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16. Abstract

This report describes the development of a new life cycle cost analysis methodology for portland cement concrete pavements — one that considers all aspects of pavement design, construction, maintenance, and user impacts throughout the analysis period. It predicts pavement performance using state-of-the-art performance models and reliability concepts, from which it determines maintenance and rehabilitation needs.

Any construction performed on a roadway has associated construction and user costs. Also associated with all highway pavement construction are external costs, upon which it is difficult if not impossible to place a value. This methodology models the effects of construction on all these aspects and, where the effects cannot yet be quantified, allows new models to be added.

Reliability concepts are used with individual models when possible, and the overall variability of the total life cycle cost is estimated. Using reliability concepts and the variability in all aspects of construction and cost models, the design engineer can define a level of confidence for predicting total life cycle costs, user costs, accidents, and other output parameters considered in the methodology.

The modular nature of the methodology allows it to be updated with new or better performing models for predicting pavement performance, user costs, and external costs associated with highway pavement construction. New pavement types, such as asphalt concrete and prestressed concrete, can also be added to the analysis in the future, using proper performance models and maintenance and rehabilitation strategies.

Many existing life cycle cost methodologies utilize preprogrammed maintenance and rehabilitation actions to determine the total life cycle cost of a particular alternative. This new methodology, however, determines when maintenance and rehabilitation activities will be required by predicting the distresses and the condition of the pavement following traffic and environmental loading.

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LIFE CYCLE COST ANALYSIS OF PORTLAND CEMENT CONCRETE PAVEMENTS

by

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and

Rob Harrison

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Research study title: *A Life Cycle Cost Analysis of Rigid Pavements*

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TEXAS DEPARTMENT OF TRANSPORTATION

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U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

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CHAPTER 1. INTRODUCTION

Although the concept of life cycle costing was introduced in the 1930s as part of federal legislation regarding flood control, it was not until the 1950s that life cycle cost analysis began to be used for the evaluation of highway projects. Life cycle cost analysis allows state agencies to evaluate different alternatives concerning proposed highway projects. The selection of different pavement types, the initial quality and strength of design, maintenance and rehabilitation strategies, and the financial impact on the agency and the motoring public are all concerns that are evaluated when performing a life cycle cost analysis. This report presents a comprehensive life cycle cost analysis procedure and computer program that was developed and customized for the conditions of Texas highways and for the objectives of the Texas Department of Transportation (TxDOT).

1.1 BACKGROUND

The American Association of State Highway Officials' (AASHO's) "Red Book" of 1960 (Ref 3) introduced the concept of life cycle cost analysis (or cost-benefit analysis) to the broader highway construction arena. At the time, the only data provided by AASHO for use in life cycle costing pertained to passenger cars in rural areas and to truck costs. This manual helped to establish the concept of economic evaluation of highway improvements at the planning level.

The next major advancement in life cycle cost analysis (LCCA) was the work performed by Winfrey in 1963 (Ref 103); his research consolidated and organized the available vehicle operating cost data into a format that highway planners were able to use in developing life cycle cost analysis over the next 15 years. Also during the 1960s, two projects were undertaken that advanced the application of life cycle cost principles to pavement design and pavement-type selection. The National Cooperative Highway Research Program (NCHRP) conducted an investigation under project NCHRP 1-10 (Ref 58) to promote the concept of life cycle cost analysis. At the same time, the Texas Transportation Institute (TTI) and the Center for Highway Research (which later became the Center for Transportation Research, or CTR) developed the Flexible Pavement System (FPS), a methodology and computer program used to analyze alternate asphalt concrete designs and rank them by overall life cycle cost (Ref 45). Later, TxDOT funded a project (Ref 49) to develop the Rigid Pavement System (RPS), which is similar to FPS in that it performs a life cycle cost analysis of rigid pavements and ranks alternate designs by total life cycle cost.

The 1986 and the 1993 American Association of State Highway and Transportation Officials' (AASHTO) Pavement Design Guides (refs 31 and 32) encourage the concept of life cycle costing, and give detailed discussions about the various costs that should be considered in life cycle cost analysis. The Design Guide contains a chapter on the economic evaluation of alternative pavement design strategies. This chapter contains an outline of the basic concepts of life cycle costing, a discussion of the various agency and user costs associated with highway pavement projects, and discussions of economic evaluation methods and the discount rate.

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) required "the use of life cycle costs in the design and engineering of bridges, tunnels, or pavement" (Ref 46) in both metropolitan and statewide planning. In response to this requirement, the Federal Highway Administration (FHWA) encouraged, and even required, the state departments of transportation to perform life cycle cost analysis on all pavement projects that exceeded $25 million.

The reauthorization of ISTEA, termed the *Transportation Equity Act for the 21st Century* (TEA-21) (Ref 94), removes the requirements for life cycle cost analysis on large highway projects. The same legislation requires the Secretary of Transportation to authorize research to develop guidelines for performing life cycle cost analyses, including user costs, analysis periods and discount rates, and trade-offs between reconstruction and rehabilitation. The following are excerpts from the *Transportation Equity Act for the 21st Century,* which outlines the requirements and suggestions for life cycle cost analysis.

TITLE I—FEDERAL-AID HIGHWAYS

…

Subtitle C—Program Streamlining and Flexibility

…

SEC. 1305. PROJECT APPROVAL AND OVERSIGHT.

…

(c) LIFE CYCLE COST ANALYSIS.—Section 106 of such title (as amended by subsection (a)(2)), is amended by striking subsection (f) and inserting the following:

''(f) LIFE CYCLE COST ANALYSIS.—

''(1) USE OF LIFE CYCLE COST ANALYSIS.—The Secretary shall develop recommendations for the States to conduct life cycle cost analyses. The recommendations shall be based on the principles contained in section 2 of executive Order No. 12893 and shall be developed in consultation with the American Association of State Highway and Transportation Officials. The Secretary shall not require a State to conduct a life cycle cost analysis for any project as a result of the recommendations required under this subsection.

''(2) LIFE CYCLE COST ANALYSIS DEFINED.—In this subsection, the term 'life cycle cost analysis' means a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment.''.

TITLE V—TRANSPORTATION RESEARCH

…

Subtitle B—Research and Technology

…

SEC. 5102. SURFACE TRANSPORTATION RESEARCH.

…

‘‘§ 502. Surface transportation research

…

‘‘(c) CONTENTS OF RESEARCH PROGRAM.—The Secretary shall include in surface transportation research, technology development, and technology transfer programs carried out under this title coordinated activities in the following areas:

…

‘‘(8) Expansion of knowledge of implementing life cycle cost analysis, including —

‘‘(A) establishing the appropriate analysis period and discount rates;

‘‘(B) learning how to value and properly consider use costs;

‘‘(C) determining tradeoffs between reconstruction and rehabilitation; and

‘‘(D) establishing methodologies for balancing higher initial costs of new technologies and improved or advanced materials against lower maintenance costs.

…”

The requirement for conducting life cycle cost analysis on highway projects has been removed from the legislation, although the Secretary of Transportation is required to fund research into the “expansion of knowledge of implementing life cycle cost analysis.” While the life cycle cost analysis requirement for pavements was removed, it is interesting to note that life cycle cost analyses for mass transit and magnetically levitated trains are still required.

A stated objective of TEA-21 is to expand the knowledge of implementing life cycle cost analysis, including:

- establishing an appropriate analysis period and discount rates,
- learning how to value and properly consider user costs,
- determining tradeoffs between reconstruction and rehabilitation, and
- establishing methodologies for balancing higher initial costs of new technologies and improved or advanced materials against lower maintenance costs.

The Texas Department of Transportation commissioned a research project to promote life cycle analysis of rigid pavements among the districts and to develop a uniform methodology for performing life cycle cost analysis that will eventually include all pavement types. The research described in this report was performed as part of this TxDOT project. In addition to this project, TxDOT personnel have been active in the FHWA Life Cycle Cost Developer's Group, which discusses many types of LCCA models and processes. TxDOT is interested in performing LCCA on new and existing pavements that will be required to carry heavy truck traffic between Mexico and the United States — traffic that has increased greatly since the enactment of the North American Free Trade Agreement (NAFTA). In addition to the efforts to develop an LCCA that considers pavement performance, maintenance, and rehabilitation, the current director of TxDOT recently issued a memorandum authorizing individual districts to evaluate the daily user costs associated with a highway project and include them in contractor bid packages. This way the user costs will be included in the life cycle cost analysis, and contractors will have to consider the impact to users when submitting construction bids.

The remainder of this section will introduce efforts being undertaken by other states and countries to promote life cycle cost analysis. It then describes the project under which this report was developed and the research objectives.

1.1.1 Existing Life Cycle Cost Analysis Programs

Throughout the past four decades, since the original AASHTO "Red Book" was published, several life cycle cost methods have been developed by various agencies, industry, and universities. The most notable rigid pavement life cycle cost analysis programs and methods have been developed and are being used by Pennsylvania, Maryland, Alabama, and Ohio. Other countries, such as Canada, Australia, and Egypt, have also developed life cycle cost analysis methodologies. In addition to the programs initiated by the states and other countries, other methods exist that also attempt to calculate life cycle costs of pavement projects. These programs have been developed by AASHTO, the Asphalt Institute, the American Concrete Paving Association, the World Bank, and the Texas Transportation Institute. This project will provide Texas with a life cycle cost analysis methodology and computer program to accompany the current version of the Flexible Pavement System already in use in Texas.

The life cycle cost analysis computer programs associated with many of these states, countries, and industry representatives contain many of the aspects recommended by this report, and where possible similar models and methods used in these programs are incorporated into this project. These programs will be discussed in more detail in Chapter 2.

1.1.2 Research Objectives

The concept of life cycle cost analysis is no longer new to the field, yet many in industry, academia, and government agencies still do not have an adequate understanding of the basic concepts of life cycle cost analysis. Because of this, Project 0-1739, *Life Cycle Cost Analysis of Rigid Pavements*, was sponsored by the Texas Department of Transportation. It was intended to improve understanding of LCCA, and to implement a functional LCCA computer program for use on new and existing projects. This project began in September 1996, under the direction of Drs. W. Frank McFarland and José Weissmann, of TTI and CTR, respectively. The major objective of this project was to develop a comprehensive, modular life cycle cost analysis methodology by which existing and future projects could be evaluated. This project produced a methodology, or framework, for life cycle cost analysis that is comprehensive in that it encompasses all aspects, to the extent possible, of pavement design, agency costs, user costs, and other costs that are created as a consequence of a highway project.

The modular characteristic of the life cycle cost framework will be beneficial in the future when costs that are currently difficult to evaluate will be calculable. Future users of the framework will easily be able to insert new methods of calculating costs into the framework without performing large updates to the computer program or to the methodology.

Other objectives of this project, which are necessary in achieving the major objective described above, are:

- identify parameters related to pavement performance, deterioration rates, agency costs, and user costs,
- implement the most advanced and best performing distress performance models, agency cost calculation techniques, and user cost calculation techniques, as determined in the review of the literature, and
- develop a software package to implement the comprehensive life cycle cost methodology.

The following sections of this chapter outline the scope of the project and of the report, the significance of the project, and how the objectives will be accomplished. This is followed by a description of the report format and the contents of each chapter.

1.1.3 Research Project Scope

In order to accomplish the objectives outlined above, a thorough review of the literature has been completed first to identify the parameters associated with pavement design that are most significantly related to pavement performance and deterioration rates. In addition to these parameters, those aspects of highway design that impact other agency costs and user costs have also been researched.

Concurrently with determining the factors that are important in pavement performance, deterioration, agency costs, and user costs, the literature review will identify the models that are best suited for inclusion in a life cycle cost framework for the state of Texas. The models that will be identified include:

- pavement performance models, including joint spalling, joint faulting, transverse cracking, punchouts and ride quality;
- pavement rehabilitation performance models, including punchouts, spalling, reflective cracking, rutting, and ride quality; and
- user cost models, such as time delay, emissions, vehicle operating costs, accidents, and those related to pavement roughness.

The models, after having been identified, will be incorporated into the new life cycle cost framework and into the first version of the computer software. As mentioned above, the modular nature of the framework will allow these models to be replaced in the future, as more advanced models and techniques become available.

The Texas Department of Transportation intends to implement the life cycle cost analysis framework and to use it in its districts to evaluate new and existing pavement projects. A major implementation project, or pilot testing program, has begun as an extension to the original TxDOT Project 0-1739. Prior to this pilot testing program, however, the framework will be tested against existing data obtained from pavement projects in Texas to verify the outcome of each possible scenario.

1.1.4 Summary

This project represents an advancement in life cycle cost analysis. It utilizes pavement performance models to predict the timing of maintenance and rehabilitation activities, as well as user cost models to capture the impact of construction activities on the motoring public. The project addresses, either directly or indirectly, each of the aspects of the life cycle costing research objectives of TEA-21. The remaining sections of this chapter will discuss the specific objectives of this report in terms of developing a new framework for performing life cycle cost analysis.

1.2 RESEARCH PROJECT SIGNIFICANCE

This project presents a new framework for life cycle cost analysis. In the four decades since the AASHO "Red Book" began advocating calculating the full costs associated with highway pavement projects, various life cycle cost methods have been developed. Each of these methods was developed for specific pavement types, for specific segments of industry, or for specific (and limited) types of agency or user costs.

The life cycle cost framework presented in this report encompasses as many aspects of pavement and highway design as possible. It is understood, however, that there are many aspects for which cost calculation models have not been developed. While it is impossible to include *all* aspects of highway planning and design, the framework is constructed in such a way that new methods and models can be incorporated into the framework without much difficulty.

This research is significant in that it presents a standardized method for considering the agency and user costs associated with pavement performance. As mentioned, many existing life cycle cost analysis procedures either treat one type of pavement only or different pavement types in different manners. The underlying philosophy behind this research with respect to pavement performance has been to treat all pavement types equally, and without bias, using appropriate performance models. Each performance model that is used in the framework is a distress prediction model that provides a prediction of the level of a particular distress that can be expected based on construction conditions and environmental and traffic loading over time.

The outcome of this research will be a method for calculating life cycle costs of highway pavement projects, and for comparing those life cycle costs between various alternate designs. This method will treat all pavement types in the same manner and will calculate the user costs, external items, and any aspect of planning and design that is independent of pavement structure equally in order to provide an unbiased life cycle cost calculation over the expected life of the project.

1.3 REPORT OBJECTIVES AND SCOPE

The previous sections have outlined the background of life cycle cost analysis as well as a short history of this project. They have also discussed the objectives of the project and the intentions of the Texas Department of Transportation in funding this project. Since life cycle costing has been performed for many decades and for many different types of projects, there exists an abundance of research and application documentation regarding this topic.

1.3.1 Report Objectives

This report documents research that has been performed under TxDOT Project 0-1739: *Life Cycle Cost Analysis of Rigid Pavements*. There are two major objectives of this report. The first is to present the models that have been used in developing the life cycle cost analysis framework. The second major objective of this report is to organize these models into a coherent and reasonable framework that can be used by the Texas Department of Transportation for new and existing projects. Secondary objectives of the report are as follows:

- Modify the models that are included in the framework, where needed, to fit the overall objectives of the report.
- Provide critical analysis of the models to ensure that poor performing models are not used, but that others are identified and included in the framework.
- Present a life cycle cost analysis framework that can be modified by future researchers to include improved models and different pavement types, and that will predict pavement performance and all associated costs more correctly than can be done at the present time.

1.3.2 Scope

This report's scope is limited in that its major contribution is a framework for a life cycle cost analysis methodology. In devising the framework, each segment was developed using portland cement concrete pavements as a prototype. Thus, it was not the intent of this research to delve into great detail for each aspect of the framework, but rather to identify the most appropriate models to be used in developing the methodology. The scope of this report includes four major parts:

1. research and identify other life cycle cost analysis techniques,
2. establish a life cycle cost analysis framework,
3. evaluate potential models to be used in the new framework and select the best performing of the existing models, and
4. develop a computer software package to implement and automate the new life cycle cost analysis framework.

The computer software package is intended to automate and facilitate the life cycle cost analysis; like the methodology for performing life cycle cost analyses, it is modular so that it can be updated with new models as necessary. During the course of this project, no new models were developed to be included either in the methodology or in the computer software, though some models were modified to improve their performance and to alter their outputs.

1.3.3 Report Organization

Chapter 2 discusses existing life cycle cost analysis methodologies and programs. In particular, it presents the results of a survey of current practice that was conducted as part of an effort to identify other life cycle cost analysis techniques and computer programs, as well as existing models that could become candidates for inclusion in the new LCCA framework. The components of the existing programs that were of interest included:

- pavement performance and distress,
- costs of construction, maintenance and rehabilitation,
- travel time delay,
- vehicle operating costs,
- emissions,
- accidents,
- other external costs,
- discounting, and
- reliability.

The major development of the life cycle cost analysis framework is presented in Chapter 3. It outlines the processes included in the framework and the integration of these processes into a coherent and rational methodology.

The discussion of the components and processes that make up the LCCA framework are discussed in Chapters 4 through 8. Chapter 4 discusses pavement performance and the different methods that are used to develop performance models. For the purposes of this project, only those performance models relating to jointed and continuously reinforced concrete pavements are included. This chapter also includes performance models relating to various types of overlays that may be used on these pavement types.

Chapter 5 discusses the methods used by the framework to analyze distresses, and explains how maintenance and rehabilitation strategies are determined and applied. Agency costs, including initial construction, maintenance, and rehabilitation costs, are discussed in Chapter 6.

Chapter 7 addresses work zones and their effects on the users of the highway segment. User costs, such as travel time delay and vehicle operating costs, are considered, as well as other indirect user costs such as emissions, accidents, and noise that occur as a result of work zone activity. Chapter 8 discusses other life cycle cost components, such as the discount rate, probabilistic methods, and the salvage value of the highway pavement project.

Chapter 9 discusses the computer program that was developed as part of this project. Required inputs are described and each input screen is illustrated; a program flowchart and an example application of the software are also included. The results of the research and our recommendations for further research are then presented in Chapter 10.

CHAPTER 2. SURVEY OF CURRENT PRACTICE

Current pavement design and analysis technology has improved significantly in the past several decades; consequently, the ability to predict and calculate a wide range of costs associated with highway pavement projects has also greatly improved.

We conducted a survey of current life cycle costing practice in order to identify the existing models that are in use, and to determine which of the different life cycle cost analysis parameters are contained in each model. Prior to performing the survey of current practice, we compiled a comprehensive list of parameters that are important in developing a life cycle cost analysis methodology. The components of life cycle cost analysis methods are shown below, grouped into three major categories:

Agency Costs

- Pavement performance and distress
- Construction, maintenance, and rehabilitation

Direct and External Societal Costs

- Travel time delay
- Vehicle operating costs
- Emissions
- Accidents
- Evaluation factors
- Discount rate
- Reliability

Existing methods were researched with the expectation that a possible candidate might be found that could be modified and used in a new framework for life cycle cost analysis. It was determined, however, that a more feasible alternative would be to develop a new framework for performing life cycle cost analyses, and then to extract portions of several existing methodologies. Developing a new LCC framework in this manner allows the most useful work of previous research to be included, while bringing new ideas and insight into the life cycle cost arena.

Each of the sections that follow describes how existing life cycle cost analysis models are currently deployed in industry and state departments of transportation. The different types range from noncomputerized methods to mainframe and personal computer programs.

While the basic life cycle cost methodology remains the same among different models, the types of costs that they consider and the way in which they calculate those costs and the expected life of pavements differ considerably. This section will describe the major computer programs and other life cycle cost models that are available and that were investigated at the beginning of this project.

In a lecture to the National Asphalt Paving Association, Dr. Matt Witczak (Ref 105) showed that most states are indeed using some method of life cycle cost analysis. The survey indicated that out of 28 states responding, almost 100% are using some form of life cycle cost analysis, mostly at the project level.

2.1 MAINFRAME PROGRAMS

Before the 1980s, computer programs were written for execution on large mainframe computers that required punch cards to manage both the program and its input. The early versions of the Flexible Pavement System (FPS) and the Rigid Pavement System (RPS) were written for mainframe applications.

2.1.1 Flexible Pavement System and Rigid Pavement System — TxDOT

The Flexible Pavement System and the Rigid Pavement System are programs that were developed in the late 1960s by the Texas Transportation Institute and by the Center for Highway Research (Refs 45, 49, and 84). The Rigid Pavement Rehabilitation Design System (RPRDS) is a modification of the RPS-3 program (Ref 86). The FPS program has been updated many times and is now in its 19th version, with an upcoming release for Microsoft Windows. Both of these programs make use of reliability concepts similar to those that will be described in this report. The variance of all important, and sensitive, variables is calculated and the variability of the overall life cycle cost is determined from these calculations. In addition, both of these programs use performance models to determine the level of distress in the pavement.

The methods that RPRDS uses in modeling performance and treatment of reliability are very similar to those that are recommended for the life cycle cost analysis program developed in this report. Several of these models will be implemented in modified form in later versions of the software.

2.1.2 Highway Performance Monitoring System (HPMS) — FHWA

The Highway Performance Monitoring System (HPMS) (Ref 40) records and updates information on the current condition of U.S. highways as a way of assessing future highway needs, as required by U.S. Code, Title 23, Section 307A. The program was developed by the Federal Highway Administration (FHWA) to meet the requirements of this code.

HPMS was developed to provide an overall estimate of conditions and future needs of the highway system. It was not specifically designed for a project-level analysis, although many of its elements are similar to those found in other programs. It uses engineering criteria and a logic structure to determine improvement needs and to estimate the cost of those improvements. To determine motorist impacts, the program calculates an adjusted traveling speed and uses that speed to calculate fuel consumption and operating costs. The accidents are calculated as a function of the overall AADT and highway type.

The output related to motorist user costs consists of average overall travel speed; operating cost per 1000 vehicle miles; fuel consumption per 1000 vehicle miles; carbon monoxide, nitrous oxide, and hydrocarbon emissions per 1000 vehicle miles; and fatal, injury and "property damage only" accidents per 100 million vehicle miles. Because overall user costs or benefits are not calculated, there are no summary calculations, such as benefit-cost ratio or net present value.

2.2 LIFE CYCLE COST PROGRAMS FOR PERSONAL COMPUTERS

By far, the greatest number of life cycle cost analysis programs has been written for the personal computer, with most such programs having been developed beginning in the early 1980s. The following describes noteworthy examples of these programs.

2.2.1 LCCOST — Asphalt Institute

The LCCOST program was developed in 1991 by the Asphalt Institute. This program considers the initial cost of construction, multiple rehabilitation actions throughout the design life, and user delay at work zones during initial construction and subsequent rehabilitation activities.

In addition to these considerations, the program considers routine maintenance, if desired by the user, that will be applied each year between rehabilitation activities. Routine maintenance is not, however, normally included in life cycle cost methodologies, since many departments of transportation do not account for the routine maintenance of individual highway segments. The magnitude of routine maintenance costs can be very large, and any disruptions to traffic may cause user costs to increase. The program includes neither performance modeling nor a structural pavement model. Salvage value of the pavement and of the individual materials that make up the layers is also considered by the models.

While the source code is not available for this software product, the concepts presented, such as routine annual maintenance, will be considered for use in the current research.

2.2.2 DARWin — AASHTO

The DARWin Pavement Design System is a program that automates the AASHTO design equations and simplifies the management of materials, layers, and construction activities. The life cycle cost module of DARWin accounts for project dimensions, initial construction, up to five preprogrammed rehabilitation strategies, and the salvage value of the pavement. It then discounts all the construction costs and salvage value to the present and reports the net present value of the project.

This program was not intended to provide a full life cycle cost analysis, but simply the agency costs associated with specific projects. The program performs very well as a database for managing materials, material properties, costs, and other aspects of pavement design and construction. Additionally, the source code was not available, as this is a product of AASHTOWare and is available for sale to the public.

2.2.3 LCCP / LCCPR — Maryland

The University of Maryland developed a set of life cycle cost analysis programs that analyze flexible and rigid pavements (Refs 79 and 106). These programs incorporate user operating costs associated with pavement roughness and other measures of user costs. These two computer programs are intended for project-level analysis, as required for this research project, but they are better suited for use in pavement management systems. They are not as applicable to the comparison of alternate highway pavement designs. These programs would require much modification and updating to be used in the current research to develop a new framework for life cycle cost analysis. The life cycle cost components that are implemented by the programs, however, are important and will be used in the development of this project.

2.2.4 EXPEAR — FHWA

The computer program EXPEAR was developed in 1989 by the University of Illinois under a Federal Highway Administration Project (Ref 36). The program performs project-level evaluation and requires data from a visual condition survey. The program recommends rehabilitation techniques that include reconstruction and resurfacing, among others. The program does not, however, consider user costs or other indirect impacts of the recommended rehabilitation techniques.

2.2.5 Highway Design and Maintenance Standards Model — World Bank

The Highway Design and Maintenance Standards Model (HDM-III) computer program was developed by the World Bank for evaluating highway projects, standards, and programs in developing countries (Ref 37). HDM-III is designed to make comparative cost estimates and economic evaluations of different construction and maintenance options, including different time staging strategies, either for a given road section or for an entire road network.

The HDM-III model is mainly designed for evaluating geometric and road surface improvements of rural roads. It considers construction costs, maintenance costs, and user costs. The vehicle operating cost calculations used in HDM-III are based on extensive operating cost studies, chief among which was a major Brazilian study (Ref 108). Special emphasis is placed on estimating vehicle operating costs as related to roadway surface type and condition (e.g., dirt surface, gravel surface, and paved surfaces of varying degrees of roughness).

The personal-computer version (HDM-PC) contains the core HDM-III model, a user interface to input data, a mechanism to use the outputs with a spreadsheet, and a constrained version of the Expenditure Budgeting Model (EBM). If HDM is used with the EBM, it is capable of comparing options under year-to-year budget constraints.

The HDM program assumes that construction costs, maintenance costs, and vehicle operating costs are a function of vertical alignment, horizontal alignment, and road surface condition. Different types of costs are calculated by estimating quantities and using unit costs to estimate total costs. A major disadvantage of this model with respect to the current project is that it does not specifically model portland cement concrete pavements.

2.2.6 MicroBENCOST

The computer program MicroBENCOST was developed by the Texas Transportation Institute in 1993 under NCHRP Project 7-12 (Ref 64). This program analyzes many types of projects including pavement rehabilitation, added lane capacity, bridge projects, and bypass projects. The program takes a large number of inputs and compares a benefit/cost analysis that considers *with* and *without* specific project alternatives. While the program can be used to compare different alternatives, its main function is to evaluate the benefits and costs of constructing a particular project.

2.2.7 Queue and User Cost Evaluation of Work Zones

The QUEWZ model is a tool for evaluating highway work zone lane closures. Although the QUEWZ model is not a life cycle cost program, it will be used in the new framework to calculate the user costs associated with work zones during maintenance and rehabilitation activities. QUEWZ simulates traffic flow through freeway segments, both with and without a work zone lane closure in place, and estimates the changes in traffic flow characteristics and additional road user costs resulting from a lane closure whose time schedule and lane configuration are described by the model user. QUEWZ can also apply the same traffic flow simulations to identify acceptable time schedules for lane closures.

The QUEWZ model has gone through many updates and currently provides daily user costs, including time delay and vehicle operating costs. The models are based on Zaniewski's vehicle operating cost relationships (Ref 109). The model also predicts vehicle emissions based on speed and time spent in queues.

The latest version of this model will, with minor modification, be included in the framework. These modifications include the modeling of narrowed lanes (instead of lane closures) and reduced posted speed limits (assuming that motorists drive the posted speed limit through work zones).

2.3 LIFE CYCLE COST PROGRAMS FOR SPREADSHEETS

Several programs are meant to be used in conjunction with spreadsheet programs to analyze life cycle costs of highway pavement projects. This type of analysis requires the use of an existing, commercially available, spreadsheet program. The user can provide inputs in the cells of the spreadsheet, and perform calculations using preprogrammed macros that execute calculations similar to those executed by a standard life cycle cost analysis computer program.

2.3.1 American Concrete Paving Association

The American Concrete Paving Association (ACPA) has developed a spreadsheet-type analysis program that is used with Microsoft Excel to analyze both rigid and flexible pavements. The spreadsheet requires that the user input preprogrammed rehabilitation activities, from which simple user-cost analysis is performed, with all costs discounted to the present.

This spreadsheet considers user costs using values from NCHRP Report 133 (Ref 18) and from Winfrey's *Economic Analysis for Highways* (Ref 102). The spreadsheet computes the level of time delay and other user costs by requiring the user to input the number of days expected for construction, the number of lanes to remain open, and other aspects of traffic control and traffic volumes.

The spreadsheet also considers reliability by requiring the user to input not only the expected values of most variables, but also a "plus or minus" value representing a 90% confidence level. Thus, the spreadsheet uses risk analysis to determine the 90% confidence level in the total discounted costs expected over the life cycle of the pavement.

2.4 OTHER LIFE CYCLE COST ANALYSIS METHODS

Other life cycle cost analysis computer programs and methodologies include a program from Pennsylvania, called LCC1 (Ref 95), and non-computerized methods from Alabama (Ref 83), Ohio (Ref 69), Australia (Ref 74), and Egypt (Ref 24). Each of these programs and methods has features similar to those described above.

2.5 SUMMARY

The life cycle cost analysis programs, spreadsheets, and other supporting routines and programs that have been described in this chapter all contribute to the development of the new framework for life cycle cost analysis that is presented in this report. Each of these models has concepts and procedures that are important in the development of a comprehensive life cycle cost analysis methodology. This report will draw the best and most important aspects of these methods in an attempt to create a framework that will have the potential to calculate all costs created by the existence of a particular highway pavement project. The framework will also draw components from these programs concerning reliability, economics, and other aspects that are important to performing proper, comprehensive, life cycle cost analysis. The remaining chapters of this report will describe the components required and will provide suggested models and methods to be used in each component to determine the expected life cycle cost of particular design alternatives.

The nature of this new framework will be modular in the sense that future developments in performance modeling, reliability, user cost calculations, etc., will be easily implemented into the framework. This modular approach will greatly improve its longevity and its adaptation to new advances in the various aspects of life cycle cost analysis.

CHAPTER 3. LIFE CYCLE COST FRAMEWORK DEVELOPMENT

In developing the framework for a new life cycle cost methodology, all aspects of pavement performance, rehabilitation, social and economic impacts, and public safety should be studied and included. Many of the various aspects of a comprehensive life cycle cost model are included in the life cycle cost methods and computer programs evaluated in the previous chapter. However, none of these methods or programs includes all the aspects, nor do they provide the means to add future components. Although many of these components are neither fully understood nor easily calculated or valuated, an attempt to quantify and valuate each aspect should be made in developing a comprehensive approach. This chapter describes the development of such a comprehensive life cycle cost evaluation method, and summarizes each of the components that make up the framework for this method. Each of the components mentioned in this chapter will be discussed in detail in Chapters 4 through 8.

3.1 MAJOR COMPONENTS OF LIFE CYCLE COST ANALYSIS

Several components make up the framework of a comprehensive life cycle cost analysis methodology. Inherent in the definition of life cycle cost analysis is the idea that all costs involved in a pavement's construction, maintenance, rehabilitation, social and economic impacts, and any other costs that can be attributed to the use, care and maintenance of a pavement and highway section are captured and considered in the design decision process. Each component of a life cycle cost methodology is reduced and combined with other components in some way to produce a cost that is borne by some entity. The major costs included in the life cycle cost process are divided into two major categories: agency costs and user costs.

In addition to the two major cost categories, and possibly of greater magnitude, are *external costs*, which are not directly attributable to the construction or maintenance of a highway section, or to the user costs associated with construction work zones. These costs, although difficult to quantify, should be included, to the extent possible given current modeling techniques, in a comprehensive life cycle cost methodology. External costs, as well as agency and user costs, will be discussed in this chapter in connection with the various activities that generate them.

An important characteristic of a comprehensive life cycle cost methodology is its applicability to any type of pavement, provided correct performance models are used to evaluate pavement distresses over the life of the pavement. The life cycle cost framework presented in this report, although developed for portland cement concrete pavements, can be implemented for any type or variation of pavement. For example, if asphalt concrete pavements are added to the framework in the future, appropriate performance models, distress evaluations, and rehabilitation strategies must be inserted into the program. However, the structure of the program and its primary algorithm will remain the same.

3.1.1 Pavement Performance

The first step in the life cycle cost framework is to evaluate a pavement design and the conditions under which it is expected to operate throughout its design life or analysis period. This portion of the life cycle cost framework is shown in Figure 3.1. This figure shows the steps required to prepare an analysis for the life cycle cost procedures. In addition to the pavement types considered in this report, Figure 3.1 shows the pavement types that may be included in future research, but that would fit into the framework without modification to its structure.

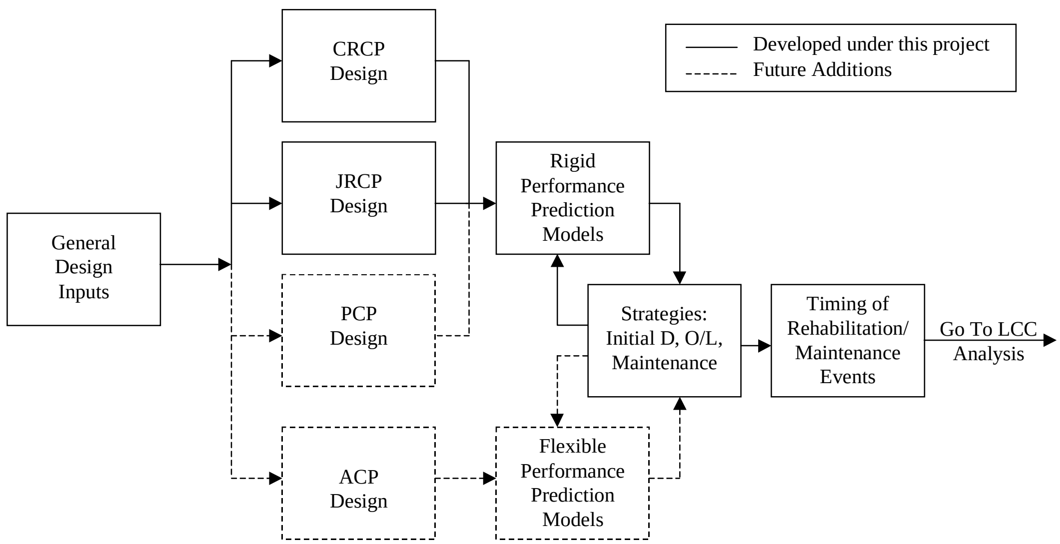


Figure 3.1. Life Cycle Cost Framework – Pavement Performance

The general inputs relating to the project as a whole, independent of pavement type, must be defined prior to defining pavement design alternatives. These inputs include such conditions as project geometry, predicted traffic patterns and pavement loading, environmental conditions, and economic variables. Each of these areas is discussed in detail in Chapters 4 through 8 of this report.

Once the general and specific conditions are defined, the life cycle cost framework simulates the predicted traffic loading and environmental conditions for each year of the analysis period. At the end of each year, the performance models predict the level of distress or damage to the pavement based on that year's current traffic and other conditions. Figure 3.2 shows the basic function of the pavement performance module. It determines the level of each distress that may become manifested in the pavement. The graph in Figure 3.2 shows the development of two different distress types over time, with the application of traffic and environmental loads. While different distress types have different acceptable levels, as shown in Figure 3.2, whichever distress is first to reach its maximum level controls the rehabilitation needs of the project. In the figure, Distress #1 reaches its terminal level much sooner than Distress #2, meaning that at that time some type of maintenance or rehabilitation should be performed so that the pavement is maintained in acceptable condition.

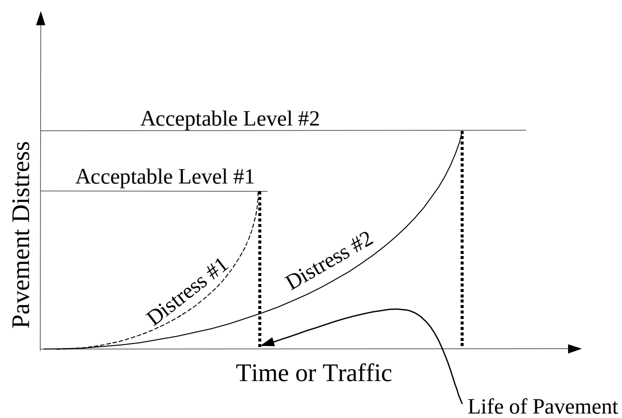


Figure 3.2. Modeling Distress Development in Portland Cement Concrete Pavement

Once a distress type reaches its maximum acceptable level, the framework enters the maintenance and rehabilitation module, which is discussed in the next section. The framework assumes that all distresses, regardless of their condition in the pavement, are repaired while the work zone is in place for the maintenance or rehabilitation activities related to the distress requiring action.

The state of pavement performance modeling is currently changing from purely empirical to more mechanistic in nature. More pavement performance models are being developed with mechanistic properties. Chapter 4 will discuss these modeling methods in greater detail. Figure 3.3 shows the prediction of one distress type over time and with traffic and environmental loading.

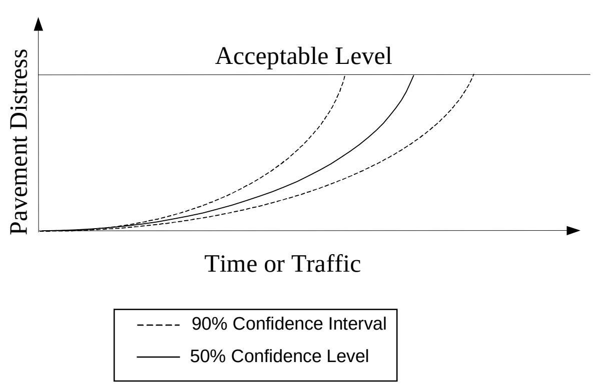


Figure 3.3. Confidence Interval for Distress Modeling

The level of reliability is specified by the engineer performing the analysis, however guidelines are given by AASHTO's Pavement Design Guide (Ref 32). The recommended level of reliability ranges from 50% – 80% for local roads to 85% – 99.9% for urban interstates. In performing life cycle cost analyses for interstate highways, it is important to use very high levels of reliability to ensure that the design has a high probability of meeting or exceeding the expected traffic and environmental loads.

Using the variability of the analysis input variables, the overall variability in the result can be determined. In distress modeling, for example, without using reliability methods the predicted distress value is normally at 50% reliability, or the mean value. In Figure 3.3, the solid curve shows the mean value of the predicted distress level (50% confidence), while the dashed curves show the 90% confidence interval. These values indicate that the engineer can be 90% certain that the predicted distress will fall within this interval throughout the design life. Using the resulting distress level, 90% reliability means that the worst case is taken (i.e., the curve in which the distress reaches its maximum allowable level in the shortest amount of time, shown as the heavy dashed line in Figure 3.4). It is this value, the worst-case value, that is used in determining the condition of a pavement and its need for maintenance or rehabilitation.

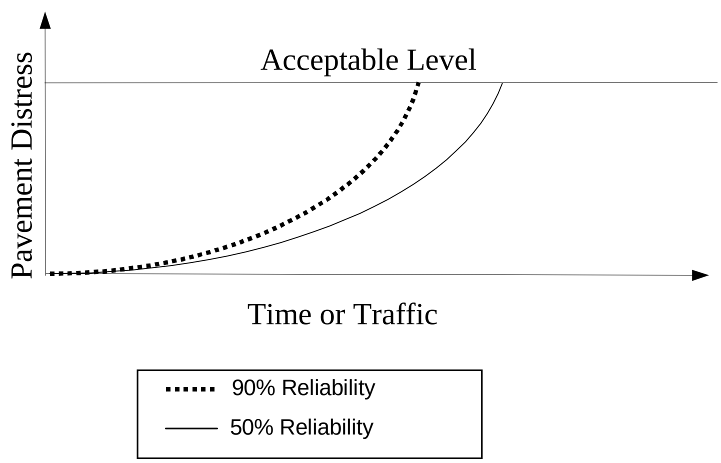


Figure 3.4. Reliability Based on 90% Confidence Interval

3.1.2 Maintenance and Rehabilitation Strategies

The pavement is evaluated at the end of each year by the performance models and the predicted distress levels are evaluated by the strategies' module. This is shown by the flowchart in Figure 3.5, to which components are added as this chapter develops. This module takes the distress levels evaluated in the pavement performance module as inputs and determines, based on individual transportation agency preferences, an appropriate maintenance or rehabilitation strategy.

