NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 122

LIFE-CYCLE COST ANALYSIS OF PAVEMENTS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **122**

LIFE-CYCLE COST ANALYSIS OF PAVEMENTS

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TRANSPORTATION RESEARCH BOARD
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WASHINGTON, D.C. DECEMBER 1985

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to pavement designers, maintenance engineers, and others concerned with selection of pavement designs and pavement rehabilitation alternatives. Information is presented on how life-cycle costing can be used to select the alternative that is least expensive over time.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

For any given paving project, there are several possible combinations of construction materials and layer thicknesses that are capable of providing the required performance. This report of the Transportation Research Board describes what life-cycle costing is and how it can be used to compare all significant costs of each pavement design alternative over the life of the pavement.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

LIFE-CYCLE COST ANALYSIS OF PAVEMENTS

SUMMARY

To evaluate the economics of a paving project, an analysis should be made of potential design alternatives, each capable of providing the required performance. If all other things are equal, the alternative that is the least expensive over time should be selected; that is, the design engineer should try to find the design that will serve the needs of the traffic volume and loads for a given level of service for the lowest cost over time. Life-cycle costing is defined as an economic assessment considering all significant costs of ownership over the economic life, expressed in terms of discounted dollars.

In general, life-cycle costs include all costs anticipated over the life (or analysis period) of the facility. The analysis requires identifying and evaluating the economic consequences of various alternatives over time. There are several economic analysis methods that can be used for comparing alternatives but discounted cash-flow methods (present worth, annualized cost, and rate of return) are most often used. Benefit-cost ratio, break-even analysis, payback period, and capitalized cost methods are used less often. Factors that will influence the analysis results include inflation, discount rate, and analysis period.

Some of the components of the economic analysis will be well known (e.g., current construction costs) but others will be highly uncertain (e.g., future maintenance activities, intervals, and costs). Methods of decision analysis are available to help in making estimates for items for which there is uncertainty. A sensitivity analysis can be performed to determine which variables have the most influence on the cost of an alternative.

Of 49 North American agencies responding to a survey for this synthesis, 22 specifically stated that they use some method of life-cycle costing in selecting pavement alternatives. Another nine agencies that claim not to be using life-cycle costing do use present-worth or annualized cost methods for selection; these are economic analysis methods used in life-cycle costing. Cost elements most often used in analyses were construction, rehabilitation, and maintenance; salvage value and user costs were used by several agencies and a few included user costs and energy. Pavement management systems are not yet providing data useful to pavement selection but are expected to do so in the future.

Identification of the potential alternatives that will satisfy the design requirements entails a thorough understanding of the problems and design parameters for the specific pavement being considered. The principles of value engineering can be used to help generate alternatives. The most promising alternatives are selected for further analysis, making certain that those selected will meet the required objectives. The analysis will

require the ability to predict the useful life of a pavement (time until major rehabilitation or reconstruction is needed), selection of analysis period (normally 25 to 40 years for new pavements, less for rehabilitation), cost factors (design, construction, maintenance, rehabilitation, user costs, salvage value), evaluation of design alternatives, and selection of the final design alternative.

CHAPTER ONE

INTRODUCTION

How to make the most effective use of all types of resources has been of great concern in most, if not all, areas affecting our way of life. This is equally true in the design, construction, and maintenance of transportation facilities as it is in other areas. There has been a great concern in recent years over the costs of highway construction, maintenance, and rehabilitation. There is a need to make economically sound decisions concerning proposed expenditures so that the most cost-effective alternatives can be selected.

The process for evaluating the economy of any engineering project includes analyzing all potential alternatives for completing the project. Each alternative should be capable of fulfilling the function required of it. If all other things are equal, the design alternative that is the least expensive over time should be selected.

McManus, in his paper related to pavement construction and maintenance cost trade-offs, stated:

> Often designers try to design pavements that are inexpensive and that are expected to last forever, without consideration of the resulting maintenance and reconstruction costs. Clearly pavements have finite and widely varying service lives that will affect these costs. Thus, designers should consider the consequences of the variability of design parameters in choosing design values (*1*).

Engineering economics generally means a type of formal analysis where the time value of money is considered and where the analysis adheres to well-recognized procedures. Design engineers are practicing engineering economy when they estimate the cost of one design alternative to accomplish a given objective and compare it with the cost of other alternative designs. Alternative designs to achieve the same objective may be constructed of different materials or they may vary in layer thicknesses and components. Design engineers try to find the design that will serve the needs of the traffic volume and loads for a given level of service for the lowest construction and maintenance costs over time (*2*).

In a paper on evaluating alternative highway maintenance standards, Harral et al. (*3*) asked the following pointed questions:

> But how are we to estimate the economic returns to maintenance outlays? What is the benefit to society of another dollar spent on maintenance compared to another dollar spent on new roads or improvements, or new investments in some other sector? Is it more economical to spend a bit more money to construct a stronger pavement initially and thereby save future outlays on maintenance or, alternatively should we follow a stage construction strategy, economizing on the initial construction and paying a bit more in the way of maintenance and upgrading cost later on, when uncertainties about traffic growth will have been resolved? How much, or how little, should we spend to maintain paved roads and how much to maintain gravel and earth roads? (*3*)

A more direct question related to the subject of this synthesis might well be: How is the most cost-effective design for a pavement selected given different alternative choices consisting of several different materials, with varying performance characteristics, and with differing future maintenance needs and costs? Life-cycle costing is a relatively new term for a procedure that is an important tool in answering the above questions.

Life-cycle costing has been defined as an "economic assessment of an item, area, system, or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars" (*4*). Lindow of the Construction Engineering Research Laboratory defined life-cycle design as an "analysis which considers the construction, operation, and maintenance of a facility during its entire design life" (*5*).

BACKGROUND

Highway engineering economics is not a new innovation but started more than a century ago when Gillespie prepared his *Manual of the Principles and Practice of Road Making* in 1847. Gillespie stated in his manual that a "minimum of expense is, of course, highly desirable; but the road which is truly the cheapest is not the one which has cost the least money, but the one which makes the most profitable returns in proportion to the amount expended upon it" (*6*). A book written by Wellington in 1877 (*7*) has been referred to as the start of engineering economics in this country. The first major emphasis in highway engineering economics began about 1920 at the start of the automotive era. Research was initiated at that time on such activities as the effect of line and grade of the roadway on fuel consumption. One of the primary objectives of this study was to demonstrate the relative economy of paved or gravel surfaces with the very common dirt roads of the time. Highway engineering economics has been studied and researched almost continuously since its serious beginning in 1920. In the 1950s, additional effort was given to improving the methods of analysis and to collecting and updating data (*2*).

The use of the term life-cycle cost is relatively recent and it has become very popular in many areas of our society. This appears to be primarily because of the need to minimize the costs of a facility over time. Lindow (*5*) stated: "Facility design and maintenance based on life-cycle cost analyses have been justified from economic and serviceability standards." Florida reported that life-cycle cost "is the preferred analytical approach for performing economic comparisons of alternative pavement designs" (*8*).

PROBLEM

Many techniques have been used over the years in selecting pavement design alternatives. Many of the agencies have based their selection strictly on first cost without consideration for future cost or pavement performance. For long-term investments, such as for pavements, the initial or first cost may not be the most critical issue. Life-cycle costs are dependent on projected performance or life of the various identified alternatives; the type, life, and cost of future maintenance and/or restoration activities; the length of analysis period; interest rates; inflation; etc. These all need to be integrated into a procedure that will ensure the lowest life-cycle cost for a given facility. Any savings that may result from lower life-cycle costs for a project, when multiplied by the amount of paving material used and number of projects constructed each year, would result in millions of dollars in annual savings throughout the United States.

RESEARCH APPROACH

The information for this synthesis was obtained through a survey of practice sent to highway and transportation departments in the United States and Canada; through personal contacts and interviews; and through an extensive literature search. Procedures used by a number of states or provinces in selecting pavement design alternatives were reviewed. The information was then prepared in synthesis form.

CHAPTER TWO

ENGINEERING ECONOMICS

A major function of engineering economics is to make decisions or to choose between alternatives when there is to be an expenditure of capital funds. Engineering economics studies are done because of a need for choosing among several alternative plans for satisfying some objective of providing a specified level of service (*9*). The differences in cost among alternatives over a given time period are a significant part of an economic analysis. A general procedure for conducting an economic study consisting of three steps is described as follows:

1. Identify and define the different alternatives among which a selection is to be made.
2. Identify and define the various elements or factors that may result in differences in the cost of the alternatives and remove from further consideration all events that have happened or may happen regardless of which alternative is selected.
3. Reduce all of the alternatives to a comparable basis by translating all of the applicable factors to a common dollar base and then make a cost comparison among the alternatives over time, considering the time value of money through the use of compound interest (*10*).

One very basic question concerning a proposed capital investment is whether the investment is likely to be recovered along with some financial return commensurate with the risk for making the investment and in comparison with the return that could have been obtained from other possible investment opportunities. Calculations that consider the time value of money are helpful in providing solutions to this question (*11*).

Engineering managers today are increasingly more concerned about the cost of pavements and the effects of different funding levels. As a result, there is a greater need to evaluate and compare alternative choices for achieving established goals and to minimize the costs over the life of the facility. Figure 1 is illustrative of many of the items that influence the process of making choices (*12*).

Oglesby and Hicks (*6*) pointed out that:

> An economy study must first answer the question: "Why do it at all?" In other words, does the proposed improvement represent an attractive investment when compared with other possible uses of available resources? Where there is only one plan for a particular improvement, a favorable answer clearly indicates that the project is desirable. However, where there are alternative methods for improvement, a second question is in order. It is "Why do it this way?" or "Which of the proposals is the best?" This is answered by finding whether the *increment* of investment between cheaper and more expensive plans also appears attractive. By successively eliminating those proposals that fail either the first or the second of these tests, the best of the lot may be found.

It is very important that economic studies be placed in their proper framework or perspective. If this is not done, or if it is done incorrectly, then the most ideal procedures or the most exact data will provide erroneous results. Oglesby and Hicks generated a set of guidelines that are recommended for use in developing a framework. These are:

> 1. Economy studies are concerned with forecasting the future consequences of possible investments of resources. Past happenings, unless they affect the future, are not considered.
> 2. Each alternative among which choices are to be made must be fully and clearly spelled out.
> 3. The viewpoint taken in the analysis must be defined and observed (*7*).

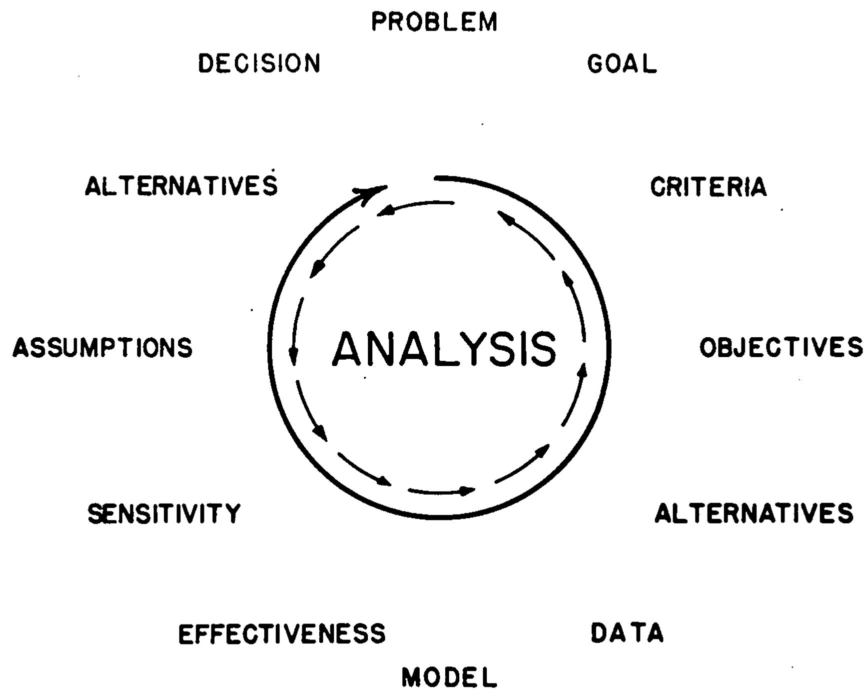


FIGURE 1 Systems analysis diagram (*12*).

This chapter includes discussion on a number of economic concepts covering the overall economic analysis procedure and its component parts.

LIFE-CYCLE COSTING

Several definitions have been generated for life-cycle costing (*1, 4, 13, 14*). In general, life-cycle costs include all costs anticipated over the life of the facility. As part of the analysis, trade-offs can be made among factors that may affect the life-cycle cost of a pavement, such as the relationship between the initial costs of construction and the future costs of maintenance. The analysis requires identifying and evaluating the economic consequences of various alternatives over time or over the life-cycle of the pavement.

A life-cycle costing study, to be of the greatest benefit to an agency, requires the use of an organized approach. One approach, as defined by Dell'Isola and Kirk (*4*), consists of four basic steps or unique sets of work elements, as illustrated in Figure 2. The first step is to select the study area; for this synthesis, the study area is pavement design. The second step, generation of alternatives, includes removing from further consideration or evaluation any item of cost that is common among all alternatives. This helps to simplify the analysis process and reduces the time required to complete an evaluation. The generation of alternatives will be discussed in greater detail in Chapter 4. The methodology for selecting design alternative will also be discussed in Chapter 4.

The third step, evaluating the designs, includes identifying the costs associated with each alternative. These include such costs as design, construction, maintenance, rehabilitation, user, and salvage, which are converted to today's dollars through a discounted cash-flow analysis. The discounted costs are summarized and the lowest cost alternative is identified. A sensitivity analysis may be needed in this step to determine if any change in values for some of the assumptions might alter the results of the analysis. The basic economic concepts for evaluating designs will be presented in this chapter and the procedures for their use will be presented in Chapter 4.

Any noneconomic factors that are considered important would be analyzed by the agency along with the results of the design evaluation as the final selection of a pavement design

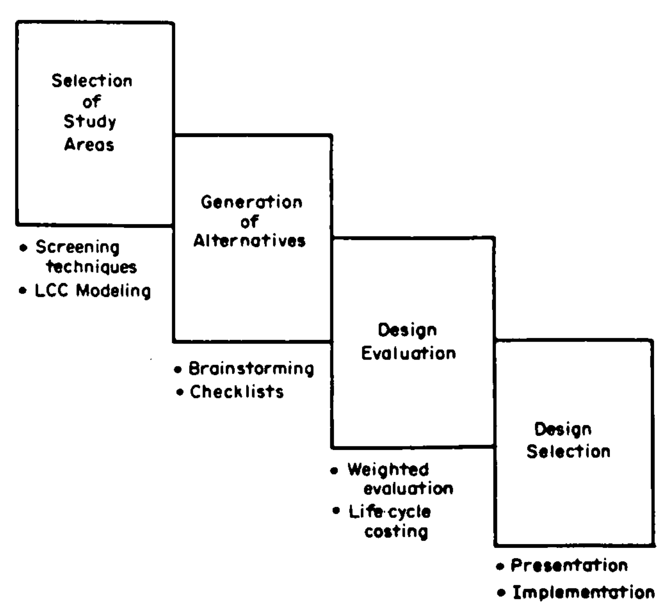


FIGURE 2 Steps in a life-cycle costing study (*4*).

alternative is made. The methodology of selecting a design alternative will be discussed in greater detail in Chapter 4.

ECONOMIC ANALYSIS METHODS

There are several different economic analysis methods that have been used as the means for comparing alternatives. The discounted cash-flow analysis methods (the present-worth method, the annualized method, and the rate-of-return method) are the methods most often used and these are discussed in a later section of this chapter (*see also* Glossary). Four other methods are sometimes used and these are described here.

Benefit-Cost Ratio Method

The benefit-cost ratio is a comparison of the equivalent uniform annual benefit (or its present worth) to the equivalent uniform annual cost (or its present worth). An alternative that yields a benefit-cost ratio greater than one is economical and the alternative that produces the highest incremental benefit-cost ratio is considered the best choice. The primary purpose for a benefit/cost analysis is to determine if the benefits to the public in dollars are greater than the cost of the project that would provide those benefits (*4, 15*).

Break-Even Analysis

The break-even analysis is a means whereby alternatives can be compared by maintaining control on certain factors while allowing one factor to change until a point of equality is achieved between the two alternatives. By changing the value of one of the factors in the analysis and keeping all of the other points of difference between the two alternative choices at constant levels, it is possible to determine the value for the factor that will result in the two alternatives being equal economically (*4, 15*). It is important in a break-even analysis that all factors are considered and priced at their proper levels.

Payback Period

The payback period is defined as the time period necessary to accumulate savings in costs or profits that would equal the investment. Payback period can be calculated with or without the time value of money and it has been used as an index to evaluate investment proposals on the basis that the alternative having the shortest payback period is the preferred selection. This analysis procedure is more generally used in the early stages of design and for relatively short time periods (*4, 15*).

Capitalized Cost

The capitalized-cost method for comparing alternatives is the present-worth method with the analysis period assumed to be infinite. With high discount rates, this method yields results comparable to the present-worth method with an analysis period of 50 years or more. The capitalized-cost method is rarely used (*15*).

INFLATION

Inflation is not generally included by highway agencies in analyzing pavement alternatives. There is a diversity of opinions on how inflation should be handled in a life-cycle cost analysis. The manner in which inflation is handled in a life-cycle cost analysis can have a significant effect on the outcome. There are two general types of price changes: inflation and differential price trends. Inflation is the general increase in prices throughout the economy whereas differential price trend is the difference between the price changes for the item being evaluated and the overall economic price trend.

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 for the analysis. Current dollars are inflated and represent price levels that may exist at some future date when the costs are incurred (*6, 8*). There is a degree of uncertainty associated with predicting the future rates for inflation and therefore the constant dollars approach has been generally recommended because only the differential inflation on future costs needs to be identified (*6, 8, 16, 17*). This will be discussed in greater detail in the following section on discount rate.

Cady (*18*), evaluated the federal-aid highway price index over a period of time, and observed that it was a power function of time. He also observed that inflation is usually presented as a compounded rate that is expressed as a percentage. This is comparable to compound interest. He noted from a GAO report covering the time period from 1970–1979 the following:

1. Inflation rate for highway construction costs: 9.4%
2. Inflation rate for highway maintenance costs: 7.4%
3. Increase in funding for highway maintenance and construction: 4.8%

Cady made a comparison on future single amounts, uniform series, and gradient series with interest rates of 5 and 10 percent and concluded the following regarding the effects of inflation:

1. The element of cash flow most seriously affected by inflation is single future amounts, followed in order by a gradient series and a uniform series.
2. Uniform series and gradient series are increasingly affected by inflation with decreasing interest rates (single future amounts are not affected).
3. The effects of inflation for all cash flow elements become more pronounced with increasing time.
4. The effects of inflation increase for all cash flow elements with increasing inflation rate.

He further concluded that "failure to account for the effects of inflation in comparing the cash flows of highway construction or maintenance alternatives will significantly understate real costs" (*18*).

Additional discussion of the use of inflation is contained in the Minnesota method of pavement selection in Appendix C.

DISCOUNT RATES

The discount rate is used as the means for comparing the alternative uses for funds by reducing the future expected costs or benefits to present-day terms. Discount rates are used to reduce various costs or benefits to their present worth or to uniform annual costs so that the economics of the different alternatives can be compared. The term *interest rate* is generally associated with borrowing money (*19*) and is often referred to as *market interest rate.* The market interest rate includes both an allowance for expected inflation as well as a return that represents the real cost of capital (*20, 21*).

Having a given amount of money now is worth more than having the same amount at some future date. Money available now will earn interest or it can be put to some beneficial use. In addition, because of inflation, a given amount of money today has a greater purchasing power than the same amount at some future date. Both interest and inflation tend to reduce the future value of a fixed amount of money. Some future cost, such as rehabilitating a pavement, that is expected to take place several years after the original pavement construction will cost more than it does today because of inflation. To properly evaluate this, it is necessary to first determine the future cost by using the inflation rate and then determine its present worth by using the interest rate. New Jersey recommended a discount rate equal to the interest rate minus the inflation rate as being a very good approximation for dealing with inflation and interest (*17*). This is sometimes referred to as the real cost of capital (*16, 20*) or the real discount rate (*22*). There is general agreement that the discount rate or real discount rate should be the difference between the market interest rate and inflation using constant dollars (*7, 8, 16, 17, 20, 22*). Market interest rates approach the real cost of capital when inflation is zero. Epps and Wootan recommended a discount rate of 4 percent based on their determination that the real long-term rate of return on capital had been between 3.7 and 4.4 percent since 1966 (*16*). Oglesby and Hicks stated that "the minimum rate for governmental investment should reflect the real cost of capital, which some have estimated as being in the range of 4%" (*7*). The AASHTO Manual on User Benefit Analysis (Red Book) stated that "if future benefits and costs are in constant dollars, only the real cost of capital should be represented in the discount rate used. The real cost of capital has been estimated at about 4 percent in recent years for low risk investments" (*20*). Florida includes inflation in the discount rate as a constant over the analysis period. They use a discount rate that they believe represents the real cost of capital and they calculate life-cycle costs in terms of constant dollars (*8*). The Portland Cement Association, based on its analysis of real interest rate trends over the last three or four decades, states that real discount rates virtually always fall between 0 and 4.5 percent with typical values between 1 and 2.5 percent (*22*).

Cady (*18*) suggested an equation that can be used to determine the "true interest rate" or the real discount rate. This equation, Eq. (1), takes into consideration interest rate, inflation rate, and the rate of increase in highway funding.

$$i^* = \frac{(1 + i)(1 + q)}{(1 + f)} - 1 \tag{1}$$

where

i^* = True interest rate (discount rate) taking into account the effects of inflation.
i = Interest rate (market interest rate).
q = Annual compound rate of increase in highway funding.
f = Annual compound rate of increase in cost of highway construction or maintenance (inflation rate).

DISCOUNTED CASH FLOW ANALYSIS

Three methods that fit under the major grouping of discounted cash flow analysis are discussed in this section. These three methods are the present worth method, the annualized method, and the rate of return method. The first two, present worth and annualized, have been the primary economic methods used in life-cycle costing analyses. The rate of return method requires more effort and calculations to perform, which are the main deterrents to its general use.

Present-Worth Method

The present-worth method is an economic method that involves the conversion of all of the present and future expenses to a base of today's costs (*4*). The present worth of some planned future expenditure is equivalent to the amount of money that would need to be invested now at a given compound interest rate for the original investment plus interest to equal the expected cost at the time it is needed. For example, an investment of 30 cents at 5 percent compound interest will equal one dollar in 25 years (*10*). All costs are predicted and they are then reduced to one single cost in the present. The totals of these present-worth costs are then compared one with another and the lowest cost alternative is chosen, providing all other things are equal (*12*).

Eq. (2) is for the single present worth of a future sum of money for a given number of years with a given discount rate. This equation is for nonrecurring costs.

$$\text{P.W.} = F \frac{1}{(1 + i)n} \tag{2}$$

where

P.W. = Present Worth.
F = The future sum of money at the end of n years from now that is equal to P.W. with a discount rate of i.
n = Number of years.
i = Discount rate per time period.

The present worth of a single future value F can be determined by multiplying it by the single-payment present-worth factor (SPW). Values for SPW can be found in the economic tables in Appendix D.

Eq. (3) is used to determine the present worth of a series of end-of-the-year payments for a given number of years with a given discount rate. This equation is for recurring costs.

$$\text{P.W.} = A \frac{(1 + i)^n - 1}{i(1 + i)^n} \tag{3}$$

where

A = End-of-year payments in a uniform series for n years that is equivalent to P.W. at discount rate i.

The present worth of a series of annual payments "A" can be determined by multiplying "A" by the uniform present-worth factor (UPW) for given values of n and i. Values for UPW can be found in the economic tables in Appendix D.

Several key items of information are needed to determine the present worth of rehabilitation and maintenance. These factors include a cost definition, a discount rate, analysis period or life, a methodology for determining salvage value, and the expected life for the various potential rehabilitation alternatives (*16*).

An example of using the present-worth method including a cash-flow diagram is given in Figure 3.

Annualized Method

The annualized method is an economic procedure that requires converting all of the present and future expenditures to a uniform annual cost (*4*). This method is one of the most valuable tools used in an economic analysis. It reduces each alternative to a common base of a uniform annual cost. The quality of the input data is important to ensure accuracy in comparing alternative choices. The procedure requires predicting all of the expected costs, whether positive or negative, over the life of the system. The costs are divided into uniform annual costs through the use of an appropriate discount rate (*12*). The annualized method can be used to convert initial, recurring, and nonrecurring costs to a series of annual payments. Recurring costs, such as estimated uniform annual maintenance expenditures, are already expressed as annual costs. A given future expenditure, such as a pavement overlay, must first be converted to its present worth using Eq. (2) before calculating its annualized cost.

