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16. Abstract This report describes a project-level pavement type selection procedure developed for use in state departments of transportation (DOTs). This reports details the overall decision framework required for making dependable pavement type selection decisions. Three important factors — agency costs, user delay costs, and performance levels associated with candidate strategies — are thoroughly evaluated and quantified for economic comparisons. The economic evaluations are primarily based on the life-cycle cost analysis and cost-effectiveness analysis. The report also describes the requirements and approach to generate candidate pavement strategies. The impact of miscellaneous factors on pavement type selection is also discussed. Some guidelines are suggested for the final strategy selection. An example case study is conducted to demonstrate the use of computer program, Texas Pavement Type Selection, or TxPTS.			
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A RATIONAL PAVEMENT TYPE SELECTION PROCEDURE

by

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Project Summary Report Number 0-1734-S

Research Project 0-1734

Project Title: "Development of a Pavement Type Selection Process"

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

by the

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IMPLEMENTATION STATEMENT

This is the final report for Texas Department of Transportation (TxDOT) Project 0-1734. This report describes the procedure developed for project-level pavement type selection. A computer-based decision support tool, the Texas Pavement Type Selection (TxPTS) program, has been developed to automate the procedure. It is the belief of the research team that an immediate implementation of the TxPTS program would greatly benefit TxDOT in making pavement type selection decisions. Some specific implementation actions are recommended as follows:

1. The pavement type selection procedure (TxPTS) described in this report will enable the Texas Department of Transportation (TxDOT) to meet the Federal Highway Administration (FHWA) policy guidelines, and will enable TxDOT engineers to make rational decisions that maximize taxpayers' dollars. Accordingly, TxDOT should sponsor hands-on implementation of the TxPTS program. The true benefit of the method can best be achieved through a coordinated and well-structured implementation effort involving the research staff. Some training sessions will also be required to demonstrate the use of TxPTS to engineers.
2. Best available performance information should be used to establish the estimates for strategies' materials and performance data. Structural design systems, flexible pavement system (FPS19) and rigid pavement design system, TSLAB, and historical performance data should be used to establish reasonable estimates of initial construction and overlay performance prediction. Local seal coat and routine maintenance policies must also be included in strategies.
3. The feasibility of adding pavement design methods into the TxPTS program should be investigated in a follow-up study.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration (FHWA) or TxDOT. This report does not constitute a standard, specification, or regulation.

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Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

SUMMARY

This report describes a project-level pavement type selection procedure developed for use in state departments of transportation (DOTs), and details the overall decision framework required for making dependable pavement type selection decisions. Three important factors — agency costs, user delay costs, and performance levels associated with candidate strategies — are thoroughly evaluated and quantified for economic comparisons. The economic evaluations are primarily based on the life-cycle cost analysis (LCCA) and the cost-

effectiveness analysis. The report also describes the requirements for and approach to generating candidate pavement strategies. The impact of miscellaneous factors on pavement type selection is also discussed. Some guidelines are suggested for the final strategy selection. Finally, an example case study is conducted to demonstrate the use of the TxPTS computer program.

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CHAPTER 1. INTRODUCTION

1.1. BACKGROUND AND PROBLEM DESCRIPTION

Given the large capital investments involved, engineering decisions regarding the selection of pavement types for new construction and reconstruction projects are very important within state departments of transportation (DOTs). Accordingly, such decisions should be based on rational procedures that can ensure reasonable and cost-effective solutions. At the same time, the Federal Highway Administration (FHWA) document, “Federal-Aid Policy Guide — Part 626: Pavement Design Policy” (FHWA 91), emphasizes that state highway agencies should have a process that is acceptable to FHWA for the type selection and design of new and reconstructed pavements. To be eligible for federal-aid funding, the design of new and reconstructed pavements should represent economical solutions based on the state’s pavement type selection and pavement design procedures. The type selection process should include both an engineering and an economic analysis for alternate designs. Since pavements are long-term public investments, it is appropriate that all costs that occur throughout a pavement’s service life (FHWA 91) be considered. FHWA guidelines underscore the importance of developing and implementing sound pavement type selection procedures.

Selecting a specific pavement type to be constructed for a given project is a complex undertaking that requires consideration of many technical, economic, and miscellaneous factors. In general, the factors related to agency costs, road user costs, and pavement performance, together with good engineering judgment, are the cornerstones of dependable type selection decisions.

In practice, while several pavement types are often technically feasible for a given roadway project, one is often selected over the others based on decisions that involve no systematic evaluation. Pavement type evaluations should be based on a consideration of all pavement strategies, including initial as well as future activities undertaken throughout the life cycle of strategies. A range of pavement materials, such as asphalt concrete, portland

cement concrete (PCC), chemically stabilized materials (lime- and cement-treated layers), and granular materials, can be used to build pavements. Several feasible structural sections for flexible and rigid pavement types can be developed for different combinations of layer materials, material properties, and performance periods for a particular set of project design data (e.g., traffic, soil condition, and climatic data).

If good technical information is available on several pavement types, then a proper economic analysis will often provide the suitable solution. In this case, however, it is necessary to consider not only construction, maintenance, and rehabilitation costs, but also road user costs associated with pavement strategies. Unless road user costs are appropriately evaluated, life-cycle economic evaluations of pavement strategies cannot be considered satisfactorily rigorous for making type selection decisions.

In a real-life decision-making environment, there typically exist several miscellaneous factors that affect pavement type selection decisions. These factors include historical practice, constructability, recyclability, maintainability, adjacent existing pavements, availability of local materials, and local preference. At times, these factors become critical as a result of prevailing project conditions. The American Association of State Highway and Transportation Officials' Guide (AASHTO 93) outlines several principal and secondary factors that affect pavement type selection. The guide recommends that pavement type selection be facilitated by economic comparison of alternative structural designs for pavement types designed through theoretical or empirically derived methods. The guide also suggests that life-cycle cost analysis (LCCA) and structural design procedures would not by their nature encompass all factors affecting pavement type determination. Such a determination should properly be one of professional engineering judgment based on the consideration and evaluation of all factors applicable to a given highway project.

At the present time the Texas Department of Transportation (TxDOT) uses no standard statewide procedure for pavement type selection. This report describes the issues encompassing pavement type selection and describes the decision support system developed to assist TxDOT in its pavement type selections.

1.2. PROJECT OBJECTIVES AND IMPLEMENTATION

The main goal of this research project is to develop a broad-based and general pavement type selection procedure that will provide assistance and guidance to engineers in selecting the most appropriate pavement type, considering influential factors in individual situations. The major research objectives include:

- Collecting up-to-date information about the pavement type selection practices of other highway agencies.
- Identifying the basic requirements for a pavement type selection procedure.
- Designing a systems' framework to integrate necessary factors for pavement type selection.
- Evaluating, quantifying, and integrating technical and economic factors included in the framework.
- Developing a computer program to automate the procedure.
- Developing guidelines for making final type selection decisions based on the consideration of economic as well as other important criteria.

The primary product of this research project is an economic-based decision support tool for making project-level pavement type selection decisions. This decision support tool will provide TxDOT district and area offices with a functional and coherent framework for selecting appropriate pavement types for roadway projects within their jurisdiction.

1.3. RESEARCH APPROACH

The major research tasks carried out under this project are described in the following sections.

1.3.1. Information Synthesis

The interim report for this project (Beg 98) presented a comprehensive information synthesis of current pavement type selection practices of highway agencies. The interim

report findings are based on the literature review and on national and Texas questionnaire surveys. The literature review and questionnaire surveys help in outlining fundamental requirements for pavement type selection and provide a synthesis of current pavement type selection practices of other highway agencies.

1.3.2. A Framework for Pavement Type Selection

The pavement type selection process is based on the comparison of feasible alternative strategies for a project. Adequate structural designs and maintenance and rehabilitation (M&R) policies for different pavement types should be used in forming candidate strategies. The issues related to pavement design, initial construction, and M&R activities are discussed.

The basic premise of pavement type selection is identifying, quantifying, and integrating fundamental factors that are essential in making sound type selection decisions. Several components of agency costs, user costs, pavement performance, and other important factors are identified and evaluated for their role in pavement type selection decisions. An integrated framework including various factors is developed. The LCCA approach forms the primary basis for comparing alternative pavement strategies. Models are developed for estimating agency and user costs. Cost-effectiveness evaluations should allow for consideration of required cost and performance trade-offs among strategies. Models are also developed for pavement performance and cost-effectiveness estimation. The framework outlines the typical required input data, mathematical models, and output economic indicators. Several factors related to life-cycle cost analysis, such as discount factor, analysis period, agency costs, and user costs, are examined.

Guidelines for final strategy recommendations are also developed. The preferred alternative should be selected based on considerations of economic factors and other nonquantifiable factors and constraints.

1.3.3. Computer Program

The Texas Pavement Type Selection (TxPTS) computer program was developed to automate the suggested pavement type selection procedure. TxPTS quantifies economic

outputs to compare alternative pavement strategies and ranks strategies according to the choice of economic output.

1.4. SCOPE AND ORGANIZATION OF THE REPORT

This report represents the project summary report for TxDOT project 0-1734. The following describes the report's organization by chapter.

- Chapter 1 presents general background and research approach for the project.
- Chapter 2 presents the development of a framework for pavement type selection.
- Chapter 3 reports the requirements and issues encompassing the development of feasible candidate pavement strategies.
- Chapter 4 describes LCCA and agency cost calculations.
- Chapter 5 describes road user costs and details the models developed for delay cost calculations.
- Chapter 6 describes the use of the cost-effectiveness approach and discusses the models developed for estimating performance and cost-effectiveness indicators.
- Chapter 7 discusses important miscellaneous factors for pavement type selection; it also includes guidelines for final strategy selection.
- Chapter 8 summarizes the TxPTS computer program and reports a case study and economic sensitivity of results.
- Chapter 9 summarizes conclusions and recommendations based on the findings of this project. It also suggests directions for further research that can improve pavement type selection procedures.

CHAPTER 2. A FRAMEWORK FOR PAVEMENT TYPE SELECTION

2.1. ECONOMIC-BASED DECISION-MAKING APPROACHES

Pavement type selection is a form of mutually exclusive decision making whereby one alternative is picked among candidate alternatives. Economic-based ranking methods have become increasingly common for evaluating roadway projects. The American Association of State Highway and Transportation Officials' Guide (AASHTO 93) emphasizes that pavement type selection should be facilitated by comparison of alternative designs for several pavement types designed using valid theoretical or empirically derived methods. Economic-based ranking procedures can be effectively employed for pavement type selection evaluations. Ranking techniques evaluate several related factors of a project simultaneously and yield a quantitative ranking value based on the evaluation of these factors. While ranking methods don't necessarily provide an optimal solution, a ranking approach is nevertheless simple to use and provides the relative order of importance of different alternatives (Jiang 90).

Economic analysis can be divided into two general categories. The first category is *cost-benefit analysis*, an analysis that provides a quantitative assessment of the relative economic costs and benefits of alternatives and that provides a common monetary measurement. If all alternatives are believed to provide the same benefit, then comparison is left only on the life-cycle costs (LCC) basis. The second category of economic analysis is *cost-effectiveness analysis*, which deals with impacts that are not so easily quantified or for which there are no easily defined monetary values (Campbell 88).

A life-cycle cost analysis (LCCA) procedure involves (1) modeling the performance of a particular pavement structure exposed to a given set of conditions over a period of time, (2) forecasting traffic, (3) assigning future maintenance and rehabilitation treatments, and (4) performing economical analysis including all costs anticipated over the life cycle of the pavement strategy (Haas 94). Cost trade-offs, such as those between the initial construction costs and the future maintenance and rehabilitation costs, can be examined using LCCA.

Cost streams are typically converted into net present worth (NPW) or equivalent uniform annual cost (EUAC) by using an appropriate discount rate.

In a cost-effectiveness evaluation, the effectiveness of each project is expressed in some standard unit, with projects then compared by a procedure analogous to that used for a benefit-cost analysis (Kurtz 84). It is customary to use a money-based index that is helpful in comparing alternatives that are intended to achieve the same goal but probably at different levels of worthiness. It is important to note that an LCCA doesn't directly take into account of effects of nonsimilar performance levels of candidate strategies. Cost-effectiveness analysis, on the other hand, is a well-known means of combining both benefits and costs into a single objective function for ranking candidate pavement strategies.

2.2. FUNDAMENTAL FACTORS FOR PAVEMENT TYPE SELECTION

2.2.1. Life-Cycle Costs

The Canadian pavement management guide (RTAC 77), Haas and Hudson (Haas 94), and several other references indicate that, from a life-cycle cost perspective, pavement costs can be broadly categorized as:

- *Agency costs*, which generally include initial construction cost, rehabilitation costs, preventive and routine maintenance costs, and salvage value.
- *User costs*, which include such indirect costs as time delay costs at work zones, vehicle operating costs (VOCs), accident costs, and discomfort costs.

Another important aspect of pavement costs is whether they are:

- *Initial costs*, which include the cost of initial reconstruction or new construction,
or
- *Future costs*, which include subsequent rehabilitation and maintenance activities performed throughout the life cycle until the pavement is reconstructed.

Both initial construction costs and life-cycle cost considerations are important for making proper decisions. Agencies typically are interested more in the initial costs, as

opposed to future costs. Moreover, relatively accurate estimates of initial costs can be established, whereas a much larger degree of uncertainty is associated with future costs (insofar as they depend on how pavements are managed in the future).

LCCA is a systematic and theoretically sound method of examining all costs accruing during the life of a pavement structure. And an important element within such analyses is the use of a discount rate to account for the time value of money. The selection of the discount rate is critical in that it can result in the selection of different alternatives if one discount rate is chosen over another. A Federal Highway Administration (FHWA) technical group presenting at the life-cycle cost analysis symposium (FHWA 94) listed the following critical technical issues related to LCCA: accuracy of performance models, service life, effect of maintenance on performance, quantify time delays/travel speeds, future traffic levels, operating costs, discount rate, and salvage value. Most of these issues are discussed in the following chapters.

2.2.2. Performance

Pavement performance is a key concern from both the agency and road user perspectives. Carey and Irick (Carey 60) established that pavement serviceability must be defined relative to the basic purpose of pavements, i.e., to provide a smooth, comfortable, and safe ride. Based on this definition, the present serviceability index (PSI) measure was developed and used at the American Association of State Highway Officials (AASHO) Road Test. Based on objective measurements of pavement surface roughness and distresses, PSI predicts pavement serviceability ratings (PSR) and public perception of ride quality. PSI ranges from 0 to 5, with 5 representing the highest level of serviceability. The area under the performance curve represents the accumulated service or performance.

Within the Texas Department of Transportation (TxDOT), both flexible and rigid pavement design procedures derive primarily from the PSI-based performance concept. Figure 2.1 illustrates a typical pavement design strategy and associated performance levels and costs for a life cycle of 30 years. Figure 2.2 shows alternative pavement strategies providing different performance levels.

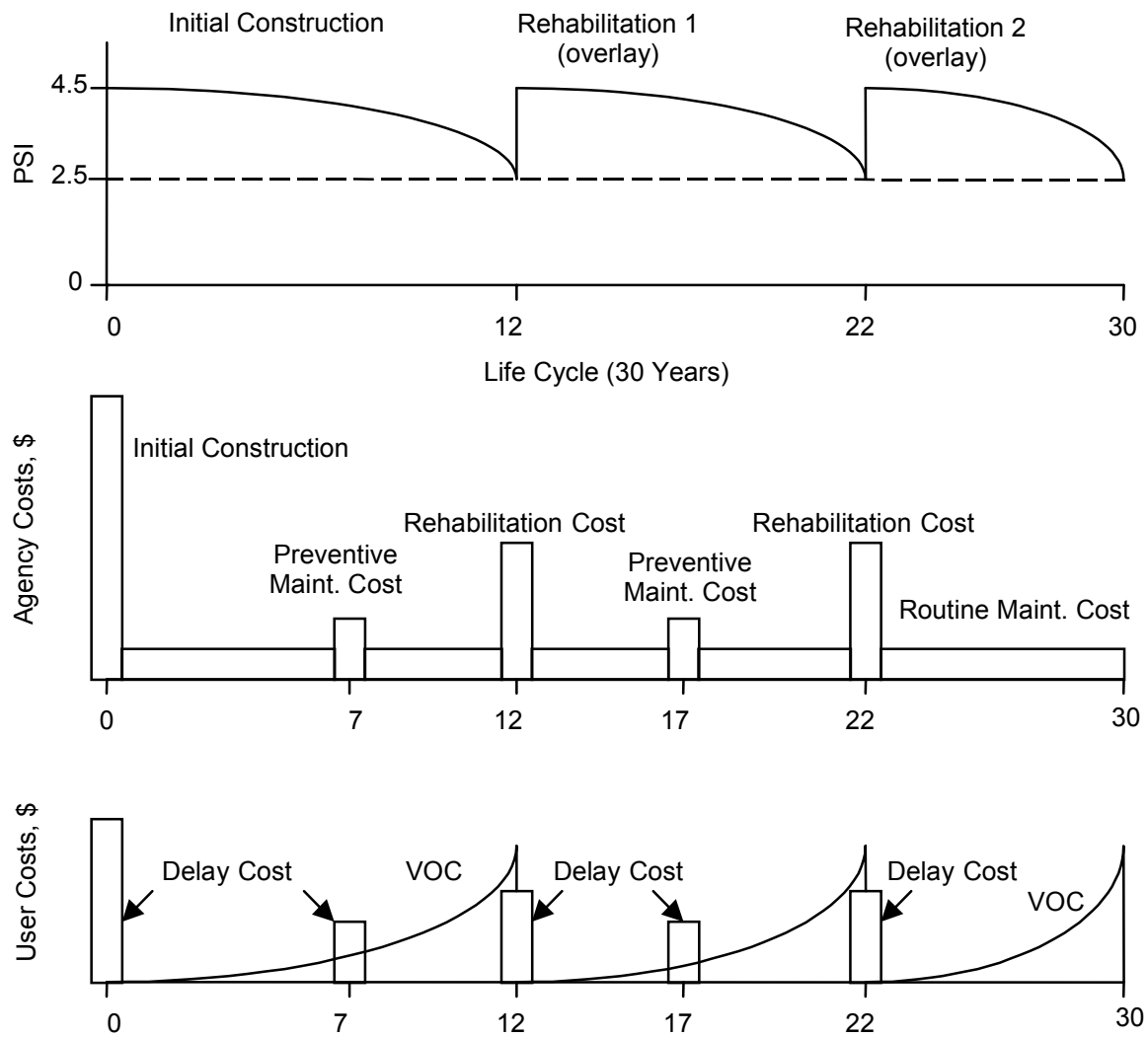


Figure 2.1. Typical pavement strategy and its life-cycle cost and performance components