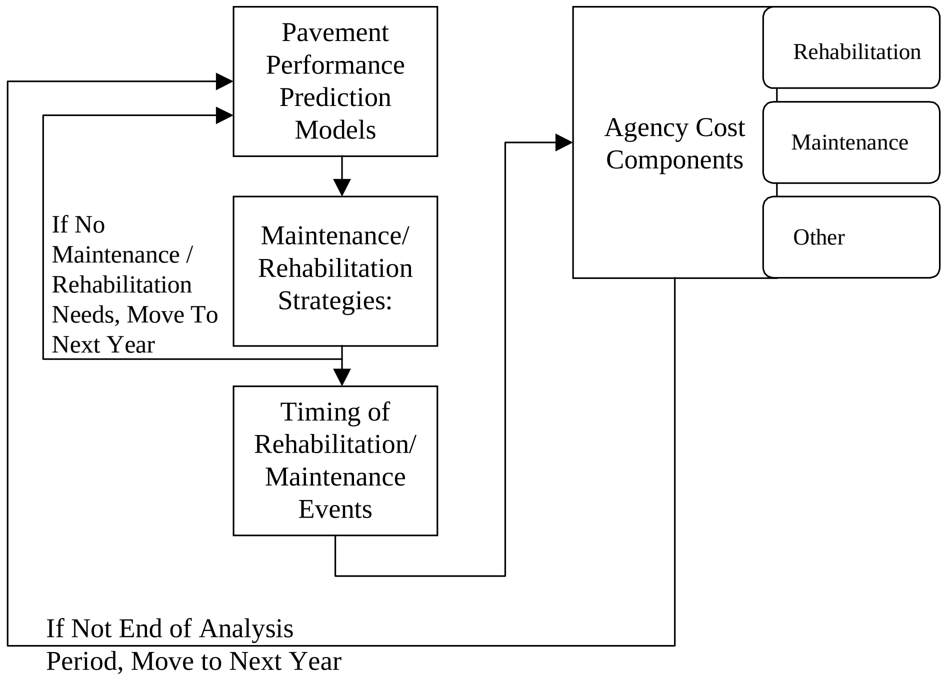


Figure 3.5. Performance Prediction and Maintenance/Rehabilitation Module

Several methods are available from which to determine the maintenance and rehabilitation needs of a pavement section. This project and the associated computer program use values that can be modified by individual agencies according to their rehabilitation preferences. Future modifications to the program may include the development of an expert system in which agencies can describe, with great detail, their rehabilitation preferences (based on budget), individual situations, and local soil, environmental, and driving conditions.

As with the performance models of the previous section, each pavement type must have its own limiting distress criteria and conditions under which different rehabilitation alternatives may be chosen. Other criteria, besides pavement distress levels, could include the cost of continued maintenance each year without performing some type of rehabilitation activity. Figures 3.6 and 3.7 show conceptual graphs of the distress level and construction costs associated with correcting that distress. Figure 3.6 shows the level of distress, while 3.7 shows annual maintenance costs associated with the particular distress, and the cumulative cost of maintenance over the life of the pavement. These figures show that with increasing distress, annual maintenance expenditures also increase, and that a point can be reached where major rehabilitation may be the most economical and reasonable decision.

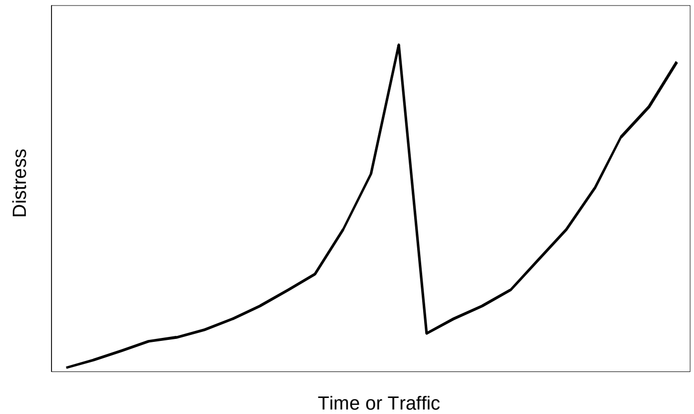


Figure 3.6. Conceptual Graph of Pavement Distress, with One Rehabilitation

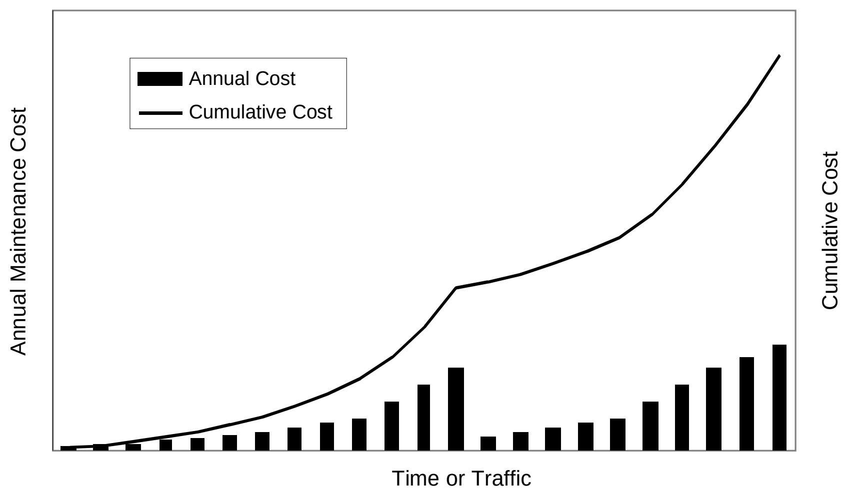


Figure 3.7. Conceptual Graph of Annual and Cumulative Maintenance Cost

These two methods, limiting distress levels and maintenance cost levels, provide the engineer and planner with information that enables them to make decisions regarding the maintenance and rehabilitation strategies that should be undertaken. Once decisions have been made regarding the maintenance and rehabilitation strategies, the decisions and pavement performance information is used by the rehabilitation module.

The rehabilitation strategy definition module within the framework can be used to aid in the design of overlays, delaying or accelerating overlay needs, and generally improving pavement performance while minimizing life cycle costs associated with the project. Although at this time the module is in a basic form, future research and work by others may incorporate more complex systems for defining the rehabilitation preferences of particular transportation agencies.

The purpose of the performance models and the maintenance/rehabilitation modules is twofold. The first purpose, and the one most critical to the transportation agency, is to predict the points over the life of the pavement when maintenance activities, rehabilitation actions, and major reconstruction must take place. This aids the agency in resource allocation and in planning for future expenditures.

The second purpose of these modules is to define the points at which work zones — which disrupt the normal flow of traffic through the section — will be implemented. These points in time will, of course, occur at the same time that the maintenance and rehabilitation work predicted by these modules occurs. The effect of work zones on traffic and the traveling public is briefly described in the next section, and will be discussed in more detail in Chapter 7.

3.1.3 User Costs Caused by Construction Activities

As mentioned above, each time a work zone is implemented, some impact is felt by the traveling public. These impacts are termed *User Costs*, since they are costs incurred by users of the system but are directly caused and attributable to the presence of a work zone and the construction activities undertaken by the transportation agency.

Many life cycle cost analysis approaches do not include any consideration for user costs, since historically these costs have been difficult to measure and valuate. One of the research objectives of this project is to account for user costs in as many instances as possible. At the present time, models exist for predicting the following user costs:

- traveler time delay costs incurred while traveling at slower speeds through work zones, and
- vehicle operating costs incurred while traveling at slower speeds through work zones.

In addition to capturing these user costs, other items for which the economic impacts are not directly tangible at the present time are calculated using other methods and will be reported in nonmonetary units. Impacts that fall into this category include vehicle emissions, accidents, decreased local business access, and driver tension. These impacts are often considered external costs, and are discussed in the next section.

Travel time delay is normally the greatest component of user costs, since the value of time and the number of hours spent in work zone queues are multiplied to determine the total cost of travelers sitting in traffic. When motorists sit idle in vehicles longer than they would have under normal traffic conditions, the time lost is a cost borne by each individual passenger. However, this is a cost that must be considered when a decision is made as to the proper design for a highway project. Minimizing the disruption of traffic flow during each construction (and therefore, work zone) period throughout the analysis period is an important aspect of any highway project's design. The user costs associated with highway construction usually exceed the agency's construction costs by a substantial amount, particularly in urban areas. This was found to be the case, for example, in El Paso, Texas, for the design and construction of a bonded concrete overlay in the downtown section of IH-10. While the estimated construction costs of the bonded concrete overlay was only $4 million, the user costs associated with the construction amounted to over $1 million per day.

The factors that are used to determine the time delay cost at work zones include vehicle speeds before, during, and beyond the work zone, and traffic volume and highway capacity during the time that the work zone will be in place. The models that calculate user costs perform the calculations twice. The first calculation determines the total cost to motorists under normal traffic conditions, while the second determines the incremental user costs added because of the presence of the work zone. Other components, such as average wage earned by motorists, value of vehicles, and cost of fuel, oil, and maintenance of vehicles, are considered in the determination of user costs at work zones, which are integral parts of each event predicted by the pavement performance models.

The components that make up the user cost calculations are evaluated each time a work zone is placed in the roadway. These components are shown in Figure 3.8, which shows their place in the life cycle cost analysis framework.

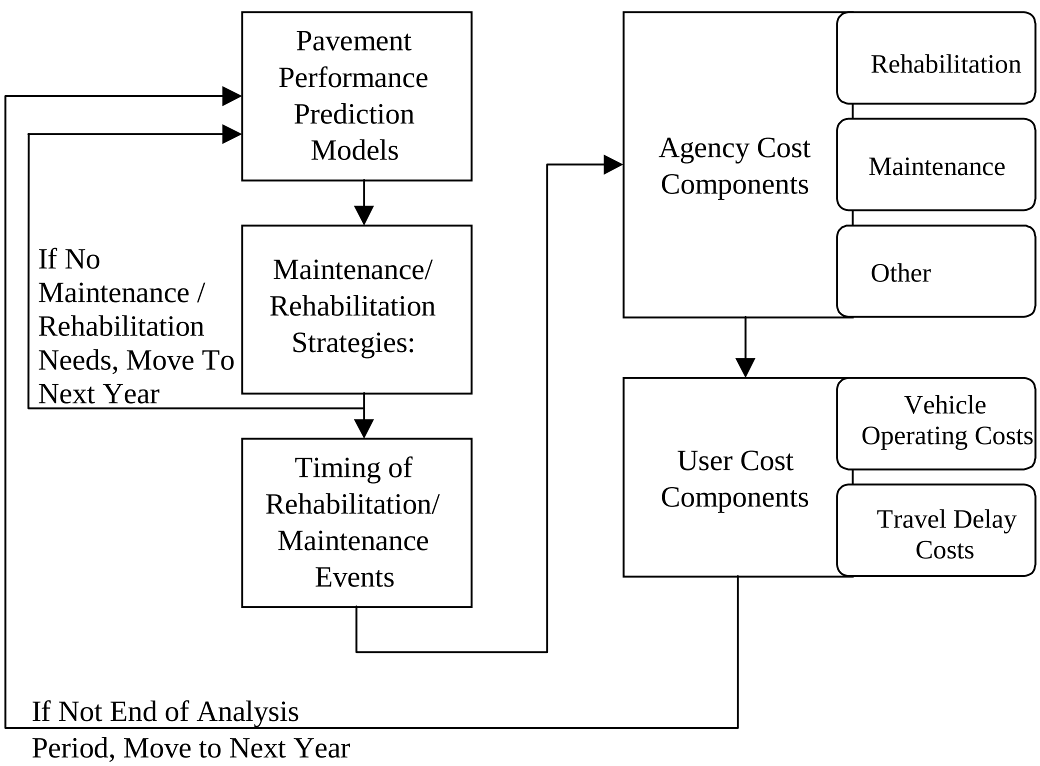


Figure 3.8. User Cost Components Added to Framework

3.1.4 External Costs

Other costs not normally considered in life cycle cost methodologies are sometimes termed *external costs*. External costs are related to the economics' concept of consumption externalities, in which the activities of one consumer have a direct effect on the welfare of another consumer, and which is not transmitted through the price mechanism (Ref 21). In other words, the costs and benefits of externalities are not reflected in market prices. Because of this, the decision of the consumer, firm, or agency creating an externality does not take its effect into account. External costs have been excluded from life cycle cost analysis in the past because they are difficult to quantify and to valuate. The nature of the methodology, however, enables future researchers to include cost calculation techniques as they become available.

An example of externalities as related to highway construction and operation is the issue of excess vehicle emissions that are produced by vehicles in congested traffic caused by highway construction or maintenance activities. The surrounding air quality is reduced, but the activities that cause this reduction in air quality are not held accountable for the effects. Another example would be an increase in highway noise caused by the construction of a new highway or a particular pavement surface. If the effects of highway noise are considered, the highway agency may be required to spend more money on a pavement surface that causes less tire noise, or to construct noise barriers for nearby residents.

A third effect of highway construction — vehicle accidents — can be considered either a user cost, an external cost, or a combination of both. Accidents at work zones incur direct user costs both from the physical property and bodily damage, as well as from increased costs relating to vehicle insurance. The external costs associated with vehicle accidents include the vehicle emissions and noise associated with traffic congestion caused by the accident.

Models exist in various forms for predicting, quantifying, and placing a value on external costs. These are evaluated in this report, and those that are acceptable are included in the life cycle cost analysis methodology. Should capable models not be found for valuing these components, the expected increases in their unit values will be reported in the framework, but not their costs.

Figure 3.9 shows the life cycle cost analysis framework flowchart with the external costs included in their proper place. Although the costs in currency are not currently determined by the models, the impact is calculated for several of the individual components and reported in the individual units. Further research should be undertaken to develop methods for placing a value on each of the external costs so that they may be included in the user-cost portion of the life cycle cost analysis framework.

3.1.5 Life Cycle Cost Calculations

The life cycle cost calculation component takes the events and their timing, as predicted by the performance and rehabilitation strategy models, and assigns a cost for each applicable component of each event. For example, the magnitude of annual maintenance will be predicted for each year, and appropriate strategies will be selected based on TxDOT practices. The estimated agency costs for the maintenance will be calculated and entered for the appropriate year. Depending on the maintenance strategy selected, either by the user or by the program's default values, the traffic control will be determined and traffic impacts will be calculated. User costs, such as vehicle operating costs, time delay costs, and the effects of excess vehicular emissions, accidents, and noise, are costs or effects that will be calculated.

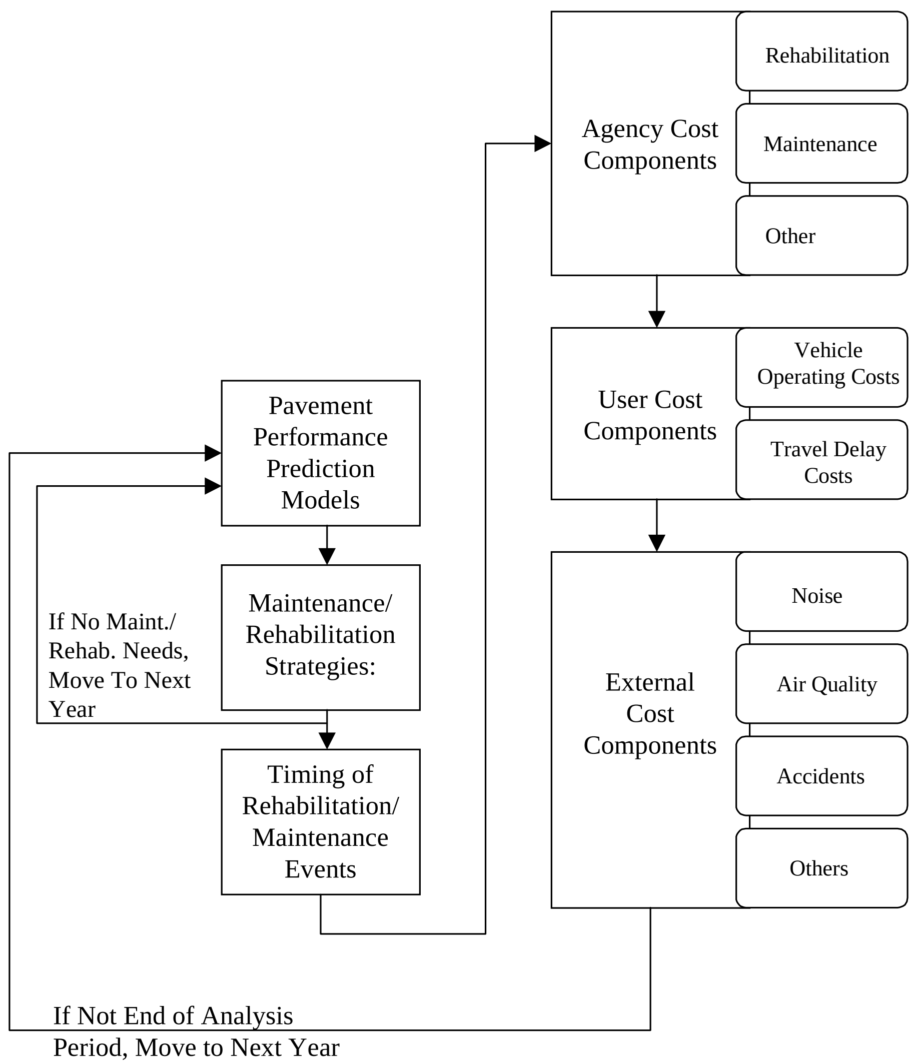


Figure 3.9. Addition of External Costs into Life Cycle Cost Analysis Framework

Major rehabilitation will be treated in the same way maintenance strategies are treated. The costs to the transportation department will be estimated and the appropriate traffic control strategies will be determined, which will affect the agency costs associated with the activity. The amount of time required to complete the work will also affect traffic control strategies and user costs associated with the traffic control.

As mentioned in previous sections of this chapter, the timing of all construction activities are recorded, with the timing then used in calculating both the agency and user costs associated with a project. This timing of events is illustrated in Figure 3.10, which shows a conceptual diagram of pavement performance, with corresponding marks on the X-axis indicating the year in which the work will be performed.

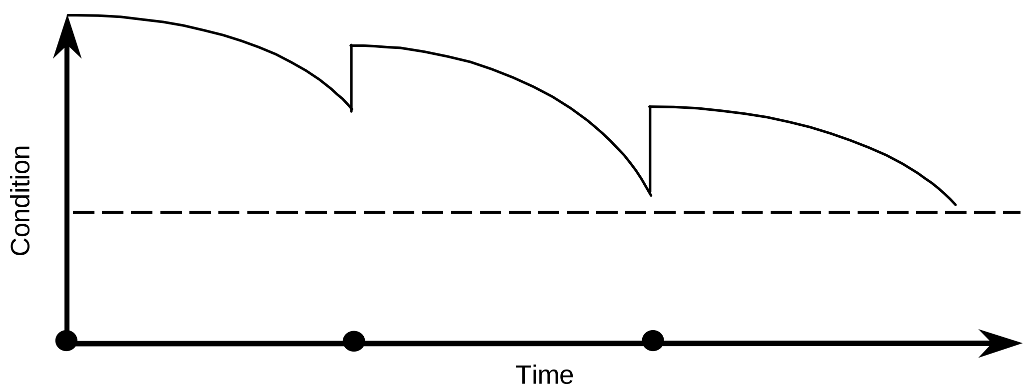


Figure 3.10. Timing of Maintenance and Rehabilitation Activities

The combined agency and user costs for each event will be entered in the life cycle cost analysis at the predicted age of the pavement. The total cost calculated for each year is then discounted to the present time to obtain its present value, for comparison. Using the economic analysis strategies described in Chapter 8, the total life cycle cost of each alternate design will be analyzed and ranked, as described in the next section of this chapter. The conceptual graph in Figure 3.11 shows the agency costs associated with each construction activity over the life of the project.

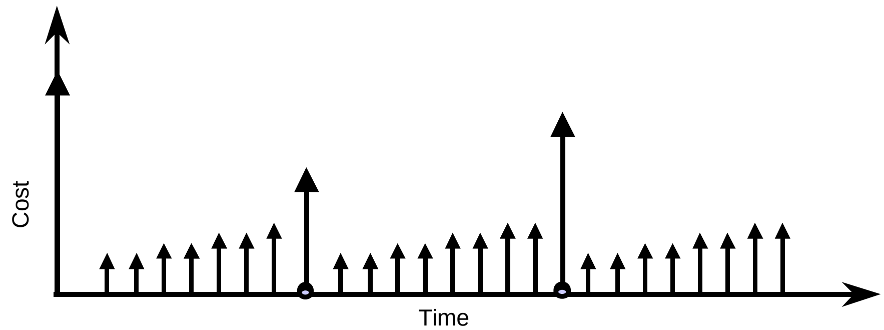


Figure 3.11. Agency Costs Associated with Construction Activities

In Figure 3.12, the large, gray arrows represent the user costs, which are associated with construction activities every time a construction work zone is in place. These costs are in addition to all agency costs that are incurred as a result of the construction activities. User costs vary greatly, depending on the number of vehicles passing through the work zone, but can easily be much greater than the total cost of the actual construction activities.

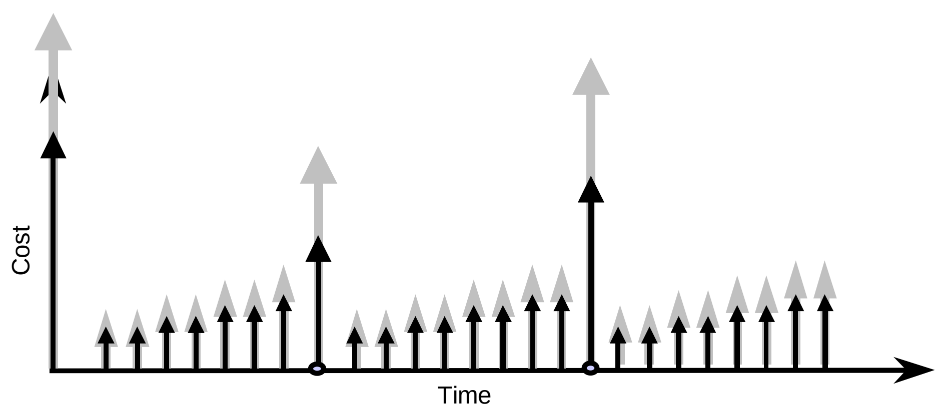


Figure 3.12. User Costs, Added to Agency Costs, Associated with Construction Activities

The essence of life cycle costing is to capture all predictable costs that may have an impact on the economy or society that could be affected by the highway pavement project under consideration. This report attempts to provide a means for identifying and estimating all costs that may have an effect on these entities involved in the construction and use of the highway section.

Figure 3.13 shows an expanded view of the cost components of the framework. For each year that a design alternative is evaluated, the maintenance and rehabilitation routine determines if repair work is needed. If such work is needed, the appropriate cost components of the framework are invoked to estimate the total cost, given present-day unit costs and production rates, to the agency in terms of construction costs, and to the users in terms of time delay, vehicle operating costs, and all other external costs that can be measured and valuated at this time.

After computing the total cost for a particular year, including agency, user, and external costs, this total is *discounted* to the present time, or the time at which the analysis is being performed. This means that the calculated cost at a future time is adjusted for inflation and prevailing interest rates. (The concept of discounting future costs to the present is discussed in more detail in Chapter 8.) After summing costs for the current analysis year and discounting those costs to the present, the framework records the level of all pavement distresses, notes any maintenance or rehabilitation work that is performed during the year, and returns to the pavement performance models to begin a new analysis year.

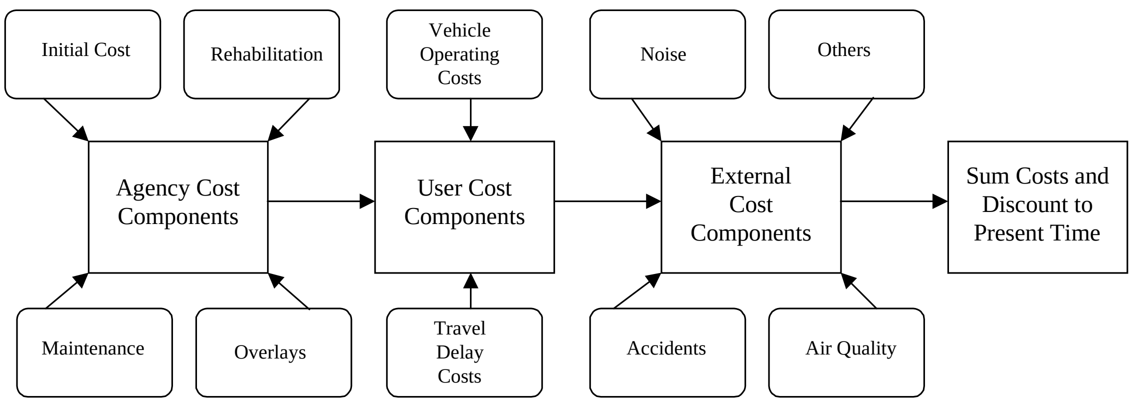


Figure 3.13. Cost Components of Framework

3.1.6 Project Ranking

Various methods are used to rank projects once the total costs have been calculated over the analysis period. As mentioned previously, the total annual costs can be discounted to the present time to provide a net present value (NPV). Another method of analyzing the total life cycle cost is by equivalent uniform annual cost (EUAC). Ranking alternatives by their overall net present value is important to the engineer who uses life cycle costing as a tool in decision making. There are, however, other aspects of life cycle cost analysis that do not currently lend themselves to monetary valuation and that can have a great impact on the way alternatives are ranked. In a proper life cycle cost analysis, the alternatives should be ranked by all components discussed in the previous sections. This includes those upon which a specific value can be placed, and those for which it is difficult, or impossible, to value. This creates the need for multi-attribute criteria decision making. For example, in a life cycle cost analysis, one alternative may have a lower net present value than another feasible alternative. The second alternative, however, might cause less traffic disruption and, consequently, less vehicle emissions or accidents over the analysis period. Thus, the life cycle cost framework must be capable of ranking all alternatives with respect to their individual components, not just to their net present value.

3.2 INTEGRATION OF LIFE CYCLE COST COMPONENTS

This section summarizes the proposed framework for life cycle cost analysis of rigid concrete pavements. A flowchart of the entire framework is shown in Figure 3.14.

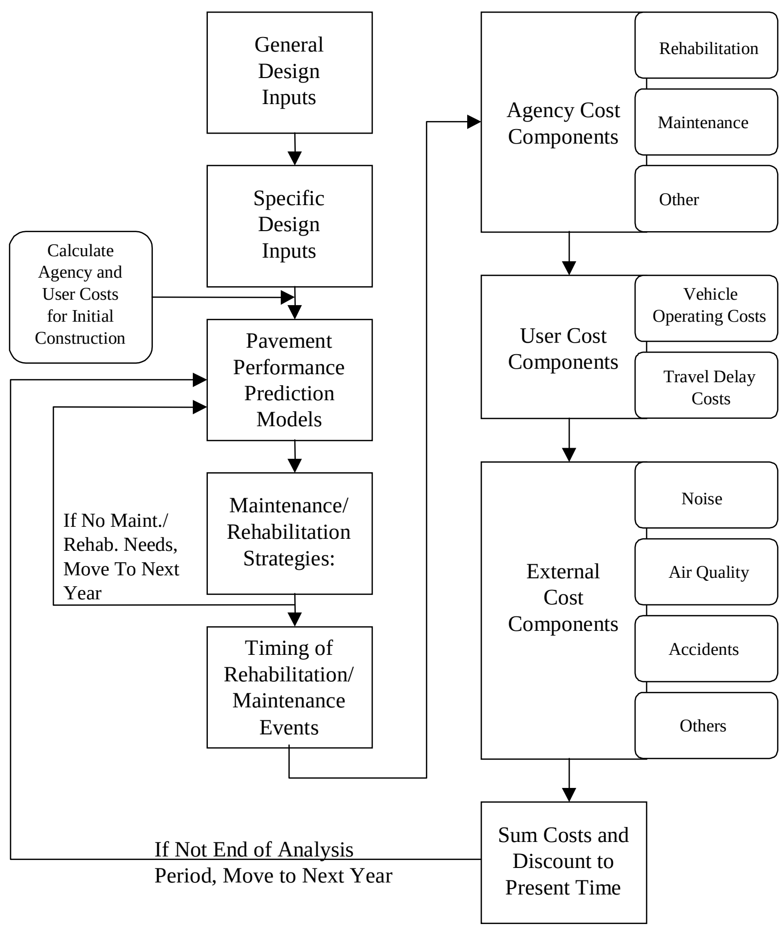


Figure 3.14. Comprehensive Life Cycle Cost Analysis Framework.

Throughout the analysis of one alternate design, there are two instances where the process will stop its analysis for one year and return to performance modeling for the next year. The first point at which this is possible is after the maintenance and rehabilitation module has determined the needs of the pavement section. If no distresses have exceeded reasonable limits, set by the user of the program, control is returned to the performance modeling module, where the next year's environmental and traffic loading conditions are prepared and used in the performance models.

The second point at which control is returned to the performance modeling module occurs at the end of the analysis of agency and user costs after a maintenance or rehabilitation action is taken. When a pavement section requires some type of maintenance or rehabilitation, the program decides (again, based on user input) the appropriate action to take. The cost calculation modules determine the level of impact to the agency and to the users, as well as the effect of work zone lane closures on externalities that are not valued in terms of currency.

The life cycle cost analysis framework presented in this chapter represents an attempt to capture all costs incurred by the transportation agency, by users of the facility, or by others affected by its presence. In capturing the full impact of a highway project, the total life cycle cost can be estimated and compared with other alternate pavement designs and configurations. In this way, the best alternative, from both the agency and user point of view, can be evaluated and selected.

3.3 SUMMARY

Although this life cycle cost framework can predict both agency and user costs over the expected life of a project, and provides the user with an informative way of comparing the results, the final decision regarding selection of a preferred alternative must be made using engineering judgment. The framework is simply a tool with which engineers and planners can view the relative differences and similarities between alternate designs. The decision as to which alternative to construct cannot be made by this life cycle cost framework alone. Many other factors exist which cannot be evaluated at this time. Perhaps future research will bring life cycle cost analysis closer to capturing *all* costs (and benefits as well) of a particular highway pavement design and configuration. But even then, human judgment will be necessary to provide final analysis, considerations, and decisions.

CHAPTER 4. PAVEMENT PERFORMANCE

The evaluation of pavement performance is a crucial step in the life cycle cost framework. The ability to predict the remaining life or the distress levels of a pavement section allows engineers, planners, and highway agencies to plan ahead for maintenance and rehabilitation activities, budget for future expenditures, and make decisions on the timing of those rehabilitation activities. With ample time to plan, state transportation agencies can minimize their costs as well as minimize the impact of their construction activities on the traveling public and others affected by such construction.

Pavement performance models are divided into two major categories: *empirical* and *mechanistic-empirical.* These types of design and analysis models will be described in the next section. Then, models used for evaluating pavement performance will be described for each type of pavement and for each major distress that may impact performance.

4.1 PAVEMENT PERFORMANCE PREDICTION

As mentioned above, two major types of design and analysis models — empirical and mechanistic-empirical — are used when designing and analyzing pavement structures. Empirical models, which are based on regression analysis, are valid only with respect to the range of data from which they were initially developed. Huang (Ref 44) states that regression equations are valid only under certain conditions and should not be applied when the actual conditions differ from those under which the model was developed. Because of this limitation, empirical models should be used only when other models are not available, and when the data being used in the models are within the range of data used in the model's development.

Another method of modeling pavement performance is mechanistic-empirical modeling, sometimes simply called *mechanistic modeling.* Mechanistic models use analytical models to estimate the stress, strain, or deflection state of pavements. This type of modeling has been used at least since 1938 by Bradbury (Ref 11) and by many others since that time. Mechanistic methods or procedures include the ability to translate the analytical calculations of pavement response to pavement performance (Ref 32). In this report, mechanistic models are used wherever possible to predict the performance of alternate pavement designs.

This type of modeling arises from the fact that many of the factors affecting pavement performance cannot be modeled precisely by purely mechanistic methods. The mechanistic models must be calibrated with observed performance from other similar pavements in the local area where the pavement will be constructed.

Where mechanistic-empirical models are not available, the framework relies on empirical models as discussed above. In keeping with the modular characteristics of the life cycle cost framework, the empirical models that are used will be easily replaced as additional mechanistic models are developed. The 1993 AASHTO Guide for Design of Pavement Structures (Ref 32) states that researchers in this field have hypothesized that mechanistic modeling of pavement should improve the reliability of the design equations by predicting distress and deterioration as a function of traffic and environment.

As mentioned, the performance models contained in this report are empirical, and mechanistic-empirical in nature. To the extent that calibration data are available in the area under consideration, the mechanistic models can be calibrated to improve their predictive abilities. The remaining sections in this chapter will discuss the performance models that are used for each type of pavement and for each distress. However, since traffic loading on pavement affects performance more than other factors, the next section is devoted to describing how the framework determines the level of traffic loading for a given period of time.

4.2 PAVEMENT LOADING

Often, vehicular loading of the pavement is the parameter that has the greatest effect on the performance of portland cement concrete pavements. Repetitive traffic loads fatigue the pavement and cause cracking, spalling, faulting, and punchouts. Although other factors, such as environmental conditions, affect the performance of pavements, they only help to modify and calibrate performance models to local conditions. The effects of vehicular loading, however, are universal and affect all pavements in any locale. This section will describe the methods in which the amount of vehicular loading is determined and predicted for the entire analysis period.

The first method that will be discussed is the condition where the engineer obtains, or predicts, the equivalent single axle loads (ESALs) for the first year, and an estimated annual growth rate. The second method, which will be included in this version of the computer program, is the one used more often by the Texas Department of Transportation (TxDOT). This method uses the average daily traffic (ADT) for the first year, predicts the ADT for the final year of the analysis period, the percentage of trucks throughout the analysis period, and the design ESAL value for the entire analysis period.

A third method that should be included in future versions of the life cycle cost analysis framework is load spectra. Under this type of analysis, vehicles are divided into many groups by axle weight. The distribution of these axle weight groups is taken into account when developing fatigue relationships for the pavement structures. Instead of combining all axle loads into a single representation in terms of ESALs, several groups are constructed to capture the effect of axle load ranges on the performance of the pavement. This functionality should be studied in more detail but can easily be implemented into the life cycle cost framework by future researchers.

In order to determine the appropriate ESAL value for each year, the traffic evaluation module begins with the initial year ESAL and increases this value annually by the growth rate. This is represented by Equation 4.1 below, which shows the calculation for the current year's ESAL value:

$$ESAL_{current} = ESAL_{initial} \bullet (1 + g)^{i} \tag{4.1}$$

where:

g = annual ESAL growth rate, and
i = current year, between 0 and analysis period.

While some performance models used require the current annual ESAL value, all require the cumulative value to predict fatigue and the level of other distresses. The algorithm used to determine annual cumulative values is as described below. Given the first and last year ADT values, an annual growth rate can be derived by the following formula:

$$ADT_{final} = ADT_{initial} \bullet (1 + g)^n \tag{4.2}$$

where:

g = annual growth rate, and
n = analysis period.

Then, solving for g:

$$g = \left(\frac{ADT_{final}}{ADT_{initial}} \right)^{1/n} - 1 \tag{4.3}$$

The annual cumulative ESAL value, then, is calculated by deriving the first year ESAL value from the growth rate and the total ESALs:

$$ESAL_{cumulative} = ESAL_{initial} \bullet \frac{(1+g)^n - 1}{g} \tag{4.4}$$

$$ESAL_{initial} = ESAL_{cumulative} \bullet \frac{g}{(1+g)^n - 1} \tag{4.5}$$

From this point, the cumulative ESAL values for each year are determined by:

$$ESAL_{annual,cumulative} = ESAL_{initial} \bullet \frac{(1+g)^i - 1}{g} \tag{4.6}$$

where:

i = current year.

4.3 ANALYSIS OF JRCP PERFORMANCE MODELS

Improved models have been developed to predict the performance and level of distresses over time for jointed reinforced concrete pavement (JRCP) by researchers in recent years. These models focus on the major distresses manifested by JRCP: transverse joint faulting in both doweled and nondoweled joints, joint spalling, and transverse midslab cracking. In addition to the prediction of specific distresses, models used for predicting the present serviceability index of JRCP will be evaluated. A sensitivity analysis will be conducted for each model and the range of the constitutive variables will be determined for which the model provides reasonable responses.

4.3.1 Transverse Joint Faulting — Doweled Joints

The model selected to be included in the LCC framework to predict transverse joint faulting for doweled joints is shown below. This is a regression model developed from data obtained in the FHWA's Long-Term Pavement Performance (LTPP) project (Ref 101).

$$\mathrm{FAULT_D} = \mathrm{MESAL}^{0.2} \bullet \left[0.0238 + 0.0006 \bullet \left(\frac{JS}{10}\right)^2 + 0.0037 \bullet \left(\frac{100}{k}\right)^2 + 0.0039 \bullet \left(\frac{AGE}{10}\right)^2 - 0.0037 \bullet ES - 0.0218 \bullet Diam \right] \tag{4.7}$$

where:

$\mathrm{FAULT_D}$	=	mean transverse doweled joint faulting, inches,
MESAL	=	cumulative 18 kip ESALs in traffic lane, millions,
JS	=	average joint spacing, feet,
k	=	modulus of subgrade reaction, psi/in.,
AGE	=	age of pavement, years,
ES	=	edge support: 1 = tied concrete shoulder, 0 = none, and
Diam	=	dowel diameter, inches.

The model statistics, using the data with which the model was developed, are as follows:

R^2	=	0.534
N	=	59 sections

Although the descriptive statistics indicate that the model is lacking in many respects, this model performs as well or better than most other doweled, faulting models. The R^2 parameter used to measure the performance of these models is a measure of the amount of variation explained by the model, called the *correlation coefficient*. It is the ratio of the explained variation to the unexplained variation, ranging from 0 (all variation is unexplained) to 1 (all variation is explained).

Figures 4.1 to 4.8 show the sensitivity of the model to the variables. It is obvious, given the small magnitude of the regression coefficients in the model, that the model is sensitive to both tensile strength and precipitation, but not to the freeze -thaw index.

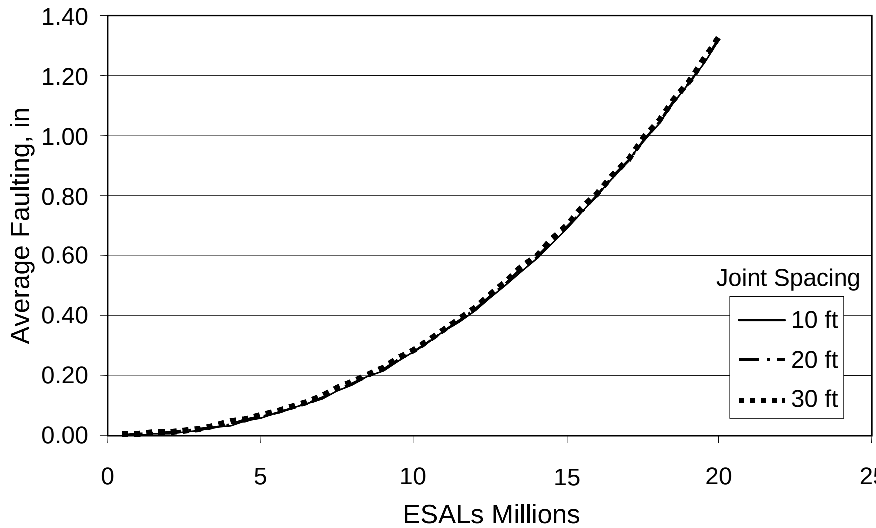


Figure 4.1. Sensitivity of JCP Doweled Faulting Model to Joint Spacing

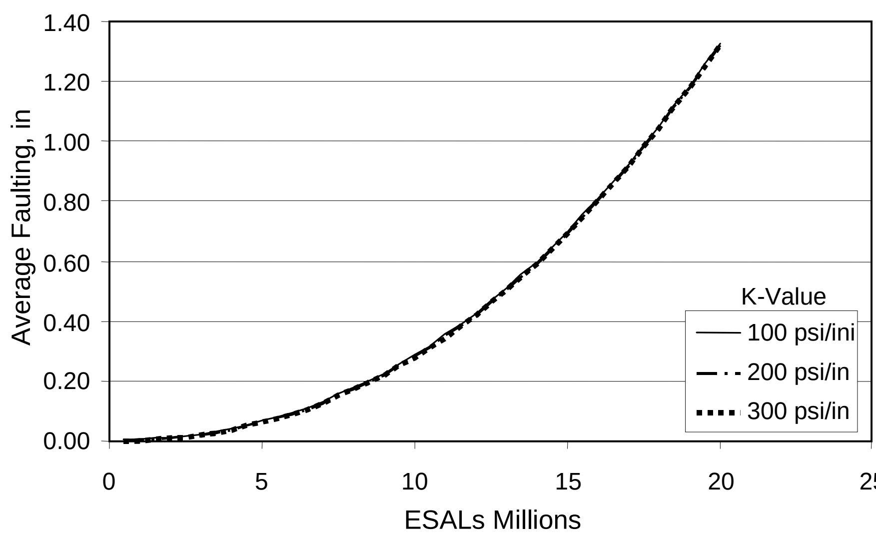


Figure 4.2. Sensitivity of JCP Doweled Faulting Model to Modulus of Subgrade Reaction

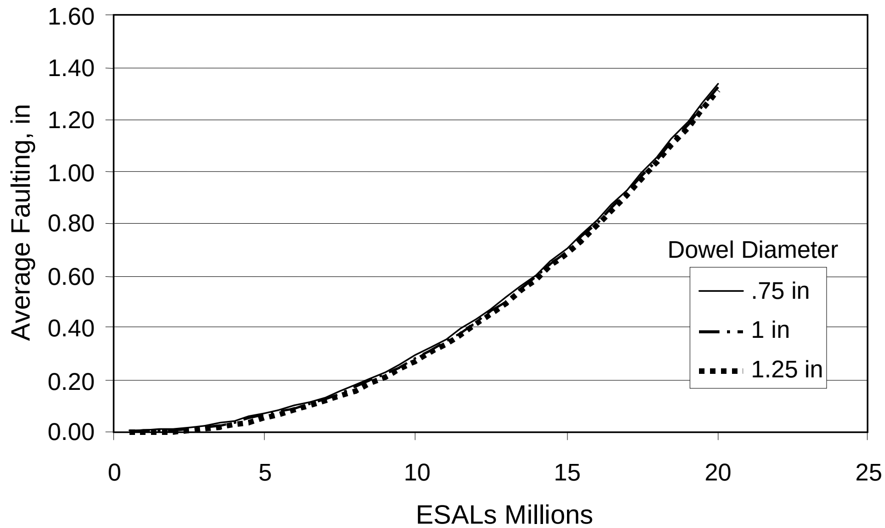


Figure 4.3. Sensitivity of JCP Doweled Faulting Model to Dowel Diameter

4.3.2 Transverse Joint Faulting — Nondoweled Joints

This model considers the faulting of joints in nondoweled conditions. The model considers such variables as freeze-thaw index, precipitation, and the tensile strength of the concrete. This model was developed under a project associated with the LTPP study (Ref 101).

$$FAULT_{ND} = KESAL^{0.94} \bullet [3.415E\text{-}2 + 1.072E\text{-}5 \bullet FTINDEX + 8.963E\text{-}5 \bullet PRECIP - 7.51E\text{-}6 \bullet f_t] \tag{4.8}$$

where:

$FAULT_{ND}$ = mean transverse non-doweled joint faulting, inches,
KESAL = cumulative 18 kip ESALs in traffic lane, thousands,
FTINDEX = average annual freeze-thaw index,
PRECIP = average Annual Precipitation, in./yr, and
f_t = tensile strength of concrete, psi.

