)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Lanes open in each direction under normal operating conditions	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Free flow capacity vehicles per hour per lane (vphpl)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Queue dissipation capacity (vphpl)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Maximum AADT (total for both directions)	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Maximum queue length (miles)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Rural or urban hourly traffic distribution	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table D.30 Typical Responses from States on the User Cost Input Data

Question 19 - Continued					
	Washington DOT	**Maryland DOT**	**Indiana DOT**	**Colorado DOT**	**Michigan DOT**
INPUT	**TYPICAL VALUES USED**				
Free flow capacity	Deterministic, Highway Capacity Manual	Not specified	Highway Capacity Manual	Deterministic Project specific	2100 vphpl*
Queue Dissipation Capacity	Not specified	Truncated Normal Distribution Mean 1800, std dev. 200, min 1400, max 2200	Highway Capacity Manual	Software calculations	750-1750 vphpl
Annual Average Daily Traffic (AADT)	Not specified	Not specified	Determined from Weigh-In-Motion Data	6,800 – 243,300	No typical value; wide ranging
Maximum AADT (total for both directions)	Not specified	=(2600vphpl) (24 hrs) (no lanes)	Determined from Weigh-In-Motion Data	200,000-418,000	No typical value; wide ranging
Annual traffic growth rate (%)	Normal Distribution. Location specific, + or - 1.0%	Truncated Normal Distribution, mean: project specific, standard deviation: 0.5, minimum: mean -1 % , maximum: mean +1%	Planning Section is consulted	Triangular Distribution 0.34 min 2.34 max 1.34 most likely	1%-3% compound
Value of time for passenger cars (/hr)	Triangular Distribution Min 12, Max 16, Most Likely 13.96, Escalated by CPI	$11.50	$17 (from Colorado DOT research)	Deterministic $17.00	$14.35
Value of time for single unit trucks (/hr)	Triangular Distribution Min 20, Max 24, Most Likely 22.34, Escalated by CPI	$18.50	$35 (from Colorado DOT research)	Deterministic $35.00	$25.32
Value of time for combination trucks (/hr)	Triangular Distribution Min 25, Max 29, Most Likely 26.89, Escalated by CPI**	$22.50	$36.5 (from Colorado DOT research)	Deterministic $36.50	$25.32

Table D.31 Usage of Salvage Value

Question 20		
Usage of salvage value		
State	**Yes**	**No**
Alabama		X
California	X	
Colorado	No for deterministic, Yes for RealCost	
Georgia	X	
Illinois		X
Indiana	X	
Iowa		X
Kansas		X
Maryland	X	
Michigan		X
Minnesota	X	
Mississippi		X
Missouri		X
Montana	X	
Nebraska	X	
North Carolina		X
South Carolina		X
Utah		X
Vermont		X
Washington	X	
Wisconsin	X	
British Columbia		X
Ontario	X	
Total Responses	**10**	**12**

Table D.32 Salvage Value Calculation

Question 21	
State	**Salvage Value Calculation**
California	Calculate serviceable life
Colorado	Calculate serviceable life
Georgia	Calculate serviceable life
Indiana	Calculate serviceable life
Maryland	Calculate serviceable life
Minnesota	The benefit of reusing any in-place bituminous or concrete material, which can be recycled back into the new pavement structure, will be incorporated into the initial cost estimate. This results in separate cost estimates for designs using virgin material and designs using the recycle material. However, no salvage value will be assigned any recyclable materials at the end of the analysis period
Montana	Calculate serviceable life
Nebraska	Calculate both residual value and serviceable life
Washington	Calculate serviceable life
Wisconsin	Calculate serviceable life

REFERENCES

1. AASHTO (1993). "Guide for Design of Pavement Structures", American Association of State Highway and Transportation Officials, Washington, DC

2. AASHTO (1993). "Life Cycle Cost Analysis Survey" American Association of State Highway and Transportation Officials, Washington, DC

3. ACPA (2002). "Life Cycle Cost Analysis: A Guide for Alternate Pavement Designs", American Concrete Pavement Association, Skokie, IL

4. Ang, A.H., and W.H. Tang (1975). "Probability Concepts in Engineering Planning and Design", Volume 1- Basic Principles, John Wiley & Sons, Toronto, Canada