Eq. (4) is used to convert today's cost expressed as present worth to its annual cost for a given number of years n and a given discount rate i.

$$A = \text{P.W.}\left[\frac{i(1 + i)^n}{(1 + i)^n - 1}\right] \tag{4}$$

where

A = Annualized cost or annual cost.
P.W. = Present worth.

The annual cost for initial costs and nonrecurring costs that have been converted to present worth can be calculated by multiplying the initial cost or the present worth of costs by the appropriate uniform capital recovery factor (UCR). Values for UCR can be found in the economic tables in Appendix D. If all other things are equal, then the alternative that yields the smallest total annual cost is the best selection.

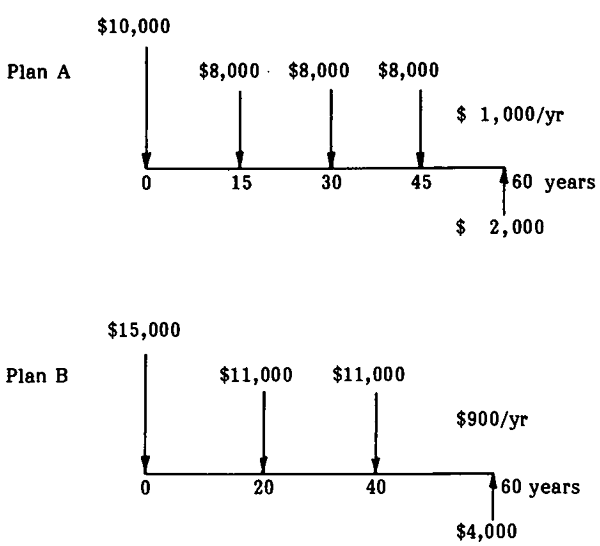
An example using the annualized method including a cash-flow diagram is given in Figure 4.

Plan A has a first cost of $10,000, an estimated life of 15 years, an annual operating cost of $1,000, and a salvage value of $2,000.

Plan B has a first cost of $15,000, an estimated life of 20 years, annual operating costs of $900, and a salvage value of $4,000.

The appropriate interest rate for comparing alternatives in this cost center is 12%.

ANALYSIS:



PLAN A:

P.W. First cost =	$ 10,000
P.W. 1st renewal = (1st cost - salvage)(SPW;15;12%)	
= ($10,000 - $2,000)(0.1827) =	1,462
P.W. 2nd renewal = (1st cost - salvage)(SPW;30;12%)	
= ($10,000 - $2,000)(0.0334) =	267
P.W. 3rd renewal = (1st cost - salvage)(SPW;45;12%)	
= ($10,000 - $2,000)(0.0061) =	49
P.W. of 60 yr operating costs = ($1,000)(UPW;60;12%)	
= ($1,000)(8.324) =	8,324
P.W. of salvage value = (-$2,000)(SPW;60;12%)	
= (-$2,000)(0.0011) =	-2
Total present worth of Plan A =	$ 20,100

PLAN B:

P.W. First cost =	$ 15,000
P.W. 1st renewal = (1st cost - salvage)(SPW;20;12%)	
= ($15,000 - $4,000)(0.1037) =	1,141
P.W. 2nd renewal = (1st cost - salvage)(SPW;40;12%)	
= ($15,000 - $4,000)(0.0107) =	118
P.W. of 60 yr operating costs = ($900)(UPW;60;12%)	
= ($900)(8.324) =	7,492
P.W. of salvage value = (-$4,000)(SPW;60;12%)	
= (-$4,000)(0.0011) =	-4
Total present worth of Plan B =	$ 23,747

FIGURE 3 Example of the present worth method and corresponding cash flow diagram.

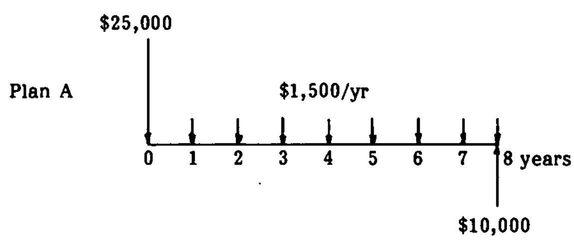
Two plans are under consideration. Plan A has a first cost of $25,000, annual operating costs of $1,500, and a salvage value of $10,000 at the end of 8 years.

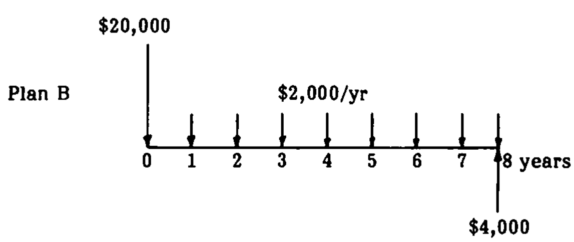
Plan B has a first cost of $20,000, annual operating costs of $2,000, and a salvage value of $4,000 at the end of 8 years.

Thus Plan A has a first cost difference of $5,000 and Plan B has an annual operating cost difference of $500 and a salvage cost difference of $6,000.

The appropriate interest rate in this cost center is 12%.

ANALYSIS:





SIMPLIFIED ANALYSIS OF DIFFERENCES

PLAN A

CR of first cost differences = $5,000(UCR;8;12%)	
= 5,000(0.2013) =	$1,006.50
Annual operating costs =	0
Annual salvage cost =	0
Total Annual Cost =	$1,006.50

PLAN B

CR =	$ 0
Annual operating costs =	$ 500.00
Annual salvage cost = $6,000(USF;8;12%)	
= 6,000(0.0813) =	487.80
Total Annual Cost =	$ 987.80

In this example, each alternative had the same life. The differences for annual capital recovery and salvage as well as annual operating difference could be used. If the lives of the two alternatives had been different, it would have been easier to work with actual costs for capital recovery and salvage value.

The difference in annual costs between these two alternatives using the estimated costs and 12% interest is only $18.70, with Plan B being lower. A very small error in the estimated costs or interest rate could mean that Plan A would have the lower cost.

FIGURE 4 Example of annualized method and corresponding cash flow diagram.

Rate-of-Return Method

The rate-of-return method consists of identifying the discount rate at which two different alternatives for an economic problem have annual costs or present worths that are equal. The first step involves determining if the project is worth doing at all. The rate of return for each proposed investment is compared with the solution that requires the least capital outlay. Those plans that fail to show a minimum attractive rate of return are discarded. The rates of return on the increase in investment between proposals having successively higher first costs are then calculated. Any of the proposals that do not show a minimum attractive return when compared with the next lower are discarded. The alternative with the highest first cost that provides more than the minimum attractive rate of return on both the total and incremental investments is considered to be the best alternative from an economic point of view (*6*).

When considering alternatives such as asphalt and concrete, the rate-of-return method requires determining the discount rate where the present worth of both alternatives are equal. This usually occurs where the discount rate as calculated is representative of the return on the added investment in the original cost as required for one of the investments relative to the other. One alternative may have a greater first cost than another but yet have lower total costs excluding interest over the analysis period. The rate-of-return method makes it possible to calculate the rate of return that may be obtained from the alternative with the greater first cost. The rate-of-return method has the advantage of not requiring the use of a set discount rate. The main disadvantage to its use is that it necessitates the calculation of rates of return on a large number of projects and on alternatives within projects in order to make comparisons. This is not currently being done in highway agencies; therefore the minimum attractive rate of return for making comparisons between the use of concrete and asphalt can only be done subjectively (*10*).

Figure 5 was prepared to simplify the understanding of the rate-of-return method and presents a simplified comparison between two different alternatives. The rate-of-return method is more complex and time-consuming than the other methods. The use of computers and calculators are very beneficial in making the calculations that are required because of the trial-and-error steps required in the procedure. If cash flow changes direction in an analysis, the results may be invalid.

ANALYSIS PERIOD

The analysis period is the time period used for comparing design alternatives. An analysis period may contain several

	Alternative	
	No.1	No.2
Initial cost	$ 80,000	$100,000
Annual maintenance cost	4,000	2,000
Analysis period (n)	20 years	20 years
6% INTEREST		
Convert initial cost to annual cost Initial cost x UCR = A Initial cost x 0.0872 =	$ 6,976	$ 8,720
Annual maintenance cost	4,000	2,000
Total annual cost at 6%	$ 10,976	$ 10,720
8% INTEREST		
Convert initial cost to annual cost Initial cost x 0.1019 =	$ 8,152	$ 10,190
Annual maintenance cost =	4,000	2,000
Total annual cost at 8%	$ 12,152	$ 12,190

Based on straight-line interpolation

$$i = 0.06 + 0.02 \left[\frac{10,976 - 10,720}{(10,976 - 10,720) + (12,190 - 12,152)}\right]$$

$i = 7.74$ %

If the attractive rate of return in 7.74% or lower, then alternative No. 2 is justified on economic grounds.

FIGURE 5 Example comparing alternatives using rate of return method.

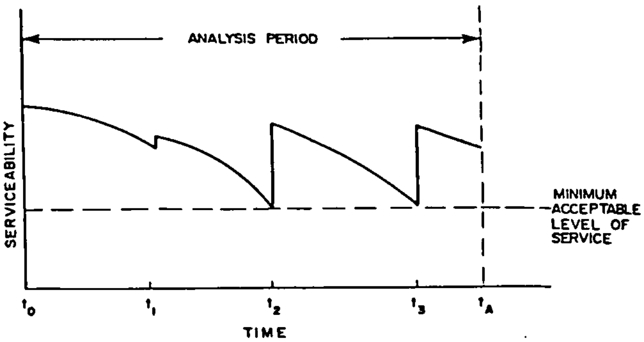


FIGURE 6 Performance curve illustrating rehabilitation and maintenance activities over the analysis period (*28*).

maintenance and rehabilitation activities during the life cycle of the pavement being evaluated. This is illustrated in the performance curve for a pavement in Figure 6.

The recommended analysis or study period for comparing new design alternatives is 25 to 40 years, which is considered a sufficient time period for predicting future costs for economic purposes in order to capture the most significant costs. This is illustrated in Figure 7 where the annual cost for 100 years discounted to present worth at a 10 percent interest rate is plotted against time. The area under the curve is the accumulation of the total present-worth cost of the system. It may be noted that 80 percent of the total equivalent cost of the system is consumed in the first 25 years (*4*).

The analysis period for comparing rehabilitation alternatives on an existing pavement may be shorter than 25 years because the pavement system may be planned for replacement before 25 years because of geometrics, traffic capacity, etc. These other factors may dictate the analysis period that should be used.

The useful life of any component in a pavement system is the expected life of that component before it would need to be replaced or upgraded. For example, the useful life of a rehabilitation activity such as an overlay might be 10 years before another overlay would need to be added.

COST FACTORS

Cost factors are those costs associated with the life-cycle cost analysis for a facility or in comparing alternative designs that cover the full cycle from initial design through the end of the analysis period. The possible costs associated with a pavement are:

1. Design Costs—The expected costs for designing a new or rehabilitated pavement including materials, site investigations, traffic analysis, pavement design, and plans and specifications.
2. Construction Costs—The costs for building a section of pavement in accordance with the plans and specifications.
3. Maintenance Costs—Those costs associated with maintaining a pavement at or above some predetermined performance level. This includes both corrective and preventive maintenance but does not include rehabilitation. These costs may be stated as cost per mile per year for a given pavement type.
4. Rehabilitation Costs—These costs cover the types of activities performed as part of rehabilitating or restoring the pavement. These represent periodic costs at future dates used to restore the pavement to an acceptable performance level.

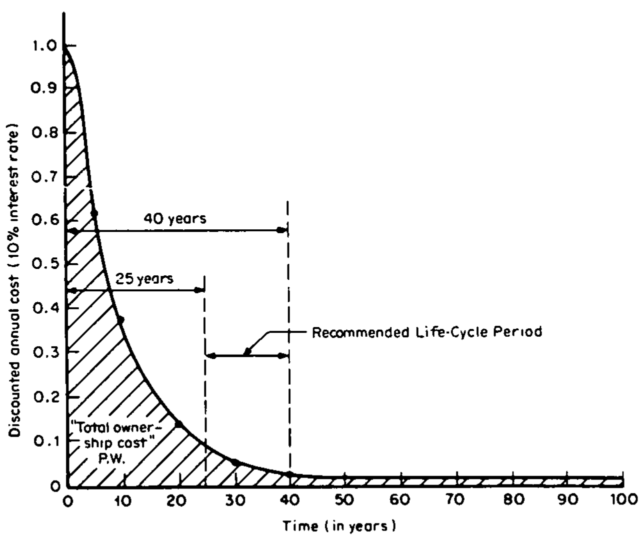


FIGURE 7 Recommended life-cycle analysis period (*4*).

5. User Costs—These costs are those accumulated by the user of the facility as related to pavement type, condition, maintenance activities, or rehabilitation work. These could be in the form of delay costs, increased operating costs, etc. The cost of denial-of-use of the pavement to the traffic is also part of this item.

6. Salvage Value—This is the value of the pavement at the end of the life cycle or analysis period. Salvage value can be either positive or negative depending on whether the material has some economic value or the cost of demolition or removal exceeds any value.

7. Energy Use—The relative energy consumption for different competing alternatives is a factor that may be considered. The dollar cost associated with this item will generally be part of construction, maintenance, or rehabilitation costs.

RISKS, UNCERTAINTIES

Risk exists when the probability is known for the occurrence of the possible outcomes from an alternative. Uncertainty exists when the probabilities for outcomes from an alternative are partly or completely unknown (*12*). Risk as it is defined can be dealt with in the analysis and its effect on costs can be calculated. Pavement design itself involves a degree of risk in that a certain probability exists that a pavement will not reach its design life. Decisions are generally based on calculated risks, which means gambling on the chances that the future will be as predicted by educated judgments. Decisions that are made with the full realization of the uncertainties assume that the future may not be the same as planned and the designer knows the effect that any variation may have on the predicted results (*4*).

The economic analysis for projects is by necessity based on uncertain future events and on predictions of performance that often are not accurate and, as a result, the measurement of any economic costs and benefits includes probability judgments whether they are explicit or not. The basic components of input and output prices and quantities in an economic analysis seldom represent definite events in that they could be described by single values. It is, therefore, desirable for an economic analysis to take into consideration the range of possible variations in the values of the basic components and that, when possible, the extent of the uncertainties related to the outcome be clearly represented on the analysis presentation. A practical introduction to risk analysis in project appraisal is given in a set of case studies prepared by Pouliquen (*23*).

The results of a life-cycle cost analysis are greatly influenced by a number of factors. Certain data that are used might be considered very reliable while other data sources might be considered unreliable. For example, current construction costs are usually known because of up-to-date bid prices and, therefore, they can be predicted with a high degree of certainty for an analysis. Future maintenance costs on the other hand may not be very accurate because of variations in pavement performance and the general lack of good reliable maintenance cost data. It is extremely difficult for most agencies to provide accurate maintenance cost data because most of it is not very definitive. That is, maintenance costs may cover a very long road section and cannot be broken out for short sections or for variations in pavement performance within the longer road section. Therefore, there is considerable uncertainty attached to future maintenance costs. The length of time until rehabilitation might be required as well as the extent necessary to restore the pavement at that time also have a relatively high degree of uncertainty attached.

Work has been done by different individuals and agencies in dealing with uncertainty through a form of decision analysis (*2, 24–28*). Alexander (*27*) discussed expected cost decision analysis and the use of decision trees. He assigned probabilities to the chances for having success with a given treatment. Kulkarni (*25*) assigned probabilities for different values of roughness and fatigue cracking in Alaska as a basis for estimating the maintenance costs for these items. He generated performance prediction curves for dealing with the treatment of uncertainties (Figure 8).

Woodward-Clyde applied the Markovian decision process to Arizona's pavement management system as the means of establishing probabilities of different pavement conditions. The Markovian decision process is suitable for pavement management decisions incorporating multiple pavement condition variables and a large number of alternative actions (*26*).

Curtayne and Servas (*28*) discussed economic considerations in the design of pavement rehabilitation and the use of decision theory. They point out that rehabilitation treatment will always have to be done under some measure of uncertainty and that decisions are made on a probabilistic basis. They used decision trees as a means of illustrating their strategies and the potential outcomes. Figure 9 illustrates a decision tree representative of part of Table 1, which was also developed by them. Table 1 presents two possible initial acts followed by possible results and further acts. Figure 9 only illustrates one of the initial acts. Figure 10 presents a typical branch of a decision tree giving possible outcomes of alternative maintenance strategies. Curtayne and Servas point out that because of "the inherent variability of pavement properties and the uncertainties about their behavior, these decisions have to be analyzed in terms of probability theory" (*28*).

SENSITIVITY ANALYSIS

Sensitivity is the relative effect that a variable may have on the decision. A sensitivity analysis consists of testing the effects of variations in designated cost and/or benefit variables on the selection of an alternative. Such an analysis is principally a procedure for identifying the variables that most influence the costs of an alternative and the extent of their influence. It may also be helpful in identifying various design options that may need to be considered in greater detail and variables that require additional information. It may also help provide some idea of the extent of project risk. A sensitivity analysis is generally more effective in the formative stages of a project and should be the normal part of an economic analysis.

In the process of selecting a pavement design alternative, the designer may not be very certain about the outcome because of inadequate input data, initial assumptions, accuracy of estimates, or any combination. The critical questions in a life-cycle cost analysis are: "(1) How sensitive are the results of the analysis to variations in these uncertain parameters? (2) Will these variations tend to justify the selection of an alternative not currently

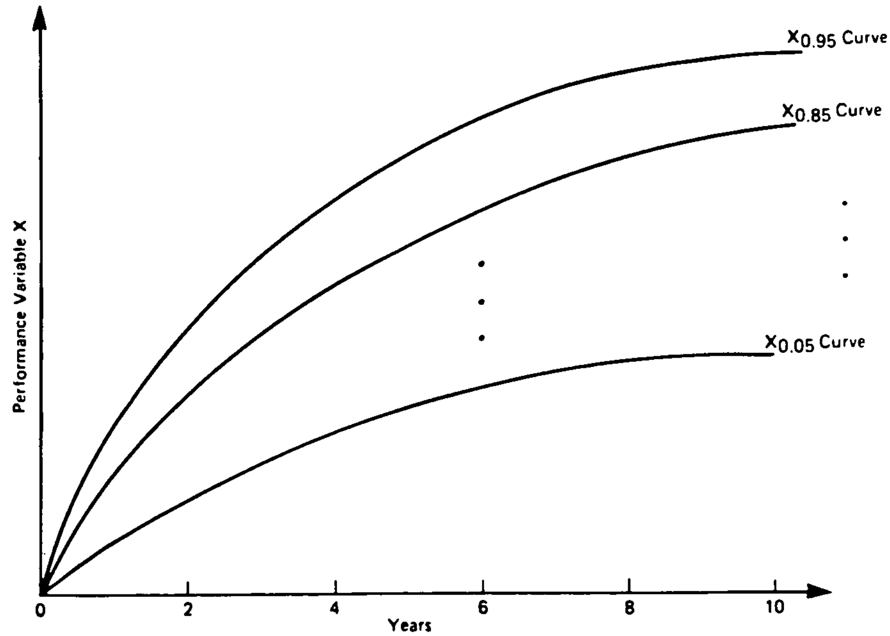


FIGURE 8 Treatment of uncertainties in performance prediction (*25*).

being considered? (3) How much variation in a given parameter is required to shift the decision to select alternative B rather than alternative A?" (*4*). The basic purposes for a sensitivity analysis are to determine how sensitive the outputs from the life-cycle cost analysis are to variations in certain inputs and to evaluate the risk and uncertainty related to a selected alternative. This allows the designer to determine the probability of selecting the wrong alternative.

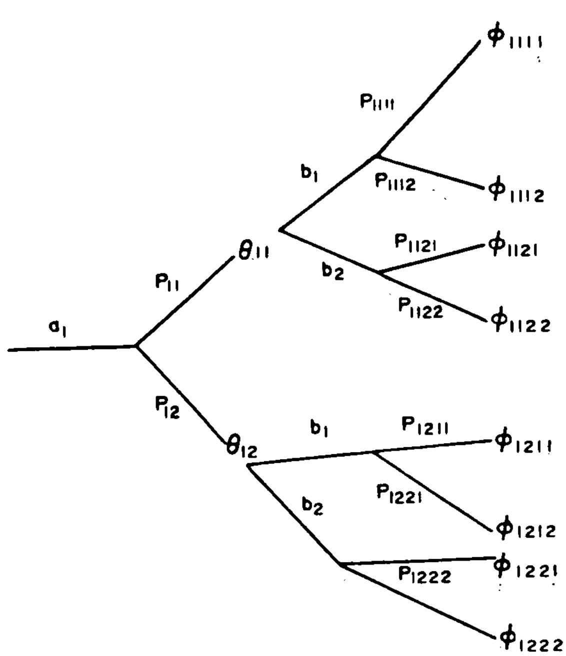


FIGURE 9 Decision tree representation of part of example given in Table 1 (*28*).

The use of a sensitivity analysis is desirable when performing more detailed life-cycle cost analyses. A sensitivity analysis is particularly beneficial when the difference between two alternatives may not be very great. Some of the items that can be varied include discount rates, analysis period, and the costs of various factors including maintenance and user costs. The process of making a sensitivity analysis is relatively simple and does not require much time. A relatively narrow band is recommended for the parameters to better control the outcome of the analysis. As pointed out earlier, there is a great amount of uncertainty associated with various input parameters for a life-cycle cost analysis. A sensitivity analysis provides the means to determine the effect of uncertainty on a number of factors.

The results of some of the sensitivity analyses that have been made will be discussed with the life-cycle costing procedures used by some agencies in Chapter 4. Some of the results that have been observed are:

- "Results of solutions by the annual cost method are markedly affected by interest rate. Low interest rates favor those alternatives that combine large capital investments with low maintenance or user costs, whereas high interest rates favor reverse combinations" (*6*).
- As the interest rates increase and the time period grows longer, then the assumption that a system will be used for an indefinite period of time becomes less significant. Forecasts into the future are less significant when interest rates are higher and the periods of time are longer than are short range forecasts using low interest rates (*12*).
- "It was found that if the resurfacing costs and/or reconstruction costs increased slightly, then with a 10% discount rate, the road would be resurfaced one more time before reconstruction. Similarly, if these costs decreased slightly and a 5% discount rate is used, the pavement would be resurfaced one fewer time before reconstruction" (*29*).

TABLE 1

EXAMPLE OF OUTCOMES ARISING FROM TWO INITIAL ACTS (*28*).

Initial act	Result	Prob.	Second act	Outcome	Probability
A_1	θ_{11}	P_{11}	b_1	ϕ_{1111}	P_{1111}
				ϕ_{1112}	P_{1112}
			b_2	ϕ_{1121}	P_{1121}
				ϕ_{1122}	P_{1122}
	θ_{12}	P_{12}	b_1	ϕ_{1211}	P_{1211}
				ϕ_{1212}	P_{1212}
			b_2	ϕ_{1221}	P_{1221}
				ϕ_{1222}	P_{1222}
A_2	θ_{21}	P_{21}	b_1	ϕ_{2111}	P_{2111}
				ϕ_{2112}	P_{2112}
			b_2	ϕ_{2121}	P_{2121}
				ϕ_{2122}	P_{2122}
	θ_{22}	P_{22}	b_1	ϕ_{2211}	P_{2211}
				ϕ_{2212}	P_{2212}
			b_2	ϕ_{2221}	P_{2221}
				ϕ_{2222}	P_{2222}

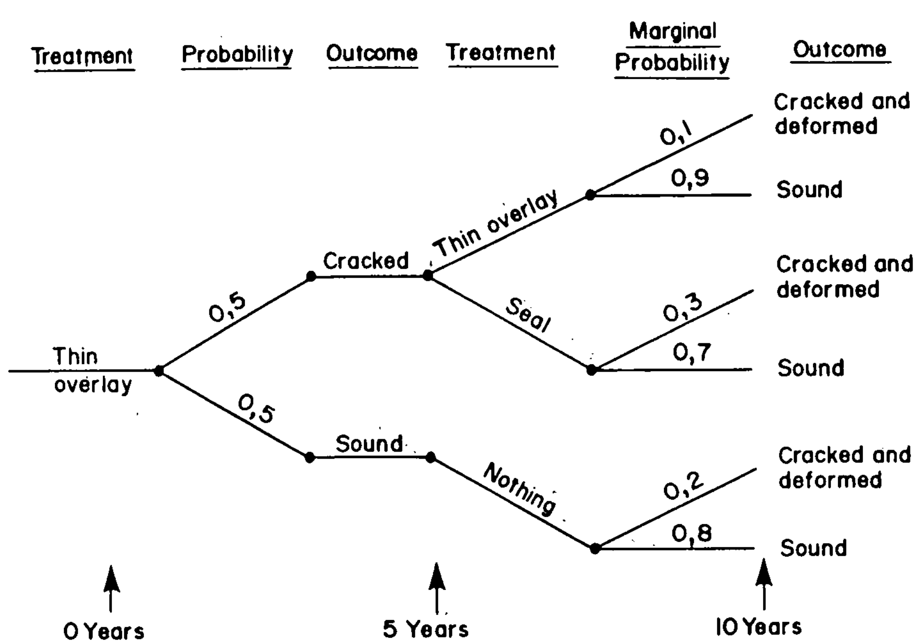


FIGURE 10 Typical branch of a decision tree giving possible outcomes of alternative maintenance strategies (*28*).