The model statistics are as follows:

R^2 = 0.966
SEE, 0.1 mm = 4.1
N = 13

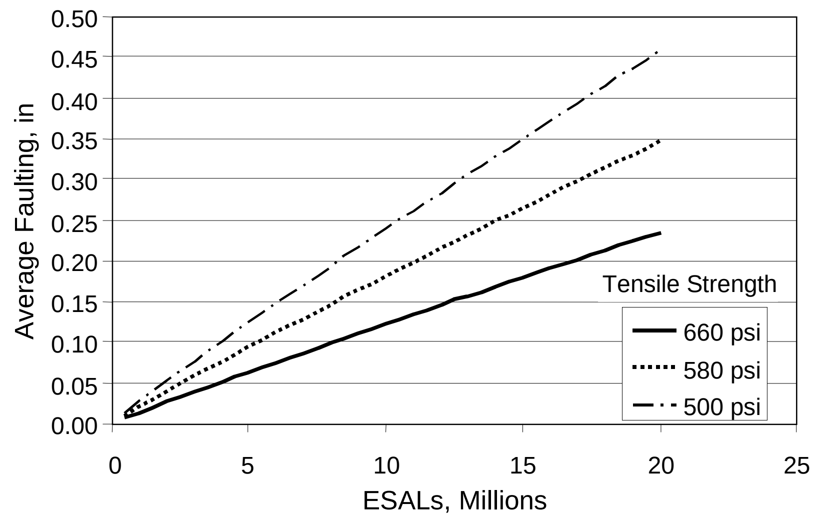


Figure 4.4. Sensitivity of JCP Non-Doweled Faulting Model to Tensile Strength

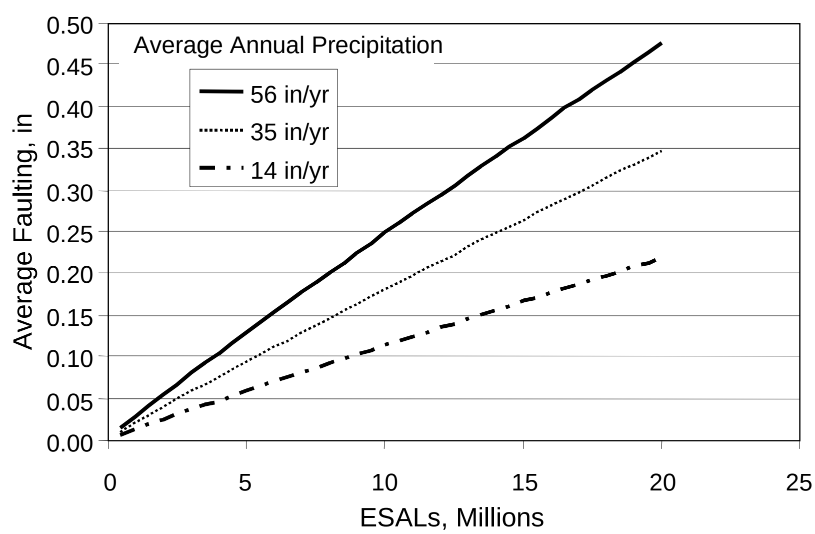


Figure 4.5. Sensitivity of JCP Non-Doweled Faulting Model to Precipitation

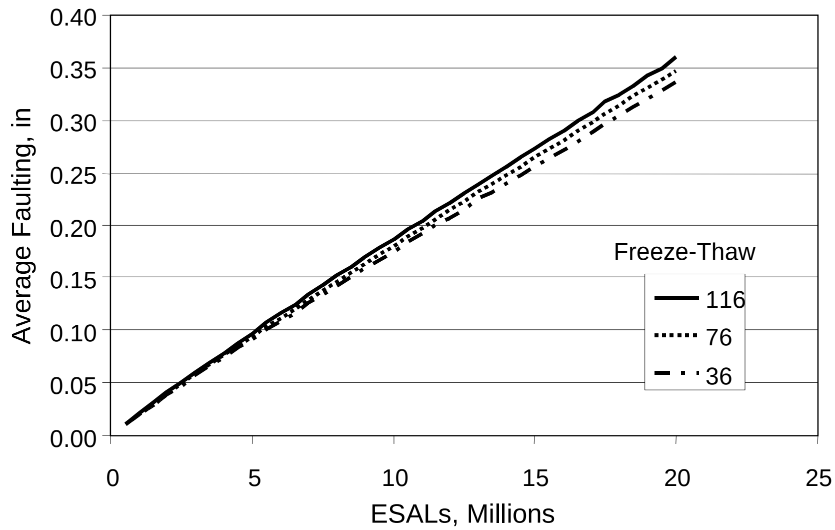


Figure 4.6. Sensitivity of JCP Non-Doweled Faulting Model to Freeze-Thaw Index

4.3.3 Transverse Joint Spalling

Many empirical models have been developed to relate environmental and construction conditions to the level and severity of spalling observed in jointed concrete pavements. Particular models of the empirical type do not perform well when variables are used that are outside the range that was used when these models were developed. In some cases, such models, and particularly with the spalling models that were investigated, negative values of distresses are predicted.

The model presented here is a mechanistic-empirical approach to determining the factors that affect the amount of spalling in jointed concrete pavements, accurately and reasonably (Ref 101). A good mechanistic model will relate not only the construction and environmental conditions to spalling, but the mechanisms by which spalling progresses within a pavement section. When such a model becomes available, as with any other distress modeled in the framework, it can easily be implemented into the life cycle cost analysis framework.

This model uses the Weibull distribution to predict failure (probability of a spall developing, or magnitude of spalling in a pavement section) in relation to traffic loading. This method was used by Zollinger and McCullough (Ref 110) to predict cracking in continuously reinforced concrete pavements. The form of the model is as follows:

$$N = \lambda_s \bullet [-\ln(S)]^{-\frac{1}{\gamma_s}} \qquad (4.9)$$

where:

S = fraction of spalled joints,

N = cumulative KESALs,
γ_s = Weibull shape parameter for spalling, and
λ_s = Weibull scale parameter for spalling.

Using two points on the Weibull distribution curve, the first being S = 0.0001 (approaching zero), and traffic equal to 1 ESAL, the parameters γ_s and λ_s can be determined. By linear regression the parameters in the Weibull distribution can be predicted. Once these parameters have been predicted using environmental and materials data from the LTPP database, and using the predicted values of N, the number of loads to cause the level of spalling can be predicted. The following equation, which is equivalent to the equation above, is used to calculate spalling, represented as a percentage of joints that are spalled.

$$S = e^{\left[\frac{-\lambda}{N}\right]^{\gamma}} \tag{4.10}$$

Using this model, maximum acceptable levels of spalling can be set by individual state agencies, and the corresponding level of traffic can be calculated. The pavement design can be evaluated to account for the amount of spalled joints that can be expected for the level of ESALs forecast by the agency.

This model has been calibrated for two climatic regions, including the *wet freeze* and the *wet no-freeze* regions, as specified by the LTPP project. Most of the pavements in Texas will be included in the wet no-freeze climatic region, and much of the state is included in the *dry no-freeze* region.

Below is the model developed for the *wet no-freeze* region, including the summary statistics. The parameters include concrete tensile strength, average annual precipitation, freeze-thaw cycles, and pavement age.

$$\ln(\lambda_s) = 10.576 + 8.43E\text{-}4 \cdot f_t - 0.0307 \cdot PRECIP - 0.127 \cdot AGE \tag{4.11}$$
$$\gamma_s = 0.347 - 3.77E\text{-}5 \cdot f_t + 7.97E\text{-}4 \cdot PRECIP + 1.21E\text{-}3 \cdot AGE \tag{4.12}$$

R^2 = 0.86
SEE, % Spalls = 8.06
N = 25

As mentioned, the two equations constituting this model were developed for wet climatic regions, and thus will not necessarily be valid for all of Texas. No areas of Texas fit the guidelines for the freezing climatic region, according to the LTPP, and those models were not included in the framework. Below are graphs showing the sensitivity of the model to the various components.

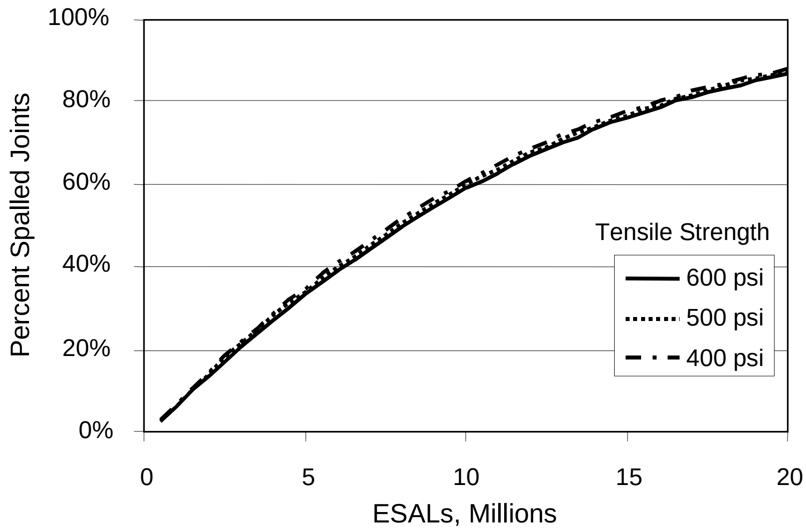


Figure 4.7. Sensitivity of JCP Spalling Model to Tensile Strength

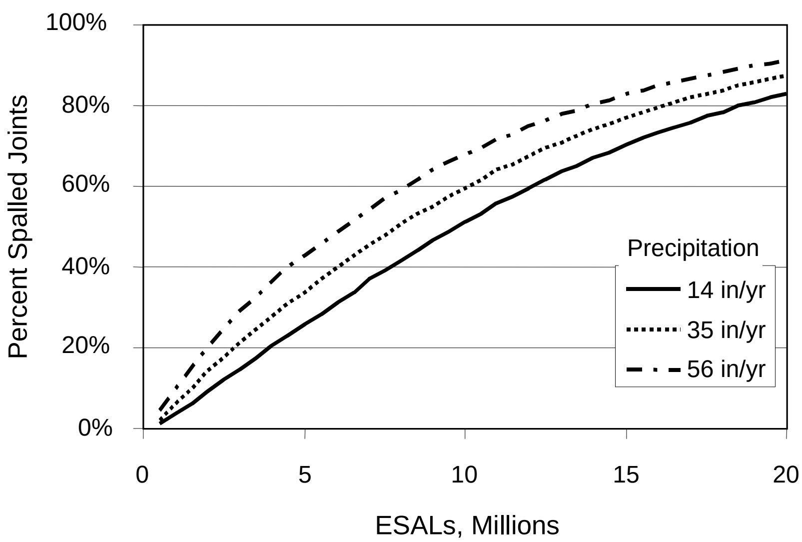


Figure 4.8. Sensitivity of JCP Spalling Model to Average Annual Precipitation

4.3.4 Transverse Cracking

The transverse cracking model was adapted from several sources, including Salsilli, Barenberg, and Darter (Ref 82), Huang (Ref 44), and Zollinger (Ref 101). This model uses

Miner's law for evaluating concrete damage, which assumes a linear accumulation of damage with the number of applied loads at a given stress level. Miner's equation is as follows:

$$D_j = \sum_{i=1}^{j} \frac{n_i}{N_i} \tag{4.13}$$

where:

D_j	=	cumulative damage,
n_i	=	traffic loading for current time period, and
N_i	=	expected allowable loads to arrive at 50% probability of a cracked slab (Damage = 1.0).

The value of N_i is determined using a fatigue model based on the ratio of concrete stress to strength. The stress value used is the edge stress, which is obtained from the Westergaard edge stress equation. This equation is as follows:

$$\sigma_e = \frac{0.572P}{h^2}\left[4\log_{10}\left(\frac{l}{b}\right) + 0.359\right] \tag{4.14}$$

where:

$$l = \sqrt[4]{\frac{E_c h^3}{12(1-\mu^2)k}} \tag{4.15}$$

$$b = \sqrt{1.6a^2 + h^2} - 0.675h \tag{4.16}$$

σ_e	=	Westergaard Edge Stress, psi,
P	=	total applied wheel load, lbs,
h	=	slab thickness, in.,
k	=	modulus of subgrade reaction, psi/in.,
μ	=	Poisson's ratio, and
a	=	radius of loaded area, in.

From the calculation of the edge stress, and using the strength of the concrete, the fatigue equation can be used to determine the number of loads to failure. The fatigue equation is as follows (Ref 19):

$$\text{Log}_{10}N_f = 17.61 - 17.61 \bullet \sigma/S_c \tag{4.17}$$

where:

N_f = loads to failure (50% slabs cracked),
σ = edge stress, psi, and
S_c = concrete flexural strength, psi.

In order to determine the number of loads to failure for 50% slabs cracked, the variability of the stress and strength must be determined. The following equations describe the derivation of the variance of each of these components. Once the number of loads to failure has been determined, and the ESAL total for the current time period has been calculated, the damage is calculated as shown in Equation 4.13. Assuming a normal distribution, the probability of D = 1.0 (representing 50% slabs cracked) is determined. The variance equations, and the remainder of the model follow. The method of mathematically calculating the variance is discussed in Chapter 8 of this report.

Let R = ratio of stress to strength, σ/S_c

$$\mathrm{Var}[R] = \left(\frac{-\sigma}{S_c^{\,2}}\right)^2 \mathrm{Var}[S_c] \tag{4.18}$$

$$\mathrm{Var}[N_f] = (17.61 \bullet \ln(10) \bullet N_f)^2 \bullet \mathrm{Var}[R] \tag{4.19}$$

$$\mathrm{Var}[\mathrm{Damage}] = \left(\frac{n_i}{N_{fi}^{\,2}}\right)^2 \mathrm{Var}[N_{fi}] \tag{4.20}$$

$$\mathrm{Cracking} = 1000 \bullet \mathrm{Prob}\left(\frac{D-1}{Var[D]^{0.5}}\right) \tag{4.21}$$

where cracking is expressed as square feet per 1,000 square feet of pavement.

4.3.5 Serviceability

The major models in use today for predicting the pavement serviceability rating, which is used in predicting the remaining serviceable life of a pavement, use a combination of the other distress prediction models. The reliability of these models comes into question, then, when the models are combined, with the respective regression error of each component model, and further regression models are produced.

For the reasons mentioned above, the present serviceability of the different alternatives, for each year, will be determined based on the AASHTO design guide equation for the design of rigid pavements. The equation is used to determine the design thickness of a rigid pavement, or the allowable loads for a specific thickness. This equation can also be used to determine the decrease in PSI for given inputs and traffic loading. The AASHTO design equation is shown below:

$$\log_{10} W_{18} = Z_R \times S_o + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624\times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \times \log_{10}\left[\frac{S'_c \times C_d\left[D^{0.75} - 1.132\right]}{215.63 \times J\left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right]}\right] \quad (4.22)$$

Each year the current level of traffic is updated in the AASHTO equation and the equation is solved for the ΔPSI value, which provides an estimate of the structural condition of the pavement. This equation can be used with a known or predicted value of ESALs to predict the PSI of a pavement, given other design parameters that will be readily available to the pavement design engineer. Using the PSI prediction, combined with the distress levels predicted by the other performance models, rehabilitation requirements will be evaluated.

The AASHTO model is used for consistency, since it is the same model that will be used for pavement thickness design. NCHRP Report 277 (Ref 20) indicated that this is an effective approach by stating, in its discussion of evaluated models, that the models indicate slab thickness affects the rate of loss of pavement serviceability. Figure 4.9 shows a typical PSI curve with respect to time or traffic. This example shows a major rehabilitation toward the end of the predicted service life, and no action taken after that.

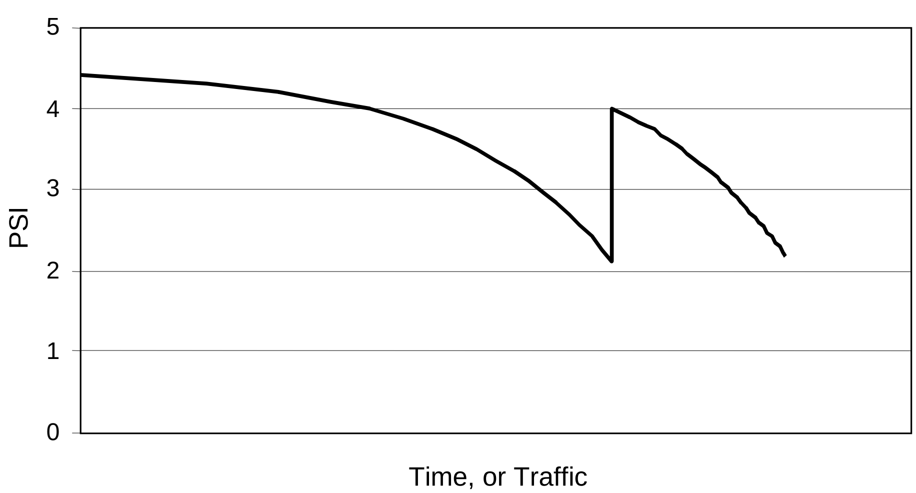


Figure 4.9. Typical Time-Traffic vs. PSI Curve with One Rehabilitation

4.4 ANALYSIS OF CRCP PERFORMANCE MODELS

Existing models that predict performance and distresses in continuously reinforced concrete pavements take different approaches. The model in the computer program CRCP-8 (Ref 107) uses a mechanistic-empirical model to predict punchouts per mile as the primary distress indicator. Other models predict crack spacing, crack progression, and pavement roughness. The CRCP performance models that will be discussed in this section include transverse cracking, punchouts, and ride quality.

4.4.1 Transverse Cracking

The transverse cracking model developed by Won et al. (Ref 107) and Suh et al. (Ref 91) used the computer program ILLISLAB, developed at the University of Illinois to predict stresses in the transverse direction caused by wheel loads. A factorial was developed to perform this analysis by varying slab thickness, transverse crack spacing, wheel load, modulus of subgrade reaction, and the structural continuity at transverse cracks. Stresses obtained from this analysis were used to develop a regression model to predict the crack spacing in CRCP. Punchouts, the primary distress in CRCP, can then be predicted with the model presented in the following section. The cracking model developed by Won and Suh predicts the crack spacing distribution.

This report will not discuss the CRCP cracking model in detail, given that the CRCP-8 computer program utilizes this model and the model has been validated and calibrated to Texas conditions. The user of the software package is required to enter the inputs that CRCP-8 uses into the new framework, which then performs a CRCP-8 analysis, from which the results are used in predicting crack spacing over time.

4.4.2 Punchouts

The most commonly used punchout model was developed in 1988 by Won et al. (Ref 107) at the Center for Transportation Research of The University of Texas at Austin. The model uses the fatigue failure model, together with the relationship between crack spacing and the transverse tensile stresses in the pavement. The amount of punchouts per mile of pavement is dependent on the crack spacing in the CRCP. The propensity for punchouts increases when crack spacing decreases. The model has been used in various versions of the CRCP design and analysis software produced by CTR.

The CTR models assume that no punchouts occur on slabs where the crack spacing is greater than 3.5 feet. For slabs shorter than 3.5 feet, the tensile stress is determined through a regression model developed through the use of ILLISLAB finite element analysis. The concrete stress is then combined with the fatigue model to obtain the number of loads to failure, or the development of a punchout. The variance of the number of loads to failure is used in this calculation much like the variability concept was utilized in the transverse cracking of jointed concrete pavements model. The form of the fatigue model in this model is as follows:

$$N_f = A\left(\frac{f}{\sigma}\right)^B \tag{4.23}$$

where:

N_f	=	number of loads to failure, ESALs,
f	=	concrete Strength, psi,
σ	=	wheel load stress, psi,
A	=	first fatigue coefficient, and
B	=	second fatigue coefficient (4.0 is widely used).

The number of punchouts per mile, then, is calculated by determining the number of slabs per mile and equating the probability of a punchout per slab to the percentage of slabs in a mile that develop a punchout. Figure 4.10 shows a typical failures per mile curve based on the number of applied ESALs.

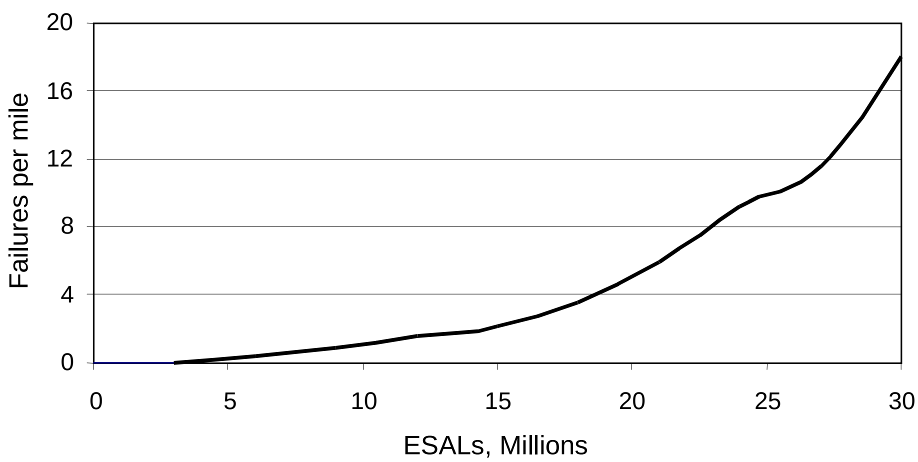


Figure 4.10. CRCP Failures (Punchouts) per Mile vs. ESALs

4.4.3 Serviceability

The serviceability model for continuously reinforced concrete pavement is the same as that used for jointed concrete pavements. The present serviceability index of the pavement is calculated using the AASHTO design equation (Ref 32). Failure criteria for CRCP will be discussed in Chapter 5.

4.5 ANALYSIS OF OVERLAY PERFORMANCE

The first step in determining the rehabilitation needs of a pavement section is to make an estimate of the remaining life of the pavement structure. At the end of each year in the analysis period, an assessment of the condition of the pavement must be made, from which one of three alternatives must be chosen: do nothing, minor maintenance, and major rehabilitation. When the decision between the three choices above is determined to be major rehabilitation, or an overlay over the original pavement surface, the performance models included in the computer program *Rigid Pavement Rehabilitation Design System* (RPRDS-1) are used.

The different overlay combinations discussed in this chapter are shown below in Figure 4.11. This section will focus only on performance and the prediction of remaining life of the different strategies, while Chapter 5 contains a section about the decisions surrounding the choice of pavement-overlay combination for a particular pavement.

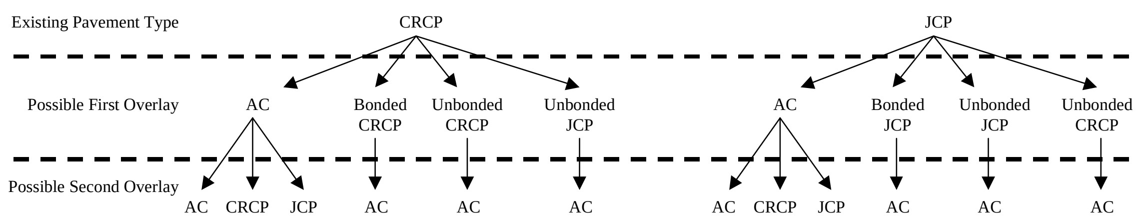


Figure 4.11. Feasible Overlay Design Strategies Available in LCC Framework

Because the life cycle cost analysis framework encourages the use of long analysis periods, secondary (or tertiary) overlay strategies may be necessary. Many life cycle analysis methods simply ask the user for specific periods of time before the first overlay and between subsequent overlays. This framework allows the user to input preferences regarding overlay strategies, but also relies upon performance models to determine the remaining life of a pavement section and the time at which an overlay becomes necessary.

The following sections of this chapter describe the various combinations of overlay strategies that are available under the LCC framework and the associated performance models that are suggested for use in this first version of the LCC framework. Chapter 5 then presents discussions regarding their reasonability, implementation into the framework, the various conditions that may constrain the choice of certain combinations, and conditions that are favorable to specific overlay combinations.

4.5.1 General Overlay Design and Analysis Methodology

The computer routines contained in RPRDS-1 use layered elastic theory to predict the stresses and strains in pavement layers, from which the remaining life is calculated using fatigue relationships. These fatigue equations were also used to generate regression models to help the computer program RPRDS-1 run faster, although the LCC framework will use the layered elastic models, since computing power is much more advanced than it was when RPRDS-1 was developed in 1982.

The general design methodology for overlays using RPRDS-1, illustrated in Figure 4.12, was adapted from Seeds, McCullough, and Hudson (Ref 86). The remaining life of the original PCC structure is reduced over time to a lower limit, at which time an overlay is placed. The RPRDS routine has the capability of comparing several overlay strategies, which will be discussed in Chapter 5. The remaining life of the entire structure is then restored to 100%, and the original structure is protected somewhat and deteriorates at a lower rate than it would have without an overlay. The remaining life of the overlay decreases at a specific rate until the overlaid structure reaches the end of its load-carrying capacity, at which time the overlay then deteriorates much more quickly.

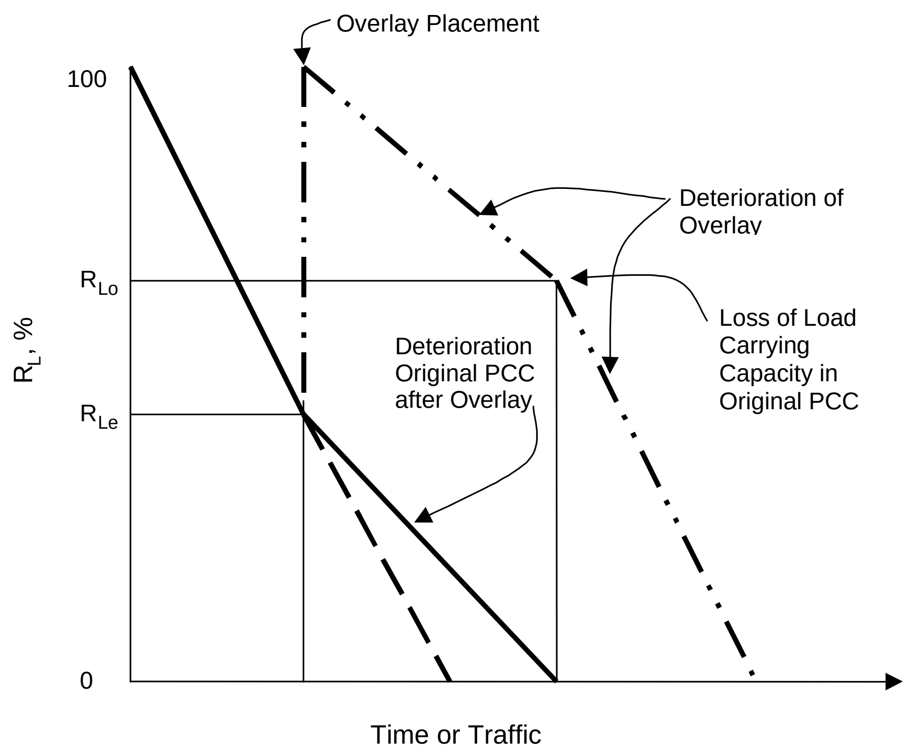


Figure 4.12. General Pattern of Remaining Life of Pavement Structure and Overlay

During each of the three periods of time shown in Figure 4.12, the stresses and strains are determined using standard 18-kip axle weights and the properties of the layers provided by the user. The three rates of deterioration are then calculated using the fatigue relationships presented by Taute (Ref 93) on data collected at the AASHO Road Test; by Gutierrez de Velasco (Ref 33) for portland cement concrete, which is based on concrete stress; and by Austin Research Engineers, Inc., (Ref 6) for asphalt cement concrete, based on strain. The framework then requires a model to provide an overlay design that will extend the life of the pavement to the end of the analysis period. If there are no feasible overlay options that will provide this performance, the RPRDS routine will perform a second overlay design. The next several sections of this chapter will discuss the various pavement-overlay combinations and the general advantages and problems associated with each type.

4.5.2 Bonded Concrete Overlays

A bonded concrete overlay (BCO) over portland cement concrete pavement will decrease the rate at which distresses develop. Depending on the thickness of the overlay, the change in the rate of distresses per mile will vary. This also depends on the condition of the pavement before the overlay is placed. If an overlay is placed when distress levels are high, the reduction in the rate of distress development will not be as effective as that of an overlay placed when the levels and rates are low. Figure 4.13 shows a relative relationship between overlay thickness, cumulative ESALs, and distresses.

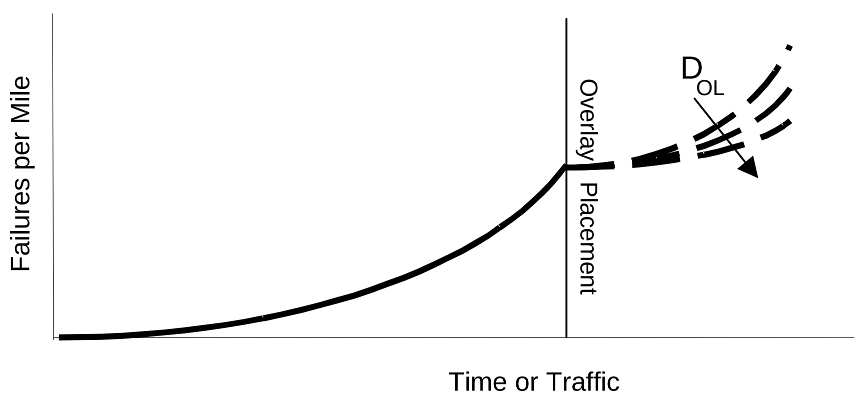


Figure 4.13. Relationship of Overlay Thickness with Traffic vs. Distresses

Although the performance of a PCC pavement with a bonded concrete overlay should be modeled differently than a pavement without an overlay, BCO performance will generally follow the performance of a CRCP of equivalent thickness. The first step in determining the equivalent thickness of a pavement in preparation for a BCO is to determine the remaining life of the original design. The remaining life of a pavement is determined by extending the critical distress (the distress that is closest to its maximum allowable value) curve to the point of failure (or the agency's definition of failure) and take the number of allowable load applications that remain. This number divided by the total expected load applications provides a relationship for the remaining life, as shown in Equation 4.24 below.

$$R_L = \left(\frac{ESALs_{\text{Re}\,maining}}{ESALs_{Total}} \right) \tag{4.24}$$

where:

R_L = remaining life of original design, expressed as a percentage.

The expected life of an overlaid PCCP, then, is determined by assuming the full depth of the overlaid pavement and the overlay as one new pavement structure, and performing an analysis to determine the total number of load applications. For example, a 2 in. BCO over an 8 in. CRCP would be analyzed as a new 10 in. CRCP. The remaining life of a new 10 in. CRCP, then, is multiplied by the percentage, R_L, calculated above, to obtain the equivalent remaining life of the original pavement rehabilitated with a bonded concrete overlay. This remaining life, in terms of allowable load applications, is compared with another, thinner, pavement, with the same allowable loads. Thus the equivalent thickness can be determined.

As mentioned above, reliable performance models should be developed to predict (1) the remaining life more closely and (2) the distress development of PCC pavements overlaid with a bonded concrete overlay. At this time, however, once the equivalent thickness is determined, the same performance models that are used for new pavements will be applied.

4.5.3 Unbonded Concrete Overlays

In order to determine the performance of an unbonded concrete overlay (UBCO) placed over a portland cement concrete pavement, the basic performance models will be used, with the assumption that the thickness of the overlay is equal to a new concrete surface layer and that the original concrete surface layer becomes a very stiff base layer. Using this method, the thinner overlay is compensated by the great reduction in concrete stress in the overlay owing to the large effective k-value. The occurrence of transverse cracking, for example, which is a function of the fatigue equation, will be affected by the stresses in the concrete and by the tensile strength of the overlay. The stresses will be calculated in the same way as the original concrete surface layer, but will use the stiffness of the concrete as a base material, thus reducing the stresses. The reduced stress in the concrete overlay will in turn extend the remaining life of the pavement.

Again, as mentioned in the preceding section discussing bonded concrete overlays, the appropriate performance models used for new PCC pavements will be used in the first version of the program, under the assumption that the models are valid for such a pavement structure. Other performance models exist that can be used in future versions of the program. These models require more information about the materials used and about the nature of the vehicular loading that is expected. In keeping with the modular nature of the LCC framework, however, the current version of the software package contains a prepared code, where new overlay models can be implemented.

4.5.4 Asphalt Overlays

In general, asphalt overlays are feasible alternatives in swelling soil subgrade environments and where the original concrete pavement has some remaining life but high roughness. The effect of swelling soils was readily seen at a research project near Texarkana, Texas (Ref 60). The Center for Transportation Research conducted a study of the effectiveness of asphalt overlays on continuously reinforced concrete pavements. In this case, the presence of an asphalt overlay decreased the development of punchouts over a long period of time.

The original concrete pavement had displayed increasing punchouts up to the time it was 12 years old, when it was then overlaid with 2 in. of asphalt concrete. Fourteen years later, the asphalt overlay section was milled in preparation for another overlay. It was found that punchout development was deterred during the 14 years that the asphalt overlay had been on the pavement section, though the asphalt showed some rutting. The situation described in this paragraph is depicted in Figure 4.14, which shows how asphalt overlays can extend the life of PCC pavements.

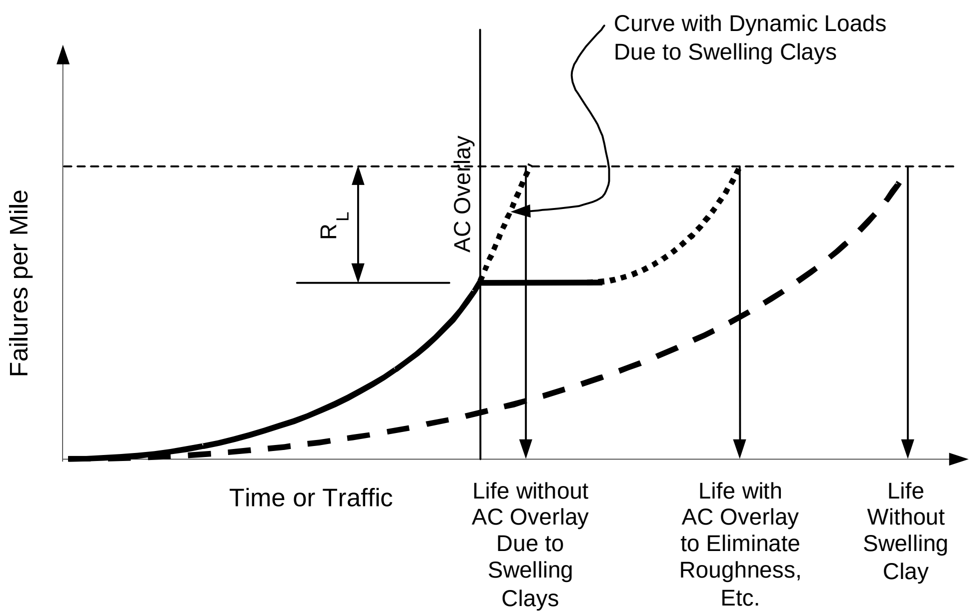


Figure 4.14. Effects of Swelling Clay and Asphalt Overlays over PCCP

The RPRDS routine will be used to calculate the remaining life of the pavement with an asphalt concrete overlay. Asphalt concrete pavement distresses will be determined through other performance models: Reflective cracking will be determined by a model developed for the Federal Highway Administration by ERES Consultants, Inc. (Ref 47), while rutting will be determined by a model developed for the Strategic Highway Research Program (Ref 87). Because these models require much more information — information that the engineer may only be able to estimate — the asphalt overlay routines included in the framework should be used with caution. Future models and availability of data will certainly improve the predictive qualities of the life cycle cost analysis framework.

4.5.4.1 Reflection Cracking

The model used for reflective cracking was developed for the FHWA under a research project for the development of asphalt overlay design methods (Ref 47). This overlay distress is only applicable to jointed concrete pavements, since it is not generally a problem noticed on continuously reinforced concrete pavements. The model uses fracture mechanics to determine the number of temperature cycles and traffic loads required to propagate a crack from the bottom of the asphalt layer to the surface. The components A_F and A_T in Equations 4.25 and 4.26, respectively, are fracture parameters for traffic related cracking and for temperature related cracking.

$$A_F = 10^{-4.40 - 2.0 \cdot n} \tag{4.25}$$

$$A_T = 10^{-2.20 - 2.4 \cdot n} \tag{4.26}$$

where:

n = Fracture parameter of asphalt
  = 2 / m
m = Slope of the log stiffness vs. log time curve for the asphalt

The model assumes that the asphalt and concrete have bonded to form a composite structure with a thickness equivalent to the thickness of the original pavement and the overlay thickness. The change in crack length versus the change in applied loads is given by Paris' law (Ref 75):

$$\frac{dc}{dN} = AK^n \tag{4.27}$$

where:

A, n = fracture parameters
K = stress intensity factor

Rearranging Equation 4.27 gives:

$$dN = \frac{dc}{AK^n} \tag{4.28}$$

and integration with Equation 4.28 yields:

$$\int_0^{N_f} dN = \int_{c_0}^{c_f} \frac{dc}{AK^n}$$

which is further reduced to:

$$N_f = \int_{c_0}^{c_f} \frac{dc}{AK^n} \tag{4.29}$$

This model considers that reflective cracks propagate by three methods: bending, shear, and thermal stresses. The fracture parameters *A* and *n* have already been calculated, and a number of regression equations were developed for the stress intensity factor for each of the three mechanisms and are used in the current framework. An example of the regression models for *K* is given below:

$$\widehat{K}_s = 0.1941 + 1.157 \bullet u - 0.723 \bullet u^2 + 1.239 \bullet u^3 \tag{4.30}$$

where:

$\widehat{K}_s$ = estimate of the stress intensity factor
u = crack to layer thickness ratio

Upon predicting *K* for each of the three failure methods mentioned above, the three corresponding applications to failure are calculated and combined using a model that has been calibrated to the various environmental zones around the United States. This leads to the following equation, which accounts for bending and shearing as well as for thermal cycling.

$$N = N_{dt} \bullet \left[\alpha_1 - \alpha_2 \bullet \frac{N_{dt}}{N_{db}} - \alpha_3 \bullet \frac{N_{dt}}{N_{ds}} \right] \tag{4.31}$$

where:

N = reflection cracking life, days,
N_{dt} = days to failure owing to thermal cycling,
N_{db} = days to failure owing to bending, and
N_{ds} = days to failure owing to shear.

The number of days to failure owing to the combination of the above three mechanisms is then divided by 365.25 to determine the year in which crack sealing will be necessary.

The discussion regarding reliability in life cycle cost analysis in Chapter 8 is useful in this section, since the amount of reflection cracking is desired each year. Using the reliability concepts, the model used for reflection cracking can be used to determine, probabilistically, the amount of cracking that can be expected in a given year, depending on the number of ESAL applications experienced by the overlaid section.

4.5.4.2 Rutting

The Long-Term Pavement Performance project of the Strategic Highway Research Program produced several regression models by which the performance of all types of pavements can be estimated. Although many of the models included in Report SHRP-P-393 (Ref 87) are poor predictors of pavement performance, with adjusted R^2 values less than 0.75 and even as low as 0.33, the rutting model for asphalt pavements can be used here as a preliminary model until a more sophisticated model is available. The model was developed for asphalt pavements over portland cement-treated base, although its adaptation for asphalt overlays of portland cement concrete pavements is reasonable. A basic assumption of unbonded concrete overlays is that the overlay becomes a new layer over a very stiff base. In the case of asphalt overlays over PCC pavements, the new layer bonds to the concrete, but also acts as if it is on a very stiff base layer.

The regression model developed under SHRP-P-393 takes the following form:

$$\text{Rut Depth} = N^B \bullet 10^C \tag{4.32}$$

where:

N = cumulative ESALs, 1000s (KESALs)

B = $b_0 + b_1 \bullet x_1$ (4.33)

C = $c_0 + c_1 \bullet x_1 + c_2 \bullet x_2 + c_3 \bullet x_3 + c_4 \bullet x_4$ (4.34)

and where the b_i, c_i, and x_i values are given in Table 4.1.

