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Guidelines for Life Cycle Cost Analysis

FINAL REPORT
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16. Abstract

Life Cycle Cost Analysis (LCCA) is an indispensable technique that employs well-established principles of economic analyses to evaluate long term performance of competing investment options. The LCCA process is performed by summing up the discounted monetary equivalency of all benefits and costs that are expected to be incurred in each option. The investment option that yield the maximum gains to the society is considered the optimal option. The analytical framework of LCCA further serves as a support system for making informed and conversant choices in infrastructure management. This report summarizes a thorough research that establishes the guidelines for conducting LCCA.

Most of the LCCA input parameters are inherently uncertain, such as the discount rate, the analysis period, and the type and timing of future rehabilitation activities that will take place in each of the life cycle options. In order to conduct LCCA in a reliable and trustworthy manner, a thorough understanding of the theoretical engineering and economics background must be acquired.

The report starts by setting LCCA in its broad perspective. It reviews the economic theory of LCCA, discusses the types and levels of analysis in project evaluation, and briefly goes over the historical background of LCCA. Next a systematic and generic approach for conducting LCCA is presented. Then, a discussion about the state-of-the-practice of LCCA in State DOTs in comparison with state-of-the-art of LCCA is introduced. After that, detailed discussions of every component of LCCA are provided. The uncertainty component in LCCA is deliberated along with the probabilistic approach. A review of the available and significant LCCA models is presented as well. Towards the end, the report discusses a distinct application of LCCA in monitoring contractor's pay schedule.

The LCCA guidelines, presented in this report, aim mainly at providing the reader with sufficient knowledge on how to perform LCCA, how to estimate its input parameters, and how to interpret its results.

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EXECUTIVE SUMMARY

Life Cycle Cost Analysis (LCCA) is an indispensable technique that employs well-established principles of economic analyses to evaluate long-term performance of competing investment options. The LCCA process is performed by summing up the discounted monetary equivalency of all benefits and costs that are expected to be incurred in each option. The investment option that yields the maximum gains to society is considered the optimal option. The analytical framework of LCCA further serves as a support system for making informed and conversant choices in infrastructure management. This report summarizes a thorough research that establishes the guidelines for conducting LCCA.

Most of the LCCA input parameters are inherently uncertain, such as the discount rate that should be employed to convert costs occurring at different points in time to a common time frame, the analysis period over which the options are to be evaluated, and the type and timing of future rehabilitation activities that will take place in each of the life cycle options. In order to conduct LCCA in a reliable and trustworthy manner, a thorough understanding of the theoretical engineering and economics background must be acquired.

The LCCA guidelines presented in this report mainly aim at providing the reader with sufficient knowledge on how to perform LCCA, how to estimate its input parameters, and how to interpret its results. The weaknesses and common flaws in LCCA practice is also pointed out in the guidelines.

The report starts by setting LCCA in its broad perspective. It reviews the economic theory of LCCA, discusses the types and levels of analysis in project evaluation, and briefly goes over the historical background of LCCA. Next a systematic and generic approach for conducting LCCA is presented. Then, a discussion about the state-of-the-practice of LCCA in State DOTs in comparison with state-of-the-art of LCCA is introduced.

After that, a detailed explanation of every component of LCCA is offered. The uncertainty component in LCCA is discussed along with the probabilistic approach. Each one of the input parameters of LCCA, namely, the discount rate, the time dimension, and the costs, is given special consideration in this report, and recommendations on how to deal with it are provided. A review of the available and significant LCCA models is presented. Towards the end, the report discusses a distinct application of LCCA in monitoring a contractor's pay schedule.

Throughout the guidelines, a "running" case study illustrates the discussions and recommendations presented in each section. The appendices of this report provide complementary information for the reader when deemed necessary.

CHAPTER 1: INTRODUCTION

Budget tightening, escalating costs for maintaining public services, functioning at an acceptable level, and increased public scrutiny of government-related expenditures have focused the attention of all segments of our socioeconomic system on the importance of effective management of resources and assets.

Transportation agencies are especially concerned in this pursuit due to many factors. To mention a few, they rank among the top sectors in public spending, and the impacts of their investment decisions touch upon every member of the society, which makes public scrutiny rather intense. Furthermore, an asset base of 3 trillion dollars (i.e. the value of the transportation system in the US as estimated by the FHWA) is under the influence of numerous natural and man-made dynamics, many of which are uncontrollable and/or uncertain.

Decision-making and management in the transportation sector must be based on informed and conversant support. One of the most recognized techniques that provide such informed support, when applied properly, is “Life Cycle Cost Analysis” (LCCA). This document reviews and establishes the guidelines for Life Cycle Cost Analysis for use by the NJDOT.

Life Cycle Cost Analysis is an economic evaluation technique that has been particularly valuable when there is a need to compare competing alternatives for projects with entailing costs and benefits that stretch over long spans of time. As a starting point, it is necessary to expound on three underlying principles that mold LCCA in the approach currently employed in transportation evaluation and recognized by its analysts. The three topics cover financial analysis and economic analysis, the systems method, and the levels of analysis.

Financial Analysis versus Economic Analysis

In principle, economic evaluation is performed by accounting for all the monetary equivalency of costs and benefits resulting from project implementation, taking into account their respective times of occurrence. At times economic analysis is confused with financial analysis, so it is imperative to differentiate between these two types of analyses. This will eliminate any possible ambiguity in the theoretical basis of LCCA.

Financial analysis comprises the comparison of revenues and expenses (initial investment, maintenance, and operating costs) recorded by the concerned fiscal agents in each project alternative (if relevant) and working out the corresponding financial return ratios. Economic analysis, on the other hand, consists of identifying and comparing fiscal as well as social benefits and costs accruing to the economy as a whole, setting aside, for example, monetary transfers between economic agents.

The Systems Method

The systems method provides the proper framework for structuring LCCA efficiently. It is a comprehensive problem-solving process that involves handling a number of interrelated problems and/or tasks on a global basis to achieve the maximum utility, as is the case in transportation infrastructure management. Figure 1 describes the major phases and components of the systems method. Haas et. al. explains the diagram as(1):

“The diagram illustrates that the recognition of a problem comes from some perceived inadequacy or need in the environment. It leads to a definition of the problem that involves a more in-depth understanding. This provides the basis for proposing alternative solutions. These alternatives are then analyzed in order to predict their probable outputs or consequences. Evaluation of the outputs is the next step in order that an optimal solution may be chosen. Implementation involves putting the solution into service, and its operation. Feedback for improving future solution, or checking on how well the system is fulfilling its function, is provided by periodic performance measurements.” (1)

Levels of Analysis

Project evaluation is performed at various levels of analysis. The level of analysis is dictated by the context of the analysis: 1) Why are we evaluating? 2) What are we evaluating? The first categorization corresponds to the first question. Two types of analysis are identified: the primary and secondary analysis (1). The primary analysis aims at establishing the economic feasibility of the project(s); if the anticipated benefits cover the estimated costs, the project is worthwhile in principle. The results of the primary analysis determine whether the project should be constructed in the first place. Furthermore, the analysis results can be used to prioritize and rank other feasible projects. An example of such analysis is the economic evaluation of a newly proposed rail line.

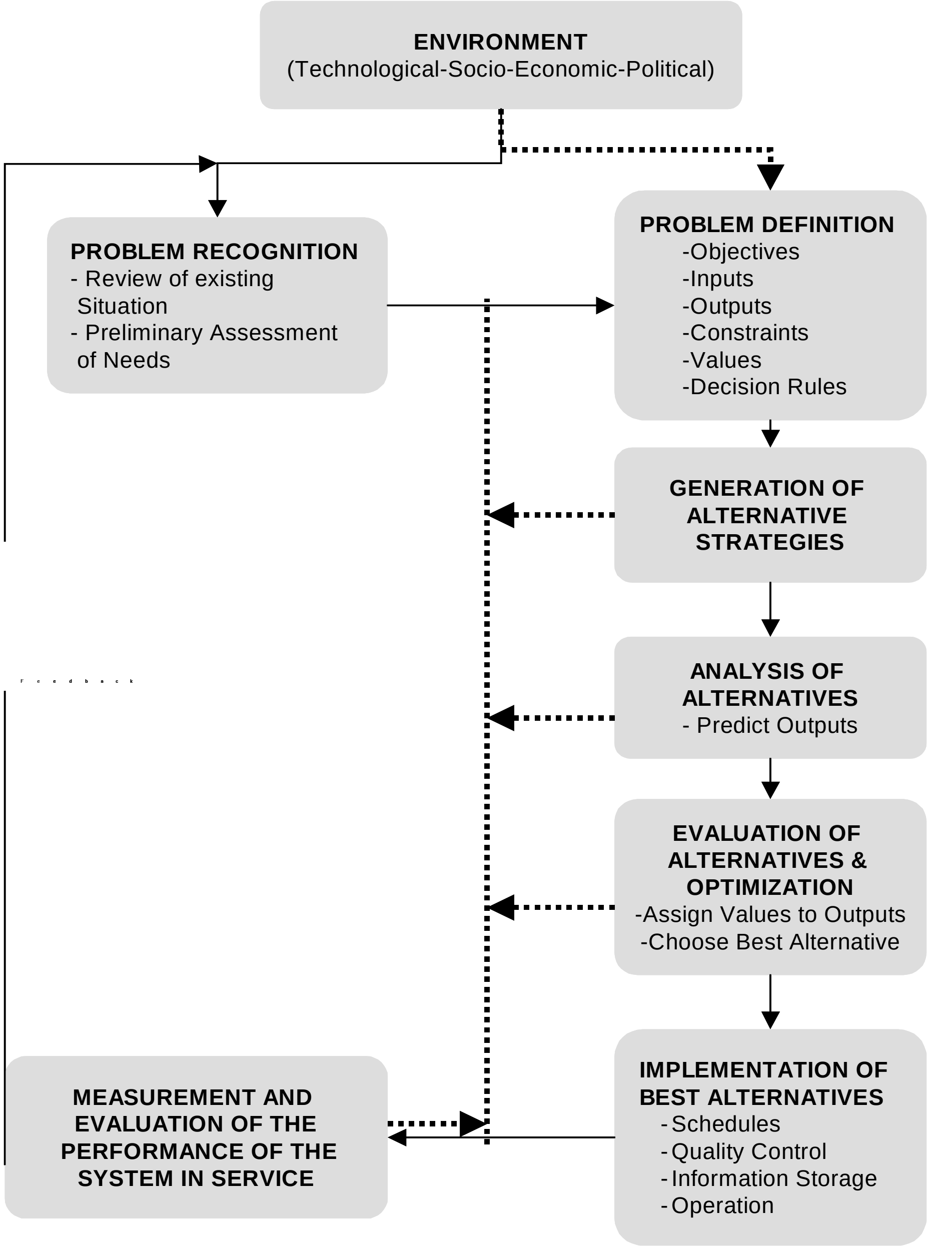


Figure 1: Major Phases and Components of the Systems Method (2)

The secondary analysis is executed after the project is chosen for implementation. Its purpose is to decide on the optimum lifecycle strategy between competing alternatives. Life cycle strategies may differ in their initial designs, type and timing of rehabilitation, and maintenance activities; however they must yield equal benefits. Evaluating a steel bridge alternative against a reinforced concrete bridge alternative is an example of secondary analysis.

The second question, “What are we evaluating?”, generates the second categorization, the project level analysis and the network level analysis (2). Project-level analysis considers one project for evaluation, while network-level considers a number of projects that constitute the network simultaneously.

Project-level analysis is a bottom-up approach. It involves the evaluation of competing alternatives for one project. This type of analysis deals with technical concerns, thus requiring very detailed information. It aims at finding the optimum life cycle strategy that achieves the maximum economy from the project under evaluation without taking funding availability or other policy considerations into account.

Network-level analysis, on the contrary, is a top-down approach; the overall network/agency goals are established first so that projects can be selected to achieve these preset goals. This level of analysis is mainly concerned with finding the best utilization of the network as a whole under various resource constraints and taking into consideration possible political factors. Normally, the main constraint that drives this level of analysis is the financial resources. The input information required is less detailed than that of the project-level. The output of network-analysis provides a program of projects to be constructed for the whole network, and such analysis may provide policy analysis under different scenarios, like the effects of decreased budget on the level of serviceability of the network.

Even though the objectives, level of information, components, and approach may vary in the different types of analysis, the results and decisions attained at each level must interface with one another continuously if efficient management is to be achieved.

This report presents the guidelines for performing Life Cycle Cost Analysis for pavement transportation projects particularly at the project-level secondary analysis.

LCCA Historical Background

Highway engineering economics was introduced as early as the end of the nineteenth century, when Gillespie issued his “Manual of the Principles and Practices of Road Making” in 1847. Gillespie characterized the most cost-effective highway project as the one that has the highest returns as to the expenses associated with its construction and maintenance (3).

Though seemingly, LCCA was present in the works of Gillespie, it was articulated especially in the 1930s as part of the federal legislation in relation to flood control. By the time the need for minimizing the costs of a transportation facility became a necessity, LCCA had grown to be an accepted practice in various disciplines of our society.

However, this concept was not used in highway projects until the 1950s. The works of the economist Winfrey in the ‘60s and the American Association of State Highway Officials (AASHO’S) “Red Book” of 1960 ushered in the concept of Life Cycle Cost Analysis to the transportation domain (4). At the time, the available information was not sufficient to perform a comprehensive and reliable LCCA that truly encapsulates all the components of the analysis. Extensive research started as a result. The research focused on issues like information gathering and integration, but for the most part, aimed at quantifying the user cost and vehicle operating cost by conducting field experiments, such as the road test experiment that was conducted by the World Bank in Brazil in the 1960s and development of empirical models based on the results (5).

In 1984 the National Cooperative Highway Research (NCHRP) commenced project number 20-5 FY 1983 with the aim of promoting LCCA (3). This project investigated the state of the practice of LCCA in transportation agencies at the time and examined the different aspects and parameters of the process. The American Association of State

Highways and Transportation Officials (AASHTO), in their Pavement Design Guides of 1983 and 1993, endorsed the use of LCCA as a means for economic evaluation and as a decision support tool.

The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 called for “the use of life cycle costs in the design and engineering of bridges, tunnels, or pavement,” both for metropolitan and statewide planning. Subsequently, the National Highway System (NHS) Designation Act of 1995 mandated the States to perform LCCA on NHS projects costing $25 million or more. In 1996, the Federal Highway Agency released its Final Policy statement on LCCA.

The Transportation Equity Act for the 21st Century (TEA-21) of 1998, which replaced the ISTEA 1991, had removed the requirement for State Highway Agencies to perform LCCA on NHS projects of $25 million or more. However, the same act continues the endorsement of LCCA by requiring the Secretary of Transportation to authorize research and development for LCCA enhanced implementation.

Demonstration Project 115 “Life-Cycle Cost Analysis in Pavement Design”, carried out by FHWA in 1998, developed an instructional LCCA workshop that has since been presented in various states many times. In addition, a resultant noteworthy technical bulletin outlining the best practice of LCCA methodology and related parameters was published.

In the year 2000, within FHWA, LCCA came under the charge of the Office of Asset Management. Its most recent product (late 2002) is the development of an LCCA instructional software package for pavement. Research commissioned by the State Highway Agencies and other interested partners continues to be conducted on a broader scale. It covers LCCA in the context of planning and management for transportation projects, as well as other aspects, such as data collection and integration, the element of uncertainty, and the boundless topic of related user costs.

CHAPTER 2: GENERAL METHODOLOGY

Life Cycle Cost Analysis is a systematic process used for evaluating public projects entailing various impacts that stretch over long periods of time. The process is performed by summing up the monetary equivalency of all benefits and costs at their respective time of occurrence throughout the analysis period. They are then converted into a common time dimension so that different alternatives may be compared properly.

Economic Indicators

In the economic evaluation of projects, there are several formats of economic indicators for the analysis results. The most common are Net Present Value (NPV), Cost-Benefit Ratio (B/C), Equivalent Uniform Annual Costs (EUAC), and Internal Rate of Return (IRR). The choice of the appropriate indicator depends largely on the level and context of the analysis. It may also depend on the degree of uncertainty in some parameters. For example, when projects are evaluated in developing countries where the discount rate is highly uncertain, the IRR format is the preferred indicator. On the other hand, when the analysis period of the project is unknown or the project is expected to last indefinitely, then EUAC is considered to be the better format since EUAC equations are derived with the assumption that the project will last indefinitely (6). The formulas of each format are presented in Table 1.

In principle, the choice of the economic indicator should cater to the following questions:

1. Are benefits included in the analysis?
2. What is the level of decision-making and/or analysis involved?
3. What methods suit the requirements of the particular agency involved?
4. How important is the initial capital investment in comparison to future expenditure?
5. What method of analysis is the most understandable to the decision-maker?

Table 1: Equations of Economic Indicators

Eq. No	Indicator	Abbreviation	Equation
1	Net Present Value	NPV	$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+d)^t}$
2	Benefit-Cost Ratio	B/C	$\frac{PVB}{PVC} = \sum_{t=0}^{T} \frac{B_t / (1+d)^t}{C_t / (1+d)^t}$
3	Equivalent Uniform Annual Costs	EUAC	$EUAC = NPV\left[\frac{1(1+d)^t}{(1+d)^t - 1}\right]$
4	Internal Rate of Return	IRR	$\sum_{t=0}^{T} \frac{B_t - C_t}{(1+IRR)^t} = 0$

NPV = Net present value of future costs and benefits, IRR = Internal Rate of Return, B/C = Benefit/Cost
PVB = Present value of future benefits, PVC = Present value of future costs
d = Discount Rate , t = time of incurrence (year), T = Lifetime of the project or Analysis period (years)
B_t= Benefits to be gained at time t, C_t= Costs to be incurred at the time t

Since the LCCA project-level secondary analysis aims at evaluating project alternatives that result in equal categorical benefits but entail unequal costs, the Net Present Value (NPV) is considered the appropriate (and the prevalent) indicator for comparing the differential economic worth of projects. The Net Present Value indicator, with its additive function, allows the analyst to account only for the differential costs (or benefits) and, at the same time, maintain consistency in the evaluation process. This characteristic reduces the computations needed in the analysis tremendously. All costs or benefits that are known (or assumed) to be equal need not be evaluated. This advantage becomes clear in our discussion of the costs component of LCCA in Chapter 6.

With equal benefits among alternatives, equation 1 becomes:

$$NPVC = \sum_{t=0}^{T} \frac{C_t}{(1+d)^t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

where C_t is the cost occurring at year t that should include all types of costs, monetary and non-monetary, encountered throughout the analysis periods.

Many LCCA documents restrict these costs to the initial construction cost, rehabilitation cost, annual maintenance cost, and salvage value (considered negative) by assuming that all user and societal costs are equal between alternatives. A detailed discussion of the types of costs that might be encountered as a result of the traditional projects (i.e. bridges and pavements) is presented in Chapter 6. Based on the above categorization of costs, the Net Present Value equation can be rewritten as:

NPV=Initial Cost+pwf(rehabilitation Costs)+pwf*(Main. Costs)-pwf*(Salvage*)……….(6)

Where

Pwf_t =present worth factor of costs incurring at year t

$$pwf_t = \frac{1}{(1+d)^t} \quad \text{……………………………………………………………………………}(7)$$

LCCA Procedure

The LCCA structured approach can be outlined in the following steps:

1) Define project's alternatives.
2) Decide on the approach: Probabilistic vs. Deterministic.
3) Choose general economic parameters: Discount Rate, Analysis Period.
4) Establish expenditure stream for each alternative:
    a) Design rehabilitation strategies and their timings.
    b) Estimate differential agency costs.
    c) Estimate differential user costs.
    d) Estimate differential societal costs.
5) Compute Net Present Value for each alternative.
6) Compare and interpret results/ Sensitivity Analysis.
7) Re-evaluate design strategies if needed.

1) Define project’s alternatives

This is the first step in the LCCA procedure. Experts and experienced professionals suggest potential life cycle strategies for the project. Each pavement design strategy specifies initial design and performance, time-dependent rehabilitation/treatment activities, and the timings of these rehabilitation activities and respective performances. At this stage, common costs between different strategies can be identified. For example, in evaluating new pavement projects, right-of-way costs are common to all alternatives. Marginal costs, especially those occurring in the future, can be insignificant with respect to the total value of the project; thus, it is helpful to identify such costs beforehand.

2) Decide on the approach that would be followed: Probabilistic vs. Deterministic

Deciding on the approach to be followed at this time should be accomplished based on information and data available for the LCCA model parameters. In all cases, most of the LCCA parameters are uncertain, and it is generally recommended that the probabilistic approach be adopted. The deterministic approach uses point estimates for all input variables for the model, whereas the probabilistic approach uses probability distributions for all unsure variables and therefore treats the inherent uncertainty in the model. Chapter Three presents the methodology for the probabilistic approach.

3) Choose general economic parameters

General economic parameters are the discount rate and the analysis periods. Both parameters should be equal for all options. The choice of these parameters is explained in detail in their respective chapters.

4) Establish expenditure stream for each alternative

Expenditure stream diagrams can be constructed as shown in Figure 2. These diagrams lay out the design strategies, including scope, and timing for each activity, with associated agency, user, and societal costs shown in real dollars for each year of the analysis period. A discussion on the type of dollars to be used is presented in Chapter 4.

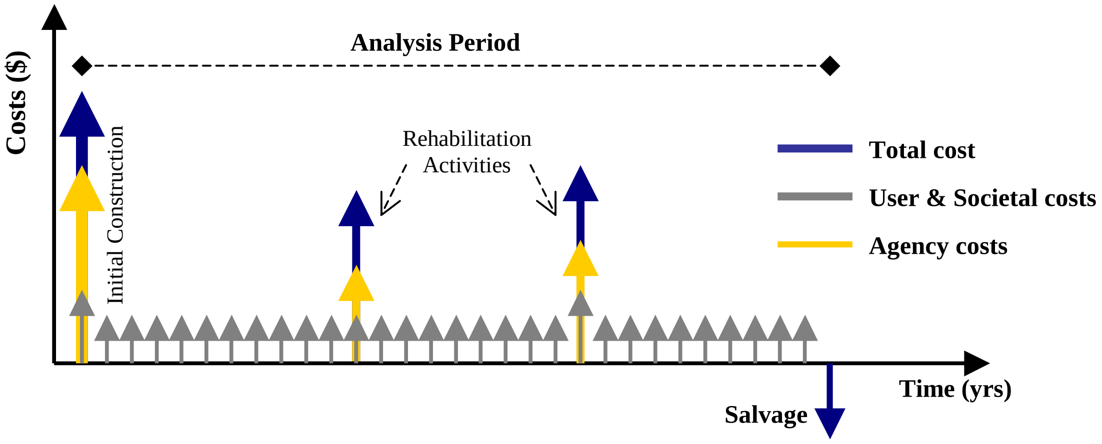


Figure 2: Conceptual Cash Flow Diagram of a Project

5) Compute Net Present Value for each alternative

After constructing the expenditure stream, computing the Net Present Value of each alternative becomes a straightforward calculation using Equations 5 or 6 and 7. It is advisable to compute the agency, user, and societal costs separately before computing the total value of a project, in order to better understand the exact contribution of each cost category to the total final worth.

6) Compare and interpret results/Sensitivity Analysis

Once NPV for each alternative is computed, with agency, user, and societal costs presented distinctively, interpretation of these results can be made. Generally, an alternative is preferred if its NPV is a minimum of 10 percent less than the NPV of other competing alternatives. If the difference between the NPV of alternatives is less than 10 percent, then such alternatives are considered similar or equivalent. A detailed discussion of the interpretation of results and the treatment of uncertainty is given in the next chapter, which presents the recommended probabilistic approach. On the other hand, if the deterministic approach is adopted in the analysis, sensitivity analysis should be conducted as a minimum. The sensitivity analysis should examine the effect of variability in the main input parameters for the analysis of the overall results. This is done by performing the analysis over a range of possible values of a particular parameter under testing while holding all other parameters constant. This analysis can give the decision-maker a better representation of the comparison, and it can rule out bias toward certain alternatives to some extent.

The most significant parameters that should be tested for sensitivity in the analysis are:

- The discount rate
- Timing of future rehabilitation activities
- Traffic growth rate
- Unit costs of the major construction components.
- Analysis period

7) Re-evaluate design strategies if needed

Presenting results and analyzing them help the process of re-assessing the design strategies, whether in regards to scope, timing, or other factors. Sometimes minor alterations of the design strategies can lead to a better choice for the project. Figure 3 illustrates the LCCA structured approach.

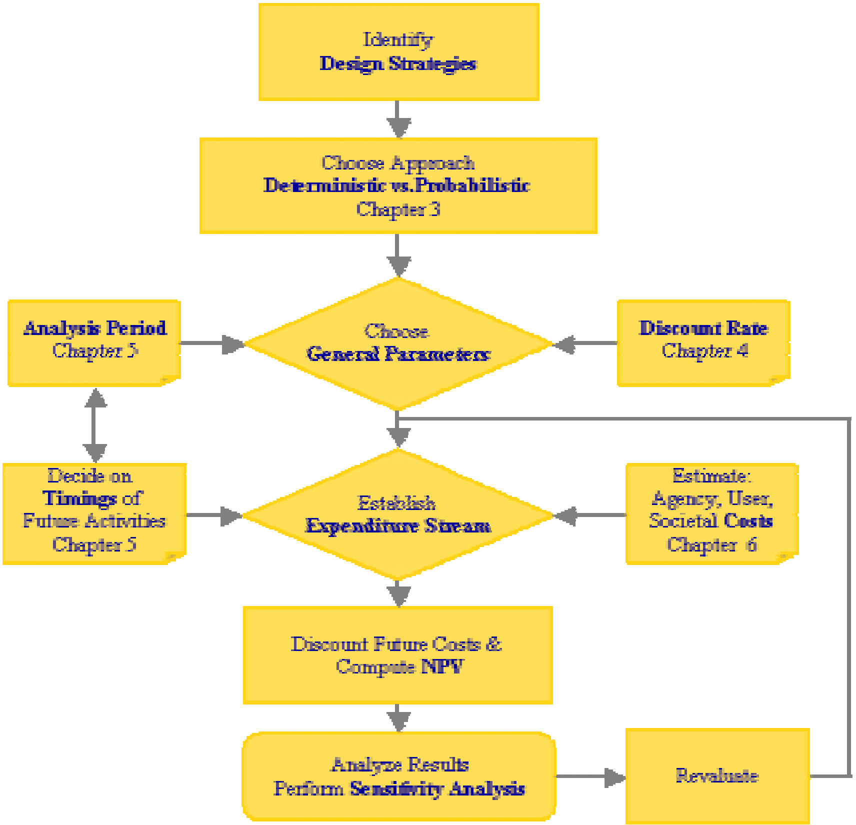


Figure 3: LCCA Process Flowchart

LCCA State-of-the-Practice versus State-of-the-Art

Establishing the “Guidelines of Life Cycle Cost Analysis” in a comprehensive and thorough manner dictated that the research follow three parallel approaches, each dealing with one facet of LCCA:

- Investigating the state-of-the-practice of LCCA.
- Reviewing the legislative requirement and federal guidance in this matter.
- Examining the state-of-the-art of LCCA.

The state-of-the-practice of LCCA was investigated by:

- A web search covering State DOTs’ web sites and other related sites
- Two-stage direct survey over two years completed by State highway agencies officials and experts.
- Direct contact when possible with highway technical practitioners and experts.

The detailed survey and its tabulated results are presented in Appendix 2 of this document. As for the legislative requirements and federal technical guidance, it was determined mainly through a literature review of related congressional acts, executive orders, and FHWA published documents and reports. The state-of-the-art was examined for the most part through a literature review of technical journals and manuscripts.

The most noteworthy finding of this research was the wide gap that exists between the state-of-the-practice and state-of-the-art, the latter referring to the advanced approach as proposed and developed in academia. Figure 4 is a diagram comparing the two states at each step of the LCCA process. This gap is quite evident from the response to the first question in the survey, which indicated that more than 30 percent of the responding State DOTs do not use LCCA in any mode. This actuality means that more than 10 billion dollars of highways capital and maintenance investments in the US are spent annually without evaluating the investments over their lifetime. The existing gap can be explained, if not fully but partially, by the mistrust and criticism of the validity of the LCCA outcome. The basis for this mistrust has conceptual and practical foundations. This research, however, does not focus on the ongoing debate about the conceptual foundation of the LCCA practice or the economic evaluation techniques, but rather on the research. The resulting guidelines focus essentially on the practical side of LCCA, in an effort to bridge the extant gap as much as possible.

The guidelines present an in-depth qualitative discussion of the LCCA and its various components. The weaknesses and strengths of each component of LCCA and their influence on the outcome will be illustrated using numerical examples. This discussion aims at providing the analyst with a complete insight into the LCCA process. Most of the available literature or guidelines about LCCA serve as an “instruction manual” without fully discussing the theoretical basis behind the steps followed. Our guidelines, alternatively, will be a short manuscript that will allow the reader to acquire a full grasp of the theoretical and practical basis of the process that is much needed to make reasonable judgment about the proper course of action to follow in project evaluation.