• "Present worth life-cycle cost determinations are sensitive to the following factors:

1. Selected discount rates
2. Length of analysis period
3. Life of rehabilitation alternative
4. Salvage value
5. Price and cost values
6. Consideration of user costs" (*16*).

Sensitivity analyses were made on various pavement designs in South Africa. The influences that the discount rate and salvage value have on the present worth for typical flexible and rigid pavements are shown in Figures 11 and 12 (*16*).

Other results of sensitivity analyses that have been made by various agencies will be discussed in Chapter 4.

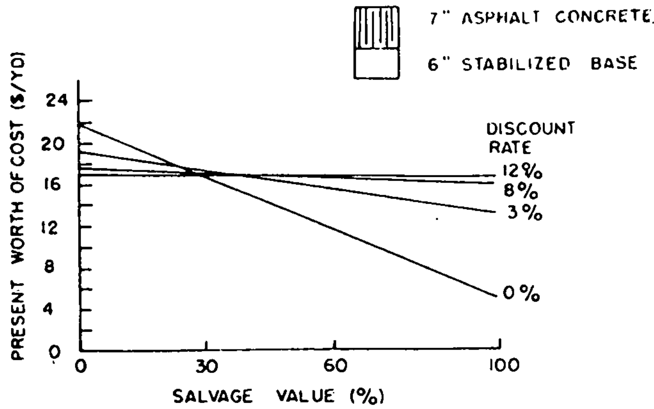


FIGURE 11 Influence of selected discount rate and salvage value on present worth of a typical flexible pavement (*16*).

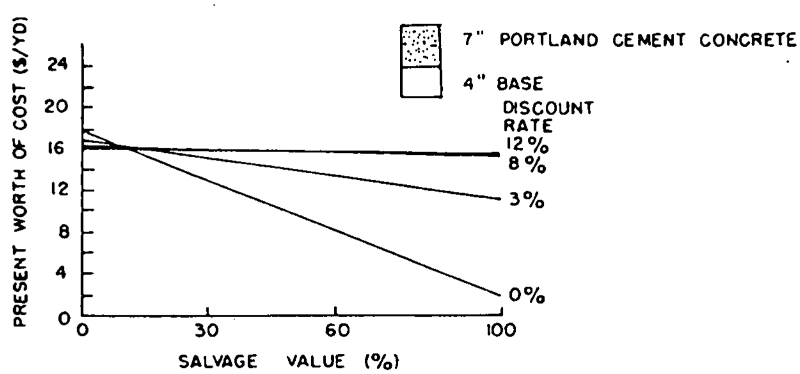


FIGURE 12 Influence of selected discount rate and salvage value on present worth of a typical rigid pavement (*16*).

CHAPTER THREE

PRESENT PRACTICE

This chapter covers the present practices of various states, provinces, and other agencies as related to selecting pavement alternatives. The information was obtained from replies to a survey of practice in 1984, personal contacts, and literature review. Survey of practice responses were received from 45 states, the District of Columbia, and 3 Canadian provinces for a total of 49. Seventeen agencies provided copies of their procedures in addition to completing the survey form (*8, 30–46*). The results of the survey of practice are detailed in Appendix A.

EXISTING PROCEDURES FOR SELECTING DESIGN ALTERNATIVES

Different procedures for selecting design alternatives for new and rehabilitated pavements were identified from the responses to the survey of practice. These procedures are identified in Table 2 where certain basic characteristics of the different types are delineated. The most common procedure identified by the various agencies was the use of some form of life-cycle costing. Those agencies identifying annual cost and present worth as methods stated that they did not use life-cycle costs even though these two methods are the basic discounted cash-flow analysis used in life-cycle costing. As may be noted in the table, only nine agencies indicated that they use a percentage rate for inflation. The procedures as used by the different agencies are illustrated on the map in Figure 13. Further details are contained in Appendix A, Table A-1.

A closer look at the agencies reporting the use of life-cycle costing as their procedure for selecting pavement alternatives showed that present worth is the most common discounted cash-flow method used in their analysis. This is presented in Table 3. Further details are available in Table A-2 in Appendix A.

A few of the responding agencies (*8, 34, 36*) also identified the use of certain governing factors for pavement type selection that were identified in the AASHTO Guide entitled "An Informational Guide on Project Procedures." The factors that were identified by the respondents are:

1. Traffic
2. Soils characteristics
3. Weather
4. Performance of similar pavements in the area
5. Economics or cost comparison
6. Adjacent existing pavements
7. Stage construction
8. Depressed surface or elevated design
9. Highway system
10. Conservation of aggregates
11. Stimulation of competition
12. Construction considerations
13. Municipal preference and recognition of local industry
14. Traffic safety
15. Availability of and adaptations of local materials or of local commercially produced paving mixes

The Federal Highway Administration developed a Policy Statement on Pavement Type Selection that "is designed to provide the public with acceptable highway service at a minimal annual or life cycle cost while permitting maximum flexibility. The policy encourages the consideration of alternate designs and strategies in the type selection process" (*47*). The policy is intended for use on both new and rehabilitated pavements.

The FHWA Policy is as follows:

> 1. Pavement type selection should be based upon an engineering evaluation considering the factors contained in the 1960 AASHTO publication entitled "An Informational Guide on Project Procedures."
> 2. Pavement type determinations should include an economic analysis based on life cycle costs of the pavement type. Estimates of life cycle costs should become more accurate as pavement management procedures begin providing historical cost, serviceability, and performance data. States without this data are encouraged to obtain it.
> 3. An independent engineering and economic analysis and final pavement type determination should be performed or updated a short time prior to advertising on each pavement type being considered.
> 4. Where the analysis reflects that two or more initial designs and their forecasted performance are determined to be comparable (or equivalent), then alternate bids may be permitted if requested by the contracting agency. The Division Administrator shall review the analysis and concur in the finding of equivalency prior to PS&E approval. Price adjustment clauses should not be used when alternate bids are permitted.
>
> This policy is written with the intention of taking advantage of fluctuating material prices while not compromising good design and pavement management practices (*47*).

COST ELEMENTS

The survey of practice requested information on the cost elements used in the economic analysis. The source of the data, data reliability, and the frequency with which data are updated were also requested. The cost elements listed on the survey of practice form were design cost, construction cost, maintenance cost, replacement cost (rehabilitation, resurfacing, etc.), user

TABLE 2

PROCEDURES USED BY VARIOUS AGENCIES IN SELECTING PAVEMENT ALTERNATIVES (1984)

Procedure	Number of Agencies Using	Average Length of Time In Use (years)	Effectiveness Rating of Procedure		Length of Analysis Period (years)		Discount Rate Used (%)		Inflation Rate Used (%)	
			Range	Average[a]	Range	Average	Range	Average	Range	Average
Life-Cycle Costing	22	13.2	Fair to V. Good	2.7 (19 agencies)	15 to 40	27.9 (21 agencies)	4 to 10	6.2 (14 agencies)	4.1 to 6	5.3 (4 agencies)
Annual Cost	4	19.7	Fair to Good	2.3 (3 agencies)	20 to 40	33.3 (3 agencies)	5 to 10	7.5 (2 agencies)	5 to 7	6.0 (2 agencies)
Present Worth	5	20.7	Poor to Good	2.0 (5 agencies)	20 to 40	29.5 (5 agencies)	4.5 to 10	7.0 (4 agencies)	0 to 12	6.0 (2 agencies)
Lowest Initial Cost	10	20.3	Fair to V. Good	2.6 (7 agencies)	20 to 30	21.0 (5 agencies)	Not Used		10	10 (1 agency)
None or Other	8	-	-	-	20 to 25	21.2 (2 agencies)	Not Used		Not Used	
Overall	49	17.5 (34 agencies)	Poor to V. Good	2.6 (34 agencies)	15 to 40	27.2 (36 agencies)	4 to 10	6.5 (20 agencies)	0 to 12	6.1 (9 agencies)

[a]Very good = 4; good = 3; fair = 2; poor = 1; very poor = 0.

costs, denial-of-use costs, energy, salvage, and other. Table 4 presents the results obtained from the responses.

Further details from the survey of practice relating to cost elements are contained in Table A-3 in Appendix A. As may be noted in Table 4, construction, replacement, and maintenance were the most frequently used cost elements. Salvage value is considered by approximately one-fourth of the respondents and design costs by about one-fifth of the agencies. User, energy, and denial-of-use costs were rarely considered. Data accuracy was identified as a concern by many of those not using user costs. The cost factors were discussed in greater detail in Chapter 2.

COST DATA

Cost data provided by the various agencies were relatively limited. Construction cost data and restoration cost data were the most readily available and were considered to be the most accurate as they are based on current bid prices or actual construction costs. The lack of good maintenance cost data is a very critical problem and there is an urgent need to improve the methods used to provide this important cost information. Some agencies have values that they use for predicting future maintenance costs in the selection of pavement alternatives that are based on reliable cost experience. For the most part, this is not the case; usually data are extracted from a very broad base that is not very definitive. Consequently, many agencies use their best judgment in setting maintenance costs for a life-cycle cost analysis. Only 26 agencies use maintenance costs, as discussed in the previous section. Five of these agencies consider their data as poor. Cost data is discussed in greater detail in Chapter 4 under Cost Components. Appendix E includes examples of some of the better cost data that are in use by the various agencies.

DEALING WITH NEW MATERIALS AND/OR TECHNIQUES

In the survey of practice agencies were asked how they handled new materials or techniques in their analysis procedure. Several agencies do not consider new materials or techniques in the analysis and they use only standard designs. A few agencies said they had no formal procedure. Some of the agencies said they handled new materials and/or techniques as demonstration and experimental projects and then considered them in a project as alternatives based on their performance.

The majority of the responding agencies perform cost estimates and performance estimates based on some form of evaluation from their own experience, information from other agencies, inquiries to manufacturers, latest bids, etc. then treat the new materials or techniques as existing ones. A number of new materials and techniques have been developed in recent years that have proven very beneficial in reducing costs or extending life of pavements.

A Florida report on asphalt and concrete discusses the use of new materials and techniques quite extensively (*8*). Some of the comments from the report are:

> Prior to the field use of any new material or process, extensive laboratory testing is conducted to determine the material's characteristics and applicability to highway construction. Documentation and reporting has been completed on the materials used in Florida highway systems.
>
> Florida has also monitored the pavement performance characteristics of select roadway sections for a number of years. Numerous test road projects have been constructed throughout the state. Each test project was constructed using different material native to the project's geographic location.
>
> Evaluation of pavement materials requires accurate reporting and documentation. Field testing of the pavement performance characteristics over a period of time allows forecasts of future project material serviceability.

The changing economy, market conditions, and state-of-the-art have necessitated the development of alternatives to the conventional materials and procedures used in pavement construction and in the repair and maintenance of the existing pavement systems (*8*).

RELATIONSHIP BETWEEN LIFE-CYCLE COSTS AND PAVEMENT MANAGEMENT SYSTEMS

The results from the survey of practice showed that 22 of the responding agencies have some form of pavement management system. Figure 14 shows the various agencies that had some form of a pavement management system in 1984. Further details can be found in Table A-4 in Appendix A. None of the agencies with a pavement management system has progressed to the point with their system that they could use it in the pavement selection process. Many agencies indicated that the application of a pavement management system to the selection of pavement alternatives was a strong possibility.

Florida has been developing a pavement management program (PMP), which they define as the "systematic *gathering of information and analysis* which together put the *right pavement type and thickness* in the *right places* at the *right time* for the *least total cost*" (*30*). Life-cycle costing is included as one part of their final reporting from their program. The new Florida Program recommends an economic analysis that considers initial cost, follow-up maintenance and rehabilitation costs, inflation, and the time value of money for each pavement type that is considered. It also requires that structurally equivalent pavement types be defined and that the load-carrying capacity for each pavement be known. Florida believes that implementing a reliable economic analysis is important to them in their process of considering the cost of different pavement types throughout their lives and in choosing the optimum design strategy.

Hassell made the following statement regarding pavement management (PM) and life-cycle costing:

> Effective PM involves the use of feedback of information on pavement performance, pavement maintenance, pavement rehabilitation activities, and the cost of providing and maintaining pavements. Our goal must be to improve the process of coordinating and managing all activities related to pavements to

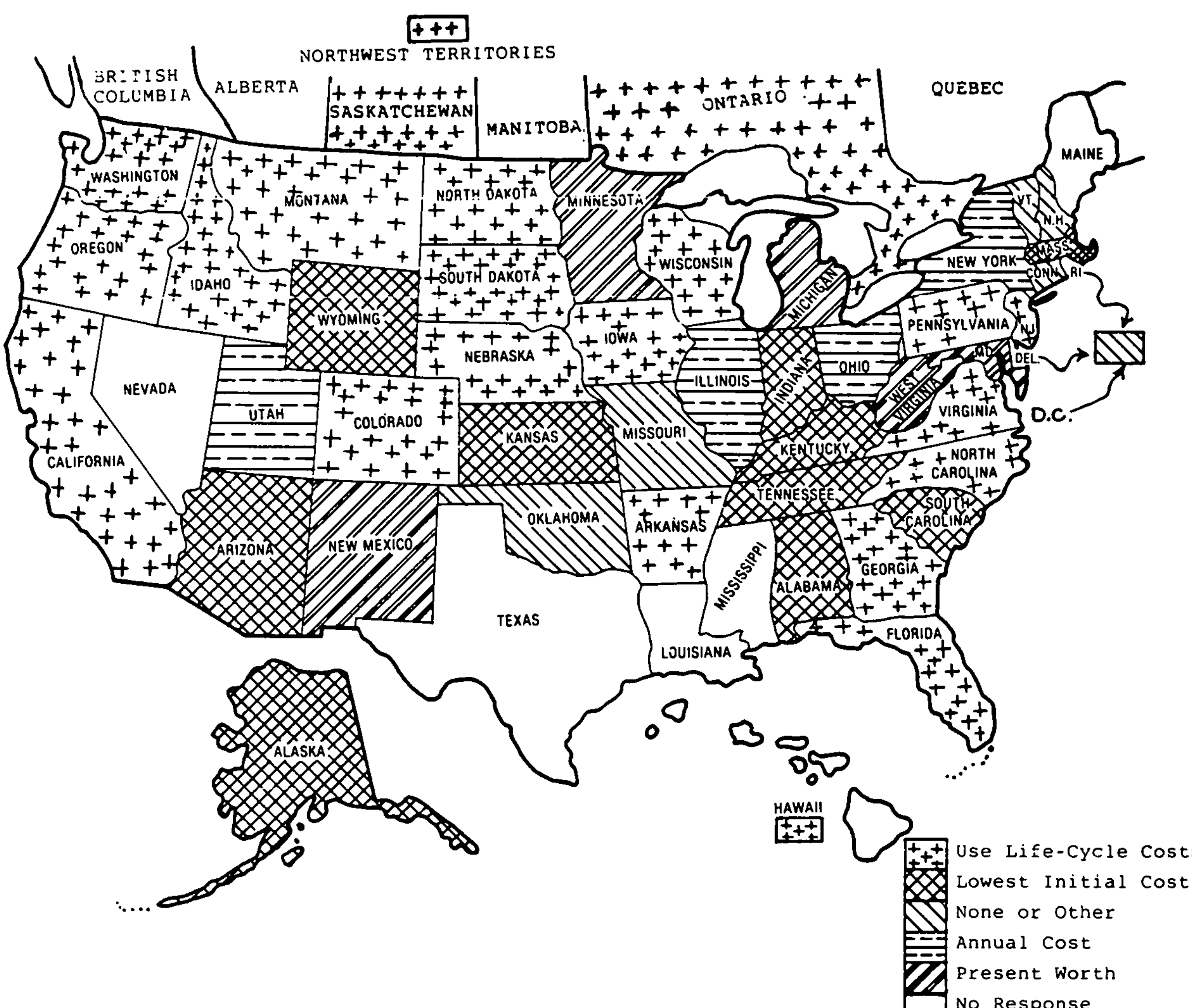


FIGURE 13 Pavement selection procedures used by various agencies (1984).

TABLE 3

DISCOUNTED CASH FLOW METHODS USED IN LIFE-CYCLE COSTING PROCEDURES

Method Used	Number of Agencies	Average Analysis Period (years)
Present Worth	13	26.0
Annual Cost or annualized	8	31.1
Other or not specified	2	30.0
Total	22[a]	27.9

[a]Florida uses both present worth and annual cost.

reduce the life-cycle cost for providing pavements in a serviceable condition (*48*).

Shahin identified certain objectives and benefits that could be obtained from a pavement maintenance management system:

1. Knowledge of the existing pavement and of the condition and health of the pavement system.
2. Rational determination of M&R [maintenance and rehabilitation] needs by setting performance standards.
3. The ability to generate or develop a list of priority M&R needs on demand.
4. Availability of information, including maintenance cost data.
5. Ability to answer "what if" questions dealing with the consequences of implementing various M&R alternatives.
6. Ability to perform life cycle costing and to determine the consequences of various M&R alternatives.
7. Ability to develop long-range M&R plans.
8. Ability to optimize a given M&R budget.
9. Establishment of or improvement of communications among the various management levels dealing with M&R (*49*).

Life-cycle costing for selecting pavement alternatives will be significantly enhanced through the implementation of a well-designed pavement management system. The essential data for making a life-cycle cost analysis would be available from a properly functioning system. Two areas that would be most benefitted are better maintenance cost and performance information and the performance characteristics of different new and rehabilitated pavement alternatives. A good pavement management system is recommended as the source for much of the information needed to make an accurate life-cycle cost analysis.

PAVEMENT PERFORMANCE PREDICTIONS

Twenty-seven of the 49 agencies responding to the survey of practice said they have performance histories for different pavement types. This is illustrated in Figure 14. Detail responses from the survey of practice are contained in Table A-4 in the Appendix A.

The ability to predict how long a pavement will perform until it reaches some predetermined performance level is essential to any procedure related to future pavement costs. The performance histories for a wide range of pavement types and conditions are necessary to predict what might happen in the future for a given set of conditions. A typical performance curve is illustrated in Figure 15, which was taken from a Utah report

TABLE 4

COST ELEMENTS USED BY THE VARIOUS AGENCIES IN THEIR ECONOMIC ANALYSIS (1984)

Cost Element	Agencies Using	Most Common Sources of Information	Data Reliability	Update frequency
Design	9	Estimating unit based on most recent bid design hours.	Poor to very good	Current; annual; quarterly
Construction	40	Previous projects; current bids; average unit prices.	Fair to very good	Monthly; semiannual; annual
Maintenance	26	Maintenance records; maintenance management system; price indices; present maintenance system.	Poor to good. Five agencies considered their data to be poor.	Annual; continuous; weekly; five years; monthly
Replacement (rehabilitation, resurface, etc.)	31	Previous projects; current bids; cost index; contract costs; average unit prices.	Poor to very good. One agency considered their data to be poor.	Yearly; quarterly; monthly; continuous
User	3	Not identified	Not rated	Not stated
Denial of Use	1	Not identified	Not rated	Not stated
Energy	2	Not identifed	Good at one agency; not rated at the other.	Semiannual
Salvage	12	Percent of life; estimating system; historical experience	Fair to excellent	Monthly; annual; continuous; per project

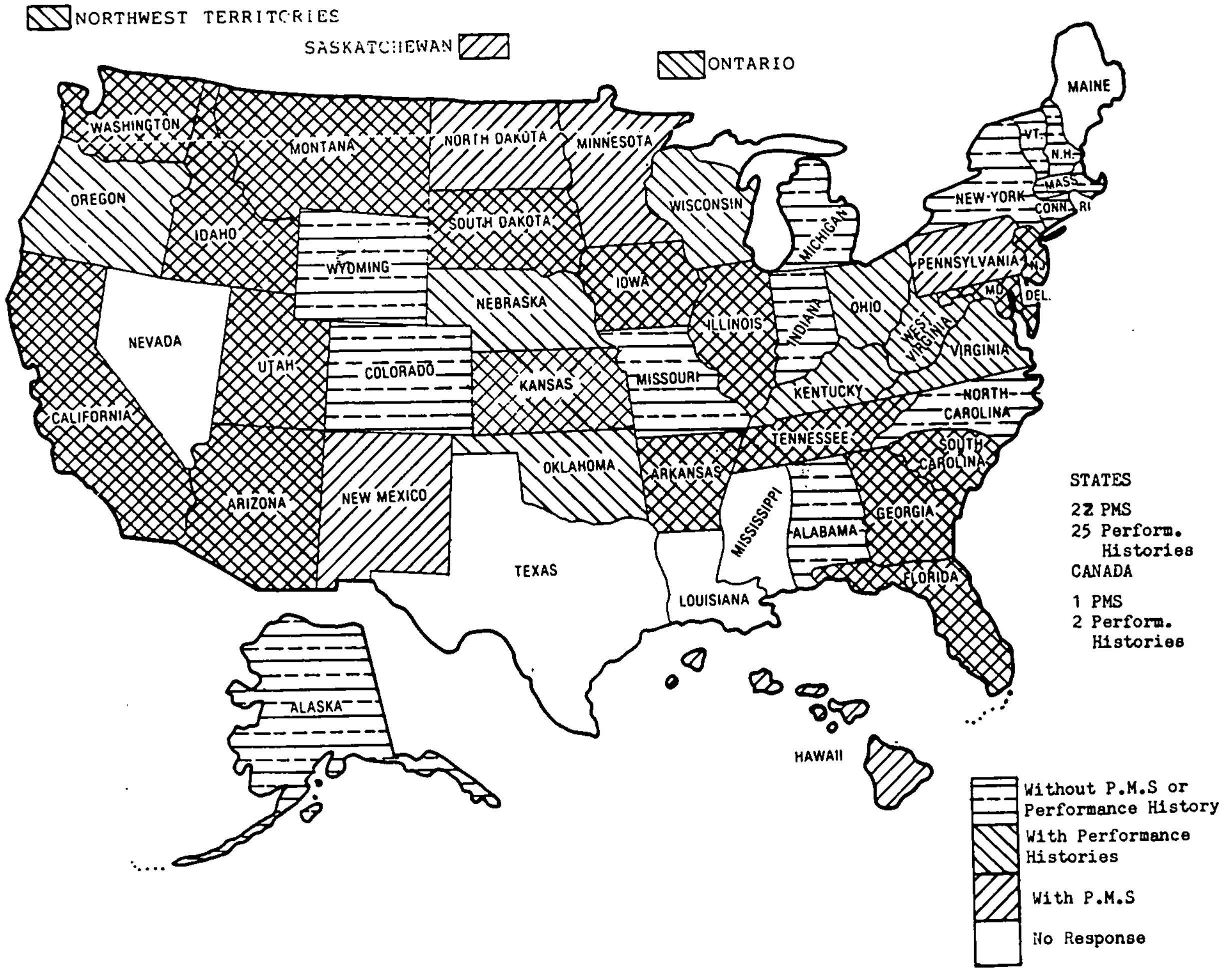


FIGURE 14 Various agencies with a pavement management system and those with pavement performance histories (1984).

on pavement performance (*50*). The relationship between measured performance (histories) and predicted performance was also illustrated in this Utah report. This is presented in Figure 16.

Figure 17 illustrates a performance curve for Portland Cement Concrete in Iowa as presented in a report by Ray (*51*).

Pavement performance prediction equations that have been developed by some individuals or agencies as reported in the literature can be applied in life-cycle costing analysis procedures (*9, 10, 16, 24, 25, 29, 31–40, 52–55*). Most of these were developed for a given area or set of conditions and cannot be applied on any expanded basis. Further work is needed in this area. This subject is related to risk and uncertainty and was discussed in Chapter 2.