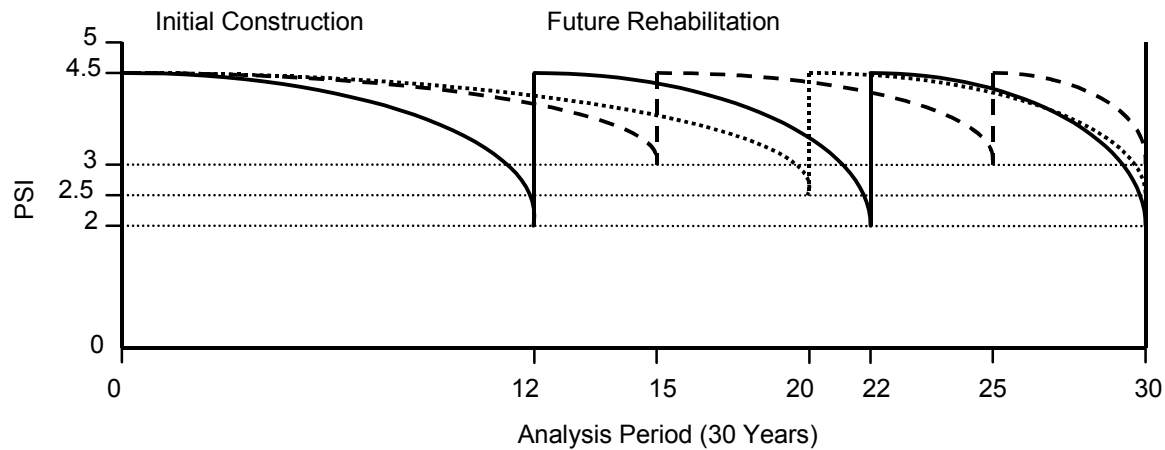


Figure 2.2. Pavement strategies with different performance periods and PSI levels

2.3. A FRAMEWORK FOR PAVEMENT TYPE SELECTION

The basic methodology for project pavement type selection is based on evaluating mutually exclusive candidate strategies. Fundamental quantifiable factors, agency costs, delay costs, and performance are important in evaluating candidate strategies, and quantification of these fundamental factors is essential in making rational type selection decisions. These factors could be combined to give reasonable output economic indicators. Figure 2.3 outlines an integrated framework for pavement type selection. The LCCA approach forms the primary basis for comparing alternative pavement strategies. Cost-effectiveness analysis is also included to allow consideration of cost versus performance trade-offs among strategies. The framework outlines three phases of a typical decision-making process:

- *Input data:* Type selection methodology is based on evaluating user-specified alternative strategies. Economic evaluation requires data pertaining to: (1) project size and location, and (2) the strategies' materials quantities and performance.
- *Mathematical models:* These include models to calculate agency costs, user costs, a strategy's performance estimate, total life-cycle cost, and cost effectiveness.

- *Output economic indicators:* Some useful outputs include initial costs, total life-cycle costs, and a cost-effectiveness index.

Several sources (Peterson 85, AASHTO 93), including national and Texas surveys (Beg 98) conducted under this project, have verified that a thorough economic analysis provides a dependable framework for evaluating candidate strategies, but that final selection criteria often include considerations that are not explicitly evaluated through economic analyses. Miscellaneous factors, such as initial budget constraints, historical practice, traffic, and local materials, often impact pavement type selection decisions as well.

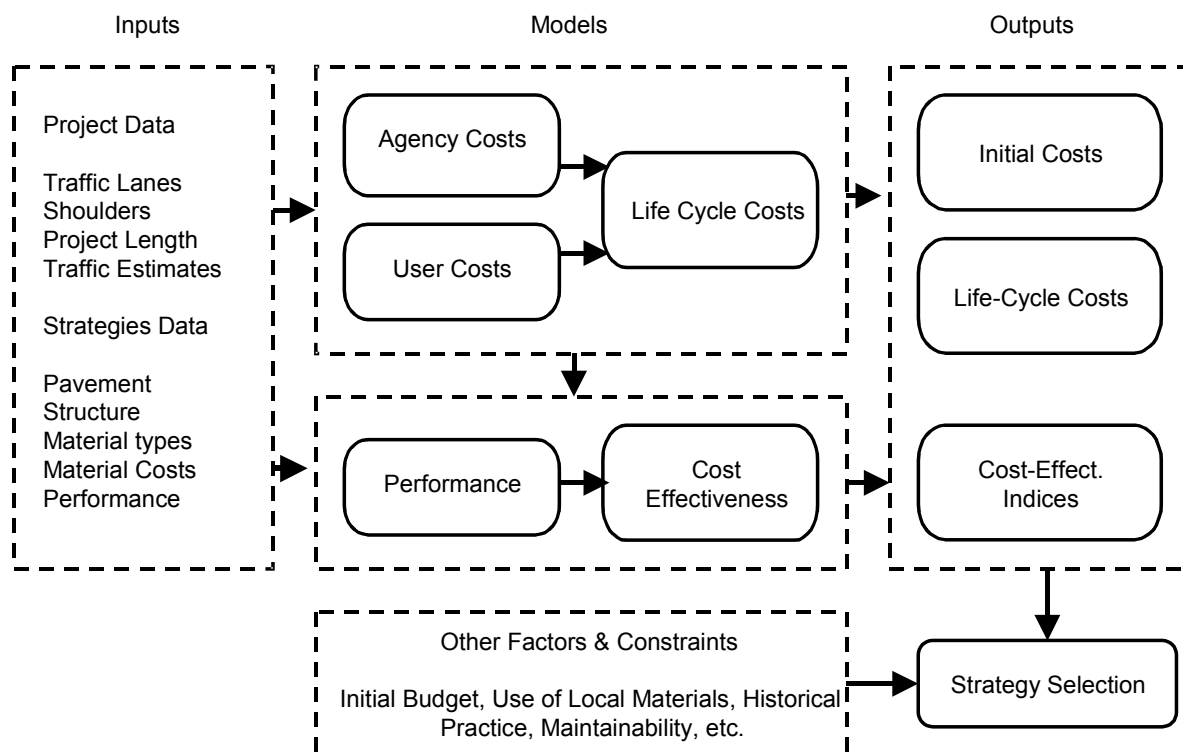


Figure 2.3. Framework for a pavement type selection process

CHAPTER 3. PAVEMENT TYPES AND STRATEGIES

3.1. PAVEMENT TYPES

Haas and Hudson (Haas 94) report that many so-called pavement types are available through modern technology, with such types termed *rigid pavement*, *flexible pavement*, *composite pavement*, and *full-depth asphalt pavement*, among others. Each of these terms has been developed for some particular reason and each has a useful connotation. The most straightforward definition of pavement type by structural function or response includes two basic types: (1) rigid pavements and (2) flexible pavements (Haas 94, AASHTO 93, Yoder 75). The term *composite pavements* is used to describe pavements that combine both rigid and flexible layers — for example, an asphalt concrete surface over an old portland cement concrete (PCC) pavement or over a cement-treated base. Haas and Hudson (Haas 94) recommend assigning composite pavements to one of the other two types not according to the visible surface type, but according to the basic load-carrying element. There are two basic differences between rigid and flexible pavements:

- 1) surface material type, and
- 2) use of different mechanical theories to describe their behavior.

3.1.1. Flexible Pavements

Flexible pavements always use asphalt concrete for the surface layer and sometimes for the underlying layers. A flexible pavement is a roadway structure consisting of a subbase, a base, and surface courses, all of which are constructed over a prepared roadbed. The materials used for underlying layers, base, and subbase construction are crushed stone or gravel. These materials can be either unbound (flexible) or treated by asphalt, lime, or cement. Another type of flexible pavement is termed *full-depth asphalt pavement*. As the name indicates, asphalt mixtures are employed for all pavement layers above the subgrade. Layered system analysis is commonly used to analyze the behaviour of flexible or asphalt concrete pavements that predominantly carry load in shear deformation.

3.1.2. Rigid Pavements

Rigid pavements consist of a PCC slab and may have a base or subbase over a prepared roadbed. The base or subbase may be composed of crushed stone or gravel, with such materials either unbound (flexible) or treated by asphalt, lime, or cement. Slab analysis is commonly used to explain the behavior of rigid or PCC pavements, which usually carry load in bending.

There are two basic types of rigid pavements: (1) jointed concrete pavement (JCP), and (2) continuously reinforced concrete pavements (CRCP). JCP has expansion and contraction joints across the direction of traffic to allow for expansion and contraction of slab with environmental changes. Joints are typically provided with tie bars and dowels for adequate wheel load transfer. Another form of JCP is termed *jointed reinforced concrete pavement* (JRCP). As the name indicates, JRCP is constructed with steel reinforcement, the benefits of which include fewer joints and longer slabs. Although it doesn't include joints, CRCP is nonetheless sufficiently reinforced to carry the load in the cracked concrete sections. Reinforcement is designed to control the occurrence of both early age crack spacing and the crack spacing that develops later in the service life.

3.1.3. The Texas Department of Transportation's Classification of Pavement Types

The Texas Department of Transportation (TxDOT) document, "Design Training Applications: Pavement Design" (TxDOT 93), categorizes pavements according to three classes: (1) flexible, (2) semirigid, and (3) rigid.

The TxDOT document explains that a true flexible pavement is typically composed of relatively thin asphalt concrete surface or asphalt seal coat over a flexible base or subbase resting on the subgrade. On the other hand, semirigid pavements have layers with relatively higher stiffness owing to either stabilized layers or to an increased asphalt concrete surface thickness. Thick-surfaced asphalt pavements and pavements with stabilized bases are included in the semirigid category. PCC pavements are considered rigid and are categorized according to their use of joints and reinforcement; these categories include JCP, JRCP, and CRCP.

3.1.4. Summary List of Pavement Types

Based on the above sources, the general pavement types for new construction and reconstruction projects include:

- Seal coat with granular (flexible) base
- Asphalt concrete pavement (thin/thick) with granular (flexible) base
- Asphalt concrete pavement (thin/thick) with stabilized base
- Full-depth asphalt concrete pavement
- JCP
- JRCP
- CRCP

3.2. PAVEMENT STRATEGIES

The traditional objective of pavement design is to recommend a suitable pavement structure (i.e., number and thickness of pavement layers and materials of construction) that will meet functional and structural performance objectives through the service life of the pavement. The concept of pavement design, however, has evolved from merely specifying an initial structural section; it now involves a pavement design strategy that seeks to identify not only the best initial structural section, but also the best combination of materials, construction policies, and maintenance and overlay policies (Haas 94). Thus, several feasible strategies for different combinations of layer materials and performance periods for a particular set of project design data (e.g., traffic, soil condition, and climatic data) can be obtained. Figure 3.1 shows the wide range of options available for generating alternative pavement strategies.

3.3. GENERATING ALTERNATIVE PAVEMENT STRATEGIES

Pavement strategies comprise initial and future maintenance and rehabilitation (M&R) activities performed through the life cycle of a roadway project. Important aspects relating to the generation of pavement strategies are discussed in the following sections.

3.3.1. Project Type

Pavement type selection determination is typically required for two types of roadway projects: (1) new construction, and (2) reconstruction. Within these project types, there exist fewer constraints to limit the choice of material types and service lives of the strategies.

For new pavement construction, the choice of basic pavement type could be either an asphalt-surfaced structure or a PCC-surfaced structure.

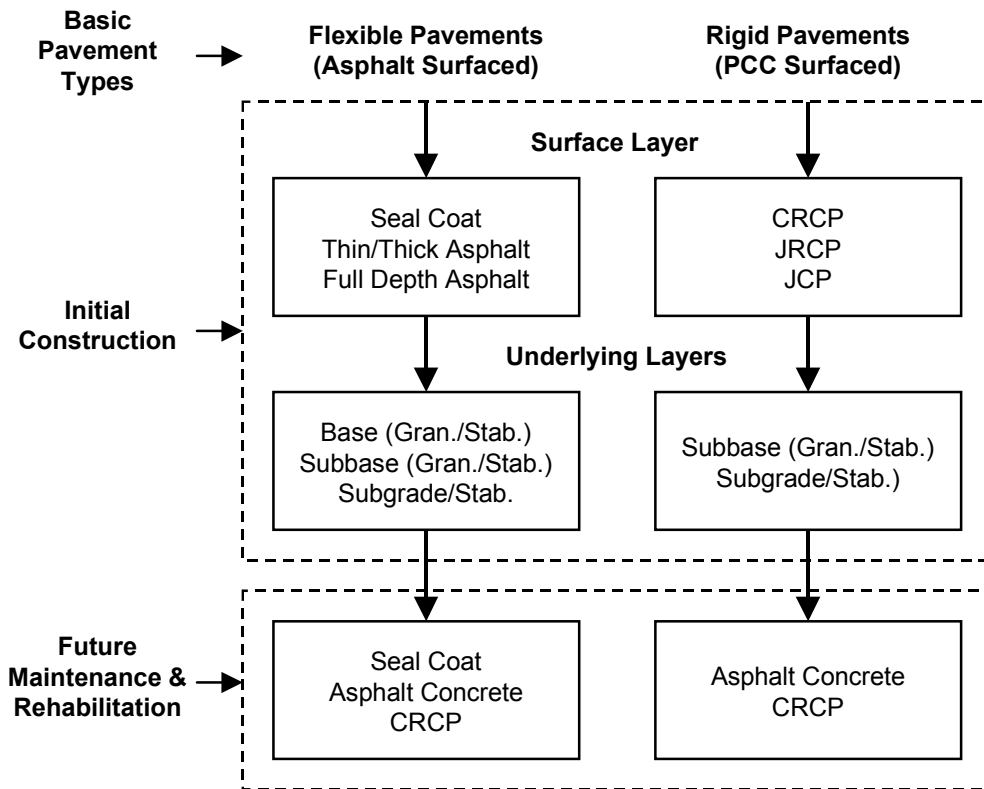


Figure 3.1. Options available for generating candidate pavement strategies

Pavement reconstruction is the construction of the equivalent of a new pavement structure; such construction involves (usually) the complete removal and replacement of an existing pavement structure, including new and or recycled materials (FHWA 91). For reconstruction projects, material type choices will depend on the existing pavement type, its condition, and the feasible alternatives.

Pavement rehabilitation, on the other hand, is a process performed in order to return existing pavement to the condition of structural and functional adequacy typically found in a new structure (FHWA 91). Rehabilitation activity generally represents an intermediate point in the life cycle of an existing pavement structure. For some projects, rehabilitation will at times be zero, thus constituting the beginning of an LCCA. A pavement type selection methodology can be used for economic evaluation of rehabilitation alternatives. For a rehabilitation/resurfacing project, there might be several alternatives, including a conventional overlay, recycling, and removing and replacing the existing surface.

3.3.2. Life Cycle

The life cycle or useful life of a pavement alternative is the length of time from initial construction until some major reconstruction is expected that will mark the beginning of a new life cycle. The end of a life cycle is essentially the point at which the pavement's effective structural and functional value is insignificant. On the other hand, the in-place material may have some negative or positive residual value. The worth of residual in-place materials can be accounted for by considering both recycling and replacement alternatives.

3.3.3. Basic Pavement Design Factors

The development of feasible pavement strategies is based on the choice and interaction of three basic factors:

- *Layer material types and thickness.* Several material types, such as asphalt concrete, portland cement concrete, asphalt-treated base, cement-treated base, and unbound granular base, are generally available for constructing pavement surfaces and underlying layers.
- *Initial and terminal serviceability levels.* The choice of serviceability levels will affect the required thickness for a certain combination of layer materials.
- *Performance periods (service life).* The period of time that a newly constructed, rehabilitated, or reconstructed pavement will last before reaching its terminal serviceability is called the *performance period* (AASHTO 93). Alternatives in

general consist of a series of performance periods where the beginning and end of each period is associated with a construction or M&R action.

Various combinations of these three factors will allow users to generate feasible pavement alternatives.

3.3.4. Performance Prediction

The ability to predict the serviceable life of pavement structure or overlay until an improvement is required is important in evaluating pavement strategies. The life cycle of a new, reconstructed, or rehabilitated pavement should be estimated by using the best available information. If quantitative performance models are not available, then engineering judgment based on experience and local knowledge must be used.

There are several information sources available within TxDOT that can help in predicting the performance of a pavement structure. Texas project-level pavement design systems used for flexible and rigid pavement projects — flexible pavement system (FPS19) and rigid pavement design system program (TSLAB) — can estimate performance periods for pavement structures. The Texas network-level pavement management information system (PMIS) also provides a wealth of pavement condition data on Texas pavements. A knowledge of historically observed performance of certain pavement structures in the region could also be helpful in specifying performance periods and serviceability levels provided by certain pavement structures.

TxDOT research project 0-1727 is also developing pavement performance models for TxDOT PMIS and is investigating approaches for integrating TxDOT network- and project-level systems. The findings of project 0-1727 will complement efforts to obtain better estimates of pavement performance for pavement type selection.

3.3.5. Future Rehabilitation Overlay Policies

Pavement rehabilitation activities aim at restoring the pavement serviceability levels to those of newly constructed pavement surfaces. Accordingly, such activities represent the beginning of a new service life/performance period (and its evolution to a point at which the pavement serviceability will again deteriorate to terminal level). Some pavement structural

design systems provide an estimate of future overlay thickness and associated performance periods. Moreover, historical pavement performance data could probably be a most helpful source in forecasting future overlay policies. And while FPS19 provides an estimate of future overlays, TSLAB does not. A combination of design systems' prediction and observed performance history could be used to establish the future rehabilitation policies for pavement strategies. Table 3.1 lists some conventional rehabilitation overlay options for rigid and flexible pavements.