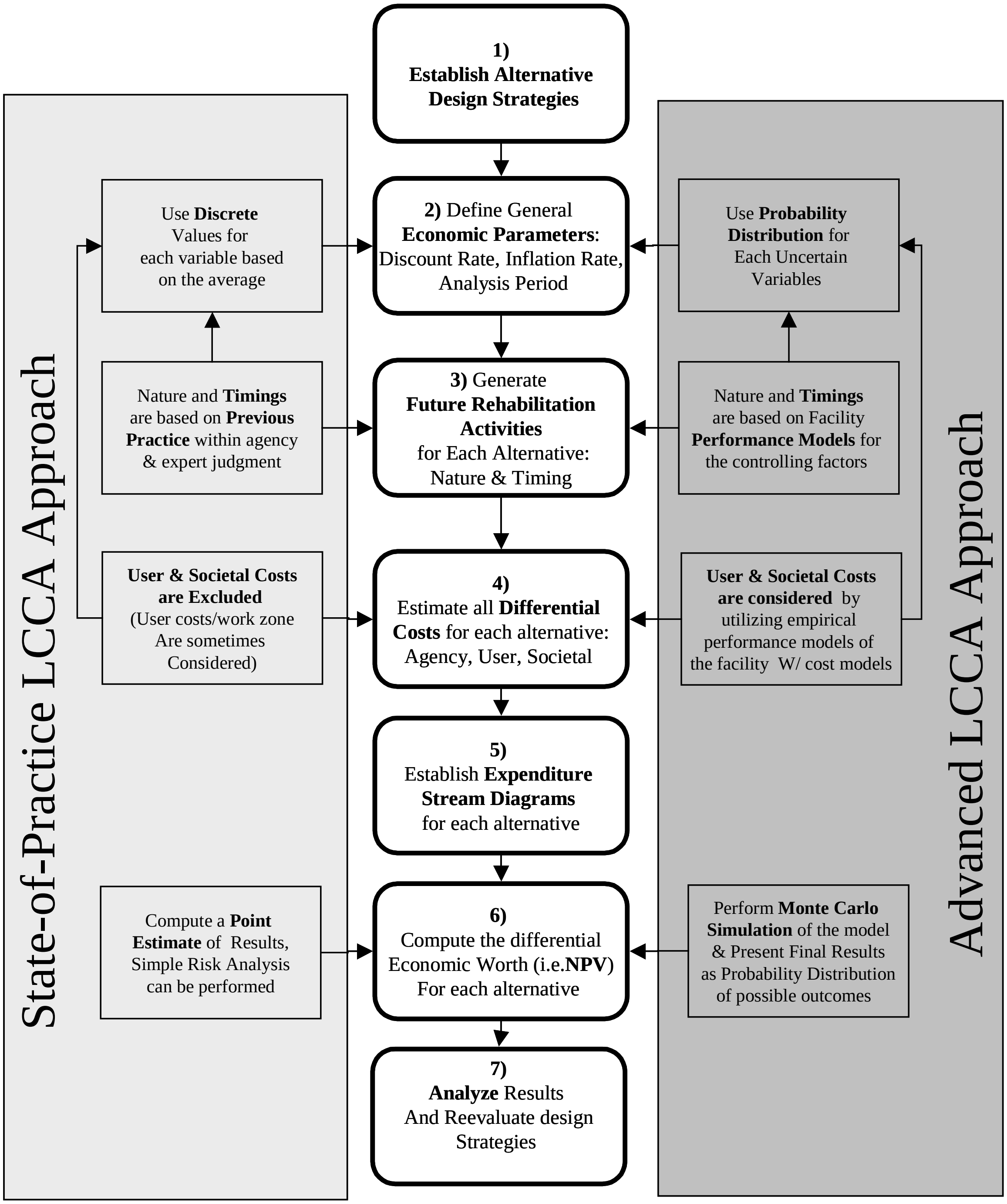


Figure 4: LCCA State-of-the-Practice versus State-of-the-Art

Life Cycle Cost Analysis (LCCA) Case Study

Two alternatives with different designs and life cycle strategies are proposed for implementing a transportation project.

Alternative A

The first design strategy has an initial construction cost of $20,000,000 with a performance life of 10 years according to the current traffic volume. During the lifetime of the project, rehabilitation activities can be performed so that they can raise the level of service to its initial value. Each activity costs $5,000,000 in real dollars.

Alternative B

The second design strategy has an initial construction cost of $25,000,000 with a performance life of 15 years according to the current traffic volume. During the lifetime of the project, rehabilitation activities can be performed so that they can raise the level of service to its original value, and each activity costs $6,500,000 in real dollars. The annual traffic growth rate is predicted at 2 percent for all types of traffic.

The Analysis

The evaluation of the two alternatives is performed using Life Cycle Cost Analysis with the net present value as the final indicator.
Only the differential costs that are anticipated are included in the analysis. User costs during normal operation and annual maintenance costs are assumed to be equal for both alternatives and accordingly are excluded from the analysis.

Defining general parameters

The real discount rate is assumed to be 4 percent throughout the project life, and the analysis period is chosen as 35 years.

Generating Future Activities

Based on historic practice and the anticipated performance life of the initial construction, the life cycle strategies are assumed to be scheduled as follows:

Year	Activities- Alternative A	Activities - Alternative B
0	Initial Construction	Initial Construction
10	Rehabilitation A/1	-
15	-	Rehabilitation B/1
20	Rehabilitation A/2	-
30	Rehabilitation A/3	Rehabilitation B/2
35	End of Analysis	End of Analysis

Note that rehabilitation activities are assumed to raise the level of serviceability to its initial level and have the same performance as the initial construction.

Calculating the Net Present Value for each alternative:

Calculating the NPV for each alternative, by accounting only for agency costs:

Year	**Alternative A Activities**	Agency Costs	Discount Factor	Dis. Agency Costs
0	Initial Construction	20,000,000	1.000	20,000,000
10	Rehabilitation 1	5,000,000	0.676	3,377,821
20	Rehabilitation 2	5,000,000	0.456	2,281,935
30	Rehabilitation 3	5,000,000	0.308	1,541,593
31	Rehabilitation 4	0	0.296	0
35	Salvage Value	-2,500,000	0.253	-633,539
	Total		**NPV Alt. A**	**26,567,810**
				NPV Alt. A

Year	**Alternative B Activities**	Agency Costs	Discount Factor	Dis. Agency Costs
0	Initial Reconstruction	25,000,000	1.000	25,000,000
15	Rehabilitation 1	6,000,000	0.555	3,331,587
30	Rehabilitation 2	6,000,000	0.308	1,849,912
35	Salvage Value	-2,000,000	0.253	-506,831
	Total		**NPV Alt. B**	**29,674,668**

The NPV value of alternative A is less than alternative B by 11.69 percent. This renders the former the favorable alternative for implementing the project.

By including the user costs during work-zone operation:

Year	**Alt. A Activities**	Agency Costs	User Costs	Discount Factor	Dis. Agency Costs	Dis. User Costs
0	Initial Construction	20,000,000	0	1.000	20,000,000	0
10	Rehabilitation 1	5,000,000	4,000,000	0.676	3,377,821	2,702,257
20	Rehabilitation 2	5,000,000	4,875,978	0.456	2,281,935	2,225,333
30	Rehabilitation 3	5,000,000	5,943,790	0.308	1,541,593	1,832,581
35	Salvage Value	-2,500,000	0	0.253	-633,539	0
	Total				26,567,810	6,760,171
					NPV Alt. A	**33,327,981**

Year	**Alt. B Activities**	Agency Costs	User Costs	Discount Factor	Dis. Agency Costs	Dis. User Costs
0	Initial Reconstruction	25,000,000	0	1.000	25,000,000	0
15	Rehabilitation 1	6,000,000	5,000,000	0.555	3,331,587	2,776,323
30	Rehabilitation 2	6,000,000	6,729,342	0.308	1,849,912	2,074,782
35	Salvage Value	-2,000,000	0	0.253	-506,831	0
	Total				29,674,668	4,815,104
					NPV Alt. B	**34,525,772**

The NPV of alternative A is less than alternative B by 3.4 percent, which makes the selection less definite.

CHAPTER 3: UNCERTAINTIES AND RELIABILITIES

Uncertainty characterizes many of the input parameters in any appraisal process. This characterization is manifested in transportation projects more so when the lifetime of the project stretches over long periods of time. No one can be completely sure what interest rate should be applied twenty years from now or how much traffic volume will be on a particular road in ten years. Engineers and economists have been working hard to estimate the uncertain parameters by deriving empirical models based on scientific research that observe and measure these uncertain variables and the factors influencing them. An example of such undertaking was the research of the effects of pavement roughness on user costs, which started in the 1960s by the World Bank (5). Nevertheless, no matter how good these models are, the reliability of their outcome can never reach the 100 percent level that is anticipated in the deterministic Life Cycle Cost Analysis models.

Regardless of the awareness of the uncertainties, many analysts appraising public projects in the past (and some still do) have used definite values for the uncertain parameters either by making assumptions about their values using expert opinions, or by using the deterministic results obtained from the prediction models, a process identified as the deterministic approach. According to our recent survey, 80 percent of the DOT respondents indicated that they are employing LCCA deterministically.

In best-case scenarios of evaluation processes, highly uncertain and sensitive variables such as the discount rates were treated with simple risk analysis approach. It consisted mainly of performing the analysis a number of times over a range of possible values for that specific variable and merely comparing and reporting the results.

Table 2: Costs in LCCA for Transportation Projects

Cost Category	Cost Component	Parameters	Source	Variable Type
Agency Cost	Initial Cost	Geometry	Design	Deterministic
		Unit Cost	Documented Bid Records	Deterministic or Probabilistic
	Rehabilitation	Geometry	Design	Deterministic
		Unit Cost	Documented Bid Records	
		Timing	Historical practice Pavement Performance Budget	Deterministic or Probabilistic
	Annual Maintenance	Geometry	Design	Deterministic
		Unit Cost	Current documented prices	Deterministic or Probabilistic
	Overlays, Reconstruction	Geometry	Design	Deterministic
		Unit Cost	Averaged Bid Records	Deterministic or Probabilistic
		Timing	Pavement Performance Models Historical Practice Budget	Deterministic or Probabilistic
	Engineering and Administration	Percentage of Investment		Deterministic or Probabilistic
	Salvage	Analysis Period	Pavement Performance Models	Deterministic or Probabilistic
User Cost	Vehicle Operating Cost	Unit Cost	Published Values	Deterministic or Probabilistic
		Traffic Volume and Distribution	Projected	Deterministic or Probabilistic
		Capacity	Design	Deterministic
		Pavement Condition	Pavement Performance Models	Deterministic or Probabilistic
	Travel Delay Time	Unit Cost	Published values	Deterministic or Probabilistic
		Traffic Volume and Distribution	Projected	Deterministic or Probabilistic
		Capacity	Design	Deterministic
	Discomfort, Reliability			
Social Costs	Accidents*	Traffic	Recorded Rates	Deterministic or Probabilistic
		Pavement Condition	Pavement Performance Models	Deterministic or Probabilistic
		Unit Cost	Published Values	Deterministic or Probabilistic
	Noise	Traffic	Projected	Deterministic or Probabilistic
	Air Pollution	Traffic	Projected	Deterministic or Probabilistic
	Others			
* Some LCCA literature consider accident costs part of user costs				

Table 2 lists the type of costs that might be incurred as a result of highway investments in general. The table also indicates their nature, whether certain or uncertain, or as expressed in the table, respectively, deterministic or probabilistic. From this table, it is apparent that only two or three of these costs are actually deterministic. As such, the mistrust in the analysis results LCCA models applied deterministically is justifiable. Deterministic approaches, or using discrete values for the parameters, result in point-estimates of the outcome, which can lead to a misleading decision support system.

Take, for example, a life cycle cost analysis model that is analyzing two alternatives for a maintenance project. The deterministic approach would yield a point estimate for the NPV of $900,000 for alternative A and $1,000,000 for alternative B, making alternative A the preferred choice without giving any indication about the inherent variability in the model parameters. On the other hand, the use of other possible values for the parameters (i.e. using a discount rate of 3 percent instead of 5 percent or varying the timing of the future rehabilitation activities by one or two years, which is a very possible practice within any DOT) might reverse the outcome, making alternative B the preferred choice.

Realizing this inherent flaw in the deterministic approach, the Federal Highway Administration has been promoting the use of reliability concepts in appraising transportation investments for the past five years (7). Reliability concepts are best applied by adopting the probabilistic approach.

The Probabilistic Approach

After the life cycle cost model is constructed, the probabilistic approach is employed by:

1) Identifying parameters that carry inherent variability in their values.
2) Constructing a probability distribution for the identified parameters that indicates all possible values of each parameter and their relative likelihood of occurrence. Probability distributions can be defined by various functions depending on the information and data available. The most common distributions are the uniform, triangular, normal, lognormal, and general.

3) After the probability distribution is defined/constructed for all uncertain variables, the final result of the model/problem can then be calculated in two ways, namely, the analytical approach and simulation (8).
   a) The analytical approach requires that the distribution of the uncertain variables in the model be described mathematically. Then the equations for these distributions are combined analytically according to the model to derive the resulting function, which describes the distribution of the possible outcomes. This approach is not practical and was developed when today’s computing power was not available. It is not a simple task to describe constructed distributions as equations, and it is more difficult to combine distributions analytically even the complexity in the models is moderate. Furthermore, the mathematical skills necessary to implement the analytical techniques are significant.
   b) Monte Carlo simulation randomly selects values for each parameter in the model, based on the probability of that value occurring for the specific parameter. It then obtains the system or model response and records this value. The sequence is performed many times. Each repetition will result in a value for the system response, and these responses will be used to construct the probability distribution of the final outcome. The number of iterations in Monte Carlo simulation depends on the required level of accuracy and the available computing power. The larger the number of iterations, the better the result, until the simulation starts to converge and any additional iteration does not affect the final distribution (Figure 5).

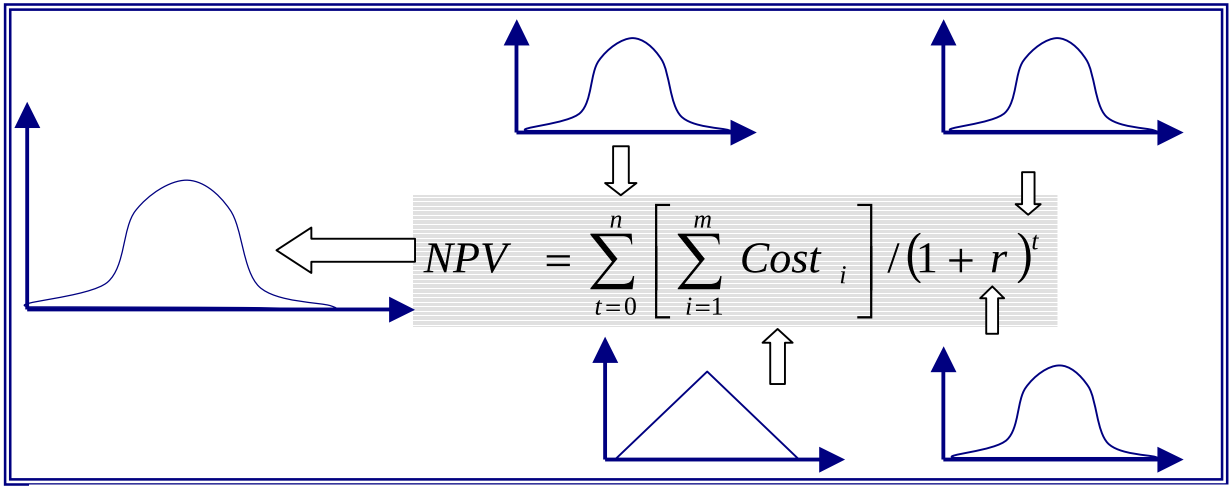


Figure 5: Calculating NPV using Monte Carlo Simulation

4) The final step of the probabilistic approach is the interpretation of the results. The final outcome of the simulation will be a probability distribution of the NPV or EUAC that gives the risk associated with each value. This outcome format provides an effective support tool for the decision making process. A wider distribution means a riskier alternative in comparison to a narrower distribution (Figure 6). Sometimes decision-makers prefer less risky projects even if the mean of the net present value is higher than the riskier alternatives. Comparing two alternatives can be done by constructing the distribution of the difference between alternatives. Another method is by plotting the cumulative probability distribution of both alternatives on the same graph where the comparison can be interpreted directly (Figure 7).

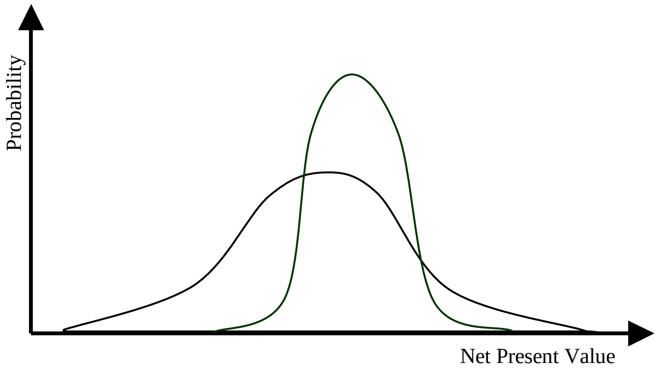


Figure 6: Conceptual Probability Distribution of LCCA output (NPV)

The probabilistic approach can also be extended to perform the sensitivity analysis. This type of analysis can help identify the significant parameters for reevaluating the design strategies when needed. This process is done by plotting a tornado graph that indicates the parameters and their correlation coefficient for each alternative. Parameters that have a large correlation coefficient, generally more than 0.5, are considered the most significant.

Recommendations

The key element in the probabilistic approach is defining the probability density function/distribution for every component. These distributions must be defined as accurately as possible based on the information available. Probability distributions of the input variables may be developed using either objective or subjective methods. The objective method uses real data (such as compiled records of the recent bid item prices, or published discount rates) to define the distribution; the subjective method uses expert opinion. The latter method is used in the absence of hard data. This method requires that the expert(s) choose a pre-defined probability distribution that can best fit the variability of the parameter according to his expertise and experience.

Wide distributions indicate high uncertainty in the parameter values (i.e. the range of possible values for the parameter is quite large in relation to its value), while narrower distribution indicates less uncertainty (Figure 6). In general, parameters that deal with activities occurring in the present or the near future are more certain than parameters for activities occurring in the distant future. For example, the values used for initial costs are relatively more certain than the costs of future rehabilitation and, therefore, the distribution shape for initial costs is expected to be narrower than the distribution shape of the costs of future rehabilitation.

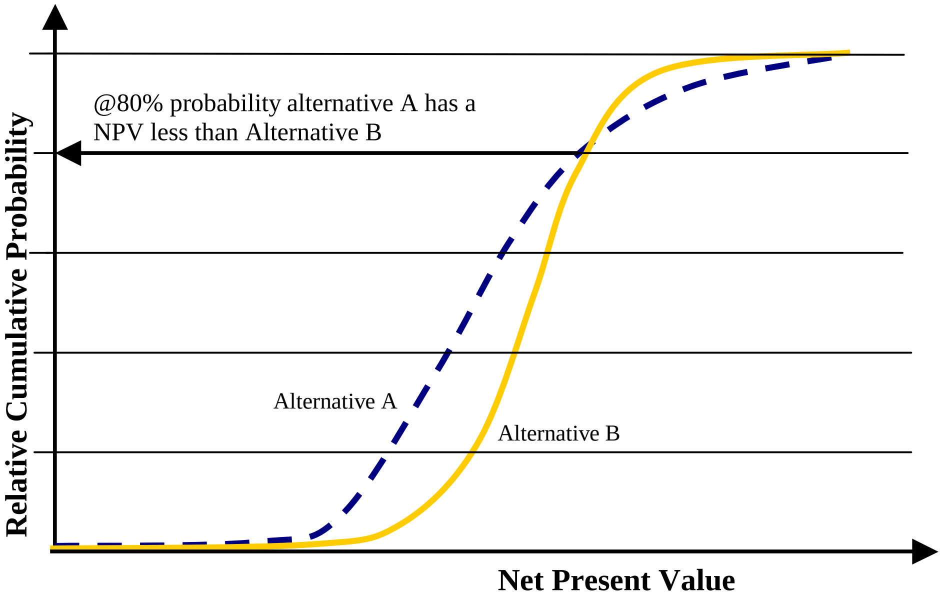


Figure 7: Cumulative Probability Distribution for Two Alternatives in LCCA

This is exhibited in the probabilistic approach when the uncertainty in initial costs is accounted for by the variability in bid item prices (minimum, average, and maximum), while the future costs take that variability and combine it with the uncertainty in the interest rate, the inflation rate, and the timing of the future rehabilitation activities.

Simulation is the preferred technique for accounting for uncertainties in LCCA. This process can be employed easily either by using one of the LCCA models that already incorporates this approach within their framework, such as the recent FHWA Probabilistic LCCA model, the Asphalt Pavement Alliance (APA) model, or by using specialized add-ins programs for simulation such as Crystal Ball or @Risk. These programs can be incorporated within spreadsheet programs like Microsoft Excel and thus provide the analyst with the ability to customize the LCCA model according to his/her specific requirements and needs.

CHAPTER 4: THE DISCOUNT RATE

Conceptual Outlook

One of the key features in the LCCA process is accounting for the future costs. The treatment of future costs is based on a well-established principle in economics according to which money has time value. That is to say, a dollar in the future is worth less than the value of the dollar today. Therefore, to be able to make decisions regarding investments with different long-term time-lines, all future costs and benefits must be converted to a common time dimension. This procedure is referred to as discounting. Discounting is performed by employing a discount rate that represents the percent change in the value of the dollar per period of time.

In the context of the LCCA, the discount rate can be defined as a value in percent used as a mean for comparing the alternative uses of funds and costs over a period of time by reducing the future amounts to present worth. In that manner the economics of the different alternatives can be compared on a common basis.

The following basic formula represents the relationship between the future cost and its present value:

$$P = F\left[\frac{1}{(1+r)^n}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where P is the present worth of a future cost, F is the future cost occurring after n time period from the present, n is the number of time periods at which F is incurred, and r is the discount rate in decimal.

The discount rate employed in the LCCA is one of the most sensitive parameters in the analysis. The value of this rate has a great effect on the final outcome. A lower discount rate would favor projects that have larger capital investments, and conversely higher discount rates would favor projects that have higher future costs whether the costs are agency, user, or societal costs. Figure 8 illustrates the sensitivity of this parameter by plotting the present value of the dollar throughout future periods using three different discount rates: 5 percent, 10 percent, and 15 percent. One dollar after 10 years from today is worth $0.61 today using a 5 percent discount rate, $0.38 using 10 percent, and $0.25 using 15 percent.

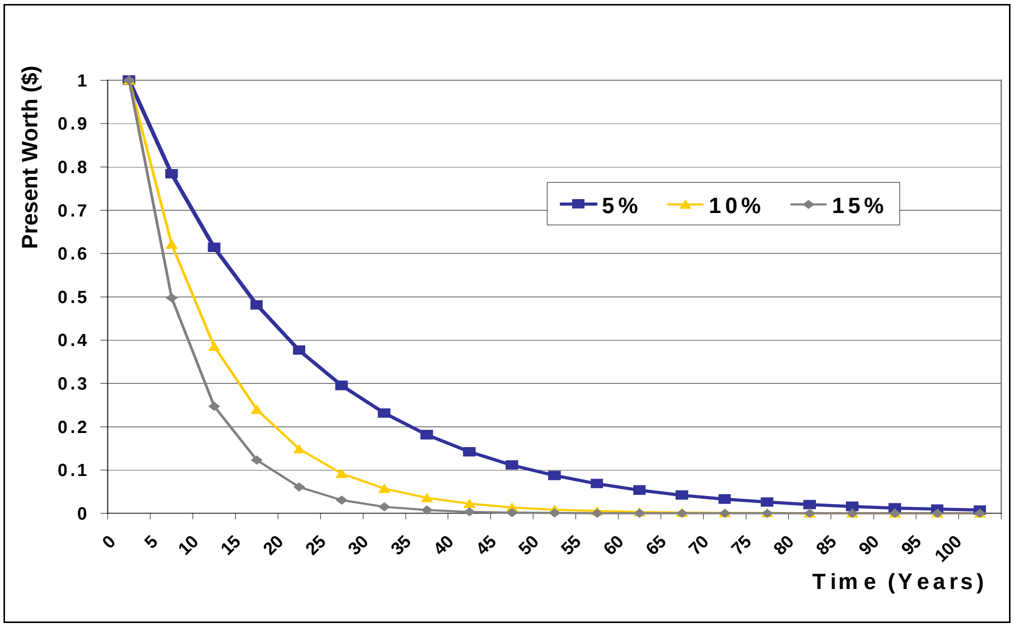


Figure 8: Effect of Discount Rate on the Present Value of a dollar

There are many factors that affect the time value of the money or the discount rate; the most significant of these are the earning capacity of the money and the inflation. Therefore, two indicators are commonly used to evaluate the change in money value:

1) The market interest rates, which represent the annual yield of the principal if invested in some form, such as bonds, treasury bills, or a bank savings account.
2) The inflation rate is the proportionate rate of change in the general price level as opposed to the proportionate increase in a specific price. Inflation is usually measured by a broad-based price index, such as the implicit deflator for Gross Domestic Product or the Consumer Price Index.

Estimates of future costs can be calculated using real (constant) or nominal (current) dollars. In this manner, *real dollars* reflect dollars with the same purchasing power over time, while *nominal dollars* reflect dollars that fluctuate in purchasing power as a function of time. In a similar manner, discount rates can be either real or nominal.

The Office of Management and Budget (OMB) circular A-94: "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs" presents a clear definition of the two types of discount rates, real (constant) and nominal (current), as follows (9):

- A *real discount rate* that has been adjusted to eliminate the effect of expected inflation should be used to discount constant-dollar or real benefits and costs. A real discount rate can be approximated by subtracting expected inflation from a nominal interest rate. A precise estimate can be obtained by dividing one plus the nominal interest rate by one plus the expected or actual inflation rate, and subtracting one from the resulting quotient.
- A *nominal discount rate* that reflects expected inflation should be used to discount nominal benefits and costs. Market interest rates are nominal interest rates in this sense.

The real discount rate can be estimated using the following mathematical formula: (The formula derivation is given in Appendix 3 of this document)

$$r^* = \frac{i - f}{1 + f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

where

f = Inflation rate
i = Nominal interest rate
r^*= Real discount rate

The real discount rate is generally approximated by subtracting the inflation rate from the nominal rate as indicated by the OMB definition above for simpler calculation.
It should be noted that in any economic analysis, nominal and real costs and discount rates must not be combined in the same analysis. Logical consistency requires that analysis be performed either in real or nominal values.

Discount Rate Philosophies

In practice, estimating the discount rate is not a straightforward matter. Most of the public projects are financed by more than one funding source. Furthermore, there is no consensus on how to value the real earning capacity of these public funds. The choice of the discount rate is one of the most debatable topics in public project evaluation. Several philosophies have been suggested over the years for choosing the appropriate discount rate. Important among them are:

- <u>Opportunity Cost of Capital</u>: Opportunity cost is the cost of the forgone investment that would have been taken if not invested by this project. The opportunity cost of capital rationale assumes that the money used for funding public projects is withdrawn from private savings, which would have gone otherwise into private investment. Accordingly, the discount rate should be the pretax rate of return that would have been experienced on the private uses of funds.
- <u>Societal rate of time preference</u>*:* This is the interest rate that reflects the government's judgment about the relative value which the society as a whole assigns, or which the government feels it ought to assign, to present versus future consumption. The societal time preference rate is not observed in the market and bears no relation to the rates of return in the private sector, interest rates, or any other measurable market phenomena.
- <u>Zero Interest Rate</u>: Advocates of a zero interest rate argue that when tax monies (e.g., highway user taxes) are used, such funds are "free money", because no principal or interest payments are required. The counter argument is that zero or very low interest rates can produce positive benefit/cost ratios even for very marginal projects and thereby take money away from more truly deserving projects. A zero interest rate also fails to discount future expenditures, making tomorrow's relatively uncertain expected costs just as important to the decision as today's known costs.
- <u>Cost of Borrowing Funds:</u> The interest rate should match the rate paid by government for borrowed money. This approach is favored by many agencies and is supported by the argument that government bonds are in direct competition with other investment opportunities available in the private sector.

State-of-the-Practice

With various rationales for choosing the discount rate, there is no right answer for what value or rationale to choose. Different agencies throughout the world are using different discount rates. The World Bank uses 15 percent in developing countries with a minimum of 12 percent depending on the local conditions. The United Nations follows this practice and assigns a value of a minimum of 12 percent. Canada Transport Ministry is currently using a discount rate of 10 percent.

The US Federal Government had set a general guidance on the values to be used for the discount rate in the above mentioned OMB Circular 94-A 1992 titled: “Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs” (9). The circular recommends using discount rates that correspond to the rate of return that the government offers on treasury notes and bonds such that the maturity dates of these notes corresponds to the analysis period of the public project under evaluation.

Both types of the discount rates, nominal and real, are updated and published annually in this circular. In the last 25 years, the nominal interest rates varied between 4.1 and 13.3 percent while the real discount rates varied between 2.1 and 7.9 percent (Figure 9).

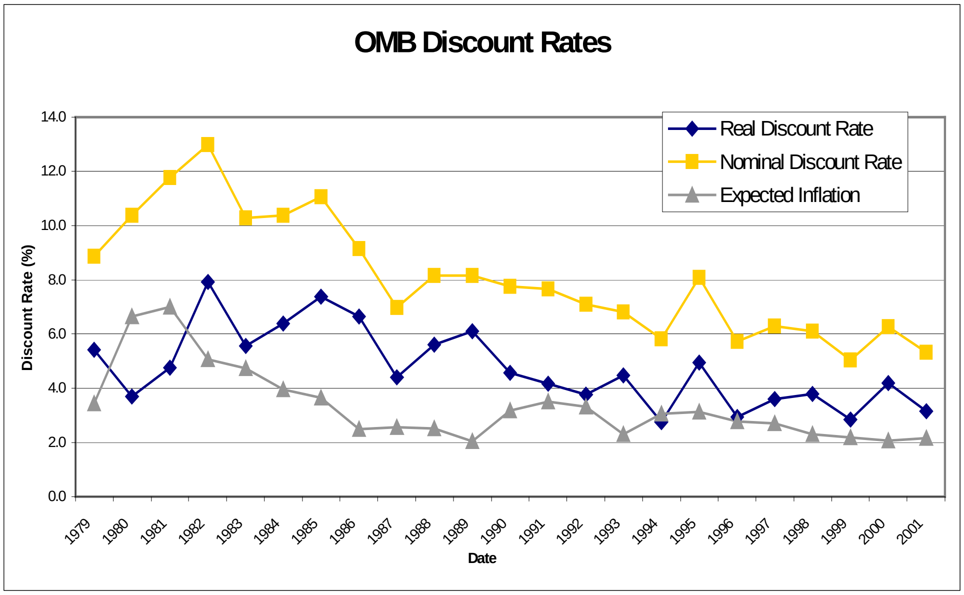


Figure 9: Historic Records of OMB Discount Rate

The Federal Highway Interim Technical Report on LCCA for pavement investment suggests that the choice of discount rate should reflect historical trends in the discount rate over long periods of time (10). It further suggests using of the rate of return on Inflation Protected Securities, which was first offered in 1997, as a good measure of the opportunity cost of the public at large.

The American Concrete Pavement Association's (ACPA) position on the choice of discount rate in LCCA within Departments of Transportation states that the nominal discount rate should be zero since the financing source for projects are the gas tax monies that are collected and spent annually and therefore they do not relinquish any investment opportunity. However, this position has its own critics as was explained earlier in the Discount Rate Philosophies.

The actual state-of-the-practice about the choice of discount rate within the transportation agencies followed the guidance provided by OMB 94-A. In 1985 the discount rate used in State DOTs ranged between 4 percent and 10 percent with an average of 6.2 percent, while the inflation rate was employed by only 19 percent of the agencies and ranged between 4.1 percent and 6 percent with an average of 5.3 percent (Figure 10) (3). The guideline provided by the FHWA LCCA technical bulletin published in1998 (10) is for a real discount rate of 4 percent with a possible range of 3 - 5 percent resulted in a better consensus of the choice of discount rate according to our 2001 survey results. The survey showed that the real discount rate employed ranged between 3 percent and 5 percent with an average of 4 percent. As for the inflation rate, it was only used by 18 percent of the agencies with a range between 2 percent and 3 percent.