Table 4.1. Regression Coefficients for HMAC Overlay Rutting in Equations 4.33 and 4.34

	Variables x_i	Units	b_i	c_i
b_0, c_0	Constant		-0.218	-0.126
b_1	HMAC Agg. < #4 Sieve	% by wt.	0.00412	0
c_1	Log(PCC Thickness)	in.	0	-0.474
c_2	Log(HMAC Thickness) • Log(% Air in HMAC)	in. % by vol.	0	-0.401
c_3	Log(HMAC Thickness) • Asphalt Viscosity at 140ºF	in. Poise	0	0.000104
c_4	HMAC Agg < #4 Sieve • Log(Ann. Min. Temp.)	% by wt. ºF	0	-0.00198

4.6 SUMMARY

This chapter has described various pavement performance models that predict the major distresses that occur not only in continuously and jointed reinforced concrete pavements, but also in the different types of overlays that are available. In addition, models have been described that predict the remaining life of concrete pavements with regard to fatigue cracking and roughness (or present serviceability index). These models are intended to serve as a beginning point for the first version of the Rigid Pavement Life Cycle Cost Analysis software package that accompanies this report.

The life cycle cost analysis framework that is developed as the major objective of this report is intended to utilize any appropriate performance model for as many distresses as possible. This means that in the future, when more advanced and reliable models are developed, they can be easily incorporated into the framework, replacing the models that are currently used. In addition, as future research improves the reliability with which other distresses are modeled, these too can be easily incorporated into the framework.

The performance models are the most critical part of the framework. Using performance modeling, the extent of distresses is predicted over the entire analysis period of the pavement's design life. All other aspects of the framework depend on the performance models for the timing of future construction activities. Future construction, agency costs, user costs, accidents, air quality, and other issues depend on this timing, insofar as it dictates to the other components of the framework when and to what magnitude these costs will occur.

CHAPTER 5. MAINTENANCE AND REHABILITATION

The effects of maintenance and rehabilitation on the life cycle cost of a highway pavement project can be significant. Historically, however, many agencies do not track their maintenance costs for specific projects. This leaves only the cost of rehabilitation projects to add to the total life cycle cost. In addition, since agencies are only now beginning to consider the effects of work zones on user costs, major rehabilitation has been the only cost considered in life cycle cost analyses. This chapter will expand on the concepts proposed in the life cycle cost framework to include both the costs of major rehabilitation and minor maintenance, as well as agency and user costs that are incurred when these activities take place.

5.1 AGENCY APPROACH TO MAINTENANCE

Two approaches have been identified based on discussions with Dr. Frank McCullough regarding transportation department agencies' attitude toward maintenance and rehabilitation. These two approaches are termed *Proactive* and *Reactive*. The basic difference between proactive and reactive maintenance approaches is that when taking a proactive approach to maintenance, the agency performs repairs on potential problem areas before they become greater problems. In taking a reactive approach, an agency will wait until problems become severe before acting to remedy the situation. Arguments can be made for or against both approaches, but normally the proactive approach will be more cost effective and will preserve pavement performance.

An example of the proactive approach can be found in the case of the City of Bedford, Texas. Although this example involves a network of city streets, the conclusions are easily translated into expected effects on a highway pavement. The city's public works administrator performed an investigation in which it was determined that the street network was in need of repair. The condition of the street network was not intolerable; in fact it was in fairly good condition, which prompted concerns by the residents who were being asked to pay for the major maintenance and rehabilitation project that was proposed. The city then presented Table 5.1 (Ref 61) to show the current and projected backlog of maintenance and rehabilitation work necessary to maintain the street network at acceptable levels.

Table 5.1 shows that, over the next 4 years, the funds required to keep the condition of the street network at an acceptable level will more than double. The city also determined that if the total backlog is cleared and all the current required work is performed, the deterioration would be slowed and the estimated $34 million would not be required. Conversely, if only routine maintenance is performed now, the current deterioration trends will continue to accelerate, with major rehabilitation required citywide by October 2001.

An illustration of the effect on deterioration rate is shown in Figure 5.1 below. This figure shows that with only routine, reactive maintenance, the deterioration trend continues to accelerate, and reaches its limit quickly. With proactive maintenance, the trend is flattened, and the pavement provides acceptable ride quality for a longer period. Although proactive maintenance is normally more expensive than reactive maintenance, based on first costs, it can be less expensive when considered from the life cycle cost perspective.

Table 5.1. Current and Projected Funding Requirements for the Street Network of the City of Bedford, Texas

	Funding Requirements		
	As of June 1, 1997	Projected October 1997	Projected October 2001
Operating Budget	$3,812,115	$3,909,943	$4,667,460
Capital Improvement	$11,567,366	$13,108,452	$38,516,708
Subtotal	$15,379,480	$17,018,395	$43,184,169
Current Funding	($1,127,750)	($688,750)	($8,763,020)
Total Backlog	$14,251,730	$16,329,645	$34,485,686

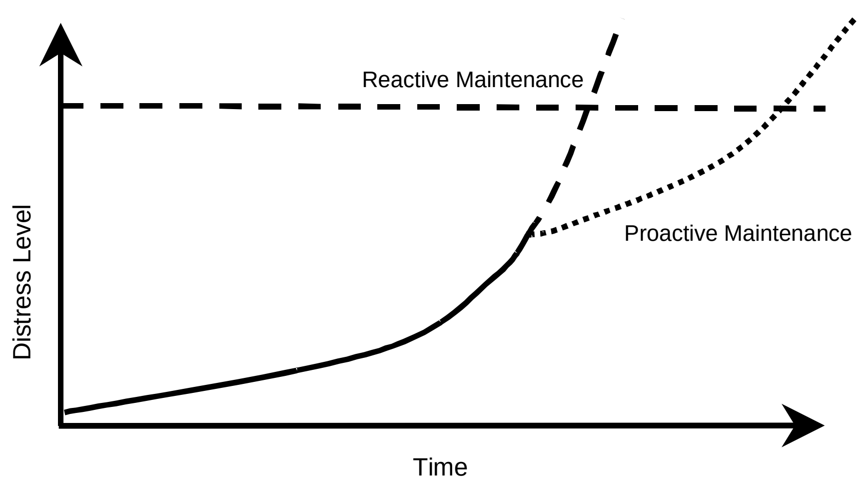


Figure 5.1. Comparison of Proactive and Reactive Maintenance Approaches

5.2 MAINTENANCE ACTIVITIES

Highway pavement section maintenance is normally undertaken either annually, for minor levels of distresses, or less often when distress levels are higher but ride quality has not dropped to critical levels. Minor maintenance activities repair distresses as they occur, and sometimes prolong the life of the pavement, depending on the extent of the repair that is performed. As mentioned in the previous section, the life-extending qualities of maintenance depend greatly on the department's philosophy regarding the effectiveness of its maintenance activities. This section identifies ways of determining the maintenance needs of a pavement for which major rehabilitation is not yet required.

5.2.1 Pavement Condition and Distress Limits

The performance models described in Chapter 5 provide information about the predicted levels of distresses at the end of each year that is simulated. The maintenance modules in the life cycle cost framework then take this information and compare the distress levels against limits preset by the engineer of the agency. These limits correspond to the level of each particular distress modeled in the pavement performance module.

The engineer can cause the framework to model the agency's maintenance approach by setting higher or lower limits for these distresses. A high limit would simulate a reactive approach to maintenance, while a lower limit would simulate a proactive approach.

When the predicted distresses exceed the preset limits, maintenance activities are triggered. When one maintenance activity triggers a work zone, the framework simulates the repair of all existing distresses. At this time, the extent of each distress is calculated, and the time required to perform each individual distress repair is determined. The repair type that requires the most work zone time to complete will control, and a work zone will be simulated for this amount of time, during which time all types of distresses will be repaired.

5.2.2 Distress Repairs

This section describes the routines that the computer program RPLCCA uses to simulate the repair of distresses that have reached or exceeded the limits set by the user. In general, at the end of each analysis year, the program checks the predicted distresses and compares them with their respective distress limits that have been set by the user of the program. The distresses that are modeled are shown in Table 5.2.

Table 5.2. Distresses Modeled by Life Cycle Cost Analysis Framework

JRCP	*CRCP*
Faulting, in	Punchouts, punchouts per mile
Spalling, % spalled joints	Transverse Cracking, mean crack spacing
Transverse Cracking, % cracked slabs	

Each of these distresses has a different model to predict its level at the end of each year, as described in Chapter 5, and each has a method of determining the extent of the repair needed to correct the problem. The extent of each distress, measured in the units shown in Table 5.2, is then multiplied to obtain the magnitude over the entire highway segment. Next, the rate at which the repair can be accomplished is applied to find the number of days required, which is multiplied by the user cost per day that is incurred owing to the presence of the accompanying work zone. The agency cost of the repair is also calculated, based on historic unit costs. A large variation is expected in the unit costs and, as such, will produce a large range of expected costs, depending on the level of confidence selected by the user for the overall analysis.

5.2.2.1 JRCP – Faulting

The faulting distress repair is determined in the following manner. First, the extent of faulting is determined. This is used in Table 5.3 to estimate the distance from the joint that must be diamond-ground to provide a smooth transition across the joint. The following values were presented by ARE, Inc. (Ref 7).

Table 5.3. Extent of Diamond Grinding Necessary Based on Faulting

Faulting Extent, in.	Distance from Joint to Grind, ft
$F < 0.125$	2.5
$0.125 \leq F \leq 0.25$	5.0
$0.25 \leq F \leq 0.375$	7.5
$0.375 \leq F \leq 0.5$	10.0
$0.5 \leq F \leq 0.675$	12.5
$0.675 \leq F \leq 0.75$	15.0
$F > 0.75$	20.0

The total amount of diamond grinding that is required over the entire highway project segment is calculated by multiplying the mean faulting value by the total width of traveled lanes and by the length of the project. This is then divided by the joint spacing to provide the number of joints, which when multiplied by the distance from the joint to grind gives the total area of grinding that must be undertaken to repair the faulting over the entire highway segment. This calculation is shown in Equation 5.1.

$$\text{Total Diamond Grinding} = (\text{Mean Faulting} / 2) \bullet \text{Pavement Width} \bullet \text{Project Length} / \text{Joint Spacing} \bullet \text{Grinding Distance from Joint} / 9 \tag{5.1}$$

The total grinding required, in square yards, is then divided by the amount of grinding that can be expected to be performed by a contractor per day. The total value is also multiplied by the cost per square yard to obtain the agency cost. The number of days required to complete the construction is used in the user cost calculation model to determine the total user costs associated with the repair.

5.2.2.2 JRCP — Spalling

The total magnitude of spalling is calculated in much the same manner as that used for faulting. The value of spalling over the project (percentage of joints that have a spall) is provided by the spalling performance model described in Chapter 4. This value is then multiplied by the project length and divided by the joint spacing to obtain the total number of joints that have spalls. It is then assumed that the average size of partial depth repair required is 3 feet square. Thus, for each joint, a 1 square yard partial-depth repair will be performed. This value is calculated as follows:

Total Partial Depth Repair = % Spalled Joints • Project Length /
Joint Spacing • 1 Square yard (6.b)

As with diamond grinding, the average production rate per day will be applied to the total magnitude of partial depth repair that must be performed. The total number of days estimated to repair the predicted spalling is then compared with the estimated days required for all the other distress repairs. The specific distress that requires the longest amount of time to repair will control, and the framework will simulate the repair of all distresses during that time.

5.2.2.3 JRCP — Transverse Cracking

The prediction of transverse cracking in jointed reinforced concrete pavements determines the amount of joint sealing that is required in a state DOT's maintenance program. The calculation for determining the amount of transverse cracking that must be sealed is similar to that used for diamond grinding:

Total Crack Sealing = % Cracked Slabs • Pavement Width • Project Length /
Joint Spacing (6.c)

5.2.2.4 CRCP — Punchouts

The magnitude of punchouts in a continuously reinforced concrete pavement is computed in the same way that spalling is computed for jointed concrete pavements. The difference is that the LCC framework applies full-depth repairs to punchouts, whereas spalls are corrected with partial-depth repairs.

5.2.2.5 CRCP — Transverse Cracking

As described in Chapter 4, transverse cracking in CRCP is predicted using the fatigue equations; the magnitude of cracking that must be sealed is then determined in the same way that transverse cracking in JRCP is determined. When failure occurs, which is usually defined as 50% of slabs cracking, the LCC framework will execute the overlay evaluation and design module; at that point different performance models will be used.

5.3 MAJOR REHABILITATION

Major rehabilitation activities should be necessary only a few times throughout the design life of a concrete pavement. Assuming good design and quality construction, a concrete pavement may require a concrete overlay in the second half of its design life, and perhaps, to maintain ride quality, an asphalt overlay towards the end of its life. For example, an 8 in. CRCP on IH-610 in Houston, Texas, has been in service for over 30 years and has experienced much more traffic loading than predicted in its design; only recently has this section received a bonded concrete overlay to maintain structural integrity and ride quality. During the previous 30 years, the pavement section received only minor maintenance and no other rehabilitation activities.

This section of the report assumes that the major rehabilitation alternative has been chosen, since the conditions affecting decisions and the effectiveness of minor maintenance activities have been discussed in the previous sections of this chapter.

5.3.1 Consideration of Ride Quality

Ride quality is of great importance when attempting to assess the rehabilitation needs of a pavement structure. Included in the pavement performance models in Chapter 4 are present serviceability index models that predict the ride quality of the pavement over the entire analysis period. Ride quality is used in combination with the levels of various distresses to determine the need for major rehabilitation activities. If the individual distresses become too extensive, the life cycle cost framework will determine if the ride quality is sufficiently low to trigger major rehabilitation or simply a maintenance activity to repair the distresses.

During rehabilitation activities that occur on concrete pavement highway sections, it is important to consider user costs and the increased potential for accidents. In addition to calculating the user costs generated by the presence of the work zone, any time an accident is predicted, the user costs must be recalculated for that day. Many assumptions must be made regarding accidents and accident rates; these are described in Chapter 7, which discusses user costs.

5.3.2 Rehabilitation Activities

The overlay options described in Chapter 4 discuss the rehabilitation activities that are suggested for the life cycle cost analysis framework. A comprehensive catalog of rehabilitation activities can be compiled in the future and easily added to the framework in a modular fashion. As mentioned several times in this report, the intention of this framework is to be modular in nature and to allow easy implementation of future advances in pavement analysis and design technology. The framework also allows other engineers and programmers to adapt the framework to include other rehabilitation activities that are not included in this version.

The sections in Chapter 4 that describe currently included rehabilitation options also describe the manner of design and the expected life of each. The framework attempts, as much as possible, to rely on performance models for rehabilitation options, instead of assuming an expected life. The expected life predicted by performance models is checked, however, against commonly accepted values to verify consistency and validity of the models.

While overlay decisions are made by the engineer using the program, the rehabilitation design module provides many possible alternatives. As described in Chapter 4, the routines contained in the computer program RPRDS-1, developed by CTR, are used to generate feasible overlay options. The best option from this list of alternatives is selected automatically by the framework, based on inputs from the program's user. The engineer using the framework can alter the type of overlay chosen by modifying the agency's preferences in the program.

5.3.3 Expected Life of Pavement Rehabilitation

As discussed in Chapter 4, the routines adapted from RPRDS-1 compute the expected remaining life of each overlay option. In addition, if the first overlay option is not predicted to last to the end of the original analysis period, a second overlay will be suggested by the RPRDS-1 routines. The overlay design and remaining life routines take inputs from the user of the program, including the current condition of the pavement predicted by the other pavement performance models.

The remaining life of the overlays designed by RPRDS-1 is determined by fatigue models that use strain at the bottom of an asphalt concrete layer, and stress at the bottom of a portland cement concrete layer. The routine contains an elastic layer module that predicts behavior; the results of this analysis are used in fatigue models, specific to the material types and pavement structures.

The definition of *fatigue life*, or remaining life, depends on the user-supplied inputs regarding the amount of fatigue cracking that is acceptable, as well as the minimum acceptable roughness of the pavement. As described in Chapter 4, the definition of 50% cracked slabs is the point where the damage reaches 1.0. For overlays, another definition of *damage = 1.0* is the point where 50% of the joints and cracks in the original PCC layer have reflected through to the surface of the overlay.

Figure 5.2, taken from Chapter 4, shows how an overlay extends the life of the pavement. The dashed line extending to 0 remaining life about midway through the analysis period shows the expected life of the pavement without any overlay placed on it. The slope of the original line is carried on to failure, since the fatigue relationships are assumed linear under equivalent stresses.

In reality, however, as the concrete weakens, the stresses will increase at the same time that the concrete strength decreases. This increases the slope of the fatigue curve, and the remaining life curve becomes steeper. In effect, the remaining life curve resembles the PSI curve, in which the curve is fairly flat but grows steeper as more traffic is applied. This phenomenon is not modeled in the current work, however, since very detailed mechanistic models are required. Future research, perhaps, will provide a closer representation of the fatigue relationships in both original pavements and overlays.

In the case of the overlay in Figure 5.2, the overall pavement structure life is extended 100% above that of the original pavement without the overlay. As can be seen in the figure, the original pavement continues to deteriorate, but at a slower rate, since the presence of the overlay reduces the stresses in the original surface layer. The stresses in the overlay increase at the point where the original PCC layer loses its structural rigidity, and its modulus of elasticity is dramatically reduced. This increase of stresses in turn increases the slope of the fatigue curve, and reduces the expected remaining life in the pavement structure.

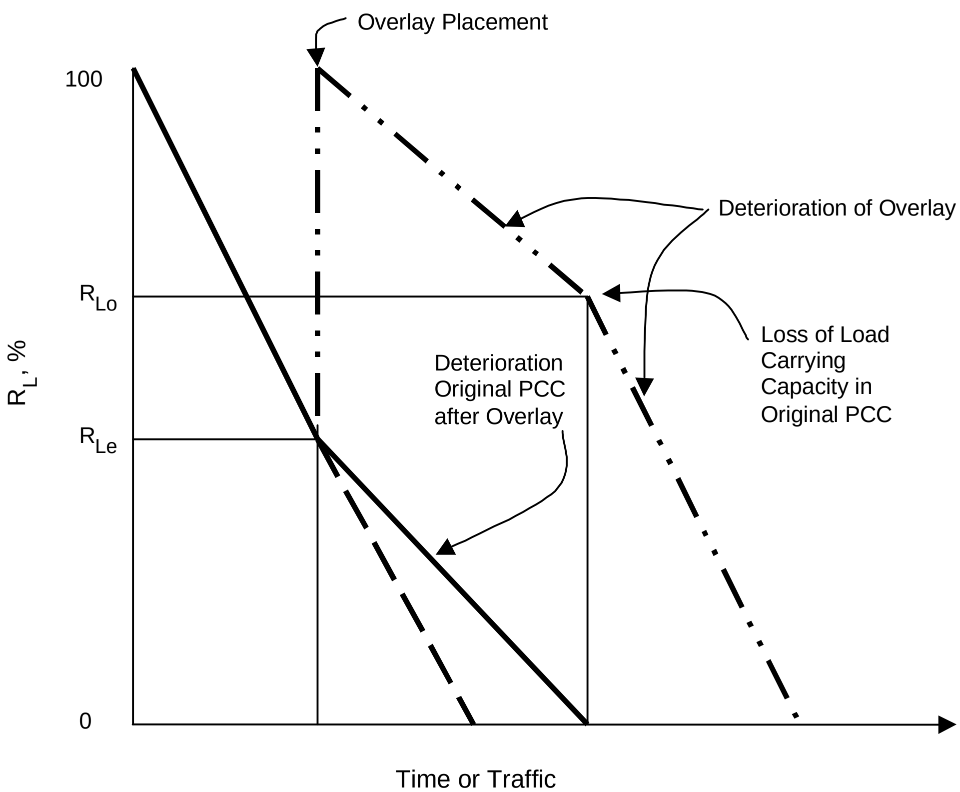


Figure 5.2. Remaining Life of Pavement Structure and Overlay

The remaining life of the pavement structure after one and two overlays are placed is determined in the above manner, using elastic layer theory to estimate stresses in the layers and using fatigue law to predict the point of failure of the original pavement surface and of the additional overlays. The life cycle cost analysis framework developed in this research uses this information to predict the costs and timing associated with overlay placement and, consequently, the user costs incurred by the work zones associated with overlay construction.

CHAPTER 6. AGENCY COSTS

6.1 INTRODUCTION

The cost of highway construction is very well understood and tracked, both by construction companies and by departments of transportation. Contractors compile cost data in order to bid on new highway construction projects, and highway departments compile the same types of data in order to make proper project estimates and to control those costs once a project has begun.

The integration of cost estimating and calculating techniques into a life cycle cost analysis framework can be more difficult than it seems. Many life cycle cost programs allow the user to input a cost per square foot for the entire pavement structure. Others allow for the unit cost of each individual layer to be input, either in dollars per area or in dollars per area per inch of thickness, from which the program calculates the total pavement structure cost. The framework proposed in this report requires the per-area-total-cost basis for estimating costs, however, future improvements to the framework should include an input for all costs involved in every aspect of the project. This would be similar to the Engineer's Estimate of construction costs. The two methods of entering cost data can be used depending on the amount of information available to the engineer at the time of the analysis, though fine tuning can be accomplished later in the planning stages by entering cost data from the Average Low Bid Unit Price list compiled by the department of transportation. An example of the Average Low Bid Unit Price sheet is shown in Table 6.1. This table provides the item number, a description of the item and units by which it is paid, and the quantity of that item that was constructed during the last period. It also provides the average bid price and the number of projects for which the particular item was bid. Although many times the bid price listed may be unreliable, as is often the case when very few projects have bid that item, it is a source for an estimate of the unit cost for a particular item. While Table 6.1 shows only items for concrete pavement, thousands of items, encompassing all aspects of highway and street construction, are tracked.

Table 6.1. Example of TxDOT Average Low Bid Unit Price List, 12-Month Moving Average

Item-Nbr.	Description	Units	Quantity	Avg Bid	Usage
360 0512	CONC PAV (CONT REINF HY STL) (15")	SY	209,012	31.48	1
360 0520	CONC PAV (JOINT REINF) (9")	SY	4,669	29.56	1
360 0522	CONC PAV (CONT REINF HY STL) (13")	SY	542,910	26.32	7

6.2 PAVEMENT CONSTRUCTION COST ITEMS CONSIDERED

This section contains a list of the general categories that should be considered when tabulating an estimate for initial construction, rehabilitation, and annual maintenance costs. All of the items in this list are viable options for construction and rehabilitation activities and should, accordingly, be considered as agency costs in the analysis of life cycle costs for a highway pavement project.

- *Initial Construction*

  Subgrade

  - Clear and Grub
  - Scarify and Recompact
  - Subgrade Compaction
  - Lime Stabilized Subgrade
  - Borrow Material

  Subbase

  - Compacted Granular Aggregate
  - Lime Treated Subbase
  - Cement Treated Subbase

  Base

  - Aggregate
  - Aggregate Treatments
  - Portland Cement
  - Asphalt
  - Lime
  - Cement-Flyash
  - Lime-Flyash

  Base Compaction

  Drainage Layer

  - Coarse Graded Aggregate
  - Filter Material

  Rigid Layers

  - Slab-Subbase Stress Relieving Layer
  - Portland Cement Concrete
  - Reinforcing Steel
  - Dowel Bars
  - Tie Bars
  - Joint Sealing Material
  - Curing Compound
  - Sawcutting
  - Concrete Shoulders
  - Asphalt Shoulders

- *Rehabilitation*

    Unbonded Concrete Overlays
    Bonded Concrete Overlays
    Asphalt Concrete Overlays
    Subsealing
    Surface Texturization
    Widening and Shoulder Retrofitting

- *Major Maintenance*

    Rigid
    - Full Depth Joint Repair
    - Full Depth Stress Relief Joints
    - Major Crack and Joint Sealing
    - Full Depth Slab Repair
    - Milling of Stepped Joints and Distortions

    Flexible Overlays
    - Rout and Seal Cracks
    - Hot-Mix Patching
    - Surface Sealing
    - Asphalt Strip Repairs
    - Distortion Corrections

- *Routine Maintenance*

    Rigid
    - Pothole Repair
    - Spall Repair
    - Blowups
    - Localized Distortion Repair
    - Minor Crack and Joint Sealing

    Flexible Overlays
    - Pothole Repair
    - Localized Spray Patching
    - Localized Distortion Repair
    - Minor Crack Sealing

All the items in the table can be tabulated and included in the total cost of a pavement structure. The initial construction items can be assigned quantities by the engineer to represent a particular design alternative, while unit costs can be provided for the other aspects of maintenance and rehabilitation activities. The program will then predict quantities of the maintenance and rehabilitation items based on the results of the performance models. All these costs are then converted into a single cost per square yard of pavement structure to provide to the engineer a comparison by which a decision can be made regarding many different design alternatives.

CHAPTER 7. USER COSTS AND WORK ZONE EFFECTS

When construction maintenance activities are undertaken on highway sections that continue to allow traffic on the facility, a system of traffic controls and protective barriers are instituted to ensure worker and traffic safety. Traffic management in work zones is influenced by the type of infrastructure, environment, traffic characteristics, duration, type of work, and available sight distance. Work zone configurations are trade-offs, balancing contractor efficiency against traffic speeds and safety. When vehicle flows are light, impacts on speed and safety may be slight. As demand increases, however, such impacts rise substantially and rapidly. Modeling these impacts must therefore not only incorporate work zones' impact on speed, but must also account for how those changes in speed translate into estimates of user costs.

In addition to the impact of speed on traditional user costs, increased traffic through a work zone impacts the amount of emissions and accidents at work zones. This chapter begins by examining existing models that perform this type of analysis. It then discusses the elements that comprise a typical work zone, relates these relevant elements to vehicle speed, and examines the literature associated with predicting user costs, traffic emissions, and accidents. Finally, models for calculating these impacts are selected, based on the results of the literature.

7.1 LITERATURE REVIEW

There is a comprehensive manual procedure for work zone evaluation adopted in the U.S. (Ref 39), which sets out a stage-by-stage process to permit the selection of the most appropriate traffic control strategy for a particular maintenance task. Some of the assessment elements are also available as routines on microcomputers. For example, estimates may be made of the additional user costs (time and vehicle operation) associated with lane closures using QUEWZ (Queue and User cost Evaluation at Work Zones) (Ref 67). An indication of the impact of traffic disruption caused by maintenance projects may be obtained from another routine called *CAHOP* (Computer-Assisted Reconstruction — Highway Operations and Planning) (Ref 55). This program provides a method of testing alternative maintenance traffic management schemes by reviewing changes in journey time and travel on the surrounding network.

The main economic appraisal procedures widely used in the United Kingdom are embodied in two Department of Transport computer programs, COBA9 (Ref 16) and QUADRO2 (Ref 78). The COBA9 program is concerned with identification, evaluation, and comparison of costs and benefits of new road schemes over a given period of time. The second program, QUADRO2, provides a method of economic assessment of road maintenance. The program models a simple network consisting of a main route containing the work zone, and a representative route around the works. The program is run with and without the work zone, and evaluations are made for the differences in time and vehicle operating costs incurred by all traffic in the network, together with accidents costs. An additional model calculates the time costs associated with breakdowns and accidents that occur in the work zone. Output available from the model includes information on the speed, queue, and diversionary behavior of traffic in each hour of a typical week during the maintenance season, plus cost summaries by vehicle type and category.

Many analytical and computer techniques and models are available to maintenance personnel to aid in decision making and scheduling of work zone lane closures. Several comprehensive computers programs, such as QUEWZ and FREECON (Ref 81), have been developed to analyze work zones on freeways.

7.2 CHARACTERISTICS OF WORK ZONES

Work zones and construction activities have significant impact on many of the components of the transportation system and, more specifically, on the flow of traffic through the work zone. The major characteristics of work zones and the traffic that flows through them are:

- work zone geometry,
- traffic volumes,
- lane capacities, and
- vehicle speeds.

This section will outline these characteristics of work zones and traffic flow, and will describe how they affect user costs and other aspects of the transportation system.

7.2.1 Work Zone Geometry

A work zone is more than the area of roadway on which the contractor is working. Effectively, it is the entire section of roadway on which traffic controls relating to construction work have been placed, including any temporary traffic control devices (Ref 56). And, from a systems perspective, it should include detour options for traffic to flow at exit points distant from the work site. A work zone consists of the following elements:

- *User Information Zone*

  The user is informed of the impending construction zone and given directions for traveling safely through it.

- *Approach Zone, Including Detour Exits*

  Consists of a variable portion of the work zone where vehicle behavior, particularly speed and direction, may change.

- *Nonrecovery Zone*

  Comprises the distance required to execute an avoidance maneuver, or the point beyond which the motorist cannot avoid the hazard unless erratic maneuvers are undertaken.

- *Construction Zone*

  First, a buffer zone is established where there is no work activity or equipment and materials. Next, the construction activity site itself is established where work is being undertaken.

- *Termination Zone*

  This zone immediately follows a work zone, where vehicles accelerate back to their normal cruising speeds.

Essentially, the elements of the work zone are hierarchical in nature. The beginning and end (the information and termination zones) are transitional, while zones related to sight distance and decision making are critical with respect to vehicle safety, so the approach and nonrecovery zones become important in work zone evaluations. The actual work zone itself, identified by cones or concrete barriers, has a transitional element that channels into the open lanes at the construction zone and then captures a work zone that may also include a buffer zone.

7.2.2 Vehicle Speed

When traveling through a work zone, drivers face posted speeds that are determined during design, with such speeds based on lane width and other physical characteristics. These reduced speed zones remain in effect until the work zone terminates. In the termination zone, two processes occur in terms of velocity. Drivers, while remaining alert, will first accelerate to the new desired speed, which when attained, will become the final speed produced by the work zone.

Speeds are important because they relate directly to vehicle operating costs and to loss of time (and, hence, to delay costs). Also, speed changes, particularly those that result in vehicle idling, produce higher levels of emissions. Finally, the transitional zone, particularly related to the nonrecovery area, is typically one where higher accident rates are recorded as vehicles merge into the constrained flows through the work zone.

Current work zone modeling in general, and certainly that specifically related to policy making, cannot address all these speed-flow elements. The work zone models generally assume a constant deceleration and acceleration and a constant speed through the work zone. In this respect, they may be somewhat conservative in nature and, consequently, will underestimate the true speed profile of vehicles.

As indicated in conversations with Rob Harrison, Frank McCullough, and the TxDOT project director, Mohan Yeggoni, the capacity of reduced-width lanes is definitely reduced during the first week after placement of the traffic control measures. After approximately the first week, however, drivers become accustomed to the conditions of the work zone and increase their average running speed.

7.2.3 Work Zone Strategies for Different Rehabilitation Activities

Three different work zone geometry choices are available for different types and durations of rehabilitation activities. Work zone strategies for short-term maintenance activities should take the form of lane closures during times of low traffic volumes, during the night, and where the required work will be performed on one lane at a time until the rehabilitation project has been completed. In order to be feasible for nighttime work, the type of work being performed must allow disassembly of the work zone during times of high traffic volumes. (This work zone geometry is, however, more suited for short-term maintenance activities, with major rehabilitation efforts unlikely to fall into this category.) The rate at which distresses can be repaired must account for the normal conditions that can be expected during daytime or nighttime work activities.

The repair rates that are used by the framework and input by the engineer are in distress units per hour or per day. Thus, a 10-hour work shift can accomplish more in one day than an 8-hour shift. The engineer, however, must consider such things as effectiveness at night or during the day and average ambient temperatures occurring during the construction season.

For major rehabilitation activities, including reconstruction and construction of additional lanes, lane-width reduction strategies are increasingly being used. This type of strategy is best suited for long-term projects, so that overall roadway capacity is not as restricted as it would be under a lane closure strategy. Although the Highway Capacity Manual (Ref 39) provides guidance regarding lane capacity reduction based on width reduction, this adjustment will be instituted only for a short time. The decreased capacity effect of narrowed lanes has been seen to diminish over time, since drivers gradually become familiar with the situation and begin to drive at normal operating speeds.

7.3 USER COSTS

Speed changes are manifested as additional costs that are measured in a variety of ways. These costs, categorized under the general label of *user costs,* comprise four elements for the purposes of work zone evaluation. The first group is related to delay, or travel time costs. Reduced speeds and speed cycle changes lengthen the trip time, which means that time is lost in making the journey (compared with that time expended on the same route without the work zone). Such time elements are typically aggregated and then converted to monetary values by dollar rates for work and social values.

The second group of user costs relate to *vehicle operating costs.* These costs concern elements of vehicle operation that result in costs incurred by the vehicle owner. These costs comprise fuel consumption, oil consumption, tire wear, vehicle maintenance, vehicle depreciation, and spare parts. Again, speed changes and queuing alter the consumption of these items, particularly those related to fuel.

The third group of costs relate to speed change cycling, which, again, work their way through certain operating costs and through emissions and other tailpipe pollutants. The final group of user costs are those associated with accidents, which are generally higher at work zones for reasons given in the previous section. Again, these are costs that would not ordinarily be generated by a regular trip, but are a result of imposing a work zone on traffic and should be included in the total user cost evaluated in a full-cost approach to work zone impacts. Figure 7.1 presents the main components of the user costs that are created by a work zone (Ref 90).

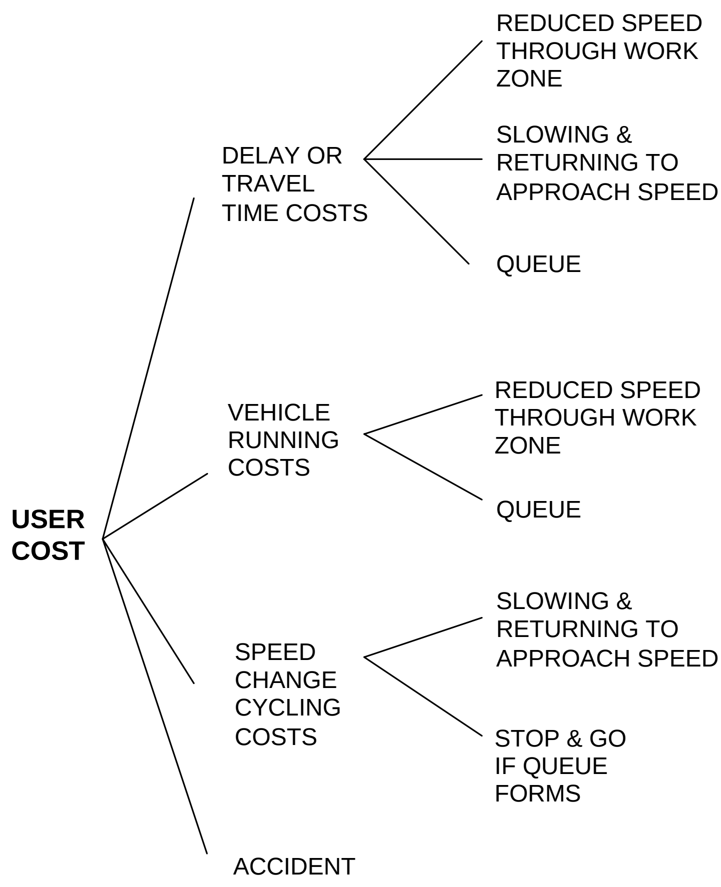


Figure 7.1. Work Zone User Cost Components

7.3.1 Time Delay Costs

The modeling process predicts cost as a function of specified inputs, using mechanisms that can vary from a simple equation to a complex simulation process. The important issues for work zone modeling is the type of the system being considered, traffic flow characteristics, available analytical relationships, and their incorporation into the model structure. For work zones, outputs could include speed projections, operating speed, distance headway distributions, and/or density levels.

Traffic stream models can often be used for uninterrupted flow situations, where demands do not exceed capacities. For interrupted oversaturated flow situations, more complex techniques such as queuing analysis and simulation modeling appear to offer greater likelihood of success.

When demand exceeds capacity for a period of time or when arrival time headway is less than the service time available at a specific location, a queue is formed. The queue may be a moving or stopped queue. Essentially, excess vehicles are stopped upstream of the bottleneck or service area, and their departure is delayed to a later time period.

Computer-based traffic engineering tools can be grouped in two ways: first, as analysis/optimization, and, second, as simulation. The former is typically based on empirical relationships, while the latter incorporates physical relationships to model the behavior of traffic flows. More complex models, particularly macroscopic approaches, utilize simulations to resolve many of the data problems that are not adequately addressed by current empirical work.

7.3.2 Vehicle Operating Costs

For many years, highway engineers have been concerned with the relationships among highway design, conditions, and road user costs, with much research conducted on these relationships. Motor vehicle costs first received attention in North America shortly after the First World War, when Agg (Ref 1) studied the performance of a small test fleet fitted with flow meters and chart distance recorders. By 1935, researchers (particularly at Iowa State College Engineering Station) had reported on the effect of geometry operating costs (Ref 2), on truck operations in Iowa (Ref 104), on tractive resistance and road surface (Ref 76), and on tire skidding characteristics, surface types, and safety (Ref 70).

One of the earliest surveys of operating costs was reported by Moyer and Winfrey (Ref 72), who examined the fuel oil, maintenance, and tire costs of rural mail carriers. Moyer and Tesdall (Ref 71) complemented this project with the results of tire wear experiments. The period to 1960 saw North American and European research concentrate on the relationships among highway geometry, vehicle performance, and costs. In the early 1950s, the first appraisal manual incorporating road user costs was produced by the American Association of State Highway Officials (Ref 3). Although it gave data for only passenger cars in rural areas and some limited information on truck costs, it established the economic evaluation of highway improvements at the planning level. Many of the technical relationships became obsolete, however, and its usefulness was limited in the 1960s, despite an update in 1959 that incorporated new unit prices. It was ultimately Winfrey (Ref 103) who synthesized the available experimental and survey operating cost data to produce a publication that profoundly influenced highway planning in the United States and in the developing world over the next 15 years. The basic work was revised in 1969 to include a section on accident costs (Ref 102).

Despite the considerable efforts devoted to collecting U.S. and European vehicle operating cost information, by 1965 only fuel consumption could be predicted with sufficient accuracy; even then, most of the information available was not well suited for use outside North America. In 1969 the World Bank initiated a program of research to develop models relevant to conditions in developing countries; that program sought models with which to examine the trade-offs between initial construction costs, future maintenance expenditures, and road user costs for alternative highway design and maintenance strategies. This effort resulted in two separate approaches being developed for user cost data. In 1981, an updated version of the Federal Highway Administration Vehicle Operating Cost and Pavement Type Manual was published (Ref 109), revising the earlier version based on Winfrey's (Ref 102) and Claffey's work on fuel consumption (Ref 13).

A project in Brazil conducted between 1975 and 1981 for the World Bank (Ref 27) followed similar survey and experimental work, but resulted in a different model. Inspired by the apparent flexibility of the Sullivan model for the U.S. Forest Service (Ref 92), researchers developed what was termed a *mechanistic model* for the prediction of fuel consumption. Fuel consumption was expressed as a function of used vehicle power, which was predicted as a function of vehicle speed and highway and vehicle characteristics. Such characteristics include engine power, rolling resistance of tires, and aerodynamic drag coefficients. The theory behind such an approach is that the user can incorporate technological developments into the modeling.

In terms of usable cost equations in the United States, those wishing to determine work zone effects have tended to rely on the models developed by Zaniewski in the early 1980s. It remains clear that predicting maintenance and repair costs is not a function of technology alone, but rather is dependent on the economic values for prices and capital. These are somewhat more difficult to model in a form that allows easy transfer over time. The items required for the VOC elements of a highway model include:

- fuel and oil consumption,
- tire consumption,
- maintenance and repair costs, and
- depreciation.

Calculating speed flow changes in order to determine the user cost elements of a work zone can also address the issue of time costs through delay. Lower travel speeds result in longer travel times through the system affected by the work zone. In this instance, time delays, particularly where they result in several minutes or more of delay, can be identified and aggregated for the traffic flow. These are then translated into monetary terms by the use of standard working wages and standard social wages for the network affected by the work zone.

It is also recognized that delays add to the tailpipe emissions emanating from the traffic flow system affected by the work zone. Though these have typically been regarded as external costs, and therefore not associated with either the private costs of the motorist or the project costs of the engineering work being carried on behind the work zone in a systems cost analysis, they should be addressed and incorporated into the analysis. The issue of traffic emissions is, therefore, one of increasing importance, particularly with respect to the Clean Air Act and environmental provisions of federal and state governments.

7.4 EMISSIONS AT WORK ZONES

Any system cost evaluation must address air quality, especially where the beneficiary of the investment creates potential health hazards to the public. A number of U.S. cities, after years of growth and industrial expansion, are now producing significant quantities of air pollution. The major constituents of air pollution and their sources are shown in Table 7.1, which shows that highway mobile sources are principal contributors of carbon monoxide (CO), nitrogen oxides (NO_X), and hydrocarbons (HC).