Table 3.1. Rehabilitation overlay options (AASHTO 93, Haas 94)

Flexible Pavements	Rigid Pavements
Asphalt overlay	Asphalt Overlay
PCC overlay	Break/crack and seat rubblized with asphalt
-	Bonded PCC overlay
-	Unbonded PCC overlay

3.3.6. Future Maintenance Policies

Apart from structural overlays, roadway structures require road maintenance activities that seek to preserve pavement serviceability levels. Several routine and preventive maintenance actions are planned and implemented by road agencies on pavement sections. Maintenance policies also form a part of pavement strategies, and local practices and experience could help in specifying maintenance policies for strategies.

Hudson et al. (Hudson 97) define routine maintenance as any maintenance done on a regular basis or schedule; it is generally preventive in nature but may also be corrective. These are small-scope activities that generally include such intermittent jobs as pothole filling, cleaning shoulders, and fixing pavement edge steps. These activities may also be characterized by the fact that they are generally performed by state agencies, though contract maintenance is becoming more popular.

With respect to preventive maintenance, Hudson et al. (Hudson 97) define these activities as those planned activities undertaken in advance of critical need or of accumulated deterioration so as to avoid such occurrences and reduce or arrest the rate of future

deterioration (Hudson 97). Preventive maintenance is performed to retard or prevent deterioration or failure of pavements. While these activities don't significantly improve the load-carrying capability of pavements, they can correct minor defects. They help maintain appropriate serviceability levels, prolong the need of major action (overlays), and to some extent improve the serviceability level at the early stages of their application. Although the beneficial effects of preventive maintenance are reported in the literature, authentic quantification of these benefits is not available in most cases. Geoffroy (Geoffroy 96), in a published survey of state departments of transportation (DOTs), reported that preventive maintenance activities, such as seal coat and microsurfacing applications, tend to extend the rehabilitation time by 5 to 6 years and can provide a 16 to 20 percent increase in serviceability. Although some responses in Geoffroy's survey were based on pavement management systems or on research studies, more than 50 percent of the responses were based on observational experiences of the responding engineers.

Haas and Hudson (Haas 94) indicate that maintenance policies can vary with type of facility, traffic volumes, available budget, or complaints from the public. They report that methods for quantitatively relating level of maintenance to serviceability loss have not yet been developed, and that it is not yet possible to consider adequately alternative levels of maintenance in terms of their benefits in a design strategy. Finn (Finn 94) also comments that any relationship between the cost of routine maintenance and pavement condition has proved elusive. Table 3.2 lists typical maintenance actions for rigid and flexible pavements.

Table 3.2. M&R actions other than overlay (AASHTO 93, Haas 94)

Flexible Pavements	Rigid Pavements
Drainage	Drainage
Crack sealing	Joint and crack sealing
Slurry seal	Retrofit load transfer
Microsurfacing	Joint spall repair
Chip seals	Subsealing
Full-/partial-depth repair	Full-/partial-depth repair
Cold milling	Slab grinding

3.4. FLEXIBLE PAVEMENT DESIGN IN THE TEXAS DEPARTMENT OF TRANSPORTATION

The FPS19 is used statewide in TxDOT to design asphalt-surfaced pavement structures. The first version of FPS was developed in 1968 (Scrivner 68) under the American Association of State Highway Officials (AASHO) Road Test satellite study, which was aimed at harmonizing AASHO Road Test results to Texas conditions. In the following years Darter and Hudson (Darter 73) pioneered the use of a reliability-based approach for pavement design in the FPS. The reliability factor was introduced in the system to take into account the inherent variability that exists in pavement design and construction. The FPS system is based on the following general premise (Scrivner 68): “It is the aim of the engineer to provide, from available materials, a pavement that can be maintained above a specified level of serviceability, over a specified period of time/traffic, with a specified reliability, at a minimum overall cost.”

FPS19 is based on the concept of a serviceability index (SI), with the index a measure of the functional and structural condition of the pavement. SI values range from 0 to 5, where a value of 5.0 represents the best pavement condition. The SI value of a pavement gradually decreases with time as a result of the effects of various factors, such as the impacts of repeated traffic load and the environment on pavement materials and foundation. The design is performed considering the initial and terminal serviceability values, serviceability loss function, equivalent single axle loads (ESALs), and structural curvature index (SCI).

The earlier versions of FPS included a pavement performance equation, which predicts serviceability loss as a function of SCI, layer materials stiffness coefficients, initial and terminal serviceability, ESALs, and temperature and swelling clay parameters (Scrivner 68). Material stiffness coefficients were developed through Dynaflect deflection testing to characterize paving materials. In the current version, FPS19, the use of stiffness coefficients is replaced by the use of a linear elastic multilayered model to calculate surface deflections under the load and 0.3m from the point of load application. It uses pavement layers moduli, Poisson’s ratio, and thickness to predict pavement deflections in calculating SCI. Thus:

$$Q = \frac{53.6 N_k S}{\bar{\alpha}}$$

where

Q = serviceability loss function

N = the cumulative number of 18-kip axle load

N_k = N at the end of the k th performance period $N_0 = 0$

S = surface curvature index

$\bar{\alpha}$ = harmonic mean of daily mean temperature over the period

$$Q = \sqrt{(5 - P_2)} - \sqrt{(5 - P_1)}$$

where

P_2 = terminal serviceability index (SI)

P_1 = initial serviceability index (SI)

$$\log N = \log N_k - Z\sigma$$

where

Z = normal deviate that depends on level of reliability

σ = standard deviation

$$S = W_1 - W_2$$

where

S = surface curvature index

W_1 = surface deflection under the load

W_2 = surface deflection at a distance of 0.3 m from the load

FPS19 also calculates the serviceability loss resulting from swelling clays:

Serviceability loss due to swelling = $F(p, V_R, \theta)$, where

P = swell probability

V_R = potential vertical rise

θ = swell rate constant

The FPS19 system includes the following pavement type options:

- Asphalt concrete + flexible base over subgrade
- Asphalt concrete + asphalt base over subgrade
- Asphalt concrete + asphalt base + flexible base over subgrade
- Asphalt concrete + flexible base + stabilized subgrade over subgrade

The program also has an option for asphalt overlay design.

One important feature of FPS19 is its integrated life-cycle cost analysis (LCCA) module. Users can specify several design constraints in the program, such as minimum and maximum layer thickness, as well as minimum time to first overlay. The program generates several pavement strategies based on a scheme of incremental increases in layer thickness. It performs LCCAs for strategies and ranks them according to their net present worth. The following observations are based on recent experience with the FPS19 program:

- It appears that, while predicting future overlays, no structural loss is assumed in the initial construction pavement structure. This apparently tends to give overpredicted performance period estimates for overlays.
- Preventive maintenance, seal coat, and costs that were included in the earlier versions of FPS are omitted from the current version FPS19.
- Delay cost calculations are based on a fixed hourly flow and percent ADT, during overlay operations. In reality, hourly traffic varies during work zone operations and peak hour flows differ drastically from off-peak flows, especially in urban locations.
- There is no on-screen input for the unit time delay cost for cars, individuals, or trucks in the program. It is therefore not clear what values are used for this purpose.

3.5. RIGID PAVEMENT DESIGN IN THE TEXAS DEPARTMENT OF TRANSPORTATION

The AASHTO Rigid Pavement Design Procedure is the only currently approved method used by TxDOT to design rigid pavements. It is available in automated or nomograph form. Automated procedures include the AASHTO DARWin® program and the TSLAB program.

TSLAB was developed by TxDOT using the American Association of State Highway and Transportation Officials (AASHTO) rigid pavement design equation (TxDOT 93). TSLAB generates concrete pavement thicknesses based on AASHTO design inputs. TSLAB, however, simplifies the AASHTO design by omitting loss in serviceability resulting from the environment. Before TSLAB, the design program rigid pavement system (RPS) was developed for TxDOT (Kher 71); though somewhat identical to FPS, RPS has not been updated and, consequently, is no longer used by TxDOT.

The AASHTO rigid pavement performance equation consists of:

$$\text{Serviceability loss due to traffic} = \text{ESALs} = F (P_i, P_t, D, E_c, k, S'_c, J, C_d, Z_R, S_o)$$

where

P_i = initial present serviceability index (PSI)

P_t = terminal PSI

D = slab thickness (inches)

E_c = PCC Elastic Modulus (psi)

k = modulus of subgrade reaction (pci)

S'_c = PCC flexural strength (psi)

J = load transfer coefficient

C_d = drainage coefficient

Z_R = normal deviate

S_o = standard deviation

$$\log W_{18} = Z_r S_0 + 7.35 \log(D+1) - 0.06 + \frac{\log \frac{\Delta PSI}{4.5-1.5}}{1 + \frac{1.624 \cdot 10^7}{(D+1)^{8.46}}} + (4.22 - .32 P_t) \log \left[\frac{S'_c C_d [D^{0.75} - 1.132]}{215.63 J \left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k} \right)^{0.25}} \right]} \right]$$

Serviceability loss due to environment = F (roadbed swelling, frost heave)

Serviceability loss due to swelling = F (p_s, V_R, θ)

where

p_s = swell probability
V_R = potential vertical rise
θ = swell rate constant

Serviceability loss due to frost heave = F (p_f, V_R, θ)

where

p_f = frost heave probability
ΔP = maximum potential serviceability loss due to frost heave
φ = frost heave rate

where

W₁₈ = predicted number of 18-kips equivalent single axel load applications
ΔPSI = difference between the initial design serviceability index, P₀₁ and the design terminal serviceability index, P_t

CHAPTER 4. LIFE-CYCLE COST ANALYSIS

4.1. IMPORTANT FACTORS IN LIFE-CYCLE COST ANALYSIS

The life-cycle cost analysis (LCCA) procedure evaluates the economic worth of candidate strategies on the basis of their life-cycle cost projections.

4.1.1. Economic Comparison Bases

Two economic indicators, net present worth (NPW) and equivalent uniform annual cost (EUAC), are typically used to convert cost streams into a single economic value by using an appropriate discount rate.

4.1.1.1. Net Present Worth Method: The NPW method involves conversion of all present and future costs to the present using an appropriate discount rate (AASHTO 93, Haas 94). All costs are predicted and are reduced to an equivalent single cost. Present-worth costs of the strategies provide a fair comparison basis, all other things being equal.

$$PWF_{i,n} = \frac{1}{(1+i)^n}$$

where

$PWF_{i,n}$ = present worth factor for a particular i and n

i = discount rate

n = number of years from year 0 to the year of expenditure

4.1.1.2. Equivalent Uniform Annual Cost Method: The EUAC method combines all initial and future costs into equal annual payments over the analysis period. This method is useful in comparing alternative choices in that it reduces each alternative to a common base of a uniform annual cost (AASHTO 93, Haas 94, Peterson 85). The capital recovery factor is used to transform present costs into a series of EUACs (White 89). For a cash flow that includes present and future costs, it is prudent to convert all costs to present worth and to then utilize the capital recovery factor to calculate annual costs.

$$CRF_{i,n} = \frac{i * (1+i)^n}{[(1+i)^n - 1]}$$

where

$CRF_{i,n}$ = capital recovery factor to convert a present cost for a particular i and n

i = discount rate

n = analysis period

4.1.2. Analysis Period

The analysis period is the time period used in comparing relative economic worth of pavement alternatives. A national questionnaire survey undertaken as part of this project showed that the analysis period used by agencies ranges from 20 to 50 years, with an estimated average of 38 years (Beg 98). Results showed also that 46 percent use analysis periods in the range of 31 to 40 years, while another 33 percent use analysis periods in the range of 21 to 30 years. A 25 to 40 year analysis period is considered a time period sufficient for predicting future costs (Peterson 85). Figure 4.1 shows the variation of present worth factor on a 50-year scale discounted to present worth at 4 percent, 7 percent, and 10 percent discount rates. The area under the curve is the accumulation of the total present worth cost of the system. It should be noted that about 90 percent of the total cost of the system is consumed in the first 25 years in the case of a 10 percent discount rate, and in 35 years in the case of a 7 percent discount rate. On the other hand, about 86 percent of the cost is consumed at the end of a 50-year period with a 4 percent discount rate. It is obvious from these findings that the use of lower discount rates should correspond with the use of longer analysis periods and vice versa.

4.1.3. Discount Rate and Inflation Rate

Cash flow streams are converted to NPW or EUAC by using discount rates, so that the economic worth of different alternatives can be compared.

It is necessary to choose between the use of “constant” dollars and “current” dollars when performing an economic analysis. Constant dollars are uninflated and represent the price levels prevailing for all elements at the base year of the analysis. Current dollars are

inflated and represent price levels that may exist at some future date when the costs are incurred. There is general agreement (Epps 81, Roy 84) that the discount rate or real discount rate should be the difference between the market interest rate and inflation using constant dollars. They argued that the use of current dollars in representing future price levels when costs are incurred would add more uncertainty to the analysis. The objective of an economic analysis is to provide management with a tool for the selection of specific options from a set of alternatives; inserting an inflation factor is no guarantee that the decisions will be better.

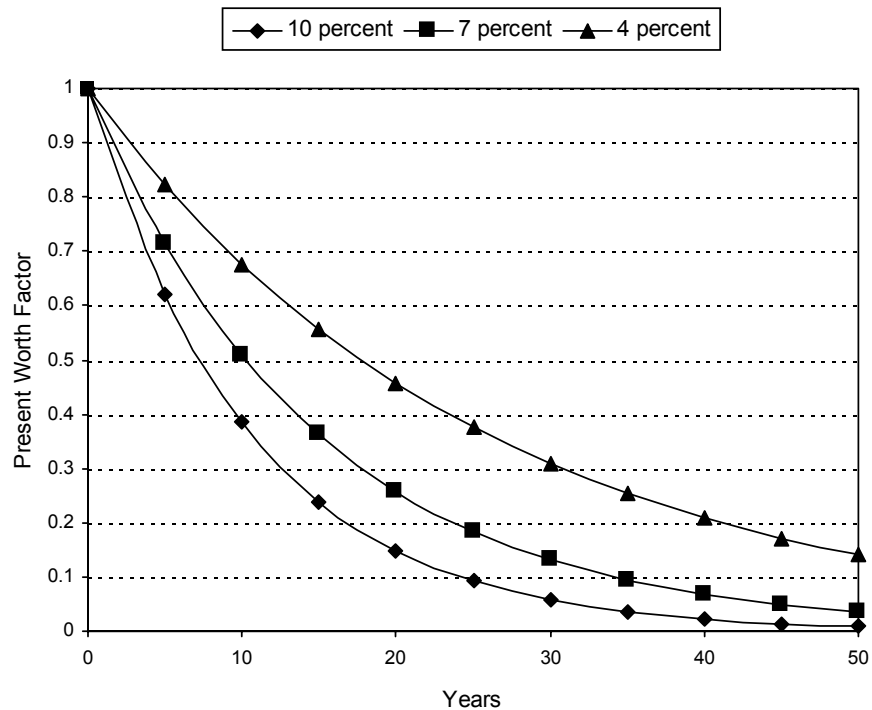


Figure 4.1. Effect of discount factor on life-cycle cost analysis

The discount rate used in an agency's cash flow calculations is a policy decision that may vary with the purpose of the analysis, the type of agency, and with the degree of risk and uncertainty. A discount rate of 4 percent appears distinctly in the relevant literature as the real cost of capital for a governmental low-risk investment (Peterson 85, Epps 81). It is, of

course, quite useful to test the sensitivity of the ranking of alternatives by varying discount rates.

4.1.4. Salvage Value

The salvage value of a pavement structure at the end of the analysis period is one of the most controversial issues in an LCCA. If a dollar value can be assigned to a given pavement structure at the end of the analysis period, then that value can be included in the LCCA as a salvage or residual value.

Because of the nature of pavements, it is not always the case that a pavement's service life is effectively over for each alternative at the end of the analysis period. Some alternatives may yield pavements that have remaining value or unspent life. Moreover, in addition to having a positive value for useful salvageable materials or remaining life, a pavement may have a negative value — that is, if it cost more to remove and dispose of the material than it is worth (Peterson 85).

4.2. SUGGESTIONS FOR CONDUCTING LIFE-CYCLE COST ANALYSIS

The above discussions prompt us to make some suggestions for conducting LCCA. Pavement strategies by their nature are bound to provide total life cycles that differ from one another. In practice, an arbitrarily fixed analysis period is typically used that also requires speculating on the pavements' salvage values. Selection of the analysis period and the quantification of salvage value are perhaps the most debatable elements of an LCCA.

A more rational approach to LCCA would be to use total predicted life cycles of individual pavement strategies as analysis periods and then compare them on the basis of EUAC. The use of true life cycles will allow a consideration of the real value of pavement alternatives — values that cannot be truly estimated through arbitrarily fixed analysis periods. This practice will not require estimating salvage values. Additionally, the use of EUAC allows us to compare cash flows that span unequal time periods, thus accounting for the inherently nonsimilar life cycles of competing strategies.

4.3. AGENCY COST COMPONENTS

Agency costs are actual capital investments required in building and operating pavements that provide acceptable levels of service. These expenditures are typically the primary concern of state agencies, insofar as these are made using public funds. Because initial construction costs form a large portion of agency costs, pavement type selection is therefore significantly affected by actual budgets available for initial construction. Initial construction cost, rehabilitation costs, routine and preventive maintenance costs, and salvage value are primary agency cost components for typical roadway construction and reconstruction projects (Haas 94, AASHTO 93, Peterson 85).

4.3.1. Initial Construction Cost

Initial construction costs include all costs incurred by agencies to procure the pavement. Previous bids and historical cost data are primary sources for identifying materials' unit costs. The most current and accurate available unit cost data should be used in the analysis. When new materials and techniques are being considered as alternatives, care should be taken in estimating costs for those items. Initial construction costs for pavement strategies comprise a combination of pavement materials. Initial construction cost could be modeled by using the following equation:

$$ICC = \sum [D_k * UC_k]$$

$$ICC_{EUAC} = \sum [ICC * CRF_{i,n}]$$

where

ICC = initial construction cost

D_k = depth of layer k (asphalt concrete, PCC, base, etc.)