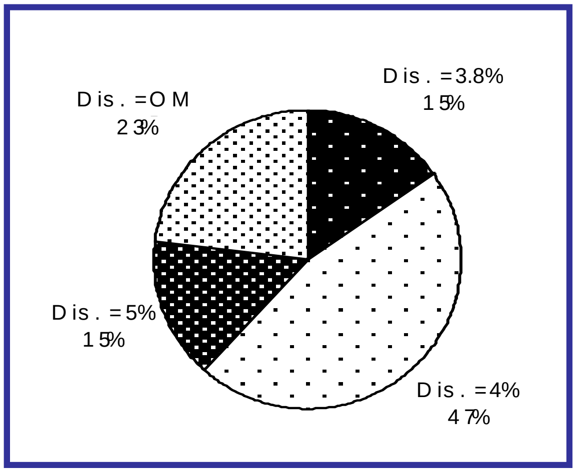


Figure 10: Pie Chart Representing the Values of Discount Rates as used by State DOTs

Recommendations for the Real Discount Rate

The recommendations presented on this section are based on the above conceptual and philosophical aspects and on the practical considerations for the project analyst.

- The choice of discount rate depends on the source of financing. If a local government is undertaking the project, then the municipal bond rate appears to be an appropriate choice for the discount rate. When financing is done by private investors, the corporate bond rate can be considered a good indicator. When the project is financed by federal funds, taking on the rate of returns on government treasury notes with 30-years maturity for analyzing new pavement construction and 10-years maturity for analyzing pavement rehabilitation projects can be selected. As for projects financed by state highway agencies, the discount rate can be chosen in the same manner as federal projects.
- Historical trends of the discount rate can be reflected in the discount rate by constructing a probability distribution of the rates for the past years that corresponds to the specified analysis period when these rates are available, and using these distributions in a probabilistic LCCA process.

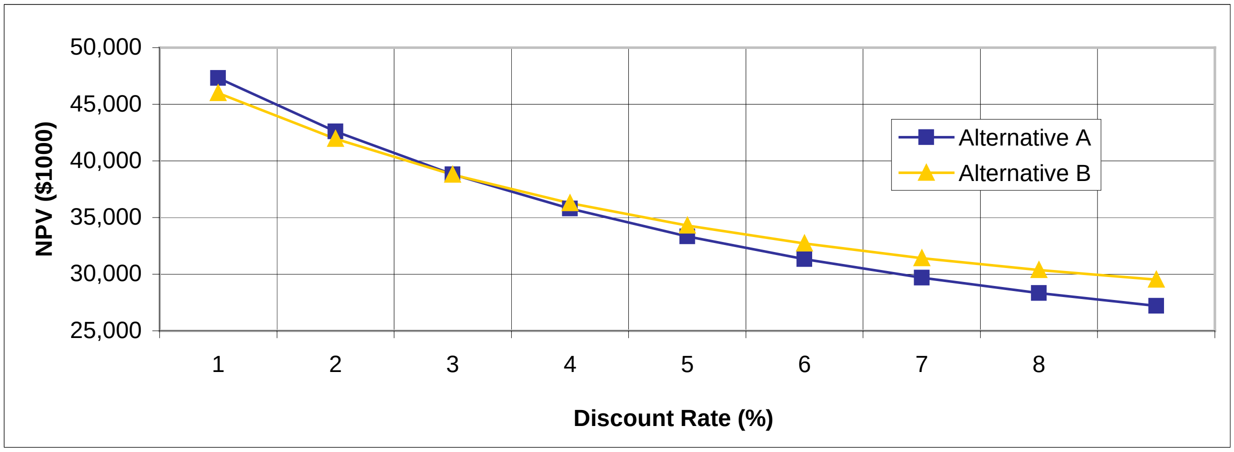
- A single rationale for choosing the discount rate should be followed when evaluating projects within the agency. A policy statement discussing the agency position on this matter can be issued and revised annually.
- The past and current discount rates (i.e. the rate of return on treasury notes) represent the rationale adopted by the agency and can be obtained from the website http://www.whitehouse.gov/omb/circulars/a094/a094.html#8

Inflation

Besides the above discussion of the effects of inflation on the discount rate in LCCA, inflation can be utilized for another purpose in LCCA. It is not uncommon to find that the available documented prices of construction, material, labor, or any LCCA-related components are dated. When this is the case, these unit prices must be converted to today's value by "inflating" them. This can be done by multiplying the "dated" price by the relative increase in the price index between the date of the price and the present. Price indexes can be a broad-based price index, such as the implicit deflator for Gross Domestic Product or the Consumer Price Index when the "dated" prices concern general items such as the value of time. Alternatively, a specific price index such as the Highway Construction price index can be considered a better indicator for prices related to construction activities.

LCCA Case Study (Continued)

In the LCCA case study presented in Chapter 1, altering the discount rate between 0 percent and 8 percent can reverse the analysis results. If the deterministic approach is adopted, a sensitivity analysis for the uncertain discount rate must be performed, as a minimum, to examine the sensitivity of the results. The sensitivity analysis result for the LCCA case study is illustrated in the chart.
By examining the chart, the analyst can deduce that the NPVs of the two alternatives are very close, and the probabilistic approach can better predict the probabilities associated with each alternative.



CHAPTER 5: TIME FACTOR

The focal point of LCCA is establishing the proper time frame of the analysis. The time frame consists of two components in LCCA: 1) the analysis period; and 2) the timing to the future 4-R (reconstruction, rehabilitation, resurfacing, and restoration) activities. This chapter will discuss both of these components in detail.

The Analysis Period

The analysis period is the period chosen over which the facility performance will be analyzed in Life Cycle Cost Analysis. Conceptually, this period should represent the useful life of the associated facilities/assets affected by the decision, or in other words, the period over which the project will be in operation.

Many of the public projects are expected to be in operation for as long as it is needed or for an indefinite period. When planning an interstate highway, we do not plan the project to be operational for some specific period after which the highway will be demolished and its right-of-way will be transferred to other uses. In such cases, the analysis period chosen when conducting LCCA has to be estimated by the service life of the most durable component of the facility, which is typically the component that carries the higher portion of the initial cost.

This period should be sufficiently long enough to reflect long-term differences between different design and rehabilitation strategies, and it may contain several maintenance and rehabilitation activities, as conceptualized in Figure 11.

When options involving facilities with different economic lives are being compared based on their life cycle cost, it is recommended that the analysis period is set the same for all options, and this period should be equal to the useful life of the most durable option. For assets having useful life remaining at the end of this timeframe, a residual value/salvage value should be estimated.

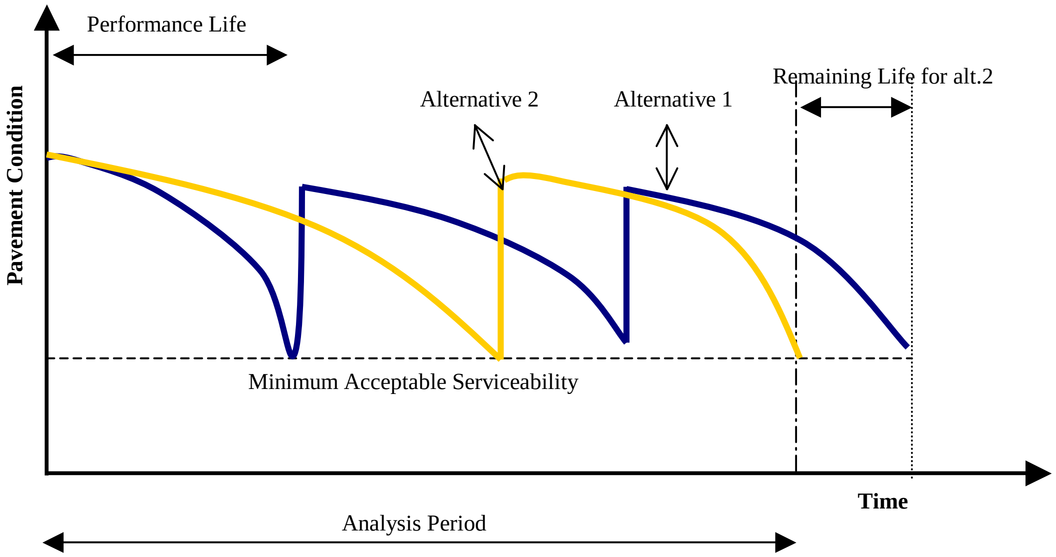


Figure 11: Conceptual Graph Representing the Serviceability of a Facility over Time

One approach, favored by some economists, for deciding on the analysis period in long-term public projects is to use a “floating” time period. 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 selected threshold). The discount rate used is then the prime factor in determining the extent of the floating time period.

Federal Guidance and State-of-the-Practice

Different types of projects necessitate different analysis periods. In the transportation sector, projects are classified under three main categories: pavement projects, bridge projects and the recently introduced ITS projects. Each category is analyzed for different analysis periods.

The FHWA Interim Policy Statement on LCCA 1994 recommends that the analysis periods should not be less than 75 years for major bridge, tunnel, or hydraulic system investment and not less than 35 year for a pavement investment. It further encourages the use of longer analysis periods for the NHS or other major routes or corridors.

The FHWA LCCA Interim Technical Bulletin published in 1998 (10), states that it might be appropriate to deviate from the recommended minimum 35-years analysis period for pavement projects when slightly shorter periods could simplify salvage value computations. It further recommends a shorter analysis period (i.e. ten years) when analyzing pavement rehabilitation/reconstruction projects. The recommended analysis period for new pavements is between 25 and 40 years and between 5 and 15 for rehabilitation alternatives. However, factors such as geometry and traffic capacity may have a bearing on the analysis period.

There may be some LCCA studies in which circumstances would call for a timeframe in excess of 30 or 40 years, as when longer-lasting pavements are deemed necessary for minimizing the future 4-R delays on very heavily traveled highways. This need introduced the use of warranties and design-build contracts by agencies in the last decade as an attempt to increase service life and reduce closures on newly designed roadways. Several nations—including the United Kingdom, France, Germany, and Netherlands—have formed the *European long-life pavement group* to develop optimal strategies for designing and maintaining long-life pavements. As discussed in the July-August 2001 editions of TR News, the concept of long-life asphalt pavements, so called *perpetual pavements,* is extensively being researched to last 50 years or more by providing a good-quality base with sufficient thickness to avoid fatigue cracking that leads to failure of the pavements.

It should be noted that the use of longer analysis periods, when analyzing bridges or perpetual pavements, had been under much scrutiny mainly because of the high level of uncertainty surrounding the different parameters in the far distant future.

In practice and based on the survey conducted by the authors of this report, 57 percent of the transportation agencies established a preset value for the analysis period when evaluating new pavement projects. These values ranged between 30 years and 50 years as shown in Figure 12. Forty-three percent of the State DOTs determine the analysis period on a project-by-project basis.

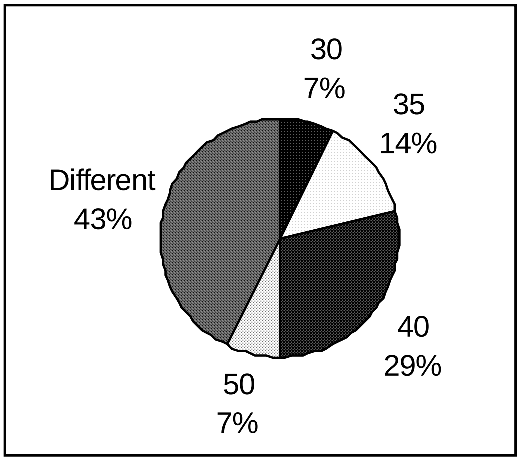


Figure 12: Analysis Period as used by State DOTs

Recommendations for the Selection of Analysis Period

- The analysis period should be identical for all alternatives under evaluation.
- When prediction and forecasting models are used in the analysis, the analysis period must be chosen in such a manner that the factors related can be forecasted with some reasonable degree of reliability.
- For new pavement projects, the recommended analysis period is between thirty-five and forty years, corresponding to the useful life of the most durable component in the project would require reconstruction.
- For new bridge projects, the analysis period is recommended to be at least seventy-five years providing that higher uncertainty levels are incorporated in the analysis.
- A small deviation from the recommended analysis periods is acceptable when such deviation simplifies the analysis (i.e., excluding the salvage value).

Rehabilitation Timings

The second component in the time factor is the timings of future activities. The treatment of this component is different from the analysis period. This parameter is one of the highly uncertain and sensitive parameters in the LCCA model. Future activities can be classified as follows:

1) Cyclic activities: This covers the activities that take place on a cyclical basis like annual maintenance and user costs/activities during normal operations. Generally the timing of these activities corresponds to the time cycles, which is taken as incremental number of years in LCCA.
2) The second is the future activities that do not recur on a cyclical basis. This covers all rehabilitation, restoration, and resurfacing activities (Figure 13). The main factor that should affect the timing of these activities is the pavement condition. Pavement performance models are being developed for the purpose of predicting the pavement deterioration levels. These models can be empirical, mechanistic-empirical or mechanistic. Nevertheless, in practice, there are other exogenous factors that affect the actual timings of these activities such as resources constraints within the agency. For those reasons, the timings of these activities are among the most important yet uncertain parameters in LCCA.

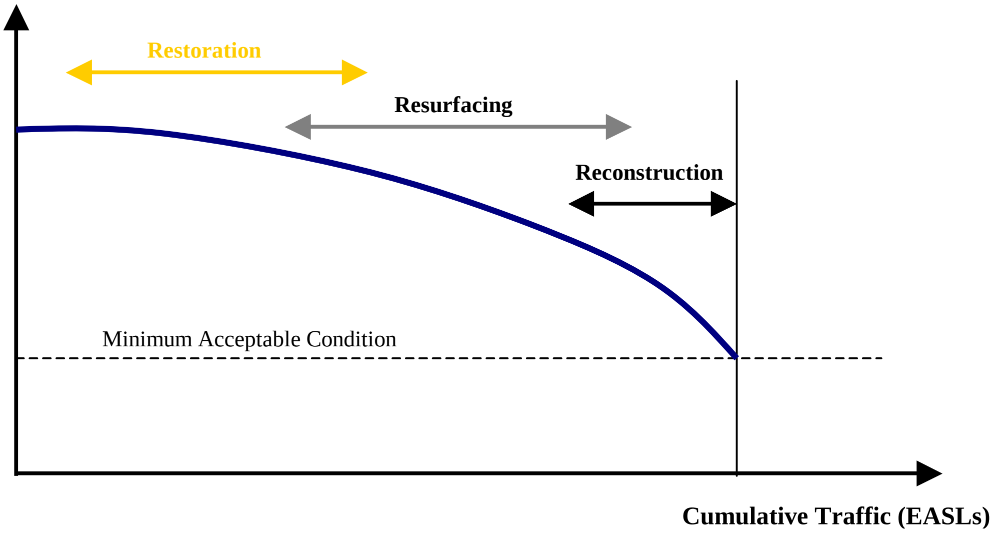


Figure 13: Timings of Future Rehabilitation Activities

In practice and theory, there are three ways to determine the timing of non-recurring future activities in LCCA.

- The most conventional method is to use engineering judgment and expert opinion when performing the initial design. This is usually done on a project-by-project basis where the designer would estimate the rehabilitation strategy for each alternative under evaluation (Figure 14).

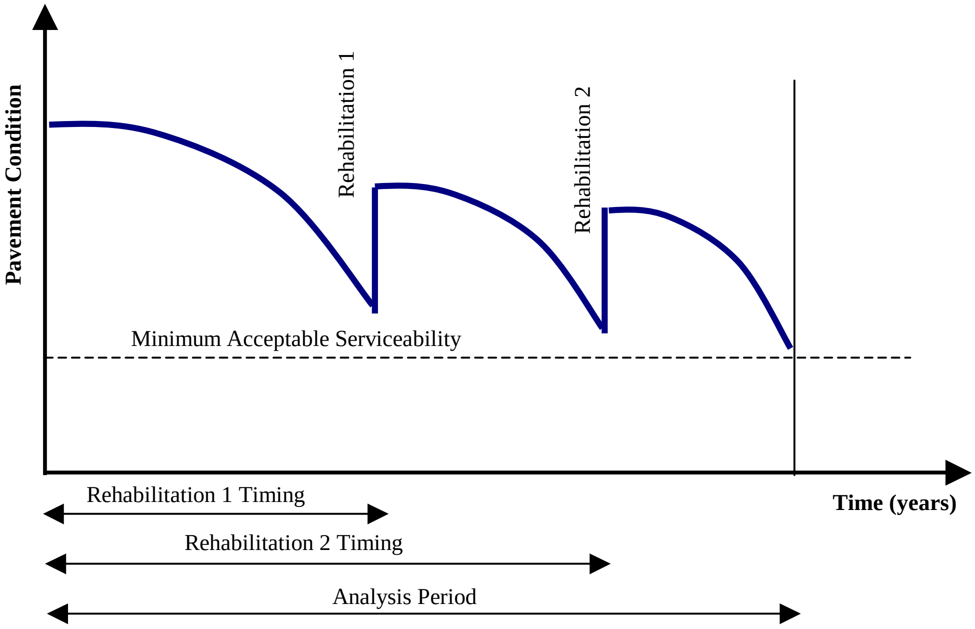


Figure 14: Analysis Period and Timings of Future Rehabilitation Activities

- Many transportation agencies have devised their standard rehabilitation strategies on the basis of past practice within the agency. Such strategies generally specify the type and timing of treatment that should be performed throughout the lifetime of the pavement. Some agencies have established their standard strategies using their experts opinions and experiences explicitly. Others developed these strategies based on statistical analysis of the information gathered in their pavement management system databases. These databases record the location, type, and timing of every activity. A probability distribution of the rehabilitation timing is then constructed for each type of pavement and for each type of rehabilitation activity that is generally performed (Figure 15). This method is useful for accounting for the variability of these timings. However, for this approach to be correct, the recorded lifecycle strategies should cover as many projects as possible and should depict the whole lifetime of these pavement projects accurately. In precise terms, these records have to not only indicate the timing of rehabilitation, but also the type and the order of the rehabilitation activity. Generally, some agencies might find this approach difficult to employ mostly because of imperfect databases in their pavement management systems.

- The third approach, which is recommended and researched extensively in academia, is to estimate rehabilitation timings based on empirical or empirical-mechanistic models that predict pavement deterioration. These models are generally a function of many factors that affect the condition of the pavement, such as traffic, loading spectra, traffic growth factor, environmental factors, pavement classification, original design characteristics, and pavement age. The future rehabilitation timings are determined by calculating the time/age at which the pavement condition will reach the minimum acceptable threshold, i.e.,

  $$Pavement\_Condition = f(V_i, T)$$

  Where V_i is a vector representing all factors affecting the pavement condition, and T is the time
- This approach appears to be realistic, systematic, and scientific. The drawback of this approach is the number of calibrated models that have to be developed for each type of pavement that exists within the jurisdiction of the highway agency. Classification of the pavement depends on pavement class (i.e. flexible, rigid), the base type, the surface type, and the type of rehabilitation it undergoes, if any. Furthermore, each region is characterized by certain environmental conditions according to which the model should be calibrated. One additional factor are the types of distresses that may occur to the pavement requiring certain correction or treatment. These distresses could include rutting, spalling, cracking, faulting, and other failures. The condition of the pavement could be measured by rough index (IRI), serviceability (PSI), or some weighted measure of the possible distresses.

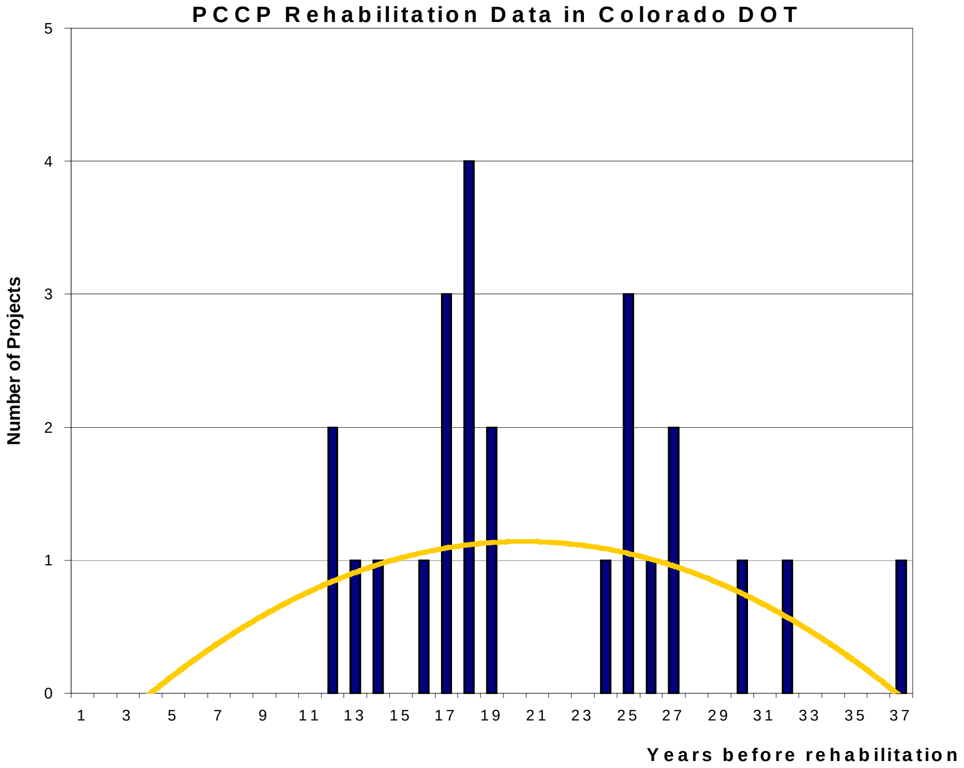


Figure 15: Probability Distribution representing possible values for timing of PCCP future rehabilitation (Source: Colorado DOT LCCA Report)

Recommendations

- When reliable data covering all types of pavement in the state is available within their pavement management system (PMS), the development of good empirical models for pavement conditions is advisable. One possible source for such data is the LTTP, even though it is yet to be completed. The threshold for the pavement condition should be set according to the actual practice in the agency.
- If data is not available, establishing rehabilitation strategies that are representative of the actual practice in the agency and judged by an expert opinion are recommended for setting up the time frame of future rehabilitation activities. Experts should verify that agency's practice is converted properly to the corresponding influencing factor, which is cumulative traffic. To clarify this point

further, if a pavement project lasts ten years till it reaches its serviceability threshold having carried a cumulative traffic of four million ESAL, its next rehabilitation should be scheduled at the year predicted for it to carry another four million ESAL, not necessarily after another ten years.

LCCA Case Study (Cont'd)

In the LCCA case study presented in Chapter 1, the rehabilitation timings were established based on the historic practice within the agency and by assuming that each rehabilitation would raise the level of the serviceability to its initial value and that the facility would have a similar performance life to that at its initial construction. This assumption probably flawed. Even if each rehabilitation activity causes the facility to perform in a similar manner as its initial construction, the performance life will be shorter because of the traffic growth. One approach to better predict the performance life after each activity is to calculate the time corresponding to the same volume of traffic that the pavement is expected to carry. The following table constructs the life cycle activities for both alternatives; the performance life of each activity is calculated based on the initial performance life and on the traffic volume it is predicted to carry in future years.

Year	**Activities-Alternative A**	**Performance Life**	**Activities -Alternative B**	**Performance Life**
0	Initial Construction	10	Initial Construction	15
10	Rehabilitation A/1	8	-	-
15	-	-	Rehabilitation B/1	11
18	Rehabilitation A/2	7	-	-
25	Rehabilitation A/3	6	-	-
26	-	-	Rehabilitation B/2	9
31	Rehabilitation A/4	5	-	-
35	End of Analysis	-	End of Analysis	-

Based on the above life cycle strategies, the NPV for each activity is estimated next:

Year	**Alternative A Activities**	Agency Costs	User Costs	Discount Factor	Dis. Agency Costs	Dis. User Costs
0	Initial Construction	20,000,000	0	1.000	20,000,000	0
10	Rehabilitation 1	5,000,000	4,000,000	0.676	3,377,821	2,702,257
18	Rehabilitation 2	5,000,000	4,686,638	0.494	2,468,141	2,313,456
25	Rehabilitation 3	5,000,000	5,383,473	0.375	1,875,584	2,019,431
31	Rehabilitation 4	5,000,000	6,062,665	0.296	1,482,301	1,797,339
35	Salvage Value	-1,000,000	0	0.253	-253,415	0
	Total				28,950,431	8,832,483
					NPV Alt. A	**37,782,915**
Year	**Alternative B Activities**	Agency Costs	User Costs	Discount Factor	Dis. Agency Costs	Dis. User Costs
0	Initial Reconstruction	25,000,000	0	1.000	25,000,000	0
15	Rehabilitation 1	6,000,000	5,000,000	0.555	3,331,587	2,776,323
26	Rehabilitation 2	6,000,000	6,216,872	0.361	2,164,135	2,242,359
35	Salvage Value	0	0	0.253	0	0
	Total				30,495,722	5,018,681
					NPV Alt. B	**35,514,404**

Based on the analysis, the NPV of alternative A is higher by 6.4 percent than alternative B.

CHAPTER 6: COSTS

The basic theory behind using an economic evaluation technique such as LCCA is that all the impacts of a project can be accounted for and converted to their monetary value so that any comparison between projects or project alternatives can be made directly. The negative impacts are considered costs and the positive impacts are considered benefits, which might be calculated as the reduction of negative impacts.

As discussed in the second chapter, the Net Present Value (NPV) and the Equivalent Annual Uniform Cost (EAUC) are the most appropriate economic indicators for evaluating alternatives of transportation projects that yield the same benefits and have similar costs. The costs that are included in LCCA can be tangible and intangible, can be current or future, and can be borne by the agency, by the user of the facility, or by the society as a whole. The first and the second differentiation are central to the LCCA analysis, because each type of these costs requires a particular course of action in its treatment. The third differentiation should not have any bearing on the outcome of LCCA in theory, but since the analytical framework of LCCA is as important to the decision-support process as the final result, it ends up being extremely pertinent. In fact, it is the most mentioned differentiation in LCCA literature.

Tangible and intangible costs: The tangible costs are the “real” out-of-pocket costs, sometimes considered as the project’s expenditures. On the other hand, the intangible costs are the costs encountered as a result of implementing the project but are incurred indirectly and are out-of-pocket. The cost of time delay is one example of such costs in transportation projects. Tangible and intangible costs are estimated through different approaches. Tangible costs can be estimated based on their available market values whereas intangible costs require monetary valuation techniques of their measurable criteria (i.e. cost of time, cost of noise, etc.).

Current and future costs: The current costs are the costs that are expected to be incurred at the present time, prior to project implementation, while future costs are the costs that are expected to incur during the whole analysis period. Discounting, an economic tool, is used to convert costs with different time frames to a common one so that a correct comparison between alternatives can be made. This process is discussed in detail in Chapter 3.

Agency, user, and social costs: This classification is based on the bearing entity of the costs. Even though the theory behind LCCA does not implicate any differential treatment for these types of costs, LCCA practices have calculated them separately, since the provision that the decision-makers may weigh them differently. For example, agency costs generally have larger weight than user costs. Figure 16 presents a diagram for costs under this classification, and Table 2 in Chapter 3 lists these costs, their influencing factors, and their statistical characteristic.

Agency costs

Agency Costs are the costs that are assumed by the agency as a result of putting the facility in service at the outset and maintaining its function at an acceptable level.

Agency costs consist of the costs of initial construction, rehabilitation and upgrading, periodic maintenance, engineering, and agency overhead. Initial construction, maintenance, and rehabilitation costs cover the costs of material, labor, machinery, traffic control, and any other contingencies. These costs can be estimated from recent bids and historic records, provided that inflation is taken into account. Most highway agencies keep detailed records of such data, and generally, acquiring these costs is a straightforward matter. Engineering judgment can assist in estimating such costs when new materials or technology is used in the project.

The salvage value is another cost component that is considered every so often as part of the agency costs. The salvage value is the value of the project at the end of the analysis period. The discounted salvage value is deducted from the total costs when calculating the net present value.

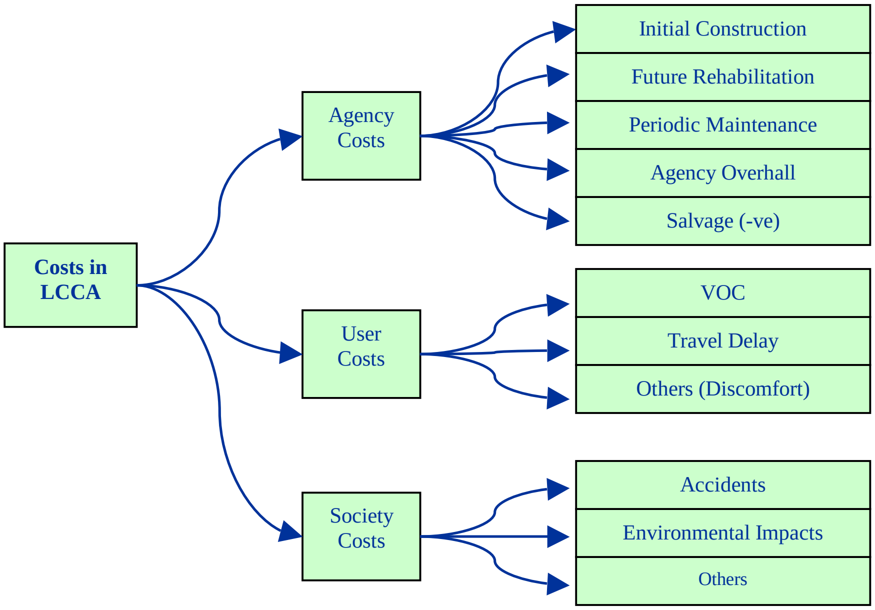


Figure 16: Costs in LCCA for Transportation Projects

There is no general consensus on how to estimate the salvage value, primarily because infrastructure projects are never terminated at the end of analysis period. One approach to estimating this component is by accounting for the costs of demolition and removal as well as adding the value of the recycled project waste. Another approach is by calculating the relative value of the remaining serviceability of the alternative with respect to the cost of the last rehabilitation activity. Each approach has its own critics, and one way to avoid such added dubious calculations is to adjust the analysis period slightly, so as that the remaining serviceability is the same for all alternatives and the salvage value can be omitted from calculations.