Table 7.1. Source and Proportion of Air Pollutants — U.S., 1982 (% of total for each)

Source	Pollutant				
	CO	HC	NO_X	SO	Particulates
Mobile Sources	72.5	33.3	47.8	4.1	18.0
Highway vehicles	63.0	26.7	38.7	2.2	14.0
Gasoline					
Cars	38.1	16.7	16.6	0.7	7.1
Light trucks	11.2	5.6	5.7	0.2	2.1
Heavy trucks	12.4	2.8	2.9	0.1	0.9
Motorcycles	0.3	0.4	*	0.0	0.1
Diesel					
Cars	*	*	0.1	*	0.3
Light trucks	*	*	*	*	0.1
Heavy trucks	0.9	1.2	13.3	1.2	4.2
Other transportation modes	9.5	6.6	9.1	1.8	3.3
Industrial Processes	6.5	39.2	3.0	14.5	31.7
Power Plants	0.4	0.0	30.8	66.9	13.2
Other Stationary					
Fuel Combustion	8.5	11.0	16.9	14.5	18.5
Solid Waste Disposal	2.9	3.3	0.5	0.0	5.3
Miscellaneous	9.2	13.2	1.0	0.0	13.2
TOTAL	100	100	100	100	100

Note:* = negligible quantities

The health effects of all photochemical smog products have not been completely determined, but are generally thought to be unhealthy, resulting in alerts being issued in cities across the nation during times of excessive smog. Carbon monoxide is also an unpleasant vehicle tailpipe emission. Internal combustion engines emit small amounts of CO that adversely affect human health when concentrated. Under adverse weather conditions, CO will remain in the vicinity of its emission for some time. One hundred parts per million (ppm) of CO can cause slight headaches, while 200 ppm can cause shortness of breath. Any situation where many vehicles are idling and changing speeds frequently (e.g., during traffic jams and long queues at stop signs) the very conditions created by work zones can give rise to such adverse effects. Finally, airborne particles are emitted from most vehicles as very fine exhaust. Diesel engines emit carbon particles that blacken buildings and simply add more material into the atmosphere, degrading its quality.

7.4.1 Air Pollution from Highway Construction

Air pollution created by highway traffic worsens (sometimes only marginally) during any pavement construction or rehabilitation work. There are two components, one created by the construction activity itself and the other representing the incremental vehicle emissions from interference with the normal traffic flow. Of course, where the construction is entirely new, existing traffic is not affected and no incremental impact is created. However, in future highway construction, more and more construction work will involve the rehabilitation of existing highways that must remain in use and where such activities will affect normal traffic flows. In such cases, both components should ideally be modeled.

Of the pollutants already mentioned, particulates and hydrocarbons from on-site construction processes are the most significant byproducts. The effect of particulate emissions on the ambient air quality in the work zone also depends on the following items (Ref 23):

- the number of concurrent operations
- weather
- soil type
- mitigation methods employed
- the nature of the haul roads or roads adjacent to the work zone
- local traffic on those roads
- main lane traffic volumes and speeds
- the type of construction equipment
- the distance from the dust source
- terrain
- the characteristics of adjacent property.

7.4.2 Air Pollution from Traffic Impacted by Work Zones

As seen in Table 7.1, a significant portion of the emissions in urban areas is generated by motor vehicles, or *mobile sources*. Much variation is exhibited by mobile sources in the type of emission owing to complex factors like engine type, the mode of operation, fuel composition, presence and working condition of emission control devices, atmospheric conditions, engine tuning, and operating characteristics (e.g., speed cycles).

The effect of these variables differs between pollutants, as reflected in Table 7.2. First, as the air/fuel ratio increases, the concentration of CO decreases rapidly owing to more complete combustion of the fuel at leaner mixes. This implies that while idling and decelerating, the CO concentration is very high. The concentration decreases during acceleration and high-speed cruising. Diesel engine emissions of CO is very low for all modes of operation. Similarly, hydrocarbon emissions are high for idling and deceleration modes, while cruising at high speeds results in a further reduction in HC emissions. High concentrations of NO_x are found during acceleration and when cruising at high speeds; lower concentrations occur during deceleration and idling (contrary to the CO and HC conditions), owing to their dependency on the temperature of combustion. Finally, particulate emissions are comprised mainly of carbon particles, lead compounds, and motor oil. Particulate emissions are significantly higher in the diesel engines that power most trucks.

Table 7.2. Relative Emission Characteristics with Respect to Operating Mode and Engine Characteristics

Operating Mode or Engine	Emission Concentration		
Characteristics	CO	HC	NO_x
Idle	High	High	Very low
Acceleration			
Moderate	Low	Low	High
Rapid	Moderate	High	Moderate
Deceleration	Very high	High	Very low
Cruise			
Low Speed	Low	Low	Low
High Speed	Very Low	Very Low	Moderate
Effect of cold engine (warm-up period)	Higher	Higher	Lower
Effect of higher compression ratio	Somewhat higher	Higher	Higher
Effect of advancing Spark ignition	Higher for rich mixtures only	Somewhat Higher	Higher, especially for lean mixtures
Effect of exhaust gas Recirculation	No effect	Higher	Considerably Lower

Source: Ref 43

Emissions are therefore mainly affected by such travel patterns as idling, acceleration, deceleration, and cruising, with different behavior exhibited by different pollutants. The travel pattern is affected by the highway structure (whether there are intersections) and by traffic volume (congestion). This clearly implies that pollution levels at work zones will be magnified as a result of traffic congestion, queue buildup, and general interference with normal flow behavior related to the construction activity.

7.4.3 Modeling Work Zone Emissions

The task of developing models to estimate pollutant concentrations generated by highway traffic is carried out by first estimating the source strength using an emissions model for the vehicle scenario in the region. Subsequently, the dispersion of the pollutant in the atmosphere is normally modeled by a Gaussian dispersion or gradient transport model. In other words, source (or tailpipe) emissions are first estimated, and then their dispersion beyond the highway is modeled. In the case of urban areas, predicting dispersion can be complex and involve many specific site-related variables, such as time of year and wind speeds. While these matters are currently being addressed under federal provisions, it will be some time before anything other than a site-by-site analysis can be undertaken.

7.4.3.1 Determination of Mobile Source Strengths

The source strength of each pollutant needs to be determined using an emissions model that accounts for traffic flows, vehicle conditions, and driving patterns. Since 1970 several such emission models have been established for a number of conditions.
An early attempt to model emissions yielded the Automobile Exhaust Emission Modal Analysis Model (Ref 53), a mathematical model developed to estimate light-duty vehicle emissions data for carbon monoxide, hydrocarbons, and nitrogen oxides over any specified driving sequence. Such models have now been superceded in planning use by the MOBILE 4.1 suite of models (Ref 99). This program calculates emissions factors for carbon monoxide, hydrocarbons, and nitrogen oxides for seven types of motor vehicles. These models are probably the most widely used for predicting mobile sources and have been considered for use by most Metropolitan Planning Organizations (MPOs), the entities responsible for enforcing federal air quality standards in densely populated areas.

The TEXAS II intersection simulation model (Ref 54) has an emissions capability that can calculate tailpipe pollutants at an intersection. This model calculates emissions at the micro-simulation level and may be appropriate for work zone analysis. FREQ7PE (Ref 80) and FRECON2 (Ref 12) are freeway corridor simulation models with emissions prediction capabilities.

7.4.3.2 Modal Emission Rate Models

The pollution emission rates occurring under various modes of operation (e.g., acceleration, cruise, deceleration, and idling) must be quantified so that the excess work zone emissions can be computed. Because emission levels vary widely with the mode of operation of the vehicle, modal emission rates are required to model air quality at locations where there are wide variations in traffic flow speeds.

Accordingly, various approaches have been used to obtain the modal emission rates of vehicles. One approach has been to use modal emissions from the Modal Analysis Model, and to then correct this value using the ratio of the results from the MOBILE model for actual and base scenarios. The base scenario is for conditions used in the Modal model, namely, a 1977 calendar year, a light-duty vehicle fleet, 100 percent hot stabilized operating conditions, a temperature of 75 °F, and the average speed of the user-defined driving sequence. The actual scenario is for the corresponding conditions in the calendar year being modeled.

The second approach has been to use emission rates from the MOBILE model and to correct them using modal correction factors. These correction factors were derived using limited sets of emissions data from driving cycle tests (Ref 85). The correction factors are usually functions of the vehicle speed and acceleration. This approach has been used in the MICRO2 (Ref 29) and CALINE4 (Ref 10) models.

The CALINE4, TEXIN2, and IMM programs were developed exclusively for modeling CO hot spots at intersections. The equations used for modeling modal CO emissions for the purpose of work zone emission prediction will follow closely those used in MICRO2 and CALINE4. The approach used in IMM and TEXIN2 is not used for reasons stated previously. MICRO2 is the only program among these four that models HC and NO_x emissions. The modal HC and NO_x emission models for the work zone problem make use of the results obtained from the MICRO2 model.

7.4.3.3 Summary

This section described computer models that predict excess energy consumption and excess mobile source emissions at freeway work zones. Given the characteristics of the work zone (e.g., configuration, schedules), the characteristics of traffic at the work zone (e.g., volume, percent trucks), and the emissions characteristics of vehicles in the area, the model is capable of providing excess emission values for two vehicle types and three pollutant types. Thus it can be used for comparing work zone construction and traffic management strategies specifically in terms of air pollution, with the results from the model then used for expedited construction strategies that reduce air pollution.

Using information obtained in the literature review, we decided to adopt a project-level work zone model for use in this project. Of the available project-level models, QUEWZ was considered the most appropriate for our use. It is firmly established in the U.S. as a planning tool, it employs a straightforward and effective structure, it can be incorporated into the Rigid Pavement Life Cycle Cost Analysis computer program, and it has recently been modified to predict mobile source emissions.

7.5 THE QUEWZ MODEL

QUEWZ was developed at the Texas Transportation Institute (TTI) for the Texas State Department of Highways and Public Transportation in the early 1980s (Ref 22). The model analyzes traffic flows through freeway work zones and estimates the traditional road user costs and queue lengths as they relate to lane closures. It can be applied to basic freeway segments having as many as six lanes in each direction, and can analyze any number of lanes closed in one or both directions. QUEWZ, specifically designed for highway work zone analysis, has been used to estimate user costs attendant on various lane closure strategies.

QUEWZ analyzes traffic flows through work zones using traditional macroscopic techniques. It first estimates speeds and queuing characteristics both with and without the work zone and then estimates the additional road user costs generated by the work zone. The following speed characteristics are estimated:

- normal approach speed,
- average and minimum speed through the work zone, and
- average and minimum speed through the queue.

The normal approach speed and average speed through the work zone are computed from relationships between speed and volume-to-capacity ratios presented in the Highway Capacity Model (Ref 39). It would be desirable to update these data with later relationships if additional resources became available. The model user has the option of modifying the parameters of the relationship to more accurately represent the road segment under analysis. The minimum speed through the work zone is estimated using a linear regression model developed at TTI. In a queue, the minimum speed is presumed to be zero and the average speed is estimated using a model developed at TTI (Ref 68). When approach volumes exceed the capacity of the work zone, the length of queue and vehicle hours of delay are computed using the approach presented in the 1985 Highway Capacity Manual. Road-user costs relate to three component groups: travel time, vehicle operations, and speed change cycle costs. Vehicle running and speed change cycling costs are estimated using equations derived from the AASHTO manual on user-benefit analysis (Ref 59).

7.5.1 Model Assumptions

Several important assumptions influence the QUEWZ results. The first QUEWZ model did not incorporate a traffic diversion option for a work zone, though this was corrected in the latest version of QUEWZ (Ref 89), where a new diversion submodel operates so that queue lengths do not exceed a user-specified level. Several assumptions are made about the diversion route in order to estimate the costs to diverting traffic. First, the length of the diversion route equals the length of the work zone plus the length of the queue, and the travel time for diverting traffic equals the time for a vehicle at the end of the queue to travel through the queue and the work zone. Next, the diverted traffic maintains a uniform speed equal to the length of the diversion route divided by the travel time; finally, the model assumes that trucks do not divert. The diversion algorithm does not consider characteristics of the alternative routes, including capacities and travel times.

Another important assumption related to the speed-volume relationship is that the same relationship applies both with and without the work zone. This limits the model somewhat, since research suggests that the speed-volume relationships may well differ substantially with and without work zones (Ref 51). Additional work is merited to determine the precise speed-volume relationships in a variety of work zones.

Another assumption that affects user costs is the behavior of traffic in a queue. It is assumed that vehicles make three 0-to-10 mile per hour speed changes per mile of queue length. This assumption is based on a series of speed profiles developed from instrumented vehicles traveling through queues. The fundamental assumption of the input-output analysis technique is that both the arrival rate and the departure rate are uniform throughout each hour.

7.5.2 Predicting Work Zone Mobile Emissions

In 1993, researchers at The University of Texas at Austin modified the QUEWZ model to enable it to predict tailpipe emissions (Ref 89). This modification led to its adoption by the Federal Highway Administration as the basic work zone user impact routine.

The emission prediction function in the model uses a four-step process. Recognizing that traffic behavior varies according to the location being modeled, the first step involves characterizing the traffic at the location where emissions are to be evaluated. For example, if emissions from free-flowing traffic on a highway are required, the key variable will be vehicle speeds and flow. To determine the source strength, these speeds can be used with an emission model that predicts vehicle emissions cruising at a given speed.

The second step is the estimation of the source strength. This requires an emissions model to account for vehicle conditions and driving patterns existing in the zone of interest. Most emission-rate analysis models (both freeway and intersection air quality models) are based on data obtained from two major studies on mobile source emissions administered by the EPA, namely, the Modal Analysis Model (Ref 53) and the MOBILE series of models (Refs 96, 97, 98, and 99).

The third step in modeling mobile source pollution near a roadway uses the emission profile from Step 2 to model the dispersion of the emitted gases along, and in the vicinity of, the roadway. The dispersion of the emissions is dependent on several factors, including source strength, width of roadway, wind direction and speed, source height, and mixing height. The fourth step involves calibrating the dispersion model using actual dispersion data collected from the site being modeled.

7.5.3 Traffic Analysis Model

The flow of traffic in the region of a work zone on a freeway is unique to the extent that it needs to be described by a combination of free-flowing traffic and stop-and-go traffic. When traffic volumes are not great enough to cause congestion and queuing, the traffic can be characterized entirely by the volume and speeds. When congestion occurs, additional information (such as queue lengths) is needed to characterize the traffic. A traffic model that is capable of comprehensively defining the work zone problem is required.

In pursuing such a traffic model, traffic passing through a work zone is characterized in three ways, from the viewpoint of emission prediction (Ref 88):

Vehicles proceeding undelayed through the work zone: When the capacity of the work zone is sufficiently greater than the demand, the vehicles passing through the work zone are processed without any delay. This scenario does not contribute toward excess emission levels.

Vehicles proceeding through the work zone at a reduced speed: As the traffic demand at the work zone approaches the capacity of the work zone, the rate at which vehicles are processed through the work zone decreases, lowering the overall speeds of vehicles. The lower average speeds in the work zone might result in lesser pollution when compared to cases where vehicles proceed unhindered at higher average speeds.

Vehicles stopping near the work zone as a result of queue formation: When the traffic demand at the work zone exceeds the capacity of the work zone, several things occur:

- queue formation upstream of the work zone involving deceleration from the approach speed to idling at the end of the queue,
- short acceleration-deceleration movements (creeping motion) through the queue,
- acceleration to work zone speed at the beginning of the work zone,
- passage through the work zone at the average work zone speed, and
- acceleration to prework zone speed at the end of the work zone.

The characteristics of this traffic behavior are illustrated in Figure 7.2. Because this scenario has the maximum impact in terms of excess emissions, an appropriate analysis is needed.

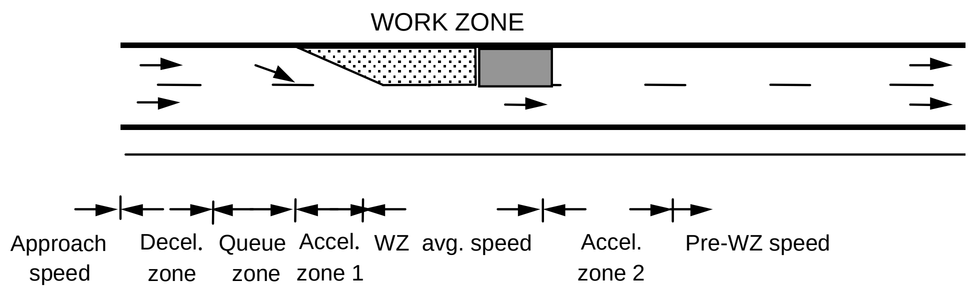


Figure 7.2. Traffic Behavior Associated with Queue Formation near a Work Zone

Excess vehicle emissions at a work zone are defined as the difference between the total emissions produced at and near the work zone minus those produced if traffic had cruised unimpeded through the work zone. These excess emissions can be determined as follows. The time spent by each vehicle in each mode of operation (acceleration, deceleration, cruise, queue) is first computed. The average emission rate for each mode and for each pollutant is then multiplied by the time spent in that mode to obtain the emission values. These emission values, when multiplied by the total number of vehicles in the analysis period, give the total mass of pollutants. The mass of pollutants generated if the vehicles were traveling over the affected length in the absence of the work zone is also computed. The difference between the two gives the excess emissions of the given pollutant during the analysis period.

If the speeds at the beginning and end of the zones described in Figure 7.2 are known, the time spent by the vehicle in these zones can be calculated by assuming constant acceleration and deceleration rates for the vehicles. To provide information on speeds at and near the work zone, as well as the time spent by vehicles in each zone, the traffic analysis model requires the following data:

- work zone capacity,
- speed-flow relationship,
- length of work zone,
- average length of the queue,
- average vehicle speeds in the queue,
- vehicle mix, and
- acceleration and deceleration rate of vehicles.

Because the QUEWZ work zone model satisfies most of these data requirements, it has been widely adopted over other models (Ref 66). The acceleration and deceleration rates of passenger cars and trucks, however, are not provided by the QUEWZ model. For the work zone emissions problem, the acceleration rates for passenger cars and trucks are assumed to be constant values of 4.5 ft/s^2 and 1.6 ft/s^2, respectively, and the deceleration rates were assumed to be constant values of 6.0 ft/s^2 and 2.2 ft/s^2, respectively, based on published values (Refs 42 and 77).

7.6 ACCIDENTS AT WORK ZONES

While accidents are rare events in terms of total vehicular utilization of highway infrastructure in the United States, they nonetheless create unfortunate consequences. These consequences may be grouped into two categories: first, those relating to the accident site and the incident (covering personal, vehicular and property damage); and second, the external costs driven by impacts that the incident has on the rest of the traffic flow. Accident studies can be broadly grouped into these two categories. There are those that attempt to determine incidents that typically focus on accident rates associated with various infrastructure elements. The consequences are covered under the valuation of these events as they relate to personal injury and property damage.

Accident rates have traditionally been determined by studying records, generally those created by the police and insurance industry. The problems associated with collecting relevant features about an accident on a form designed by these sources has, however, frustrated efforts to understand and model accident causes. There is little empirical evidence to support consistent relationships between accident rates or severity and infrastructure characteristics that are relevant to work zone configurations.

Much of the literature associated with accidents has been related to political needs as well as to federal and state highway planning of a very general nature. For example, the decision to reduce highway speeds in the 1970s was promoted both on fuel efficiency grounds and on accident reduction grounds. Also, it can be seen that improvements in highway design, such as those related to guardrails and collapsible devices, have reduced the severity of many accidents. Finally, rates are used to justify enforcement, particularly the expenditures related to policing the highways both to enforce speed standards and to control driver behavior impaired by drugs and intoxication.

Modeling accidents, in general, can be difficult because of the complexity of reasons affecting an incident and the difficulties of obtaining data to develop statistical relationships. Moreover, the problems extend into the valuation of accidents, particularly those related to injury and fatalities. The substantial debate over the figures used by planning authorities to justify accident reductions suggests that any modeling of accidents that extend into the area of cost benefit must be accompanied by sensitivity testing to permit variations in the valuations to be tested.

7.6.1 Accidents on Highways and Other Roadways

Several roadway factors and conditions influence the rates and categories of accidents. The Organisation for Economic Cooperation and Development (OECD) produced a project report that enumerated the most influencing factors and ranked them in order of importance (Ref 9). The project concluded that the factor that most affects accident rates is the width of traffic lanes. The OECD project reports a decrease in accidents when lanes are widened from 9 feet to 10, 11, 12, and 13 feet. For example, a 12-foot-wide lane is reported as having a 32 percent reduction in the amount of accidents relative to a 9-foot-wide lane.

The factor that next most affected the accident rate on highways is the width of shoulders. The OECD project showed that highways with shoulders had significantly fewer accidents than those without paved shoulders. A roadway with a 2-foot shoulder on each side would have an accident rate 16 percent less than that of a highway with no shoulders. Similarly, a 6-foot shoulder would reduce the accident rate by 40 percent. Other factors that may have an effect on the accident rate for a particular roadway include striping (edge line, centerline), lighting, and intersection design (i.e., sight distance).

7.6.2 Cost of Accidents

Accident costs are difficult to determine because they are influenced by the methodology adopted and by the location and country where the project was undertaken. Table 7.3 (Ref 16) shows the results of one project conducted in Great Britain that attempted to quantify the costs of accidents of differing severity. The costs in this table are in 1988 U.S. dollars.

Table 7.3. Components of Accident Costs, 1988 Values and Prices

Costs per Casualty, $ (1988)				
Fatal Casualty			297,800	
Serious Casualty			31,010	
Slight Casualty			2,530	
Costs per Personal Injury Accident, $				
	Police and Administration	Damage to Property		
		Urban	Rural	Motorway
Fatal Accident	230	620	2010	1790
Serious Accident	180	670	1790	1740
Slight Accident	130	590	1210	1340
Costs per Damage Only Accident, $				
Urban			410	
Rural			490	
Motorway			580	

Source: Ref 16

This table reveals a problem typical with accident assessment that is also prevalent in the U.S. and Canada, namely, that only vehicles directly affected in the accident are evaluated. The massive costs that are associated with highway accidents in terms of congestion and time delays are completely ignored. And it shows the bias associated with fatalities in cost-benefit analysis that fails to reflect the value drivers themselves put on their own lives. Though these data are for the UK, similar differentials in valuation are exhibited in data for the U.S.

Table 7.4. U.S. Estimates of Cost Vehicle Accident Types

Injury Type	Cost in 1988 prices, $
Fatal Injury	1,744,000.00
Incapacitating Injury	134,00.00
Non-incapacitating Injury	23,000.00
Possible Injury	10,000.00
Property Damage	960.00
Unreported	250.00

Source: Ref 17

Table 7.4 provides estimates of the cost for various types of accidents, ranging from fatalities to property damage only. Again, wide variations in cost differentials can be noted. Such variations are confirmed in other U.S. studies (Refs 5 and 17). Emphasis on the cost consequences of personal injury (and little else) can be seen in the reported results of U.S. studies "where the average crash in a rural area tends to be more severe and costlier than a crash in an urban area. These variations should be considered in any cost estimates that are used for areas smaller than the entire United States" (Ref 8).

The dangers of focusing on personal injury while ignoring the costs associated in terms of congestion and time delay to others not involved are clearly seen. If full costs were addressed, accident impact would not be dependent on location only, but would also need to address the effects the accident has on traffic flow, congestion, and time delays.

7.6.3 Accidents at Work Zones

The previous sections demonstrate that there are a wide variety of accident rates in the United States. However, these rates and their underlying methodologies ignore the impact that accidents have on other traffic users. Researchers have also shown that drivers have different perceptions of, and behavior towards, work zone safety, in spite of such zones being inherently more dangerous than open lanes. An extensive literature search by Ha and Nemeth (Ref 34) presented data on the increase in accidents in several project sites in ten states where work zones were present. Table 7.5 shows their findings, including the site where the project was performed and the change in the accident rate when a work zone was present.

Table 7.5. Accident Experience during Construction Period

Project	Project Site	% Change in Accident Rate
California	California	+21.4 to +7.0
Virginia	Virginia	+119.0
Georgia	Georgia	+61.3
Midwest Research Institute	Colorado Minnesota Ohio New York Washington	+6.8
Ohio	Ohio	+7.0
Rouphail	Unknown	+88.0
New Mexico	New Mexico	+33.0 (Rural Interstate) +17.0 (Federal-Aid Primary) +23.0 (Federal-Aid Secondary)

Source: Ref 34

The results shown in the table vary widely, from a 7 percent to a 119 percent increase. Part of the variability in the results of these studies is due to the rarity of accidents, and especially to that of accidents at work zones. As part of the above research, a more detailed project in Ohio was conducted. Of accidents occurring in Ohio from 1982 to 1986, 1.7 percent were attributed to work zones. Several factors were identified as contributing to the increase of work zone accidents in Ohio. These factors included:

- inadequate or confusing traffic control,
- edge drop or soft shoulder,
- traffic slowdowns,
- lane changing or merging,
- guardrails,
- use of berm as a travel lane, and
- DUI or DWI.

The project by Ha and Nemeth also investigated the location within work zones where accidents occur. Table 7.6 shows that most of the accidents in work zones in these four sites occur in the work area itself. The next most dangerous sections of work zones are the advance zone and the taper (nonrecovery) area. As stated previously, the information cited in this table was compiled from several studies by Ha and Nemeth in order to compare the rates and characteristics of accidents in work zones in different settings.

Table 7.6. Distribution of Accidents by Location

<table>
<tr><th colspan="2" rowspan="2">Location</th><th colspan="4">Project</th></tr>
<tr><th>Virginia</th><th>Ohio Rural</th><th>Kentucky</th><th>Ohio Turnpike</th></tr>
<tr><td colspan="2">Advance Zone</td><td>12.7%</td><td>15.9%</td><td>5.6%</td><td>6.5%</td></tr>
<tr><td colspan="2">Taper</td><td>13.3%</td><td>22.5%</td><td>7.9%</td><td>9.2%</td></tr>
<tr><td rowspan="2">Work Area</td><td>Lane Closure or Buffer Area</td><td rowspan="2">44.7%</td><td>39.1%</td><td rowspan="2">54.1%</td><td rowspan="2">23.2%</td></tr>
<tr><td>Construction Area</td><td>16.6%</td></tr>
<tr><td>Ramp</td><td></td><td>0.0%</td><td>3.3%</td><td>0.0%</td><td>0.0%</td></tr>
<tr><td>Crossover</td><td></td><td>0.0%</td><td>0.0%</td><td>0.0%</td><td>34.1%</td></tr>
<tr><td>TLTWO</td><td></td><td>0.0%</td><td>0.0%</td><td>0.0%</td><td>22.2%</td></tr>
<tr><td colspan="2">Others (Intersection)</td><td>29.3%</td><td>2.6%</td><td>32.4%</td><td>4.8%</td></tr>
</table>

Source: Ref 34

In Table 7.7 (Ref 73), the number of accidents and their respective percentages for the Ohio Turnpike, a 240-mile freeway, are reported. The Turnpike in general seems to be less dangerous than the interstate system as a whole, judging by fatality rates. In 1978 there were 0.6 fatalities per 100 million vehicle miles traveled. On the entire U.S Interstate system, the rate for the same year was 1.9 per 100 million vehicle miles traveled. Although these data are 20 years old, they were the most recent when the project report was published in 1983. This shows the need to conduct fundamental research in this area — research supported by the latest available data reflecting improvements in both vehicular, driver, and work zone safety.

Table 7.7. Accident Types: Construction and all Turnpike Accidents

	Construction Accidents		All Accidents	
Type of Accident	Number	Percent	Number	Percent
Rear End	42	22.70	696	20.29
Hitting Objects	97	52.43	1,297	37.82
Side Swipe	18	9.73	451	13.16
Non Collision and other	28	15.14	985	28.73
Total	185	100.00	3,249	100.00

Source: Ref 73

The table above, representing the results of a 28-month project, reports the number of accidents in work zones and all accidents combined. It appears that the percentages of rear-end and hitting-objects types of accidents increase when a work zone is in place. The project report states, however, that comparisons between accidents at work zones and other accident rates are not possible owing to a lack of exposure data.

The information presented in Table 7.8 (Ref 73) gives the location and other characteristics of the accidents observed during the Ohio Turnpike investigation. Over 41 percent of all accidents occurred at night; accidents in work zones showed a similar trend. The percentage of accidents where fault was attributed to trucks was 52 percent in work zones, but this value increased to 56 percent when all accidents were considered. These values are calculated by the total number of accidents occurring during the 28 months of the project. If accidents are measured by vehicle miles traveled, the percentage of accidents caused by trucks is reduced to 37 percent.

When the locations of work zone accidents are compared, those occurring in the upstream crossover area and the bidirectional area of the work zones were the most dangerous. This is evident in the number of accidents that occurred in these areas shown in Table 7.8.

Table 7.9 (Ref 25) gives the percent increase in accident rates depending on the length of the work zone and the duration of the construction project that causes the work zone to be needed. Figure 7.3 presents a clearer picture of the trends and importance of the findings.

Table 7.8. Summary of Work Zone Accidents

Zone	No. of Accidents	At Night		Trucks at Fault		Injury Accidents		Multiple Vehicle Accidents	
		No.	(%)	No.	(%)	No.	(%)	No.	(%)
Advance	12	1	(8.3)	2	(16.7)	3	(25.0)	5	(41.7)
Taper	17	6	(35.3)	7	(41.2)	3	(17.6)	7	(41.2)
Single Lane	43	13	(30.2)	23	(53.5)	16	(37.2)	19	(44.2)
Crossover:									
First Curve	49	34	(69.4)	36	(73.5)	9	(18.4)	9	(18.4)
Total	63	39	(61.9)	47	(74.6)	11	(17.5)	14	(22.2)
Bi-Directional	41	18	(43.9)	16	(39.0)	19	(46.3)	22	(53.7)
Other Work (a)	9	3		1		--	--	2	
Zone Total	185	80	(43.2)	96	(51.9)	52	(28.1)	69	(37.3)
All Turnpike	3,429	1,431	(41.7)	1,915	(55.8)	1,054	(30.7)	1,147	(33.4)

(a) Location could not be determined

Table 7.9. Percentage Difference in Accident Rates

Work Zone Lengths (miles)	Duration (Days)								
	100	150	200	350	300	350	400	450	500
0.2	50.96	71.89	79.26	80.70	79.11	75.82	71.53	66.64	61.39
0.4	32.54	52.28	58.81	59.60	54.47	53.73	49.05	43.82	38.25
0.6	30.52	49.56	55.59	56.00	53.56	49.56	44.65	39.21	33.47
0.8	32.99	51.54	57.23	57.36	54.71	50.51	45.44	39.86	33.99
1.0	37.15	55.32	60.73	60.66	57.83	53.49	48.29	42.60	36.63
1.2	42.01	59.86	65.05	64.81	61.84	57.38	52.08	46.30	44.31
1.4	47.13	64.71	69.72	69.33	66.24	61.68	56.29	50.44	44.31
1.6	52.31	69.68	74.52	74.00	70.81	66.17	60.70	54.78	48.60
1.8	57.48	74.63	79.33	78.71	75.42	70.70	65.18	59.19	52.95
2.0	62.56	79.53	84.10	83.38	80.01	75.22	69.64	63.60	57.31

Source: Ref 25

Figure 7.3. Percentage Difference in Accident Rates (Ref 25)

The increase in accident rates is reduced for each project duration until about 0.6 miles in length. At that point, the increases slowly rise again and, at 2.0 miles in length, reach a level equal to what was seen at about 0.2 miles in length. Within each set of construction duration times, the accident rate increases with the project duration until about

350 days, and then decreases. In long work zones, the percent increase in the accident rate during a 500-day construction project is less than that of a 100-day project.

Garber and Woo (Ref 26) conducted a research project of traffic control effectiveness in 1991 to find aspects of traffic control and the specific control devices that contribute to the safety of work zones (including those that do not). The results of this research project showed that the most effective traffic control devices include cones, flashing arrows, and flagmen, assuming that these are used correctly. The research project also found that the use of barricades in some cases actually increased the rate of accidents at work zones. The accident rate at work zones appeared to be greater in any combination of traffic control devices when compared to the same combination of traffic control devices without the barricades.

The most influential factors in bridge-related accidents are the average daily traffic (ADT), approach curvature, and the bridge width. Using these factors as inputs, a regression equation was derived that estimates the number of accidents on a given bridge per year. This equation is given below in Equation 7.1. The formula in this model excludes work zones as an independent variable, though the width variable could be used as a surrogate. Although this equation was developed for bridge construction, it can also be applied to work zones on highway sections.

$$\text{Number of Accidents} = 0.783 \cdot ADT^{0.073} \cdot LENGTH^{0.033} \cdot (WDIFACC + 1)^{0.05} - 1.33 \quad (7.1)$$

where:

ADT	=	average daily traffic,
LENGTH	=	work zone length, and
WDIFACC	=	difference between an acceptable width and the existing width.

7.6.4 Conclusions

The various data sources, found both in the United States and elsewhere in the world, confirm broad tendencies but exhibit disparities that make modeling their impacts difficult. More than any other travel issue, accidents have been substantially influenced by developments occurring over the past 25 years. First, careful attention is paid to improve driver information with respect to regular highway conditions and to temporary conditions (such as work zones). Second, control of traffic moving through such construction areas as work zones is now given high priority in basic project design: In urban areas, traffic programming and measures frequently account for more than 15 percent of the project cost. In addition to these engineering measures, new safety measures, such as barriers and collapsible barrels, have reduced the severity of accidents.

There is a distinct possibility of incorporating an accident component to the life cycle cost analysis models developed in this research project and, like the benefit cost economic model (MicroBENCOST) developed at TTI (Ref 63), it could use lane width as its main determinant. Reasonable assumptions based on engineering judgment could be incorporated into such a modification of this, and a general prediction of the increased number of accidents at work zones will be made using the modified models. There is little doubt that in order to fully address the systems' impacts inherent in the inclusion of user costs into life cycle cost analyses, accidents should be addressed. However, the current literature seems inadequate to perform this in an accurate and equitable fashion, and, accordingly, it is an important area to be included in future research.

7.7 NOISE

Noise can affect the residents and businesses adjacent to a highway project in many ways. Tire noise along with vehicle engine noise are the major contributors to the levels of noise attributed to pavements and highways. Other noise factors include air brakes, wind noise, horns, and skidding tires.

Several studies have been performed to measure the levels of all aspects of highway noise (Refs 4, 65). However, placing a value or a cost on a level of noise is very difficult. For the purposes of this report, no attempt at directly placing a value on noise will be made. When specifications dictate, or when otherwise required, sound walls and other methods of noise attenuation will be constructed as part of the highway construction project. When conditions such as these arise, the cost of noise attenuation devices are added to the cost of the project and will therefore be considered in the life cycle cost analysis.

The National Cooperative Highway Research Program commissioned two studies in the early 1970s that investigated the level of noise resulting from highway pavement projects (Refs 28, 52). These reports focus on the measurement and the reduction of traffic noise when designing new and rehabilitated pavements.

7.8 EFFECTS OF PAVEMENT ROUGHNESS ON USER COSTS

The previous sections of this chapter have discussed how construction work zones affect the costs of the users of the facility. This section, however, will discuss the effects on user costs occurring during normal operation of the highway section. More specifically, the discussion will focus on the increase in operating costs of vehicles as the pavement becomes increasingly rough over time. The greatest increase in vehicle operating costs arises from the decrease in safe operating speeds when pavements become rough. Another cause of increased vehicle operating costs is vertical acceleration owing to rough pavement. This contributes not only to the increased rate of deterioration of vehicles, but also to the decreased safety of vehicle drivers and passengers.

7.8.1 Accidents Resulting from Pavement Roughness

Zaniewski et al. (Ref 109) researched the increase in vehicle accidents that occur as a result of rough pavements. That report concluded that, although there is some correlation between pavement surface roughness and vehicular accidents, there is not sufficient correlation to develop models to predict accidents. The models attempted to predict accidents in the following three manners:

- Number of Accidents = F(Section Length, ADT, PSI)
- Accidents per Mile = F(ADT, PSI)
- Accidents per Million Vehicle Miles Traveled = F(PSI)

None of these approaches produced models with an R^2 value greater than 0.41, with the R^2 values for most other models closer to 0.0. The conclusions of the accident analysis state that perhaps the correlation is small enough to be "trivial," but that the authors do not believe this to be the case given the billions of vehicle miles traveled each year.

7.8.2 Vehicle Operating Costs and Delay Caused by Pavement Roughness

Zaniewski et al. (Ref 109) also considered the increased vehicle operating costs and time delay generated by pavement type and roughness. Their report mentions a report by Karan et al. (Ref 48) in which the effects of pavement roughness on vehicle speeds were analyzed. Using the results of the Karan report, of Hazen's project (Ref 38), and of the Transportation and Road Research Laboratory (Refs 14 and 15) project, the Zaniewski report developed a model for speed adjustment factors (F) based on average running speed (ARS) and present serviceability rating (PSR). Three models were developed, based on the range of the average running speed. These are shown below:

For ARS ≥ 35 mph:

$$F = 0.8613 \bullet PSR^{0.0928} \tag{7.2}$$

For 35 < ARS ≤ 15 mph:

$$F = 0.8613 \bullet PSR^{0.0928} + (1 - 0.8613 \bullet PSR^{0.0928}) \bullet \frac{35 - ARS}{20} \tag{7.3}$$

For ARS < 15 mph:

$$F = 1.0 \tag{7.4}$$

These models are incorporated into the life cycle cost analysis framework by computing the speed reduction factor and performing a user cost analysis using the QUEWZ model. In this case, however, there are no lane closures and no lane width restrictions, but only speed reductions based on the speed reduction factor, F. The increased user costs will be calculated by QUEWZ using all 24 hours of the day over the entire length of the project. The user costs calculated for one day are then multiplied by 365.25 to obtain the user costs over an entire year. The calculation of user costs related to pavement roughness will only be performed, however, in years where major rehabilitation improvements are not performed.

More research should be performed regarding the relationship between speed and pavement surface roughness. Since the Zaniewski report (1980), many changes have taken place in vehicle technology, driver experience, and road safety.

7.9 SUMMARY

This chapter has discussed the various types of user costs and how these costs are incorporated into the life cycle cost analysis framework. The user costs that are not included in the current framework — particularly those that have not been studied in detail or that are currently extremely difficult to model — should be researched more thoroughly so that they may be incorporated into the life cycle cost analysis framework sometime in the future.

The speed at which vehicles travel through a highway segment is possibly the greatest factor in determining the costs borne by users of the facility. Other factors contribute to user costs and compound the effects of reduced speeds. Other costs that are borne by both users and nonusers of the facility can have great effects as well. Increased noise and air pollution, for example, have an effect on all who live and work nearby. A comprehensive life cycle cost analysis should be capable of identifying the pavement design alternative that represents the best combination of agency costs, user costs, and external costs, as well as the one that provides the best overall performance while considering all these components.

CHAPTER 8. OTHER LCC COMPONENTS

Throughout the previous chapters on pavement performance, maintenance and rehabilitation, agency costs, and user costs, the discussion has alluded to three underlying ideas. These ideas are (1) the present value of future costs, also known as discounting; (2) the project's analysis period; and (3) the variability inherent in both the physical aspects of the pavement and in the costs associated with construction and user impacts. This chapter discusses these essential components of the life cycle cost analysis framework. In addition, it discusses the salvage component of life cycle cost analysis, along with the method by which it is treated in this framework.

The concepts of the discount rate and of variability in materials and costs are important in evaluating the true effect of various alternatives when making decisions for a highway construction project. Yet, however important they are, they are sometimes omitted from such an analysis.

8.1 THE DISCOUNT RATE

The discount rate is used by agencies to account for the time value of money. It provides an agency, planner, or decision maker with a way to compare future expenditures with those occurring in the present. In a proper economic analysis, all future costs and benefits are *discounted* to the present, accounting for the prevailing and expected interest and inflation rates. Since the future value of a sum of money in the present is greater owing to compounding interest, the reverse must also be true. The present value of a future sum is worth less than it would be at the present. Because an economic analysis can be highly sensitive to the discount rate, it must be selected with care. This section will discuss how the interest rate and inflation rate can be used to determine a proper value of the discount rate; also discussed are some common values that are suggested by various agencies in the United States.

8.1.1 Calculating the Discount Rate

The discount rate can be calculated from the interest rate and the inflation rate that may be expected over the life of the highway project. The equation to calculate the discount rate is as follows:

$$\text{Discount} = \left(\frac{\mathit{interest} - \mathit{inflation}}{1 + \mathit{inflation}} \right) \tag{8.1}$$

where:

Discount = calculated discount rate,

interest = expected interest rate, and

inflation = expected inflation rate.

The difficulty in predicting interest and inflation rates over the life of the project is somewhat attenuated by using the discount rate. Since the end of World War II, the discount rate (determined from the calculation above) has been fairly stable, even though actual interest and inflation rates have varied widely. Illustration 8.1 shows the difference between the yield on a 10-year Treasury note and the actual yield to investors after accounting for inflation.