UC_k = unit cost of layer k material

$CRF_{i,n}$ = capital recovery factor to convert a present cost for a particular i and n

i = discount rate

n = analysis period

4.3.2. Rehabilitation Costs

Future rehabilitation policy is an important constituent of life-cycle activities. Material type and cost data for rehabilitation are similar to those associated with initial construction. As is the case for initial construction, rehabilitation costs also comprise a combination of pavement work items. The following equation can be used for calculating life-cycle rehabilitation costs:

$$RC_{NPW} = \sum [RC_j * PWF_{i,j}]$$
$$RC_{EUAC} = \sum [RC_{NPW} * CRF_{i,n}]$$

where

RC = rehabilitation costs

j = activity year

RC_j = rehabilitation cost at year j

4.3.3. Maintenance Costs

Pavement maintenance activities are typically grouped into two categories: (1) annual routine maintenance, which includes minor and spot work (e.g., pothole repair), and (2) preventive maintenance, which includes periodic pavement work (e.g., crack seal and seal coat activities).

Routine maintenance costs include minuscule details of intermittent spot maintenance operations that are undertaken throughout the year. It is extremely unwieldy to try to use material items based on estimation of routine maintenance costs. A common practice in dealing with routine maintenance costs is to specify the costs in terms of a fixed lump sum annual expenditure. If sufficient information is available, different annual costs can be used through different phases of the life cycle.

The following equation can be used for calculating life-cycle preventive maintenance costs.

$$PMC_{NPW} = \sum [PMC_j * PWF_{i,j}]$$

$$PMC_{EUAC} = \sum [PMC_{NPW} * CRF_{i,n}]$$

where

PMC = preventive maintenance cost

PMC_j = preventive maintenance cost at year j

4.3.4. Total Agency Costs

Total agency costs include the sum of initial construction and future maintenance and rehabilitation (M&R) costs for pavement strategies.

Total agency costs = \sum Agency cost components

$$TAC_{EUAC} = CRF_{i,n} * [ICC + RC + PMC] + RMC$$

$$TAC_{EUAC} = CRF_{i,n} * \left[\sum [D_k * UC_k] + \sum [RC_j * PWF_{i,j}] + \sum [PMC_j * PWF_{i,j}] \right] + RMC$$

where

TAC = total agency cost

ICC = initial construction cost

RC = rehabilitation costs

PMC = preventive maintenance cost

RMC = routine maintenance costs

j = activity year

i = discount factor

n = analysis period

RC_j = rehabilitation cost at year j

PMC_j = preventive maintenance cost at year j

D_k = depth of layer k (asphalt concrete, PCC, base, etc.)

UC_k = unit cost of layer k material

$CRF_{i,n}$ = capital recovery factor to convert a present cost for a particular i and n

4.4. QUANTIFICATION OF AGENCY COSTS

Agency costs are the sum of costs for several material items (such as asphalt concrete and granular base) that are used in certain pavement activity — for example, initial construction and rehabilitation. Pavement strategies provide a sequence of when and how many work items or material types are used. These work items are quantified individually using some customary unit (for example, \$/cubic meter or \$/square meter); these individual costs are combined to calculate total activity costs. An item-wise cost breakdown approach is typically used for costing pavement strategies. Pavement work items are generally quantified in one of the following measurement categories:

- Materials measured in volume/mass (\$/cubic meter, \$/ton)
- Materials measured in areas (\$/square meter)
- Materials measured in linear length (\$/linear meter)
- Lump sum (\$)

Pavement material unit costs are typically quantified from historical records and average bid prices. While relatively accurate estimates of initial costs can be established, a much larger degree of uncertainty is associated with future costs (as they depend on how pavements are managed in the future). Table 4.1 lists several pavement material items and the units customarily used for their measurement.

Agency cost components, initial construction, and M&R are inherently similar in a sense that each requires providing a certain specific set of material items as predicted in pavement strategies. Most pavement work items can theoretically be used in all agency cost components. Table 4.2 shows a tentative assessment of the potential use of pavement work items in agency cost components.

Table 4.1. A tentative list of common pavement work items and their customary units

Pavement Work Items (M&R Actions)	Measurement Units
Items/Materials Typically Measured in Volume/Mass	
Asphalt concrete (wearing, binder, leveling)	\$/Cubic Meter, \$/Ton
Granular base	\$/Cubic Meter
Stabilized base (cement, lime, fly ash)	\$/Cubic Meter
Subbase	\$/Cubic Meter
Embankment material	\$/Cubic Meter
BOMAG (Rework existing pav. with agg. & stabilizer)	\$/Cubic Meter
Portland cement concrete (PCC)	\$/Cubic Meter
Reinforced cement concrete (RCC)	\$/Cubic Meter
Items/Materials Typically Measured in Areas	
Seal coat (single surface, double surface)	\$/Square Meter
Fog seal, Slurry seal	\$/Square Meter
Microsurfacing	\$/Square Meter
Asphalt patching (full depth, partial depth)	\$/Square Meter
Concrete Patching	\$/Square Meter
Items/Materials Typically Measured in Linear Length	
Clean & seal joints	\$/Linear Meter
Pavement base drain	\$/Linear Meter
Lump Sum Items	
Mobilization	
Traffic handling	

Table 4.2. Potential use of several pavement material items in life-cycle activities

Pavement Work Items (M&R Actions)	Initial Const.	Rehab.	Preventive Maint.
Items/Materials Typically Measured in Volume/Mass			
Asphalt concrete (wearing, binder, leveling)	X	X	-
Granular base	X	X	-
Stabilized base (cement, lime, fly ash)	X	X	-
Subbase	X	X	-
Embankment material	X	X	-
BOMAG (Rework existing pav. with agg. & stabilizer)	X	X	-
Portland cement concrete (PCC)	X	X	-
Reinforced cement concrete (RCC)	X	X	-
Items/Materials Typically Measured in Areas			
Seal coat (single surface, double surface)	-	-	X
Fog seal, Slurry seal	-	-	X
Microsurfacing	-	-	X
Asphalt patching (full depth, partial depth)	X	X	X
Concrete Patching	X	X	X
Items/Materials Typically Measured in Linear Length			
Clean & seal joints	X	X	X
Pavement base drain	X	X	-
Lump Sum Items			
Mobilization	X	X	X
Traffic handling	X	X	X

CHAPTER 5. USER COSTS

5.1. COMPONENTS OF USER COSTS

The literature (Haas 94, Peterson 85, Epps 81) shows two broad categories for pavement-related user costs:

- Vehicle operating costs (VOCs), where the function of a VOC is (1) to simulate the effects of the physical characteristics and condition (roughness) of a road on the operating speeds of various types of vehicles and on their consumption of resources (fuel, lubricants, tires), and (2) to determine their total operating cost.
- User costs associated with work zone activities. These costs primarily include user delay costs resulting from lower operating speeds, stops, stop-and-go travel, and speed-change cycling.

Some other user costs, such as travel time, denial-of-use cost, discomfort cost, and accident cost, are also mentioned, but there is little evidence that they are considered by agencies.

Road user concerns appearing throughout the literature review and survey results are time delay and discomfort caused by work zone activities (Beg 98). The impact of time delay should be included in the analysis, either in the form of dollar value or some other parameter. Assigning a dollar value to time delay is a much-debated issue. Nonetheless, average estimates are available through some literature sources.

In practice, engineers are often reluctant to consider user costs in life-cycle cost analysis (LCCA), given that they prefer to view hard agency dollars separately from less tangible user costs. Ullidtz and Kulkarni (Ullidtz 94) document two general opinions expressed at a workshop on user costs versus agency costs: (1) user costs should be quantified in a monetary value, even if they involve a number of political decisions; and (2) because of the uncertainties that can lead to improper decisions, the impact on users should be considered using more stable parameters (rather than quantifying user costs in monetary value). They reported practitioners' concerns that user costs (primarily VOC) tend to

overwhelm agency costs. Most practitioners saw a need to distinguish between “hard” agency dollars and less tangible user benefits. In general it was agreed that, while delay costs caused by construction and maintenance activities can be quantified in monetary terms, quantifying safety costs and VOCs was considered difficult (though still possible). Finn (Finn 1994) emphasizes that the questions that should be answered include how user costs are related to levels of roughness or distress and how to estimate costs of delays incurred by users as a result of maintenance and rehabilitation activities.

5.2. VEHICLE OPERATING COSTS

5.2.1. Texas Research and Development Foundation – FHWA Study

In a major study, the Texas Research and Development Foundation (TRDF) investigated the effect of highway design and pavement condition on VOC. The model TRDF developed drew on the Brazil highway design and standards model (HDM) study, particularly in the effects of pavement roughness on VOC. Zaniwski et al. conclude that fuel consumption is not affected by roughness for the range of conditions encountered in the United States (Zaniwski 82). Measurements were taken on portland cement concrete (PCC), asphalt concrete, and surface treatment to determine if surface type had an influence on fuel consumption. In general there were no statistically significant differences at the 95 percent level between the fuel consumption on the paved sections. Nonfuel VOCs are found to be influenced by pavement condition, though the study also suggests that the cost of the nonfuel components was allocated primarily on research performed in Brazil, where extremely rough conditions exist. However, the fuel experiments did not substantiate the effect of roughness on fuel consumption that was defined in Brazil. Thus, the question of the transferability of the Brazil data to the United States is raised (Zaniwski 82).

5.2.2. World Bank Study

The World Bank developed the HDM from data collected in Brazil between 1975 and 1984. The HDM model, which can aid feasibility studies of highway networks or individual projects, is based on the premise that user costs are related to highway construction and

maintenance standards through the effect of road geometry and pavement surface condition, and the surface roughness is the principal road-related factor affecting user costs in free-flow traffic that can be related to all major pavement performance variables (Watanatada 87). The quantities of resources consumed are determined as a function of the characteristics of each vehicle group (10 groups), surface type (paved or unpaved), vehicle speeds, and current condition of the road (roughness). Relations for predicting vehicle speed, fuel consumption, and tire wear are based on principles of vehicle mechanics and driver behavior, while those for predicting maintenance parts and labor requirements are based on an econometric analysis of user survey data. HDM VOC models consider only paved and unpaved pavement types, and no further classification is sought in the paved category. Bein, after reviewing the HDM-III model, comments that it is basically relevant to the study of rural road infrastructure design and planning issues (Bein 90). Although it was formulated for developing countries, the VOC submodel is practical and can be used in developed countries to appraise those roads that do not experience impeded traffic flows.

Zaniewski (Zaniewski 82) and Watanatada (Watanatada 87) indicate that the effects of VOC are significant when comparing paved versus unpaved roads. Their results show that when pavements are constructed and maintained at reasonable performance levels, the VOC differences among pavements are insignificant. Based on this evidence, we chose not to consider VOC in the LCCA for pavement type selection.

5.3. TIME DELAY COST AT WORK ZONES

The other major user cost component is time delays caused by reduced capacity at work zones. Consideration of time delay is very important because it reflects unavailability of the required level of mobility, a situation that conflicts with a highway agency's objective to provide mobility to the public.

The work zone is that portion of road where drivers are restricted as a result of roadwork being carried out. The work zone's effects encompass not only the physical work zone, but also a distance in advance and beyond the zone. Work zones impact road users two primary ways (Greenwood 96):

- Work zone reduce operating speed
- Work zones reduce road capacity, with such reductions often resulting in queue development

5.3.1. Review of Existing Delay Cost Models

Three delay cost models, QUEWZ (Memmott 82), TxDOT's flexible pavement design system (FPS19) (Scrivener 68), and PennDOT's (Penn DOT 96) LCCA procedure, were specifically reviewed to set up the requirements for time delay cost calculation procedures for pavement type selection.

5.3.1.1. QUEWZ: Developed by Memmott and Dudek (Memmott 82), QUEWZ analyzes the flow of traffic through freeway work zones and estimates the queue lengths and additional road user costs that would result from alternative work zone configurations and schedules. The data elements required to run QUEWZ include the lane closure strategy, total number of lanes, number of open lanes through the work zone, length of closure, hours of closure, hourly traffic volumes, average speeds, and the development of a queue when demand exceeds capacity. A typical hourly speed-volume relationship is assumed in the model, which can be modified by the user as part of the input data. Outputs from QUEWZ include vehicle capacity, average speed through the work zone, hourly road user costs, daily user costs, and, if queue develops, the average length of queue each hour.

User cost calculations in QUEWZ fall into three general categories:

- Time delay costs resulting from slowing down and going through the work zone at a reduced speed, and the delay of vehicles in the queue if one develops
- Change in vehicle running/operating costs due to a lower average running speed through the work zone and queue (if one develops)
- Speed-change cycling costs resulting from decelerating and accelerating, respectively, before and after the restricted length, and stop-and-go conditions if there is a queue

5.3.1.2. *FPS19 Delay Cost Model:* TxDOT's flexible pavement system (FPS19) (Scrivner 68) also considers some elements of time delay costs at work zones. FPS outlines the following two main sources for vehicle time delay:

- Traveling at a reduced uniform speed in the restricted area
- Stopping because of congestion when the traffic demand exceeds the capacity of the restricted area

The user has to specify one of the five default traffic control and detour strategies and the input traffic flow rate during construction. User costs resulting from work zone activities include the following components in FPS:

- Excess time and operating costs resulting from traveling through work zones at a constant reduced speed
- Excess time and operating (idling) costs resulting from being stopped
- Excess time and operating costs resulting from speed reduction from the approach speed to through speed and returning to the approach speed (cycling)

One major limitation of FPS19 delay cost calculations is that it assumes a fixed hourly flow rate during work zone operations.

5.3.1.3. *PennDOT Delay Cost Model:* PennDOT (PennDOT 96) developed a procedure for conducting an LCCA for pavement type selection. The PennDOT LCCA procedure includes the following delay cost components:

- Delay and operating costs resulting from restricted capacity, lower speed, and travel
- Delay and operating costs resulting from stops caused by volume exceeding the capacity

Although the PennDOT LCCA procedure is quite comprehensive and detailed, it doesn't explicitly take into account the formation of a queue once the capacity situation is

reached. Because the method assumes that each approaching vehicle stops for a certain fixed time increment when flow increases the capacity, it thus calculates vehicle-stopping costs. The QUEWZ program offers an approach to modeling queue delay that is relatively more rational than that offered by the PennDOT and FPS19 procedures.

5.3.2. Variables Related to User Delay Costs

In assessing the impact of work zones, there are a number of factors that require consideration:

- time of day and duration of activity
- traffic volume and hourly distribution
- road capacity
- speed-volume characteristics for the road
- mix of vehicle types in traffic stream
- posted speed and approach speed
- length of work zone

The capacity of the work zone has a significant impact on the queue length and delay. Other factors having a great impact include the hourly flow profile for arriving vehicles, the length of the work zone, and speed-volume characteristics of the road.

5.3.3. Delay Cost Computations

The following models are proposed for calculating the two primary delay cost components.

5.3.3.1. Delay Due to Reduced Operating Speed: A lower speed is posted at work zones because of the reduced capacity and for safety reasons. Vehicles travel through work zones at a reduced speed and possibly under congested conditions. This low speed travel through the work zone leads to the occurrence of user delay costs. The daily delay costs can be computed based on the hourly traffic distribution. Figure 5.1 shows a simplified speed

profile of a vehicle passing through a work zone, while the equation below shows the reduced speed delay model:

$$RSD = \left[\frac{1}{S_P} - \frac{1}{S_A} \right] * L * V * [P_T * UDC_T + P_C * UDC_C]$$

where

RSD = reduced speed delay

S_A = approach (unrestricted) speed (km/hr)

S_P = posted (restricted) speed (km/hr)

L = length of work zone (km)

P_T = percentage of trucks

UDC_T = unit delay cost for trucks (\$/veh-hr)

P_C = percentage of cars

UDC_C = unit delay cost for cars (\$/veh-hr)

V = traffic volume for hour i (veh)

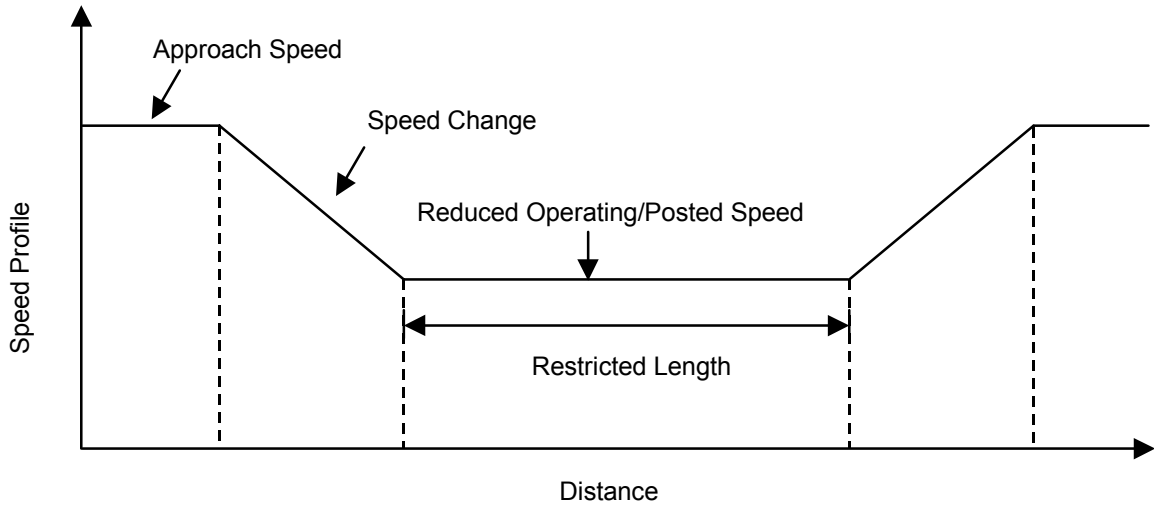


Figure 5.1. A simplified conceptual vehicle speed profile through a work zone

Work zone vehicular speed data are used to calculate user delay resulting from reduced speed travel. Most work zones have posted speed restrictions that require vehicles to decelerate from approach speeds to the posted speed while passing through the work zone. Actual operating speed through a work zone can be considered equivalent to the posted speed. Speed inputs are based on specific work zone characteristics and other policy issues. Vehicles can be assumed to move at constant speed (posted) through the work zone.

Work zone length is the length of road that is under the influence of work zone conditions. The length of a work zone is affected by several factors, such as construction planning of the contractor, agency policy, contractor daily productivity, and scope of the project. The length of the work zone will vary according to the unique project conditions and constraints. Memmott et al. (Memmott 82) proposes an increment of approximately 0.15 km (0.1 miles) on both sides of a work zone. An increase in work zone length is appropriate to show the effect of deceleration and acceleration of vehicles before and after the work zone.