User Costs

User costs are the costs encountered by the project users. These costs generally occur during the lifetime of the project. In addition, the majority of these costs are intangibles. The intangible user costs that have been accounted for in transportation projects are:

1) The cost of travel delay time during normal operation and work-zone operation.

2) Vehicle operating costs during normal operation and work-zone operation (e.g. some LCCA literature considers this type of costs real or out-of-pocket costs).

User costs are estimated differently during the normal operation of the facility and during work-zone operation.

Travel Delay Time Costs

The cost of travel delay time during normal operation is typically a function of the distance and the vehicle speed, which is dependent on the demand and capacity of the facility. All of these factors are expected to be equivalent for all alternatives in LCCA (i.e. project-level and secondary analysis), which leads to the exclusion of this type of costs. On the other hand, travel delay time during the work zone operation of rehabilitation activities depends on many other factors such as the work-zone plan (i.e. number of lanes closed, time of day of operation, and number of days of operation), traffic volume and characteristics, and vehicle speed (during normal operation and during work-zone). Even though the calculations needed for this type of costs are cumbersome, some computer programs can be utilized to estimate them independently of LCCA such as “Quewz”, or as part of LCCA such as the FHWA Probabilistic LCCA program, which incorporates a sub-module for calculating the user costs during work-zone operation. The importance of including user delay time during work-zone operation has been increasingly emphasized in all LCCA literature. These costs can exceed agency costs during rehabilitation activities by far, especially on highly traveled facilities in urban areas. Moreover, increasing scrutiny by the public of the unwarranted delay time costs they are incurring because of mismanaged work-zone activities makes these costs as relevant as agency costs, if not more.

Figure 17 represents user costs that are encountered during work zone operation. The FHWA technical bulletin (10) provides a detailed eight-step procedure of how to estimate these costs.

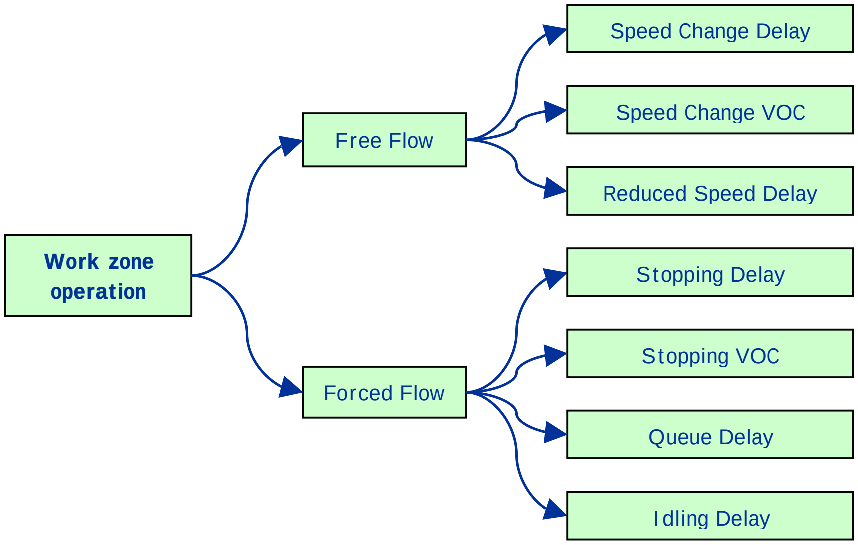


Figure 17: Work-zone Operations Costs

Vehicle Operating Costs

At this level of the LCCA, Vehicle Operating Costs (VOC) is dependent on the facility serviceability (i.e. pavement roughness) and the traffic volume and characteristics only, since the roadway curvature and gradient are similar for all alternatives. The VOC includes fuel consumption, lubricant consumption, tire wear, labor and parts costs for vehicle maintenance, and depreciation. In order to estimate these costs, two types of models are needed; models that accurately predict facility serviceability (i.e., pavement performance models) and models that relate VOC of different types of vehicles (i.e., passenger cars, commercial vehicles) to pavement serviceability.

Academic literature contains many models that have been developed for this purpose. Highway agencies can either utilize general models that are appropriate to their relevance, calibrate available models to local conditions, or develop their own models from databases of their pavement management systems (PMS). The FHWA LCCA technical bulletin (10) considers that vehicle-operating costs (VOC) are equivalent for different alternatives when the level of serviceability is maintained above the threshold (PSI is above 2.5), and accordingly suggests that VOCs during normal operation can be excluded from LCCA. Appendix 4 illustrates a detailed example of a LCCA that incorporates user cost during work-zone operation.

Other types of user costs include discomfort and reliability. In the LCCA literature there is no evidence that these costs had been included in the analysis mostly because it is not proven that such costs varies between different alternatives.

Social Costs

Social costs are the costs encountered by the society as a whole. These costs vary widely in nature. The most recognized, but rarely included in the analysis, are the costs of accidents and the costs of environmental impacts. Accident costs have been estimated as a dollar per unit length for different types of facilities (rural, urban, freeway, etc.). Some research has estimated accident rates as a function of skid resistance, but this is a special case in which aggregates used in the wearing surface might differ between alternatives. In general, there is not enough research that shows that the accident rate can vary among alternatives with different serviceability, neither is there research about the rates of accidents during work-zone operation even though such costs might vary among alternatives. The environmental impacts could affect the air, water, biodiversity, natural resources, noise, and heritage. Among these, only the costs of air pollution and noise have been monetized up to date in transportation evaluation. Other social costs could include barrier effects to non-drivers, social cohesion, equity, and integration. Nevertheless, as in the cost of discomfort or reliability incurred by users, the inclusion of such costs depends mainly on the proof that they vary among alternatives with different serviceability or performance.

The LCCA survey indicates that only 10 percent of State highway agencies include user costs in their analysis. The 90 percent majority of the agencies consider only agency costs. This practice is due to one or a combination of the following reasons:

- Agencies are mainly concerned about the effect of different alternatives on their own expenditure.
- There are complexities involved in obtaining reliable models that can predict user costs correctly.

- There is an assumption that user and social costs are common to all alternatives as long as the serviceability level is above the minimum acceptable level (PSI larger than 2.5), which is generally the case for the roads network.

The FHWA guidance on this matter, besides taking the agency costs into account, stresses the importance of including user costs during work-zone operation.

Each agency must specify the costs it must include in its LCCA. The quality level of information must depend on the project's specifics and investment. For example, vehicle operating costs or travel delay can have very little effect on the analysis results when the project under evaluation is a rural road with little traffic. When deciding to include any such cost in LCCA, models that estimate these costs must be readily available and calibrated to the local conditions. Further, these models must have at least one parameter that performs differently for each alternative (such as roughness or skid resistance), otherwise the differential costs cannot be estimated.

CHAPTER 7: SOFTWARE PACKAGES

Software packages that perform LCCA vary greatly in level of sophistication. Generally, they can be classified into three categories:

- Packages evaluating transportation investments on the network-level analysis: These packages require modeling the complete transportation network that must be evaluated. Such packages can evaluate highway projects that result in traffic demand changes on the whole network. Secondary analysis can be performed using such programs. Even though LCCA is done at the project-level, the data, information, time, and costs required exceeds the resources generally available for this level of analysis.
- LCCA packages dedicated for project-level secondary analysis: These programs are designed to perform LCCA. Some are designed and can be applied for any evaluation, regardless of the region. There are other customized LCCAs modeled by State DOTs. Generally, these programs are spreadsheet models that incorporate cost and other database parameters according to the individual DOT practice.
- Multi-module programs that are designed to perform other tasks, such as pavement design and pavement management, incorporate LCCA as one module in the program.

Examples of these software packages are presented next with a brief description of their capabilities.

Network-Level LCCA Models

HERS and HERS-ST

The Highway Economic Requirements System (HERS) is a benefit-cost analysis system developed by the Office of Asset Management at the Federal Highway Administration. It is used to compare improvements to highway segments including resurfacing, reconstruction, widening, etc. While it has primarily been applied at a national level, the states of Oregon and Indiana have adopted it to analyze statewide investment strategies. These features have been adopted into a new state-level version of the software known as HERS-ST.

HDM4

The Highway Development and Management Tools (HDM-4) model was developed by the World Bank after a series of earlier versions. It estimates road user benefits, infrastructure costs, and externalities, including accidents, energy consumption, and emissions for alternative investment strategies. It can be applied at either the project or program level. Previous versions of the model have commonly been used internationally to evaluate tradeoffs between highway expansion and preservation. The new HDM-4 provides a very powerful system for the analysis of road management and investment alternatives. The system can be applied to many areas such as road management, programming road works, predicting road network performance, estimating funding requirements, budget allocations, project appraisal, and policy impact studies (Figure 18).

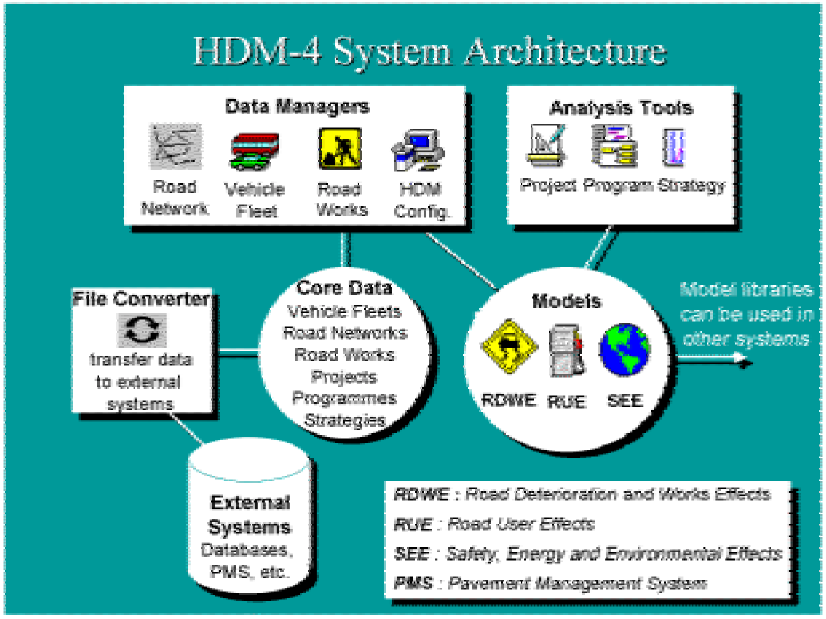


Figure 18: HDM4 System Architecture (Source: The World Bank)

Project-Level LCCA Models

FHWA LCCA Model

The FHWA LCCA Model was developed and released in 2002. It is a spreadsheet model based on the FHWA LCCA Technical Bulletin of 1998. It is a user-friendly model, allowing the required level of sophistication while still remaining user friendly (Figure 19).

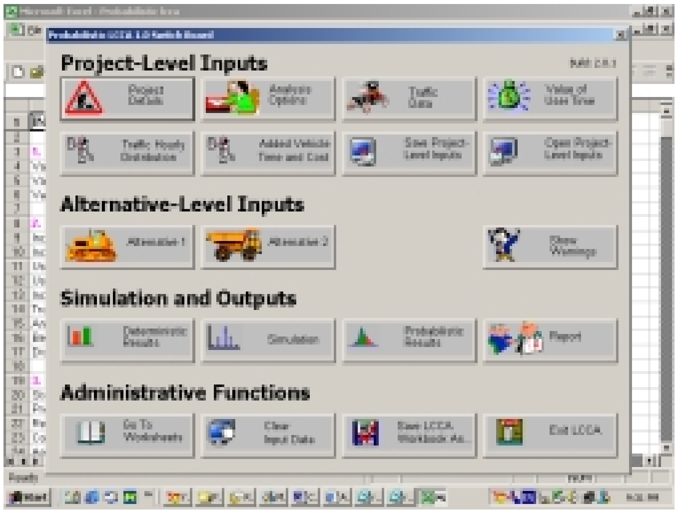


Figure19: General options screen of FHWA LCCA model

Asphalt Pavement Alliance Model

The APA model is also based on FHWA technical bulletin. It has the ability to perform LCCA in either a probabilistic or deterministic form for up to four alternatives. For the probabilistic analysis, information is required on the mean value and distribution of the discount rate, traffic growth and construction duration. When it is not possible to estimate these distributions, the deterministic mode may be used. It allows for the inclusion of user costs resulting from delay time during work zones, and generates the resulting detailed analysis graphically and in excel format.

State DOT's Customized Software's

Many State DOTs have developed their own customized software for LCCA, and many of these software programs are in a spreadsheet format. Some of these models are:

1. LCCA: Idaho
2. LCC1: Pennsylvania
3. LCCP/LCCRP: Maryland
4. RPLCCA: Texas
5. PID: Washington
6. Cal-BC : California

Each one of these programs incorporates specific modules specially for dealing with functions like user costs and pavement performance. PID, for example, uses LCCA for the purpose of optimizing pavement investment decisions based on the preset standards of pavement performance while importing the required input data from the DOT pavement management system database.

Most of these models can be utilized only within the state DOT that developed them unless some modifications to their sub-modules can be made according to specifics of the project or the state. The last two, PID and Cal-BC, are developed for objectives beyond computing the NPV using LCCA. The models perform LCCA as part of their overall objective, which is network rehabilitation, planning for the former model, and establishing economical feasibility for the latter.

General Packages that incorporate LCCA module

DARWin 3.1

DARWin is one of the AASHTO Ware products. It is a powerful pavement design program and a computerized version of the 1993 AASHTO *Guide for Design of Pavement Structures.* The first generation, DNPS86, was then replaced by DARWin and now is no more in use.

DARWin 3.1 is divided into four modules, each of which addresses a specific item in the overall pavement design process. Collectively, these modules can be used to design and compare alternative pavement designs.

The fourth module, which is of our concern, is the *Life Cycle Cost Analysis Module*. It is the economic analysis tool for evaluating pavement projects. The costs considered in the analysis are the initial construction costs, maintenance costs, rehabilitation costs, and salvage costs. The results can be output using different evaluation methods (net present value or equivalent uniform annual cost) and different cost parameters (total cost or cost per unit length in one or two directions). Cash flow diagrams are generated automatically for each project.

Even though this program performs LCCA in a simple manner, it is currently by far the most used program as indicated by our survey results for performing LCCA of pavement projects among all State DOTs.

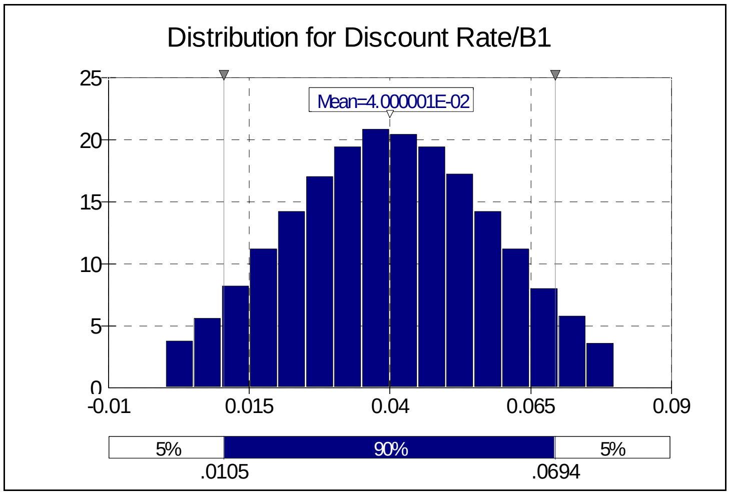
Case Study (Cont'd)

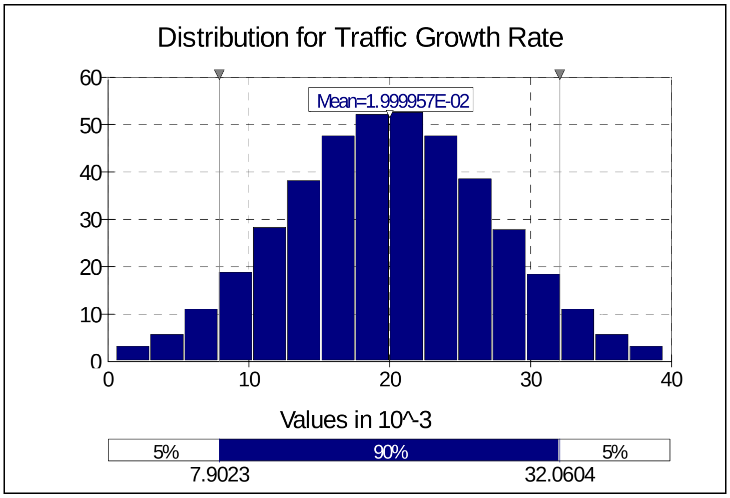
The case study presented to this point has evaluated the two life cycle alternatives for the project by applying LCCA deterministically. In this section, LCCA will be applied probabilistically. This approach is explained in Chapter 3 and it is highly recommended to treat the uncertainties that exist in the assumptions column of LCCA framework.

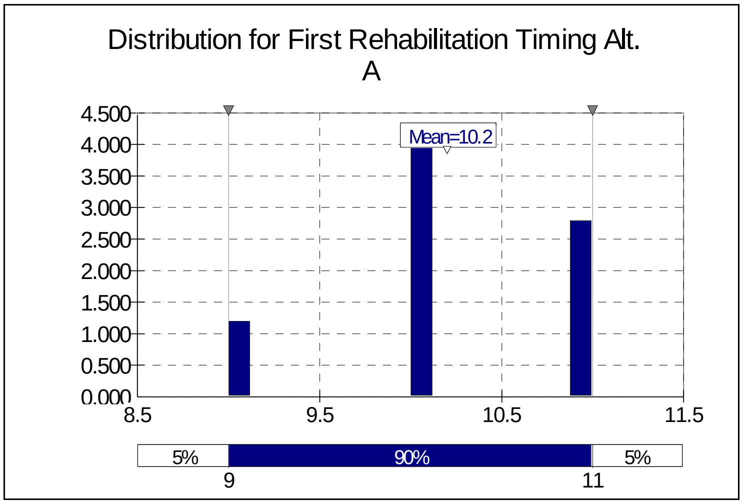
Following the steps for conducting Monte Carlo simulation, we first identify the uncertain input parameters of LCCA model. The parameters are identified as the discount rate, the traffic growth rate, the initial construction costs, the future rehabilitation costs, and the timing of the first rehabilitation activity (i.e. which also represents the performance life).

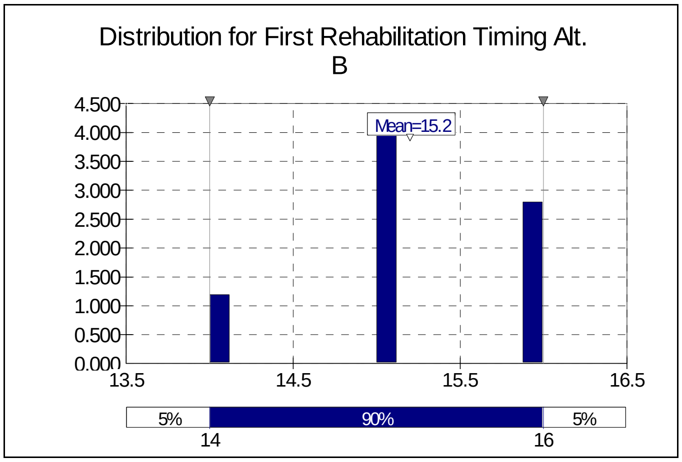
Using @Risk software, the distributions of the uncertain parameters are constructed by best-fitting/describing the possible values for each parameter. The distributions used for the case study and their related parameters are described in the table. The figures illustrate the distributions for the input parameters in LCCA model.

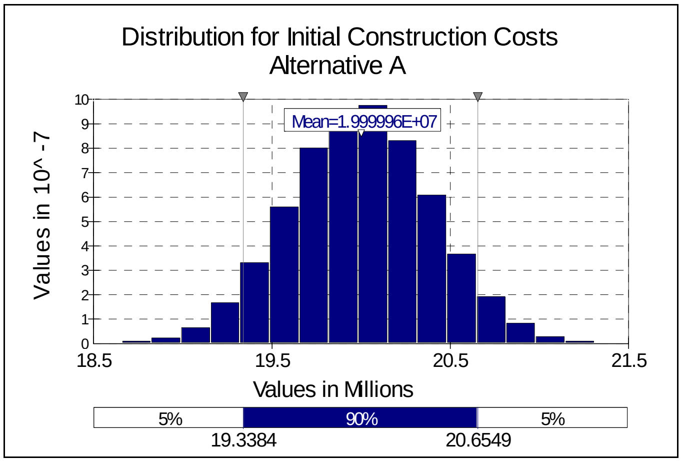
Input Name	Distribution	Minimum	Maximum	Mean	Std Dev
Discount Rate	Normal-Truncated	0.00018289	0.07988669	0.04000001	0.01759961
Initial Construction Costs (Alt. A)	Normal	18658770	21311380	19999963.7	399998.317
Performance Life (Alt. A)	Discrete	9	11	10.2	0.67857237
Rehabilitation Costs (Alt. A)	Normal	4662563	5346542	5000027.14	100024.618
Initial Reconstruction Costs (Alt. B)	Normal	23404380	26606682	24999931.1	500042.138
Performance Life (Alt. B)	Discrete	14	16	15.2	0.67857237
Rehabilitation Costs (Alt. B)	Normal	5526237	6394180	5999915.85	120284.822
Traffic Growth Rate	Normal-Truncated	0.00057261	0.03945474	0.01999957	0.00726722

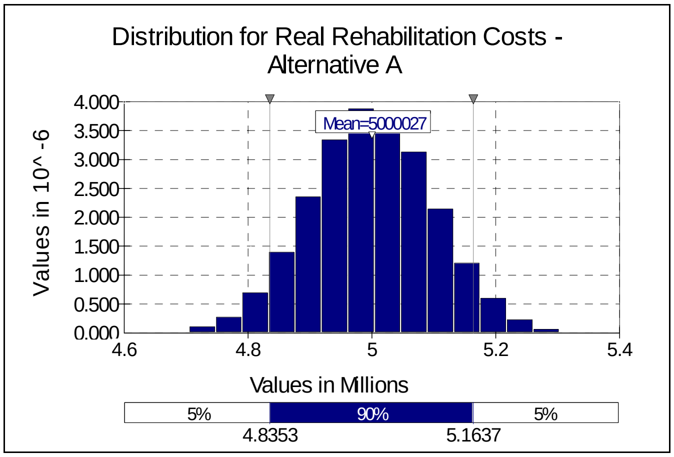

Distribution for Discount Rate/B1
Mean=4.000001E-02
25
20
15
10
5
0
-0.01
0.015
0.04
0.065
0.09
5%
90%
5%
.0105
.0694

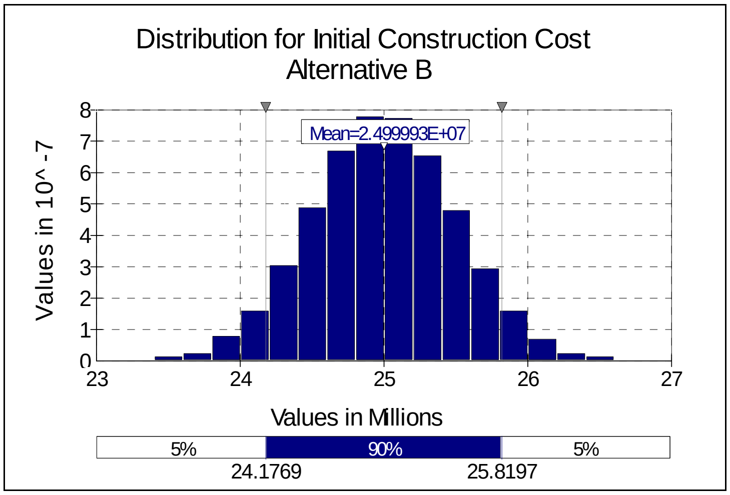

Distribution for Traffic Growth Rate
Mean=1.999957E-02
60
50
40
30
20
10
0
0
10
20
30
40
Values in 10^-3
5%
90%
5%
7.9023
32.0604

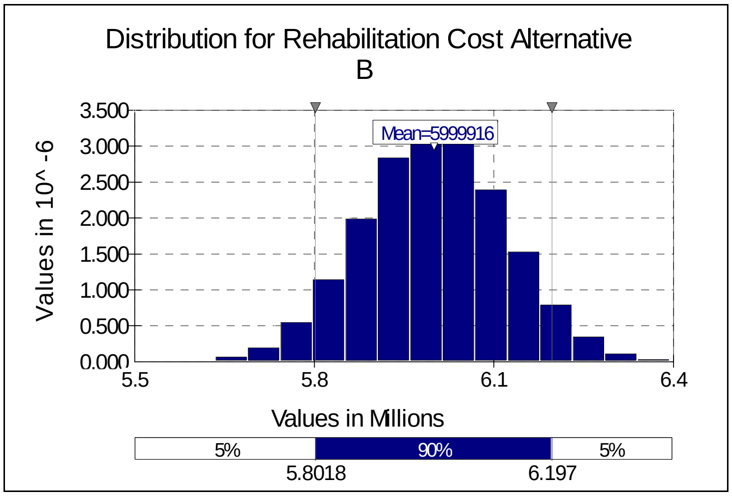

Distribution for First Rehabilitation Timing Alt. A
Mean=10.2
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
8.5
9.5
10.5
11.5
5%
90%
5%
9
11


Distribution for First Rehabilitation Timing Alt. B


Distribution for Initial Construction Costs Alternative A


Distribution for Real Rehabilitation Costs - Alternative A



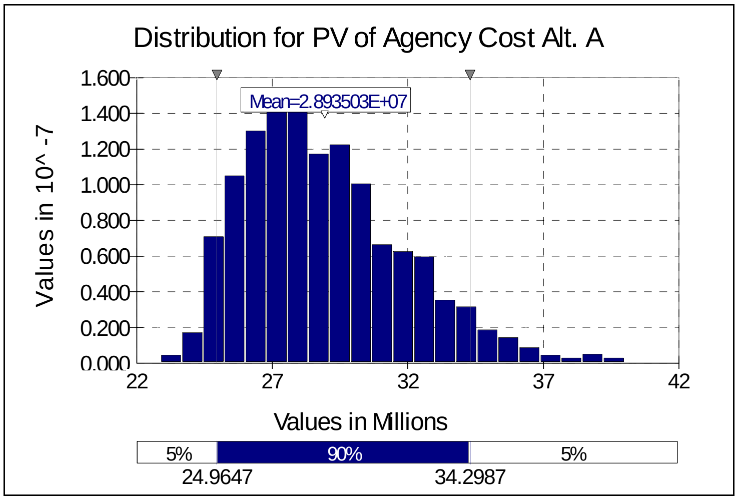


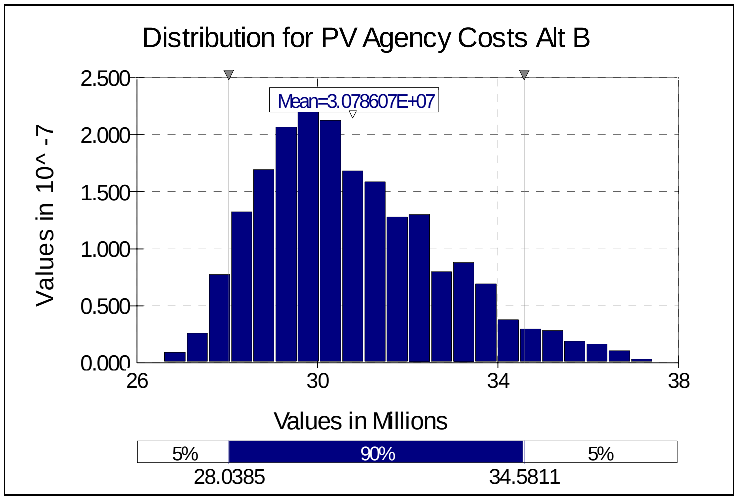
After the input distributions are defined, simulation parameters are set such as the auto-stop convergence rate is at 1%. The simulation is done twice. The first simulation is done using Monte Carlo sampling, and the second is done using Latin Hypercube sampling.

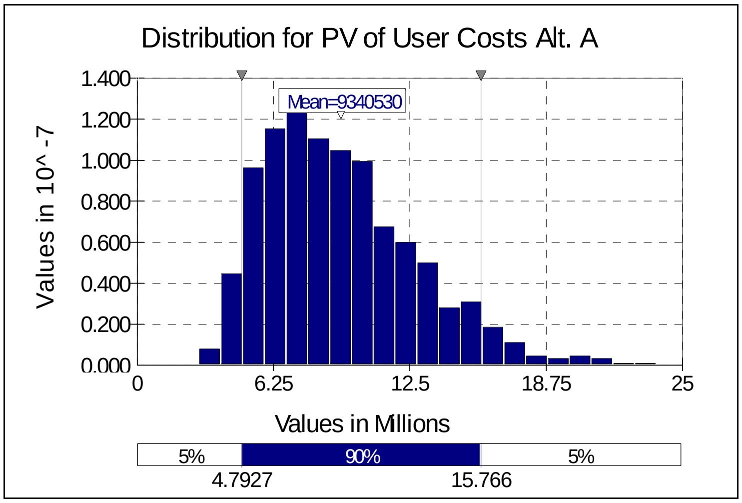
Using Monte Carlo sampling, the convergence occurred after ten seconds and performed 2,500 iterations. Using Latin Hypercube sampling, the convergence occurred after seven seconds and performed 1,700 iterations.

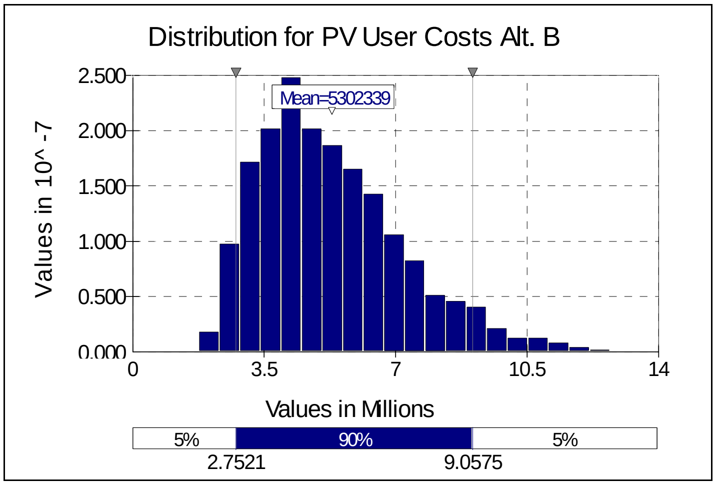
Alternative A has a lesser mean of the present value of agency costs than alternative B at $28.9 million for A versus $30.7 million for B. The mean of the user costs for A was larger than the user costs for B at $9.3 million for A versus $5.3 for B.