5. Beg M.A., Zhang Z., and Hudson W.R. (1998). "A Rational Pavement Type Selection Procedure" Report No:FHWA/TX-04/0-1734-S, Austin, TX

6. Berthelot et al. (1996). "Mechanistic-Probabilistic Vehicle Operating Cost Model" Journal of Transportation Engineering Vol:122 No:5, pp 337-341

7. CDOT (2000). "Life Cycle Cost Analysis State-of-the-Practice" Report No: CDOT-R1-R-00-3, Colorado Department of Transportation, Aurora, CO

8. Chacko G.K. (1991) "Decision-making under uncertainty : an applied statistics approach" Praeger, New York

9. Christensen P.N., Sparks, G.A., and Kostuk K.J. (2005). "A method-based survey of life cycle costing literature pertinent to infrastructure design and renewal" Canadian Journal of Civil Engineering, Vol. 32 : 250–259, Saskatoon, Canada

10. Cross S.A., and Parsons, R.L. (2002). "Evaluation of Expenditures on Rural Interstate Pavements in Kansas", 81th Annual TRB Meeting, Washington, DC

11. Daniels G., Stockton W. R., and Hudley R. (2000). "Estimating Road User Costs Associated with Highway Construction Projects-Simplified Method" In Transportation Research Record: Journal of the Transportation Research Board, No. 1732, Washington DC, 2000, pp. 70-79

12. Danish Road Institute (2002). "Economic Evaluation of Pavement Maintenance, PAV-ECO" Report 114, Denmark

13. Dewan, S.A., and Smith R. E. (2002). "Estimating International Roughness Index from Pavement Distress to Calculate Vehicle Operating Costs for the San Francisco Bay Area". In Transportation Research Record: Journal of the Transportation Research Board, No. 1816, pp. 65-72, Washington, DC

14. FHWA (1999). "Asset Management Primer", Office of Asset Management, Washington, DC

15. FHWA (2003). "Economic Analysis Primer", Office of Asset Management, Washington, DC

16. FHWA (2004). "Life-Cycle Cost Analysis, RealCost User Manual" Office of Asset Management, Washington, DC

17. Flintsch and Kuttesch (2004). "Application of Engineering Economic Analysis Tools for Pavement Management". 83rd Annual TRB Meeting, Washington, DC

18. Florida Department of Transportation (2005). "Pavement Type Selection Manual" Document No. 625-010-0005-d, Tallahassee, FL

19. Goldbaum J. (2000). "Life Cycle Cost Analysis State-of-the-Practice" Report No CDOT-R1-R-00-3, Aurora, CO

20. Gharaibeh N.G. and Darter M.I. (2003). "Probabilistic Analysis of Highway Pavement Life for Illinois". Transportation Research Record 1823, Paper No, 03-4294 pp 111-120, Washington, DC

21. Haas R., Tighe S., and Falls L.C. (2006). "Determining the Return on Long Life Pavement Investments", 85th Annual TRB Meeting, Washington, DC

22. Herbold, K. (2000). "Using Monte Carlo Simulation for Pavement Cost Analysis" Public Roads Vol. 64 Issue 3. pp 2-7

23. Jawad D. and Ozbay K. (2006). "The Discount Rate in Life Cycle Cost Analysis of Transportation Projects". 85th Annual TRB Meeting, Washington, DC

24. Jung J., Kabush K.E., and Way G.B. (2002). "Life Cycle Cost Analysis: Conventional Versus Asphalt-Rubber Pavements" Submitted to Rubber Pavements Association, Tempe, AZ

25. Lane B. and Kazmierowski T. (2005). "Guidelines for the use of Life Cycle Cost Analysis on MTO Freeway Projects". Ontario, Canada

26. Lamptey G., Labi S., and Sinha K.C. (2004). "Development of Alternative Pavement Rehabilitation and Maintenance Strategies for Pavement Management" 83rd Annual TRB Meeting, Washington, DC
27. Lee E., Harvey J.T., and Samadian M.M. (2005). "Knowledge-Based Scheduling Analysis Software for Highway Rehabilitation and Reconstruction Projects" Transportation Research Record, No 1907, pp 15-24 Washington, DC