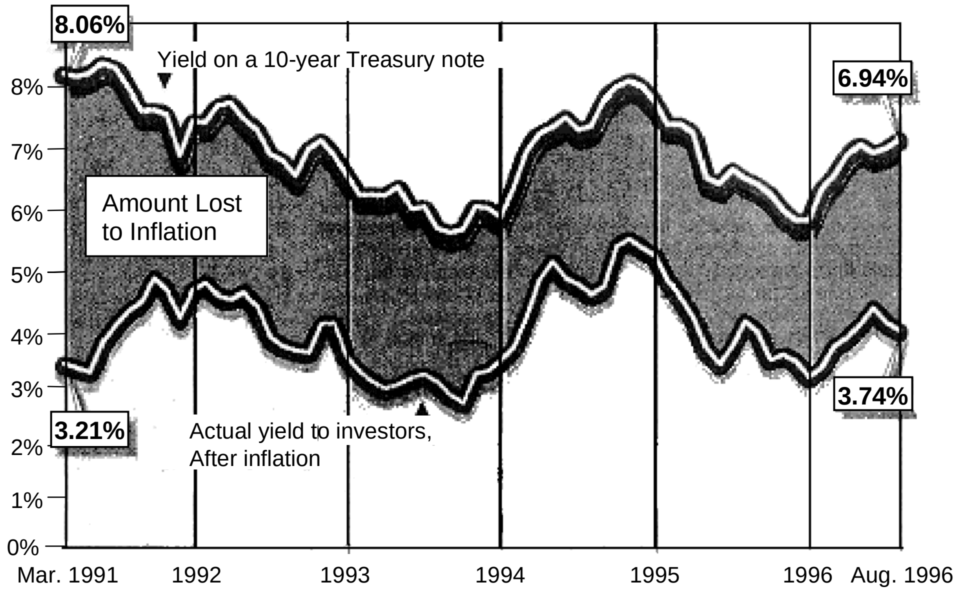


Illustration 8.1. Historical Effect of Inflation on Investment Return.

8.1.2 Common Discount Rates

The Federal Highway Administration has recommended standard discount rates for use in various highway pavement projects. The level of the discount rate depends largely on the type of agency that is financing the work. The rate also depends on the agency's cost of funds, tax-exempt status (for bond investors), creditworthiness (based on ratings by investment banks), and many other factors. In general, the following rates have been recommended for the indicated entities:

Table 8.1. Recommended Discount Rates

Agency Type	Appropriate Discount Rate
State / Municipal	2.5%
Federal / Long-Term Project	3.5%
Privately Funded Projects	4.5%

8.2 ANALYSIS PERIOD

The period of time over which the pavement and the total life cycle cost will be analyzed is called the *analysis period*. This term has been used throughout this report when discussing other aspects of the life cycle cost analysis framework. The analysis period is used to define the time during which the pavement performance is analyzed, and during which all the costs and other aspects of the framework are calculated. During the analysis period, the pavement must be kept above minimum standards for structural and functional capacity.

The Federal Highway Administration provides some guidelines regarding appropriate analysis periods for highway pavement projects. The analysis period should be sufficiently long to reflect the long-term differences between various design alternatives (Ref 100). The FHWA Final Policy of September 1996 recommends a minimum analysis period of at least 35 years for all pavement projects, both flexible and rigid. This includes all types of construction as well, such as new construction, rehabilitation, restoration, and resurfacing projects (Ref 57). This recommendation also suggests, however, that shorter analysis periods may be appropriate in some cases (e.g., low volume roads) or when a short rehabilitation project will extend the life of a pavement a few years until a total reconstruction is planned.

The FHWA's life cycle cost Interim Technical Bulletin (Ref 100) also indicates that the analysis period should be greater than the pavement design period, which allows enough time to incorporate at least one rehabilitation activity. This concept was also promoted in a lecture to the National Asphalt Paving Association in 1997 (Ref 105).

It is important to understand that future pavement performance becomes more difficult to predict as the analysis period grows longer. This is offset, however, by the more important component of life cycle cost analysis, namely, user costs associated with frequent maintenance and rehabilitation. Using the reliability concepts that will be discussed in this chapter, pavements can be designed with a high degree of confidence. The result can be pavement structures that are very likely to provide performance throughout the entire design life, with minimal disruptions to traffic flow.

The analysis period chosen for a particular project should meet or exceed the recommendations provided by the FHWA. Using the life cycle cost analysis framework, inadequate designs can be modified and reanalyzed fairly quickly, leading to the development of a design that meets the constraints set by the analysis period.

8.3 PROBABILISTIC APPROACH TO LIFE CYCLE COST ANALYSIS

The Federal Highway Administration has been promoting risk analysis for use in life cycle costing for the past several years. Risk analysis utilizes the uncertainty in material properties, construction costs, user costs, and other aspects of design to determine the overall variance in the life cycle cost prediction. Two ways of determining the probability characteristics are the *Monte Carlo Simulation* and *mathematical derivation*. This section describes these two approaches and explains how the mathematical derivation approach is used in this first version of the framework.

8.3.1 Reliability Concepts

Another name for the use of probabilistic methods is reliability. The use of reliability concepts in the development of a life cycle cost analysis framework is important in making comparisons between alternate designs. In order to provide an adequate comparison between different designs using different materials but that meet the same design criteria or performance over the analysis period, it is important that the performance models as well as the cost calculation techniques evaluate variability in the same fashion between the different designs. This may be accomplished by consistently applying probabilistic concepts that will provide comparable levels of reliability in a format where all design results are equitably accounted for in the analysis.

In the past, pavement performance modeling has been largely deterministic in that very few design inputs were explicitly associated with a mean and variance. Many times a factor of safety was applied to certain design inputs to imply variability of the specific input. While this approach may account for some of the variance, such empirical modifications only result in confounded estimates of the design reliability. Using factors of safety provide no way to reasonably assess the level of reliability of the design procedure (Ref 50).

Reliability equations associated with many design parameters were developed so that the resulting pavement design procedure can provide accurate comparisons between alternate designs while simultaneously considering the inherent variability in paving materials, the environment, and pavement loading conditions.

8.3.2 Monte Carlo Simulation

The Monte Carlo simulation takes randomly selected values for each component in a system, based on the probability of that value occurring for the specific component. The simulation then obtains the system response and records this value. This sequence is performed many times to obtain the probability density distribution of the system's response to the variability of each component.

For such an analysis to be effective, the shape of the probability density function must be known and must be programmed into a computer for the simulation to be efficient. For example, to obtain the probability distribution of the number of loads to failure in the concrete fatigue equation, the following procedure is used:

Using the fatigue equation,

$$\mathrm{Log}(N_f) = 17.61 - 17.61 \bullet (\sigma/S_c) \tag{8.2}$$

where:

N_f = loads to failure, ESALs,

σ = concrete stress, psi, and

S_c = concrete flexural strength, psi, Each of the variables in this model has inherent variability that must be considered. Also, each of the variables has descriptive statistics, such as mean and standard deviation, which define the shape of the probability distribution. The Monte Carlo simulation uses random values from these probability distributions to obtain values of the concrete stress and strength, as shown in the examples in Figures 8.1 and 8.2.

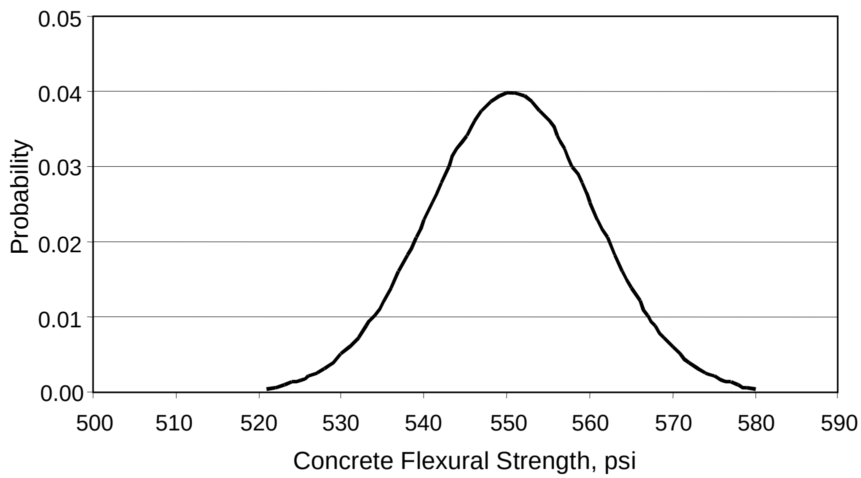


Figure 8.1. Example Probability Distribution of Concrete Flexural Strength

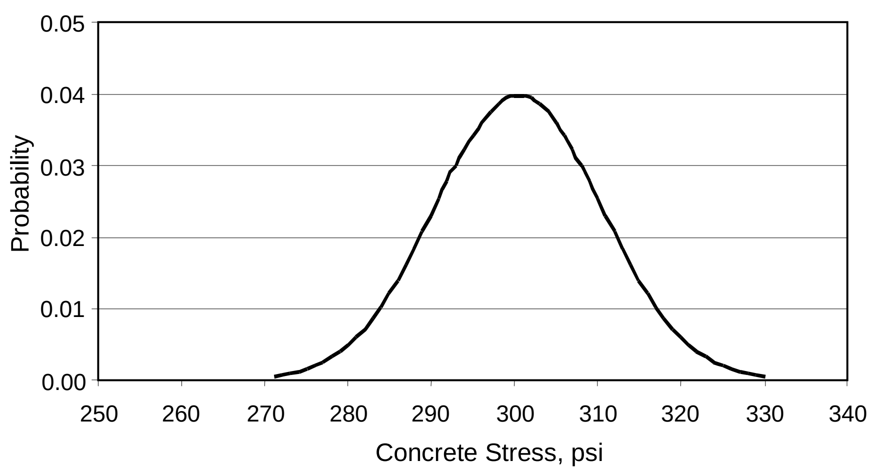


Figure 8.2. Example Probability Distribution for Concrete Stress

Using the randomly selected values in many simulations, the probability distribution of the loads to failure can be predicted using the fatigue equation in Equation 8.2. From there, using a user-specified confidence interval, the probability of specific levels of loads to failure can be determined and used in the life cycle cost analysis. Figures 8.3 and 8.4 show the combined probability distribution from the Monte Carlo simulation for 100 and for 10,000 iterations, respectively. As can be seen, the number of iterations greatly affects the ability of the simulation to develop the overall probability distribution.

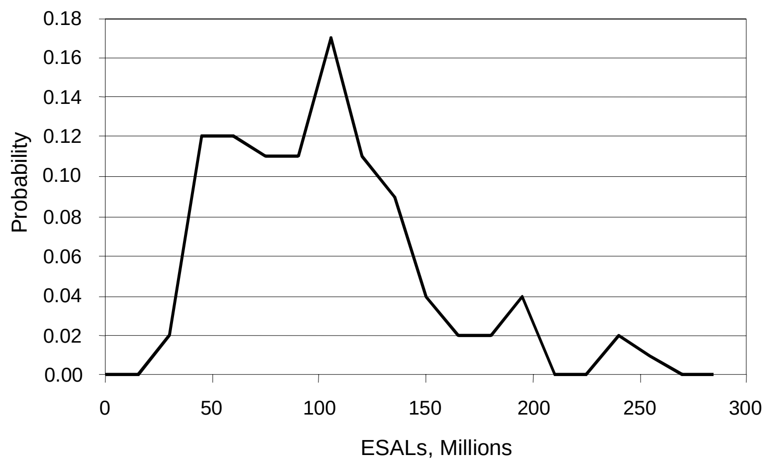


Figure 8.3. Example N_f Probability Distribution, 100 Iterations

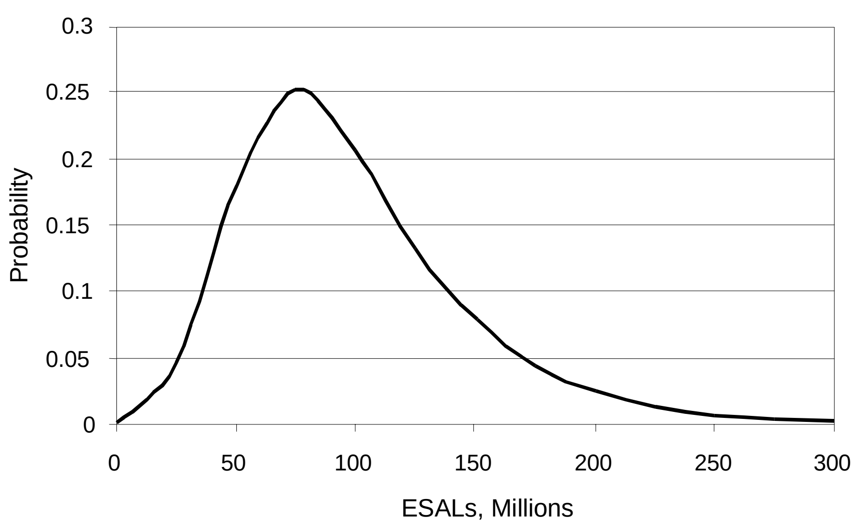


Figure 8.4. Example N_f Probability Distribution, 10,000 Iterations

8.3.3 Mathematical Derivation

An alternative to the Monte Carlo simulation is a mathematical derivation of the probability distribution. A limitation of this analysis, in the form used in this preliminary version of the framework, is that it assumes a normal distribution for all components of the life cycle cost framework. More complex mathematical solutions exist, however, that model other distributions besides the standard normal. For the advanced solutions to be of use, one must know not only the shape of the distribution, but also the mathematical properties of that distribution.

One major benefit of this type of analysis is that only one set of calculations must be performed, whereas the Monte Carlo simulation requires hundreds and perhaps thousands. Using the example from the previous section, and using the same descriptive statistics, with the exception of assuming a normal distribution for the first component in Figure 8.1, a mathematical representation of the variability can be derived.

The mean of loads to failure, N_f, is calculated by using the means of each component in the model. The variance of N_f is obtained through the following calculations, which is termed the first order, second moment theorem (Ref 50).

$$\mathrm{Var}[N_f] = \left(\frac{\partial N_f}{\partial \sigma}\right)^2 Var[\sigma] + \left(\frac{\partial N_f}{\partial S_c}\right)^2 Var[S_c] \tag{8.3}$$

Since the variance is simply the square of the standard deviation, the mean and standard deviation of the computed loads to failure are known. This example is valid for all computations in the life cycle cost framework, as long as variance information is known for each component and the distribution can be assumed to be normal. In cases where the standard deviation of a particular component is not known, a coefficient of variation can be assumed, from which an estimate of the standard deviation can be determined. This form of probabilistic analysis is used within the life cycle cost framework in a limited manner, although this analysis can be expanded to all models in the framework.

8.4 SALVAGE VALUE

Much discussion has taken place regarding the salvage value of a pavement structure at the end of the analysis period. Haas, Hudson, and Zaniewski (Ref 35) describe the salvage, or residual, value of a pavement project as possibly significant, since it involves the value of reusable materials at the end of the analysis period. The salvage value of a pavement section can depend on several factors, such as volume and position of the material, contamination, age, durability, and anticipated use.

There are several methods that can be used to determine the salvage value of the remaining pavement at the end of the analysis period. It can, for example, be represented as a percentage of the original material cost; it can also be calculated by taking the estimated performance remaining after the analysis period as a percentage of the performance provided by the pavement during the analysis period.

Another way to estimate salvage value of pavement structures is to account for the value of the existing material at the *beginning* of the project. Thus, for new construction, no existing pavement will exist and no salvage value is available. However, if a highway pavement project is to be constructed over an existing pavement, such as in designing major rehabilitation, the value of the existing pavement as a base course or similar material reduces the cost of constructing such a base course.

8.4.1 Salvage Value in Life Cycle Cost Framework

This project utilizes the salvage value at the beginning of the project analysis (since it is more accurate in placing a value on the material available), rather than predicting 30 to 40 years into the future. In this method, salvage value is used is to create a new material type in the materials database with a very small, or zero, cost associated with it. The cost of preparing the existing material to make it suitable for a base course is the only cost associated with the layer in the material database.

The advantages of this method are, as mentioned above, that current costs are used in valuing the material; no discounting is made from the end of the project analysis to the present. Also, a more accurate evaluation of the material's contribution to the pavement design is available to the engineer. Engineers planning for the next analysis period of 30 to 40 years can then use any remaining life at the end of the analysis period.

CHAPTER 9. DESCRIPTION OF COMPUTER PROGRAM

The major objective of this report is to develop a comprehensive, modular life cycle cost analysis framework by which existing and future projects can be evaluated. As an aid in the development and in the future implementation of the framework, a computer software package was developed to perform the calculations necessary to predict the life cycle cost of different alternatives. This chapter describes the software package and serves as a user's manual for its use and operation. The software package is the *Rigid Pavement Life Cycle Cost Analysis* (RPLCCA).

Part of the need for this user's manual is to provide the user with more detail regarding the specific inputs that are required by the software. Accordingly, this chapter will also explain how to obtain some of the information requested by the program, such as the types of references that may be needed to complete the data input.

Chapter 3 described the basic format of the life cycle cost analysis framework and the components that are included. Chapters 4 through 8 then described in detail how each component works and interacts with the other components in the framework.

The first section of this chapter explains the various steps required to proceed through an RPLCCA exercise. The sections that follow describe the inputs required and suggest some default values that may be used for analyses of projects in Texas. The discussion then introduces the outputs provided by the program and explains how to interpret results.

9.1 RIGID PAVEMENT LIFE CYCLE COST ANALYSIS PROCEDURE

The RPLCCA computer program requires the user to proceed through several steps in order to prepare for a complete life cycle cost analysis of the project. This section briefly describes the steps that are required to perform the analysis.

9.1.1 Step 1: Prepare Design Alternatives

During this step, the user can create new design alternatives and edit or delete existing ones. This step includes the pavement design, layer properties, overlay and rehabilitation criteria, and construction and variability components of the specific design. As many alternatives as desired may be created. This allows the user to compare two alternatives that are identical with the exception of one input, in order to determine the sensitivity of that particular aspect of the design, such as strength or pavement thickness. The effects of different levels of variability in a particular component can also be investigated.

9.1.2 Step 2: Describe General Analysis Criteria

This step requires that the user input the criteria that will remain unchanged throughout all design alternatives. This includes such inputs as traffic loading, project geometry, environmental loads, allowable distress limits, unit costs, user costs, and the discount rate. Each of these inputs will be applied to all design alternatives.

9.1.3 Step 3: Choose Analysis Options

The final step before executing the analysis is to choose the main analysis options that are desired. The program allows users to omit some of the components if conditions warrant. For example, a highway pavement project in a remote area will have different considerations regarding air quality and user costs, so those portions of the analysis may not be required. The user cost components, emissions, and accidents are options offered to the user, as well as the decision to consider user costs during the initial construction, as would be needed for the analysis of a reconstruction or major rehabilitation project.

9.2 DESCRIPTION OF RPLCCA INPUT VARIABLES

This section describes each input and provides a resource or reference for use in obtaining the necessary data. Each screen for which the user must provide input will be shown, and a detailed description of the inputs required for that particular screen will be given.

9.2.1 Main Analysis

In this screen, the user inputs the basic information governing the performance of the analysis. The user inputs the name of the analysis project (or filename), the name of the engineer performing the analysis, and the date the analysis. The second portion of this window is for alternative management. On the left, new alternatives can be selected and created; based on user input, the program creates a copy of the currently visible alternative on the right; an alternative can also be created based on RPLCCA default values. The former method is convenient because an exact copy of the current alternative is made, from which the engineer can slightly change the design to view the differences in life cycle cost. The right side of the alternative management area contains a list of all current alternatives in the project. Alternatives shown in this box can be edited or deleted from the project using the corresponding buttons.

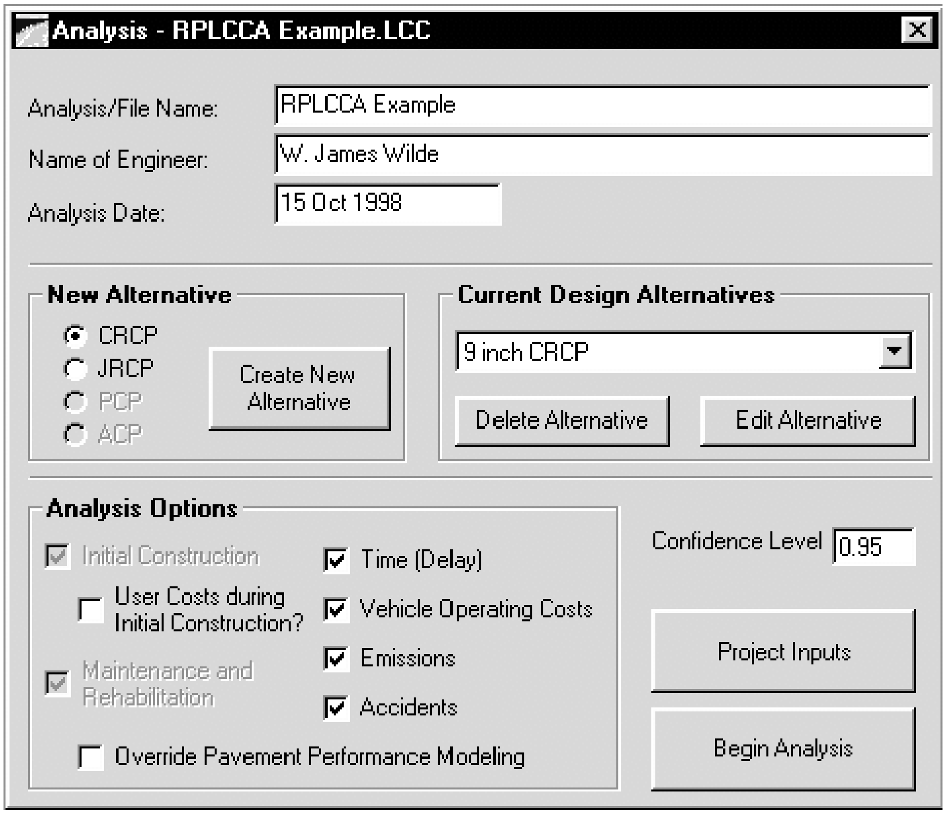


Illustration 9.1. RPLCCA Analysis Window

The bottom segment of the screen contains a list of analysis options; using this screen, the engineer can select the types of analyses to include or omit from the project. In all projects, the initial construction and the maintenance and rehabilitation costs should be counted; accordingly, these are grayed out as a minimum analysis. Other options include the analysis of user costs during the initial construction, time delay, vehicle operating costs, and excess emissions and accidents caused by work zones. The user costs during initial construction should be selected if the current analysis includes the design of a pavement rehabilitation instead of new construction. In such a case, there will be traffic control and other impacts imposed on the traveling public during the construction phase; thus, user cost components will be calculated in addition to the agency's initial cost

Another option provided in the analysis is the ability to ignore the performance and rehabilitation modeling and simply program maintenance and rehabilitation strategies for different alternatives. For example, the user can schedule overlays every 15 years, or crack and joint sealing and spall repairs every 7 years, according to local conditions and preferences. If the pavement performance models or the rehabilitation modules are not performing properly, or if they do not predict reasonable values based on reasonable inputs provided by the user, this option is available. The different inputs that are required when this option is selected are described in a later section.

The overall confidence level to be used in the analysis is also an overall analysis input and should be entered here. Chapter 8 discusses reliability and the confidence interval, and the AASHTO Design Guide provides suggestions regarding confidence levels to use for various facilities.

The two buttons at the bottom right of the screen allow the user to enter project-level inputs and to execute the analysis. The next section will detail all the inputs that are required at the project level. These are inputs that do not change from one alternative to the next (i.e., they remain constant throughout all alternate designs).

9.2.2 Project-Level Inputs

This section discusses project-level inputs required to perform the analysis. Illustration 9.2 shows the first tab of this screen, the description of expected pavement loads over the design life.

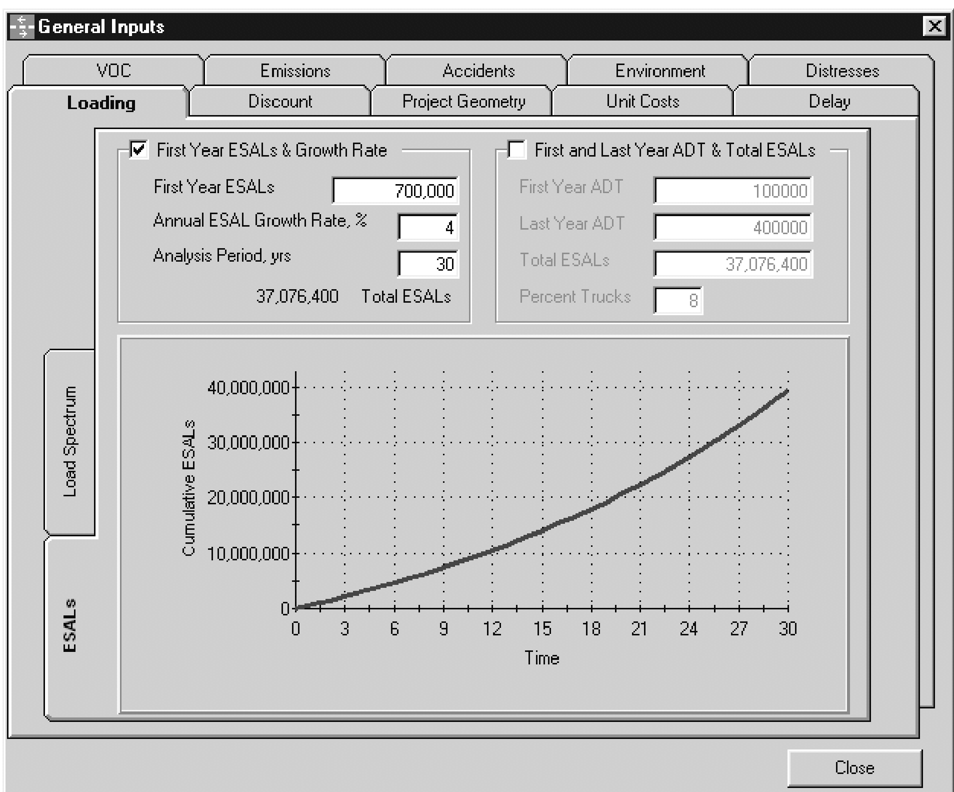


Illustration 9.2. Pavement Loading Description

Illustration 9.2 shows the screen for input of the pavement loading information. At the top-left side of this screen, check the box for providing the first year's ESAL value and the ESAL growth rate. Input the ESAL value expected during the first year after construction. Also, the annual ESAL growth rate and the analysis period are entered here. The total cumulative ESALs is calculated and shown just below, and a graph of annual cumulative ESALs is given.

Another option is available at this time for defining pavement loading over the analysis period. Check the box on the right side of this screen to enter average daily traffic values for the first year after construction and the last year of the analysis period. Also enter the total cumulative ESAL value for the project. This option allows the engineer to define pavement loading using standard values provided by TxDOT's planning department. Again, the graph of annual cumulative ESALs is given below the input area of the screen.

The figure in Illustration 9.3 shows the two methods of entering the discount rate that should be used for the analysis. If the discount rate is given, or suggested, and should not be calculated, enter this value under the heading "Discount Rate." If both the expected interest and inflation rates can be reasonably predicted, these can be entered (the discount rate will be calculated from these values). A third method, using the yield-maturity curve for U.S. Treasury bonds to estimate the long-term risk in interest rates, may be used in future versions of the software.

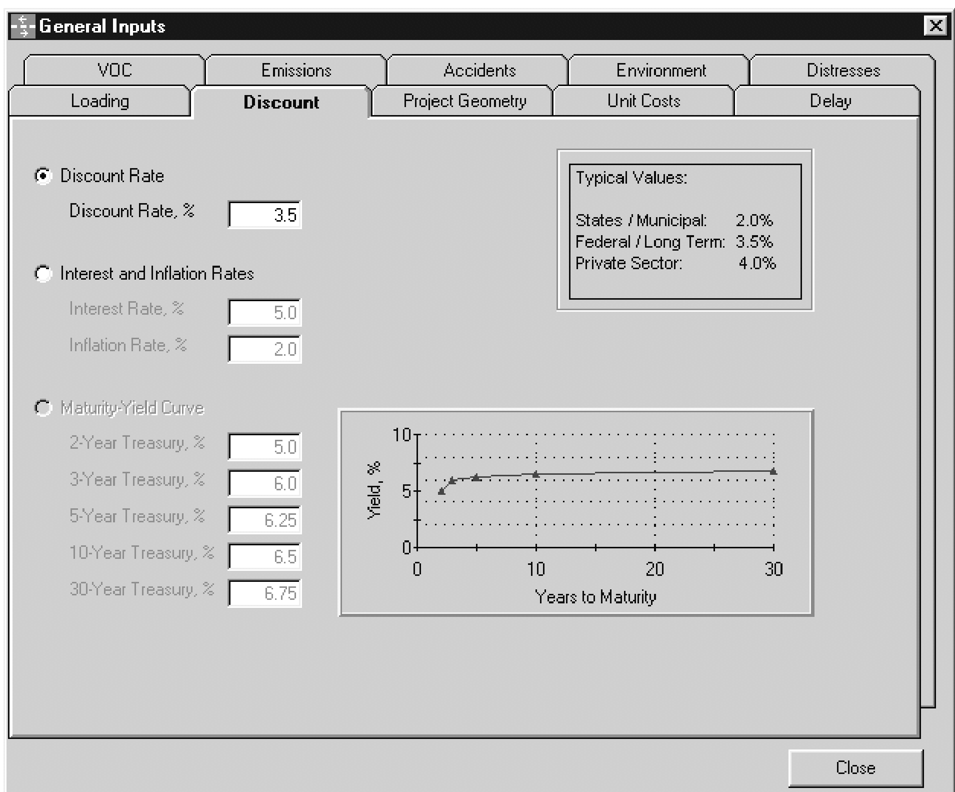


Illustration 9.3. Discount Rate

The screen shown in Illustration 9.4 allows the user to define the geometry of the project. The length of the highway section, in miles, and the total number of lanes, in both directions is input on the left. The inside shoulder width, outside shoulder width, and the width of lanes, in feet, are also input on this screen.

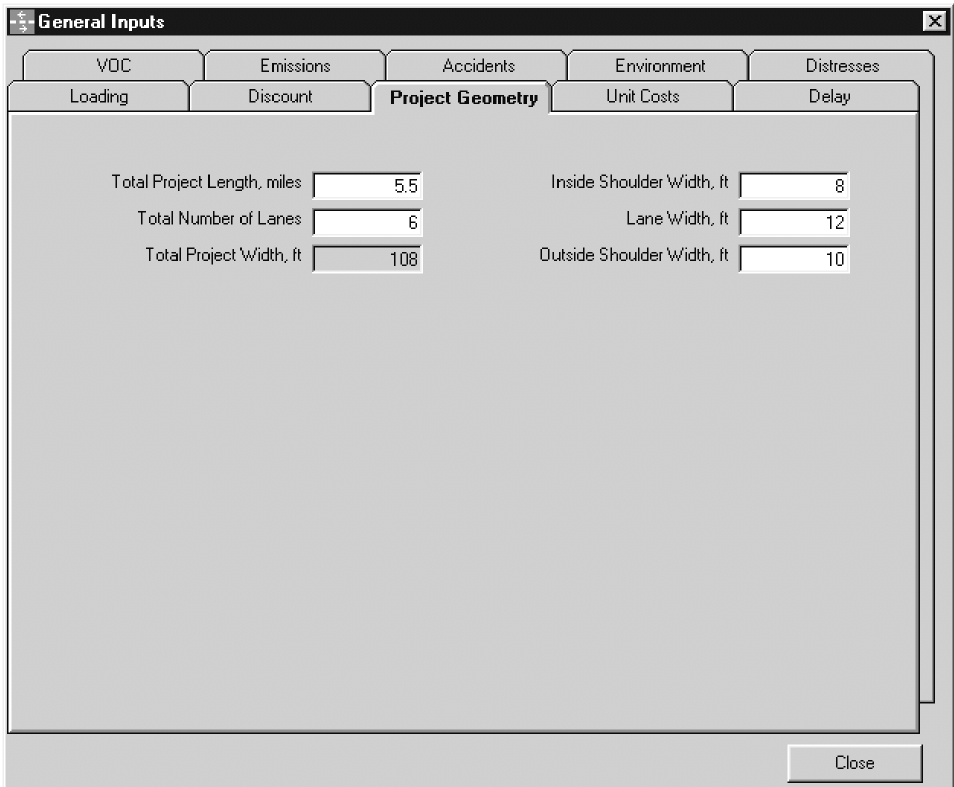


Illustration 9.4. Project Geometry

This tab in the General Inputs window shown in Illustration 9.5 contains four subtabs, each of which requires input by the engineer to describe the work zone geometry, speed and capacity under different conditions of the roadway, traffic volumes, and the standard work zone schedule, for use when lanes are closed for construction but reopened each day. When major rehabilitation activities occur, this construction schedule is ignored, and it is assumed that lanes are closed for the duration of the construction, day and night, or that lanes are narrowed, as given in one of the options in this screen. In the case of narrowed lanes, the lane width must be input in order to model lane capacity and user costs.

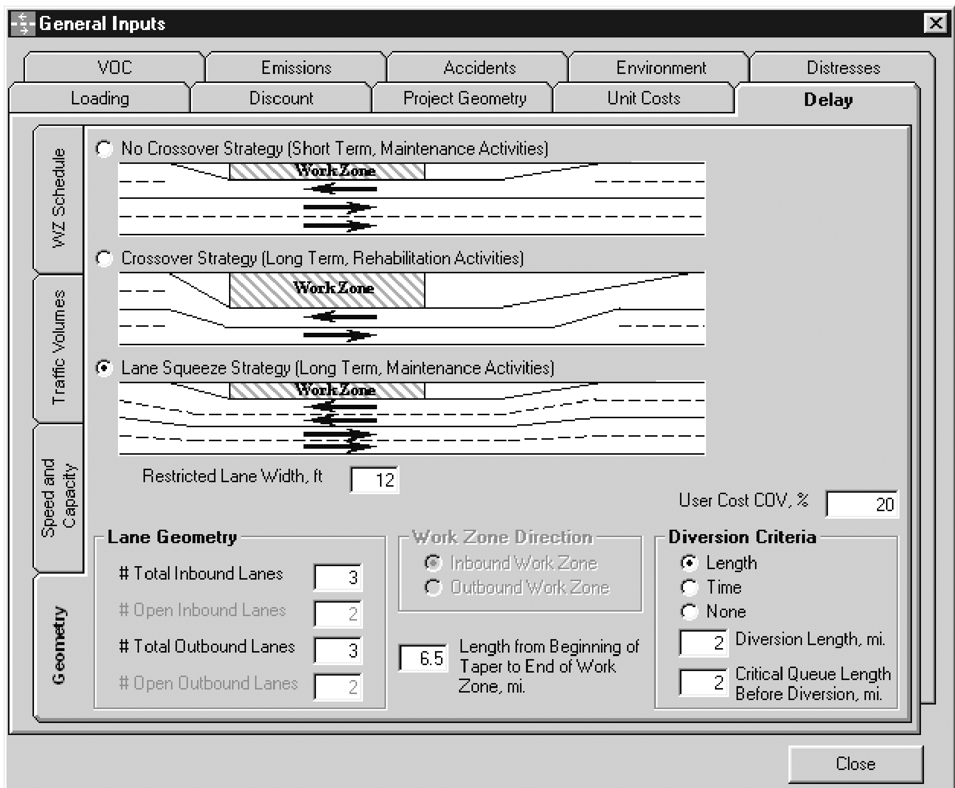


Illustration 9.5. Work Zone Strategy Definition

The inputs required in the screen shown in Illustration 9.5 are the basic work zone geometry (either a single lane closed in one direction, a lane closed in each direction with traffic crossing over to the opposite direction, or a lane-narrowing configuration where all lanes remain open but are narrower than lanes used in normal operation). The direction of the work zone is another input that is required. Inbound work zones are those that are in the direction of the construction. Outbound work zones are those located in the opposite direction. In the case of a crossover geometry, where an entire direction of pavement is under construction, the user costs in both directions are analyzed. The length of the work zone, from the beginning of the taper to the end of the work zone, is also required.

The screen shown in Illustration 9.6 also takes input regarding queues that will form under work zone conditions. The diversion length is the distance that vehicles will drive to avoid the work zone. Diversions occur, however, only when the queue grows to a certain length, or if the time required to go through the work zones becomes too long. This choice is made in the "Diversion Criteria" section of this screen. If there is no option for diversion at the project, "None" should be selected. Depending on whether queue length or time is selected, the appropriate value is entered for the critical queue length or time before vehicles begin to divert.

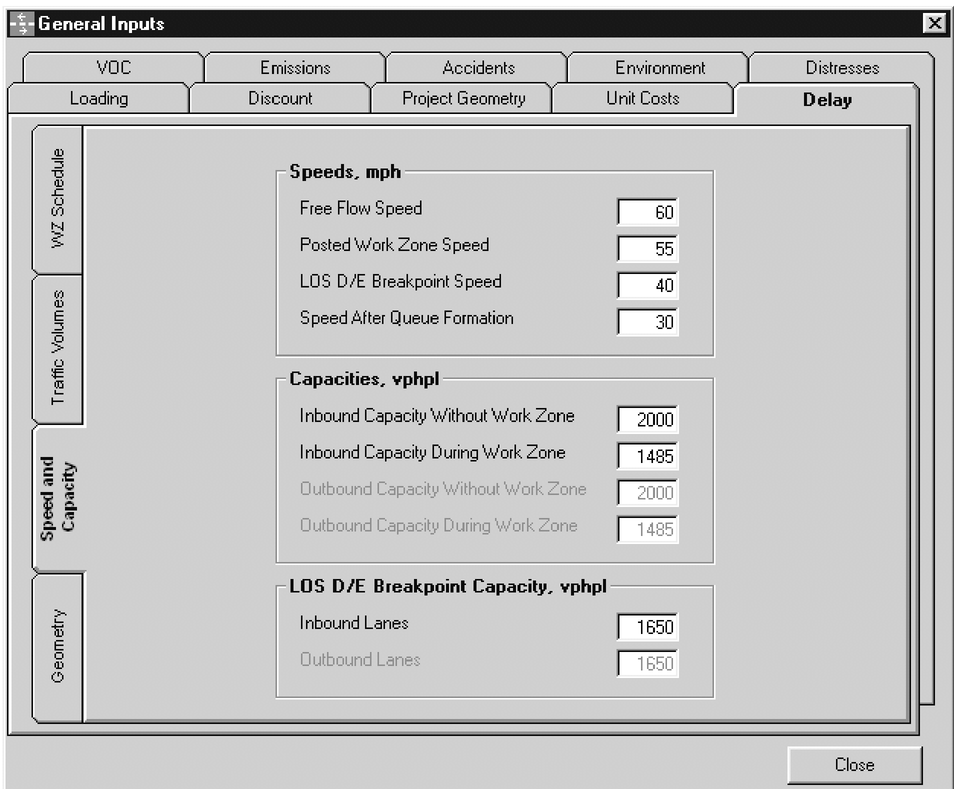


Illustration 9.6. Speed and Capacity in and around Work Zones

The prevailing speeds and restricted speeds, along with free flow and work zone lane capacities, are entered in this screen. The free flow speed is the speed at which traffic flows under normal conditions (i.e., without a work zone present). This can also be a posted speed limit. "Level of Service D/E" breakpoint speed is the speed at which the level of service degenerates from LOS D to LOS E. The speed after queue formation describes the speed of vehicles in a queue. This speed can greatly affect the calculation of user costs, since the time delay costs are determined by the time required to travel through the work zone.

The capacity of each lane is described as "Without Work Zone," "During Work Zone," and "LOS D/E Breakpoint Capacity." These capacities refer to the free flow capacity, restricted capacity during a work zone (based on References 22 and 68), and the capacity at the point where the level of service degenerates from LOS D to LOS E, respectively.

The traffic volumes that can be expected for the first year are entered in the screen shown in Illustration 9.7. The program requires hourly volumes in order to determine queue lengths and work zone speeds. These values can be entered in two ways. The expected ADT can be entered along with the functional class to fill the hourly volumes with a standard hourly distribution for the particular functional class. The engineer can also override the hourly values by entering them directly in the appropriate hour.

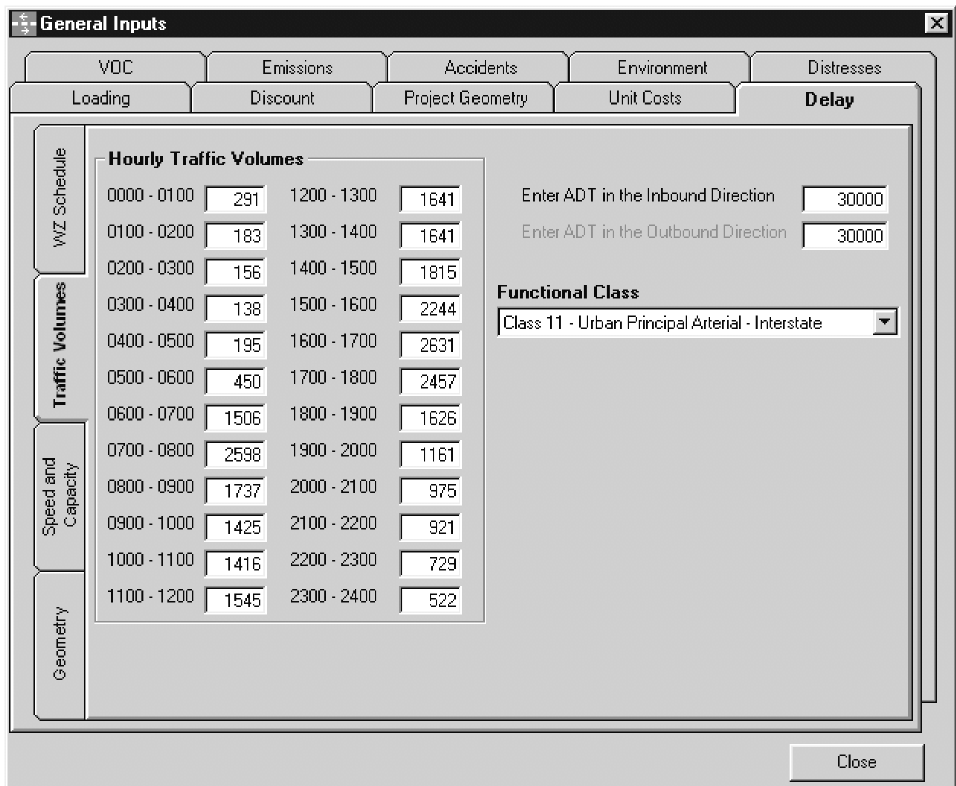


Illustration 9.7. Traffic Volumes

The screen shown in Illustration 9.8 simply takes the time that traffic control is set up and removed, and the time that construction work actually begins and ends. The times requested in this screen must be in 24-hour military standard time. During work zones in which the traffic control devices remain for an extended period of time, these values are ignored, since the work zone is in place every hour of the day.