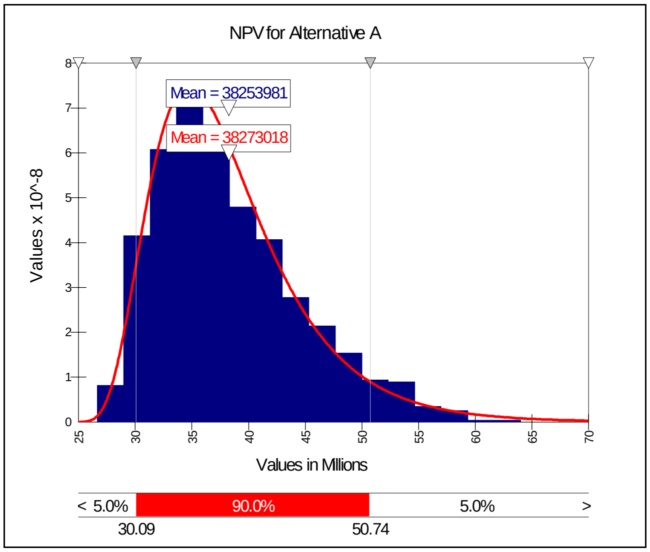
On the total, the mean of the NPV for alternative A is $38,253,981 and for alternative B is $36,064,675 which makes alternative B the preferred one. The distributions of the NPVs are shown in the graphs illustrated next.

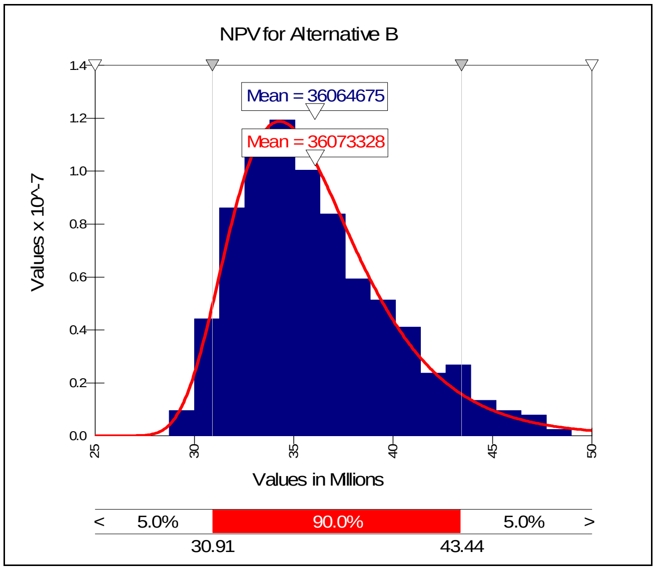

Distribution for PV of Agency Cost Alt. A
Mean=2.893503E+07
Values in 10^ -7
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
22
27
32
37
42
Values in Millions
5%
90%
5%
24.9647
34.2987


Distribution for PV Agency Costs Alt B
Mean=3.078607E+07
Values in 10^ -7
2.500
2.000
1.500
1.000
0.500
0.000
26
30
34
38
Values in Millions
5%
90%
5%
28.0385
34.5811

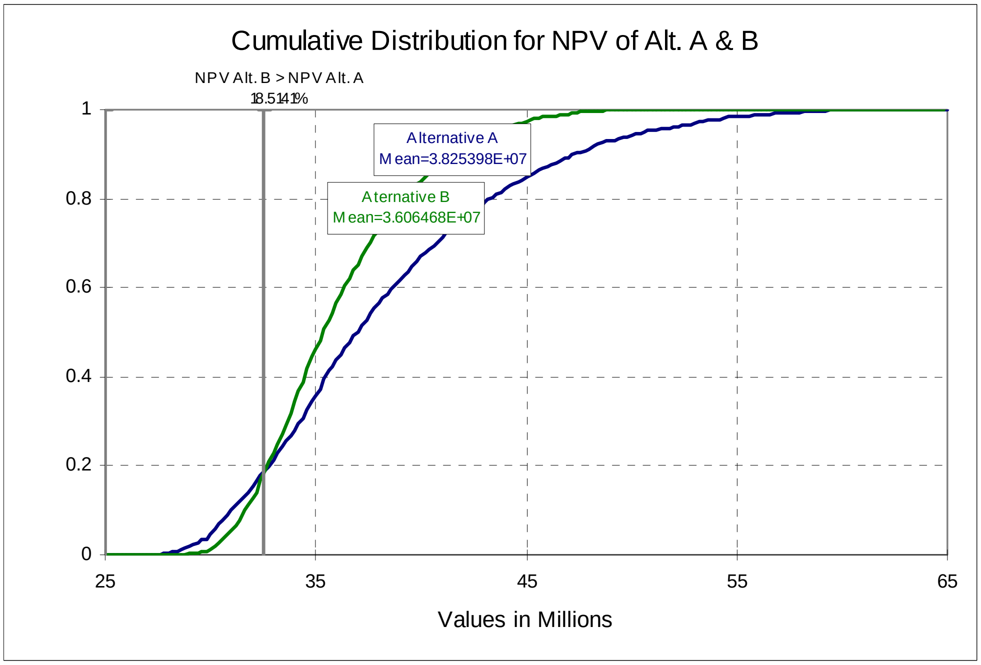

Distribution for PV of User Costs Alt. A
Mean=9340530
Values in 10^ -7
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
0
6.25
12.5
18.75
25
Values in Millions
5%
90%
5%
4.7927
15.766


Distribution for PV User Costs Alt. B
Values in 10^ -7
2.500
2.000
1.500
1.000
0.500
0.000
Mean=5302339
0
3.5
7
10.5
14
Values in Millions
5%
90%
5%
2.7521
9.0575


NPV for Alternative A
Values x 10^-8
8
7
6
5
4
3
2
1
0
Mean = 38253981
Mean = 38273018
25
30
35
40
45
50
55
60
65
70
Values in Millions
< 5.0%
90.0%
5.0%
>
30.09
50.74

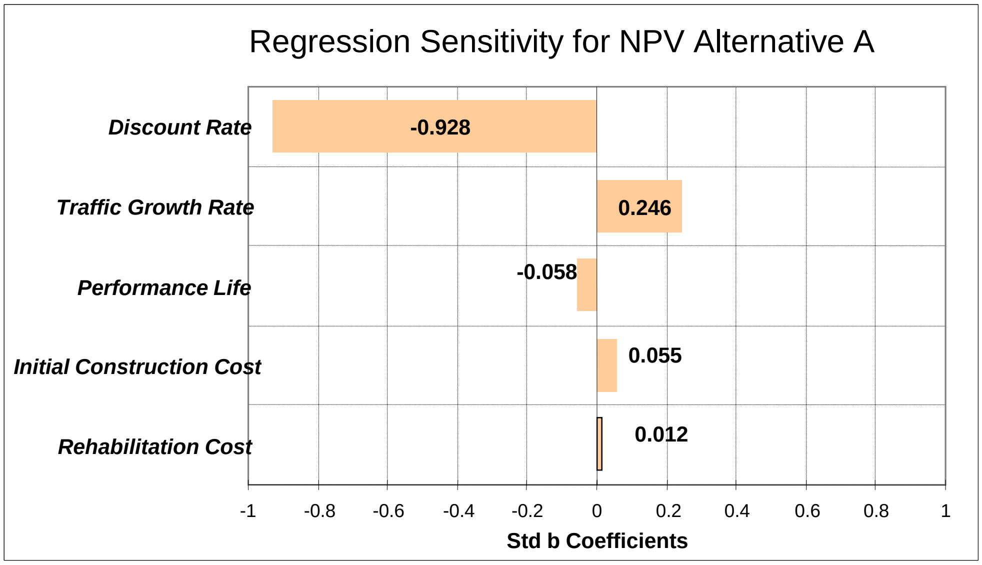

NPV for Alternative B
Values x 10^-7
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Mean = 36064675
Mean = 36073328
25
30
35
40
45
50
Values in Millions
<
5.0%
90.0%
5.0%
>
30.91
43.44

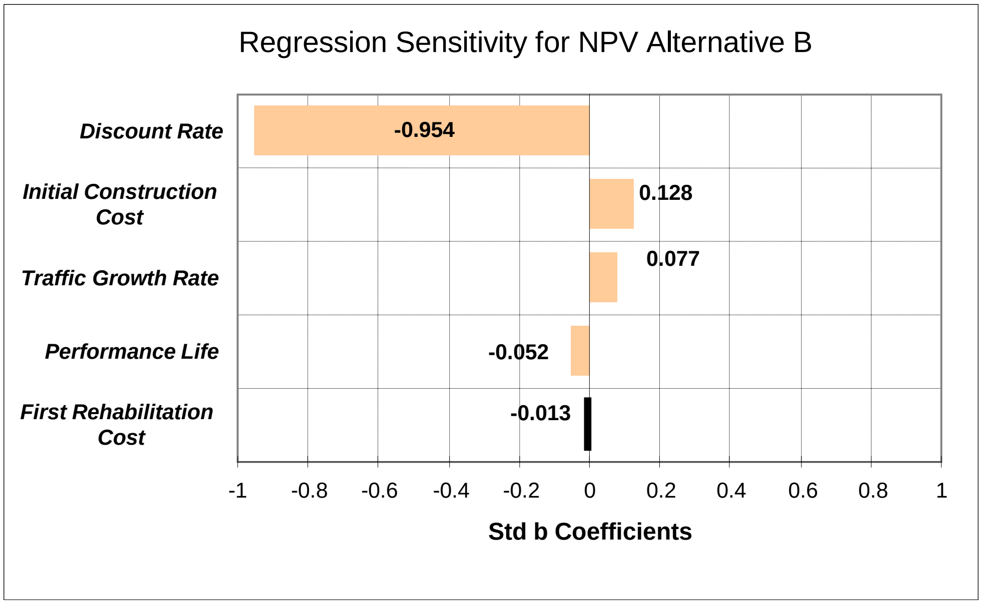
By plotting the cumulative distributions of the NPVs of both alternatives on the same graph as shown in the figure below, we are further able quantify the probability that alternative B might have a larger NPV than alternative B by 18.5%.



Performing regression sensitivity for the NPV of alternative A and B and plotting it in a tornado graph as shown in the two figures below, we can identify the input parameters that has the highest effect on the variability of the NPV.

For both alternatives in the case study, the variability of the discount rate has the highest effect on NPV with a negative correlation coefficient greater than 0.9. In alternative A, the traffic growth rate is the next affecting parameter, which is explained by the fact that this alternative has a larger number of rehabilitation activities during the analysis period that will cause higher user costs. In Alternative B, the next affecting parameter is the initial construction agency cost with a positive correlation coefficient. In both cases, the correlation coefficients for these parameters are less than 0.5, which means that their effect is not significant.





Conclusions

Both the deterministic approach and the probabilistic approach that account for growth in traffic when calculating the timing of the future rehabilitation indicate that alternative B has a lesser NPV. Yet the probabilistic approach provides further insight on the effects of the variability in the assumptions of the model parameters and quantifies the probability that alternative B has a lesser NPV.

CHAPTER 8: CONTRACTOR PAY SCHEDULE

Many factors should be considered in the establishment of pay schedules that are agreeable to both the contractor and highway agency alike. This approach focuses principally on economic impacts of inferior/superior construction to the highway agency. It assumes that an appropriate penalty for inferior construction should be the added cost to the highway agency and a bonus for superior construction should be no greater than the added savings to the highway agency.

For new construction, these costs/savings are associated primarily with subsequent pavement rehabilitation. Inferior construction hastens future rehabilitation and may increase the cost of rehabilitation as well. As a result, inferior construction increases the present worth of future rehabilitation costs. Superior construction, on the other hand, reduces the present worth of these costs by largely deferring the future rehabilitation. The difference in present worth of rehabilitation costs, as constructed versus as designed, provides a rational basis for setting a level of penalty/bonus for inferior/superior construction quality. Computation of the differential present worth of future rehabilitation requires two different models: a performance model for determining the effect of construction quality on anticipated pavement performance and a cost model for translating these effects into dollars.

A number of different mechanisms affect the performance of a flexible pavement. These mechanisms eventually lead to one or more types of pavement distresses such as cracks and ruts. AASHTO equations lump multiple distresses into one composite index – Pavement Serviceability Index (PSI) – which emphasizes ride quality and virtually ignores the individual distresses that frequently dictate maintenance and rehabilitation strategies. On the other hand, by predicting the individual distresses and roughness separately, using mechanistic-empirical relationships, a flexible pavement design process can be optimized to meet a given agency's specific needs. The predominant distresses for a flexible pavement are roughness, rutting, thermal cracking, and fatigue cracking, while those for a rigid pavement are roughness, joint faulting, spalling, and fatigue cracking.

This concept is demonstrated here with a flexible pavement example developed using the Strategic Highway Research Program (SHRP) predictive distress models and New York State Department of Transportation (NYSDOT) cost models. It is assumed that the SHRP testing procedures are accurate and produce reliable results. The model does not consider means and variances of the construction quantities such as air-void content, asphalt-concrete thickness, and other variables. The models used in this example were calibrated for the NYS wet freeze region. Initial costs for flexible pavement are fixed costs affiliated with new construction or reconstruction of the pavement structure. These costs included excavation, subgrade preparation, subbase course, and asphalt paving. NYSDOT developed nine design cases and the respective costs associated for each case. In this example, the calculation of future “scheduled” maintenance and rehabilitation costs are based on the predictive quantity of rutting and thermal cracking.

Life Cycle Performance Cost Approach

The predicted future life cycle cost of a pavement lot is the overall quality characteristic used for determining contractor pay adjustments. The pavement or lot life cycle cost can generally be defined as the cumulative Present Worth (PW) value of the future pavement performance-related costs expected to be incurred by the State Highway Agency (SHA) and users over the chosen analysis period. The SHRP performance model and NYSDOT cost model were both integrated into a Microsoft Excel spreadsheet. All the future costs were converted into present value using a 4 percent discount rate.

The sensitivity of the variables, which affect the pavement performance and ultimately the agency cost, was tested. The following variables which may vary during construction from as-designed values, were considered:

- Air-voids
- HMAC aggregate passing #4 sieve
- Sub base passing #200 sieve
- Asphalt concrete thickness

- Base layer thickness

It is assumed that as-built variables will be within a narrow range of the specifications. Figures 20 to 24 plot the effect of the above variables versus the life of the pavement in terms of Equivalent Standard Axle Loads (ESALs) and years at the following distress triggered the values:

- Roughness = 100 inch/mile
- Rutting = 0.38 inch
- Thermal crack spacing =15 ft

Air-Voids

Figure 20 shows the sensitivity of air-voids on roughness, rutting, thermal cracking, and agency cost. An increase in air-voids from its design value (4 percent) would result in an early trigger for roughness and a delayed trigger for rutting. The thermal cracking was not affected by variation in air-voids content. The plot shows that roughness is very sensitive to a change in air-void content ranging from 3 percent to 5 percent and stabilizes somewhat thereafter. Since in this example the agency cost is based on rutting and thermal cracking quantities, an increase in air-void content would result in lower agency cost because of an improvement in rutting (delayed trigger), while a decrease would result in a higher agency cost.

HMAC Aggregate Passing #4 Sieve

Figure 21 plots the sensitivity of the percent by weight of HMAC aggregate passing #4 sieve versus the life of the pavement. The plot demonstrates that an increase in the proportion of the HMAC aggregate passing #4 sieve from its design value (65 percent) would result in a stronger pavement to resist rutting but a weaker pavement to resist thermal cracking; a decrease in content would yield opposite results. Roughness was found to be insensitive to variation of HMAC aggregate passing #4 sieve. The combined effect of rutting and thermal cracking would result in a higher life cycle agency cost with an increase in aggregate contents and a lower cost with decrease in aggregate contents passing #4 sieve.

Subbase Passing #200 Sieve

The effect of subbase passing the #200 sieve (percent weight) is shown in Figure 22. In this case, roughness and rutting are not affected by variation of subbase contents passing the #200 sieve. However, a 5 percent decrease from its design value (10 percent) resulted in a thermal cracking trigger 2.5 years earlier (from 20.5 years to 18.0 years) and a 5 percent increase resulted in a 2.5 year delayed trigger (from 20.5 years to 23 years). In other words, finer particles in the subbase would result in less thermal cracking and ultimately a lower life cycle agency cost.

HMAC Layer Thickness

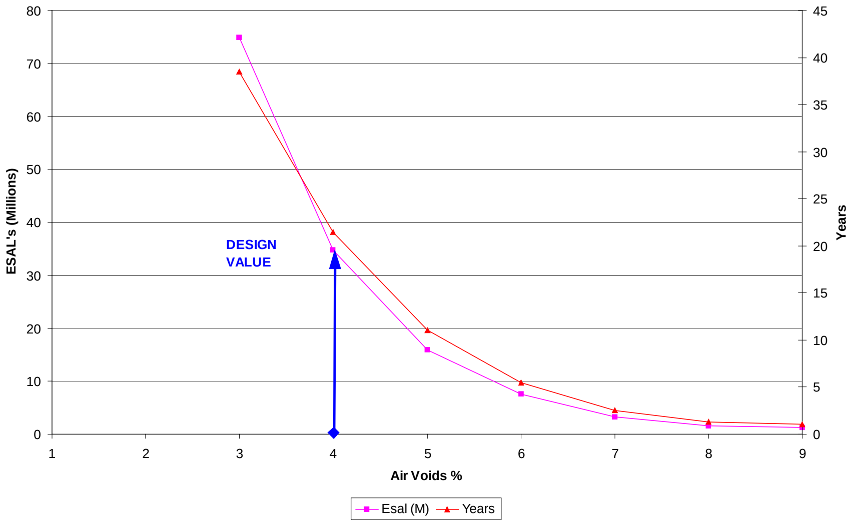
The effect of variation on asphalt concrete (AC) thickness is shown in Figure 23. A one-inch increase in AC thickness triggers the roughness to its critical value 2 years earlier, rutting 1.5 years later, and thermal cracking 0.5 year earlier. In other words, the thicker the pavement, the greater the resistance to rutting but the weaker to roughness and thermal cracking. The combined effect of these distresses would be a higher life cycle agency cost for thicker pavement, as shown in Figure 24.

Base Layer Thickness

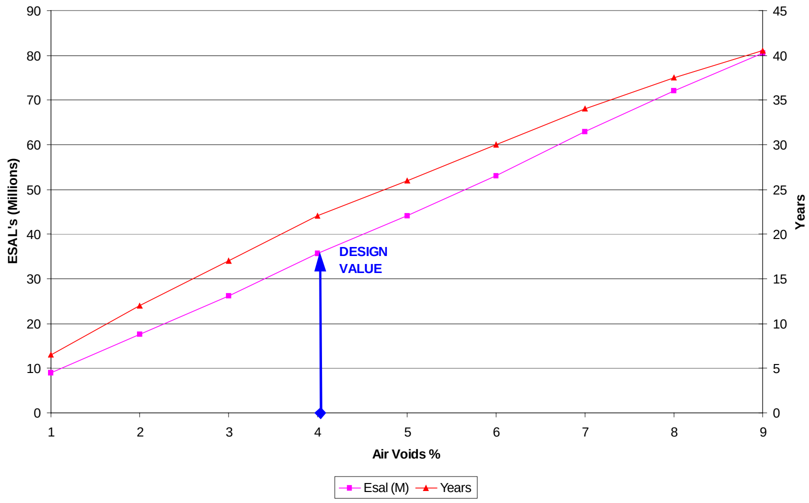
The variation in base thickness would affect all three distresses, as shown in Figure 24. Base layer thickness includes 4” permeable AC base, 12” subbase, and 12” granular select fill, adjusted by layer coefficient (design value =24” for this example). Plots show that a decrease in base course thickness would result in lower pavement resistance to roughness and rutting but a greater resistance to thermal cracking; an increase would yield the opposite effect. For example, a two-inch decrease in base layer thickness triggers the critical roughness and rutting 2 million ESALs earlier, but the thermal cracking 2 million ESALs later. The combined effect on the life cycle agency cost would be a higher cost for the thicker base layers.

FIGURE 20: EFFECT OF AIR VOIDS ON ROUGHNESS, RUTTING, THERMAL CRACKING AND AGENCY COST

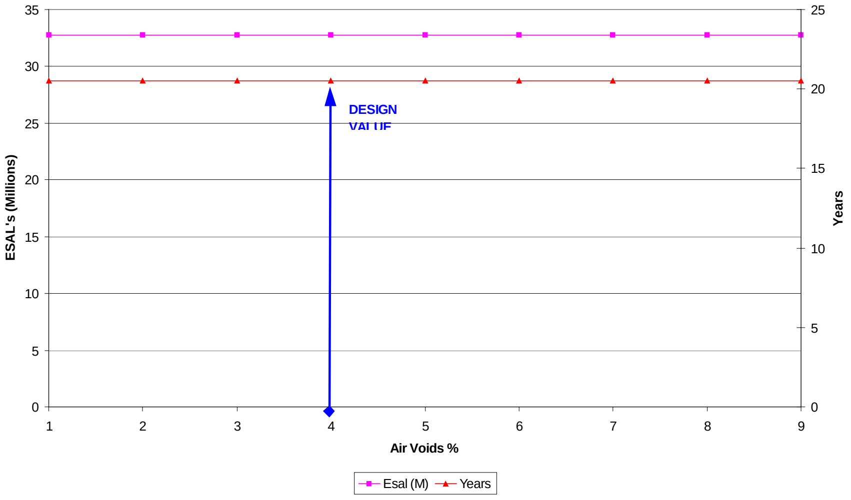
ROUGHNESS SENSETIVITY
Air Voids VS Expected Life at IRI=100 in/mi



RUTTING SENSTIVITY
Air Voids VS Expected Life at Rutting=0.38 in



THERMAL CRACKING SENSITIVITY
Air Voids VS Expected Life at Thermal crack spacing = 15 ft.



AGENCY COST SENSITIVITY
Air Voids VS Life Cycle Agency Cost

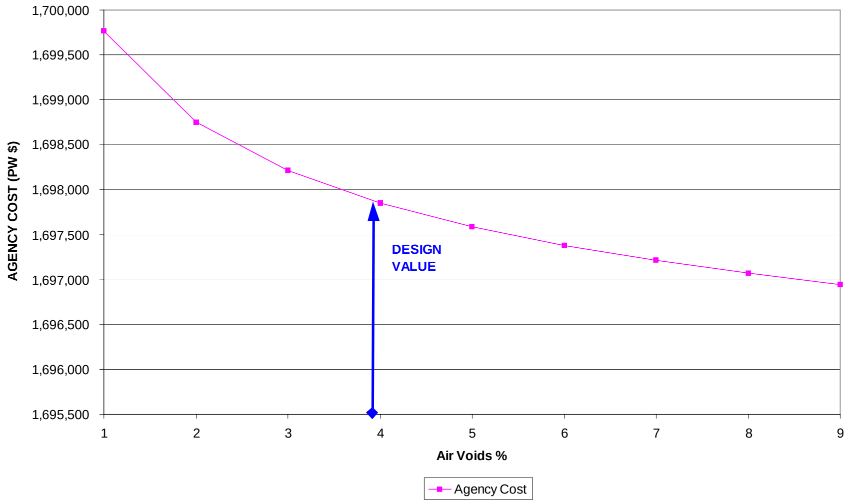
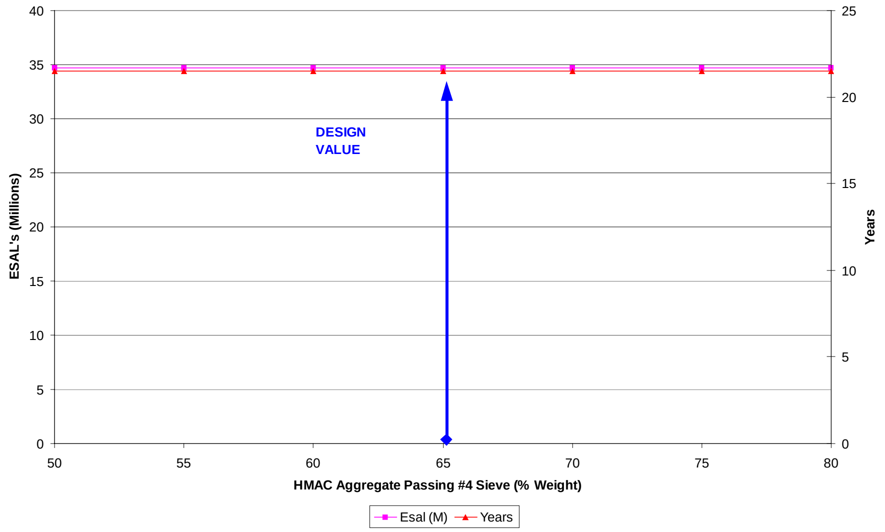


FIGURE 21: EFFECT OF HMAC AGGREGATE PASSING # 4 SIEVE (% WEIGHT) ON ROUGHNESS, RUTTING, THERMAL CRACKING AND AGENCY COST

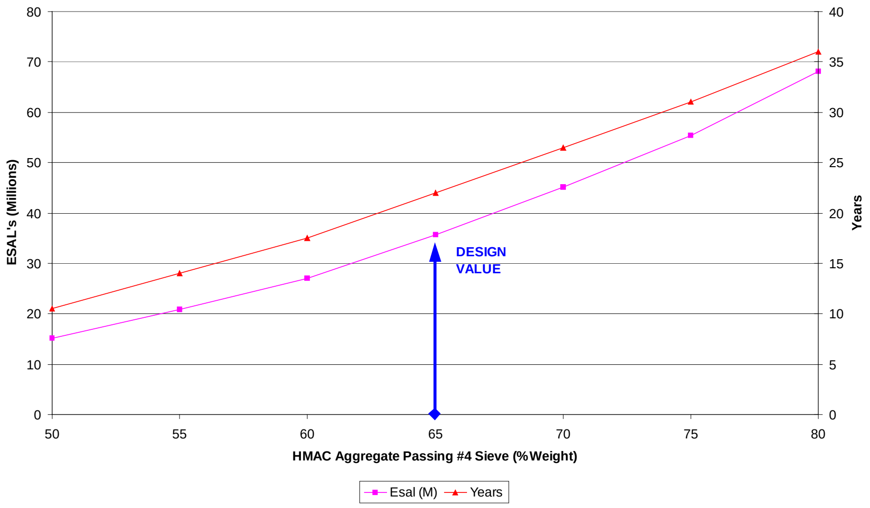
ROUGHNESS SENSETIVITY

HMAC Aggregate Passing #4 Sieve VS Expected Life at IRI=100 in/mi



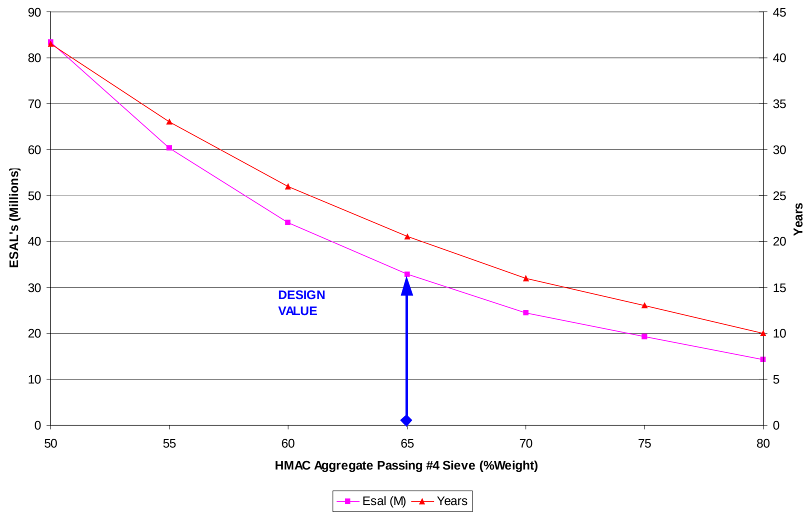
RUTTING SENSTIVITY

HMAC Aggregate Passing #4 Sieve VS Expected Life at Rutting=0.38 in



THERMAL CRACKING SENSITIVITY

HMAC Aggregate Passing #4 Sieve VS Expected Life at Thermal crack spacing = 15 ft.