MINIMUM ACCEPTABLE PERFORMANCE LEVELS

According to the results from the survey of practice, 20 agencies use some level of PSI (present serviceability index) as the minimum acceptable performance level. That would be the theoretical level when upgrading of the pavement should be undertaken. No attempt is made here to summarize levels being used because of variations in measuring equipment and equations from agency to agency. Seven agencies use a minimum ride score as the lowest acceptable performance level. Twelve agencies stated that they use no minimum acceptable perfor-

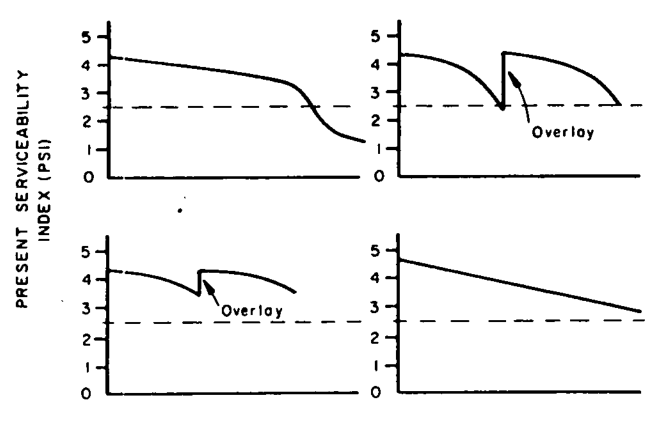


FIGURE 15 Typical performance curves (*29*).

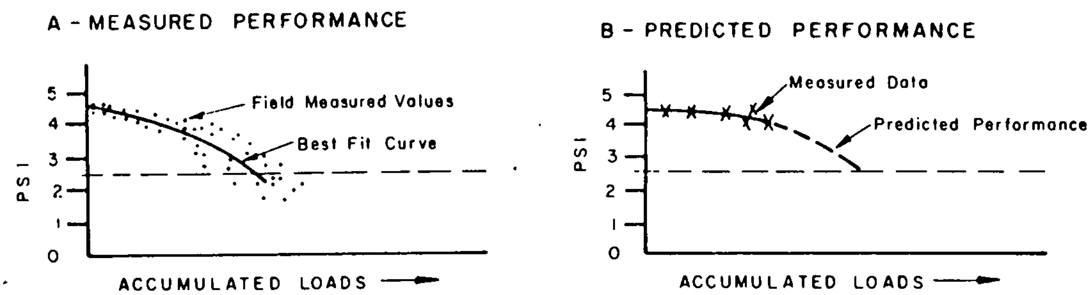


FIGURE 16 Predicting pavement performance (*29*).

mance level in their procedure and three agencies said they plan to include such a system. Details from the survey of practice related to minimum acceptable performance levels as obtained from the various agencies are contained in Table A-4 of Appendix A.

AUTOMATION OF ANALYSIS

There were only 10 agencies that reported using a computer in their analysis. Florida reported that they use their department's main frame in the TSO (time-shared operation) mode with a simple routine for present worth and annual cost analysis. Ontario probably has the most comprehensive computerized economic analysis system (*24*). This computerized system, known as OPAC (Ontario pavement analysis of costs), compares the cost and performance of hundreds of flexible pavement design alternatives within just a few hours. Pavement design engineers can choose the most cost-effective pavement design with this system. OPAC includes life-cycle costing and is discussed in greater detail in Chapter 4. Further information can be found on the use of automation in life-cycle cost analysis by the various agencies in Table A-1 in Appendix A.

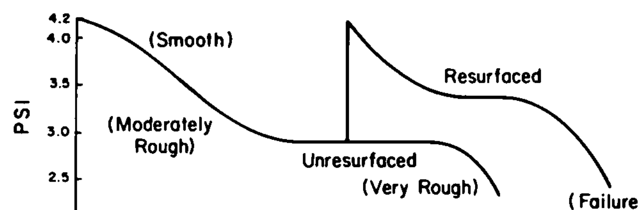


FIGURE 17 Iowa primary road system typical performance curve—PCC (*51*).

OTHER FACTORS CONSIDERED BY AGENCIES FOR EVALUATING PAVEMENT DESIGN ALTERNATIVES

A question asked in the survey of practice was: What other basis do you use in pavement type selection? Thirty-six of the 49 agencies responded with a basis in addition to or in lieu of the economic analysis that was identified earlier on the survey form. The AASHTO guide entitled "An Informational Guide on Project Procedures" was identified by nine agencies. Most of the factors contained in the guide were identified at least once more by other agencies. For example, continuity of pavement type was listed by 10 more agencies in addition to the nine listing the AASHTO guide, safety was identified by six additional agencies, soils characteristics by three, materials availability by three, and conservation of aggregates by two additional agencies. Other factors not listed in the AASHTO guide but included by some of the agencies included politics, ease of maintenance, aesthetics, noise sensitivities, cost advantage of recycling, driver visibility, and energy savings. Further details are available in Table A-1 in Appendix A.

The question was also asked in the survey of practice if such factors as constructability, ease of implementation, and maintainability were considered in the selection process. Approximately half of the agencies considered these or similar factors. They were generally used as secondary factors with the economic analysis being primary and they were generally always treated in a subjective manner. In a few cases, these factors were used to eliminate certain alternatives before the more detailed analysis was made. Further details of the responses to this question are contained in Table A-4 in Appendix A. Specific examples of selected procedures are discussed in greater detail in Chapter 4.

CHAPTER FOUR

PROCEDURES AND METHODOLOGY

This chapter covers the various steps required to complete a life-cycle cost analysis in the process of selecting pavement design and rehabilitation alternatives. The process begins with generating alternative designs and concludes with the final design selection. Also included in this chapter is a recommended procedure for updating the process or component parts of the process for using life-cycle costing for selecting pavement design alternatives. Examples of some typical life-cycle costing procedures as used by some of the agencies are highlighted.

GENERATING ALTERNATIVE DESIGNS

Once the determination has been made that a pavement will be constructed or rehabilitated the next step is to identify all potential alternatives that will satisfy the design requirements. For a new pavement the choice might be between a bituminous surface or a portland cement concrete surface. For a proposed rehabilitation project there might be several alternatives from which to choose including a conventional overlay, recycling, placing a fabric or rubber interlayer before resurfacing, and removing and replacing the existing surface. To a great extent, the alternative choices for rehabilitating an existing surface will be dictated by the condition of that surface.

The first step in the process of generating alternatives is to make certain that a thorough understanding exists of any problems and of the design parameters for the particular pavement being planned. Any characteristics unique to the site should be identified. The next step is to identify all possible alternatives using creative thinking or brainstorming techniques. No attempt is made to evaluate the potential alternatives in this step as that will be accomplished in follow-up steps. The basic objective here is to generate a wide range of possible solutions. The no-build alternative must also be considered.

The principles of value engineering can be utilized as one method of brainstorming in the process of generating alternatives. Figure 18 is illustrative of the relationship between life-cycle cost analysis and value engineering. In this flow diagram, "start design" is on the left of the process and design selection is on the right at the end of the process. The value-engineering function is part of generating alternatives and is identified with creativity and brainstorming (*4*).

Value engineering is defined by AASHTO as an "analysis of materials, processes and products in which functions are related to cost and from which a selection may be made for the purpose of achieving the required function at the lowest overall cost consistent with the requirements for performance, reliability and maintainability; sometimes called Value Analysis" (*56*). Value engineering is an organized problem-solving effort directed toward optimizing the total cost of ownership. It is directed at analyzing the various functions of construction, maintenance, rehabilitation, procedures, methods, and so forth with the objective of obtaining the lowest total cost of ownership consistent with the need for performance, reliability, quality, and maintainability (*57, 58*). The value-engineering methodology has great utility in the process of generating alternative solutions because of the creativity and brainstorming techniques built into it (*4*). The basic objective of value engineering is to obtain the maximum performance per unit of cost for a product with value being the ratio of performance to cost. Each component of a system contributes to the cost and the performance of the entire system (*59*).

Once a number of alternative treatments or solutions have been identified, then the next step is to select for further analysis those that are most promising. During the process of creativity or brainstorming there is a conscious effort not to inhibit input. Once that effort is complete, it is necessary to evaluate the items identified to refine the list of choices. There are several different criteria that can be used in this evaluation process:

1. Will the idea work? Can it be modified or combined with another?
2. What is the life cycle cost savings potential?
3. What are the chances for implementation?
4. Will it satisfy all of the user's needs? (*14*)

An initial evaluation usually takes place to screen the number of alternatives that may have been identified. Preparing a list of the advantages of each alternative is generally helpful in screening the most promising for the later life-cycle cost analysis. No alternative is eliminated until it receives at least a preliminary evaluation. The remaining alternatives are developed further with more detail designs and cost estimates.

The designer must be certain that each alternative will adequately perform the required objectives regardless of how efficient or inefficient the proposed pavement might be. It is a waste of time and money to include an alternative for further study if it is known that the proposed pavement will not produce desired results. Also, if the designer knows by inspection that a particular alternative is not as good as another, he or she may not want to include it in further comparisons.

The surviving alternatives are then ready for consideration in the design evaluation step that includes life-cycle costing.

USEFUL LIFE OF ALTERNATIVES

The useful life of a pavement alternative is considered to be the time from initial construction until some major improvement, such as an overlay, is required. The analysis period could

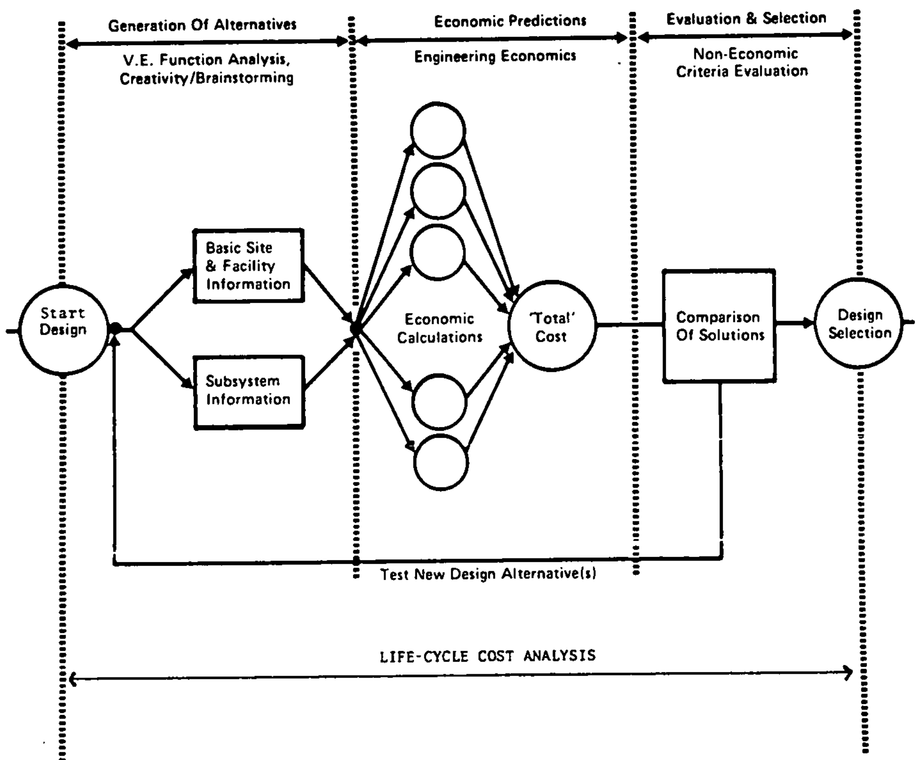


FIGURE 18 Interrelationships of life-cycle cost analysis and value engineering (*4*).

consist of one or more major improvements to the pavement. For example, if the analysis period were 40 years and the pavement as initially constructed lasted 40 years without any major activities then the useful life and analysis period would be the same. If the pavement lasted only 20 years before rehabilitation or some other major activity then the pavement would have a useful life of 20 years. The ability to predict the useful life of a particular pavement until some major improvement is required is important in life-cycle cost analysis.

Information from pavement evaluation programs is very beneficial in developing the useful life of a particular pavement. A number of factors can influence the life of a new or rehabilitated pavement as designed. Some of these are: change in traffic, heavy truck weights, weather, construction quality, maintenance timeliness and quality, etc. A good pavement evaluation program is invaluable in tracking pavement performance and in developing the data base for predicting the life of a pavement. It also provides information for predictions of when a pavement will fail so that preventive maintenance can be performed or rehabilitation can be planned. Delaying maintenance or rehabilitation until after a pavement fails can increase costs by as much as four times what it would have cost had the work been done before failure (*50*).

A nationwide program now being planned on long-term performance of pavements will help to fill the void that currently exists in this area. It is recommended that the useful life of a new pavement or a rehabilitated pavement be estimated for the life-cycle cost analysis by using the best information available to an agency. If performance data are not available, then best judgment based on experience will have to do.

ANALYSIS PERIOD

The length of analysis period being used by the various agencies ranged from 15 to 40 years. It is recommended when starting with a new pavement that the normal length for the analysis period be from 25 to 40 years with 40 as a maximum for any analysis. Analysis periods of less than 25 years may be used when selecting rehabilitation alternatives that call for retiring or replacing a section of pavement at some future date less than the 25 years. It would not be uncommon for the analysis period for selecting rehabilitation alternatives to be 5 to 15 years. A sensitivity analysis can be used to compare different analysis periods for a given location to help ensure that the correct decision is being made.

COST COMPONENTS

The selection of the proper cost components or factors and the use of reasonably accurate data are important parts of making a life-cycle cost analysis. The recommended cost factors for use in the analysis are design, construction, maintenance, rehabilitation, user, and salvage. The cost of energy is part of the cost of the other factors and, therefore, is not included here. In the event a serious energy shortage develops it is recommended then that energy be considered as one of the other factors that may override the results from the life-cycle cost analysis. It should be pointed out that costs that are common to each of the alternatives being considered should not be included in the analysis. For example, if the same base material is common to all, it should not be included, but if one alternative requires a different or a thicker base then it must be included. Examples of actual cost data as provided by various agencies are contained in Appendix E.

Initial Costs

There are two different types of costs that are included as initial costs and these are design and construction. Design costs themselves would only need to be included if the cost of designing one alternative is different from those of another. If the design costs for all alternatives being considered are identical then it should be so noted and not included in the analysis. Design costs were only considered by nine agencies based on the survey of practice responses. The source of information identified for design costs was bid design hours and the rating of reliability for the data ranged from poor to very good.

One of the most important cost components, if not the most important, is construction cost. This cost component is used by more agencies than any other component and it had the best reliability rating of any ranging from fair to very good. The sources of information for construction costs were primarily previous bids, previous projects, historical cost data, etc. The data are updated relatively frequently with the maximum time between updates being yearly. The construction costs used in the analysis should be the most current and the most accurate data available. When new materials or techniques are being considered as part of alternatives where previous bids or contracts are not available, then care should be taken in generating the estimated costs for those items. If there is a possible range in cost for new items, then it may be desirable to run a sensitivity analysis to determine the effect of cost variations on the end result.

Maintenance Costs

Maintenance costs are one of the most difficult areas to deal with in a life-cycle cost analysis. There are certain inherent problems in obtaining accurate and reliable maintenance costs. The cost of pavement maintenance is directly influenced by the type and extent of maintenance work performed at various time intervals into the future. There is a problem predicting very far in advance what type of maintenance will be required and when it will be needed. Maintenance needs are influenced by pavement performance, which also needs further work in order to improve prediction capabilities.

Maintenance costs themselves are generally not gathered with the precision required for a life-cycle cost analysis. Twenty-six agencies reported using maintenance costs in their pavement selection process. The data reliability was rated from poor to good by these agencies with five considering their data poor. Table 5 shows some typical maintenance costs and Figure 19 shows maintenance cost trends. NCHRP Synthesis 46 (*60*) provides some direction on how to improve the reliability of maintenance cost data. NCHRP Synthesis 110 (*61*) and NCHRP Synthesis 77 (*62*) should also be of considerable help to agencies in improving their capability for predicting future maintenance needs and costs. In a study for Alaska, Kulkarni (*25*) worked on a relationship between certain performance characteristics,

TABLE 5

TYPICAL PAVEMENT MAINTENANCE COSTS (*8*)

Maintenance Activity	Expenditure[a] ($/lane mile)
ASPHALT PAVEMENT	
Plant-mix patching (hand labor)	90
Major plant-mix patching (mechanical)	10
Major plant-mix patching (hand labor)	45
Base repair	10
Surface treatment paving	5
Pavement striping	105
Total	265
CONCRETE PAVEMENT	
Slabjacking (pressure grouting)	80
Void filling (pressure grouting)	30
Joint sealing	60
Surface repair	10
Base repair	10
Pavement striping	110
Concrete repair with asphalt	50
Total	350

[a]Total expenditures in 12 months by activity on each pavement type divided by total lane miles of each pavement type.

such as fatigue cracking and maintenance costs (*25*). This is illustrated in Figure 20. The differential in maintenance requirements for the various alternatives being considered is the most important item. If maintenance costs are identical for all alternatives, then there would be no need to include maintenance in the analysis.

Maintenance costs can also be adversely affected if a maintenance activity is delayed. Cost of maintenance significantly increases as pavement condition decreases. This subject is addressed extensively in the NCHRP Synthesis 58 (*63*) and in

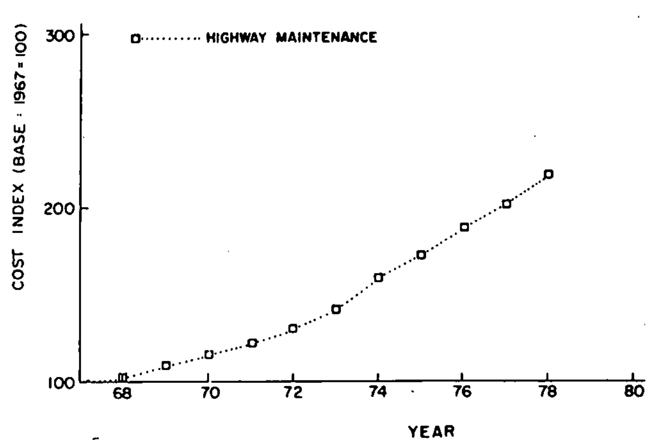


FIGURE 19 Maintenance cost trends (*16*).

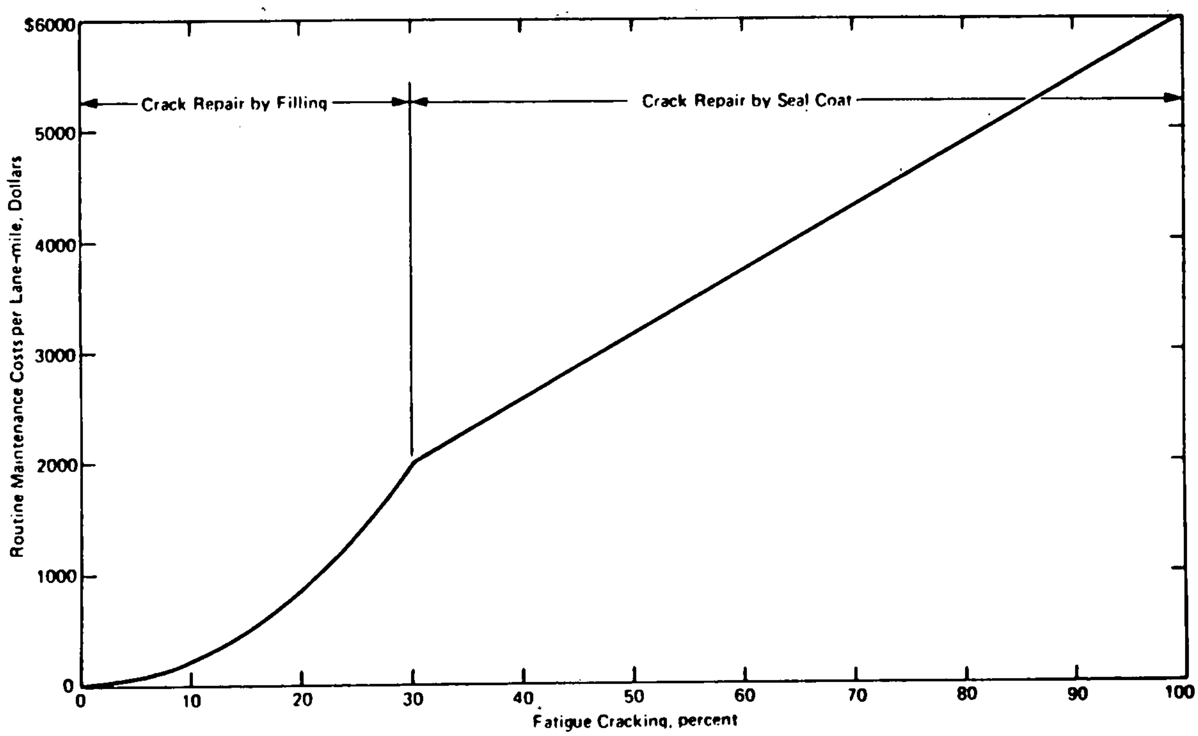


FIGURE 20 Relationship between routine maintenance cost and fatigue cracking (*25*).

NCHRP Project 14-6, which will be published in 1986. Maintenance costs can also be adversely affected by changes in truck load limits (*64, 65*). Failure to enforce weight limits will significantly affect pavement performance and costs.

Rehabilitation Costs

The costs included in this area are those types of activities that are contained in the rehabilitation or the restoration of a pavement. Some typical costs for rehabilitation projects are given in Table 6.

The cost data normally used for rehabilitation are the same general type as that used for new pavement construction. Pavement rehabilitation projects are normally bid and constructed under the same basic criteria as for new pavement construction. There are two different times for rehabilitation as related to a life-cycle cost analysis that need to be identified. For many projects, rehabilitation will be at time zero and therefore constitutes the beginning of a life-cycle analysis. This is the situation for many projects where the pavement has existed for years and long-term improvements are needed. Rehabilitation in this case would be treated in a similar manner to initial construction of a pavement. The second time sequence for rehabilitation is the future rehabilitation needs for a new pavement or for a newly rehabilitated pavement. One major problem with future rehabilitation is the inability to accurately predict at what time in the future rehabilitation might be required. It is necessary to make the best estimate possible of when it might be required. Good historical pavement performance data would be very helpful in this process. A sensitivity analysis could be made while varying time to rehabilitation to determine to what extent it might alter the final design selection.

New materials and/or techniques will most likely occur in the rehabilitation of pavements. It is suggested that these new materials be studied as much as possible through laboratory evaluations and on experimental projects before their general use. Only those demonstrating a high degree of success should be considered for widespread use.

User Costs

User costs should be included to the extent they might affect the choice of pavement alternatives. In most cases the data are not precise enough to detect vehicle operating cost differences between two pavements with different surface types at the same general performance level. There are significant user cost dif-

TABLE 6

TYPICAL PAVEMENT REHABILITATION COSTS (*16*)

Rehabilitation Alternative	Approximate Thickness (in.)	Representative Price ($/sq yd) Average	Range
Chip seal coat	1/2	0.60	0.40 - 0.90
Fabric interlayers	1/4	1.20	0.75 - 1.75
Asphalt-rubber interlayers	1/2	1.25	0.90 - 1.50
Open-graded friction course	5/8	1.50	1.00 - 2.50
Asphalt concrete (dense-graded)	1	1.65	0.90 - 2.50
Asphalt concrete (dense-graded)	2	3.15	1.80 - 4.74
Asphalt concrete (dense-graded)	3	4.75	2.60 - 7.00

ferences between paved and unpaved roads and cost differences between a smooth and rough pavement of the same surface type (*66–70*). Vehicle operating costs for such items as parts, tires, etc. increase with an increase in pavement roughness (*66–70*). An increase in pavement roughness results in an increase in fuel consumption (*67–69*), which was found to be true on both paved and unpaved roads in Brazil (*69*). These higher user costs caused by deteriorating pavements result in a need for higher rates for such transportation services as freight and bus. These higher costs should have an effect on such areas as minimum allowable pavement performance levels and maintenance policies.

Other sources of high user costs are delay costs through slow downs caused by construction and maintenance activities and denial-of-use costs from having to close down a section of highway during major repairs. Vehicle operating costs increase where a longer alternative route must be used and where traffic is stopped or slowed by construction, rehabilitation, or maintenance activities.

A useful reference for user costs in addition to those identified earlier in this subsection is "A Manual on User Benefit Analysis of Highway and Bus Transit Improvements" prepared by AASHTO and referred to as the "Red Book" (*20*).

The relative effect of user costs for different alternatives could be assessed using a sensitivity analysis if sufficient applicable data could be identified for the case being studied. Only three agencies indicated that they utilize user costs. None of these three identified any data sources.

An example of a life-cycle cost analysis where user costs are included is contained in a later section of this chapter.

Salvage Value

Salvage value may more appropriately be called residual value because the value at the end of a life-cycle analysis may have either a positive or a negative value. Because of the nature of pavements, it is not always possible to have the life used up for each alternative being considered at precisely the end of the analysis period. One or more of the alternatives may have some remaining value or life at that time. Twelve agencies indicated that they consider salvage value as part of their life-cycle cost analysis in the selection of pavement alternatives. They based their determination of value on such factors as percent of pavement life remaining, experience, and history and they rated the reliability of their data as fair to excellent.