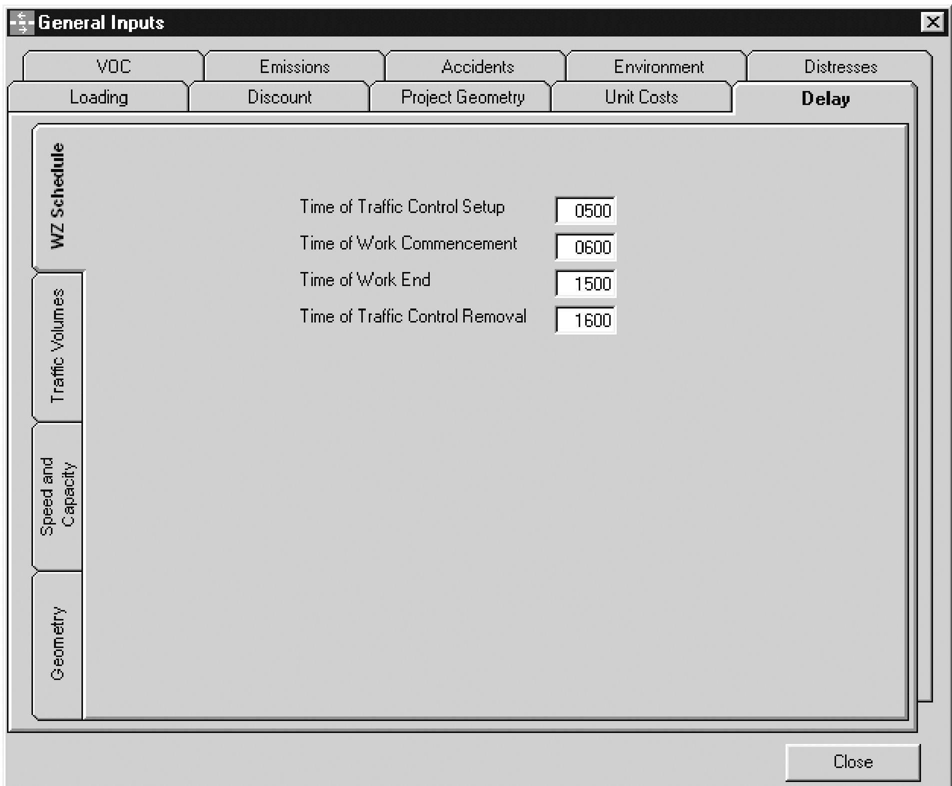


Illustration 9.8. Work Zone Schedule

The screen shown in Illustration 9.9 requires the user to enter present values for the various items relating to the calculation of vehicle operating costs. The costs are separated into categories of "Cars" and "Trucks," since each type of vehicle consumes these items at different rates.

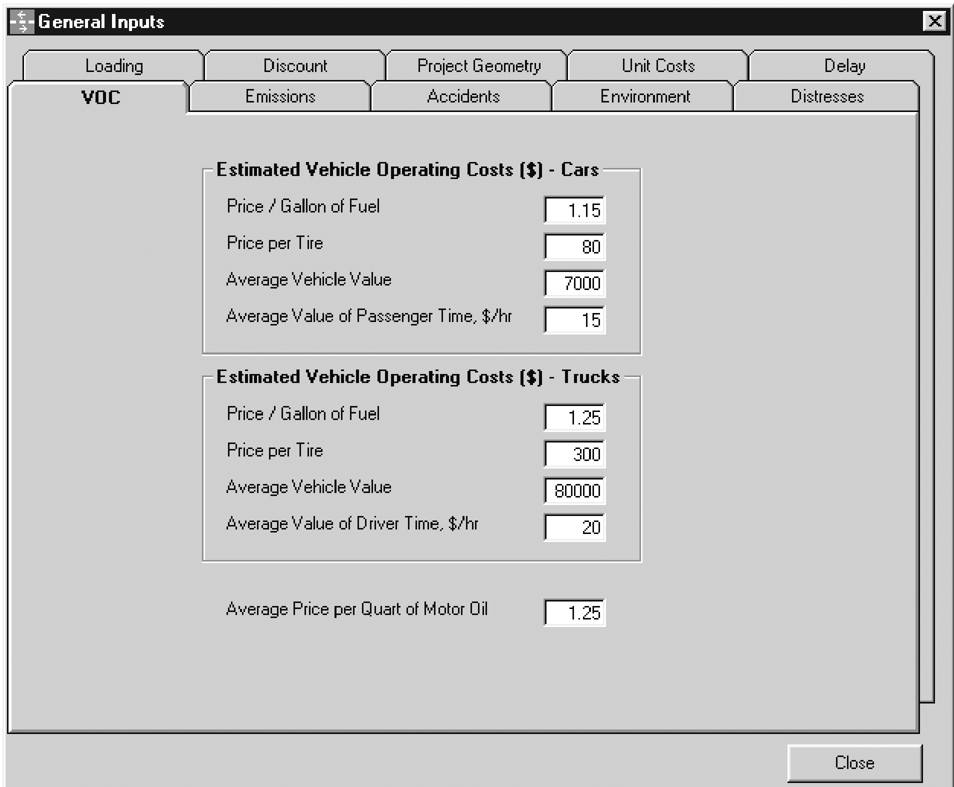


Illustration 9.9. Unit Costs of Vehicle Consumption Items

Current prices for motor fuel, tires, and average vehicle values are required, along with the value of driver and passenger time. Fuel and tire prices may be input using current prices found "at the pump" and at tire service centers, as can the cost of a quart of oil. Since the same types of oil are used for both cars and trucks, only one value is used in the program. The average value of vehicles on the street can be predicted considering average age, purchase price, and depreciation rates.

The value of passenger and driver time differs greatly between passenger cars and commercial trucks. For cars, this value is defined as the average hourly rate earned by the local population. One source for this information is the local chamber of commerce. For truck drivers, the value of time should depend on the type of highway and the predominant mix of truck traffic. For interstate highways with high volumes of cross-country truck traffic, a national value should be used for the value of time, whereas for local highways having fewer interstate trucks, a local value should be used. This input should also consider not only the truck driver's hourly rate, but also the trucking company's operational cost per hour.

The screen shown in Illustration 9.10 allows the user to change the average rates of emissions produced by cars and trucks. These values are measured in grams per hour for each type of emission and for each type of vehicle. Excess amounts of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) are predicted. These values have been determined through extensive research and should not be changed by the engineer unless reliable information is provided regarding updated values to be used in these fields.

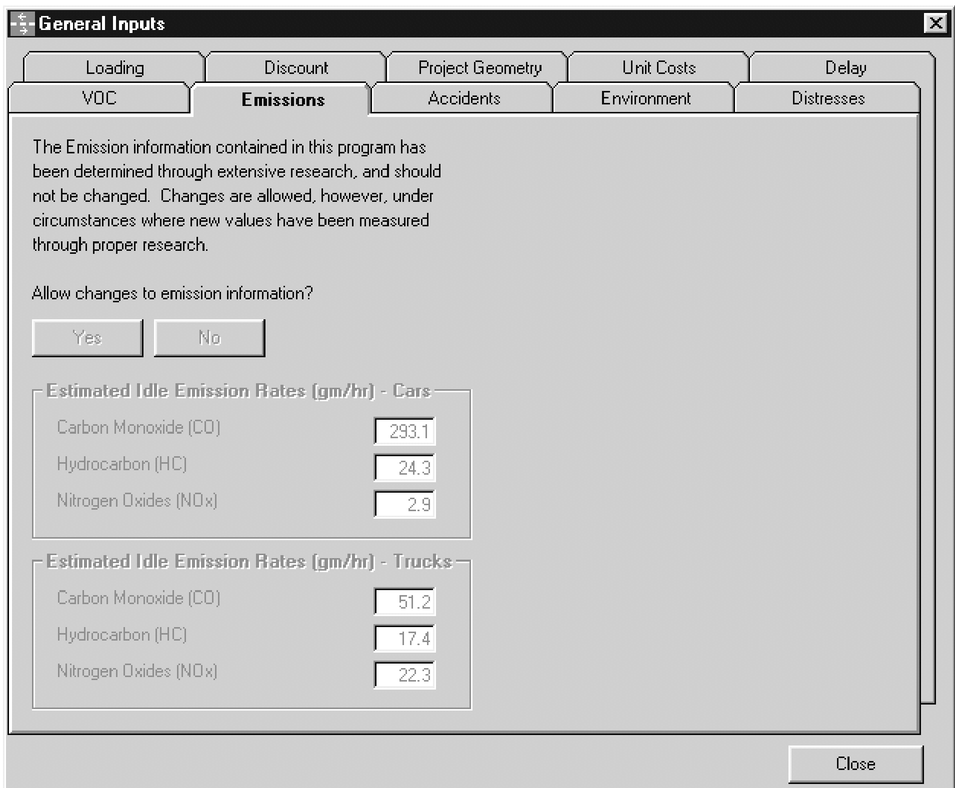


Illustration 9.10. Emission Rates

The screen shown in Illustration 9.11 requires the engineer to input the average accident rate per 100 million vehicle miles traveled under normal driving conditions and the rate for work zones. National accident rates are available (Refs 30 and 41), while several of the references in Section 7.6 describe increased rates of accidents at work zones.

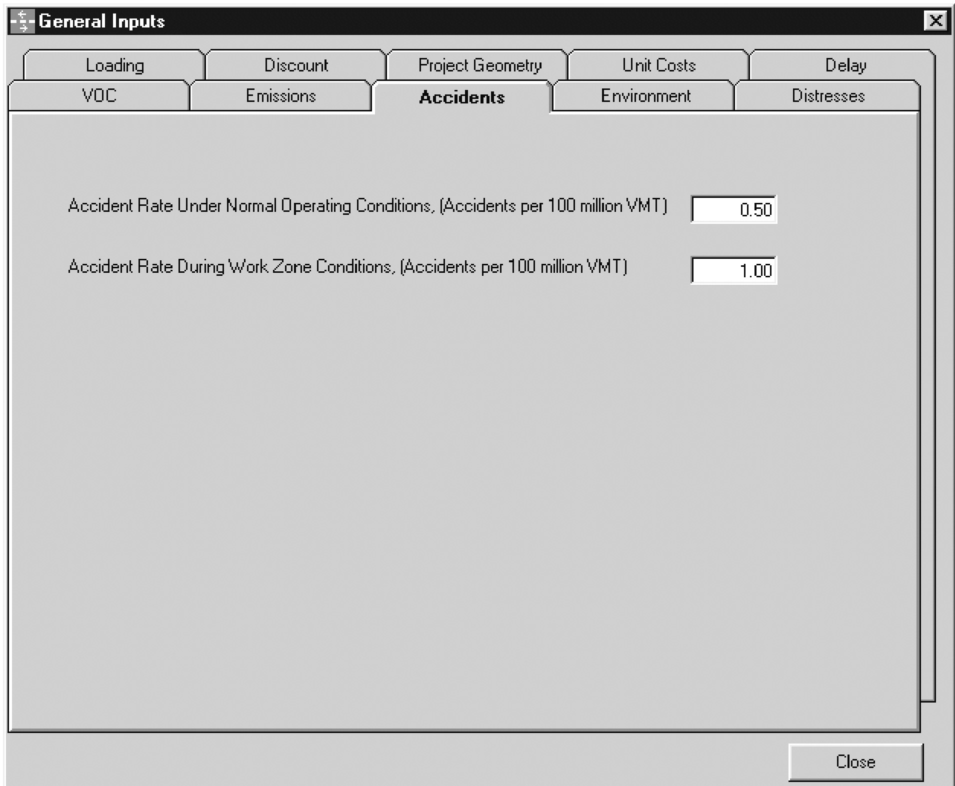


Illustration 9.11. Accident Rates

Environmental parameters affect the performance of concrete throughout the life of the pavement as well as during the first few days following its construction. The minimum and maximum annual temperatures are entered in the screen shown in Illustration 9.12, as well at the average low temperatures for the 28 days immediately following construction. In addition to the ambient temperatures, the number of freeze-thaw cycles per year and the average rainfall must be provided for the current performance models to predict the future pavement distresses that can be expected. Since pavement performance is highly correlated with environmental parameters, it is expected that future models will require environmental parameters other than only those listed. Thus, ample space is provided in this screen for future additions to the environmental parameters.

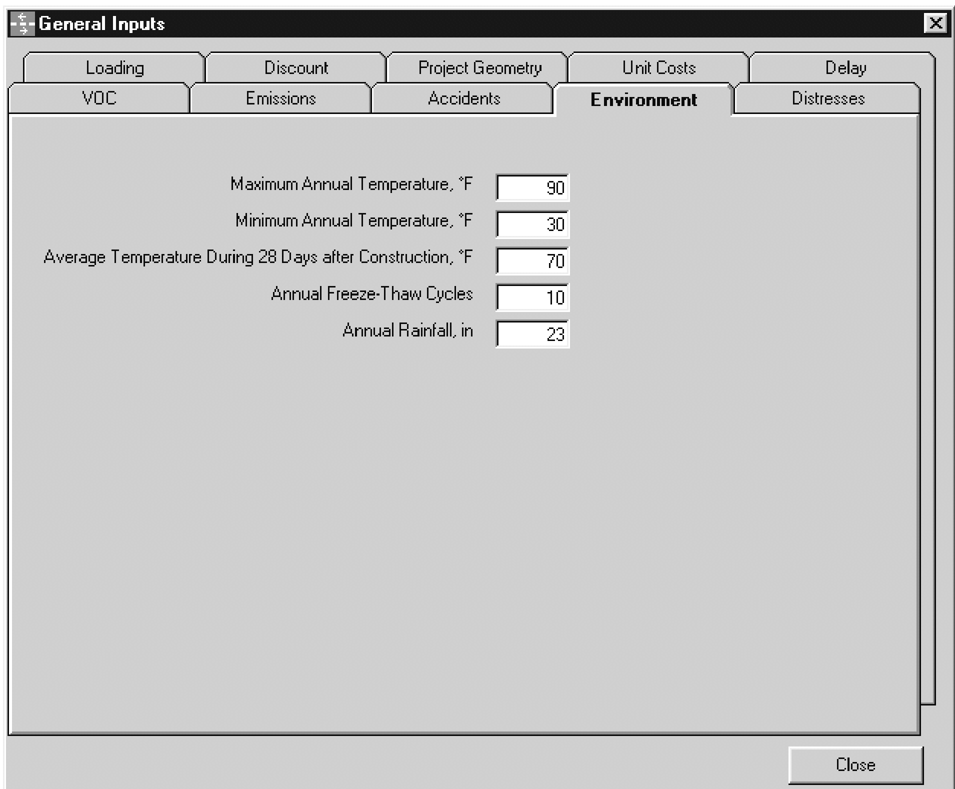


Illustration 9.12. Environmental Parameters

The pavement performance models predict the number of distresses in each category that will occur during any given year. The screen shown in Illustration 9.13 contains the allowable limits for each distress that are set by individual agencies. When the performance models predict distress levels greater than the limits set by the engineer, the program calls the maintenance and rehabilitation routines to repair the distresses. The distresses analyzed, and whose limits are entered in this screen, are faulting, spalling, transverse cracking, punchouts, and the minimum present serviceability index.

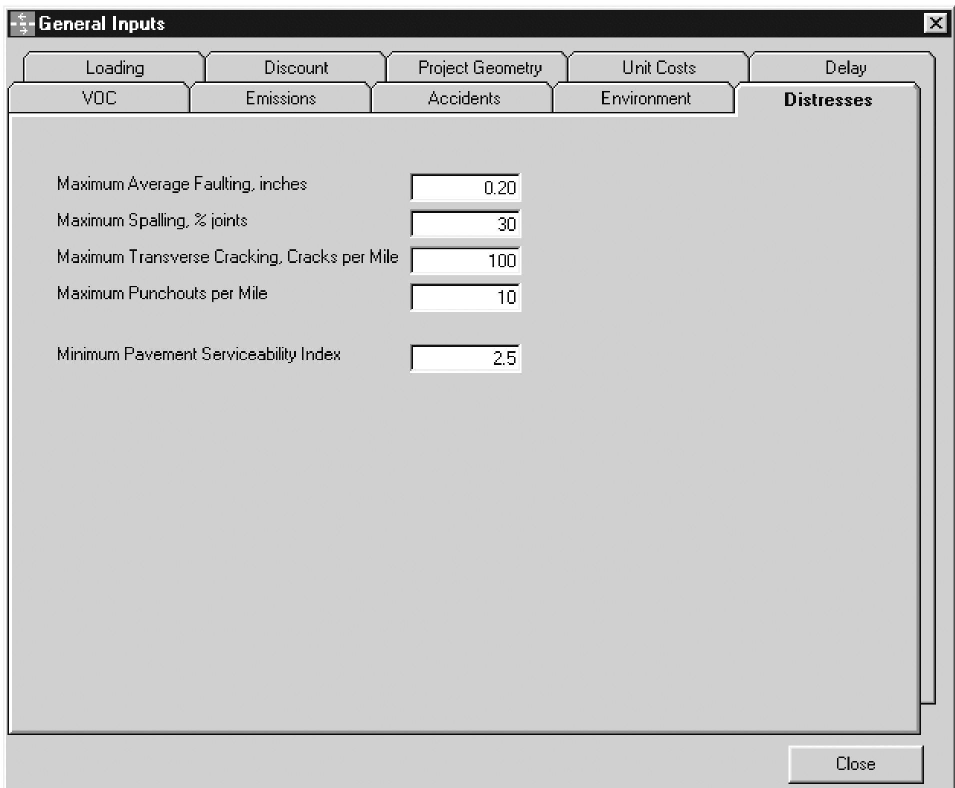


Illustration 9.13. Pavement Distress Limits

9.2.3 Performance Model Override

While the intent of the life cycle cost analysis framework is to predict the timing of maintenance and rehabilitation activities based on pavement performance models, it is not reasonable to expect the performance models to predict well under all circumstances and with any range of inputs. In such cases, and in the case of poorly performing distress prediction models, the screen shown in Illustration 9.14 is available. This screen is shown to the user alternately with the distress limits input screen. When the checkbox in the main analysis window is checked, the preprogrammed maintenance and rehabilitation inputs are shown. When this box is not checked, the distress limits screen is shown. When using the preprogrammed strategies, many of the previously described inputs are not required. For example, the pavement loading and environmental parameters are not used. Also, none of the inputs in the individual alternatives screens are required, with the exception of the material costs. The other inputs, concerning user costs, accidents, unit construction costs and production rates, however, are all used in calculating the costs and effects of the preprogrammed maintenance and rehabilitation activities.

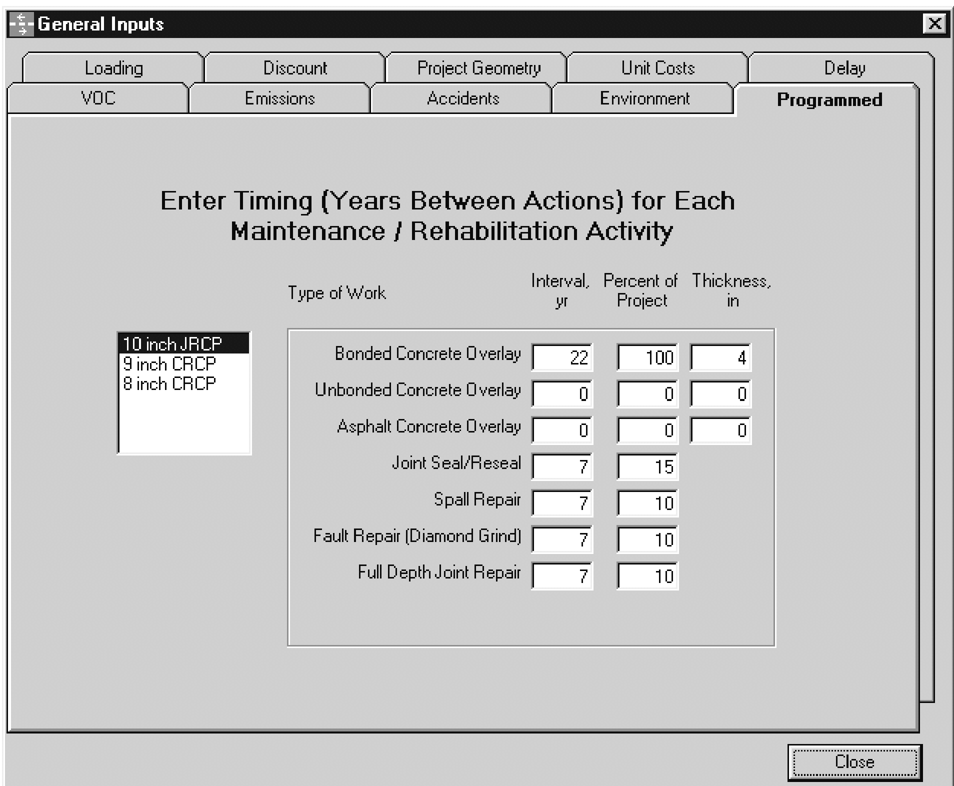


Illustration 9.14. Programmed Maintenance and Rehabilitation Inputs

If the user chooses to preprogram the maintenance and rehabilitation activities, the desired strategy can be defined for each existing alternative. The interval, expressed in years between a specific activity, is entered in the first column, followed by the extents to which the activity is estimated to be required (meaning the fraction of the project area or the joints in the project, etc.). For example, in the illustration above, it is expected that every 7 years the following activities will be required for the jointed concrete pavement alternative:

- Joint Sealing, 20%,
- Spall Repairs, 15%,

- Fault Repairs, 15%,
- Full-Depth Joint Repairs, 10%.

During the analysis, after the appropriate time interval for each programmed item, a work zone and maintenance or rehabilitation activity is triggered. The analysis then computes the construction cost and the associated user costs and other options chosen by the user.

The next section discusses the inputs that are unique to each alternative. These inputs are necessary for the full performance-based analysis, but are not required for the programmed maintenance analysis.

9.2.4 Design-Level Inputs

The previous section discussed inputs that are identical to all alternate designs analyzed by the program. This section, however, outlines the specific inputs that may be different for any design, such as pavement structure and reinforcement, rehabilitation options, and construction and variability parameters.

The "General Inputs" tab in the "Alternative" window (shown in Illustration 9.15) displays basic information regarding the design alternative.

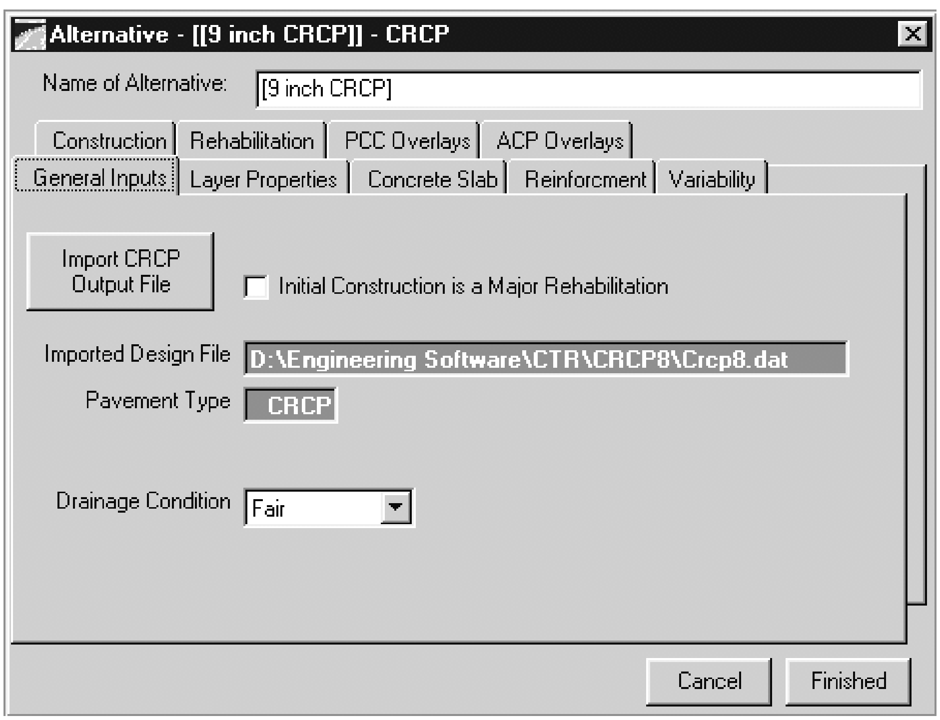


Illustration 9.15. General Design Inputs

From this tab an output file can be imported from either the CRCP-8 or JRCP-6 computer programs developed at the Center for Transportation Research. This helps avoid duplicating data entry by extracting all the inputs that were entered for the CRCP-8 or JRCP-6 analysis. If a design file has been imported, the name and location of the file is listed in this window, along with the pavement type. Finally, the overall drainage condition for the project segment is chosen here, which affects inputs into the AASHTO rigid pavement design equation. In this screen, as in all screens in the design alternative window, the name of the alternative can be edited.

The screen shown in Illustration 9.16, "Layer Properties," shows the pavement structure and the materials used in the construction. At the bottom of the screen, the number of layers in the pavement structure can be selected, which displays the appropriate number of layers in the window above it. By clicking on a specific material type, the Materials Database window will open, from which material descriptions can be edited, new materials entered, and materials dragged and dropped into the material type column at the appropriate layer. Once the materials are in place that describe the elastic modulus and cost per cubic yard, the thickness of each layer can be changed to represent the pavement structure. Also in this screen, the modulus of subgrade reaction is entered. This screen also shows the total cost of the pavement structure, as calculated by the program from the cost per cubic yard for each material, and the thickness of each layer.

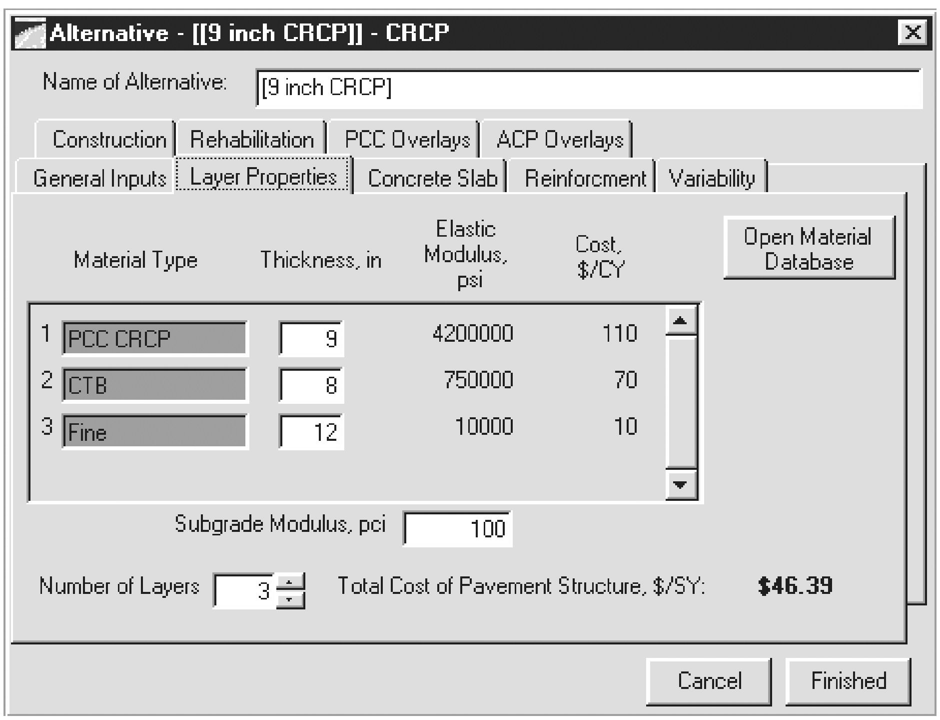


Illustration 9.16. Pavement Structure

The "Concrete Slab" screen shown in Illustration 9.17 displays the properties of the concrete slab, as well as the fatigue coefficients and the friction characteristics of the slab and the base layer. The inputs required here are as follows:

- ultimate concrete drying shrinkage,
- concrete coefficient of thermal expansion,
- concrete tensile strength,
- concrete flexural strength,
- concrete compressive strength,
- the fatigue coefficients A and B, used in the CRCP-8 analysis, and
- the friction characteristics at the slab-base interface, which include the movement of the slab when it begins to slide, and the maximum friction force at that point.

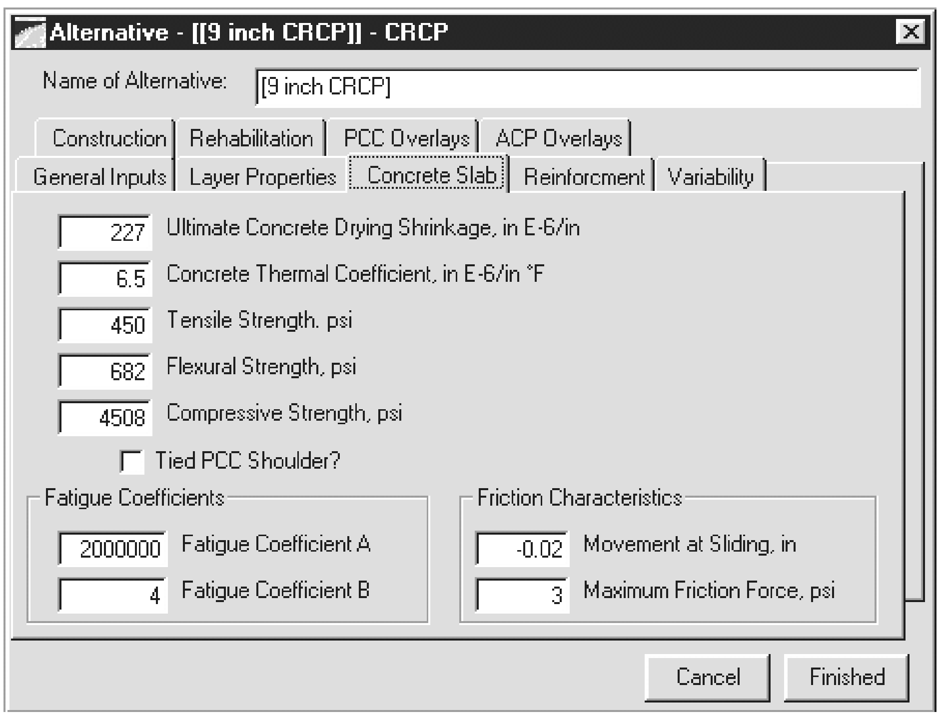


Illustration 9.17. Concrete Properties

The screen shown in Illustration 9.18 requires the engineer to input the reinforcement design for the pavement. This includes the percent steel in both the longitudinal and transverse reinforcement, as well as bar diameters and the steel yield stress. For jointed concrete pavements, the joint spacing and the dowel diameter must be entered.

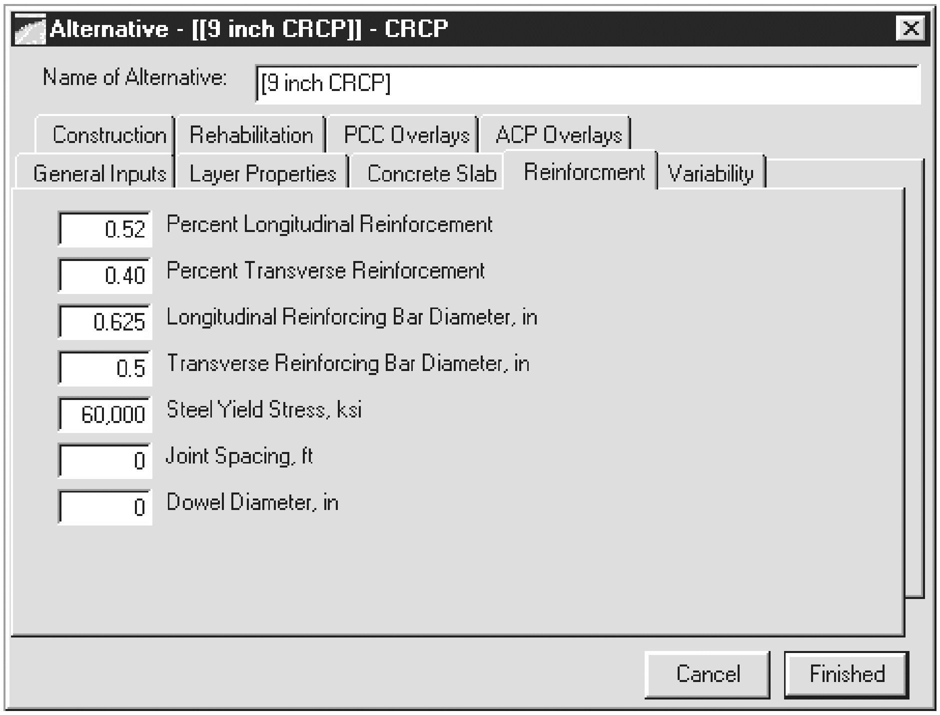


Illustration 9.18. Reinforcement Design

The "Variability" screen shown in Illustration 9.19 requires the user to input the coefficient of variation in the four parameters listed above. These are: concrete tensile strength, slab thickness, surface roughness, and the variation in distress modeling. The coefficient of variation is found by dividing the standard deviation of a parameter by its mean, as shown below:

$$COV = \frac{\sigma}{\mu} \qquad (9.a)$$

where:

COV	=	coefficient of variation,
σ	=	standard deviation, and
μ	=	mean.

The performance models use these coefficients of variation to provide reliability in the overall life cycle cost of each design alternative.

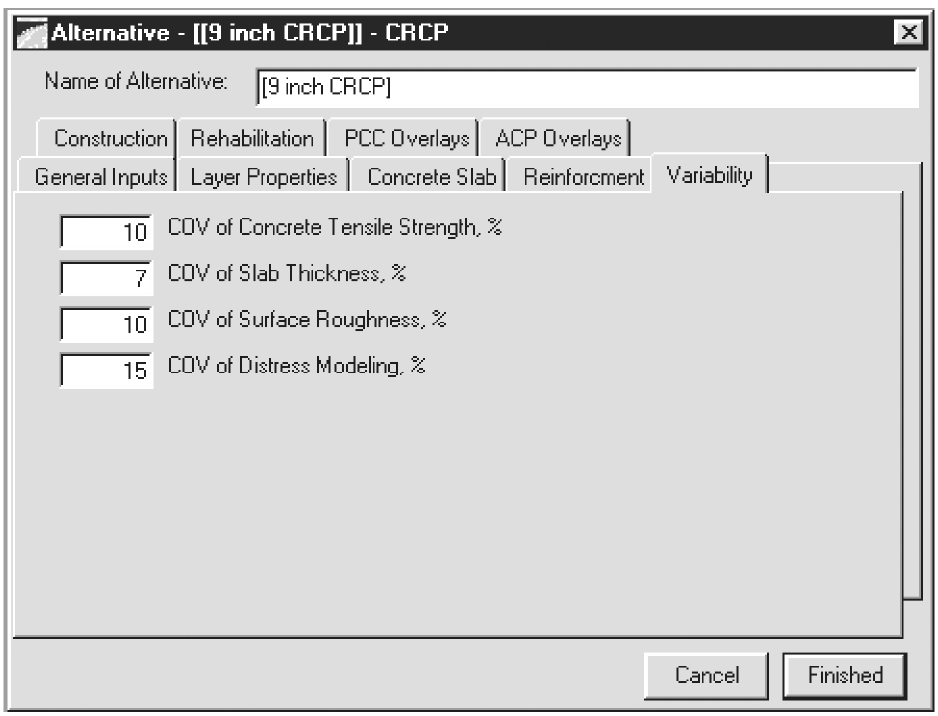


Illustration 9.19. Variability in Design Components

The inputs required on the screen shown in Illustration 9.20 are used to predict the strength and the stresses occurring in the concrete pavement during the first few days after its construction. It is here that the effects of fast-track paving and other expedited construction practices are modeled. The time until traffic is applied is important, since failing to provide adequate curing time before construction traffic is applied can significantly reduce the fatigue life of the pavement.

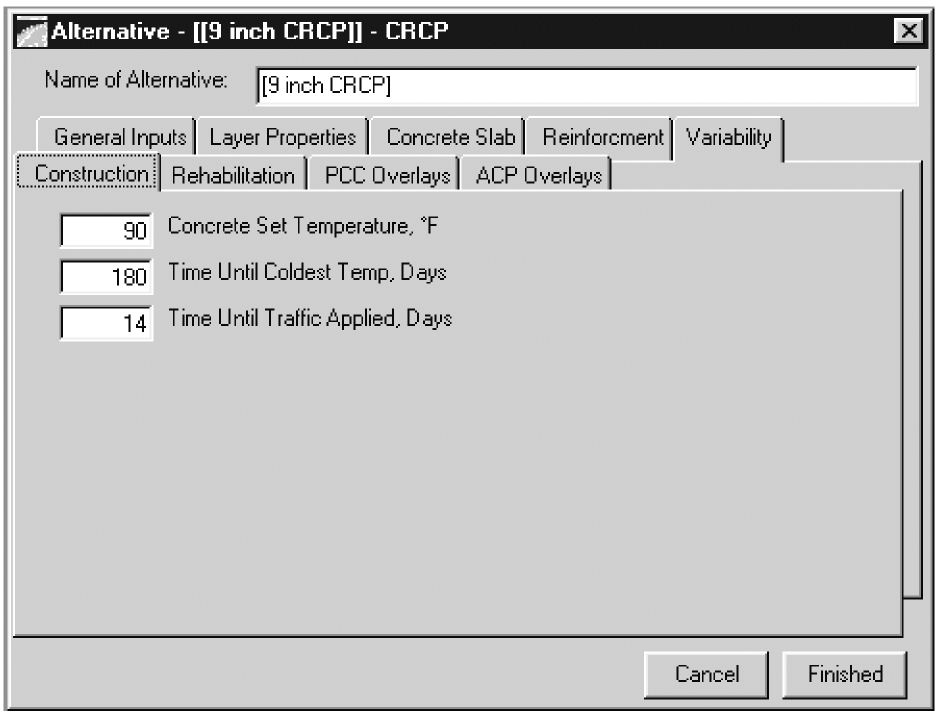


Illustration 9.20. Construction Related Parameters

The concrete set temperature and the time until the lowest temperature of the year occurs are also important during the first year after construction. The set temperature becomes the basis for measuring the contraction or expansion of the concrete with temperature. If the concrete set temperature is too high, the temperature drop associated with the first winter may cause unacceptable cracking to occur in the concrete. If the lowest temperature of the year occurs too soon after placement, the concrete may not have time to reach its ultimate strength at the same time that the stresses are reaching their maximum, which may cause excessive cracking.

The general rehabilitation inputs that must be entered include the estimated stiffness of the concrete after it has cracked excessively, the minimum time required between overlays, the maximum time allowable for heavy maintenance before overlay action is taken, the minimum remaining life of the pavement before overlay action is taken, and the maximum total overlay thickness. These inputs describe the general boundaries set by the engineer for overlay design, within which the framework, and the computer program, must work. The local agency can mold the output of the program by defining its rehabilitation strategy in these inputs.

The bottom portion of the screen shown in Illustration 9.21 is a user preference to consider unbonded PCC overlays or to consider only bonded concrete overlays. Other overlay choices will be given in the next two screens.