AGENCY COST SENSITIVITY

HMAC Aggregate Passing #4 Sieve VS Life Cycle Agency Cost

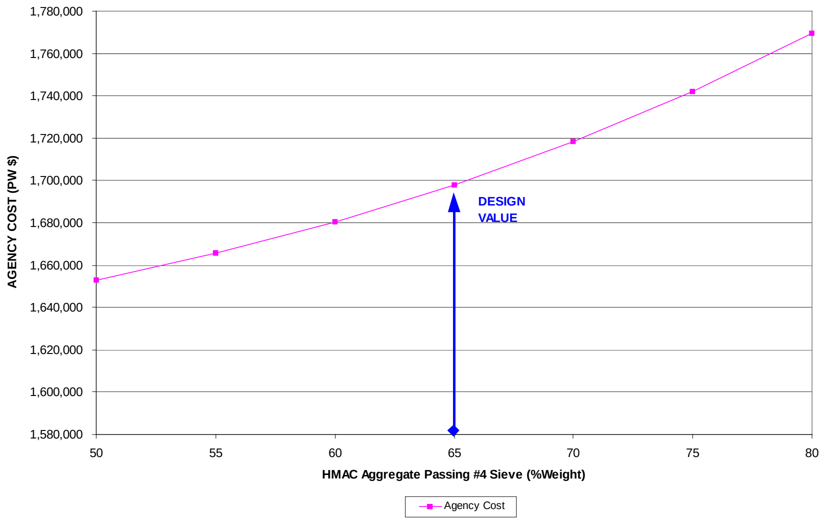
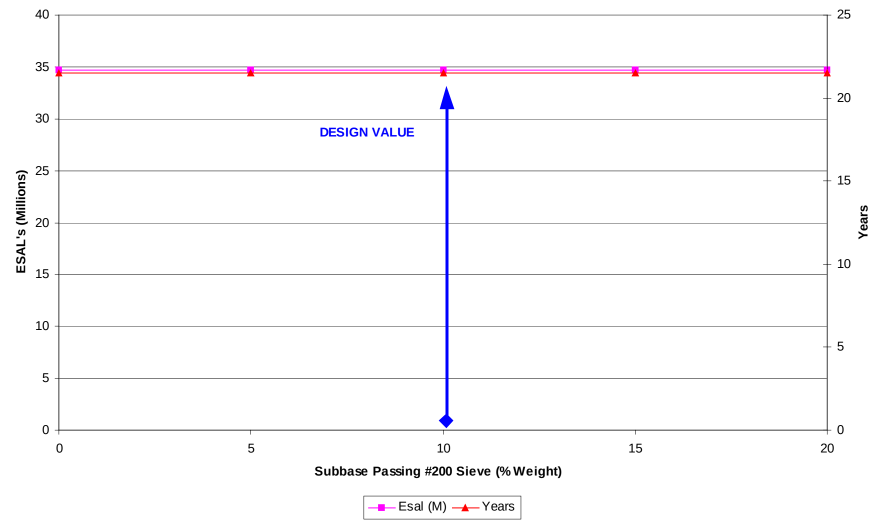
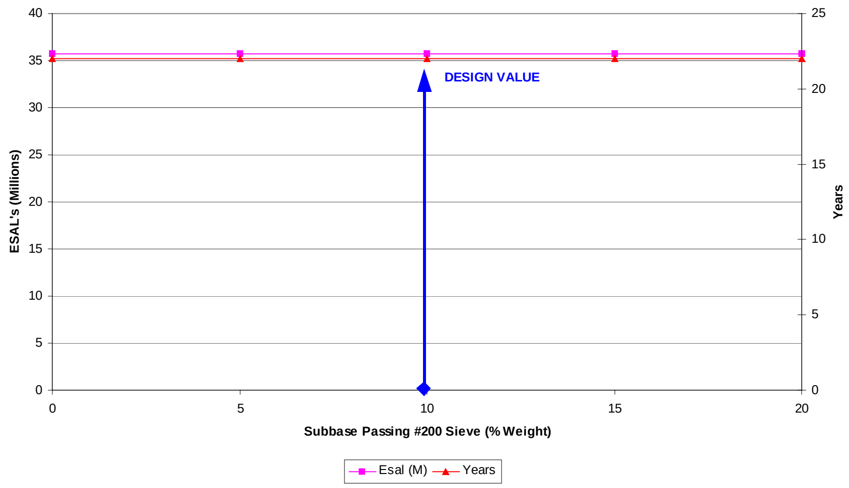


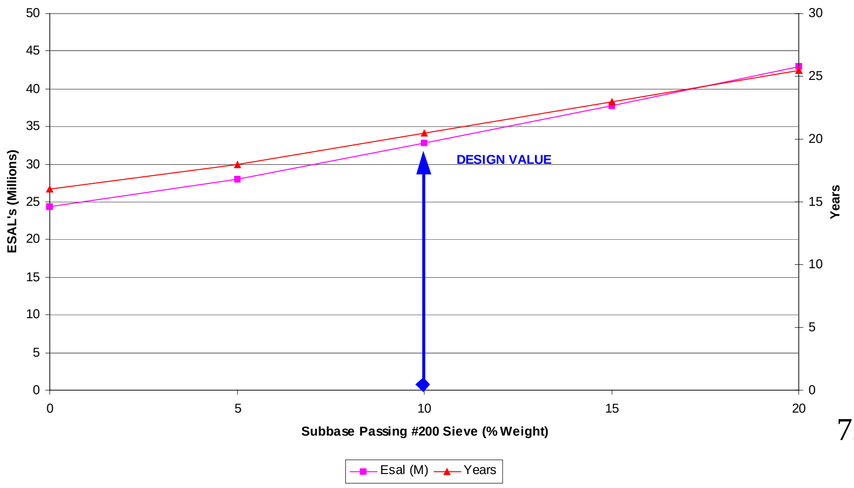
FIGURE 22: EFFECT OF SUBBASE PASSING # 200 SIEVE (% WEIGHT) ON ROUGHNESS, RUTTING, THERMAL CRACKING AND AGENCY COST


ROUGHNESS SENSETIVITY

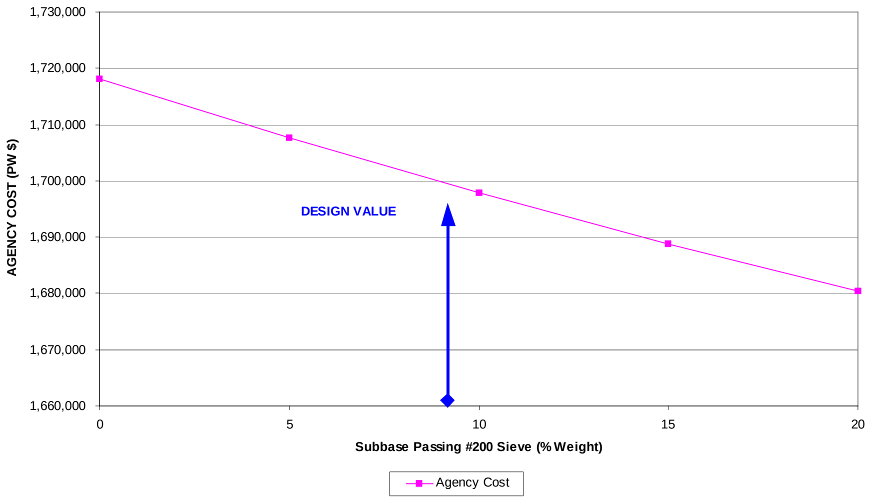
Subbase Passing #200 Sieve VS Expected Life at IRI=100 in/mi


RUTTING SENSTIVITY

Subbase Passing #200 Sieve VS Expected Life at Rutting=0.38 in

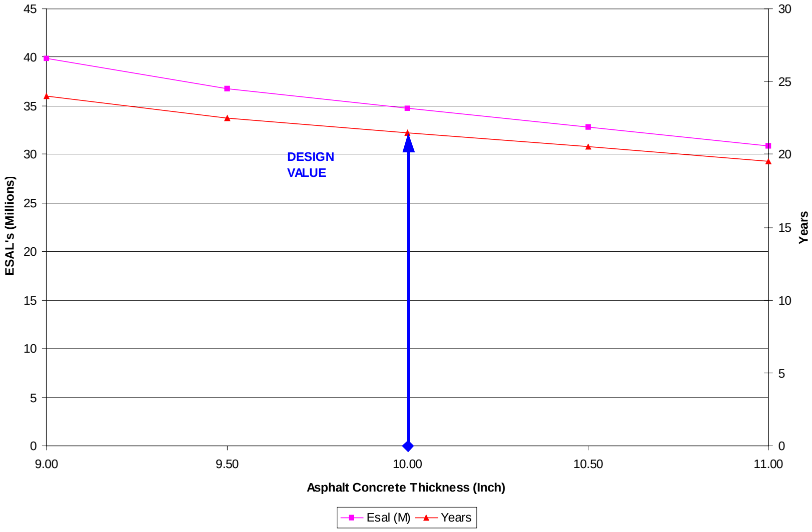

THERMAL CRACKING SENSITIVITY

Subbase Passing #200 Sieve VS Expected Life at Thermal crack spacing = 15 ft.

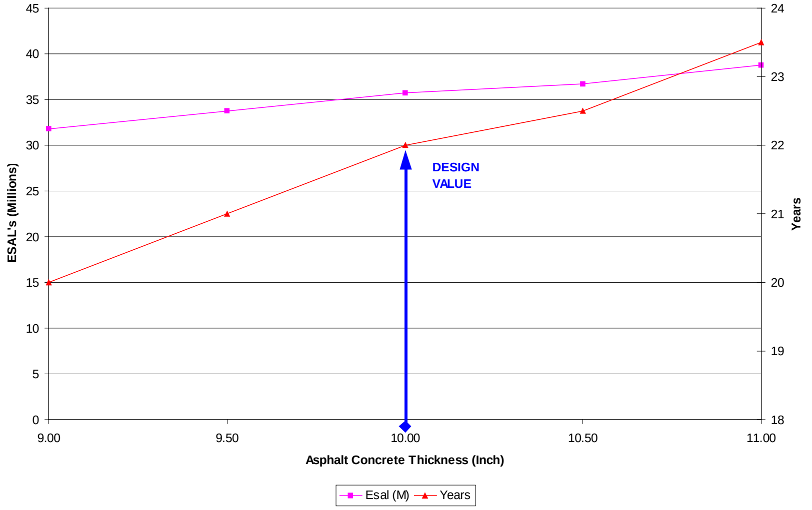

AGENCY COST SENSITIVITY

Subbase Passing #200 Sieve VS Life Cycle Agency Cost

FIGURE 23: EFFECT OF AC THICKNESS ON ROUGHNESS, RUTTING, THERMAL CRACKING AND AGENCY COST

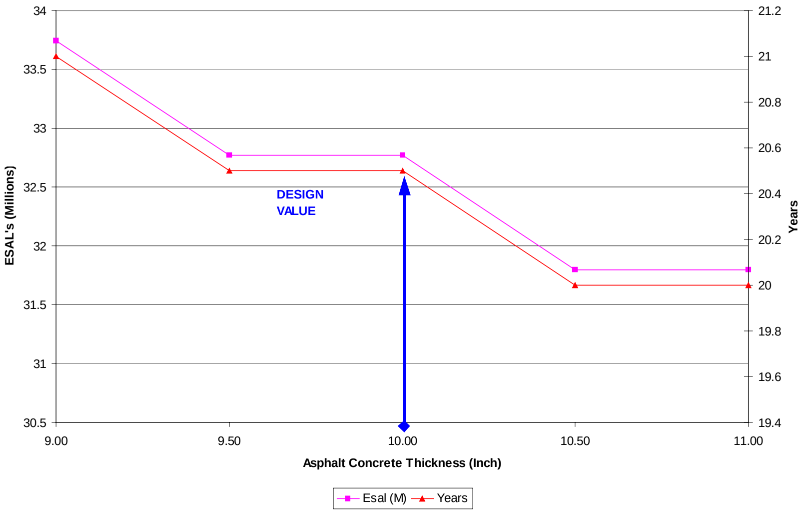


ROUGHNESS SENSETIVITY
AC Thickness VS Expected Life at IRI=100 in/mi



RUTTING SENSTIVITY
AC Thickness VS Expected Life at Rutting=0.38 in

THERMAL CRACKING SENSITIVITY
AC Thickness VS Expected Life at Thermal crack spacing = 15 ft.



AGENCY COST SENSITIVITY
AC Thickness VS Life Cycle Agency Cost

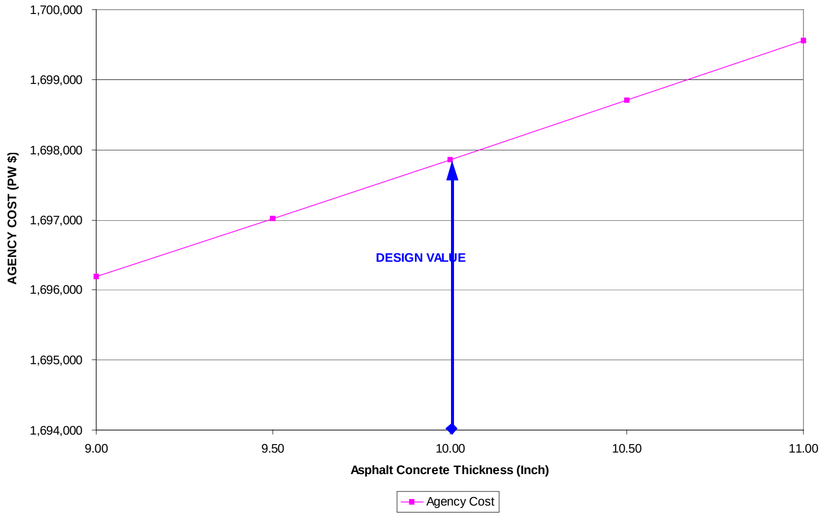
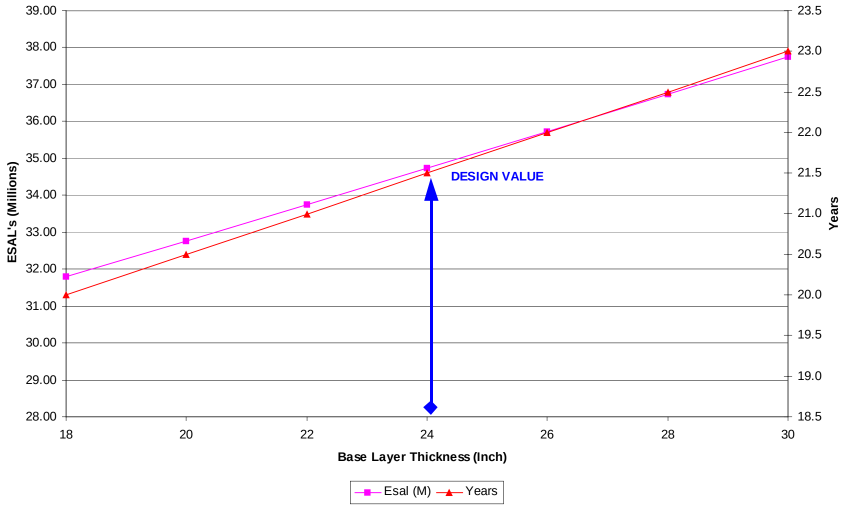


FIGURE 24: EFFECT OF BASE LAYER THICKNESS ON ROUGHNESS, RUTTING, THERMAL CRACKING AND AGENCY COST

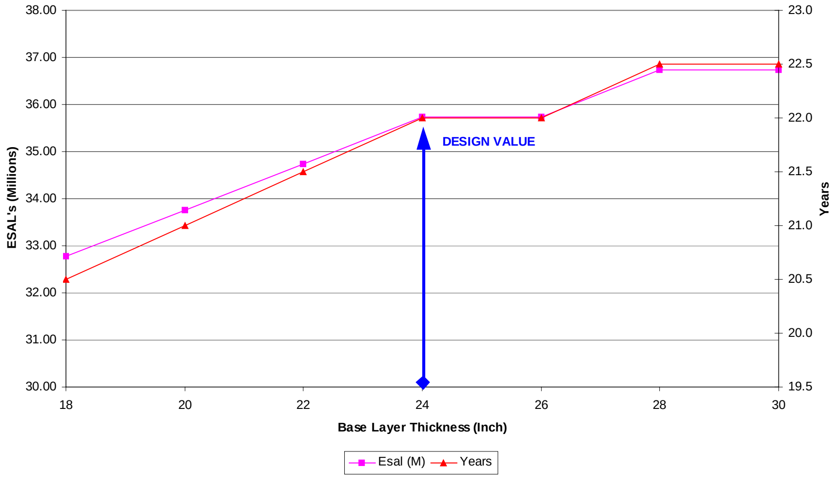
ROUGHNESS SENSETIVITY

Base Layer Thickness VS Expected Life at IRI=100 in/mi



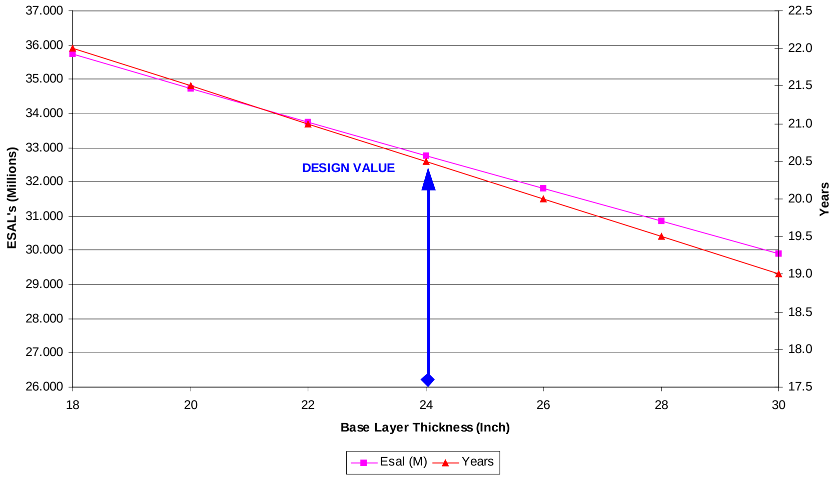
RUTTING SENSTIVITY

Base Layer Thickness VS Expected Life at Rutting=0.38 in



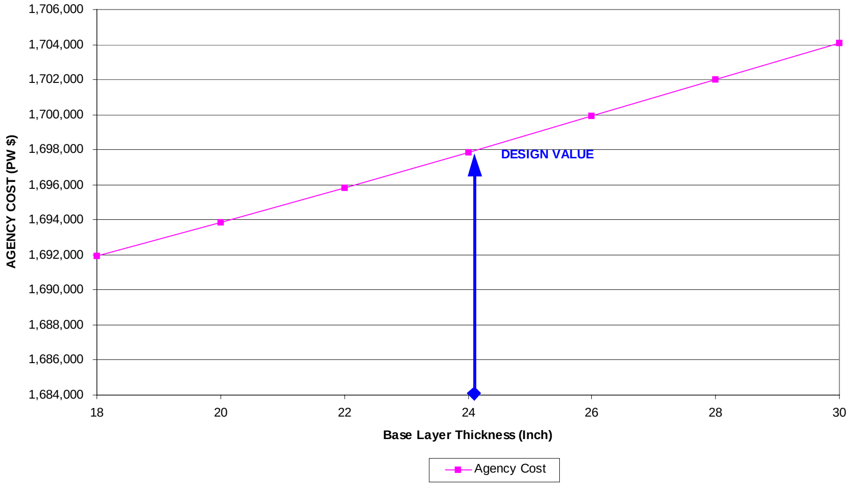
THERMAL CRACKING SENSITIVITY

Base Layer Thickness VS Expected Life at Thermal crack spacing = 15 ft.



AGENCY COST SENSITIVITY

Base Layer Thickness VS Life Cycle Agency Cost



Combined Sensitivity

The mechanistic approach to the projection of pavement performance is based on a complex interplay of several variables that characterize both the properties of the constituent materials and the mechanical properties of the “composite” product (pavement). There is no single variable sufficient for assessing pavement performance. One should check the as-built variance of all variables that affect the pavement performance and its life cycle agency cost to make an adjustment to the contractor’s pay schedule. Table 3 demonstrates this concept, where a combination of varying as-built deviations results in a projected additional agency cost of $10,719, all or a portion of which may be deducted from the contractor’s payment.

Table 3: Combined Effect of As-Built Variations on Life Cycle Cost

Variable QA/QC	**As-Designed Value**	**As-Built Value**	**Variation in Life Cycle Agency Cost ($)***
Air-void contents (%)	4%	5%	+ 264.00
HMAC aggregate passing # 4 sieve (% weight)	65%	70%	- 20350.00
Subbase passing #200 sieve (%weight)	10%	15%	+ 9061.00
Asphalt concrete thickness (inch)	10”	11”	- 1706.00
Base layer thickness (inch)	24”	22”	+ 2012.00
Total pay adjustment			**- 10719.00**

*NOTE: Lower agency cost is taken as positive and higher agency cost as negative value.

Figure 25 shows a model, developed by Maryland State Highway Administration (11), for adjusting the contractors pay schedule as a function of roughness. Deviation from the designed value is considered an incentive in the case of improved roughness and a disincentive in case of poor roughness. Certain limits were fixed after which correction would be necessary before accepting the quality. The SHRP roughness model could be used to establish similar curves based on mechanistic performance. However, this would require adjustment of cost models based on roughness, instead of rutting and thermal cracking.

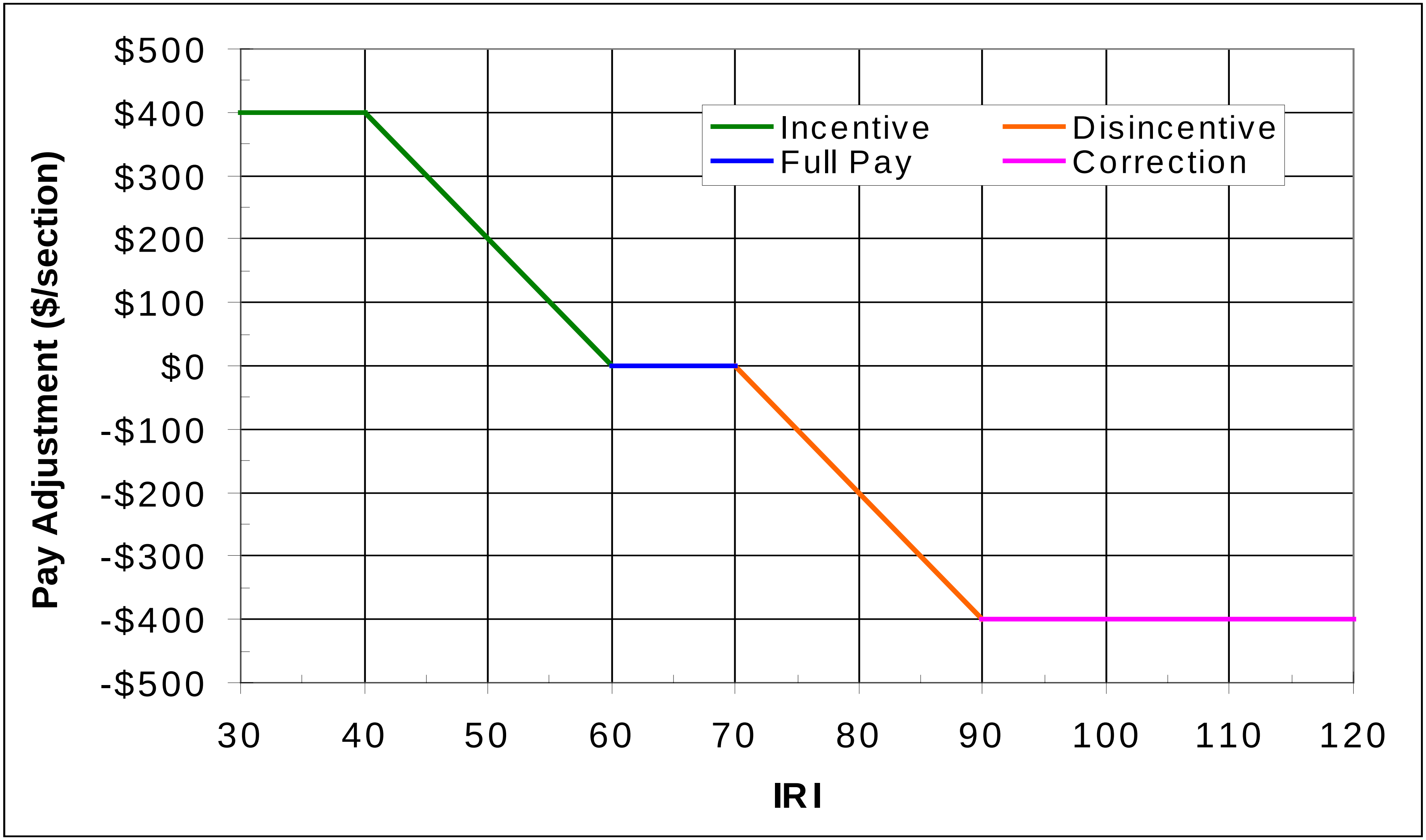


FIGURE 25: Pay Adjustment and Spec Limits (Source: Maryland State Highway Administration)

Conclusions

The continuing challenge for the State agencies is to establish acceptance quality levels (AQL) of constructed pavements for full payment and rejectable quality levels (RQL) at and below which they will be rejected. The conventional approaches to pay adjustment are shown in reference (12). Typically, quality assurance procedures call for random sampling of a material parameter – representing mix properties, density, and smoothness—in each "lot", and on the basis of which, a "percent within limits" (PWL) or "percent defective" (PD) is calculated. A PWL or PD estimates the percentage of a lot falling within upper and lower specification limits, or without, respectively, is calculated. This calculated value is then input to a predetermined relationship to determine the associated pay adjustment. Predetermined relationships may be graphical, as in Figure 25 for smoothness, or in the form of pay factor equations, as in Table 4 for hot mix asphalt concrete overlays. Note that in Table 4, New Jersey and New York use a composite material test property – density – in contrast to some states, which use the mix properties directly.

A much more difficult prospect is determination of the difference in expected life and the life-cycle costs of initial construction and successive maintenance, rehabilitation, and reconstruction, between the as-built and as-designed (specified) pavement. Conceptually, what would be required here is the ability to predict performance – rutting, cracking and roughness— of both the as-built and specified pavements under the same load assumptions, compute the present values (PV), and use the difference in PVs as the basis for a pay adjustment.

Table 4: Pay Factor Equations

State	**Pay Equation**	**Test Property**	**Sample Size n**	**RQL, PWL**
New Jersey	PF = 102 - 0.2*PD PF = 10 + 1.0*PWL[a]	Density	5	50
New Mexico	PF = 55 + 0.5*PWL	AG, AC, AV, Density	3 (minimum)	60
New York	PF = 21.7 + 0.833*PWL (PWL>94) PF = 57.8 + 0.499*PWL (PWL>94)	Density	4	5[b]
South Dakota	PF = 55 + 0.5*PWL	AG, AC, AV, VMA, Density	5	60
Vermont	PF = 83 + 0.2*PWL	AV	3 (minimum)	50
Virginia	PF = 55 + 0.5*PWL	AC, AV, VMA	4	40

AG = Aggregate Gradation
AC = Asphalt Content
AV = Air Voids
VMA = Voids in Mineral Aggregate
[a] Equation given as an example in the specification only
[b] Remove and replace for material PWL<5

Source: NCHRP Report 447, Transportation Research Board 2001

Weed (13) proposed an equation, which relates pay adjustment to the difference between the expected lives of the specified (as-designed) pavement and the as-built pavement, as follows:

$$PAYADJ = C\,(R^D - R^E) / (1 - R^O) \ldots\ldots (10)$$

where:

PAYADJ = appropriate pay adjustment for pavement or initial overlay (same units as C);

C = present total cost of resurfacing (typical value = \$23.92/m^2 (\$20/sy));

D = design life of pavement or initial overlay (typically 20 years for new pavement, 10 years for overlay);

E = expected life of pavement or initial overlay (variable);

O = expected life of successive overlays (typically 10 years); and

R = (1 + INF) / (1 + INT), with:

INF = long-term annual inflation rate in decimal form (typically 0.04); and

INT = long-term annual interest rate in decimal form (typically 0.08).

The expected life, E, would be a function of the PWL for the quality acceptance variable (density in the case of New Jersey and New York) of the as-built pavement. The life cycle performance cost approach presented here, however, directly addresses the distress manifestations of failure – rutting, cracking and roughness – using SHRP mechanistic-empirical relationships, as an example, and computes the costs of repair and rehabilitation as a function of the severity and extent of those distresses. These costs are shown in Figures 20 to 24, as being sensitive to mix properties (HMAC and subbase aggregate) and laydown properties (air-voids and base layer thickness). The reality is that an as-built pavement will exhibit variances in a number of specified variables, and that future performance will be a function of all such variables.

Recommendations

The measures of construction quality, such as are shown in Table 4, may not, by themselves, be good surrogates of performance, and it is strongly recommended that pay adjustments be evaluated on the basis of distress propagation estimated from the next generation of mechanistic-empirical relationships. In this respect, one would be moving away from the traditional concept of “pay adjustment schedule”, which typically refers to only one quality characteristic, to a state-of-the-art concept of a “pay adjustment system”, which refers to more than one schedule or to a schedule which considers several quality characteristics (14).

APPENDIX 1: GLOSSARY

- Analysis Period --The analysis period is the time period used when evaluating projects economically. For example, in pavement projects, the Federal Highway Administration (FHWA) recommends that the analysis period chosen should contain at least one rehabilitation project, but may or may not contain maintenance activities during the life cycle of the evaluated pavement. The analysis period should be of sufficient time for predicting future costs so as to capture all the significant costs. One important note is that the analysis period must be the same for all alternatives under evaluation when LCCA is used for comparing various design alternatives.
- Constant Dollars or Real Dollars—Economic units measured in terms of constant purchasing power. The constant dollars are un-inflated and represent the prevailing price for all elements at the base year for the analysis. Real values can be estimated by deflating nominal values with a general price index, such as the implicit deflator for Gross Domestic Product (GDP) or the Consumer Price Index (CPI).
- Cost-Effectiveness – A systematic quantitative method for comparing the costs of alternative means of achieving the same stream of benefits for a given objective.
- Current Dollars or Nominal Dollars—Economic units measured in terms of purchasing power of the date in question. Current dollars are inflated and represent the price levels that may exist at some future date when costs are incurred. The uncertainty associated with predicting future rates of inflation, and incorporating price changes into the economic analysis, is extremely complex. An accepted approach of dealing with this issue is using constant dollars and a discount rate.
- Deterministic Approach – The deterministic approach considers applying procedures and methodologies without regard for the variability or uncertainty of the input parameters.

- Discount Factor - The factor that translates expected costs and benefits in any given future year into the present terms. The discount factor is equal to $1/(1+i)^t$ where *i* is the interest rate and *t* is the number of years from the date of commencement for the project until the given year.
- Discount rates - A value in percent used in calculating the present value of future costs and benefits when comparing the alternative uses of funds over a period of time. A detailed discussion about discount rates is presented in Chapter 4.
- Inflation – The proportionate rate of change in the general price level, as opposed to the proportionate increase in a specific price. Inflation is usually measured by a broad-based price index, such as the Consumer Price Index (CPI) or the implicit deflator for Gross Domestic Product.
- Initial Cost - The total investment required to construct a project. For example, in highway projects the initial cost will include the estimated cost of pavement construction and may include other costs such as preliminary engineering, traffic control, and construction engineering. The initial costs used in the analysis should be the most current and accurate data available. If costs for the same project elements are identical in different alternatives, it should be noted and these costs may not be included in the analysis.
- Maintenance Costs - The cost of preserving an existing facility and keeping it functioning above the minimum acceptable level of service. These costs include the unavoidable routine maintenance costs that are incurred annually.
- Net Present Value (NPV) - It is the net cumulative present worth of difference between a series of benefits and costs that are encountered in the life time (analysis period) of a project. The PV method involves the conversion of all present and future expenses and benefits to a base of today's costs. The present worth of planned future funds is equivalent to the amount of money needed to be invested now at a given compound interest rate for the original investment plus interest, to equal the expected cost at the time needed.

- Nominal Interest Rate - An interest rate that is not adjusted to remove the effects of actual or expected inflation. Market interest rates are generally nominal interest rates.
- Opportunity Cost - The maximum worth of a good or input among possible alternative uses.
- Probabilistic Approach – This approach applies the recognized procedures but taking into account the uncertainty of the input variables. The results of this approach will be an entire range of outcomes with probability distribution.
- Real Interest Rate – An interest rate that has been adjusted to remove the effect of expected or actual inflation.
- Rehabilitation Costs - The cost for the activities associated with restoring or rehabilitating the facility to function at an acceptable level of service.
- Shadow Price – An estimate of what the price of a good or input would be in the absence of market distortions, such as externalities or taxes.
- Sunk Cost – A cost incurred in the past that will not be affected by any present or future decision. Sunk costs should be ignored in determining whether a new investment is worthwhile.
- Treasury Rates – Rates of interest on marketable Treasury debt. Such debt is issued in maturities ranging from ninety-one days to thirty years.
- Unit Value of Time - In transportation projects this term refers of the cost of time attributed to one hour of travel, which is usually different for cars and trucks.
- User Costs - Indirect or non-agency (soft) costs which are accrued by the facility user and the excess costs incurred by those who cannot use the facility because of some agency requirement. In highway project, these costs should include time delays, vehicle operating and crash costs associated with using a facility under normal and forced operation.
- Value of Travel Time - Vehicle travel time multiplied by the average unit value of time.