Most delay cost calculation examples in the literature tend to assign a different dollar value to the delayed passenger car and truck traffic (Memmott 82, PennDOT 96). Values of \$9.45 and \$15.75 for cars and trucks, respectively, are suggested in the PennDOT LCCA document (PennDOT 96). Memmott reports the use of \$9.52 for cars and \$22.63 per hour for trucks, and proposed that these numbers be updated using an appropriate price index, such as the consumer price index (CPI) (Memmott 90).

5.3.3.2. *Queue delay*: Greenwood et al. (Greenwood 96) report that queuing at a work zone arises when:

- The vehicle arrivals approach the restricted capacity of the work zone (owing to the randomness and fluctuations in the arrival rate)
- The vehicle arrivals exceed the restricted capacity of the work zone

For vehicles delayed, there are two states:

- A moving queue where the vehicles move forward at a slow speed based on the restricted capacity of the work zone

- A stationary queue where all the vehicles are stopped temporarily for a period of time

It is of interest that, in theory, as long as some finite capacity exists, the queue will always be moving. However, in reality when the capacity is sufficiently small, the queue alternates between moving and stationary conditions. The rate of queue buildup and dissipation is a particularly important consideration in modeling road user effects. Memmott and Dudek (Memmott 82) suggest that the size of the queue at any given time is a function of arrival and departure traffic flows. These may be governed by the capacity, by traffic control devices, or by both. They assume that: (1) If demand exceeds capacity of the work zone, a queue will form; and (2) there will be no change in demand as the queue forms, and no traffic will divert to avoid the queue. They establish that if vehicles are assumed to arrive at a constant rate during a given hour, then the average delay for each hour a queue is present, in vehicle hours, is the average of the accumulated vehicles in the queue at the beginning of hour i and at the end of hour i . This queue delay modeling approach is adopted for this study. In Figure 5.2 the size of a queue at any time is given by the difference between cumulative arrivals (flow) and cumulative departures (capacity).

Work zone capacity calculations are based on the lane capacity and on the total number of open lanes. Furthermore, it is assumed that the traffic volume is equally divided among the open lanes.

$$QD = \frac{TV_{i-1} + TV_i}{2}$$

$$QDC = QD * [P_T * UDC_T + P_C * UDC_C]$$

where

QD = queue delay

QDC = queue delay cost

TV_{i-1} = accumulated total traffic volume beyond capacity at the beginning of hour i (vehs)

TV_i = accumulated total traffic volume beyond capacity at the end of hour i (vehs)
 P_T = percentage of trucks
 P_C = percentage of cars
 UDC_C = unit delay cost for cars (\$/veh-hr)
 UDC_T = unit delay cost for trucks (\$/veh-hr)

Operating speed is assumed to drop down to the capacity speed level during queue hours. A reduced speed delay calculation would be based on capacity speed rather than on the work zone posted speed during these hours.

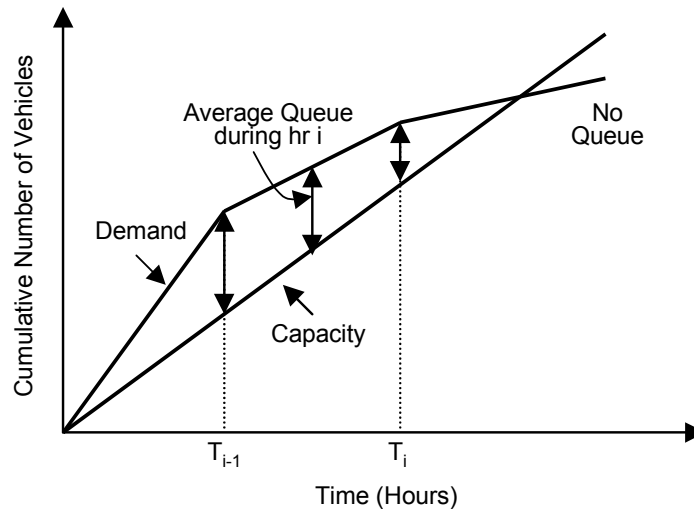


Figure 5.2. Queue delay estimation based on demand and capacity flows

5.3.4. Total Time Delay Costs

All delay costs occurring throughout the life cycle should be combined to estimate the total time delay costs. Duration of the work zone operation (days) is used to convert daily delay costs into the total activity delay cost.

$$\text{Total delay costs} = \sum \text{Delay costs}$$

$$\text{TDC}_{\text{NPW}} = \sum [\text{DC}_j * \text{PWF}_{i,j}]$$

$$\text{TDC}_{\text{EUAC}} = \sum \text{TDC}_{\text{NPW}} * \text{CRF}_{i,n}$$

where

TDC = total delay costs

j = activity year

DC_j = delay cost at year *j*

i = discount rate

n = number of years from year 0 to the year of activity

CHAPTER 6. COST-EFFECTIVENESS ANALYSIS

6.1. NEED FOR COST-EFFECTIVENESS ANALYSIS

In project-level decision making, there are frequently problems in relating costs of proposed improvements to the level of attainment of objectives (benefits) and to the magnitude of impacts generated. A cost-effectiveness analysis is a method of combining both benefits and costs into a single objective function for use in ranking objectives. User benefits related to well-maintained and high-performance pavements are numerous and are often difficult to quantify in monetary terms. These benefits include increased average performance, reduced vehicle operating costs (VOCs), fewer accidents, reduced travel times, reduced tort liability, increased riding comfort, and reduced or deferred capital expenditures through the preservation of a capital asset (Geoffroy 96).

Campbell and Humphrey (Campbell 88) report that cost-effectiveness analysis arose out of recognition of two basic realities of overall evaluation:

- the frequent difficulty of transforming all major impact measures into monetary values in a credible manner, and
- the fact that important evaluation factors could often be stated in quantitative or definitive qualitative terms using measures more meaningful than dollar costs.

Candidate strategies generally provide overall performance levels that differ according to the corresponding performance periods, serviceability levels, and, hence, the shape of the performance curves. A rational evaluation procedure should be capable of taking into account unequal performance levels associated with strategies. Some practitioners assume that the use of a certain fixed terminal serviceability level for all candidate strategies make them equivalent in terms of performance. Fwa and Sinha (Fwa 1991) argue that specifying a certain minimum serviceability level for strategies doesn't satisfy the explicit consideration of pavement performance, because many strategies with similar terminal serviceability levels can be formulated with different overall performance.

The ability to explicitly consider the effects of unequal performance and different terminal serviceability levels would lend further flexibility in a complete economic evaluation.

In general practice, all variations of cost-effectiveness methods have in common the use of nonmonetary effectiveness measures to assess the relative impacts of alternatives on the same scale. Nonmonetary effectiveness measures are used in combination with cost values, often, but not always, in the form of ratios. In the case of pavements, performance is typically considered as a surrogate to benefits, since it is based on the user perception of ride quality. Campbell reports (Campbell 88) the use of a pavement performance curve as a means of assessing and quantifying nonmonetary benefits of high performing pavements.

6.2. COST-EFFECTIVENESS ANALYSIS METHODOLOGY

Campbell also reports (Campbell 88) that a cost-effectiveness analysis assumes that some required tasks can be accomplished by several alternatives that differ in both cost incurred and degree of performance obtained. The effectiveness of each project is therefore expressed in some single standard unit, with projects then compared.

Campbell presents (Campbell 88) three basic criteria for selecting the optimum alternative using cost-effectiveness analysis:

1. Maximize net benefits, i.e., the amount by which benefits exceed costs. These criteria seek to provide an explicit trade-off between monetary costs and all other important impacts. However, it requires all evaluation factors to be translated into dollar terms, a requirement that is typically not possible to achieve.
2. Minimize the amount of resources required to (a) achieve a given level of service and (b) meet other requirements demanded of the particular situation. However, in many situations “requirements” are not absolutes and are more correctly characterized as objectives having varying levels of satisfaction that depend on the nature of alternatives and on the amount of resources that are put into each. However, it is most applicable when a relatively high degree of consensus exists

on the specific agency/community objectives, such as performance or delay to be achieved.

3. Maximize the level of service or other system performance measures from a given level of investments and operating costs. As long as cost constraints can be pre-established, while significant variations in the level of service and other objectives can occur among alternatives, this criterion can provide a basis for evaluation. This is most applicable when budgets are relatively fixed and when the variable part of the analysis — level of service — can be defined in terms that facilitate comparisons among alternatives in terms of pavement performance, total travel time, or user delay.

Although, a unique “best” alternative can hardly be determined from straightforward application of one of the above-mentioned criteria, either or all of the three criteria can provide a good framework for analyzing trade-offs among costs and performance measures. In practice, it is generally desirable to prepare estimates for several cost-effectiveness measures, rather than a single measure, because no single criterion satisfactorily represents the relative cost effectiveness of quite different alternatives. Several cost-effectiveness indices can be used for comparing alternatives — for example, total capital per user or total performance per total life-cycle cost or vice versa. Moreover, further investigations are needed to evaluate realistic cost-effectiveness indicators to improve on the customary simple linear ratios. It is always possible that the preference levels are nonlinear based on the degree of extra costs incurred and on the relative increase in the effectiveness.

6.3. PAVEMENT PERFORMANCE CURVE AS THE SURROGATE OF BENEFITS

There are several examples in the literature illustrating the use of area under the performance curve or some other representation of performance history to represent the benefits associated with pavement strategies. Some notable examples are discussed in this section.

The Texas Department of Transportation (TxDOT) network-level pavement management information system (PMIS) includes the use of a cost-effectiveness ratio for prioritization of projects at the network level (Stampley 95). A surrogate, the area under the distress and ride utility curves, is used in place of monetary benefits.

The Ontario Ministry of Transportation program, Pavement Rehabilitation Life-Cycle Economic Analysis Model (PRLEAM), assists in evaluating pavement strategies. He and Haas (He 94) report that PRLEAM provides quantitative decision support to engineers in selecting project-specific rehabilitation treatments. In considering agency costs and delay costs for economic evaluation, the program requires input for analysis period; discount rate; initial and future agency cost and service life estimates; estimates of pavement condition index (PCI), a performance measure at the beginning and the end of the life span of initial and future rehabilitation treatments; and parameters to estimate traffic delay. The program ranks rehabilitation alternatives in ascending order of cost effectiveness, where this factor is calculated as the ratio of an effectiveness measure (benefit or area under the performance curve) to total present worth of life-cycle costs. Although PRLEAM can quantify costs and benefits of alternative rehabilitation strategies, it is not a design or optimization tool. It can consider only those alternatives provided by the designer. Nevertheless, He and Haas (He 94) consider PRLEAM a most useful complement to the underdeveloped new version of Ontario's pavement design system, Ontario Pavement Analysis of Cost (OPAC 2000).

Haas and Hudson (Haas 94) suggest that calculations of cost effectiveness for pavement strategies can be based on the area under the deterioration curve. Effectiveness is defined as the net area under the rehabilitation deterioration curve multiplied by the length of section and volume of traffic. A simple ratio of effectiveness divided by cost is used as a measure of cost effectiveness. This ratio has no physical or economic meaning per se, but is valuable in the relative comparison of alternatives and in carrying out priority programming. Though this illustration is used in the context of network-level pavement management, it is also applicable to project-level pavement type selection. Application at the project level is actually simpler, since parameters such as length of section or traffic volume don't have any effect, insofar as they are the same for all alternatives.

Fwa and Sinha (Fwa 1991, 1992) argue that, although pavement conditions and serviceability data are commonly used in establishing the values of individual cost items, no consideration is explicitly given to the overall pavement performance in the analysis. They propose an index, the pavement performance quality index (PPQI), that represents the average serviceability rating for strategies. They also developed models for agency and user values of pavement performance based on interview surveys of agency officials and road users. Those models, however, as stated by researchers, are relevant only to the highway agencies of Indiana and to the road users of the Purdue University community.

6.4. A GENERIC METHOD TO DEVELOP PAVEMENT PERFORMANCE CURVE

A generic method is proposed for developing pavement performance curves that can be used in determining area under the curve or average annual performance as a surrogate to user benefits for cost-effectiveness analysis. Stampley et al. (Stampley 95) report the use of the sigmoid (S-shaped) equation form to develop pavement distress prediction curves. The sigmoid equation is very robust and is used to develop several shapes for these models. We propose a generic method for developing pavement performance curves using the sigmoid equation.

$$P_n = P_{\max} - \alpha e^{-\left(\frac{\rho}{n}\right)^\beta}$$

where

P_{\max} = present serviceability index (PSI) at year 0

n = age of pavement, years

P_n = PSI at year n

e = base of the natural logarithm

α = alpha, a horizontal asymptote factor that controls the maximum level of performance that can be lost

β = beta, a slope factor that controls the shape of the curve, how steeply performance is lost in the middle of curve

ρ = rho, a prolongation factor, in years, that controls the position of the inflection point at the specified terminal serviceability level

Value of α is controlled by the relationship:

$$\alpha = \frac{(P_{\max} - P_t)}{\left(\frac{1}{e}\right)}$$

P_t = PSI at year n , end of performance period

β controls how steeply performance is lost in the middle of the curve. If the β value is small, the curve will have a sharp initial slope followed by a gradual approach to the minimum serviceability value. If β is large, there will be a slow initial rate of deterioration followed by a steep rate of deterioration. The final slope will asymptotically approach the α value. The ρ controls “how long” the performance curves will “last” above a certain terminal serviceability value.

The sigmoid equation provides a flexible methodology for representing pavement performance curves. Figure 6.1 illustrates the use of the sigmoid equation using $P_{\max} = 4.5$, $P_t = 2.5$, and $\rho = 15$ that forces the curve to pass through P_t at year 15. The effect of β on the shape of the performance curve is demonstrated by using three different beta values. The ordinate is a performance index, PSI, which ranges from 0 to 5. The abscissa provides a measure of the pavement’s age, in years, since its construction or reconstruction. One limitation of this equation, however, is its tendency to underestimate the decrease in PSI in the early years of the performance period. The use of a relatively lower beta value that tends to shed more PSI at the middle of the curve, however, can offset this effect.

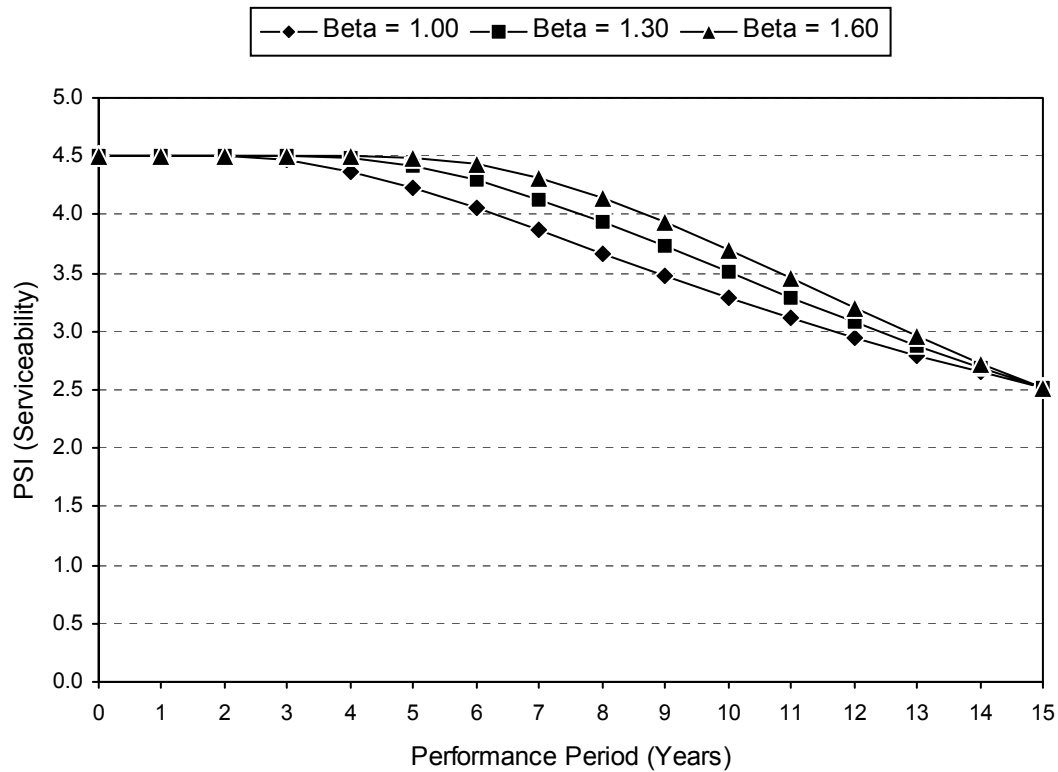


Figure 6.1. Pavement performance curves developed by using sigmoid equation

A sigmoid-form performance curve is compared with the one obtained by using the flexible performance system (FPS19) performance equation. The idea is to arrive at a tentative default beta value that can be used in cases where properly calibrated beta values for different pavement types are unavailable. An example FPS19 solution was generated using the following typical set of data: terminal serviceability (P_t) of 2.5, initial serviceability (P_i) of 4.5, temperature constant ($\bar{\alpha}$) of 60 degrees, reliability level of 95 percent, standard deviation of 0.35, initial year equivalent single axle load (ESAL) (N_k) of 1 million, and a growth rate of 3 percent. The minimum time to first overlay constraint was used to acquire a pavement design with a first performance period of 15 years. Since FPS19 doesn't provide the estimate of structural curvature index (SCI), its value was backcalculated using the FPS19 performance equation. The resultant SCI value was calculated as 0.000318. Afterwards, the P_n and annual PSI values were calculated for each year in the performance

period using the given data and the SCI value. The annual average PSI value of 3.69 is estimated by averaging all PSI values calculated from the FPS19 performance equation. The following FPS19 equation is used for this analysis.

$$\sqrt{(5 - P_n)} - \sqrt{(5 - P_i)} = \frac{53.6 * 10^{(\log N_k + Z_s) S}}{\bar{\alpha}}$$

Similar calculations were performed for P_n and annual PSI using the sigmoid equation for the following parameter values: $P_{\max} = 4.5$, $P_t = 2.5$, and $\rho = 15$. An average PSI of 3.68 is obtained by using a beta value equal to 1.0, and 3.73 by using a beta value equal to 1.1. This preliminary check indicates that a beta value within the range of 1.0 to 1.2 will probably provide a reasonably close approximation of the performance estimation. Figure 6.2 shows the comparison of these two performance curves.