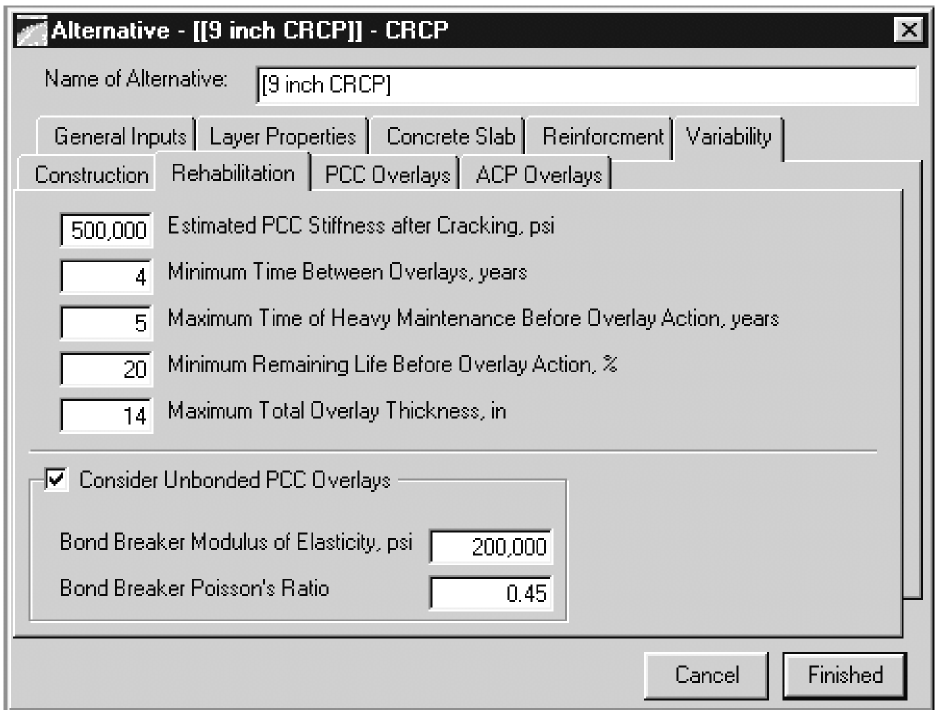


Illustration 9.21. General Rehabilitation Inputs

The screen shown in Illustration 9.22 details the specific inputs for portland cement concrete overlays. The first input on this screen is a check asking whether to consider the use of PCC overlays in the design routines. If so, the engineer must input a trial PCC overlay thickness. This trial value will be used, and the life of the overlay, using the other inputs provided, will be determined. If this value is inadequate, or more than adequate, the routine will attempt another thickness close in value to the trial value supplied by the engineer.

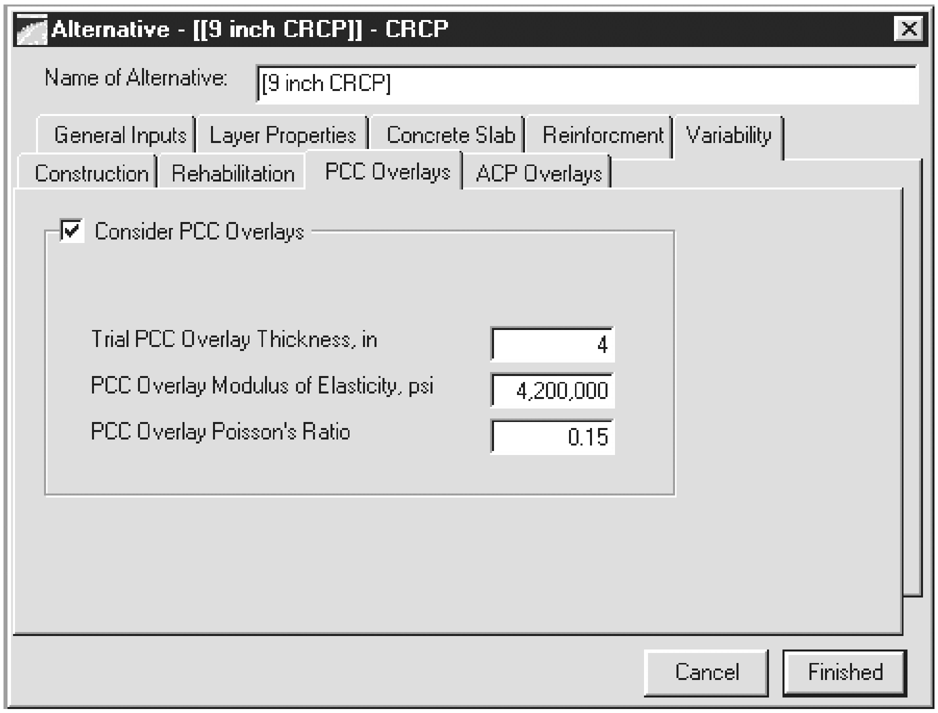


Illustration 9.22. PCC Specific Overlay Inputs

The other two inputs required here are the elastic modulus and the Poisson's ratio of the concrete to be used. These values are used in the layered elastic routines included in the overlay design module that is used in this program.

The screen shown in Illustration 9.23 is identical to the previous screen for PCC overlays. The choice of considering asphalt concrete pavement overlays is provided, and if this is selected, the trial overlay thickness is required. Also input by the engineer are the elastic modulus of the asphalt and the Poisson's ratio.

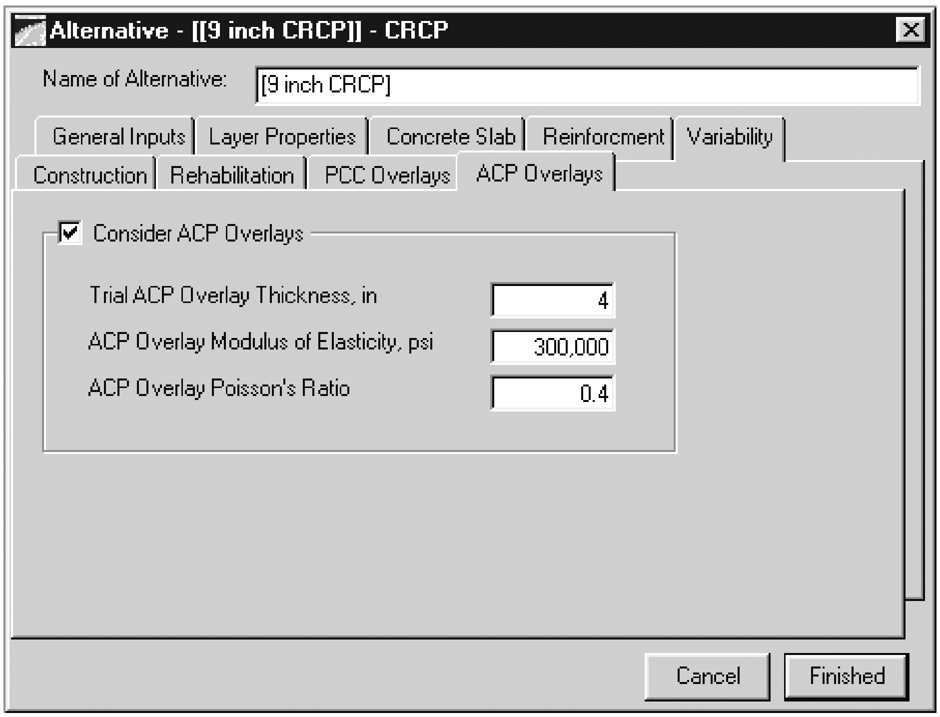
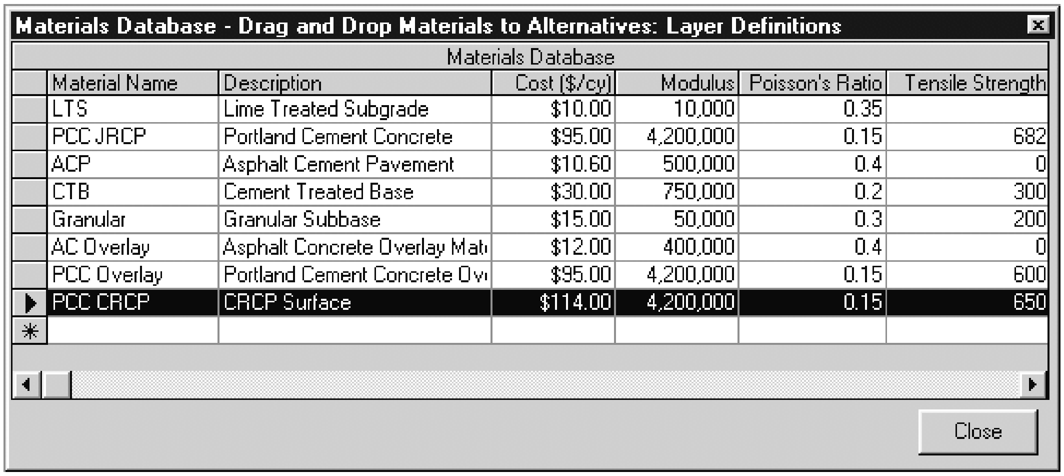


Illustration 9.23. ACP Specific Overlay Inputs

9.2.5 Materials Database

The material database was included in the RPLCCA computer program to provide a way to organize the different materials that are used for various analyses. The screen shown in Illustration 9.24 displays some of the materials in the database and the properties associated with each one. The database can be filled with materials available to the local engineer, thus further customizing the RPLCCA program to the local environment.



Materials Database - Drag and Drop Materials to Alternatives: Layer Definitions

Material Name	Description	Cost ($/cy)	Modulus	Poisson's Ratio	Tensile Strength
LTS	Lime Treated Subgrade	$10.00	10,000	0.35	
PCC JRCP	Portland Cement Concrete	$95.00	4,200,000	0.15	682
ACP	Asphalt Cement Pavement	$10.60	500,000	0.4	0
CTB	Cement Treated Base	$30.00	750,000	0.2	300
Granular	Granular Subbase	$15.00	50,000	0.3	200
AC Overlay	Asphalt Concrete Overlay Mat	$12.00	400,000	0.4	0
PCC Overlay	Portland Cement Concrete Ov	$95.00	4,200,000	0.15	600
PCC CRCP	CRCP Surface	$114.00	4,200,000	0.15	650

Close

Illustration 9.24. Materials Database

The individual materials listed in the rows of this database can be dragged from this window to the layer definitions in the "Alternatives" window. The drag-and-drop operation places the cost, elastic modulus, Poisson's ratio, and tensile strength values in the appropriate fields in the "Alternatives" window.

The materials database can be accessed either from the "Alternatives" window or from the main menu bar in the RPLCCA main window. The database window can be viewed at all times during analysis preparation and execution.

9.3 RPLCCA OUTPUTS

After commencing the analysis, the program displays the screen shown in Illustration 9.25 to update its progress. The time required to perform the analysis depends on the type of computer, number of alternate designs, and pavement types. This section details the analysis progress and the outputs produced by the RPLCCA program.

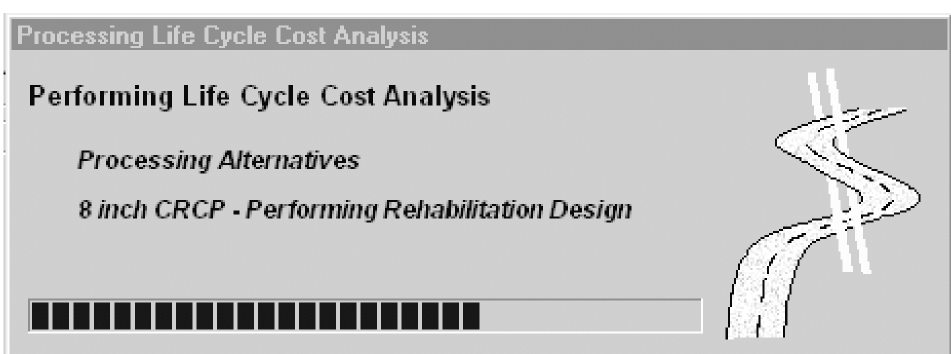


Illustration 9.25. Analysis Execution Progress Screen

The window shown in Illustration 9.26 provides the current status of the program to the user and, as shown, allows interaction with the user by giving a selection of different overlays from which to choose. The user can press "Compute Construction and User Costs" to extend the analysis from the current year to the end of the analysis period. This is not done automatically, since the computation can require significant computer time. The extra information can be computed, however, to improve the decision-making process. The information shown in the spreadsheet in this screen can be sorted by any column simply by clicking the header for the desired column. Once a desired overlay strategy has been determined, the user must highlight the particular row, and press "Choose Selected Strategy" to continue the analysis to the end of the analysis period.

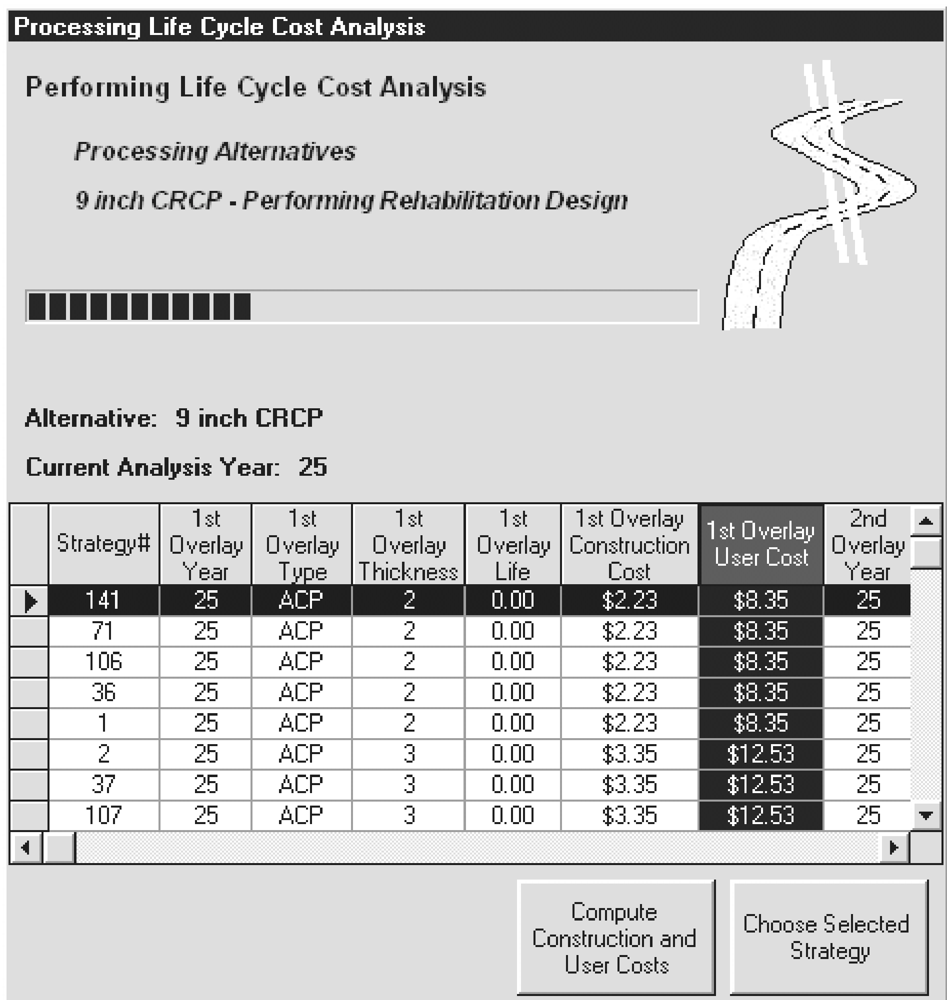


Illustration 9.26. Overlay Strategy Selection Screen

The window shown in Illustration 9.27 allows the user to see the various distresses that are modeled by the RPLCCA program over time. The example in the illustration shows the development of punchouts in the "9 inch CRCP" alternative, over the entire analysis period. The distresses that are available in this window are faulting, spalling, transverse cracking and present serviceability index for jointed concrete pavements; and punchouts, cracking and present serviceability index for continuously reinforced concrete pavements. As can be seen, in the distresses that are repaired whenever they reach the limits set by the engineer, in this case ten punchouts per mile, the level of distress is reduced and the condition of the pavement is restored. The PSI value in this window, however, is not restored when routine maintenance activities occur. This value is restored only when major rehabilitation is undertaken. When an overlay is placed on the pavement, the PSI is restored to its original value, though it tends to decrease more quickly than it did before at the same level.

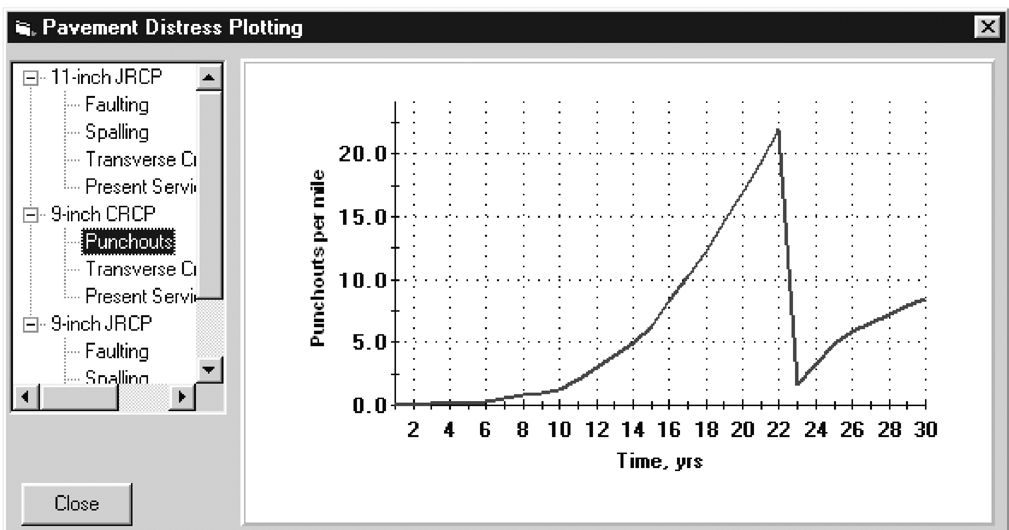


Illustration 9.27. Pavement Distresses vs. Time

The total life cycle cost of each design alternative can be seen in these two screens below. The graph in Illustration 9.28 shows the total life cycle cost of each design, in addition to the variability in the total cost. The variability in the total cost is based on the reliability concepts described in Chapter 8 and the level of confidence provided by the user in the main analysis screen. Illustration 9.29 shows the same total life cycle cost information but with the addition of the calculated user costs.

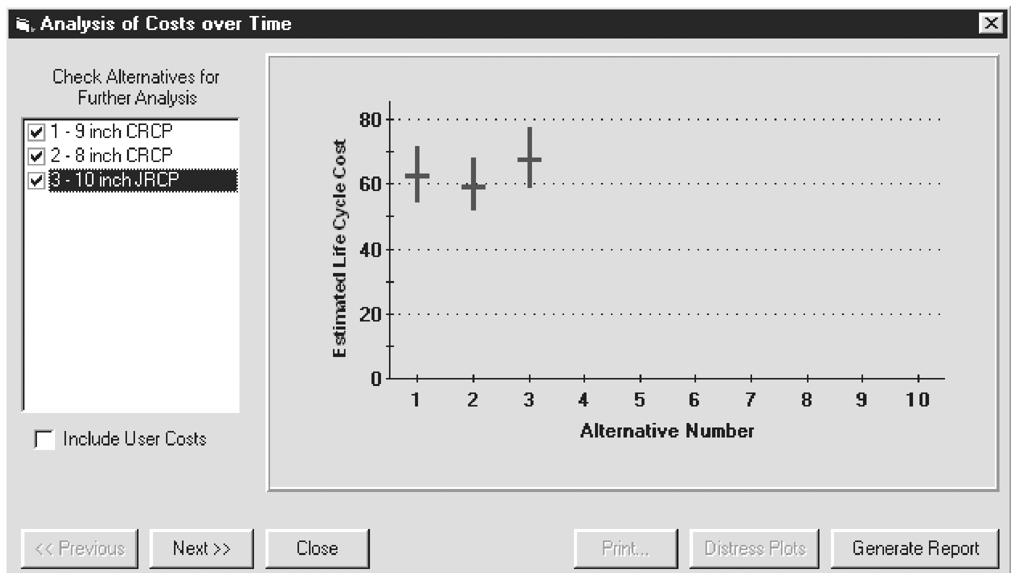


Illustration 9.28. Ranking of Alternatives: Total Life Cycle Cost Ignoring User Costs

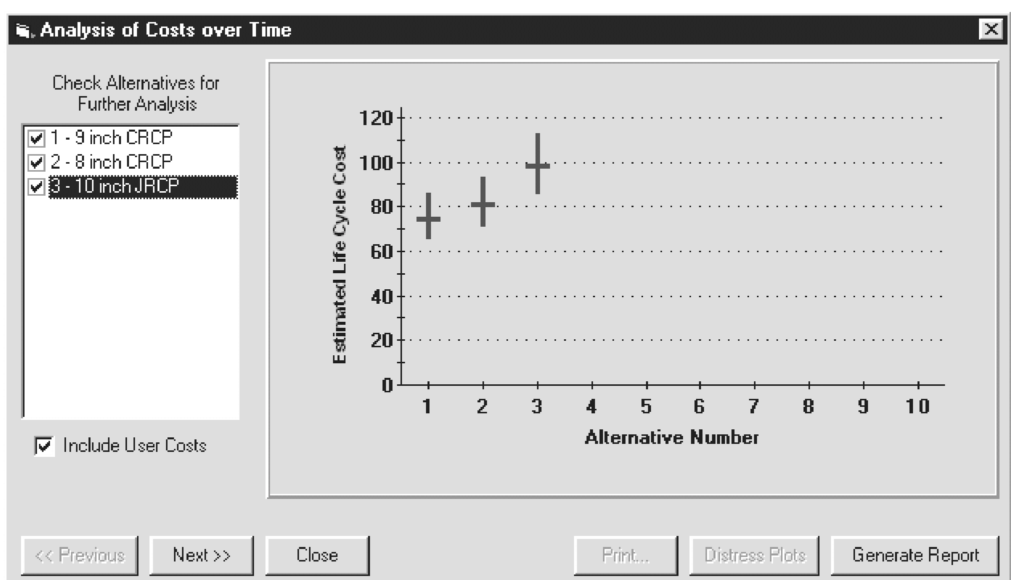


Illustration 9.29. Ranking of Alternatives: Total Life Cycle Cost Including User Costs

These two screens indicate the large influence that user costs can have on the total cost to both the agency and to society. The total costs shown in Illustration 9.29 actually underestimate the user costs, since only delay and vehicle operating costs are included. As more types of user costs are more readily evaluated, the total life cycle costs will increase for those alternatives that require many work zone-related construction activities.

This measure of the life cycle cost represents the total present value of the project. The screen shown in Illustration 9.30 gives the annual cumulative life cycle cost. Each year, the total costs are summed for the work performed during the year and the user costs incurred owing to that work, and the value is discounted to the present. The discounted value is then shown in this cumulative graph. As in the two previous illustrations, Illustrations 9.30 and 9.31 show the difference between the cumulative annual life cycle cost with and without user costs added. The effects of user costs are obvious in these graphs. Each time maintenance or rehabilitation work is performed, the costs incurred by the traveling public grow substantially.

It can be seen in these graphs that the initial cost of the pavement structure is not necessarily indicative of the final present value of the project. Even when user costs are removed from the analysis, often the total life cycle cost can affect a decision that might have been made using only initial costs.

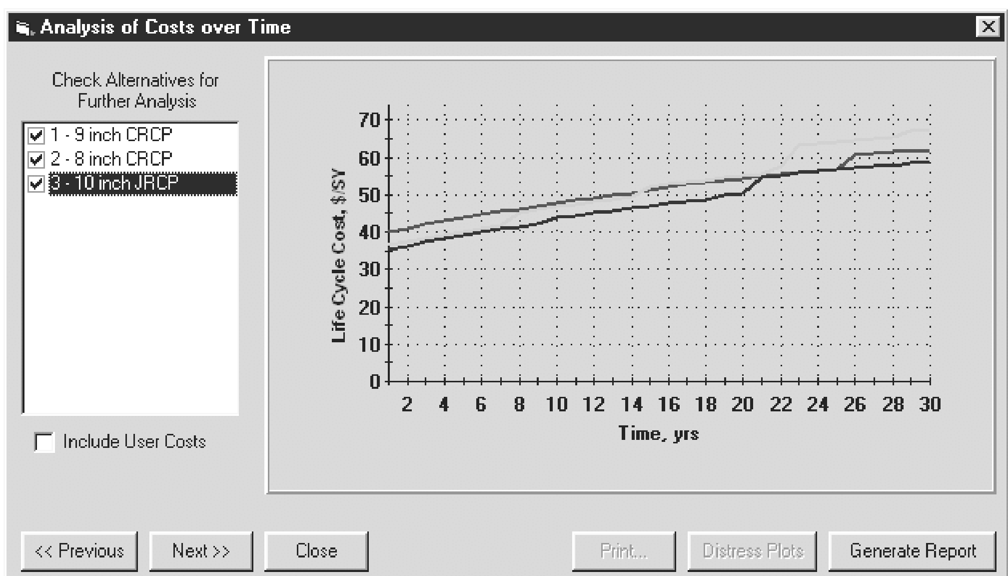


Illustration 9.30. Ranking of Alternatives: Annual Cumulative Life Cycle Cost, without User Costs

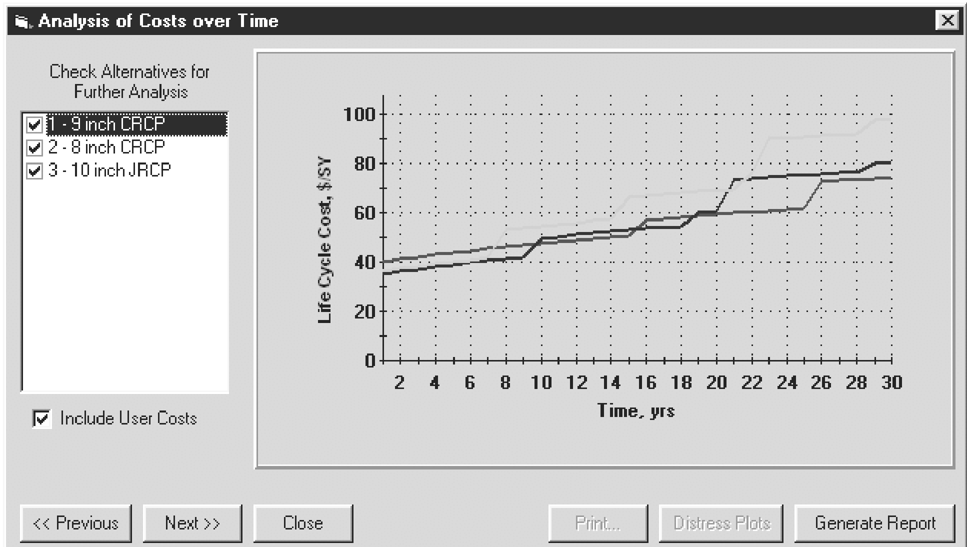
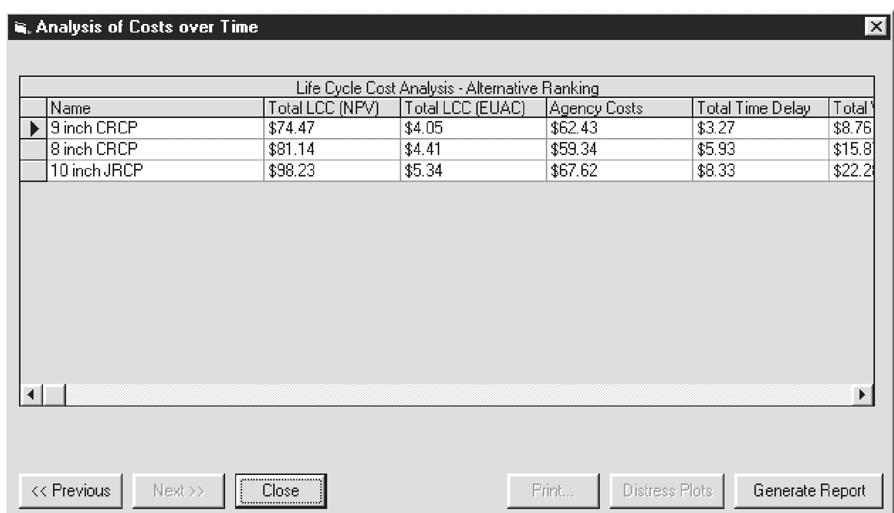


Illustration 9.31. Ranking of Alternatives: Annual Cumulative Life Cycle Cost, without User Costs

The tabular screen is accessed by clicking on "Next" in the alternative ranking window. The screen shown in Illustration 9.32 displays the total cost of individual components. It also shows the magnitude of components that are not valuated, such as emissions and accidents. Using this tabulation, in conjunction with the perspective offered by the two previous screens showing different views of the life cycle cost of each alternate design, the engineer can make a more informed decision regarding the best design option for the highway pavement project.



Life Cycle Cost Analysis - Alternative Ranking

Name	Total LCC (NPV)	Total LCC (EUAC)	Agency Costs	Total Time Delay	Total
9 inch CRCP	$74.47	$4.05	$62.43	$3.27	$8.76
8 inch CRCP	$81.14	$4.41	$59.34	$5.93	$15.8
10 inch JRCP	$98.23	$5.34	$67.62	$8.33	$22.2

Illustration 9.32. Ranking of Alternatives: Tabular Format

The screen shown in Illustration 9.33 provides a report of all construction, maintenance, and rehabilitation activity predicted throughout the design life of the pavement. The values reported here are in currency per area of pavement.

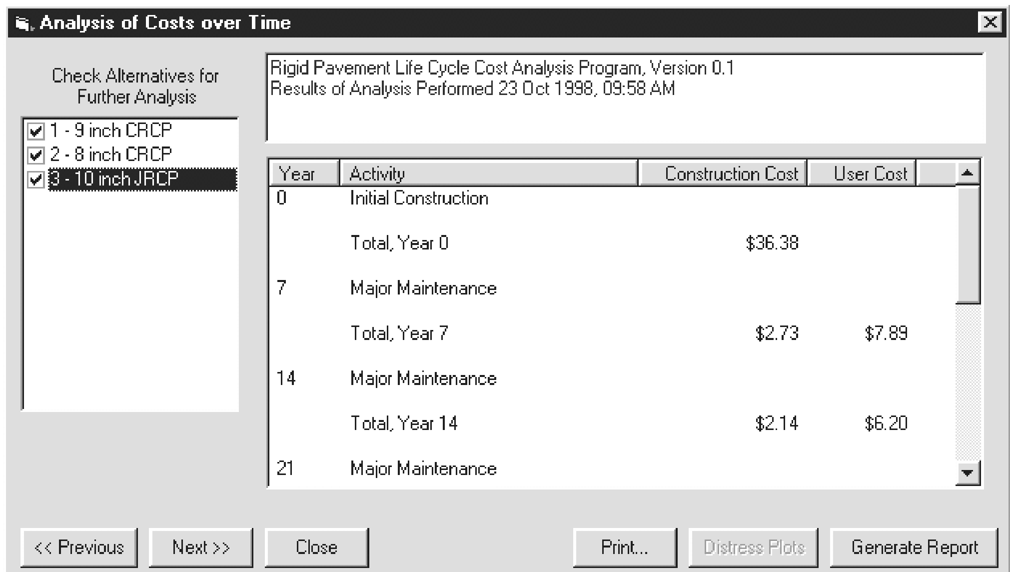


Illustration 9.33. Report of Outputs

In this particular analysis, the alternative named "10 inch JRCP" requires maintenance activities approximately every 7 years, as specified by the user in the previous screens. Illustration 9.34 shows the same screen, but shows the total life cycle cost for the alternative. In this case, the total discounted cost of construction is $44.79 per square yard, and the total discounted cost of calculated user costs is $26.83. The annual maintenance cost that is generated, as specified by the user in the "General Inputs" screens, is accumulated for all the years in which other maintenance or rehabilitation is not performed. The discounted cost of annual minor maintenance is $23.57, giving a total life cycle cost of $95.19. The same report is generated for all the alternatives, and the total life cycle cost can then be compared for each alternative.

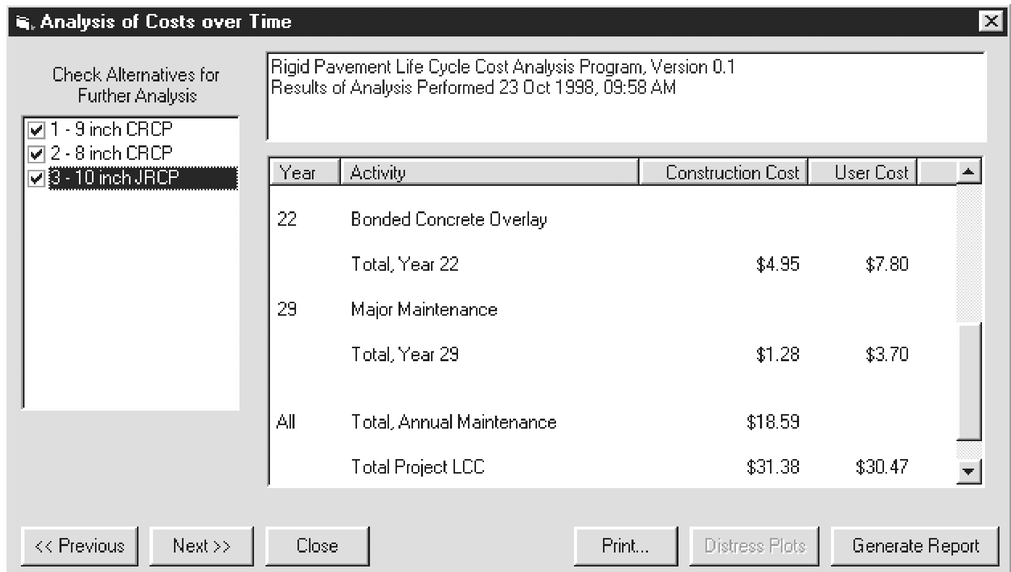


Illustration 9.34. Generated Output Report Showing Total Project LCC

9.4 SUMMARY OF RESULTS

The previous section illustrates the results of the analysis performed as an example for this chapter. Illustrations 9.33 and 9.34 show the annual costs for all construction, maintenance, rehabilitation, and user costs that are calculated over the pavement's design life. Table 9.1 shows the results of all three alternatives, a 10-inch jointed reinforced concrete pavement and two continuously reinforced concrete pavements, 8- and 9-inches thick.

Table 9.1. Comparison of Alternatives

Cost, $	10" JRCP	8" CRCP	9" CRCP
Initial Construction + Rehabilitation	49.18	40.94	44.04
Minor Maintenance	18.58	18.51	18.40
User	30.47	21.69	12.03
Total	98.23	81.14	74.47

In the table above, the analysis shows that between the two continuously reinforced alternatives, the 9-inch design is more expensive to construct and to rehabilitate, but the lower overall life cycle cost is apparent when user costs are considered. Looking at the maintenance schedule in the preprogrammed screen in Illustration 9.14, the reason for the lower user costs under the 9-inch CRCP alternative is that major maintenance is predicted to occur every 15 years, instead of every 9 years under the 8-inch CRCP alternative.

Comparing the continuously reinforced to the jointed reinforced concrete pavement, not only are the construction, maintenance, and rehabilitation costs greater than the two CRCP alternatives, but so are the user costs that are predicted for each of the major maintenance and rehabilitation activities. This comparison between the 10-inch JRCP and the 8-inch CRCP was made expressly to compare the results with actual agency costs experienced in the Houston District of the Texas Department of Transportation. After 30 years in service, two pavement sections with similar traffic, soil, and environmental conditions were compared based on historical construction and financial records. The two pavements were built within one year of each other, and one is 10 inches of jointed reinforced concrete pavement, while the other is 8 inches of continuously reinforced concrete pavement. Over the 30 years of service, the 10-inch JRCP had an average agency cost 16% greater than the average agency cost for the 8-inch CRCP. In the example calculation shown in the previous sections, the predicted agency cost for the 10-inch JRCP has an agency cost that is 20% greater than the agency cost for the 8-inch CRCP.

The calculation of agency and user costs incurred over the life of a pavement are highly dependent not only on the unit costs provided by the engineer, but also on the production rates, maintenance and rehabilitation timing, and the extent of the project over which the preprogrammed maintenance will take place. If the engineer is satisfied with the distress prediction provided by the performance models, the timing and extents are not preset by the user and thus are eliminated from the input requirements.

The RPLCCA software package allows the user to perform a very detailed analysis, provided that all the required inputs are available and provided that the user can properly utilize them in the analysis. This also depends on the performance models and the level of confidence that the user places in the distresses predicted by the program. If the user is not satisfied with the predictions provided by the models, a simplified analysis can be performed by providing preprogrammed maintenance and rehabilitation intervals for specific distresses, and by defining the extent of the entire project over which the particular type of maintenance or rehabilitation will be performed.

CHAPTER 10. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Life cycle cost analysis is becoming a more important aspect of highway planning and pavement design. The Federal Highway Administration recommends such an analysis for large, federally funded projects, and is encouraging its use for all types of highway pavement projects. As pavement design and computer technology expand the resources and abilities to predict the behavior and performance of pavements, comprehensive life cycle cost analysis is becoming more readily available on all types of pavement projects.

The primary objective of this work was achieved by the development of a new, comprehensive methodology for performing a life cycle cost analysis that incorporates all components impacting the total cost of a pavement project. This methodology also facilitates the incorporation of new and improved components as they are made available in the future.

This work also accomplished the secondary objectives stated in the introductory chapter, the first of which was to identify the parameters related to pavement performance, deterioration rates, agency costs, and user costs. These factors are identified and evaluated in Chapters 4 through 8 of this report.

The secondary objectives included implementation of the most advanced models for pavement performance, agency cost calculation, and user cost calculation, and the development of a software package to implement the comprehensive life cycle cost analysis methodology. The methodology and the software application provide a significant improvement over current methodologies, using pavement performance models to predict the distress levels and ride quality of a pavement over time, subjected to a predicted level of traffic applications.

10.1 SUMMARY

The development of this comprehensive life cycle cost analysis methodology required that all aspects of pavement design and performance for the entire life of the pavement be considered during the planning stages of the project. The components that are included in the current framework are:

- pavement performance and distress, including new and rehabilitation construction activities,
- costs of construction, maintenance and rehabilitation,
- travel time delay,
- vehicle operating costs,
- emissions,
- accidents,
- discounting costs to the present time, and
- reliability.

Other possible components were considered that could be implemented into the framework in the future, when more reliable cost calculation techniques are developed. These components include vehicle and tire noise, accident costs, the social costs of reduced air quality, the effects of driver tension owing to stressful driving situations at work zones or rough pavement, and the effects of work zones on nearby businesses affected by traffic control measures.

The reliability component of the framework is very important. This component allows the highway project designer or planner to understand the probabilistic nature of the total life cycle costs of a particular design alternative. The probability of a specific level of costs can be determined with a certain level of confidence, thereby providing an additional tool that can be used to clarify difficult issues.

The Rigid Pavement Life Cycle Cost Analysis (RPLCCA) computer program was developed to implement the new framework discussed in this report. The program's components, described in Chapters 4 through 8, include pavement performance, rehabilitation, agency costs, user costs, discounting, and reliability. The program also maintains the modularity and expandability envisioned in the framework's development. This computer software package is described in detail in Chapter 9.

One weakness in the current application of the life cycle cost analysis methodology is that the performance models used, although they are the best currently available, do not predict distresses in pavements over time with great accuracy. We recommend that further research be conducted to develop better performing distress prediction models. Until such time, whenever a pavement designer or engineer is dissatisfied with the distress prediction models, a default method has been included in the software application. This method overrides the performance modeling and allows the user to use programmed maintenance and rehabilitation strategies. In this case, the software program functions in a way similar to most other life cycle cost analysis methodologies. It takes the maintenance and rehabilitation activities as preset by the user and calculates both the agency and user costs, after which it discounts these costs to the present. The need to use this overriding method should decrease in the future as new performance models are developed that better predict the performance and distress levels in pavements.

10.2 CONCLUSIONS

The development of this comprehensive life cycle cost analysis framework contributes to the idea that highway pavement projects affect not only the transportation agency's budget, but also the surrounding economy and air quality. This research promotes full-cost analysis when performing life cycle cost analysis by including components from all aspects of affected entities in the calculation of total life cycle cost. Although it is not possible to account for all costs that are incurred by all parties affected by the project, this research project has advanced an awareness of the ability of life cycle cost analysis to capture these costs, with an expectation that other costs may be identified and predicted in the future. Such costs may include the effects of excess emissions, additional accidents, increased noise, or heightened driver stresses that can lead to more accidents. The present model considers user costs related to excess fuel and oil consumption, tire wear, and vehicle maintenance and depreciation, as well as the cost of excess time spent in work zone-related traffic.

To present a working prototype of the new life cycle cost analysis framework, this report includes discussion regarding existing models for all aspects of life cycle cost analysis that are included in the framework. These models work together to provide the engineer with the information and tools needed to make more informed decisions regarding the choice of pavement type, rehabilitation activities and their timing, and other maintenance activities performed by the agency. This framework not only provides decision tools for agency costs, it also allows the engineer to consider the impacts of specific design alternatives on user costs and other impacts of maintenance and rehabilitation activities resulting from the presence of work zones. Using this framework, either alone or with the RPLCCA software package, pavement design engineers and planners will have an improved tool with which to make decisions before a design has been completed or before construction begins.

10.3 RECOMMENDATIONS FOR FUTURE RESEARCH

This study presented a framework for performing life cycle cost analyses. Included in this report are models that predict pavement performance, perform rehabilitation designs, and predict user costs and accident rates at work zones. Many of these models are outdated and should be replaced by more reliable models and calibrated to specific local conditions. This is especially applicable to the pavement performance models. Research should be undertaken to replace these models and to improve the predictive qualities of the framework. The models that are included in the computer software can be easily replaced with newer models as they are developed.

In addition to replacing the existing models that are out of date and, hence, poor predictors of pavement performance, new models should be developed that can predict the effects of increased air pollution, business impacts, noise, and any other components that may be identified in future research.

A major improvement would be the ability to automatically calibrate the performance models using local condition survey data. This could be accomplished by allowing the engineer to enter distress information along with historical environmental and as-built construction data. In addition to this information, variability in construction aspects, such as concrete strength, slab thickness, and the surface roughness, should be used to calibrate the models. Once a methodology is developed, this functionality can be implemented into the RPLCCA software.

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