- Vehicle Operating Cost - The mileage-dependent cost of driving cars, trucks, and other motor vehicles on the highway. This includes the expense of fuel, oil, tires, maintenance, and vehicle depreciation attributable to highway miles.
- Vehicle Travel Time - The total hours traveled by a specific vehicle.

APPENDIX 2: LIFE-CYCLE-COST-ANALYSIS QUESTIONNAIRE

State: ____________

Department:______________________________Unit:_____________________

Name of person filling out the questionnaire:_____________________________

Job Title: _____________________________________

Contact address: Phone: _______________ E-mail__________________

Notes:

- Please answer all questions below to the best of your knowledge. If you are unable to answer any question, please proceed to the next one.
- In multiple choice questions, you can choose more than one answer if needed
- LCCA: Life-Cycle-Cost Analysis

Section 1: General

1. Number of lane miles of highways under your department's jurisdiction? _____________
2. Annual budget for operations, maintenance and construction? $_____________________
3. What percentage of your annual budget goes to

- Construction and rehabilitation of highways ______%
- Road maintenance ______%
- Other projects ______%

(i.e. Intelligent Transportation Systems, Traffic Signals)

4. What is the total number of employees in your department?

____

5. Does your department use Life-Cycle Cost Analysis?

☐ Yes

☐ No

(If your answer is yes, please proceed to the following questions. Otherwise you don't have to proceed further)

Section 2: General LCCA Methodology

6. For how long has your department been using LCCA?_______________

7. Who performs LCCA in your department?

   ☐ Research & Development Office

   ☐ Different offices (Please specify):

   ____

8. Is there a formal LCCA Guideline that is used in your department?

   ☐ Yes (Please attach the guideline document to this questionnaire, if possible)

   ☐ No

9. For what types of projects do you use LCCA?

   ☐ Pavement

   ☐ Bridge Construction

   ☐ Intelligent Transportation Systems

   ☐ Others (please specify)____

10. Do you apply LCCA to all projects?

   ☐ Yes

   ☐ No, please specify criteria for applying LCCA

   ____

11. Do you use any specialized software for LCCA?

☐ No

☐ Yes: - Customized software
Standard: Name of software:

12. Is LCCA used in combination with value engineering?

☐ Yes, in the design stage

☐ Yes, in the bidding stage

☐ No

☐ No, but may be in the future

13. Does your agency use LCCA as the basis for pay schedules for construction acceptance procedures?

☐ Yes

☐ No

☐ No In selected cases

Section 3: LCCA Parameters and Data

14. Does your DOT specify values for the following parameters to be used in LCCA?

- Discount Rate ______ Yes _______ No
- Inflation Rate ______ Yes _______ No
- Analysis Period ______ Yes _______ No
- User Costs ______ Yes _______ No
- Social Costs ______ Yes _______ No

15. What discount rate is used? (If it is not a fixed value, please explain briefly)

____

16. What inflation rate is used?________________________________

17. What analysis period is used?

- ☐ Same for all projects: ____ years
- ☐ May be different for different project

18. Are social costs considered in your analysis?

- ☐ Yes _____ Please specify type used
  - ☐ Environmental and pollution concerns
  - ☐ Labor-related problems
  - ☐ Lost revenue to business
  - ☐ Others (please specify)
- ☐ No

19. Please determine your data sources that are used in LCCA:

- ☐ Own Computerized Data Base
- ☐ Own archives
- ☐ Other DOT archives or Data Base
- ☐ Consultants
- ☐ Other

____

Section 4: LCCA Application

20. Do your project contracts include any condition for using LCCA?

- ☐ Yes
- ☐ No

21. Is LCCA used in selecting winning bidders?

☐ Yes, always

☐ No

☐ Sometimes, please
explain____

22. What are the major reasons that are considered for applying LCCA in your DOT?

(List them according to importance in your opinion)

1)________________________________
2)________________________________
3)________________________________

23. How do you rate the use of LCCA in your DOT?

☐ Successful
(explain)____

☐ Neither successful nor unsuccessful

☐ Unsuccessful

24. Do you have a database or reports that document the use of LCCA in your department?

☐ Yes

☐ No

25. In your opinion, the use of LCCA in DOT projects should?

☐ Not be used (please explain)

☐ Be used the same as it is (please explain)

☐ Be used more often (please explain)

26. In your opinion, what are the pros and cons of using LCCA for project evaluation?

Cycle-Cost-Analysis Survey Results

General - 1

State DOT	Unit	Lane-Miles of Highways	Annual Budget	% of Annual Budget*	No. of Employees	Practice of LCCA
Arkansas	Roadway Design					Yes
California	65	60,000	8.3 Bil	80,15,5	23000	Yes
Colorado	Pavement Design/Management	22,759	946 Mil	73.3,16.6,10	3296	Yes
Connecticut	1310	11,400	621 Mil	73,24,3	4000	No
Delaware	Pavement Management	11,111	36 Mil (Pav. Rehab.)	100	1000	Yes
Iowa	Pavement Design/Management	22,500	770 Mil	60,20,20	3800	Yes
Maine	Transportation Research	15,900			1500	No
Michigan	Pavement Management	13,000 (Centerline)	1.7 Bil	84,14,2	3000	Yes
Mississippi	Roadway Design Division & Research	27,000	800 Mil	74,17,1	3200	Yes
Montana	Pavement Analysis & Research	12,000	380 Mil	64,22,7	2000	No
Nebraska	Pavement Design	10,000	360 Mil		46	Yes
New Hampshire	Commissioner's Office	9,221	306 Mil	75,25	2421	No
New York	Materials Bureau	36,000				Yes
North Dakota	Planning & Programming	16,000	250 Mil	80,15,5	1000	Yes
Ohio	Pavement Engineering Office	19,000	1.2 Bil		5882	Yes
Oklahoma	Research & Development	12,200	1093 Mil	79,12,4	2476	No
Pennsylvania	Bureau Of Maintenance And Operation	40,000	2.6 Bil	50,45,5	12000	Yes
South Carolina	Engineering/Planning	89,359	904 Mil	66,19,15	5400	No
Utah	Pavement Management	6,000	860 Mil	55,8,1	1800	Yes
Virginia	Research Council		3 Bil	50,33,17	10400	Yes
Washington	Materials Lab	17,900	807 Mil	53,10,37	6800	Yes
Wyoming	Planning	6,000	250 Mil	70,15,5	1950	

*** : % of Annual Budget : Construction and Rehabilitation, Road Maintenance, Other Project**

Life-Cycle-Cost-Analysis Survey Results

General LCCA Methodology - 2

State DOT	Period of Using LCCA	Who Perform LCCA	Formal Guide-Lines	Type of Projects	Criteria For LCCA	Software	In Comb. w/ Value Eng.	LCCA & Pay Sched.
Arkansas	> 25 Yrs	Roadway Design	No	Pavement	Only Major Interstate	No	In Design Stages	No
California	N/A	District, Structures, Maintenance	Yes	Pavement, Bridges, ITS, Program Development	All Projects	No	In Design Stages	
Colorado	From 1990	Regional Material Engineer, Consultant	Yes	Pavement, Bridges	> 1 Mil.	Darwin	In Design Stages	No
Connecticut								
Delaware	8 Yrs	Materials & Research	No	Pavement	No Criteria	No	No, In Future	No
Iowa	20 Yrs	Design	No	Pavement	All New Construction Replacement	No	In Design Stages	No, In Future
Maine								
Michigan	Mid 80's	Pavement Management Unit	Yes	Pavement	> 1 Mil	No	No, In Future	No
Mississippi	20 Yrs	Roadway Design	No	Pavement	New Const., Federal Aid	Yes	No	No.
Montana								
Nebraska	30 Yrs	Pavement Design Section	Yes	Pavement	New Const.	Yes, DNPS86, Darwin	Yes, In Design Stages	No
New Hampshire								
New York	17 Yrs	Design, Materials Engineers	Yes	Pavement	More than one Alternative	Yes	No, In Future	No
North Dakota	N/A	Design Division	No	Pavement	No	No	No	No
Ohio	>25 Yrs	Pavement Specialist	Yes	Pavement	No	No	No	No
Oklahoma								

State DOT	Period of Using LCCA	Who Perform LCCA	Formal Guide-Lines	Type of Projects	Criteria For LCCA	Software	In Comb. w/ Value Eng.	LCCA & Pay Sched.
Pennsylvania	1980	Pavement Design	Yes	Pavement	Interstate >1 Mil., All Projects>10 Mil.	Yes, Customized	Yes, In Design Stages	No
South Carolina								
Utah	10 Yrs	Pavement Management Engineers	Yes	Pavement	More than Alternative	No	No, In Future	No
Virginia	> 8 Yrs	Materials, Bridges, Equipment, Research	No	Pavement, Bridges, Equipment	> 5 Mil.	Yes, Customized	Yes, In Design	No
Washington	1992	Materials , Design Offices	Yes	Pavement	No	Yes, Customized	Yes, In Design Stages	No
Wyoming	10 Yrs	Materials, Bridges	No	Pavement, Bridges	No, Case by case	Yes	Yes, In Design Stages	No

Life-Cycle-Cost-Analysis Survey Results
LCCA Parameters and Data – 3

State	Specify Values*	Discount Rate	Inflation Rate	Analysis Period	Social Costs	Data Sources
Arkansas	Disc.,Inf., Ana.	3.8 %	3 %	35 Yrs	No	Own Archives
California	Disc., Inf., Ana., User, Social	4 %	2-3%	Different	Environmental, Labour, Lost Revenue	Other DOT Data Base
Colorado	Disc., Ana.,User	4 %	NA	30 Yrs	No	Own Archives, Database
Connecticut						
Delaware	Non	4 %	Varies	35 – 50 Yrs	No	Own Archives, Database, Consultants
Iowa	Disc., Ana.	3 %	N/A	40 Yrs	No	Own Archives, Database, Others
Maine						
Michigan	Disc., Ana., User	4.2 % OMB	Non	Varies	No	Own Archives, Database, Others
Mississippi	Disc.4-7 %, Inf. 1-3 %., Ana.: 40 Yrs, User, Social	Market Interest Rate		40 Yrs	No	Own Archives, Database, Others
Montana						
Nebraska	Disc., Inf., Ana., User	3.08 %	Non	50 Yrs	No	Own Archives, Database
New Hampshire						
New York	Disc., Ana.	4 %	N/A	30 Yrs	No	Own Archives, Database
North Dakota	Non	N/A	N/A	N/A	No	Own Archives
Ohio	Ana.	0 – 6 %	Non	35 Yrs	No	Own Archives, Database, Others
Oklahoma						
Pennsylvania	Inf., Ana., User		Inf. = Current Index/1972 Index	40 Yrs	No	Own Database, Const. Mana. System
South Carolina						
Utah	Disc.	4 %	Non	Varies	No	Own Database

State	Specify Values*	Discount Rate	Inflation Rate	Analysis Period	Social Costs	Data Sources
Virginia	Non	5 %	Non	Varies	No	Own Database, Consultants
Washington	Disc., Ana., User	4 %	N/A	40 Yrs	No	Own Database
Wyoming	Inf., Ana.	N/A	N/A	Varies	No	Own Archives, Database

- **Disc. : Discount Rate, Inf. : Inflation Rate, Ana. : Analysis Period, User : User Cost, Social : Social Cost**

Life-Cycle-Cost-Analysis Survey Results

LCCA Application - 4

State	Project Contracts	Selection Of Bidders	Reasons For LCCA	Rating Of LCCA practice	Available Reports	Recommend. Of LCCA Usage
Arkansas	No	No	Evaluating Alternatives	Neither Successful./Unsuccessful	No	Be Used As Same
California	N/A	Yes	Using Taxes Efficiently, Saving Money, Tight Budget	Successful	No	Be Used As Same
Colorado	No	No	Economically Sound Decisions, Unbiased, Cost-Effective	Successful	Yes	Be Used More Often.
Connecticut						
Delaware	No	No	Best Value, Look At Annual Maintenance Cost	Neither Successful./Unsuccessful	No	Be Used More Often
Iowa	No	No	Using Taxes Efficiently	Successful	No	Be Used More Often
Maine						
Michigan	No	Yes	Evaluating Alternatives, Evaluating User Delay Costs	Successful	No	Be Used The Same
Mississippi	No	No	Most Economical	Successful	No	Be Used The Same
Montana						
Nebraska	No	No	Insure Best Material, Review Alternatives	Successful	No	Be Used The Same
New Hampshire						
New York	Yes	No	Evaluating Alternatives	Neither Successful./Unsuccessful	No	Not Be Used : Should Include User Cost
North Dakota	No	No	FHWA Desire, Dispute Over Use Of PCC/AC	Neither Successful./Unsuccessful	No	Be Used The Same
Ohio	No	No	Size Of Project	Neither Successful./Unsuccessful	Yes	Be Used The Same
Oklahoma						

State	Project Contracts	Selection Of Bidders	Reasons For LCCA	Rating Of LCCA practice	Available Reports	Recommend. Of LCCA Usage
Pennsylvania	No	No	Determine Total Cost, Keep Parity, Determine Alternatives	Successful	No	Be Used The Same
South Carolina						
Utah	No	No	Evaluating Pavement Alternatives	Neither Successful./Unsuccessful	No	Be Used More Often
Virginia	No	No	Saving Money	Successful	No	Be Used More Often
Washington	No	No	Lowest Cost Over Time, Account For User Cost, Document Selection	Successful	No	Be Used More Often
Wyoming	No	No		Neither Successful./Unsuccessful	Yes	Be Used More Often

APPENDIX 3: DERIVATION OF LCCA BASIC FORMULAS (15)

This appendix will present the standard derivation of formulas used in LCCA guidelines The following notation will be used for derivations:

P = The present-day cost or value; the present sum of money.
F = The cost sum at a future date, n interest payment periods from the present
A = End-of-period annuity
r = Value in decimals representing specific change over time periods; discount rate per period of time
n = Number of discount periods; number of period-end payments; it is mostly expressed in years

Single Present Sum

If P is the present cost-sum and it is invested at a discount rate r:
the interest for the first year is rP and the total amount at the end of the first year is $P+rP= P(1+r)$.
The second year the interest on this is $rP(1+r)$, and the amount at the end of this year is $P(1+r)+iP(1+r)=P(1+r)^2$. Similarly, at the end of the third year the amount is $P(1+r)^3$; at the end of n year years it is $P(1+r)^n$.
This is the formula for the compound future amount, F, obtainable in n years from a principal, P,

$$F = P(1+r)^n \quad \text{.....(11)}$$

If we express P in terms of F, r, and n,

$$P = F\left[\frac{1}{(1+r)^n}\right] \quad \text{.....(12)}$$

P may be then thought of as the principal that will give a required amount F in n years; in other words, P can be considered as the present worth of a payment of F, after n years

Uniform Annual Series of End-of-year Payments

If A is invested at the end of each year for n years, the total amount at the end of n years will obviously be the sum of the compound amounts of the individual investments. The money invested at the end of the first year will earn interest for $(n-1)$ years; its amount will thus be $A(1+r)^{n-1}$. The second year's payment will amount to $A(1+r)^{n-2}$; the third year's to $A(1+r)^{n-3}$; and so on until the last payment, made at the end of n years, which has earned no interest.

The total amount F is $A\left[1+(1+r)+(1+r)^2 .... +(1+r)^{n-1}\right]$

This expression for F in terms of A may be simplified to its customary form by the following algebraic manipulations:

$$F = A\left[1+(1+r)+(1+r)^2 .... +(1+r)^{n-2}+(1+r)^{n-1}\right]$$

$$F = A\sum_{t=1}^{n}(1+r)^{t-1} \quad \text{.....(13)}$$

Multiplying both sides of the equation by (1+r)

$$(1+r)F = A\left[(1+r)+(1+r)^2.......+(1+r)^{n-1}+(1+r)^n\right] = A\sum_{t=1}^{n}(1+r)^t$$

Subtracting the original equation from this second equation

$$iF = A\left[(1+r)^n - 1\right]$$

Then

$$A = F\left[\frac{i}{(1+r)^n - 1}\right] \qquad (14)$$

To find the uniform end-of-year payment, *A*, which can be secured for *n* years from a present investment, *P*, by substituting the value *F* calculated earlier in the last equation:

$$A = F\left[\frac{r}{(1+r)^n - 1}\right] = P(1+r)^n\left[\frac{r}{(1+r)^n - 1}\right] = P\left[\frac{r(1+r)^n}{(1+r)^n - 1}\right]$$

which can be expressed also as :

$$A = P\left[\frac{r}{(1+r)^n - 1} + r\right] \qquad (15)$$

Derivation of the exact Real Discount Rate

The nominal discount rate is the discount rate that is not adjusted to remove the effects of actual or expected inflation. The real discount rate is rate that has been adjusted to eliminate the effect of expected inflation.

Following the same notation defined in the previous section and adding to it the following:

PW =	Present worth of a future sum or cost
F' =	Cost of performing future services taking into account the effects of inflation
f =	Inflation rate; the proportionate rate of change in the general price level, as opposed to the proportionate increase in a specific price. Inflation is usually measured by a broad-based price index, such as the implicit deflator for Gross Domestic Product or the Consumer Price Index.
i =	Market interest rate
r^*=	Real discount rate

To calculate the effects of inflation on the cost of certain services (Cost at present = *P*) after *n* years employing equation (1):

$$F' = P(1+f)^n \qquad (16)$$

To calculate the present worth (*PW)* of the calculated inflated cost (*F)* with respect to the time value of money, we employ equation (2):

$$PW = F'\left[\frac{1}{(1+i)^n}\right] \qquad (17)$$

By substituting *F'* in the above two equations we arrive at:

$$PW = P\left[\frac{1+f}{1+i}\right]^n \text{ ....(18)}$$

Defining the discount rate as the rate when applied to the current (non-inflated) cost of services, it will account for inflation and the time value of money if the services were to be performed n years from present:

$$PW = P\left[\frac{1}{1+r^*}\right]^n \text{ ....(19)}$$

Substituting

$$\left[\frac{1}{1+r^*}\right]^n = \left[\frac{1+f}{1+i}\right]^n$$

Resulting in

$$r^* = \frac{1+i}{1+f} - 1 \text{ ....(20)}$$

which could be written as

$$r^* = \frac{i-f}{1+f} \text{ ....(21)}$$

APPENDIX 4: LCCA EXAMPLE W/ USER COST DURING WORK-ZONE

Compare two alternatives for reconstruction of the outbound direction of a suburban expressway on a 6-lane highway (three lanes in each direction). The total length of the segment is 5 mile. The average daily traffic for the base year is 62,500 vehicles, consisting of 10% commercial traffic, forecasted to increase at a growth rate of 2.0 percent. The unrestricted upstream approach speed is posted at 55 mph and the grades on the facility are less than 2 percent.

A 5.0-mile work zone will be in place from 10AM to 3 PM and 8PM to 5AM the following morning, with a single lane closure. Work zone posted speed is 40 mph. The work zone will be in place for 30 days during overlays.

Alternative 1: 10” HMAC Flexible Pavement with 1.5” overlay in Year 30 and 40

ALTERNATIVE 1:

NYS Design Case Number	**8**	
HMAC Layer Thickness	**10**	inch
Permeable AC Base	**4**	inch
Subbase	**12**	inch
Select Granular Fill	**12**	inch
Cost per Lane-mile w/OH ($)	**$ 358,414.00**	

Age	Prediction Models			MR&R Strategies				Agency Cost
Year	Predicted IRI (inch/mile)*	Predicted Rutting (inch)*	Predicted Thermal Cracking (spacing-ft)*	Predicted Maintenance Strategy	Required Crack Fill (LF)	Required Shimming (TON)	Required Overlay (SF)	Estimated Agency Cost
0.0	26.00	0.00	0.00	Initial Construction	-	-	-	7,168,280.00
5.0	66.79	0.28	37.01	Crack Fill	34,241.68	-	-	74,646.85
10.0	80.44	0.32	23.76	Shim & Fill	53,337.62	157.85	-	394,648.57
15.0	90.18	0.35	18.33	Crack Fill	69,123.60	-	-	150,689.45
20.0	98.18	0.37	15.25	Shim & Fill	83,083.00	182.63	-	462,155.66
25.0	105.20	0.39	13.22	Crack Fill	95,824.47	-	-	208,897.35
30.0	111.60	0.41	11.77	Overlay 1.5"	107,672.53	200.59	950,400.00	952,614.92
30.0	66.79	0.28	37.01					
35.0	80.44	0.32	23.76	Crack Fill	53,333.33	-	-	116,266.67
40.0	90.18	0.35	18.33	Overlay 1.5"	69,132.57	173.25	950,400.00	865,661.05
40.0	66.79	0.28	37.01					
45.0	80.44	0.32	23.76	Crack Fill	53,333.33	-	-	116,266.67
50.0	90.18	0.35	18.33	End Life	-	-	-	-

Roughness:

~ Initial = 26.00 inch/mile

~ Terminal = 170.00 inch/mile

Rutting:

~Low severity-less than 0.38 inch

~Medium severity-greater than 0.38 through 0.75 inch

~High severity greater than 0.75 inch

Note: The above table shows the quantities and costs for 5-mile segment.

Alternative 2: 11” PCC Slab- Rigid Pavement with no Overlay

ALTERNATIVE 2:								
Design Case Number		**4**						
PCC Slab Thickness		**11**	inch					
Permeable AC Base		**4**	inch					
Subbase		**12**	inch					
PCC Slab Length		**18**	feet					
Cost per Lane-mile w/OH ($)		**$ 663,280.77**						
Dowel Bar Diameter (inch)		**1.38**	inch					
Age	**Prediction Models**			**MR&R Strategies**				**Agency Cost**
Year (Six Month Interval)	**Predicted IRI (inch/mile)***	**Predicted Faulting (inch)**	**Predicted Spalling (% slab)**	**Predicted Maintenance Strategy**	**Required Sealing (LF)**	**Required Patching (SF)**	**Required Grinding (SF)**	**Estimated Agency Cost**
0.0				Initial Construction	-	-	-	13,265,615.42
5.0	79.67	-	1.57					-
10.0	83.64	-	2.66	Seal & Patch	184,800.00	25,275.67	-	979,825.81
15.0	87.62	-	3.74					-
20.0	91.59	-	4.83	Seal & Patch	184,800.00	45,891.43	-	1,268,034.17
25.0	95.57	0.01	5.91					-
30.0	99.54	0.04	7.00	Seal & Patch	184,800.00	66,507.19	-	1,556,242.54
35.0	103.52	0.08	8.08					-
40.0	107.49	0.13	9.17	Seal & Patch	184,800.00	87,122.96	-	1,844,450.91
45.0	111.47	0.20	10.25	Grind & Reseal	184,800.00	-	356,400.00	932,976.00
50.0	115.44	0.27	11.34	End Life	-	-	-	-
Roughness:			**Faulting:**					
~ Initial = 26.00 inch/mile			**Critical faulting, which effects roughness, is greater than 0.19 inches.**					
~ Terminal = 170.00 inch/mile			**~Low severity-less than 0.38 inch**					
			~Medium severity-greater than 0.38 through 0.75 inch					
			~High severity greater than 0.75 inch					

Note: The above table shows the quantities and costs for 5-mile segment.

Assumptions:

It is assumed that the initial construction period for the flexible pavement and rigid pavement is the same and therefore work zone user cost during the initial construction period is not considered.

Work zone is assumed to be in place only during the major rehabilitation, for example, overlays. No work zone is considered, during shimming, crack filling, sealing or patching.

The life of 1.5” overlay is 10 year and therefore no salvage value is considered at the end of analysis period in year 50.

Work Zone User Cost Calculation

Step 1: Project Future Year Traffic Demand

Future Year AADT = Base Year x Vehicle Class percent x $(1+\text{growth rate})^{(\text{Future Yr. – Base Yr.})}$

Projected Year 30 AADT

Passenger Vehicles = $62500 \times 0.90 \times (1.02)^{(30)}$ = 101, 889
Trucks = $62500 \times 0.10 \times (1.02)^{(30)}$ = 11, 321
Total Traffic = 113,210

Projected Year 40 AADT

Passenger Vehicles = $62500 \times 0.90 \times (1.02)^{(40)}$ = 124, 202
Trucks = $62500 \times 0.10 \times (1.02)^{(40)}$ = 13,800
Total Traffic = 138,002

Step 2: Calculate Work Zone Directional Hourly Demand

The agency data should be used for directional hourly traffic distribution. If not available, then default hourly distribution factors generated by MicroBENCOST and presented in FHWA Report[1] can be used. The following table presents the directional hourly traffic distribution for the inbound and outbound trips. In this example, we would be using the outbound trips.

Directional Hourly Traffic Distribution

Year 30 AADT = 113210
Year 40 AADT = 138002

Hour (24-Hour Clock)	% ADT	Default Factors		Year 30 Demand		Year 40 Demand	
		Inbound	Outbound	Inbound	Outbound	Inbound	Outbound
0 - 1	1.2	47	53	639	720	778	878
1 - 2	0.8	43	57	389	516	475	629
2 - 3	0.7	46	54	365	428	444	522
3 - 4	0.5	48	52	272	294	331	359
4 - 5	0.7	57	43	452	341	551	415
5 - 6	1.7	58	42	1116	808	1361	985
6 - 7	5.1	63	37	3637	2136	4434	2604
7 - 8	7.8	60	40	5298	3532	6458	4306
8 - 9	6.3	59	41	4208	2924	5130	3565
9 -10	5.2	55	45	3238	2649	3947	3229
10 - 11	4.7	46	54	2448	2873	2984	3502
11 - 12	5.3	49	51	2940	3060	3584	3730
12 -13	5.6	50	50	3170	3170	3864	3864
13 -14	5.7	50	50	3226	3226	3933	3933
14 - 15	5.9	49	51	3273	3406	3990	4152
15 - 16	6.5	46	54	3385	3974	4126	4844
16 -17	7.9	45	55	4025	4919	4906	5996
17 - 18	8.5	40	60	3849	5774	4692	7038
18 -19	5.9	46	54	3073	3607	3745	4397
19 - 20	3.9	48	52	2119	2296	2583	2799
20 -21	3.3	47	53	1756	1980	2140	2414
21 -22	2.8	47	53	1490	1680	1816	2048
22 -23	2.3	48	52	1250	1354	1524	1651
23 -24	1.7	45	55	866	1059	1056	1290
			Total	**56483**	**56727**	**68852**	**69150**

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[1] FHWA-SA-98-079, "Life Cycle Cost Analysis in Pavement Design", Pavement Division Interim Technical Bulletin, September 1998.

Step 3: Determine Roadway Capacity

In analyzing work zone user costs, there are three capacities that need to be determined:

Free flow capacity of the facility under normal operating condition
Capacity of the facility when work zone is in place
Capacity of the facility to dissipate traffic from a standing queue

The Highway Capacity Manual (HCM) procedure should be used to determine the capacity of a facility. The FHWA Report[2] uses the 1994 HCM procedure to calculate the capacity and presents all corresponding tables and charts. However, it is recommended that the latest version of HCM (current version: HCM 2000) should be used.

Free-Flow Capacity

Using Table 3.4 FHWA Report or Table 3-4, 1994 HCM, for 10 percent truck and highway grade of less than 2 percent,

Truck equivalency factor =1.5

Table 3.6 (6-Lane facilities), with a truck factor of 1.5 and truck percentage of 10 percent,

Free-flow capacity = 2,190 veh/hr/ln
Total free-flow capacity for 3-lanes = 6,570 veh/hr

Work Zone Capacity

Using Table 3.8 for 3-lane facility with –1-lane closure and 50 percent reliability,
Average work zone capacity = 2,980 veh/hr
50 percent reliability indicate that half of the time the capacity will be greater than 2,980 and half the time less than 2,980. Here we use a reliability factor of 80 percent. From Figure 3.4,
Work zone capacity = 1,415 veh/hr/ln
Total Work zone capacity (2-Lane operated) = 2,830 veh/hr/ln
The 80 percent reliability indicates that the work zone capacity will be at least equal to 2,830 vehicles per hour 80 percent of the time.

Queue Dissipation Rate

Capacity during queue dissipation is less than the capacity for free-flow conditions, even though the lanes are unrestricted. This rate comes into play when work zone

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is in place for certain hours of the day, that is, when work zones are removed during peak traffic flow period. Using Table 3.7,
Average queue dissipation capacity = 1,818 veh/hr/ln
Total queue dissipation capacity (3-lanes) = 5,454 veh/hr

Step 4: Identify User Cost Components

Compare the roadway capacity with hourly demand.

Work Zone Analysis Matrix (Year 30)

AADT =	113210		Queue Rate	Number of Queued Vehicles	Lanes Open	Operating Conditions	Cost factors
Hour (24-Hour Clock)	**Outbound Demand**	**Capacity**					
0 - 1	720	2830	-2110	0	2	Free-flow work zone in place, no queue	1.Speed change VOC in WZ 2. Speed change delays in WZ 3. Traversing delays in WZ
1 - 2	516	2830	-2314	0			
2 - 3	428	2830	-2402	0			
3 - 4	294	2830	-2536	0			
4 - 5	341	2830	-2489	0			
5 - 6	808	6570	-5762	0	3	Free-flow, no work zone, no queue	No Costs
6 - 7	2136	6570	-4434	0			
7 - 8	3532	6570	-3038	0			
8 - 9	2924	6570	-3646	0			
9 -10	2649	6570	-3921	0			
10 - 11	2873	2830	43	43	2	Forced flow, WZ in place, queue exists	1.Stopping VOC 2. Stopping Delay 3. Idling VOC 4. Crawling delay in queue 5. Free-flow delay in traversing WZ
11 - 12	3060	2830	230	273			
12 -13	3170	2830	340	613			
13 -14	3226	2830	396	1009			
14 - 15	3406	2830	576	1586			
15 - 16	3974	5454	-1480	106	3	Partial forced flow, no WZ, queue exists in first hour	1.Stopping VOC 2. Stopping Delay 3. Idling VOC 4. Crawling delay in queue
16 -17	4919	5454	-535	0			
17 - 18	5774	6570	-796	0			
18 -19	3607	6570	-2963	0			
19 - 20	2296	6570	-4274	0			
20 -21	1980	2830	-850	0	2	Free-flow work zone in place, no queue	1.Speed change VOC in WZ 2. Speed change delays in WZ 3. Traversing delays in WZ
21 -22	1680	2830	-1150	0			
22 -23	1354	2830	-1476	0			
23 -24	1059	2830	-1771	0			

Notes:
1. Shaded areas represents hours the work zone is in place.
2. Once build queue dissipate, the capacity returns from queue dissipating to free-flow.