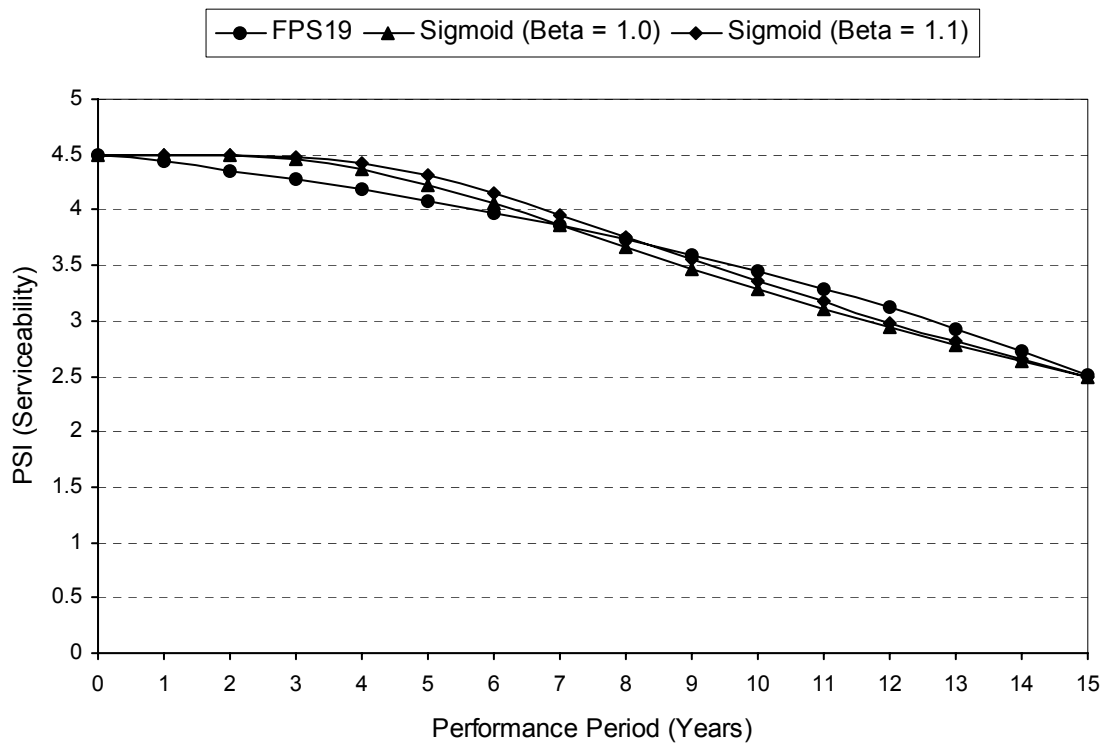


Figure 6.2. Comparison of pavement performance curves

6.5. COST-EFFECTIVENESS INDICES

Annual average PSI can be used as a performance indicator in all, equal or unequal, time period situations. Annual average PSI and equivalent uniform annual cost (EUAC) are mutually compatible in that they represent annual average values of performance and cost, respectively. The difference between annual average PSI and the minimum tolerable PSI provides a rational effectiveness parameter. The American Association of State Highway Officials (AASHO) Road Test suggests the value of 1.5 for the minimum tolerable PSI. The minimum tolerable PSI value should not be confused with the terminal PSI value. The former is a single fixed value used for all strategies, while the latter can vary among the strategies and/or activities within a strategy. This adjustment will give an estimate of effective relative performance among strategies. Figure 6.3 shows the suggested effectiveness parameter to use in cost-effectiveness evaluations.

A ratio of cost and effectiveness is proposed for representing the cost effectiveness of candidate pavement type strategies.

$$CE\ Index = \frac{(EUAC)}{(AAP - P_0)}$$

where

CE Index = cost-effectiveness index

AAP = annual average performance of pavement strategy, PSI

P₀ = minimum tolerable PSI (based on agency policy, typical 1.5)

EUAC = equivalent uniform annual cost of pavement strategy, \$

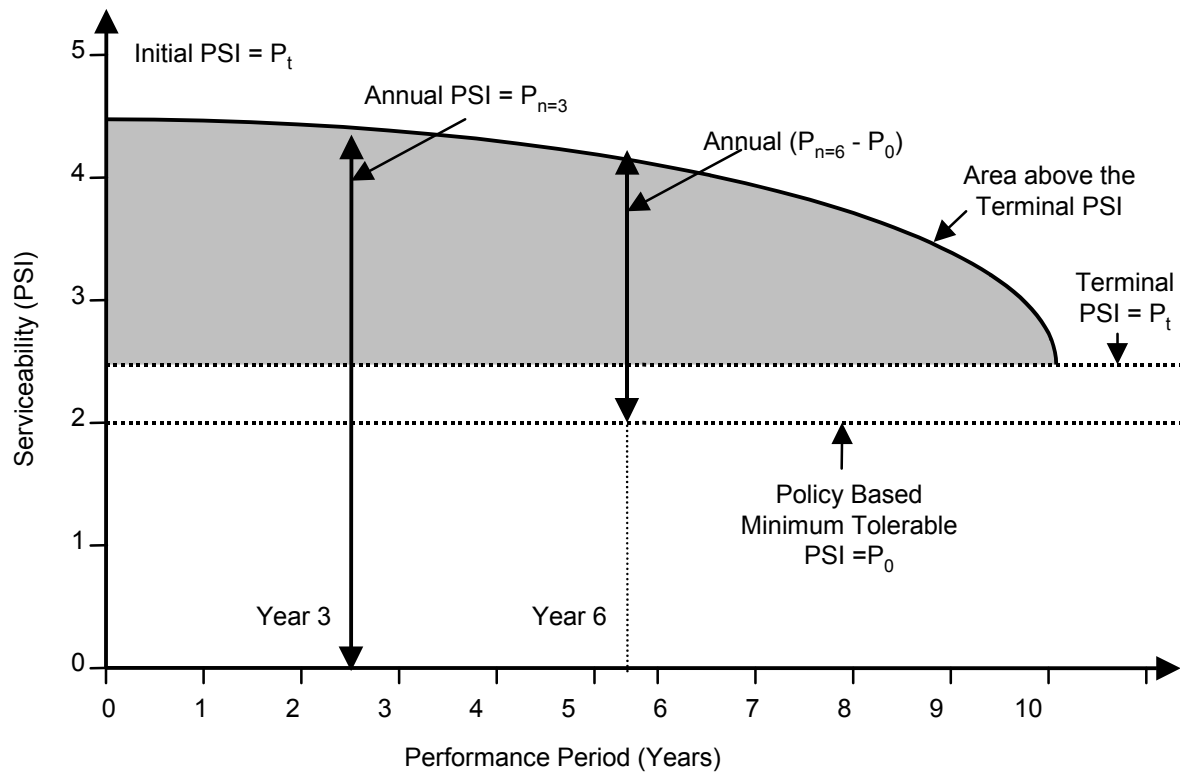


Figure 6.3. Comparison of pavement performance curves

CHAPTER 7. FINAL STRATEGY SELECTION

7.1. LIMITATIONS OF ECONOMIC EVALUATIONS

Several sources (Peterson 85, AASHTO 93), including the national and Texas surveys (Beg 98) conducted under this study, substantiate that, while economic analysis provides a dependable framework for evaluating candidate strategies, the final selection criteria most of the time also include considerations that are not explicitly evaluated in economic analyses. Van Dam and Thurston (Van Dam 94) list the following limitations of typical life-cycle cost analysis (LCCA).

- The procedure cannot accommodate nonmonetary factors, such as the availability of materials, contractor expertise, or agency policies.
- The accuracy of the estimation of each cost component varies from good (initial costs and duration) to poor (maintenance, rehabilitation, user costs, and timing).
- The procedure treats all costs as if they are considered to be equally important. Most agencies are far more concerned with their own direct costs than those incurred to users; this may not be desirable. Moreover, rehabilitation and construction are often financed through federal money whereas maintenance activities are not. Agencies may desire to weigh maintenance costs more heavily.

In response to a survey of road agencies inquiring about the use of cost-effectiveness analysis for highway projects, the majority report that a cost-effectiveness index is only one of several factors considered in the decision process (Campbell 88). The general concern of agencies was that “a magic number can sometime hide as much as it reveals.”

The pavement type selection framework proposed in Chapter 2 of this report includes a partial list of miscellaneous factors that generally entail an overwhelming influence in real-life pavement type selection decisions. Sometimes these concerns are real, but they certainly can also be misplaced or exaggerated at other times. It is important to clearly understand the underlying objectives guarded by these factors. In this chapter we first discuss miscellaneous

factors that play a role in pavement type selection, and then present guidelines for use in final strategy selection.

7.2. AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS GUIDELINES

The American Association of State Highway and Transportation Officials Guide (AASHTO 93) reports that pavement type determination should properly be one of professional engineering judgment based on the consideration and evaluation of all factors applicable to a given highway section. The guide cautions that design methods are not absolutely precise and do not guarantee a certain level of performance from alternatives and comparable service for all alternatives. It emphasizes that LCCA procedures are also not precise because reliable data for subsequent stages of construction, maintenance, rehabilitation work, and salvage value are not always available. Also, economic analyses are altruistic in that they do not consider present or future financial capabilities of highway agencies. Even if structural design and economic analysis procedures were perfect, they would not by their nature encompass all factors affecting pavement type determination. The guide, however, supports the use of life-cycle cost comparisons where there are no overriding factors and where several alternative pavement types would serve satisfactorily.

The guide outlines several principal and secondary factors that influence pavement type selection. The principal factors include those factors that may have major influence and may dictate the pavement type in some instances. Some of these major factors are also incorporated in pavement design procedures. These factors include cost comparisons, traffic, subgrade soil characteristics, weather, construction considerations (speed of construction, traffic handling, ease of replacement, anticipated future widening, and season), opportunity to recycle material from an existing pavement structure, and potential of future recycling. The secondary factors include performance history of similar pavements in the area, adjacent existing pavements providing continuity of pavement type, availability of local materials, conservation of materials and energy, stimulation of competition, and municipal preference.

7.3. DISCUSSIONS OF MISCELLANEOUS FACTORS

This section discusses miscellaneous factors that generally affect type selection decisions. National and Texas survey results show that several miscellaneous factors are considered important in making type selection decisions (Beg 98):

- Traffic volume obtained the maximum importance ranking in both surveys.
- Both surveys present a similar ranking of factors.

Table 7.1 compares national and Texas Department of Transportation (TxDOT) survey responses for “always considered” in the pavement type selection category.

Table 7.1. Percentage of responses for “always considered” category of miscellaneous factors

Miscellaneous Factors	TxDOT Survey (%)	National Survey (%)
Traffic Volume	100	85
Constructability	89	76
Initial Budget Constraints	87	75
Soil Subgrade	87	77
Historical Practice	82	60
Easy Maintenance	63	60
Road Functional Classification	58	58
Pavement Continuity	54	44
Local Material	51	62
Traffic at M&R	38	48
Climate	36	58
Recycled Materials	17	47
Percent Truck Traffic	91	-

Traffic volume is important primarily because of the potential traffic delays occurring during construction activities. TxDOT survey results substantiate that interstate/high-volume/urban projects are typically built with both asphalt and portland cement concrete (PCC) pavements. On the other hand, farm-to-market/low-volume/rural projects are mostly

built with asphalt or seal coat pavements. Results show that seal coat pavements are widely considered (90 percent) for low-volume/rural and FM road projects, but are rarely considered (13 percent to 19 percent) for high-volume/urban or IH projects. Moreover, asphalt pavements are popular (64 percent to 81 percent) for all listed road classes. Rigid pavement types are rarely used in low-volume/rural/FM projects, while continuously reinforced concrete pavement (CRCP) is notably considered (64 percent) for high-volume/urban or IH projects. Table 7.2 presents these results. The rules of thumb based on the use of traffic volume may work in extreme traffic situations. However, using rules of thumb repeatedly without systematic evaluation of individual projects cannot be relied upon; a sound economic analysis is vital for the acceptance and accuracy of such decisions.

Table 7.2. Comparison of “yes” response for pavement types based on traffic volume and functional class

Pavement Types	High-Vol. / Urban Proj. (%)	IH Proj. (%)	Low-Vol. / Rural Proj. (%)	FM Proj. (%)
Seal Coat + Gran. Base	19	13	90	89
ACP + Gran. Base	76	62	81	80
Full Depth ACP	60	56	36	27
ACP + Stab. Base	81	67	74	73
CRCP	62	64	2	20
JRCP / JCP	29	28	7	11

The initial construction budget is a critical real-life constraint; consequently, implementation of LCCA is often hampered by initial funding constraints. Agencies should consider an unbiased set of feasible pavement strategies and then screen out the strategies that could be accomplished within the budget. Alternatively, agencies should also try to keep their project-level budget appropriations more amendable so that a better value strategy could be implemented.

Constructability is referred to as the expediency with which a facility can be constructed. It can be enhanced by the proper use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives

(CII 86). Most of the constructability issues are related to actual execution of the construction job, efficient scheduling, optimizing equipment productivity, and facilitating construction under traffic. It is recognized that some material types/layers are complex and take a longer time to build. For example, PCC construction (before pouring concrete) includes steel reinforcement, dowels, and joint layout; PCC pavements also require controlled curing before roadways are opened to traffic. On the other hand, flexible pavement construction appears simpler, though it generally requires more material layers. These contrasting inherent features of rigid and flexible pavement construction make it difficult to rank them on the basis of their constructability levels.

Maintainability is defined as the ease with which a facility or system can be maintained, or as the capacity to carry out maintenance with ease and minimum expenditure. Two basic aspects of maintainability are the mean time between maintenance actions — number of maintenance and rehabilitation (M&R) actions during the life cycle — and mean time to repair or activity duration. A lower value for both of these factors could mean a higher degree of maintainability. Identifying maintainability can, however, be difficult. For example, flexible pavements typically require more frequent maintenance treatments, though such maintenance is generally simpler and requires less time. The reverse is true for rigid pavements: While fewer maintenance actions are typically required, such maintenance is generally complex and requires more time. It is therefore difficult to assign maintainability preference to either flexible or rigid pavements as they both provide differing aspects of maintainability.

Historical practice is another important factor that generally affects type selection decisions within highway agencies. Responses to the Texas survey indicate that agencies tend to build pavements that, according to historical experience, have performed better in that region. Historical pavement choices are often based on the personal preferences of engineers rather than on strict rationality. To achieve maximum value for the money spent, it is important to provide an equal chance to all probable pavement type options for projects.

Continuity of pavement type is another factor based on the general opinion that similar pavement types will be more easily and cost effectively maintained in the long run.

The consideration of continuity of pavement type is closely related to the concept of economies of scale, which relate activity costs to the total quantity of work to be performed. The larger the quantity, the lower the unit cost. And while it is appropriate to use similar pavement types for short road sections, other potential options should also be considered in the case of longer road sections.

The use of local materials and recycled materials is also an important factor. The cost impacts of considering specific material types, however, should reflect an increase or decrease in costs and performance. Sometimes prevailing societal, environmental, and political concerns lead to favoring certain material types, though such concerns should be addressed on a special case basis. Few TxDOT districts report the common use of reclaimed existing pavement in rehabilitation and reconstruction projects. It is prudent that strategies using reclaimed materials compete with other candidate strategies through economic analysis; in cases of no significant cost difference, recycling options could be preferred.

Percent of truck traffic, subgrade soil type, and climatic conditions are primarily pavement design factors that are considered at the structural design stage of the project. Truck traffic largely contributes to equivalent single axle load (ESAL) calculations, which are a key input for pavement structural design. Other factors, such as subgrade soil type and climatic conditions, are also design-related factors that are part of most design methods.

7.4. EXAMPLES OF DEPARTMENTS OF TRANSPORTATION TYPE SELECTION GUIDELINES

Peterson reports (Peterson 85) that the California Department of Transportation requires an economic comparison of pavement types. Properly designed structural sections that would normally be approved for construction if they were selected are used in the economic comparisons. Exceptions to the requirement for an economic comparison are made under the following conditions:

- Where an existing pavement is to be widened or resurfaced with a similar material
- Where the area of new pavement is less than four lane miles

- Where unavoidable future flooding or a high water table dictates the use of portland cement concrete pavement
- Where it is economically unreasonable to locate and construct the highway so that unequal settlement or expansion will be eliminated, in which case asphalt concrete pavement must be used
- Where short freeway-to-freeway connections are made between similar types of pavement

The Ontario pavement selection policy emphasizes that the most appropriate pavement alternatives of both rigid and flexible pavement should be considered. The conservation of mineral aggregates and the use of local materials in candidate strategies are encouraged, with life-cycle costs of pavement alternatives evaluated as part of the process (He 94).

The New York DOT pavement type selection policy allows a threshold traffic limit of 35,000 AADT for considering alternatives with longer service life over lower service life without performing LCCA calculations. Other factors, such as traffic, drainage, soil type, environment, and design or construction constraints, are allowed for consideration in the decision process. A few DOTs allow a certain percentage — Nebraska 15 percent, Virginia 10 percent, Minnesota 5 percent — up to which all alternatives larger than the lowest cost alternative are considered equivalent. Other departments, for example those in Virginia and Washington, also allow the consideration of miscellaneous factors (traffic, construction consideration, recycling, or local materials), together with an LCCA. The Ohio DOT uses life-cycle cost and lane closure time for the final strategy selection (Beg 98).

7.5. COMBINED INDEX

A combined index is sometimes used to combine two or more evaluation attributes and to communicate a summary evaluation to relevant personnel. The primary use of composite indices is to convey summary information at the network level (Haas 94). While combined indices are common at the network level of pavement management, their use for

making project-level decisions is uncommon. Hudson et al. (Hudson 97) show in Figure 7.1 the levels of data that are generally appropriate to various levels of decisions for infrastructure management. The first level involves specific activities and technical engineering decisions for project evaluation and design of maintenance, rehabilitation, and reconstruction treatments. Pavement type selection evaluations fall under the first level in Figure 7.1. The second level involves aggregation and decisions for network-level pavement management. At this level, combined indices are useful for establishing priorities for the selection of projects at the network level. Composite indices are required at the third level, which involves administrative and political decisions. At this level aggregated data are typically needed to portray the overall quality of the network and to project future quality as related to budget.