In addition to a positive value for useful salvageable materials or remaining life, a pavement may have a negative value. A negative value would exist if it cost more to remove and dispose of the material than it is worth. If a value (either positive or negative) can be assigned to a given pavement alternative at the end of the analysis period, then that value can be included in the life-cycle cost analysis as a salvage or residual value. The salvage value is brought back to its present worth through the use of Eq. (2) in Chapter 2 using the proper discount rate and number of years. If the comparison between alternatives is based on present worth, then the present worth cost obtained for salvage value would be used with the appropriate alternative. If the comparison being made between alternatives is annualized, then the present worth of salvage value would be converted to an average yearly cost or benefit through the use of Eq. (4) for converting present worth to annual costs.

Energy Costs

Energy costs, as such, are not included separately in the life-cycle cost analysis because any cost associated with energy would be part of construction, maintenance, and rehabilitation costs. Analysis of energy costs as a separate factor in life-cycle cost analysis would be extremely difficult. A more appropriate consideration of energy would be as one of the other factors after the life-cycle cost analysis is completed. Generally it would not be considered as an independent or overriding factor because it is part of other costs that are in the analysis.

DESIGN EVALUATION

The design evaluation phase consists of further reducing the alternatives left at the end of the generation of alternatives phase. The first basic step in the process of evaluating design alternatives is to compare and rank the ideas contained in them. These ideas can be evaluated according to the following on a preliminary basis:

1. Ability to perform the function-ratings might be excellent, good, fair, poor.
2. Ease of implementation, including cost and schedule-rating might be:
   a. Simple idea: easy to implement.
   b. Moderately complex idea: moderately easy to implement.
   c. Complex idea: difficult to implement.
3. Magnitude of savings (initial and life cycle) (*4*).

The advantages and disadvantages of the different alternatives and the ideas contained in them should be judged in an objective manner. This initial analysis should result in a shorter listing of ideas that have passed a preliminary screening. This selection process should include an estimate of the potential reduction in life-cycle costs of the different alternatives and how well each meets the required functions.

The remaining alternatives are then developed further to include more detailed estimates of cost. These estimates of cost should be as accurate and as complete as possible. They should be consistent among the various alternatives. Some questions that should be considered as part of the evaluation of each surviving alternative are:

1. Will the idea work? Can it be modified or combined?
2. What is the life-cycle savings potential?
3. What are the chances for implementation? Will it be relatively easy or difficult to make the change?
4. Will it satisfy all the user's needs? (*4*)

Once the preliminary evaluation is complete and the best available cost data have been obtained, then the life-cycle cost analysis of the remaining alternatives should be made. An example of a relatively simple life-cycle cost analysis is contained in Figure 21. A cash-flow diagram for the information used in the life-cycle cost analysis is contained in Figure 22.

DESIGN SELECTION

Once the life-cycle cost analysis is completed for the remaining pavement design alternatives, then the final selection is made. Life-cycle costing may indicate the desirability of one alternative

	Treatment A	Treatment B
GIVEN:		
Initial Cost	$7.50/s.y.	$5.00/s.y.
Maintenance (Annual)	0.75/s.y.	1.00/s.y.
Useful Life	12 years	8 years
Discount Rate (no inflation)	10%	10%
Analysis Period	24 years	24 years
MAINTENANCE		
P.W. = A x UPW = A x 8.985 =	$ 6.73	$ 8.98
REPLACEMENT		
Year 8, Treatment B P.W. = F x SPW = 5.00 x 0.4665 =		2.33
Year 12, Treatment A P.W. = F x SPW = 7.50 x 0.3186 =	2.39	
Year 16, Treatment B P.W. = F x SPW = 5.00 x 0.2176 =		1.09
INITIAL COST	7.50	5.00
TOTAL LIFE-CYCLE PRESENT WORTH COST	$16.62	$17.40

Treatment A would be selected on the basis of life-cycle costs.

FIGURE 21 Example of life-cycle cost analysis.

over another, but because of other considerations a different alternative may be selected. Some of these other factors, such as those contained in the AASHTO informational guide and identified in Chapter 3 of this synthesis, may override economics. Some of these other factors are continuity of pavement type, safety, soils characteristics, materials availability, and conservation of aggregates.

The probability of successful implementation and the ease of maintenance should be considered in the process of making the final selection. If two different alternatives are relatively close in life-cycle costs, a sensitivity analysis may be desirable as a way to verify that the selected alternative is still low cost even if the input variables or conditions were to change slightly.

SYSTEM UPDATING

Once a procedure has been established for selecting pavement alternatives, it should be reviewed periodically and updated as appropriate. For example, the results of a program for evaluating pavement performance may result in changes in some of the parameters used in the analysis process. If better cost data were to become available, they should be implemented into the analysis. Performance of pavements selected through the use of life-cycle costing techniques should be periodically monitored to see if the pavements are in fact responding as planned in the analysis.

EXAMPLES OF TYPICAL LIFE-CYCLE COSTING PROCEDURES

Examples of life-cycle costing procedures for selecting pavement alternatives are summarized in this section. The procedures are from California (*34*), Florida (*8*), the Federal Aviation Administration (*16*), and an FHWA Training Course on Techniques for Pavement Rehabilitation (*71*). Other examples are contained in Appendix C.

Economic Comparisons of Pavements in California

California (*34*) considers two general types of pavements in their economic analysis of pavement alternatives. These are portland cement concrete and asphalt concrete. Their choice of pavement type is based on the governing factors listed in the AASHTO Guide *An Informational Guide on Project Procedures.*

California's procedure requires an economic comparison of pavement types when the pavement contains structural sections designed for a Traffic Index greater than 10.0 based on a 20-year EAL (equivalent axle loading) or when the use of portland cement concrete is recommended. Exceptions to the requirement for an economic comparison are made under the following conditions:

(a) Where an existing pavement is to be widened or resurfaced with a similar material.
(b) Where the area of new pavement is less than 4 lane miles.
(c) Where unavoidable future flooding or a high water table dictates the use of portland cement concrete pavement.
(d) Where it is economically unreasonable to locate and construct the highway so that unequal settlement or expansion will be eliminated, and asphalt concrete pavement must be used.
(e) Where short freeway to freeway connections are being made between pavements of the same type.

When economic comparisons are not made, the reasons should be stated fully with the pavement type submittal (*34*).

Properly designed structural sections that would normally be approved for construction if they were selected are used in the economic comparisons in California. The structural section selected and used in the life-cycle cost analysis is to be used in the final plans; if changes are made then a new approval must be obtained.

The economic comparison in California is made according to the following instructions:

(a) The structural sections to be compared shall be shown by sketches so that quantities can be computed and checked.
(b) An appropriate economic analysis period shall be chosen for each project based on the average life to first resurfacing of concrete pavements in the area that served under comparable conditions. In general, this will range from 20 years upward based on present experience.
(c) Compound interest at the rate of 5 percent shall be used as necessary to convert all costs to present worth.
(d) Initial costs shall be computed for the entire pavement structural section, including shoulders for one direction of travel and a length of one mile. Detailed estimates showing the initial cost of both pavement types shall be made a part of the documentation.
(e) Engineering charges on initial construction shall be omitted, but preliminary and construction engineering charges in connection with resurfacing shall be included. This shall be expressed as a percent of the future resurfacing cost and is to be determined by the District from past records.

(f) Estimates of resurfacing cost must include all supplemental work made necessary by the resurfacing. Traffic handling, temporary traffic stripe, replacing permanent traffic stripe, protection or temporary removal of guardrails and guide posts, adjustments of drainage facilities, and other supplemental work should be carefully estimated.

(g) The costs of traffic delay shall be estimated and added to the cost of resurfacing. Data usually can be obtained from the District Traffic Branch.

(h) Maintenance costs shall be included where District records can be used to demonstrate a difference in cost between the two pavement types.

(i) Salvage values shall be used only as necessary to bring both estimates to the same analysis period, and should be applied to last resurfacing only. Salvage value should be the proportional cost representing the remaining service life of the last resurfacing beyond the end of the analysis period (*34*).

Examples of the application of the procedures in California for the economic comparisons for two theoretical projects are presented in Figure 23. The California procedure makes the computation of present-worth cost for a given pavement in accordance with the following relationship.

Present worth cost = initial cost + (resurfacing cost + engineering cost + supplemental work cost + traffic delay cost) × present worth factor_1 + maintenance cost × present worth factor_2 − salvage value × present worth factor_3. Using obvious symbols, this also can be expressed as follows:

$$PWC = IC + (RC + EC + SC + DC)\, PWF_1 + MC \times PWF_2 - SV \times PWF_3 \quad (34)$$

The California procedure omits resurfacing cost and salvage value computations for portland cement concrete in most cases and in some cases includes two resurfacings or some other type of treatments for asphalt concrete pavement. It stresses the fact that careful attention must be given to the computations and to the input data to ensure the most realistic and factual comparison possible between the different pavement alternatives.

Florida Department of Transportation Comparative Analysis

The Florida procedure (*8*) considers a number of factors in the pavement selection process. These factors are general characteristics, pavement design, construction criteria, comparative maintenance requirements, recycle or reuse of materials, life-cycle cost analysis, energy considerations, soil cement base, asphalt adjustment clause, and alternative bid considerations. This subsection deals primarily with the life-cycle cost analysis. Florida's report provided details on the economic comparison of asphalt and concrete pavements for one of the typical rural four-lane interstate highway projects in Florida. The designs were for a 20-year period with an assumption of 10 million 18-kip loadings during that time. Pavement designs were prepared and recommended for the comparison and the quantities of material required to construct a one-mile section were calculated for each pavement type.

Thirty years was the recommended analysis period but Florida also considered 40 years for comparison. Annual routine maintenance was included along with the initial construction costs. The present worth of the terminal salvage value was also considered in the analysis. Table 7 contains the design alternatives used by Florida in the analysis.

Florida concluded the following points:

1. The analysis was conducted in accordance with generally accepted economic principles and their application to engineering problems.
2. A positive discount rate must be used.
3. The opportunity cost of capital is the correct discount rate to use in calculating the life-cycle cost of various pavement design alternatives.
4. To avoid the need to speculate about inflation, a discount rate that represents the real cost of capital while calculating life-cycle costs in terms of constant dollars should be used.
5. Differential prices should only be used when there is overwhelming evidence that certain inputs are expected to experience significant price changes relative to the general price level. Even then, such changes in real prices should only be included in a sensitivity analysis.

Thirty- and 40-year life-cycle analysis periods were used in the comparison of alternatives. Florida recommended the use of 7 percent as the correct discount rate but also included 5 and 10 percent in order to determine the sensitivity of the results. Table 8 contains the total life-cycle present worth comparison made in Florida. The Florida analysis showed in this example that the life-cycle cost of the asphalt pavement design is lower than concrete irrespective of the discount rates or analysis periods selected by them.

Details of the life-cycle present worth analysis as done by Florida for the 40-year analysis period for concrete and for asphalt are presented in Tables 9 and 10. Table 11 presents the method Florida used to calculate terminal salvage value.

The PCA (*22*), using a lower range of discount rates and a shorter time interval to overlaying of asphalt pavement and using the Florida data, calculated that concrete had a lower life-cycle cost than asphalt in the example given of an Interstate pavement. This suggests that a sensitivity analysis should be used covering the ranges of potential values in any subjective item contained in a life-cycle cost analysis. Good judgment based on experience is an important ingredient in the analysis.

Federal Aviation Administration

An engineering manual on *Economic Analysis of Airport Pavement Rehabilitation Alternatives* (*16*) was prepared by Epps and Wootan for the Federal Aviation Administration. The manual covers selection of rehabilitation alternatives, overlay thickness determinations, an economic analysis method, price data, price updating procedures, analysis procedures, examples, and sensitivity analysis. This subsection will deal primarily with the economic analysis method. The price data are contained in Appendix E of this synthesis.

The economic analysis method recommends the use of present worth with a discount rate of 4 percent using constant dollars. This is an inflation-free rate of return. The following types of initial and recurring costs were included in the manual as those associated with pavement rehabilitation.

1. Agency costs, including initial capital costs of rehabilitation, future rehabilitation costs, maintenance costs, salvage return, and engineering and administrative costs.

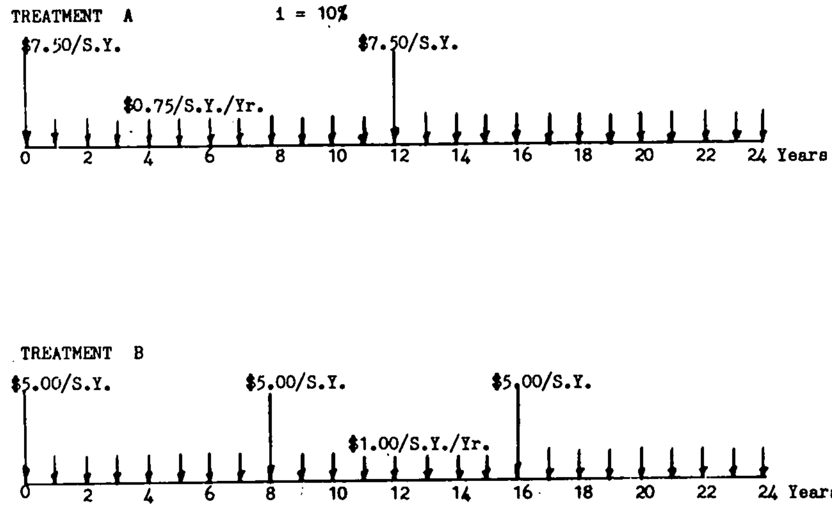


FIGURE 22 Cash-flow diagram for Figure 21.

PROJECT A (25 YEAR COMPARISON PERIOD)

		Cost per 3 lane mile with shoulders
PORTLAND CEMENT CONCRETE PAVEMENT		
Initial Cost		$137,638
Maintenance for 25 years ... $345 (14.094)		4,862
Present Worth Cost		$142,500
ASPHALT CONCRETE PAVEMENT		
Initial Cost		$127,352
Resurfacing 0.20′ at 14 years	$25,494	
Engineering ... $25,494 (0.1133)	2,888	
Supplemental work ... $25,494 (0.0871)	2.221	
Traffic delay	300	
	$30,903	
The present worth of resurfacing is ... $30,903 (0.5051)		$15,609
Maintenance for 25 years ... $690 (14.094)		9,725
Subtotal		$152,686
* Less Salvage ... (3/14) ($30,903) (0.2953)		− 1,955
Present Worth Cost		$150,731
Savings Per 3 Lane Mile Using Portland Cement Concrete		$8,231

* For purposes of this example, the original asphalt concrete pavement is expected to require resurfacing in 14 years and the 0.20′ blanket is assumed to last 14 years, so the total service period is 28 years. At the end of the 25 year comparison period, the blanket is expected to serve 3 years longer. This provides a salvage value of 3/14 the cost of the resurfacing.

PROJECT B (20 YEAR COMPARISON PERIOD)

		Cost per 2 lane mile with shoulders
PORTLAND CEMENT CONCRETE PAVEMENT		
Initial Cost		$93,320
Maintenance for 20 years ... $230 (12.462)		2,866
Present Worth Cost		$96,186
ASPHALT CONCRETE PAVEMENT		
Initial Cost		$70,840
Resurfacing 0.15′ at 14 years	$11,640	
Engineering ... $11,640 (0.1133)	1,319	
Supplemental work ... $11,640 (0.0871)	1,014	
Traffic Delay	300	
	$14,273	
Present worth of resurfacing is ... $14,273 (0.5051)		$7,209
Maintenance for 20 years ... $460 (12.462)		5,733
Subtotal		$83,782
* Less Salvage ... (8/14) ($14,273) (0.3769)		− 3,074
Present Worth Cost		$80,708
Savings Per 2 Lane Mile Using Asphalt Concrete		$15,478

* For purposes of this example, the original asphalt concrete pavement on this project is expected to require resurfacing in 14 years and the 0.15′ blanket is assumed to last 14 years, hence the total service period is 28 years. At the end of the 20 year comparison period, the blanket is expected to serve 8 years longer. This provides a salvage value of 8/14 the cost of the resurfacing.

FIGURE 23 Economic comparisons of pavement in California (*34*).

TABLE 7

DESIGN ALTERNATIVES FOR A LIFE-CYCLE COST ANALYSIS IN FLORIDA (*8*)

	Design Alternative			
	30-Year Life		40-Year Life	
Total Life-Cycle Cost Item	Concrete	Asphalt	Concrete	Asphalt
Initial Construction Cost	Initial cost	Initial cost	Initial cost	Initial cost
Expected Maintenance Expenditures				
at 10 years	Reseal joints	Stage II	Reseal joints	Stage II
at 20 years	Reseal joints	Recycle 3"	Reseal joints	Recycle 3"
at 30 years	-	-	Reseal joints	Recycle 3"
Annual Routine Maintenance	Annual routine maintenance	Annual routine maintenance	Annual routine maintenance	Annual routine maintenance
Terminal Value	Terminal value	Terminal value	Terminal value	Terminal value

TABLE 8

TOTAL LIFE-CYCLE PRESENT WORTH COMPARISON IN FLORIDA (*8*)

	Discount Rate		
30-Year Life Cycle	5%	7%	10%
Concrete Pavement	$794,778	$792,831	$788,357
Asphalt Pavement	715,372	682,758	651,391
40-Year Life Cycle			
Concrete Pavement	811,964	803,680	793,641
Asphalt Pavement	770,305	720,595	667,494

TABLE 9

CONCRETE PAVEMENT LIFE-CYCLE PRESENT WORTH ANALYSIS FOR 40-YEAR PERIOD IN FLORIDA (*8*)

	Discount Rate - i		
	5%	7%	10%
Initial Investment	$765,728	$765,728	$765,728
PW of Resealing Costs (Yr.10)	20,340	16,842	12,773
PW = $33,131 (P/F, i, 10)			
PW of Resealing Costs (Yr.20)	12,487	8,562	4,925
PW = $33,131 (P/F, i, 20)			
PW of Resealing Costs (Yr.30)	7,666	4,352	1,899
PW = $33,131 (P/F, i, 30)			
PW of Annual Maintenance Cost of 1,044/yr	17,914	13,918	10,209
PW = 1,044 (P/A. i, 40)			
PW of Terminal Value(Yr.40)	(12,171)	(5,722)	(1,893)
PW = $85,686 (P/F, i, 40)			
Total life cycle present-worth	$811,964	$803,680	$793,641

2. User costs, including travel time, vehicle operation, accidents, discomfort, delay, and extra operating costs during major maintenance or resurfacing.
3. Nonuser costs.

The FAA manual suggested using all of these costs if a detailed economic analysis were to be done but recognized that some of the costs were difficult to obtain. The manual recommended for simplicity that only the following costs be included.

1. Initial capital costs of rehabilitation.
2. Future capital costs of reconstruction or rehabilitation.
3. Maintenance costs
4. Salvage value.

The manual suggested that certain user costs, such as time delay costs during rehabilitation, be considered on certain facilities.

An analysis period of 20 years was suggested for use unless the life of a selected alternative was expected to be greater than 20 years. A simplified method is utilized to determine salvage value for use in the analysis.

$$SV = \left(1 - \frac{L_A}{L_E}\right)C \qquad (5)$$

where

SV = Salvage or residual value of rehabilitation alternative.
L_A = Analysis life of the rehabilitation alternative in years; i.e., difference between the year of construction and the year associated with the termination of the life-cycle analysis.
L_E = Expected life of the rehabilitation alternative (useful life).
C = Cost or price of the rehabilitation alternative (*16*).

The manual recommended that the life of rehabilitation alternatives be based on the experience of the engineer with consideration given to local materials, environmental factors, and contractor capability.

Price data were included in the manual for pavement construction, reconstruction, recycling, and maintenance opera-

TABLE 10

ASPHALT PAVEMENT LIEF-CYCLE PRESENT WORTH ANALYSIS FOR 40-YEAR PERIOD IN FLORIDA (*8*)

	Discount Rate - %		
	5%	7%	10%
Stage I Investment	$544,981	$544,981	$544,981
PW of Stage II Costs (Yr.10)	134,993	111,781	84,777
PW = $219,890 (P/F, %, 10)			
PW of Recycling Costs in Yr.20	67,470	46,262	26,610
PW = $179,018 (P/F, %, 20)			
PW of Recycling Costs (Yr. 30)	41,420	23,517	10,259
PW = $179,018 (P/F, %, 30)			
PW of Annual Maintenance Cost of $528/year	9,060	7,039	5,163
PW = 528 (P/A, %, 40)			
PW of Terminal Costs	($27,619)	($12,985)	($4,296)
PW = $194,436 (P/F, %, 40)			
Total life cycle present-worth cost	$770,305	$720,595	$667,494

tions. Some of these are contained in Appendix E of this synthesis. A procedure was provided to update prices; this is also included in Appendix E.

The basic equation used in the FAA manual to determine present worth of rehabilitation and maintenance is as follows:

$$PW = C + M_1 \left(\frac{1}{1+r}\right)^{n_1} + \ldots M_i\left(\frac{1}{1+r}\right)^{n_i} - S\left(\frac{1}{1+r}\right)^{z} \quad (6)$$

where

PW = Present worth.
C = Present cost of initial rehabilitation activity.
M_i = Cost of the ith maintenance or rehabilitation alternative in terms of present costs, i.e., constant dollars.
r = Discount rate (4%).
n_i = Number of years from the present to the ith maintenance or rehabilitation activity.
s = Salvage value at the end of the analysis period.
z = Length of analysis period in years (20 years) (*16*).

The manual stated that from a practical standpoint for life-cycle cost analysis, if the difference in the present worth of costs between two rehabilitation alternatives is 10 percent or less it can be assumed to be insignificant and the two alternatives can be considered to be the same.

The step-by-step procedure recommended in the manual is summarized as follows:

1. Identify and record key project descriptions.
2. Determine the condition of the existing pavement and record the data.
3. Determine the required overlay thickness.
4. Identify feasible rehabilitation and maintenance alternatives.
5. Record life-cycle cost information for each alternative to be evaluated.
6. Summarize the life-cycle present-worth costs together with the first cost of each alternative, the length of time required to complete the rehabilitation activity, and the chance for success of the rehabilitation alternative. Engineering judgment is used to establish the chance for success associated with each of the various rehabilitation alternatives; this is the chance of being able to successfully rehabilitate the pavement through the use of the rehabilitation strategy being analyzed.
7. Select the most promising rehabilitation alternative based on factors such as life-cycle cost, first cost, length of time required to rehabilitate, maintainability of the selected rehabilitation strategy, and user safety during construction.

An example using the techniques presented in the FAA manual for a light aircraft facility is included here. The existing pavement shows signs of deterioration and a 3-inch overlay is required to rehabilitate the facility. Seven rehabilitation alternatives were considered. Table 12 contains the project description, the condition of the pavement, and the rehabilitation alternatives. Life-cycle cost information is given in Table 13. The present worth calculations for alternative No. 1 are shown in Table 14.

The life-cycle present worth costs for the example are contained in the bottom section of Table 12 for each one of the seven different alternatives that were considered. Alternative No. 4 was recommended because of the low life-cycle cost, the reasonable initial cost, the relatively short time period needed for construction, and the high probability of being able to complete the rehabilitation as scheduled (*16*).

TABLE 11

TERMINAL SALVAGE VALUE IN FLORIDA (*8*)

Material		Value ($/ton)
CONCRETE		
1 ton virgin aggregate		9.87
Remove, haul, and crush		6.00
Terminal value of concrete (per ton)		3.87
ASPHALT		
1 ton virgin aggregate[a]	10.66	
Asphalt cement, 6% (14.12 gal x $0.60/gal)	8.47	
1 ton virgin asphalt		19.13
Mill 3" ($0.45/sy ÷ 300 lb/sy x 2000 lb/ton)	3.00	
Haul 20 mile (20 mile x $0.07/ton-mile)	1.40	
Stock pile cost		4.40
Terminal value of asphalt (per ton)		14.73

[a]Difference in cost of virgin aggregate is due to a larger percentage of more costly coarse aggregate in the asphalt mixture.

TABLE 12

PROJECT SUMMARY SHEET (*16*)

Description of Project

Location: Southwestern United States

Type of Facility: Runway, length 3,200 ft. - width 75 ft.

Critical Aircraft: 24,000 lbs. gross weight

Annual Departures: 3,000

Existing Pavement:

Type of Material	Thickness	Condition	Equivalency Factor	Equivalent Thickness
AC Surface	4	Fair	1.2	4.8
Untreated Base	10	Good	1.0	10.0
Subgrade				
				Total = 14.8

Condition of Pavement

Condition Survey: Alligator cracking, moderate 20 percent of area; transverse cracking, moderate, 1-4 per station; longitudinal cracks, moderate, 150 ft. per station.