Work Zone Analysis Matrix (Year 40)

AADT =	138002		Queue Rate	Number of Queued Vehicles	Lanes Open	Operating Conditions	Cost factors
Hour (24-Hour Clock)	Outbound Demand	Capacity					
0 - 1	878	2830	-1952	0	2	Free-flow work zone in place, no queue	1.Speed change VOC in WZ
1 - 2	629	2830	-2201	0			2. Speed change delays in WZ
2 - 3	522	2830	-2308	0			3. Traversing delays in WZ
3 - 4	359	2830	-2471	0			
4 - 5	415	2830	-2415	0			
5 - 6	985	6570	-5585	0	3	Free-flow, no work zone, no queue	No Costs
6 - 7	2604	6570	-3966	0			
7 - 8	4306	6570	-2264	0			
8 - 9	3565	6570	-3005	0			
9 -10	3229	6570	-3341	0			
10 - 11	3502	2830	672	672	2	Forced flow, WZ in place, queue exists	1.Stopping VOC
11 - 12	3730	2830	900	1572			2. Stopping Delay
12 -13	3864	2830	1034	2606			3. Idling VOC
13 -14	3933	2830	1103	3709			4. Crawling delay in queue
14 - 15	4152	2830	1322	5032			5. Free-flow delay in traversing WZ
15 - 16	4844	5454	-610	4422	3	Forced flow, no WZ, queue exists	1.Stopping VOC
16 -17	5996	5454	542	4964			2. Stopping Delay
17 - 18	7038	5454	1584	6548			3. Idling VOC
18 -19	4397	5454	-1057	5491			4. Crawling delay in queue
19 - 20	2799	5454	-2655	2835			
20 -21	2414	2830	-416	2419	2	Forced-flow work zone in place, queue exists	1,2. Stopping VOC and delay
21 -22	2048	2830	-782	1637			3. Idling VOC
22 -23	1651	2830	-1179	457			4. Crawling delay in queue
23 -24	1290	2830	-1540	0			5. Free-flow delay in traversing WZ

Notes:

1. Shaded areas represents hours the work zone is in place.
2. Once build queue dissipate, the capacity returns from queue dissipating to free-flow.

Step 5: Quantify Traffic Affected by Each Cost Component

This step quantifies the number of vehicles involved with each cost component, that is, the number of the vehicles that (i) traverse the work zone, (ii) traverse the queue, (iii) stop for the queue, and (iv) those that merely have to slow down.

Expanded Work Zone Matrix (Year 30)

Operating Conditions

AADT =	113,210		Queue Rate	Number of Queued Vehicles	Number of Vehicles tha		
Hour (24-Hour Clock)	Outbound Demand	Capacity			Traverse Work Zone	Traverse Queue	Stop 55-0-55 (mi/h)
0 - 1	720	2,830	(2,110)	-	720	-	-
1 - 2	516	2,830	(2,314)	-	516	-	-
2 - 3	428	2,830	(2,402)	-	428	-	-
3 - 4	294	2,830	(2,536)	-	294	-	-
4 - 5	341	2,830	(2,489)	-	341	-	-
0 - 5					2,299	-	-
5 - 6	808	6,570	(5,762)	-	-	-	-
6 - 7	2,136	6,570	(4,434)	-	-	-	-
7 - 8	3,532	6,570	(3,038)	-	-	-	-
8 - 9	2,924	6,570	(3,646)	-	-	-	-
9 -10	2,649	6,570	(3,921)	-	-	-	-
5 - 10					-	-	-
10 - 11	2,873	2,830	43	43	2,830	2,830	2,873
11 - 12	3,060	2,830	230	273	2,830	2,830	3,060
12 -13	3,170	2,830	340	613	2,830	2,830	3,170
13 -14	3,226	2,830	396	1,009	2,830	2,830	3,226
14 - 15	3,406	2,830	576	1,586	2,830	2,830	3,406
10 - 15					14,150	14,150	15,735
15 - 16	3,974	5,454	(1,480)	106	-	5,454	3,974
16 -17	4,919	5,454	(535)	-	-	1,076	971
17 - 18	5,774	6,570	(796)	-	-	-	-
18 -19	3,607	6,570	(2,963)	-	-	-	-
19 - 20	2,296	6,570	(4,274)	-	-	-	-
15 - 20					-	6,530	4,945
20 -21	1,980	2,830	(850)	-	1,980	-	-
21 -22	1,680	2,830	(1,150)	-	1,680	-	-
22 -23	1,354	2,830	(1,476)	-	1,354	-	-
23 -24	1,059	2,830	(1,771)	-	1,059	-	-
20 - 24					6,073	-	-
0 - 24					22,522	20,680	20,680

Notes:

1. Shaded areas represents hours the work zone is in place.
2. Once build queue dissipate, the capacity returns from queue dissipating to free-flow.
3. *Values shown are prorated based on the portion of the hour required to clear the queue (106/535*5454) and (106/535*4949)

Expanded Work Zone Matrix (Year 40)

Operating Conditions

AADT =	138,002		Queue Rate	Number of Queued Vehicles	Number of Vehicles tha		
Hour (24-Hour Clock)	Outbound Demand	Capacity			Traverse Work Zone	Traverse Queue	Stop 55-0-55 (mi/h)
0 - 1	878	2,830	(1,952)	-	878	-	-
1 - 2	629	2,830	(2,201)	-	629	-	-
2 - 3	522	2,830	(2,308)	-	522	-	-
3 - 4	359	2,830	(2,471)	-	359	-	-
4 - 5	415	2,830	(2,415)	-	415	-	-
0 - 5					2,803	-	-
5 - 6	985	6,570	(5,585)	-	-	-	-
6 - 7	2,604	6,570	(3,966)	-	-	-	-
7 - 8	4,306	6,570	(2,264)	-	-	-	-
8 - 9	3,565	6,570	(3,005)	-	-	-	-
9 -10	3,229	6,570	(3,341)	-	-	-	-
5 - 10					-	-	-
10 - 11	3,502	2,830	672	672	2,830	2,830	3,502
11 - 12	3,730	2,830	900	1,572	2,830	2,830	3,730
12 -13	3,864	2,830	1,034	2,606	2,830	2,830	3,864
13 -14	3,933	2,830	1,103	3,709	2,830	2,830	3,933
14 - 15	4,152	2,830	1,322	5,032	2,830	2,830	4,152
10 - 15					14,150	14,150	19,181
15 - 16	4,844	5,454	(610)	4,422	-	5,454	4,844
16 -17	5,996	5,454	542	4,964	-	5,454	5,996
17 - 18	7,038	5,454	1,584	6,548	-	5,454	7,038
18 -19	4,397	5,454	(1,057)	5,491	-	5,454	4,397
19 - 20	2,799	5,454	(2,655)	2,835	-	5,454	2,799
15 - 20					-	27,270	25,074
20 -21	2,414	2,830	(416)	2,419	2,830	2,830	2,414
21 -22	2,048	2,830	(782)	1,637	2,830	2,830	2,048
22 -23	1,651	2,830	(1,179)	457	2,830	2,830	1,651
23 -24	1,290	2,830	(1,540)	-	1,748	841	383
20 - 24					10,238	9,331	6,496
0 - 24					27,191	50,751	50,751

Notes:

1. Shaded areas represents hours the work zone is in place.
2. Once build queue dissipate, the capacity returns from queue dissipating to free-flow.
3. *Values shown are prorated based on the portion of the hour required to clear the queue (457/1540*2830) and (457/1540*12

Step 6: Compute Reduced Speed Delays

The next step is the computation of the delay time through the work zone and queue.

WZ Delay = WZ Length / WZ Speed – WZ Length / Upstream Speed

Queue Delay = Queue Length / Queue Speed – Queue Length / Upstream Speed

Work Zone Reduced Speed Delay

Work Zone Length (Miles)	Time at 40 mi/h (Hours)	Time at 55 mi/h (Hours)	Work Zone Delay /Veh.	
			(Hours)	(Minutes)
5.00	5/40 = 0.125	5/55=0.0909	0.0341	2.0

Queue Reduced Speed Delay

Queue reduced speed delay is computed in the same manner, however; first we need to calculate queue speed and queue length.

Queue Speed Calculations:

Speed through the queue can be determined by using the *Forced-Flow Average Speed* versus *Volume to Capacity (V/C)* ratio graph for level of service F contained in the earlier editions of the *Highway Capacity Manual* and presented in FHWA – SA-98-079 Figure 3.5.

Factors	Daily Time Period		
	10 a.m. – 3 p.m.	3 p.m. – 8 p.m.	p.m. – 11 p. m
Volume (Queue)*	2,830	5,454	2,830
Capacity (Roadway)**	6,570	6,570	6,570
V/C	0.43	0.83	0.43
Speed	8 mi/h	18 mi/h	8 mi/h

This is the volume that moves out of the queue in a 1-hour period.
The queue forms upstream of the work zone (3-lanes)

Queue Length Calculation:

The next step is to determine the hourly queue lengths from the average number of queue vehicles for each hour as shown in the following table.

Average Queue Length Calculations - 30 Year

	Volume		**Speed**		**Density**			**Average No. of Queued Vehicles**
Hour (24-Hour Clock)	**Through Queue**	**Up Stream of Queue**	**In Queue**	**Up Stream of Queue**	**In Queue**	**Up Stream of Queue**	**Change**	
(a)	(b)	(c)	(d)	(e)	(f=b/d)	(g=c/e)	(h=f-g)	(I)
10 - 11	2,830	2,873	8	55	354	52	302	22
11 - 12	2,830	3,060	8	55	354	56	298	158
12 -13	2,830	3,170	8	55	354	58	296	443
13 -14	2,830	3,226	8	55	354	59	295	811
14 - 15	2,830	3,406	8	55	354	62	292	1,298
Average for the 10 a.m. to 3 p.m.								**546**
15 - 16	5,454	3,974	18	55	303	72	231	846
16 -17	5,454	4,919	18	55	303	89	214	53
Average for 3 p.m. to 5 p.m.								**450**

Notes:

1. Average number of queued vehicle is the airthmetic average of the number of vehicles queued at the beginning and end of each hour.

Average Queue Delay Time - 30 Year

Period	**Average Queue Length (Miles)**	**Queue Speed**	**Time (hours)**		**Average Queue Delay Per Vehicle**	
			`@ Queue Speed	**`@ 55 mi/h**	**Hours**	**Minutes**
	(a)	(b)	(c = a/b)	(d = a/55)	(e = c-d)	
10 - 15	1.86	8	0.2323	0.0338	0.1985	11.91
15 - 17	1.96	18	0.1087	0.0356	0.0732	4.39

Average Queue Length Calculations - 40 Year

Hour (24-Hour Clock)	Volume		Speed		Density			Average No. of Queued Vehicles
	Through Queue	Up Stream of Queue	In Queue	Up Stream of Queue	In Queue	Up Stream of Queue	Change	
(a)	(b)	(c)	(d)	(e)	(f=b/d)	(g=c/e)	(h=f-g)	(I)
10 - 11	2,830	3,502	8	55	354	64	290	336
11 - 12	2,830	3,730	8	55	354	68	286	1,122
12 -13	2,830	3,864	8	55	354	70	283	2,089
13 -14	2,830	3,933	8	55	354	72	282	3,158
14 - 15	2,830	4,152	8	55	354	75	278	4,371
Average for the 10 a.m. to 3 p.m.								2,215
15 - 16	5,454	4,844	18	55	303	88	215	4,727
16 -17	5,454	5,996	18	55	303	109	194	4,693
17 - 18	5,454	7,038	18	55	303	128	175	5,756
18 -19	5,454	4,397	18	55	303	80	223	6,019
19 - 20	5,454	2,799	18	55	303	51	252	4,163
Average for 3 p.m. to 8 p.m.								5,072
20 -21	2,830	2,414	8	55	354	44	310	2,627
21 -22	2,830	2,048	8	55	354	37	317	2,028
22 -23	2,830	1,651	8	55	354	30	324	1,047
23 -24	2,830	1,290	8	55	354	23	330	229
Average for 8 p.m. to 12 a.m.								1,483

Notes:

1. Average number of queued vehicle is the airthmetic average of the number of vehicles queued at the beginning and end of each hour.

Average Queue Delay Time - 40 Year

Period	Average Queue Length (Miles)	Queue Speed	Time (hours)		Average Queue Delay	
			`@ Queue Speed	`@ 55 mi/h	Hours	Minutes
	(a)	(b)	(c = a/b)	(d = a/55)	(e = c-d)	
10 - 15	7.87	8	0.9837	0.1431	0.8406	50.44
15 - 20	24.51	18	1.3618	0.4457	0.9162	54.97
20 - 24	4.70	8	0.5879	0.0855	0.5024	30.14

Step 7: Select and Assign VOC Rates

Table 3.17 in FHWA Report shows additional hours of delay and additional VOC (in August 1996 dollars) associated with stopping 1000 vehicles from a particular speed and returning them to that speed for the three vehicle classes. To make these factors applicable to current analysis, the value shown in the following table have been escalated to reflect current year dollars. The escalation factor for VOC is determined by using the transportation component of the Consumer Price Index (CPI).

Escalation factor = 154.9 (Oct 2002) / 142.8 (August 1996) = 1.084

Added Time and Vehicle Running Cost /1000 Stops and Idling Costs

Initial Speed (mi/h)	Added Time (Hr/1000 Stops) (Excludes Idling Time)		Added Cost ($/1000 Stops) (Exclude Idling Time)	
	Passenger Cars	Trucks	Passenger Cars	Trucks
55	5.84	20.72	90.77	782.40
40	4.42	11.09	57.13	522.71
55-40-55	5.84-4.42=1.84	20.72-11.09=9.63	0.77-57.13=33.64	782.4-522.71=259.68
Idling cost ($ Veh- Hr)			0.7508	0.8940

Step 8: Select and Assign Delay Cost Rates

Table 3.19 in FHWA Report shows the range of recommended values of travel time ($/Veh-Hr) in August 1996 dollars. To make these factors applicable to current analysis, the following values have been escalated to reflect current year dollars. The escalation factor for delay cost is determined by using the *All Items* component of the Consumer Price Index (CPI).

Escalation factor = 181.3 (Oct 2002) / 152.4 (August 1996) = 1.189

Passenger Vehicles = $11.58 x 1.189 = $13.77/Veh-Hr
Trucks = $22.31 x 1.189 = $26.52/Veh-Hr

Step 9: Assign Traffic to Vehicle Classes (Summary of results from step 5)

Affected Traffic by Vehicle Class and User Cost Component

Cost Component	30-Years			40-Years		
	Affected Vehicle Mixed Flow	Passenger Vehicles (90%)	Trucks (10%)	Affected Vehicle Mixed Flow	Passenger Vehicles (90%)	Trucks (10%)
Speed Change (55-40-55)	8,372	7,535	837	3,710	3,339	371
Traverse WZ	22,522	20,270	2,252	27,191	24,472	2,719
Stopping (55-0-55)	20,680	18,612	2,068	50,751	45,676	5,075
Queue Delays (10-15)	14,150	12,735	1,415	14,150	12,735	1,415
Queue Delays (15-20)	6,530	5,877	653	27,270	24,543	2,727
Queue Delays (20-24)	-	-	-	9,331	8,398	933

Step 10: Compute User Cost Component by Vehicle Class

Daily user costs by vehicle class for each cost component are computed by multiplying the affected traffic by the appropriate unit cost rates (either VOC or delay) for the various components. The individual costs are computed in the following tables for year 30 and 40.

COST COMPONENTS FOR YEAR 30

User cost component #1 - speed change VOC (55-40-55 mi/h)

Vehicle Class	Affected vehicles	Added VOC (55-40-55) $/1,000 vehicles	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	7,535	33.64	253.48	7,604
Trucks	837	259.68	217.35	6,521
Total Speed change VOC	8,372		470.83	14,125

User cost component #2 - speed change delay cost (55-40-55 mi/h)

Vehicle Class	Affected vehicles	Added Time (55-40-55) Hrs/1,000 veh	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	7,535	1.84	13.77	190.91	5,727
Trucks	837	9.63	26.52	213.76	6,413
Total Speed change VOC	8,372			404.67	12,140

User cost component #3 - work zone reduced speed delay cost

Vehicle Class	Affected vehicles	Added Time Hours (from step 6)	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	20,270	0.0341	13.77	9,517.92	285,538
Trucks	2,252	0.0341	26.52	2,036.56	61,097
Total Speed change VOC	22,522			11,554.48	346,634

User cost component #4 - topping VOC (55-0-55 mi/h)

Vehicle Class	Affected vehicles	Added VOC (55-0-55) $/1,000 vehicles	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	18,612	90.77	1,689.41	50,682
Trucks	2,068	782.40	1,618.00	48,540
Total Speed change VOC	20,680		3,307.41	99,222

User cost component #5 - stopping delay cost (55-0-55 mi/h)

Vehicle Class	Affected vehicles	Added Time (55-0-55) Hrs/1,000 veh	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	18,612	5.84	13.77	1,496.72	44,902
Trucks	2,068	20.72	26.52	1,136.35	34,091
Total Speed change VOC	20,680			2,633.07	78,992

User cost component #6 - idling VOC

Vehicle Class	Affected vehicles	Added Time Hours (from step 6)	Idle VOC Rates ($/1000 Veh-Hr) (from step 7)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars			750.80		
10 a.m. - 3 p.m.	12,735	0.1985		1,897.95	56,938
3 p.m. - 8 p.m.	5,877	0.0732		322.99	9,690
8p.m - 11 a.m	-	-		-	-
Sub Total	18,612			2,220.94	66,628
Trucks			894.00		
10 a.m. - 3 p.m.	1,415	0.1985		251.10	7,533
3 p.m. - 8 p.m.	653	0.0732		42.73	1,282
8p.m - 11 a.m	-	-		-	-
Sub Total	2,068			293.84	8,815
Total idling VOC	20,680			2,514.77	75,443

User cost component #7 - queue reduced speed delay cost

Vehicle Class	Affected vehicles	Added Time Hours (from step 6)	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars			13.77		
10 a.m. - 3 p.m.	12,735	0.1985		34,809.15	1,044,274
3 p.m. - 8 p.m.	5,877	0.0732		5,923.80	177,714
8p.m - 11 a.m	-	-		-	-
Sub Total	18,612			40,732.95	1,221,989
Trucks			26.52		
10 a.m. - 3 p.m.	1,415	0.1985		7,448.87	223,466
3 p.m. - 8 p.m.	653	0.0732		1,267.65	38,029
8p.m - 11 a.m	-	-		-	-
Sub Total	2,068			8,716.52	261,496
Total idling VOC	20,680			49,449.47	1,483,484

COST COMPONENTS FOR YEAR 40

User cost component #1 - speed change VOC (55-40-55 mi/h)

Vehicle Class	Affected vehicles	Added VOC (55-40-55) $/1,000 vehicles	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	3,339	33.64	112.32	3,370
Trucks	371	259.68	96.34	2,890
Total Speed change VOC	3,710		208.67	6,260

User cost component #2 - speed change delay cost (55-40-55 mi/h)

Vehicle Class	Affected vehicles	Added Time (55-40-55) Hrs/1,000 veh	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	3,339	1.84	13.77	84.60	2,538
Trucks	371	9.63	26.52	94.75	2,842
Total Speed change VOC	3,710			179.35	5,380

User cost component #3 - work zone reduced speed delay cost

Vehicle Class	Affected vehicles	Added Time Hours (from step 6)	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	24,472	0.0341	13.77	11,491.00	344,730
Trucks	2,719	0.0341	26.52	2,458.88	73,766
Total Speed change VOC	27,191			13,949.88	418,496

User cost component #4 - topping VOC (55-0-55 mi/h)

Vehicle Class	Affected vehicles	Added VOC (55-0-55) $/1,000 vehicles	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	45,676	90.77	4,146.01	124,380
Trucks	5,075	782.40	3,970.68	119,120
Total Speed change VOC	50,751		8,116.69	243,501

User cost component #5 - stopping delay cost (55-0-55 mi/h)

Vehicle Class	Affected vehicles	Added Time (55-0-55) Hrs/1,000 veh	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars	45,676	5.84	13.77	3,673.12	110,194
Trucks	5,075	20.72	26.52	2,788.68	83,661
Total Speed change VOC	50,751			6,461.80	193,854

User cost component #6 - idling VOC

Vehicle Class	Affected vehicles	Added Time Hours (from step 6)	Idle VOC Rates ($/1000 Veh-Hr) (from step 7)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars			750.80		
10 a.m. - 3 p.m.	12,735	0.8406		8,037.34	241,120
3 p.m. - 8 p.m.	24,543	0.9162		16,882.71	506,481
8p.m - 11 a.m	8,398	0.5024		3,167.74	95,032
Sub Total	45,676			28,087.80	842,634
Trucks			894.00		
10 a.m. - 3 p.m.	1,415	0.8406		1,063.37	31,901
3 p.m. - 8 p.m.	2,727	0.9162		2,233.64	67,009
8p.m - 11 a.m	933	0.5024		419.05	12,572
Sub Total	5,075			3,716.06	111,482
Total idling VOC	50,751			31,803.86	954,116

User cost component #7 - queue reduced speed delay cost

Vehicle Class	Affected vehicles	Added Time Hours (from step 6)	Delay Cost rate ($) (per Veh-Hr)	Cost ($) per day	Total Costs ($) (30 days)
Passenger cars			13.77		
10 a.m. - 3 p.m.	12,735	0.8406		147,408.41	4,422,252
3 p.m. - 8 p.m.	24,543	0.9162		309,636.30	9,289,089
8p.m - 11 a.m	8,398	0.5024		58,097.77	1,742,933
Sub Total	45,676			515,142.49	15,454,275
Trucks			26.52		
10 a.m. - 3 p.m.	1,415	0.8406		31,544.19	946,326
3 p.m. - 8 p.m.	2,727	0.9162		66,259.62	1,987,789
8p.m - 11 a.m	933	0.5024		12,430.96	372,929
Sub Total	5,075			110,234.77	3,307,043
Total idling VOC	50,751			625,377.26	18,761,318

Step 11: Sum Total Work Zone User Costs

The following tables show a master summary of all costs, and the percent distributions of those costs. The first three cost components represents the cost associated with free-flow, while the remaining four cost components represents the forced-flow queuing costs.

Master summary - total (30 day) work zone user cost

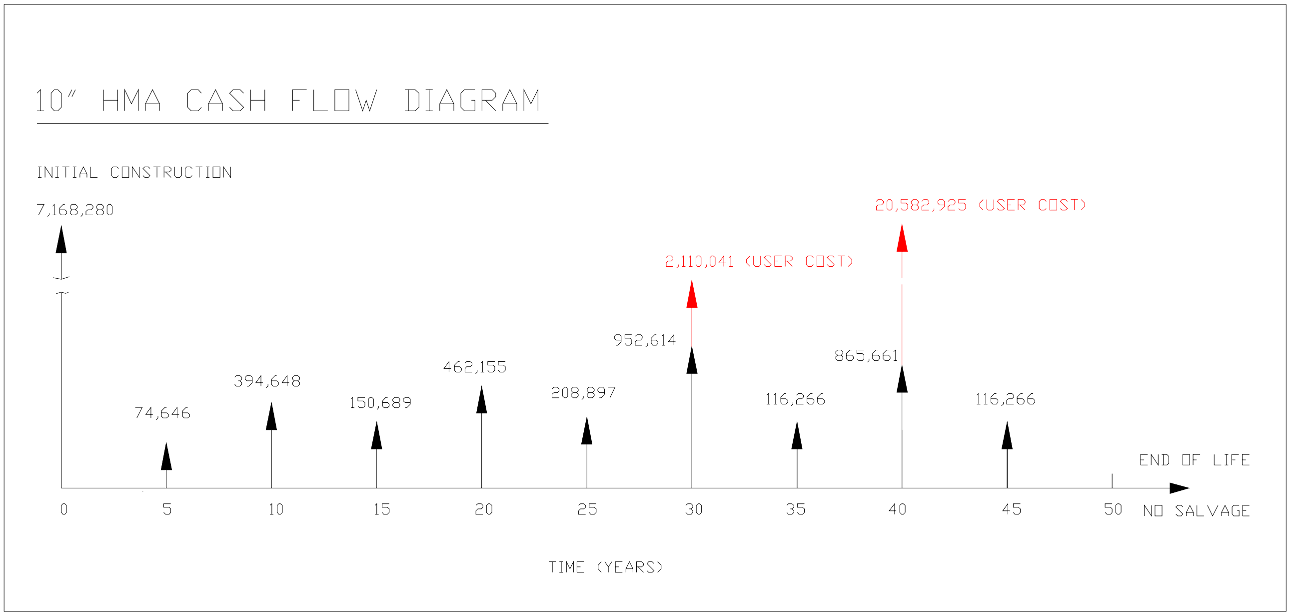
User Cost Component	30-Years			40-Years	
	Passenger Cars	Trucks	Total ($)	Passenger Cars	Trucks
1. Speed Change VOC	7,604	6,521	14,125	3,370	2,890
2. Speed Change Delay	5,727	6,413	12,140	2,538	2,842
3. WZ-Reduced Speed Delay	285,538	61,097	346,634	344,730	73,766
4. Stopping VOC	50,682	48,540	99,222	124,380	119,120
5. Stopping Delay	44,902	34,091	78,992	110,194	83,661
6. Queue Idling VOC	66,628	8,815	75,443	842,634	111,482
7. Queue Speed Delay	1,221,989	261,496	1,483,484	15,454,275	3,307,043
Grand Totals	1,683,070	426,971	2,110,041	16,882,120	3,700,805
Grand Totals %	79.76%	20.24%	100.00%	82.02%	17.98%

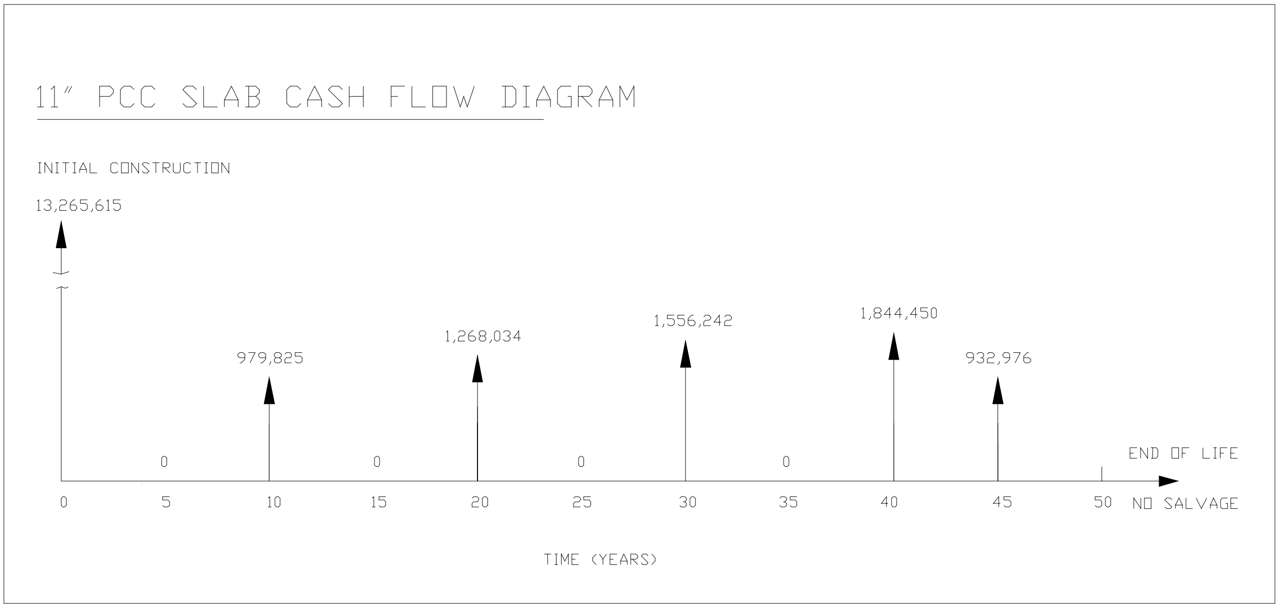
Master summary - work zone user cost distribution (%)

User Cost Component	30-Years			40-Years	
	Passenger Cars	Trucks	Total	Passenger Cars	Trucks
1. Speed Change VOC	0.36%	0.31%	0.67%	0.02%	0.01%
2. Speed Change Delay	0.27%	0.30%	0.58%	0.01%	0.01%
3. WZ-Reduced Speed Delay	13.53%	2.90%	16.43%	1.67%	0.36%
4. Stopping VOC	2.40%	2.30%	4.70%	0.60%	0.58%
5. Stopping Delay	2.13%	1.62%	3.74%	0.54%	0.41%
6. Queue Idling VOC	3.16%	0.42%	3.58%	4.09%	0.54%
7. Queue Speed Delay	57.91%	12.39%	70.31%	75.08%	16.07%
Grand Totals	79.76%	20.24%	100.00%	82.02%	17.98%

DEVELOP EXPENDITURE STREAM DIAGRAM

Expenditure stream diagrams are graphical representations of expenditures over time. They are generally developed for each pavement design strategy to help visualize the extent and timing of expenditures.





Net present value calculation

NPV Calculation Using 4% Discount Rate Factor

Year	ALTERNATIVE 1: FLEXIBLE PAVEMENT			ALTERNATIVE 2: RIGID PAVEMENT		
	Cost ($)	Discount Factor	Discounted Cost ($)	Cost ($)	Discount Factor	Discounted Cost ($)
0	7,168,280	1.0000	7,168,280	13,265,615	1.0000	13,265,615
5	74,646	0.8219	61,354	-	0.8219	-
10	394,648	0.6756	266,610	979,825	0.6756	661,935
15	150,689	0.5553	83,672	-	0.5553	-
20	462,155	0.4564	210,922	1,268,034	0.4564	578,714
25	208,897	0.3751	78,361	-	0.3751	-
30	952,614	0.3083	293,709	1,556,242	0.3083	479,818
30	2,110,041	0.3083	650,565	-	0.3083	-
35	116,266	0.2534	29,464	-	0.2534	-
40	865,661	0.2083	180,308	1,844,450	0.2083	384,179
40	20,582,925	0.2083	4,287,198	-	0.2083	-
45	116,266	0.1712	19,905	932,976	0.1712	159,724
50	-	0.1407	-	-	0.1407	-
Total NPV			**13,330,346**			**15,529,985**

Note: Shaded rows show work zone user costs in year 30 and 40.

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