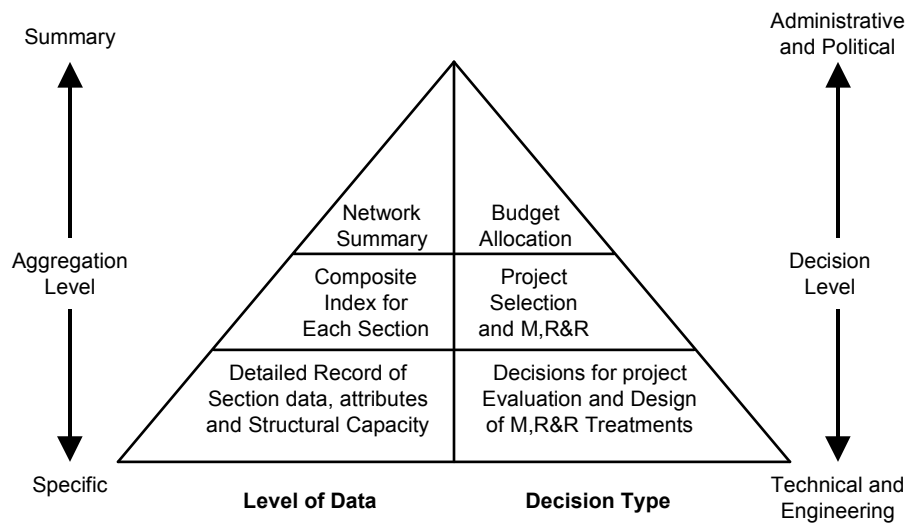


Figure 7.1. Data aggregation and level of decision

Based on the above arguments, it is suggested that consideration of any combined index, including economic and other factors, for pavement type selection would probably increase confusion rather than improve decision making. The combined index would mask strengths and weaknesses of alternatives with reference to individual factors. Moreover, the

development of such an index requires significant effort, expert panels, and explicit descriptions and logical rating scales for all relevant factors. Van Dam and Thurston (Van Dam 94) discuss the use of weighting methods that can be used either to supplement the LCCA or to replace it in evaluating candidate pavement strategies. They report that even though a weighing method allows considering nonmonetary design attributes in the analysis, a number of limitations still exist:

- The establishment of weighing factors is somewhat arbitrary and may not accurately reflect the true preferences of decision makers.
- Biases are easily introduced into the rating process, since alternatives are rated one after another in an open format.
- Preference is assumed to be linear over the entire range of the attribute. In reality, the preference could be nonlinear.
- Interactions between attributes are not readily identifiable and are typically ignored.

7.6. FINAL STRATEGY SELECTION GUIDELINES

The practices and examples from the literature of state DOTs provide a variety of useful guidelines for final pavement strategy selection. The following section outlines some suggestions for final strategy selection. It is recognized that actual implementation by the agency will suggest additional aspects that could be included in future guidelines. Moreover, considering the size of Texas and the different strategies practiced throughout the state, it is difficult to layout a specific set of final selection guidelines at this stage. Further experience with the implementation of the pavement type selection procedure will bring forward additional practical aspects that can be included in future guidelines.

Strategies displaying closer costs and cost-effectiveness ratios within 5 to 10 percent could be deemed equivalent, and other factors (traffic, local materials, and recyclability) could be considered along with economic outputs.

The impacts of some of the above-discussed miscellaneous factors would be indirectly considered at the time of generating candidate strategies; unfeasible options will not be included for economic comparisons. Moreover, to some extent the economic analysis addresses the impact of these factors in terms of increased or decreased costs or performance levels. Therefore, the miscellaneous factors can be used to complement the decision making, but certainly not to veto the carefully performed economic-based evaluations.

CHAPTER 8. TEXAS PAVEMENT TYPE SELECTION COMPUTER PROGRAM

This chapter describes the main features of the Texas Pavement Type Selection (TxPTS) computer program. An example case study is conducted using TxPTS, and the economic sensitivity of the results regarding the discount factor is evaluated.

8.1. DESCRIPTION OF THE TEXAS PAVEMENT TYPE SELECTION PROGRAM

TxPTS is written in Microsoft Visual Basic version 5.0. Visual Basic is an object-oriented programming language that allows for development of a user-friendly graphical user interface. Developed to automate the economic evaluation of candidate strategies, TxPTS features four primary windows used for input data and another window used for output calculations and ranking and printing options.

A window with *new* and *open* options is loaded by clicking on the program icon. Microsoft Access file format is used to store the input and output data files. The program imports a default input file each time the *new* project option is selected. The user can interactively edit the inputs and perform analysis. The user can add the required number of candidate-flexible and rigid pavement strategies for the project. Figure 8.1 shows the program's start-up windows.

8.1.1. Project Information Data

This window includes inputs for the project location and roadway facility data. Inputs include project description, district, county, highway, control begin, control end, project length, number of lanes, lane width, shoulder widths, and traffic direction. Users can interactively change the inputs to represent the scope of the current project. The roadway facility data are used to establish the total area and volume estimates that are used for agency cost calculations. This window also includes a pop-up window for default values for the following inputs: performance curve shape parameter (beta), discount factor, and minimum tolerable serviceability level. Figure 8.2 shows the program's project information window.

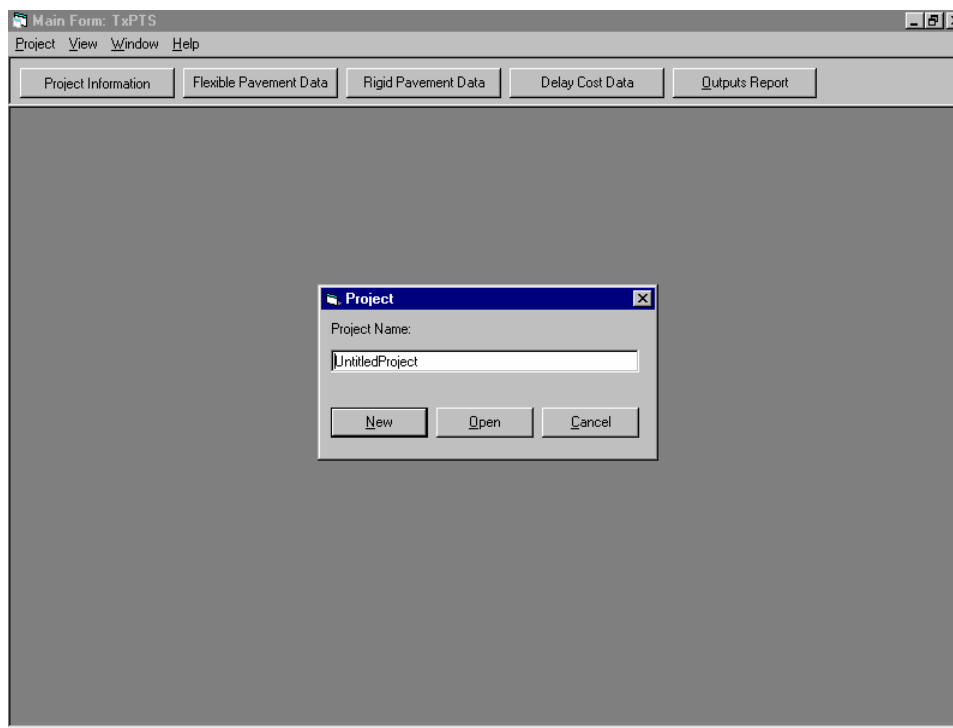


Figure 8.1. Main and project new/open windows

The screenshot shows the 'Main Form: TxPTS - [Project Information]' window. The 'Project Information' tab is active, displaying various input fields for project details.

Project Description: Reconstruction

Location Data

District:	Austin	Control Begin:	xxx
County:	Travis	Control End:	yyy
Highway:	USA 183		

Project Layout

Project Length (km): 10 Lane Width (m): 3.65

☒ S-bound ☒ N-bound
☐ W-bound ☐ E-bound

No. of Lanes: 2 No. of Lanes: 2

Shoulder Widths (m): 3.65 3.65 3.65 3.65

Default Inputs

Default input data for candidate strategies:

Figure 8.2. Project information window of the program

8.1.2. Flexible and Rigid Pavement Strategies Data

The program includes two nearly identical windows, one each for flexible and rigid pavement strategies data. For each strategy, the user provides input data for analysis period/life cycle and annual routine maintenance cost. Each strategy includes initial construction and several future maintenance and rehabilitation activities. For each individual activity, the user provides input data for the activity year, duration of activity, initial and terminal present serviceability index (PSI) levels, and performance periods. The data entries for initial and terminal PSI and performance period for preventive maintenance activities (seal coats, etc.) should be kept equal to zero insofar as no models currently available can represent the effect of preventive maintenance activities at PSI levels. The sum of the performance periods should be equal to the life cycle for each strategy. The user also specifies the quantity of materials used in each strategy. The list of material items includes two blank entries to cover any item not included in the default items list. The window also includes a pop-up window for providing material unit cost data. Figures 8.3 and 8.4 show the flexible and rigid strategies input data windows, respectively.

Main Form: TxPTS - [Flexible Pavement Strategies]

Project View Window Help

Project Information Flexible Pavement Data Rigid Pavement Data Delay Cost Data Outputs Report

Add Strategies
Clicking this button will load a default strategy dataset.
Add New Strategy

General Data
Material Unit Cost Data

Strategy	Life Cycle (yrs)	Routine Maint (\$/yr)
Flex 1	30.00	1,000.00
Flex 2	30.00	1,200.00
Flex 3	25.00	1,200.00

Flexible Pavement Strategies Data

Performance Related and Activity Duration Data

Strategy	Data Items	Ini Const	M&R 1	M&R 2	M&R 3	M&R 4	M&R 5	M&R 6
Flex 1	Activity Year, (Year)	0.00	10.00	15.00	20.00	0.00	0.00	0.00
Flex 1	Performance Period, (Years)	12.00	10.00	0.00	8.00	0.00	0.00	0.00
Flex 1	Initial Serviceability, (PSI)	4.50	4.50	0.00	4.50	0.00	0.00	0.00
Flex 1	Terminal Serviceability, (PSI)	3.00	3.00	0.00	3.00	0.00	0.00	0.00
Flex 1	Activity Duration, (Days)	270.00	120.00	60.00	120.00	0.00	0.00	0.00
Flex 2	Activity Year, (Year)	0.00	10.00	15.00	20.00	25.00	0.00	0.00

Materials Quantity (thickness, area, linear, lump-sum)

Strategy	Material Items	Ini Const	M&R 1	M&R 2	M&R 3	M&R 4	M&R 5	M&R 6
Flex 1	Asphalt Concrete, (MM)	150.00	100.00	0.00	100.00	0.00	0.00	0.00
Flex 1	Granular/Flex Base, (MM)	200.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Asphalt Treated Base, (MM)	175.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Cement Treated Base, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Lime Treated Base, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Subbase, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Treated Subbase, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Rework Exist Pav/Base, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Flex 1	Seal Coat, (%Area)	0.00	0.00	100.00	0.00	0.00	0.00	0.00
Flex 1	Asphalt Patching, (%Area)	0.00	1.00	1.00	2.00	0.00	0.00	0.00
Flex 1	Mobilization, (Lump Sum)	80,000.00	60,000.00	30,000.00	60,000.00	0.00	0.00	0.00

Figure 8.3. Flexible pavement strategies input data window

Main Form: TxPTS - [Rigid Pavement Strategies]

Project View Window Help

Project Information Flexible Pavement Data **Rigid Pavement Data** Delay Cost Data Outputs Report

Add Strategies
Clicking this button will load a default strategy dataset.
Add New Strategy

General Data
Material Unit Cost Data

Strategy	Life Cycle (yrs)	Routine Maint (\$/yr)
Rigid 1	35	1000
Rigid 2	35	1000

Rigid Pavement Strategies Data

Performance Related and Activity Duration Data

Strategy	Data Items	Ini Const	M&R 1	M&R 2	M&R 3	M&R 4	M&R 5	M&R 6
Rigid 1	Activity Year, (Year)	0.00	15.00	25.00	0.00	0.00	0.00	0.00
Rigid 1	Performance Period, (Years)	25.00	0.00	10.00	0.00	0.00	0.00	0.00
Rigid 1	Initial Serviceability, (PSI)	4.50	0.00	4.50	0.00	0.00	0.00	0.00
Rigid 1	Terminal Serviceability, (PSI)	2.50	0.00	2.50	0.00	0.00	0.00	0.00
Rigid 1	Activity Duration, (Days)	300.00	0.00	120.00	0.00	0.00	0.00	0.00
Rigid 2	Activity Year, (Year)	0.00	15.00	25.00	0.00	0.00	0.00	0.00

Materials Quantity (thickness, area, linear, lump-sum)

Strategy	Material Items	Ini Const	M&R 1	M&R 2	M&R 3	M&R 4	M&R 5	M&R 6
Rigid 1	RCC, (MM)	300.00	0.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Subbase, (MM)	150.00	0.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Asphalt Treated Subbase, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Cement Treated Subbase, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Lime Treated Subbase, (MM)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Asphalt Concrete, (MM)	0.00	0.00	100.00	0.00	0.00	0.00	0.00
Rigid 1	Concrete Patching, (% Area)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Asphalt Patching, (% Area)	0.00	1.00	2.00	0.00	0.00	0.00	0.00
Rigid 1	Clean & Seal Joints/Cracks, (M)	0.00	60,000.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Mobilization, (Lump Sum)	100,000.00	30,000.00	0.00	0.00	0.00	0.00	0.00
Rigid 1	Detour & Traffic Handling, (LS)	50,000.00	15,000.00	0.00	0.00	0.00	0.00	0.00

Figure 8.4. Rigid pavement strategies input data window

8.1.3. Delay Cost Data

The input data for delay cost calculations include average daily traffic (ADT), truck percentage, annual traffic growth, lane capacity, work zone length, unrestricted approach speed, capacity speed, unit delay cost for cars and trucks, directional distribution, open lanes through work zones, work zone posted speed, hours of work zone operations, and hourly traffic distribution. The program allows users to choose whether one or both directions are affected by the work zone operation. Figure 8.5 shows the delay cost input data window.

Main Form: TxPTS - [Delay Cost Data]

Project View Window Help

Project Information Flexible Pavement Data Rigid Pavement Data **Delay Cost Data** Outputs Report

Delay Cost Inputs

Base Year ADT Both Dir (veh): 20000 Approach Speed (km/hr): 110

Trucks (%): 15 Workzone Length (km): 1

Annual Traffic Growth (%): 3 Unit Delay Cost Car (\$/per-hr): 10

Lane Capacity (vphpl): 1600 Unit Delay Cost Truck (\$/per-hr): 22

Workzone Methodology

☐ Lane Closure in One Direction ☒ Lane Closure in Both Direction

Southbound Directional Traffic Data

Directional Distribution (%): 50

Open Lanes including temp lanes and shoulders: 2

WZ Running Speed (km/hr): 70

WZ Active From (hr#): 0 To (hr#): 23

Hour #	Hour	% ADT
0	00 to 01	1.00
1	01 to 02	1.00
2	02 to 03	1.00
3	03 to 04	1.00
4	04 to 05	1.00
5	05 to 06	2.00
6	06 to 07	5.00
7	07 to 08	8.00

Check Sum (should be 100): 100

Northbound Directional Traffic Data

Directional Distribution (%): 50

Open Lanes including temp lanes and shoulders: 2

WZ Running Speed (km/hr): 70

WZ Active From (hr#): 0 To (hr#): 23

Hour #	Hour	% ADT
0	00 to 01	1.00
1	01 to 02	1.00
2	02 to 03	1.00
3	03 to 04	1.00
4	04 to 05	1.00
5	05 to 06	2.00
6	06 to 07	5.00
7	07 to 08	8.00

Check Sum (should be 100): 100

Figure 8.5. Delay cost data window

8.1.4. Outputs and Ranking

This window allows users to calculate the economic outputs that include initial agency cost, life-cycle agency cost, total life-cycle cost, cost-effectiveness ratio based on agency LCC, and the cost-effectiveness ratio based on total LCC. The program allows users to rank strategies based on any of these outputs.

Several report-printing options are provided. Users can print ranking reports, strategy data, and project information data. Figure 8.6 shows the output calculation and ranking window. Figure 8.7 shows a pop-up report of ranked strategies.