Skid Resistance: Good

CBR of Subgrade: 4

Required Thickness of New Pavement: 18", min. 2" AC, 5" base

Equivalent Thickness of Old Pavement: 14.8"

Required Overlay Thickness: 3" AC

Rehabilitation Alternatives	First Cost $/yd^2	Life Cycle PW, $/yd^2	Time for Rehab.	Chance for Success
1. Asphalt-rubber chip seal to delay overlay	1.25	7.31	2 days	90
2. 3 inch AC overlay	4.95	9.88	5 days	95
3. Heater-scarification + 2 inch overlay	4.20	7.32	4 days	97
4. Asphalt-rubber interlayer + 2 inch overlay	4.55	6.76	4 days	97
5. Fabric interlayer + 2 inch overlay	4.50	7.62	4 days	97
6. Cold recycle with asphalt emulsion 6" + 2" AC	6.60	7.56	6 days	97
7. Hot recycle with AC 7"	8.10	8.46	6 days	99

FHWA Training Course on Techniques for Pavement Rehabilitation

A training course was prepared for FHWA by ERES Consultants on *Techniques for Pavement Rehabilitation* (*71*). The approach described in this course contained six basic steps:

> (1) Conduct a thorough evaluation, (2) develop several preliminary alternative designs, (3) determine the monetary and nonmonetary decision criteria that will be used in selecting the preferred alternative, (4) conduct a life-cycle cost analysis of each alternative, (5) evaluate each alternative with respect to the selected decision criteria, and (6) select the "preferred" alternative considering all important decision factors (*71*).

A flow chart illustrating the process of selecting rehabilitation alternatives is contained in Figure 24.

A thorough evaluation of the project planned for rehabilitation is essential in the design process. The basic causes of any pavement deterioration are an absolute must if any long-term correction is to be achieved.

Value-engineering concepts and methodology are recommended in the training course as a means of identifying and developing cost-effective rehabilitation alternatives. The four major types of rehabilitation alternatives are suggested for initial consideration in the process of generating alternatives. These are (a) restoration, (b) recycling, (c) resurfacing, and (d) reconstruction. There are many variations within each of these major types that could also be considered. The recommended outcome from this step of generating alternatives is to identify feasible alternatives for further evaluation and consideration.

The next recommended step from the training course is to select the preferred alternative design. This step includes consideration of overriding factors, such as those from the AASHTO guide (see Chapter 3). These factors are particularly useful if two or more alternatives have similar life-cycle costs. If the life-cycle cost study identifies a clear-cut best alternative and if this alternative meets other constraints, then it would usually be considered as the preferred alternative design.

Life-cycle costs of two different classes are identified. These are the costs to the highway agency and those to the highway user. Agency costs include initial construction, future maintenance and rehabilitation, and future salvage value. User costs include traffic delay caused by lane closure during rehabilitation and extra costs caused by increased roughness. The training course suggests that it may be necessary to neglect user costs in the analysis until such time that improved estimating methods are available.

The training course suggests an analysis period of from 5 to 20 years depending on the future use of the facility and other factors. The need to have good pavement performance data including rehabilitated pavements is stressed as very desirable in estimating the useful life of a proposed alternative. Without the data, then professional engineering judgment is required to make the best estimate of the life for a given pavement alternative. Future maintenance and rehabilitation costs also must be estimated and previous experience on a similar project, if available, should be used. Salvage value would need to be used if alternatives have unequal lives. It can be estimated as a percentage of the original cost or as the value of recycled materials. The course suggested using annual interest and inflation rates as specified by management based on agency policy. An example of a life-cycle cost analysis of pavement rehabilitation alternatives is contained in Figure 25 (*71*).

A CASE STUDY

A case study prepared by Faiz (*72*) is different from other procedures contained in this synthesis in that it incorporates user costs in the analysis. The procedures used in the case study are summarized in this chapter and the case study is printed in its entirety in Appendix B. The case study relates to a pavement that is scheduled for rehabilitation but the procedures used could be adapted to a new pavement.

The procedure consists of certain steps that are designed to incorporate the necessary data and conduct the proper analysis to select the most appropriate rehabilitation alternative. The steps are:

1. Obtain the site data for the pavement to be rehabilitated. These site data include pavement and soil characteristics, terrain, present pavement condition including roughness and cracking, traffic load history, and a deflection evaluation.

TABLE 13

LIFE-CYCLE COSTS ASSOCIATED WITH REHABILITATION ALTERNATIVES IN ILLUSTRATIVE EXAMPLE, DOLLARS PER SQUARE YARD (*16*)

	Rehabilitation Alternatives							
Year	1 A-R Chip Seal	2 3" AC	3 HS + 2" AC	4 A-R + 2" AC	5 Fabric + 2" AC	6 Cold Recycle	7 Hot Recycle	8
Initial	1.25	4.95	4.20	4.55	4.50	6.60	8.10	
1								
2		0.10						
3	0.25	0.15						
4	4.95	0.20						
5		0.20	0.10		0.10			
6		0.25	0.10		0.10			
7		2.50	0.10		0.10			
8			0.15	0.10	0.15			
9		0.10	0.25	0.10	0.25			
10	0.10	0.15	2.50	0.10	2.50	0.05		
11	0.10	0.20		0.15				
12	0.10	0.20		0.25		0.05	0.05	
13	0.15	0.25		2.50				
14	0.25	2.50	0.10		0.10	0.10	0.05	
15	2.50		0.15		0.15	0.15		
16		0.10	0.25		0.25	0.25	0.10	
17		0.15	2.50	0.10	2.50	2.50		
18		0.20		0.15			0.10	
19	0.10	0.20		0.25			0.20	
20	0.15	0.25		2.50			0.25	
Salvage Value	0.71	0.35	1.43	2.50	1.43	1.43	0	

A-R - Asphalt-Rubber H-S - Heater-Scarification AC - Asphalt Concrete

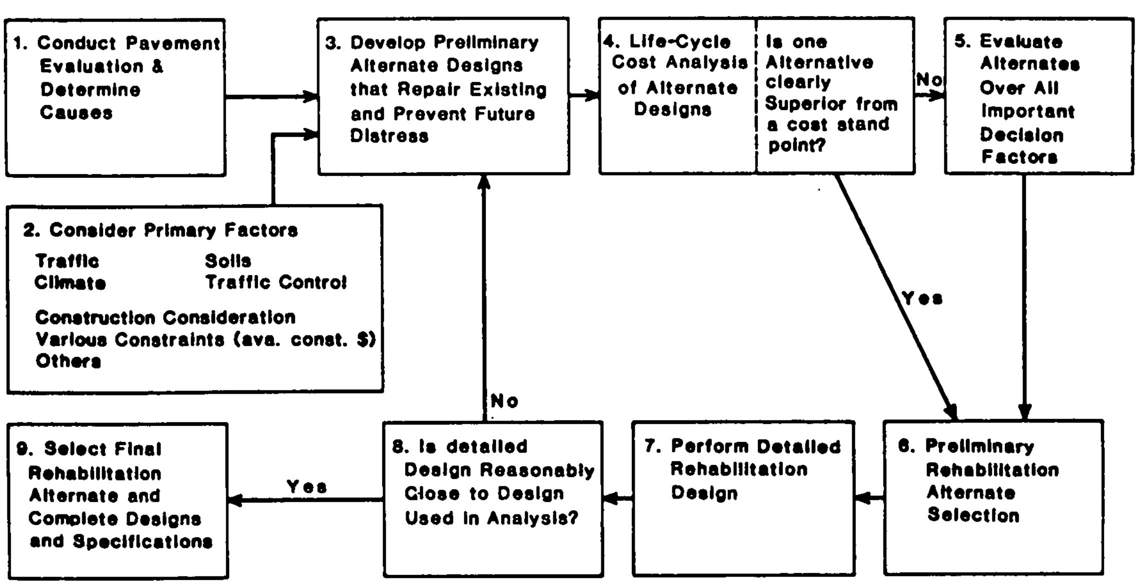


FIGURE 24 Rehabilitation alternative selection process (*71*).

TABLE 14

CALCULATION FORM FOR PRESENT WORTH LIFE-CYCLING COSTING FOR ALTERNATIVE 1

Year	Cost, Dollars Per Square Yard		Present Worth Factor, 4 Percent	Present Worth, Dollars
Initial Cost	1.25	A-R Chip Seal	1.0000	1.25
1			0.9615	
2			0.9246	
3	0.25	Maintenance	0.8890	0.22
4	4.95	3" AC	0.8548	4.23
5			0.8219	
6			0.7903	
7			0.7599	
8			0.7307	
9			0.7026	
10	0.10	Maintenance	0.6756	0.07
11	0.10	Maintenance	0.6496	0.06
12	0.10	Maintenance	0.6246	0.06
13	0.15	Maintenance	0.6006	0.09
14	0.25	Maintenance	0.5775	0.14
15	2.50	1 1/2" AC	0.5553	1.39
16			0.5339	
17			0.5134	
18			0.4936	
19	0.10	Maintenance	0.4746	0.05
20	0.15	Maintenance	0.4564	0.07
Salvage Value	0.71		0.4564	-0.32
Total =	9.19		Total =	7.31

Uniform Annual Cost = Present Worth x Capital Recovery Factor

= 7.31 x 0.07358

= 0.538

Example of a Preliminary Life-Cycle Cost Analysis of Pavement Rehabilitation Alternatives.

This life-cycle cost analysis is an example of the procedures and concepts only, and nothing should be concluded as to the economic benefits of one alternative over the others. The costs of construction and pavement conditions vary widely, and thus completely different results may be obtained in another location and for a different pavement condition.

Step 1. Existing Pavement Design:
Jointed plain concrete pavement, controlled access rural four lane divided highway. Design is 9 in. slab, 4 in. cement treated base over a silty clay subgrade. Joint spacing is random (12 to 19 ft.), skewed with no dowels. Pavement age is 15 years. Total accumulated 18-kip equivalent single axle loads is 6 million in one direction in outer lane.

Step 2. Existing Pavement Condition:

a. 7 % shattered slabs to replace in outer lane.
b. 50 SY partial depth patching for spall repair.
c. Pumping along approximately three-quarters of the project(outer lane only).
d. Faulting in outer lane is serious, averaging 0.20 ins. Inner lane is only 0.05 ins.
e. Serviceability Index averages 2.8 in the outer lane and 3.8 in the inner lane.
f. Asphalt concrete outer shoulder in fair condition.

Step 3. Select Feasible Alternatives(that both <u>repair</u> and <u>prevent</u> distress):

WORK ITEMS	Alternatives No. 1	No. 2	No. 3
Replace Shattered Slabs	X	X	
Patch Spalls	X		X (outer lane)
Subseal Slabs(75% panels)	X	X	
Subdrains	X	X	
Grind Surface Outer Lane	X		
AC Overlay		X	
Replace Outer Lane (recycle existing concrete as lean concrete base)			X
Place Tied PCC Shoulder			X
Design Service Life(years)	7	12	20

Step 4. Select Analysis Period:
The three example alternatives have different service lives. All alternatives must be analyzed over the same analysis period(e.g., 20 years) to conduct a present worth economic analysis. However, to conduct an equivalent uniform annual cost(EUAC) analysis, unequal lives can be used. Since most rehabilitation alternatives do not have equal lives, this example will use unequal lives to illustrate the concepts.

Step 5. Select Interest and Inflation Rates:
An interest rate of 10 percent is selected based on typical long term bond rates. An inflation rate of 6 percent is selected based on expected future construction cost increases.

Step 6. Estimate Life-Cycle Costs and Compute Present Worths:
The unit costs to perform each of the work tasks are estimated using previous bid estimates and other information. The unit costs are estimated for the 1984 year which will be the first year of the analysis period.
Future preventative type maintenance is planned to be applied about once every 5-7 years to each of the alternatives. This includes resealing of joints, sealing of cracks and subsealing if necessary.
The salvage values represent the expected worth of the existing pavement at the end of its service life. They were estimated as a percentage of their original construction and subsequent rehabilitation cost.

All costs are computed per two-lane mile including shoulders.

No. 1. Restoration

Year	Work Type	Cost	Present Worth
1984	Restoration	90,580	90,580
1991	Restoration	45,760	35,308
1998	Resurface	144,322	85,924
2005	Maintenance	10,000	4,594
2010	End of Service Life		
	Salvage Value	-67,500	<u>-25,766</u>
	Total Present Worth		= $ 190,640

Total life of alternative = 26 years

FIGURE 25 Example of preliminary life-cycle cost analysis of pavement rehabilitation alternatives (*71*).

No. 2. Resurfacing

Year	Work Type	Cost	Present Worth
1984	Resurfacing	180,162	180,162
1990	Maintenance	10,000	8,007
1996	Resurfacing	96,215	61,688
2001	Maintenance	10,000	5,328
2008	End of Service LIfe		
	Salvage Value	-85,000	-34,941
	Total Present Worth	=	$ 220,244

Total life of alternative = 24 years

No. 3. Reconstruct Outer Lane And Shoulder

Year	Work Type	Cost	Present Worth
1984	Replace Lane/Sh.	255,700	255,700
1994	Maintenance	10,000	6,904
1999	Maintenance	10,000	5,737
2004	End of Service Life		
	Salvage Value	-60,000	-28,603
	Total Present Worth	=	$ 239,738

Total life of alternative = 20 years

Present worth calculations were performed using the following expression:

$$\text{Present Worth} = \text{Cost}((1 + \text{inf.})/(1 + \text{int.}))^{n}$$

Where Inf. = 0.06
Int. = 0.10
n = Time in years since 1984

Step 7. Compute Equivalent Uniform Annual Costs:

Alternative	Analysis Period(years)	Present Worth	CRF	EUAC
No.1 Restoration	26	190,640	0.1092	$ 20,818
No.2 Resurfacing	24	220,243	0.1113	$ 24,513
No.3 Replace Lane/Sh.	20	239,738	0.1175	$ 28,169

EUAC calculations were performed using the following expression:

$$\text{EUAC} = \text{Present Worth } (\text{int.}/(1 - 1/(1 + \text{int.})^{n})$$

Step 8. Summary of Results

The life cycle cost analysis has shown that Alternative No.1 --Restoration has the least equivalent uniform annual cost. This alternative would cost the agency the equivalent of a yearly payment of $20810 yearly over a 26 year period at the assumed interest and inflation rates. Alternative No. 2 is 18 percent more than No.1, and No. 3 is 35 percent more than No. 1.

User costs due to lane closures or extra user costs due to increased roughness have not been included. If traffic was not heavy, the user costs would probably not effect the results of the analysis much. However, if traffic volume was very high, the alternative that had the most lane closure would have a much higher user cost and the consideration of user costs could possible change the cost analysis significantly.

Given the preceding results, an important question that could be asked is: if the estimate of pavement life was in error, how much would this effect the resulting life cycle costs(or EUAC)? To answer this question, consider that the restoration alternative only lasts five years instead of the seven assumed. This would be an error of 40 percent. The following average annual costs result for this service life using the same costs as above and placing an overlay at 10 years instead of 14 years:

EUAC = $22,513

This value is 8 percent higher than the cost for a restoration life of seven years. Thus, a fairly large error in life prediction will result in a much smaller error in the average annual cost. This occurs because of the effect of interest to discount future costs.

FIGURE 25 (*Continued*)

2. Identify potential pavement management strategies and select alternatives for further evaluation. Each strategy should include a recommended initial treatment and proposed future treatments at suggested time intervals. The projected future traffic would also need to be included in this step.

3. Estimate future routine and periodic maintenance needs for each alternative. Routine maintenance consists of pothole patching, crack sealing, etc., whereas periodic maintenance would include surface treatments to be applied at some specified time interval. The surface treatments would be designed to reduce the roughness levels or to cover patched and cracked areas.

4. Analyze the rehabilitation alternatives using life-cycle costs. Select a life cycle or analysis period and determine as appropriate a salvage or terminal value for any of the alternatives. Analyze the alternatives to determine life-cycle costs using selected discount rate. The case study used rates of 0, 5, and 10 percent.

Based on the results of the case study, Faiz reported that, over the range of discount rates used in the analysis and including vehicle operating costs, the reconstruction alternative was the most economical. If only agency costs consisting of construction and maintenance are analyzed at discount rates of 0 and 5 percent, then the initial overlay alternative is the most economical. At a 10 percent discount rate, it was more economical to defer the application of the overlay for 5 years.

The most important conclusions reached by Faiz are:

a. Road user costs are the dominant element in the life cycle cost of a pavement and their exclusion from the analysis of road improvements is likely to result in suboptimal solutions.

b. Lower discount rates tend to favor improvements with longer service lives and, as expected, alternatives with a higher level of capitalization. Conversely, higher discount rates are likely to result in the selection of stage construction alternatives.

c. The minimum requirements for the evaluation of life cycle costs are:

(1) An objective and quantifiable measure of pavement condition (roughness in this case study).

(2) A predictive model that relates pavement condition to time (or indirectly axle-load applications).

(3) A model that relates changes in pavement condition to user costs.

(4) A model that converts changes in pavement condition to discrete pavement maintenance requirements and costs (*72*).

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS, RESEARCH NEEDS

CONCLUSIONS

The following conclusions were reached in this synthesis:

1. The life-cycle cost analysis of new pavement design alternatives is a proven and acceptable procedure in the process of selecting the preferred alternative. Several agencies use life-cycle cost analysis with reasonable success.

2. Life-cycle cost analysis can be and is being successfully used in the process of selecting alternatives for the rehabilitation of pavements.

RECOMMENDATIONS

The recommended procedural steps in the process of selecting the preferred design alternatives for new or rehabilitated pavements are:

1. Determine the site characteristics and other input data that may influence the pavement design or the rehabilitation design. This should include a detail evaluation of the existing pavement if rehabilitation is planned.

2. Identify various pavement management strategies that might be used to achieve the life requirements for the project.

3. Identify all feasible alternatives that might satisfy the needs for the project, whether for new pavement construction or the rehabilitation of an existing pavement. Each alternative should be capable of providing the required structural service life for the analysis period. Brainstorming techniques, including the use of value engineering should be used in the process of generating alternatives.

4. Remove from further consideration any item or items that are common among all alternatives.

5. Select the analysis period to be used. Twenty-five to 40 years is recommended for new pavement construction. A lesser time comparable to the time until major reconstruction or replacement may be used for rehabilitation projects.

6. Select a suitable discount rate. Currently a 4 percent rate based on constant dollars is suggested. It is suggested that local agencies obtain guidance from their economists in selecting the rate for their use.

7. Predict the performance characteristics of the different alternatives being considered. Determine the time intervals for future maintenance and rehabilitation activities.

8. Make cost estimates for each alternative being considered.

This includes the future costs for maintenance and rehabilitation. Include user costs as appropriate.

9. Calculate present worth of costs for the alternatives. Annualized costs could also be used.

10. Make a sensitivity analysis on items or factors that may be subject to variation to ensure the selection of the proper alternative.

11. Evaluate the alternatives against other potentially overriding factors such as those contained in the AASHTO guide entitled "An Informational Guide to Project Procedures."

12. Select the most promising or preferred new pavement design or rehabilitation design based on all of the factors that were evaluated.

RESEARCH NEEDS

There are three areas of research needs that appear to be the most significant in being able to make improved life-cycle cost analysis of new and rehabilitated pavement design alternatives:

1. There is a critical need for more good usable cost data for pavement maintenance. There is a need for research on the costs for different types of maintenance as related to the different pavement alternatives. The additional cost for gathering more precise maintenance cost data should be small compared to the benefit gained from having such data. With a pavement management system and with the proposed long-term monitoring program, additional cost information will become available.

2. A better understanding is needed of user costs or benefits and their relationship to the life-cycle cost analysis of pavement alternatives. There has been extensive research done on the effect of major changes in surface type or condition but there is very limited information on such changes as going from a bituminous surface to a concrete surface or vice versa.

3. There is a need for improved performance data for different pavement types and rehabilitation activities. The performance characteristics of a specific rehabilitation action on a pavement with known defects are needed for a wide range of pavement conditions and rehabilitation activities. The proposed national long-term pavement performance monitoring program should be of significant help in this area.

GLOSSARY

alternatives Different courses of action or systems that will satisfy objectives and goals (*12*).

analysis period The time period used for comparing design alternatives. An analysis period may contain several maintenance and rehabilitation activities during the life cycle of the pavement being evaluated. It is sometimes referred to as the economic life, which is that period over which an investment is considered for satisfying a particular need (*4*). The length of time for the analysis period would be established by the agency.

annualized method Economic method that requires conversion of all present and future expenditures to a uniform annual cost (*4*).

benefit/cost analysis Technique intended to relate the economic benefits of a solution to the costs incurred in providing the solution (*4*).

brainstorming A widely used creativity technique for generating a large quantity and wide variety of ideas for alternative ways of solving a problem or making a decision. All judgment and evaluation are suspended during the free-wheeling generation of ideas (*4*).

cash-flow diagram Schematic diagram of dollar costs and benefits with respect to time (*12*).

constant dollars Dollars that have not been adjusted for the effects of expected future inflation or deflation; sometimes referred to as dollars as of a specific date (for example, "1980 dollars") (*4*).

corrective maintenance Type of maintenance used to take care of day-to-day emergencies and repair deficiencies as they develop. May include both temporary and permanent repairs; sometimes referred to as remedial maintenance (*62*).

current dollars An expression of costs stated at price levels prevailing at the time costs are incurred. Current dollars are inflated and represent price levels that may exist at some future date when the costs are incurred (*6, 8, 16*).

denial-of-use costs Extra costs occuring during the life cycle because occupancy or income (production) is delayed as a result of a process decision (*14*).

depreciation The allocation of the cost of a fixed asset over the estimated years of productive use. It is a process of allocation, not valuation. (Straight line; Declining Balance; Sum of Years—Digits) (*12*).

design life The length of time (in years) for which a pavement facility is being designed, including programmed rehabilitation. At the end of this period, the physical life of the facility is considered to be ended, i.e., the pavement structure has deteriorated to a point where total reconstruction would be necessary (*5*).

discount rate A value in percent used as the means for comparing the alternative uses for funds by reducing the future expected costs or benefits to present day terms. Discount rates are used to reduce various costs or benefits to their present worth or to uniform annual costs so that the economics of the different alternatives can be compared.

engineering economics Technique that allows the assessment of proposed engineering alternatives on the basis of considering their economic consequences over time (*4*).

equivalent dollars Dollars, both present and future, expressed in a common baseline reflecting the time value of money and inflation (*4*).

escalation (differential) rate That rate of inflation above the general devaluation of the purchasing power of the dollar (*4*).

failure Unsatisfactory performance of a pavement or portion such that it can no longer serve its intended purpose (*62*).

flexible pavement A pavement structure that maintains intimate contact with and distributes loads to the subgrade and depends on aggregate interlock, particle friction, and cohesion for stability (*56*).

inflation A continuing rise in the general price levels, caused usually by an increase in the volume of money and credit relative to available goods (*4*).

initial costs Costs associated with initial development of a facility, including project costs (fees, real estate, site, etc.) as well as construction cost (*4*).

interest A ratio of the amount paid for using resources for a given period of time to the total investment (*12*). A term generally associated with borrowing money (*19*) and is often referred to as market interest rates. The market interest rate includes both an allowance for expected inflation as well as a return that represents the real cost of capital (*20*).

life-cycle costing An economic assessment of an item, area, system or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent dollars (*4*).

maintenance Anything done to the pavement after original construction until complete reconstruction, excluding shoulders and bridges. It includes pavement rehabilitation and restoration (*62*).

minimum attractive rate of return Reflects the cost of using resources and the risk that the project may fail to produce the expected results. The risk portion of the minimum attractive rate of return varies with different cost centers and even with projects within cost centers (*12*).

nonrecurring cost Cost that occurs, or is expected to occur, only once (*4*).

opportunity rate That rate of return that the organization could make by investing its resources in the most beneficial (profitable) projects to the limit of the resources available (*12*).

pavement condition The present status or performance of a pavement (*62*).

pavement management system A set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time (*62*).

pavement performance Measure of accumulated service provided by a facility; i.e., the adequacy with which it fulfills its purpose based on all indicators or measurement types (*62*).

present-worth method Economic method that requires conversion of all present and future expenditures to a baseline of today's cost (*4*).

preventive maintenance The type of maintenance intended to keep the pavement above some minimum acceptable level at all times. It is used as a means of preventing further pavement deterioration that would require corrective maintenance. It may include either structural or nonstructural improvements to a pavement surface (*62*).

rate of return The interest rate that, over a period of time, equates the benefits derived from an opportunity to the investment cost of the project (*4*).

recurring costs Costs that recur on a periodic basis throughout the life of a project (*4*).

rehabilitation The act of restoring the pavement to a former condition so that it can fulfill its function (*62*).

replacement costs Those one-time costs to be incurred in the future to maintain the original function of the facility or item (*4*).

rigid pavement A pavement structure that distributes loads to the subgrade having as one course a portland cement concrete slab of relatively high bending resistance (*56*).

risk Exists when each alternative will lead to one of a set of possible outcomes and there is a known probability of each outcome (*12*).

salvage value The value (positive if it has residual economic value and negative if requiring demolition) of competing alternatives at the end of the life cycle or the analysis period (*4*). Sometimes referred to as residual value.

sensitivity analysis A technique to assess the relative effect a change in the input variable(s) has on the resulting output (*4*).

time value of money Recognition that all organizations have limited resources (finances, people, facilities, equipment) and that the commitment of these to a project precludes their use for any other investment. Whether internal resources are used, or borrowed ones are used, the interest that these resources could produce is a cost to the project (*12*).

trade-offs Giving up one thing to obtain something else (*12*).

uncertainty Exists when the probabilities of the outcomes are completely or partially unknown (*12*).

useful life The period of time over which a building element may be expected to give service. It may represent physical, technological, or economic life (*4*).

user costs Those costs that are accumulated by the user of a facility. In a life-cycle cost analysis these could be in the form of delay costs or change in vehicle operating costs.

value engineering (VE) An analysis of materials, processes, and products in which functions are related to cost and from which a selection may be made for the purpose of achieving the required function at the lowest overall cost consistent with the requirements for performance, reliability, and maintainability; sometimes called value analysis (*56*).