28. Lindley J.K. and Clark P.R. (2003). "Adjustments to Pavement Life-Cycle Cost Analysis Procedures", UTCA Report 02409, University Transportation Center for Alabama, Tuscaloosa, AL

29. Lindley J.K. and Clark P.R. (2004). "Characterizing Work Zone Configurations and Effects", UTCA Report 04406, University Transportation Center for Alabama, Tuscaloosa, AL

30. MoDOT (2004). "Pavement Design and Type Selection Process" Phase I Report, MO

31. Mravira G. (1999). "Sensitivity Analysis of Computer Models: World Bank HDM III Model" Journal of Transportation Engineering. Vol 125 No 5.

32. NCHRP (2003). "Bridge Life-Cycle Cost Analysis" NCHRP Report 483, TRB, Washington, DC

33. Office of Management and Budget (1992—updated 2006), "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," Circular No. A-94 (Revised), Original Publication October 29, 1992 but updated with new discount rates, January 2006

34. Ozbay, K. et al (2003) (a). "Guidelines for Life Cycle Cost Analysis", Final Report, Report No FHWA-NJ-2003-012, Trenton, NJ

35. Ozbay, K. et al. (2004) (b). "Life-Cycle Cost Analysis: State-of-the-Practice vs State-of-the- Art", 83rd Annual TRB Meeting, Washington, DC

36. Pantelias, A. (2005). "Asset Management Data Collection For Supporting Decision Processes" M.S. Thesis, Blacksburg, VA

37. PENNDOT (2003). "Pavement Policy Manual" Publication No: 242, Harrisburg, PA

38. Peterson, D. (1985). "Life Cycle Cost Analysis of Pavements", Synthesis of Highway Practice 122, NCHRP Report, Washington, DC

39. Reigle J.A. and Zaniewski J.P. (2002). "Risk-Based Life Cycle Cost Analysis for Project-Level Pavement Management" Presented at the 82th Annual TRB Meeting Proceedings, Washington, DC
40. Rister B.W. and Graves C. (2002). "The Cost of Construction Delays and Traffic Control for Life Cycle Cost Analysis of Pavements" Lexington, Kentucky

41. Simpson A.L., Ostrom B.K., Schmalzer P.N. (2005). "Guidelines for the collection of Long-Term Pavement Performance Data" Report No: FHWA-RD, McLean, VA

42. Temple W. H. et al. (2004). "Agency Process for Alternate Design and Alternate Bid of Pavements" 83rd Annual TRB Meeting, Washington, DC

43. Tighe S. (2001). "Guidelines for Probabilistic Pavement Life Cycle Cost Analysis" Transportation Research Record, no 1769, pp. 28-38., Washington, DC

44. VDOT (2002), Life Cycle Cost Analysis Pavement Options, Virginia Department of Transportation, Materials Division/ Virginia Transportation Research Council, Virginia

45. Walls, J. and M. R. Smith. (1998). Life-Cycle Cost Analysis in Pavement Design—Interim Technical Bulletin. Federal Highway Administration, Washington, DC

46. Wei C. and Tighe S. (2004). "Development of Preventive Maintenance Decision Trees Based on Cost-Effectiveness Analysis An Ontario Case Study" 83rd Annual TRB Meeting, Washington, DC

47. Wilde W.J., Waalkes S., and Harrison R. (2001). "Life Cycle Cost Analysis of Portland Cement Concrete Pavements" Research Report 167205-1, Austin, Texas

48. WisDOT (1994). "The Pavement Type Selection Process" Wisconsin Department of Transportation, WI

49. WSDOT (2005). "Pavement Type Selection Protocol". Washington State Department of Transportation, Olympia, WA

50. Zimmerman K.A. and Walters A.S. (2004). "Local Road Surfacing Criteria" Report No. SD2002-10-F, Champaign, IL

51. Zimmerman K.A., Smith K.D., and Grogg M.G. (2000) "Applying Economic Concepts from Life-Cycle Cost Analysis to Pavement Management Analysis. *Journal of the Transportation Research Board, No.* 1699,TRB, National Research Council, Washington DC