Main Form: TxPTS - [Outputs & Reports]

Project View Window Help

Project Information Flexible Pavement Data Rigid Pavement Data Delay Cost Data Outputs Report

Outputs

Calculate Pavement Strategies Outputs: Sorting Pavement Strategies Outputs:

Description	Initial Agency Cost (\$)	Annual Agency LCC (\$)	Annual Tot LCC (\$)	Cost Eff Index (Ag)	Cost Eff Index (Tot)
Strategy	Init-Ag-Cost	Ag-LCC	Tot-LCC	CE-Ag	CE-Tot
Flex 1	9,464,000.00	909,448.40	936,163.30	489,160.26	503,529.27
Flex 2	7,712,000.00	828,734.37	857,808.69	526,358.92	544,825.07
Flex 3	6,690,000.00	787,386.29	814,634.75	484,577.03	501,346.40
Rigid 1	11,282,500.00	911,976.95	937,445.28	539,832.14	554,907.77
Rigid 2	12,195,000.00	951,452.20	976,920.54	502,874.14	516,335.00

Reports

Project Information and Delay Cost Data

Flexible Pavement Strategies Data Rigid Pavement Strategies Data

Life Cycle and Routine Maint Data
Performance and Duration Data
Materials Quantity Data
Materials Unit Cost Data

Life Cycle and Routine Maint Data
Performance and Duration Data
Materials Quantity Data
Materials Unit Cost Data

Strategies Ranking Criteria

Init-Ag-Cost
Ag-LCC
Tot-LCC
CE-Ag
CE-Tot

Figure 8.6. Project output calculations and ranking and printing options window

Main Form: TxPTS - [Outputs & Reports]

Project View Window Help

Project Information Flexible Pavement Data Rigid Pavement Data Delay Cost Data Outputs Report

Outputs

Calculate Pavement Strategies Outputs: Sorting Pavement Strategies Outputs:

TxDOT Pavement Type Selection 11/11/98

Strategies Ranked According to Total Life Cycle Cost (\$ Annu

Strategy	Init-Ag-Cost (\$)	Ag-LCC (\$-Ann)	Tot-LCC (\$-Ann)	CE Ratio-Ag	CE Ratio-Tot
Flex 3	6,690,000.00	787,386.29	814,634.75	484,577.03	501,346.40
Flex 2	7,712,000.00	828,734.37	857,808.69	526,358.92	544,825.07
Flex 1	9,464,000.00	909,448.40	936,163.30	489,160.26	503,529.27
Rigid 1	11,282,500.00	911,976.95	937,445.28	539,832.14	554,907.77
Rigid 2	12,195,000.00	951,452.20	976,920.54	502,874.14	516,335.00

1 of 1 5 of 5 Total: 5 100%

Reports

Project Information and Delay Cost Data

Flexible Pavement Strategies Data Rigid Pavement Strategies Data

Life Cycle and Routine Maint Data
Performance and Duration Data
Materials Quantity Data
Materials Unit Cost Data

Life Cycle and Routine Maint Data
Performance and Duration Data
Materials Quantity Data
Materials Unit Cost Data

Strategies Ranking Criteria

Init-Ag-Cost
Ag-LCC
Tot-LCC
CE-Ag
CE-Tot

Figure 8.7. A sample ranking report printing window

8.2. AN EXAMPLE CASE STUDY AND ECONOMIC SENSITIVITY

We conducted an example case study using TxPTS for a hypothetical reconstruction project. Five design strategies, three flexible and two rigid, were evaluated using TxPTS. The objective of this example is to demonstrate the use of the program.

The flexible pavement system (FPS19) was used to determine the initial construction sections for flexible pavement strategies. Pavement design option 3 (asphalt concrete over asphalt base over flexible base) in FPS19 is used to generate Flex 1 and Flex 2 strategies. Terminal serviceability levels of 3.0 and 2.5 are used for Flex 1 and Flex 2, respectively. Pavement design option 2 (asphalt concrete over asphalt base) in FPS19 is used to generate Flex 3 strategy with a terminal serviceability of 2.5. Appropriate overlay, seal coat, and routine maintenance policies are established for each strategy.

Table 8.1 shows some basic design variables used to develop initial construction structural sections. Table 8.2 shows general project data. Table 8.3 reflects delay cost inputs used in the case study. Unit material cost estimates are based on personal contacts with Texas Department of Transportation (TxDOT) engineers and on historical bid averages posted at the TxDOT web page.

Table 8.1. Typical design data

Design Variables	Values
Reliability Factor	95%
Initial Serviceability, P_i	4.5
Initial Year ESALs (Both Directions)	1 million
Growth Factor	3%
Directional Distribution	50%

Table 8.2. Project data

Project Data	Value
Project Length (km)	10
Lane Width (m)	3.65
Total number of lanes	4
Total Shoulder Width (m)	14.6

Table 8.3. Delay cost data

Delay Cost Data	Value
Base year ADT both directions	20,000
Truck percent (%)	15
Traffic growth rate (%)	3
Lane capacity (vphpl)	1,600
Approach speed (km/hr)	110
Capacity speed (km/hr)	30
Work zone length (km)	1
Unit delay cost for cars (\$/veh-hr)	10
Unit delay cost for trucks (\$/veh-hr)	23
Directional distribution (%)	50
Number of Open lanes	2
Posted speed (km/hr)	70

Table 8.4 shows the life cycles/analysis period for each strategy. Tables 8.5 to 8.9 show data for future maintenance and rehabilitation (M&R) activity years, performance periods, and terminal serviceability.

Table 8.4. Candidate strategies' life cycles

Strategy	Life Cycle (years)
Flex 1	30.00
Flex 2	30.00
Flex 3	25.00
Rigid 1	35.00
Rigid 2	35.00

Table 8.5. Flex 1 life-cycle activities

Data Items	Ini Const	Overlay	Seal Coat	Overlay
Activity Year (Year)	0.00	12.00	17.00	22.00
Performance Period (Years)	12.00	10.00	0.00	8.00
Terminal Serviceability (PSI)	3.00	3.00	0.00	3.00

Table 8.6. Flex 2 life-cycle activities

Data Items	Ini Const	Overlay	Seal Coat	Overlay	Seal Coat
Activity Year (Year)	0.00	10.00	15.00	20.00	25.00
Performance Period (Years)	10.00	10.00	0.00	10.00	0.00
Terminal Serviceability (PSI)	2.50	2.50	0.00	2.00	0.00

Table 8.7. Flex 3 life cycle activities

Data Items	Ini Const	Overlay	Overlay
Activity Year (Year)	0.00	10.00	18.00
Performance Period (Years)	10.00	8.00	7.00
Terminal Serviceability (PSI)	2.50	2.50	2.50

Table 8.8. Rigid 1 life-cycle activities

Data Items	Ini Const	Maint.	Overlay
Activity Year (Year)	0.00	15.00	25.00
Performance Period (Years)	25.00	0.00	10.00
Terminal Serviceability (PSI)	2.50	0.00	2.50

Table 8.9. Rigid 2 life-cycle activities

Data Items	Ini Const	Maint.	Overlay
Activity Year (Year)	0.00	15.00	25.00
Performance Period (Years)	25.00	0.00	10.00
Terminal Serviceability (PSI)	3.00	0.00	3.00

A sensitivity analysis consists of checking the effects of variations in constituent variables on the value of the outputs. Such an analysis is primarily a procedure for identifying the variables that most influence outputs and the extent of their influence. We used three values — 3 percent, 6 percent, and 9 percent — of discount factors to check the sensitivity of strategies' rankings. Table 8.10 presents the normalized comparison among candidate alternatives.

Flex 2 comes out economically superior among all alternatives. The difference between Flex 2 and the others is much narrower in the case of 3 percent discount rate, compared with 6 percent or 9 percent. Rigid 2 comes out better than Flex 2 on the basis of cost effectiveness at a 3 percent discount rate, but huge savings in initial cost continue to make Flex 2 the most favorable alternative. It is observed that low interest rates favor those alternatives that combine large initial investments with lower future costs, whereas high interest rates favor reverse combinations. Forecasts are less significant when interest rates are higher and time periods are longer.

Table 8.10. Comparison of strategies according to the choice of discount factor

Discount Factor	Strategy	Initial Cost	Total LCC	CE Index (Tot-LCC based)
9%	Flex 1	1.41	1.20	1.05
	Flex 2	1.15	1.08	1.11
	Flex 3	1	1	1
	Rigid 1	1.69	1.26	1.21
	Rigid 2	1.82	1.34	1.15
6%	Flex 1	1.41	1.15	1.01
	Flex 2	1.15	1.05	1.09
	Flex 3	1	1	1
	Rigid 1	1.69	1.15	1.11
	Rigid 2	1.82	1.20	1.03
3%	Flex 1	1.41	1.09	1.06
	Flex 2	1.15	1.03	1.18
	Flex 3	1	1	1.11
	Rigid 1	1.69	1.03	1.10
	Rigid 2	1.82	1.05	1

CHAPTER 9. CONCLUSIONS AND FUTURE DIRECTIONS

9.1. CONCLUSIONS

The research and work documented herein produced the following conclusions and recommendations.

- The pavement type selection procedure will enable the Texas Department of Transportation (TxDOT) to meet the Federal Highway Administration (FHWA) policy guidelines, and will enable TxDOT engineers to make rational decisions that make the best use of taxpayers' dollars.
- The use of an economic-based pavement type selection procedure has significant potential for improving pavement type selection decisions within TxDOT. The procedure is based on evaluating and integrating three basic factors — agency costs, user delay costs, and pavement performance — in a rational pavement type selection process. For the multicriteria decision environment, the pavement type selection method is able to evaluate trade-offs among these factors.
- The procedure provides a range of useful output economic indicators, such as initial construction cost, agency life-cycle cost, total life-cycle cost, and cost-effectiveness index, for comparing candidate strategies.
- Best available performance information should be used to establish the estimates for strategies' materials and performance data. Structural design systems, flexible pavement system (FPS19) and rigid pavement design system, TSLAB, and historical performance data should be used to establish reasonable estimates of initial construction and overlay performance prediction. Local seal coat and routine maintenance policies must also be included in strategies.
- Vehicle operating costs (VOCs) are not included in the Texas Pavement Type Selection (TxPTS) program. Previous studies indicate that the effects of VOC are more significant when comparing paved versus unpaved roads. Their results show that when pavements are constructed and maintained at reasonable performance levels, the VOC differences among pavements are small.

- The use of equivalent uniform annual cost (EUAC) allows the flexibility to evaluate strategies with unequal life-cycle/analysis periods for candidate strategies.
- The cost-effectiveness evaluation method provides a logical method for evaluating the cost-performance trade-off among strategies. The area under the performance curve provides an accepted surrogate of “benefits” or “effectiveness” of pavement strategies.
- The sigmoid-form-based generic equation provides a robust tool for estimating the annual average present serviceability index (PSI) of strategies. The cost-effectiveness evaluation based on equivalent uniform annual cost and annual average PSI provides a dependable method for evaluating cost-performance trade-offs.
- The final strategy selection should primarily be based on the economic indicators. The decision should be the one that also uses engineering judgment, honest consideration of project constraints, and impacts of miscellaneous factors in reaching the final decision.

9.2. FUTURE DIRECTIONS

9.2.1. Implementation and Training

TxDOT should sponsor hands-on implementation of the TxPTS program. The true benefit of the method can best be achieved through a coordinated and well-structured implementation effort involving the research staff. Some training sessions will also be required to demonstrate the use of TxPTS to engineers.

9.2.2. Integrated Pavement Design and Pavement Type Selection

Pavement type selection is closely related to pavement design. One main difference is that the level of information and detail required for proper engineering design is greater than that required for pavement type selection evaluations. Currently, TxDOT has stand-alone programs for flexible and rigid pavement design. TSLAB is a simple program, while

FPS19 is a comprehensive structural design system. For the pavement type selection process, it may prove cumbersome to run typical FPS19 solutions through TxPTS. The current version of TxPTS provides user flexibility in inputting candidate strategies. This flexibility, however, becomes a limitation in that TxPTS lacks readily available pavement performance estimates and proper structural sections. The feasibility of adding pavement design methods to TxPTS should be investigated in future research efforts. This format would allow the automatic generation of candidate strategies. TxPTS can then evaluate these strategies based on the established economic procedures.

9.2.3. Modeling Uncertainty in Economic Analysis

Pavements are inherently variable in their performance as a result of such factors as traffic variability, difference between “as designed” and “as built” material properties, and lack of fit in prediction models. Climatic variations, increases in load limits, and changes in vehicle technology also have an impact. Sources of inaccuracy in life-cycle cost analysis (LCCA) are cost estimates used in computations and relative inaccuracy of future rehabilitation and maintenance costs. Similarly, user cost calculations are subject to uncertainty resulting from the variability in such factors as traffic, construction activity duration, and monetary value of time delay. The potential use of Monte Carlo simulations and other uncertainty modeling techniques should be investigated. Eventually the fixed value output estimates may be replaced by estimated confidence intervals. Important related issues would involve estimating standard deviations of input factors and their associated probability distributions.

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APPENDIX A:
CASE STUDY DATA

CASE STUDY DATA

The following tables show the remaining input and output data for the case study presented in Chapter 8. Tables A.1 to A.5 show the material items data for flexible and rigid pavement strategies. Tables A.6 and A.7 show the unit costs for flexible and rigid pavement material items. Tables A.8 to A.10 show the values of TxPTS outputs for three values of discount factor.

Table A.1. Flex 1 material items data

Strategy	Material Items	Ini Const	M&R 1	M&R 2	M&R 3
Flex 1	Asphalt Concrete, (MM)	150.00	100.00	0.00	100.00
Flex 1	Granular/Flex Base, (MM)	200.00	0.00	0.00	0.00
Flex 1	Asphalt Treated Base, (MM)	175.00	0.00	0.00	0.00
Flex 1	Seal Coat, (%Area)	0.00	0.00	100.00	0.00
Flex 1	Asphalt Patching, (%Area)	0.00	1.00	1.00	2.00
Flex 1	Mobilization, (Lump Sum)	80,000.00	60,000.00	30,000.00	60,000.00
Flex 1	Detour & Traffic Handling, (LS)	40,000.00	30,000.00	15,000.00	30,000.00

Table A.2. Flex 2 material items data

Strategy	Material Items	Ini Const	M&R 1	M&R 2	M&R 3	M&R 4
Flex 2	Asphalt Concrete, (MM)	100.00	100.00	0.00	100.00	0.00
Flex 2	Granular/Flex Base, (MM)	200.00	0.00	0.00	0.00	0.00
Flex 2	Asphalt Treated Base, (MM)	150.00	0.00	0.00	0.00	0.00
Flex 2	Seal Coat, (%Area)	0.00	0.00	100.00	0.00	100.00
Flex 2	Asphalt Patching, (%Area)	0.00	1.00	1.00	2.00	2.00
Flex 2	Mobilization, (Lump Sum)	80,000.00	60,000.00	30,000.00	60,000.00	30,000.00
Flex 2	Detour & Traffic Handling, (LS)	40,000.00	30,000.00	15,000.00	30,000.00	15,000.00

Table A.3. Flex 3 material items data

Strategy	Material Items	Ini Const	M&R 1	M&R 2
Flex 3	Asphalt Concrete, (MM)	100.00	100.00	100.00
Flex 3	Asphalt Treated Base, (MM)	200.00	0.00	0.00
Flex 3	Asphalt Patching, (%Area)	0.00	2.00	2.00
Flex 3	Mobilization, (Lump Sum)	80,000.00	60,000.00	60,000.00
Flex 3	Detour & Traffic Handling, (LS)	40,000.00	30,000.00	30,000.00

Table A.4. Rigid 1 material items data

Strategy	Material Items	Ini Const	M&R 1	M&R 2
Rigid 1	RCC, (MM)	275.00	0.00	0.00
Rigid 1	Subbase, (MM)	150.00	0.00	0.00
Rigid 1	Asphalt Concrete, (MM)	0.00	0.00	100.00
Rigid 1	Concrete Patching, (% Area)	0.00	0.00	2.00
Rigid 1	Asphalt Patching, (% Area)	0.00	1.00	2.00
Rigid 1	Clean & Seal Joints/Cracks, (M)	0.00	60,000.00	60,000.00
Rigid 1	Mobilization, (Lump Sum)	100,000.00	30,000.00	60,000.00
Rigid 1	Detour & Traffic Handling, (LS)	50,000.00	15,000.00	30,000.00

Table A.5. Rigid 2 material items data

Strategy	Material Items	Ini Const	M&R 1	M&R 2
Rigid 2	RCC, (MM)	300.00	0.00	0.00
Rigid 2	Subbase, (MM)	150.00	0.00	0.00
Rigid 2	Asphalt Concrete, (MM)	0.00	0.00	100.00
Rigid 2	Asphalt Patching, (% Area)	0.00	1.00	2.00
Rigid 2	Clean & Seal Joints/Cracks, (M)	0.00	60,000.00	60,000.00
Rigid 2	Mobilization, (Lump Sum)	100,000.00	30,000.00	60,000.00
Rigid 2	Detour & Traffic Handling, (LS)	50,000.00	15,000.00	30,000.00

Table A.6. Flexible material items unit cost data

Material Items	Unit Cost
Asphalt Concrete, (\$/M3)	90.00
Granular/Flex Base, (\$/M3)	35.00
Asphalt Treated Base, (\$/M3)	65.00
Seal Coat, (\$/M2)	1.50
Asphalt Patching, (\$/M2)	80.00
Mobilization, (unit)	1.00
Detour & Traffic Handling, (unit)	1.00

Table A.7. Rigid material items unit cost data

Material Items	Unit Cost
RCC, (\$/M3)	100.00
Subbase, (\$/M3)	25.00
Asphalt Concrete, (\$/M3)	80.00
Concrete Patching, (\$/M2)	250.00
Asphalt Patching, (\$/M2)	80.00
Clean & Seal Joints/Cracks, (\$/M)	5.00
Mobilization, (unit)	1.00
Detour & Traffic Handling, (unit)	1.00

Table A.8. TxPTS outputs using 3% discount rate

Strategy	Init-Ag-Cost	Ag-LCC	Tot-LCC	CE-Ag	CE-Tot
Flex 1	9,464,000.00	726,284.64	749,753.37	390,642.93	403,265.93
Flex 2	7,712,000.00	680,441.90	706,381.02	432,173.05	448,647.92
Flex 3	6,690,000.00	664,583.52	688,219.49	409,001.16	423,547.32
Rigid 1	11,282,500.00	689,037.24	709,318.46	407,866.06	419,871.25
Rigid 2	12,195,000.00	699,052.30	719,333.52	369,472.39	380,191.69

Table A.9. TxPTS outputs using 6% discount rate

Strategy	Init-Ag-Cost	Ag-LCC	Tot-LCC	CE-Ag	CE-Tot
Flex 1	9,464,000.00	909,448.40	936,163.30	489,160.26	503,529.27
Flex 2	7,712,000.00	828,734.37	857,808.69	526,358.92	544,825.07
Flex 3	6,690,000.00	787,386.29	814,634.75	484,577.03	501,346.40
Rigid 1	11,282,500.00	911,976.95	937,445.28	539,832.14	554,907.77
Rigid 2	12,195,000.00	951,452.20	976,920.54	502,874.14	516,335.00

Table A.10. TxPTS outputs using 9% discount rate

Strategy	Init-Ag-Cost	Ag-LCC	Tot-LCC	CE-Ag	CE-Tot
Flex 1	9,464,000.00	1,118,828.18	1,149,327.94	601,778.27	618,183.02
Flex 2	7,712,000.00	996,672.15	1,029,430.26	633,022.23	653,828.08
Flex 3	6,690,000.00	925,374.65	956,712.61	569,498.48	588,784.64
Rigid 1	11,282,500.00	1,175,431.37	1,207,110.66	695,780.34	714,532.46
Rigid 2	12,195,000.00	1,245,763.49	1,277,442.78	658,427.44	675,171.00