REFERENCES

1. McManus, P. F., "Impact of Subgrade Variability on Pavement Construction—Maintenance Cost Trade-Offs, *TRB Special Report 148: Innovations in Construction and Maintenance of Transportation Facilities,* Transportation Research Board, National Research Council, Washington, D.C. (1974) pp. 12–23.
2. Winfrey R. and C. Zellner, *NCHRP Report 122: Summary and Evaluation of Economic Consequences of Highway Improvements,* Highway Research Board, National Research Council, Washington, D.C. (1971).
3. Harral, C. G., P. Fossberrg, and T. Watanatada, "The Evaluation of Alternative Highway Maintenance Standards," Paper presenting a methodology for economic evaluation of alternative maintenance standards. Water Dept., World Bank, Washington, D.C. (undated).
4. Dell'Isola, A. J. and S. J. Kirk, *Life Cycle Costing For Design Professionals,* McGraw-Hill, New York (1981).
5. Lindow, E. S., *Systems Approach to Life-Cycle Design of Pavements,* Vol I, *Life 2 Users Manual.* Report No. CERL-TR-M-253. Construction Engineering Research Laboratory, Dept. of Army (1978).
6. Oglesby, C. H. and R. G. Hicks, *Highway Engineering,* 4th Edition, Wiley, New York (1982) pp. 97–159, 791–793.
7. Wellington, A. M., *The Economic Theory of the Location of Railways,* Wiley, New York (1877).
8. *A Comparative Economic Analysis of Asphalt and Concrete Pavements,* Florida Department of Transportation (1984).
9. Carmichael, R. F., III, F. L. Roberts, and H. J. Treybig, "Procedure For Evaluating The Effects of Legal Load Limits on Pavement Costs," *Transportation Research Record* 725: *Pavement Systems: Assessment of Load Effects, Design, and Bases,* Transportation Research Board, National Research Council, Washington, D.C. (1979) pp. 1–8.
10. Stanford Research Institute, *Economics of Asphalt and Concrete for Highway Construction.* Report No: SRI Project IE-3153. American Petroleum Institute, New York (1961).
11. Grant, E. L. and W. G. Ireson, *Principles of Engineering Economy,* 4th Edition, Ronald Press Company, New York (1960).
12. Keely, B. J. and J. W. Griffith, "Life Cycle Cost-Benefit Analysis. A Basic Course in Economic Decision Making," Report No. HEW/OFEPM-75/06. Department of Health, Education, and Welfare, Washington, D.C. (1975).
13. Byrd, L. G. and C. C. McMullen, "Life Cycle Costing in Selecting Maintenance Strategies," *APWA Reporter* (1984).
14. Kirk, S. J., "Life Cycle Costing: Problem Solver for Engineers," *Specifying Engineer* (1979) pp. 123–129.
15. Winfrey, R., *Economic Analysis for Highways,* International Textbook Company, Scranton, Pennsylvania (1969).
16. Epps, J. A. and C. V. Wootan, "Economic Analysis of Airport Pavement Rehabilitation Alternatives—An Engineering Manual," Report No. Dot-FAA-RD-81-78, Federal Aviation Administration, Department of Transportation, Washington, D.C. (1981).
17. Weed, R. M., "Basic Engineering—Economics Concepts," Memorandum Report, New Jersey Department of Transportation (1984).
18. Cady, P. D., "Inflation and Highway Economic Analysis," *ASCE Journal of Transportation Engineering,* Vol. 109, No. 5, Paper No. 18248 (1983) pp. 631–639.
19. Haas, R. and W. R. Hudson, *Pavement Management Systems,* Krieger Publishing Co., Melbourne, Florida (1982).
20. Standing Committee on Highways, *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements,* American Associations of State Highway and Transportation Officials, Washington, D.C. (1977).
21. Transportation Research Board, *NCHRP Report 215: Pavement Management System Development,* Transportation Research Board, National Research Council, Washington, D.C. (1979) 32 pp.
22. Roy, R. and G. K. Ray, *Discussion of "A Comparative Economic Analysis of Asphalt and Concrete Pavements," Florida Department of Transportation.* Portland Cement Association, Skokie, Ill. (1984).
23. Pouliquen, L. Y., "Risk Analysis in Project Appraisal," World Bank Staff Occasional Paper No. 11 (1970).
24. Kher, R. and W. A. Phang, "OPAC Design System," Ontario Ministry of Transportation, Ontario, Canada (1977).
25. Kulkarni, R. B., "Life-Cycle Costing of Paved Alaskan Highway," in *Transportation Research Record 997: Pavement Management Activities,* Transportation Research Board, National Research Council, Washington, D.C. (1984) pp. 19–27.
26. Kulkarni, R. B., "Dynamic Decision Model for a Pavement Management System," in *Transportation Research Record 997: Pavement Management Activities,* Transportation Research Board, National Research Council, Washington D.C. (1984) pp. 11–18.
27. Alexander, J. A., "Application of Maintainability and Expected Cost Decision Analysis to Highway Design," in TRB *Special Report 148: Innovations in Construction and Maintenance of Transportation Facilities,* Transportation Research Board, National Research Council, Washington, D.C. (1974) pp. 3–11.
28. Curtayne, P. C. and V. P. Servas, "Economic Considerations in the Design of Pavement Rehabilitation," Technical Report RC-2-83. National Institute For Transport and Road Research, CSIR, South Africa (1983).
29. McNeil, S. and C. Hendrickson, *Three Statistical Models of Pavement Management Based on Turnpike Data with an Application to Roadway Cost Allocation,* Federal Highway Administration, Department of Transportation, Washington, D.C. (1981).
30. "Pavement Management Program Development and Im-

plementation Plan," Florida Department of Transportation (1984).
31. "Report on the Method of Pavement Selection," Minnesota Department of Transportation (1978).
32. "Comparison of Preliminary Estimated Costs for Surface Determination," S.P. 2906-09 T.H.71, Minnesota Department of Transportation (1983).
33. "Method of Pavement Selection," Minnesota Department of Transportation (1983).
34. "Highway Design Manual—Selection of Pavement Type," (7-661), California Department of Transportation (1974).
35. "Design of Pavement Structure," Design Manual, Colorado Department of Transportation (1981).
36. "Pavement Type Determination," 610-Procedure, Idaho Department of Transportation (1979).
37. Pavement Design Manual, Section 7, Illinois Department of Transportation (1983).
38. "Economical Analysis for Pavement Type Determinations," Iowa Department of Transportation (1976).
39. "Pavement Type Selection Procedure," North Carolina Department of Transportation (1981).
40. "I-97 North of Maryland Route 450 to Hawkins Road," *Economic Pavement Comparison Summary,* Maryland Department of Transportation (1983).
41. "Pavement Selection and Design Policy," New Mexico State Highway Department (1984).
42. "Economic Analysis," IR 15-4 (55) 200 Helena-North, Montana Department of Transportation (1982).
43. "Type Determination Procedure," 11.8. Pennsylvania Department of Transportation (undated).
44. *Pavement Structure Policy,* Chapter 4, New York Department of Transportation (1973).
45. "Unit Costs For Surfacing Materials," Wyoming Highway Department (1982).
46. "Annual Cost for Equal Time Period," (Form), Wisconsin Department of Transportation (1979).
47. Federal Highway Administration, "Pavement Type Selection; Policy Statement," *Federal Register,* Vol. 46, No. 195 and "Pavement Type Selection; Policy Statement; Clarification," *Federal Register* Vol. 46, No. 216; *23 CFR* Ch. 1, Department of Transportation, Federal Highway Administration, Washington, D.C. (1981).
48. "Remarks by Deputy Federal Highway Administrator John S. Hassell, Jr.," in *Transportation Research Record 781: Maintaining the Maintenance Management System,* Transportation Research Board, National Research Council, Washington D.C. (1980) pp. 3–5.
49. Shahin, M. Y., "Components of a Maintenance Management System," in *Transportation Research Record 781: Maintaining the Maintenance Management Systems,* Transportation Research Board, National Research Council, Washington, D.C. (1980) pp. 31–39.
50. Peterson, D.E., "Good Roads Cost Less (Pavement Rehabilitations Needs, Benefits and Costs in Utah)," Report No. UDOT-MR-77-8, Utah Department of Transportation, Research and Development Unit, Salt Lake City, Utah (1977).
51. Ray, G. K., "Life-Cycle Cost Studies for Pavements," a paper prepared for presentation to the Association of Cost Engineers 1st Annual Region IV Seminar, Chicago (1983).
52. Johnson, C., "Pavement Maintenance Management Systems," *APWA Reporter* (1983) pp. 15–28.
53. Rauhut, J. B. and W. J. Kenis, "Factorial Study of Relations between Pavement Cost and Legal Axle Loads," in *Transportation Research Record 725: Pavement Systems: Assessment of Load Effects, Design, and Bases,* Transportation Research Board, National Research Council, Washington, D.C. (1979) pp. 22–30.
54. Finn, F. N. and J. A. Epps, "Pavement Failure Analysis with Guidelines for Rehabilitation of Flexible Pavements," Research Report 214-17, Texas Transportation Institute, College Station, Texas (1980).
55. Anderson, D. I., D. E. Peterson, L. W. Shepherd, and C. C. Sy, "Pavement Rehabilitation Design Strategies," Report No. FHW/UT-79-6, Utah Department of Transportation (1980).
56. American Association of State Highway and Transportation Officials, *AASHTO Highway Definitions,* Special Committee on Nomenclature, AASHTO, Washington, D.C. (1968).
57. Johnson, E. D., "Value Engineering for Highways and Its Application to Highway Maintenance," Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. (1975).
58. Dell'Isola, A. J. and S. J. Kirk, *Life Cycle Cost Data,* McGraw-Hill, New York (1983).
59. Chow, W. W. C., *Cost Reduction in Product Design,* Van Nostrand Reinhold, New York (1978).
60. Transportation Research Board, *NCHRP Synthesis 46: Recording and Reporting Methods for Highway Maintenance Expenditures,* Transportation Research Board, National Research Council, Washington, D.C. (1977).
61. Transportation Research Board, *NCHRP Synthesis 110: Maintenance Management Systems,* Transportation Research Board, National Research Council, Washington, D.C. (1984).
62. Transportation Research Board, *NCHRP Synthesis 77: Evaluations of Pavement Maintenance Strategies,* Transportation Research Board, National Research Council, Washington, D.C. (1981).
63. Transportation Research Board, *NCHRP Synthesis 58: Consequences of Deferred Maintenance.* Transportation Research Board, National Research Council, Washington, D.C. (1979).
64. Carmichael, R. F., III, F. L. Roberts, P. R. Jordahl, H. J. Treybig, and F. N. Finn, "Effect of Changes in Legal Load Limits on Pavement Costs," Vol I, *Development of Evaluation Procedure,* Report No. FHWA-RD-79-73, Federal Highway Administration, Washington, D.C. (1978).
65. Carmichael, R. F., III, F. L. Roberts, P. R. Jordahl, H. J. Treybig, and F. N. Finn, "Effect of Changes in Legal Load Limits on Pavement Costs," Vol II, *Users Manual for Program NULOAD,* Report No. FHWA-RD-79-74, Federal Highway Administration, Washington, D.C. (1978).
66. Hide, H., "Vehicle Operating Costs in the Caribbean: Results of a Survey of Vehicle Operators, TRRL Laboratory Report 1031, Transportation and Road Research Laboratory, Crowthorne, Berkshire, England (1982).
67. Hide, H., Abaynayaka, Sayer, and Wyatt, "The Kenya Road Transport Cost Study: Research on Vehicle Operating Costs," TRRL Laboratory Report 672, Transportation and Road Research Laboratory, Crowthorne, Berkshire, England (1975).
68. PICR Final Report, "Research on the Interrelationships between Costs of Highway Construction, Maintenance, and

Utilization," Volume 5, *Study of Road User Costs,* Ministerio Dos Transportes, Empresa Brasileira de Planejamento de Transportes—GEPOT, United Nations Development Program (UNDP), International Bank for Reconstruction and Development (IBRD), Texas Research and Development Foundation (TRDF) (1981).

69. Harrison, R. and A. Chesher, *Road User Cost Savings: An Econometric Approach,* draft report (1985) (forthcoming World Bank publication).
70. Watanatada, T. et al., *Models for Predicting Vehicle Speeds and Operating Costs Based on Mechanistic Principles: Theory and Quantification,* draft report (1985) (forthcoming World Bank publication).
71. Federal Highway Administration, *Techniques for Pavement Rehabilitation Training Course—Participant Notebook,* prepared by ERES consultants, Inc. Contract No. DOT-FH-11-9580, U.S. Department of Transportation, Federal Highway Administration, National Highway Institute (1984).
72. Faiz, A., *Life Cycle Cost Analysis of Pavements—Case Study,* The World Bank, Washington, D.C. (1985).

APPENDIX A

SURVEY OF PRACTICE SUMMARY (1984)

TABLE A-1

PROCEDURES FOR SELECTING PAVEMENT DESIGN ALTERNATIVES

STATE OR AGENCY	ECONOMIC PROCEDURE(S) USED TO SELECT PAVEMENT DESIGN ALTERNATIVES	HOW LONG IN USE	EFFECT-IVENESS OF PRO-CEDURE IN MIN-IMIZING PAVEMENT COSTS	LENGTH OF AN-ALYSIS PERIOD USED	OTHER BASIS USED FOR SELECTING PAVEMENT TYPES	WHAT COMPUTER AND PROGRAM USED FOR ANALYSIS IF ANY
ALABAMA	Lowest Initial Cost	Do not know	Good	- -	Some politics location	None
ALASKA	Cost of Construction	Since State-hood 1959	Adequate	- -	Politics minor	None
ARIZONA	Lowest first cost with constraints on acceptable limits of thickness based on past performance	10 + yrs	Very effective in minimizing 1st cost long term effect un-determined	20 yr design life on AC vs AC 30 yrs in AC vs PCCP	Continuity of pavement type given considerable weight	Yes, IBM Main frame using ADOT developed programs.
ARKANSAS	Life-Cycle cost	One Project	Unknown	35 yrs main-tained life	AASHTO Factors for selection	None
CALIFORNIA	Life-Cycle Cost	Since 1952	Good	20-25 yr 30-35 yr in the future	Gap closures, environment, soil condition, as additional info in deciding pavement type	No, but hope to have one in the future
COLORADO	Life-Cycle Cost	2 yrs	Fair	40 yrs	Secondary factors listed pp. 6 of attachment, Analysis Techniques not specified.	No, use of IBM PS's and Rainbow 100+ will be considered
CONNECTICUT	None	- -	- -	- -	Method indicated in 1963 AASHTO an information guide on project procedure.	None
DELAWARE	Currently we have no formal procedure which considers economics in the pavement selecting (design) process	- -	- -	- -	Ease of traffic maint. (On existing roadways) ability to use existing road as base, cost advantages of recycling (savings plus additional 5%) FHWA participation	None
FLORIDA	Life-Cycle cost in pilot Mode, will implement in routine production when training & staffing comp.	Intermit-tently since 1971	Reasonably Effective	Var. 30 yrs Max	AASHTO Pavement Selection Guideline, Revised Draft 1/81 is used on major projects	Dept IBM Main Frame in TSO mode simple routine present worth & annual Cost Analysis.

TABLE A-1 (Continued)

STATE OR AGENCY	ECONOMIC PROCEDURE(S) USED TO SELECT PAVEMENT DESIGN ALTERNATIVES	HOW LONG IN USE	EFFECT-IVENESS OF PRO-CEDURE IN MIN-IMIZING PAVEMENT COSTS	LENGTH OF AN-ALYSIS PERIOD USED	OTHER BASIS USED FOR SELECTING PAVEMENT TYPES	WHAT COMPUTER AND PROGRAM USED FOR ANALYSIS IF ANY
GEORGIA	Life-Cycle Cost	1981±	Good	20 yrs	Varies with each project but a major factor is the ability to construct a project in a given loco.	None
HAWAII	Life-Cycle Cost	20 yrs	Good	20 yrs	Rigid pvmts not used in area susceptible to settlement. Aesthetics & safety used only when costs are approx equal	None
IDAHO	Life-Cycle Cost	Approx 15 yrs	Uncertain	40 year study period		None
ILLINOIS	Annual Cost utilizing the R.H. Baldock Method	Present technique since 1967 Latest revision occured in 1982 & 1983	Good	40 yrs	Try to match type, full-ramps and crossroads same type as mainline; special surfaces for high accident locations are identified.	None
INDIANA	Use AASHTO Interim Guide for design of pvmt. Structures 1972 Chapt III Revised 1981. Due to lack of Hist Data on pvmt Life-Cycle Costs, generally only consider Initial Costs.	Several years	Presently can only effectively minimize the initial cost of alt. pvmt designs	N/A		I.D.O.H. IBM 370 Computer being utilized in PMS
IOWA	Present worth of a Life-Cycle Procedure Attached	20 yrs	Very good for initial construction costs and Investment	30 yrs	Short sectors such as bridge approach, intersections 1 mile or less are determined by material availability and policy	Mini-computer used in design phase programs based on AASHTO (ACC) and PCA (PCC)
KANSAS	First term cost only	20 plus years	Moderately effective, maint cost not available	20 yrs	Politics	None
KENTUCKY	Pavements are assumed to be structurally equal; therefore, initial cost is utilized	25-30 yr	- -	- -	1. Traffic 2. Soils 3. Weather 4. Perf. of similar pvmt in area 5. adjacent existing pvmt. 6. Stage const. 7. Depressed surface, or elevated designs 8. 8. Stimulation of completion 9. Use of local aggr. or pvmt. matls. 10. Municipal preference and recognition of local industry 11. Traffic safety	We developed and used a computer program to calculate initial cost

TABLE A-1 (Continued)

STATE OR AGENCY	ECONOMIC PROCEDURE(S) USED TO SELECT PAVEMENT DESIGN ALTERNATIVES	HOW LONG IN USE	EFFECTIVENESS OF PROCEDURE IN MINIMIZING PAVEMENT COSTS	LENGTH OF ANALYSIS PERIOD USED	OTHER BASIS USED FOR SELECTING PAVEMENT TYPES	WHAT COMPUTER AND PROGRAM USED FOR ANALYSIS IF ANY
MARYLAND	Consider Economics and availability of material (Procedure attached)	±30 yrs with periodic updating	Procedure results in economic selection of designed alternatives	Alt. Des.are predicated on 20yr economic analysis pred.on 30 yrs include periodic maintenance	Economic impact of ind. suppliers in local areas Aesthetics, compatibility, adjacent roadways public convenience (Traffic control and safety)	Yes, used for economic analysis & loadmeter & traffic patterns Sperry Univac Model 1180
MASSACHUSETTS	Comparison of initial cost using common design period	19 yrs	Unknown	20 yr design period	- -	None
MICHIGAN	Currently Capital Expenditure. moving rapidly to Life-Cycle Present worth system	Since 50's at least	Reasonable with some political problems	20 yr design life will be using 35 yr service life	Vary, all enter in at one time or another	Not yet
MINNESOTA	Comparative Annual costs per mile.	Since 1959 modified 1978 & 1982	Good	35 yrs	See page 15 of 1983 edition	Not yet, working on
MISSOURI (letter response)	No written policy for pavement type selection			20-25 years		
MONTANA	Life-cycle	1970	Good	20 yr flex. 40 yr rigid.	Industry consideration (near cement plant or oil refinery). Safety (special skid resistance) Environmental (severe climate conditions).	No, probably should have one
NEBRASKA	Life-Cycle costs & Benefit costs	- -	Average	40 yrs on Interstate	Regional factors for Aggregates for PCC	Yes AASHTO
NEW HAMPSHIRE	None	N/A	N/A	N/A	N/A	N/A
NEW JERSEY	Life-Cycle Cost	15 yrs	Moderate effective	20 yr flex. 40 yr rigid	N/A	None
NEW MEXICO	Present-worth	$2\frac{1}{2}$ yrs	Low	20 yrs	- -	None

TABLE A-1 (Continued)

STATE OR AGENCY	ECONOMIC PROCEDURE(S) USED TO SELECT PAVEMENT DESIGN ALTERNATIVES	HOW LONG IN USE	EFFECTIVENESS OF PROCEDURE IN MINIMIZING PAVEMENT COSTS	LENGTH OF ANALYSIS PERIOD USED	OTHER BASIS USED FOR SELECTING PAVEMENT TYPES	WHAT COMPUTER AND PROGRAM USED FOR ANALYSIS IF ANY
NEW YORK					- -	None
NORTH CAROLINA	First cost except for major projects, when concrete pvmt is an alt. then use a modified life cycle cost.	Approx 10 yrs	Good	20 yrs	Safety as related to maint. of traffic during const., Availability of matls., Continuity of type, subgrade, soil condition, etc.	None
NORTH DAKOTA	Life-Cycle Cost limited basis	2 yrs	Effectiveness has not been determined	25 yrs	Significant portion of states pri. & sec., hwys are devel. on stage basis which generally dictates flexible pavement	Not at this time; however, we are interested in the automated process.
OHIO	Annual Cost	Since 1960±	Probably as well as other procedures	20 yrs	Follow the AASHTO Pavement Selection process	Use HP 41 CV with the AASHTO equation
OKLAHOMA	- -	- -	- -	20 yr	- -	None
OREGON	Life-Cycle Cost	15 yrs	Good	20 yr min. 35 yr max.	We address the primary & secondary factors in AASHTO Guidelines	None
PENNSYLVANIA	Life-Cycle cost using present worth	15 yrs for new design	Good	20 yrs for new varies for rehab & overlays	See attached	None
RHODE ISLAND	No set procedure, all decisions based on experience with inclination toward long term life	12 yr +	Not presently rated	N/A	No other specific bases	None
SOUTH CAROLINA	Engineering judgement considering current const. and maintenance costs and trends	- -	Satisfactory	20 yrs	Present location and local availability of materials	None
SOUTH DAKOTA	Life-Cycle cost	12 yrs	Good	40 yrs	Conservation of available materials, continuity, subgrade stability	None
TENNESSEE	Pvmt design alternatives are based on initial const. costs, due to unavailability of operating and maint. costs	N/A	N/A	N/A	- -	- - -
UTAH	Annual Cost Basis	Since 1966	Fair	40 yrs	- -	None
VERMONT (letter response)	Use basically all AC.					

TABLE A-1 (Continued)

STATE OR AGENCY	ECONOMIC PROCEDURE(S) USED TO SELECT PAVEMENT DESIGN ALTERNATIVES	HOW LONG IN USE	EFFECTIVENESS OF PROCEDURE IN MINIMIZING PAVEMENT COSTS	LENGTH OF ANALYSIS PERIOD USED	OTHER BASIS USED FOR SELECTING PAVEMENT TYPES	WHAT COMPUTER AND PROGRAM USED FOR ANALYSIS IF ANY
VIRGINIA	Life-Cycle Cost (Annual cost 24' lane mile)	10 yrs off & on	Good	25 yrs CRCP all others equated	Engineering Considerations RE: Long term settlement means flex. pvmt, existing pvmt., etc.	No, prices only
WASHINGTON	Life Cycle Costs	20 yrs	Reasonable	25 yrs	None	None
WEST VIRGINIA	Present Worth	21 yrs	Experience has proven our procedure **effective** for layered flex. pvmt. but not full **depth asph.** or resurfacing.	40 yrs	Continuity of pavements frost susceptibility in all cases	None
WISCONSIN	Annual cost for equal time periods (this essentially a life-cycle cost procedure	18 yrs	Satisfactory	- -	These and other factors such as stimulation of competition and municipal preference either **singly or collectively** to varying degrees play a part in the selection process.	None
WYOMING	Presently consider initial surfacing const. costs only 20 year design period used	- -	Effective for comparing initial design alternatives	20 yrs primarily for traffic analysis	Politics influence can can be 0-100% depending on situation; past experience in similar traffic or environmental conditions, conc. pavement at intersection, etc.	Yes IBM 370 Fortran program developed in house
ONTARIO	Initial & Life-Cycle costing, some benefit/cost calculations are carried out to develop maint. programs	8 yrs	High	30 yrs	Safety, Noise (Urban areas) continuity/uniformity	O.P.A.C. System
NORTHWEST TERRITORIES	Benefit/costs & Life-Cycle Cost	Approx. 5 yrs	Fair	20 yr	Economics is basic justification to date	Computer used in earthwork design only
SASKATCHEWAN	Life-Cycle	15 yrs.	Fairly Good	15 yrs	Little	None
WASHINGTON D.C.		N/A	N/A	N/A	N/A	N/A

TABLE A-2

LIFE-CYCLE COST PROCEDURES USED

STATE OR AGENCY	PRESENTLY USED OR PLAN TO USE LIFE-CYCLE COST	METHOD USED AS THE BASE FOR ECONOMIC ANALYSIS	DISCOUNT RATE USED AND WHEN LAST CHANGED	INFLATION RATE AND TYPE USED IF IDENTIFIED	HAS SENSITIVITY ANALYSIS BEEN USED TO DETERMINE THE EFFECT OF CHANGE IN VALUES FOR FACTORS USED IN PROCEDURE	WHAT RESEARCH IF ANY CONDUCTED OR IN PROCESS ON PAVEMENT TYPE SELECTION
ALABAMA	Looking into the possibility	Present Worth	Not used	None	No	None
ALASKA	Not in immediate future	Present Worth	Varies	None	No	None
ARIZONA	Under discussion no definite plan	Present value without consideration of interest or inflation	N/A	N/A	No	Not at this time reviewing Faromar Attached pvmt preserv. policy
ARKANSAS	Yes	Present worth	9%	4.1% Flat Inflation rate	No	None
CALIFORNIA	Plan to improve by making it more comprehensive	Present Worth	At present 8% Yes, reviewing interest and cost trends	None	No	Not specifically, our involvement as one of 8 states involved in long term pavement monitoring should provide info. in the future that will have a bearing on type selection.
COLORADO	Yes	Present Worth	4% not changes	None	No	No (Procedure attachment)
CONNECTICUT	Possibly	- -	- -	- -	No	None
DELAWARE	No definite plan though considering it some.	See #1, No formal procedure	- -	- -	No	None

TABLE A-2 (Continued)

STATE OR AGENCY	PRESENTLY USED OR PLAN TO USE LIFE-CYCLE COST	METHOD USED AS THE BASE FOR ECONOMIC ANALYSIS	DISCOUNT RATE USED AND WHEN LAST CHANGED	INFLATION RATE AND TYPE USED IF IDENTIFIED	HAS SENSITIVITY ANALYSIS BEEN USED TO DETERMINE THE EFFECT OF CHANGE IN VALUES FOR FACTORS USED IN PROCEDURE	WHAT RESEARCH IF ANY CONDUCTED OR IN PROCESS ON PAVEMENT TYPE SELECTION
FLORIDA	Is in pilot mode	Both Present worth & Annual cost	5%, 7%, 10% Yes, increased	Yes, see attached Book. Inflation included in discount rate as const. over analysis period	Change Analysis period to determine "break even point between alt., choice is made on judgement concerning performance of alternatives.	Need Pavement Perf. model. this will get underway in the next 24 months.
GEORGIA	Yes	Present Worth	5%, 7%, 10% prevailing int. rates. Yes, have changed with time.	Variable Flat	Yes, only on discount rates	Yes, Research branch constantly monitors pvmt structures to offer better designs for selected pavements.
HAWAII	Yes	Present Worth	None	None	No	No
IDAHO	Yes	Annualized	None	None	No	No (Attched Procedure)
ILLINOIS	No	Annualized	10% , increased from 6-10% in 1980	7%/yr, It is a flat inflation rate which is compouned annually	No	Yes, there is a research project underway for development of a mechanistic design procedure for flex. pvmts. also engaged in early stages on PCC overlay, PCC Recycling, break & seat, Bit. conc. overlay performance.
INDIANA	Yes as part of P.M.S.	N/A	N/A	Usually at 10% Usually flat inflation rate.	N/A	I.D.O.H., on their own & with other agencies has conducted research related to pvmt type selection. Now investigating most cost effective subbase to be used for flex. and rigid pvmts.

TABLE A-2 (Continued)

STATE OR AGENCY	PRESENTLY USED OR PLAN TO USE LIFE-CYCLE COST	METHOD USED AS THE BASE FOR ECONOMIC ANALYSIS	DISCOUNT RATE USED AND WHEN LAST CHANGED	INFLATION RATE AND TYPE USED IF IDENTIFIED	HAS SENSITIVITY ANALYSIS BEEN USED TO DETERMINE THE EFFECT OF CHANGE IN VALUES FOR FACTORS USED IN PROCEDURE	WHAT RESEARCH IF ANY CONDUCTED OR IN PROCESS ON PAVEMENT TYPE SELECTION
IOWA	Future pvmt management system	Initial cost plus present worth of future resurfacing	7% Interest rate not in 10 yrs ±	None	No	Periodically compare methods and procedures with surrounding sts.
KANSAS	Yes, our P.M.S should address life cycle cost	None	None	None	No	In progress. New design proc. will be imple. in the proj. optim. system of PMS
KENTUCKY	Possibly if reliable fact. can be obtained	Initial cost	N/A	None	No	None
MARYLAND	Under consideration the method comp. is subj. to update See Research column	Present worth	None	0% to 12% varies using latest bid prices as base	Yes, design components are eval. for variance to assure realistic cost analysis	Research in progress "Microcomputer Solution of the Project Level P.M.S. Life-Cycle Cost Model"
MASSACHUSETTS	No	First Cost	- -	- -	- -	- -
MICHIGAN	Definitely	Capital costs & Quantities moving to Present Worth	Probable 4-5%	Probably won't use	- -	No
MINNESOTA	No	Annual Cost Per mile based on present Worth factor	Constant 4.5% Real Estate Rate	No separate rate	No	No, Attachments-report on Method of pvmt selection Dec. 78 Method pvmt Selection 1983, Cost Summary Example
MONTANA	Yes	Annualized	Avg. current Changed as above	Avg. current or Government predicted, flat	No	Only Pvmt Condition Surveys
NEBRASKA	Yes	Annualized	None	Partially flat	No	Underway in conjunction with Pavement Management Program
NEW HAMPSHIRE	No	N/A	N/A	N/A	No	None
NEW JERSEY	Yes	Present Worth	Interest rates assumed to be constant 1% G.T. Const. cost increased	(See Discount rate)	No	Yes
NEW MEXICO	Not Immediately	Present Worth	10% Use Prefailing rate	None	No	None; Pvmt Selection and Design Policy

TABLE A-2 (Continued)

STATE OR AGENCY	PRESENTLY USED OR PLAN TO USE LIFE-CYCLE COST	METHOD USED AS THE BASE FOR ECONOMIC ANALYSIS	DISCOUNT RATE USED AND WHEN LAST CHANGED	INFLATION RATE AND TYPE USED IF IDENTIFIED	HAS SENSITIVITY ANALYSIS BEEN USED TO DETERMINE THE EFFECT OF CHANGE IN VALUES FOR FACTORS USED IN PROCEDURE	WHAT RESEARCH IF ANY CONDUCTED OR IN PROCESS ON PAVEMENT TYPE SELECTION
NEW YORK	– –	Annualized	None	No	No	Initial Development underway
NORTH CAROLINA	Yes, a modified life - cycle cost	Present Worth (See attachment)	9% (Discount rate equals inflation rate) See Attachment	Yes, Flat	No	No
NORTH DAKOTA	Yes	Annualized	None	Yes, 6% Flat Rate	No	None
OHIO	Yes	Present Worth	5% Based on information from Estimating Section	5%, Flat Inflation rate	No	No May have some demonstration projects in the future
OKLAHOMA	Yes	– –	– –	– –	– –	Research Project for Evaluation of our Pavement Design Process
OREGON	Yes	Annualized	4%; changed; Yes, at various time we have assumed that inflation & Investment opportunities cancel each other	No, we consider the value of money is 4% greater than inflation	No	Yes; None recent
PENNSYLVANIA	Yes	Present Worth	6% has changed only once from 5%	No	No	No; Attachments-Type Determination
RHODE ISLAND	Yes, as part of pvmt management program being Implemented	N/A	N/A	No	No	Yes, Pavement Performance Evaluation Study FHWA Grant Study In Progress
SOUTH CAROLINA	Not at this time	Present Costs	– –	– –	No	No
SOUTH DAKOTA	Yes	Costs computed 3 ways 1. Life-cycle at todays prices 2. with 6% infl. 3. 4% "Real Int."	4%	6% flat	No	No
TENNESSEE	Yes	N/A	N/A	No	No	– –

TABLE A-2 (Continued)

STATE OR AGENCY	PRESENTLY USED OR PLAN TO USE LIFE-CYCLE COST	METHOD USED AS THE BASE FOR ECONOMIC ANALYSIS	DISCOUNT RATE USED AND WHEN LAST CHANGED	INFLATION RATE AND TYPE USED IF IDENTIFIED	HAS SENSITIVITY ANALYSIS BEEN USED TO DETERMINE THE EFFECT OF CHANGE IN VALUES FOR FACTORS USED IN PROCEDURE	WHAT RESEARCH IF ANY CONDUCTED OR IN PROCESS ON PAVEMENT TYPE SELECTION
UTAH	Probably If theres good procedure	Annualized	Use of Int. Controversial, Use of int. favors flex. no int. favors concrete	No	No	No
VIRGINIA	Yes	Annual Cost; 24' Lane Mile includes Maintenance Costs	- - - -	- - - -	No	None
WASHINGTON	Yes	Used total cost in past, but may be switching to Present Worth	4%; No change	Only as the discount rate relates to diff. between Infl. and Interest Flat	No	No
WEST VIRGINIA	Only thinking at this time	Present Worth	9%; 4½% in 1963	Do not use	No	No
WISCONSIN	Essentially, Yes	Annual cost for Equal Time Periods	None	No	No	No
WYOMING	Done some preliminary development	N/A	N/A	No	No	None other than in house devel. of PMS and Life cycle Cost Comparison
ONTARIO	Yes	Present Worth	Usually 6%; No change	No	Use only to check OPAC sys. during its development	Brampton Rd. test Hwy 3N Leamington (conc) Attachments: OPAC Design System
NORTHWEST TERRITORIES	Yes	EVAC	4%	5% Flat	Varied discount rate up to, 8% Asph. Surf. was not viable for some sections when discount rate was increased.	No
SASKATCHEWAN	Yes	Present Worth	8%; No change	No	Yes, effect of Int. rate in selecting staged pvmts of high init. cost chnged alt. selection.	None regarding performance lives of exist. stnds. some has been done on in-house economic comp. of alt. designs.
WASHINGTON D.C.	Yes, for rehab alt. not for pvmt type selection	N/A	N/A	N/A	No	HPR Study to optimize repair and rehab alt. on a Life-Cycle Cost Basis.

TABLE A-3

COST ELEMENTS USED

STATE OR AGENCY		DESIGN COST	CONSTRUCTION COST	MAINTENANCE COST	REPLACEMENT COST	USER COST	DENIAL OF USE COST	ENERGY	SALVAGE VALUE
ALABAMA	USE IN ANALYSIS	No	Yes	No	No	No	No	No	No
	SOURCE		Bids						
	DATA RELIABILITY		Very Good						
	UPDATE FREQUENCY		Monthly						
ALASKA	USE IN ANALYSIS	– – –	Yes	– – –	Yes	– – –	– – –	– – –	– – –
	SOURCE								
	DATA RELIABILITY								
	UPDATE FREQUENCY								
ARIZONA	USE IN ANALYSIS	No	Yes	No	Yes	No	No	No	No
	SOURCE		Previous Projects		Previous Projects				
	DATA RELIABILITY		Good		Good				
	UPDATE FREQUENCY		Yearly		Yearly				
ARKANSAS	USE IN ANALYSIS	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	SOURCE		Historical Costs	Maintenance Records					
	DATA RELIABILITY		Good	Good					
	UPDATE FREQUENCY		Yearly	Yearly					
CALIFORNIA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	Yes
	SOURCE		cost ind. cur. bids	district maint.	cost index cur. bids				% of life
	DATA RELIABILITY		Good	Good	Good				Good
	UPDATE FREQUENCY		Annual & latest	Annual	Annual & latest				
COLORADO	USE IN ANALYSIS	Yes	No	No	Yes	No	No	No	No
	SOURCE	Estimating Unit			Estimating Unit				
	DATA RELIABILITY	±10%			±10%				
	UPDATE FREQUENCY	quarterly			quarterly				
DELAWARE	USE IN ANALYSIS	Yes	Yes	Yes	Yes	No	No	No	No
	SOURCE	In house	In house	Maint.Mgt. system	In house				
	DATA RELIABILITY	Poor	Fair	Fair	Fair				
	UPDATE FREQUENCY	monthly	Project Basis	Annual	Project Basis				

TABLE A-3 (Continued)

STATE OR AGENCY		DESIGN COST	CONSTRUC-TION COST	MAINTE-NANCE COST	REPLACE-MENT COST	USER COST	DENIAL OF USE COST	ENERGY	SALVAGE VALUE
FLORIDA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	Yes
	SOURCE		Estimating System	Maint. Mgt. System	Estimating System	not avail.	not available	not avail.	Estimate System
	DATA RELIABILITY		Excellent	Fair	Excellent	Very Poor	Very Poor	Very Poor	Excel-lent
	UPDATE FREQUENCY		Monthly	Continuous	Monthly	None	None	None	Monthly
GEORGIA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	Yes
	SOURCE		Avg. of Pre. bids	Maintenance Records	Previous Bids				Engr. Judgemnt
	DATA RELIABILITY		Good	Fair	Fair				Fair
	UPDATE FREQUENCY		Yearly	Yearly	Yearly				Yearly
HAWAII	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Prior Project	Assumed	Prior Projects				
	DATA RELIABILITY		Good	Fair	Good				
	UPDATE FREQUENCY		By Project	As needed	By Project				
IDAHO	USE IN ANALYSIS	– –	Yes	Yes	Yes	– –	– –	– –	– –
	SOURCE		Dpt. con-tract cost	Maint. costs	Dpt. con-tract cost				
	DATA RELIABILITY		Good	Good	Good				
	UPDATE FREQUENCY		Semi Annual	Weekly	Semi Annual				
ILLINOIS	USE IN ANALYSIS	No	Yes	No	Yes	No	No	No	No
	SOURCE		Estimat. Unit	Equal for alt. types	Estimating Unit				0 at end of 40 yr
	DATA RELIABILITY		Good		Good				
	UPDATE FREQUENCY		Each job		Each job				
INDIANA	USE IN ANALYSIS	Yes	Yes	No	No	No	No	No	No
	SOURCE	±3% of the const.	Contract Proposal	Section of I.D.O.H.					
	DATA RELIABILITY	cost	Fair to Good						
	UPDATE FREQUENCY		Yearly						
IOWA	USE IN ANALYSIS	No	Yes	No	Yes	No	No	No	Yes
	SOURCE		Const./ Maint.		Contracts				Experien. Recycled
	DATA RELIABILITY		Very Good		Good				Fair
	UPDATE FREQUENCY		Monthly		Annually				Annually
KANSAS	USE IN ANALYSIS	No	Yes	No	Yes	– –	– –	– –	– –
	SOURCE		Const.		Const.				
	DATA RELIABILITY		Good		Good				
	UPDATE FREQUENCY		Yearly		Yearly				
KENTUCKY	USE IN ANALYSIS	No	No	No	No	No	No	No	No
	SOURCE								
	DATA RELIABILITY								
	UPDATE FREQUENCY								

TABLE A-3 (Continued)

STATE OR AGENCY		DESIGN COST	CONSTRUCTION COST	MAINTENANCE COST	REPLACEMENT COST	USER COST	DENIAL OF USE COST	ENERGY	SALVAGE VALUE
MARYLAND	USE IN ANALYSIS	---	Yes	Yes	Yes	Yes	No	No	Yes
	SOURCE		Current Bid Price	Price Indices	Current Bid Prices				Hist. Perf.
	DATA RELIABILITY		Good	Good	Good				Good
	UPDATE FREQUENCY		Contin. Update	Current & Projection	Continuous				Continuous
MASSACHUSETTS	USE IN ANALYSIS	---	Yes	---	---	---	---	---	---
	SOURCE		Recent Projects						
	DATA RELIABILITY		95%						
	UPDATE FREQUENCY		Quarterly						
MICHIGAN	USE IN ANALYSIS	Yes	Yes	No	No	No	No	No	No
	SOURCE	Design Hours	Bids						
	DATA RELIABILITY	Excellent	Good						
	UPDATE FREQUENCY	Current	Current Quarterly						
MINNESOTA	USE IN ANALYSIS	No	Yes	Yes	No	No	No	No	No
	SOURCE		Estimating Section						
	DATA RELIABILITY		Good						
	UPDATE FREQUENCY		Current Pricing						
MONTANA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	Yes	Yes
	SOURCE								
	DATA RELIABILITY		Good	Fair	Fair			Good	Good
	UPDATE FREQUENCY		Semi-Annual	Semi-Annual	Semi-Annual			Semi-Annual	Per Project
NEBRASKA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	Yes
	SOURCE		Avg. unit Prices	Time Periods	Avg. unit Prices				Est. & AUP
	DATA RELIABILITY		Fair	Fair	Fair				Fair
	UPDATE FREQUENCY		6 mo.	Annual	6 mo.				Annual
NEW JERSEY	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Past const projects	Pres. Maint Cost	Past const Projects				
	DATA RELIABILITY		Good	Good	Good				
	UPDATE FREQUENCY		Yearly	Yearly	Yearly				
NEW MEXICO	USE IN ANALYSIS	Yes	Yes	Yes	Yes	No	No	No	No
	SOURCE	Bid tabs	Bid Tabs	From Experience	From Experience				
	DATA RELIABILITY	Good	Good	Poor	Poor				
	UPDATE FREQUENCY								
NORTH CAROLINA	USE IN ANALYSIS	No	Yes	No	Yes	No	No	No	No
	SOURCE		Previous Bids		Previous Bids				
	DATA RELIABILITY		Good		Fair				
	UPDATE FREQUENCY		Monthly		Monthly				

TABLE A-3 (Continued)

STATE OR AGENCY		DESIGN COST	CONSTRUCTION COST	MAINTENANCE COST	REPLACEMENT COST	USER COST	DENIAL OF USE COST	ENERGY	SALVAGE VALUE
NORTH DAKOTA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Past Lettings	Estimation	Past Lettings				
	DATA RELIABILITY		Good		Good				
	UPDATE FREQUENCY		On-going		On-going				
OHIO	USE IN ANALYSIS	Yes	Yes	No	Yes	No	No	No	Yes
	SOURCE	Estimating	Last yrs Summary		Estimating				Estima.
	DATA RELIABILITY								
	UPDATE FREQUENCY	Annual	Annual		Annual				Annual
OREGON	USE IN ANALYSIS	No On small	Yes	No	Yes	No	No	No	Yes
	SOURCE	projects but Yes	Contract Bids	Reliable Info not	Contracts Bids	Consi- der if		In cost no but	
	DATA RELIABILITY	on Bigger	Good	Available	Fair	can be Quanti-		Decision Yes	
	UPDATE FREQUENCY		Annual		Annual	fied			
PENNSYLVANIA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Recent Projects	Maint. Mgt System	Recent Projects	Used for few			
	DATA RELIABILITY		Very Good	Poor	Good	High Volume			
	UPDATE FREQUENCY		Continu- ously	5 years	Continu- uously	Designs			
RHODE ISLAND	USE IN ANALYSIS	Yes	Yes	Yes	Yes	No	No	No	No
	SOURCE	Previous yr. cost	Pre. yr. avg unit pr.	Estimated	Pre. Yr. avg unit pr.				
	DATA RELIABILITY	Good	Very Good	Fair	Very Good				
	UPDATE FREQUENCY	Yearly	Yearly	N/A	Yearly				
SOUTH CAROLINA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Contract Data	Actual Record	Projected				
	DATA RELIABILITY		Good	Good	Fair				
	UPDATE FREQUENCY		Monthly	Monthly	As needed				
SOUTH DAKOTA	USE IN ANALYSIS	No	Yes	Yes	No	No	No	No	No
	SOURCE		In-house	In-house					
	DATA RELIABILITY		Good	Good					
	UPDATE FREQUENCY		Current	Annual					
TENNESSEE	USE IN ANALYSIS	---	Yes	---	---	---	---	---	---
	SOURCE		Historical Data						
	DATA RELIABILITY		Excellent						
	UPDATE FREQUENCY		Update 6 wks						
UTAH	USE IN ANALYSIS	No	Yes Average	Yes Based on	No	No	No	No	No
	SOURCE		Low bid Work con-	Calendar Year					
	DATA RELIABILITY		tracted during	Prices					
	UPDATE FREQUENCY		Calendar year	Yearly					

TABLE A-3 (Continued)

STATE OR AGENCY		DESIGN COST	CONSTRUCTION COST	MAINTENANCE COST	REPLACEMENT COST	USER COST	DENIAL OF USE COST	ENERGY	SALVAGE VALUE
VIRGINIA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	Yes
	SOURCE		Computer Prices	Experience	Experience				
	DATA RELIABILITY			Average	Average				40%
	UPDATE FREQUENCY								
WASHINGTON	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Const. cost files	Model	Constr. Cost files				
	DATA RELIABILITY		Good	Fair	Good				
	UPDATE FREQUENCY		Yearly	Yearly	Yearly				
WEST VIRGINA	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		Latest bid price		Latest bid				
	DATA RELIABILITY		Good	Poor	Good				
	UPDATE FREQUENCY		Continu-ous		Continu-ous				
WISCONSIN	USE IN ANALYSIS	Yes	Yes	Yes	Yes				
	SOURCE		Bid Data	Maint. Cost Selec	Bid Data				
	DATA RELIABILITY	Good	Good	Poor	Good				
	UPDATE FREQUENCY	Annual	Annual		Annual				
WYOMING	USE IN ANALYSIS	No	Yes	No	No	No	No	No	No
	SOURCE		Hist. bid item data						
	DATA RELIABILITY		very good						
	UPDATE FREQUENCY		Ea. proj. Letting						
ONTARIO	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	Yes Designed
	SOURCE		M.T.C Estimated	Designed Assigns	M.T.C. Estimated				assigns assumed
	DATA RELIABILITY		Good Current	Fair	Good				to be 20% of mtl.
	UPDATE FREQUENCY		data; may be 6 mo.	Low	Current				cost at end
NORTHWEST TERRITORIES	USE IN ANALYSIS	– – –	Yes	Yes	No	Yes	– – –	– – –	– – –
	SOURCE								
	DATA RELIABILITY		Fair	Fair					
	UPDATE FREQUENCY		Yearly	Yearly					
SASKATCHEWAN	USE IN ANALYSIS	No	Yes	Yes	Yes	No	No	No	No
	SOURCE		In-house	In-house	In-house				
	DATA RELIABILITY		Good	Good	Good				
	UPDATE FREQUENCY		Annually	Annually	Annually				
WASHINGTON D.C.	USE IN ANALYSIS	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	SOURCE								
	DATA RELIABILITY								
	UPDATE FREQUENCY								

TABLE A-4

PAVEMENT MANAGEMENT, PERFORMANCE, TYPES, CONSTRUCTABILITY, NEW MATERIALS

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
ALABAMA	The dept in process of developing a system	No	PSI of 2.5 as defined by AASHTO	Conc. 37% of interstate Bituminous 63% of Interstate Other unknown	Yes, ease of Construction	Not considered
ALASKA	No	No	No	100% Asphaltic Concrete	Constructability; Maintainability.	N/A
ARIZONA	Yes, used to establish funding level but not specific design.	Considerable data but limited anal. of it	See attachment	Almost exclusively AC except in urban areas 95% AC 5% PCCP	Policy constraints have been devel. to elim. unaccept. designs from consideration	Perform cost estimate & estimate performance then treat the same as other tech. & materials.
ARKANSAS	Yes, provides Maint. data	Yes	Yes; PSI 2.5	Flexible 95.3%; Rigid 4.5% Rigid Continuous 0.2%	No	Same as old ones.
CALIFORNIA	Yes, does not relate, prim. used to determine cond. of existing pvmt. and which areas need rehab. PMS does not predict perf. or life.	Yes, but not in readily avail. form. One weakness is lack of good info. on actual truck wts. and vol. on a project basis.	On pvmts. over 1000 ADT the ride sco. of 45 or more triggers need for rehab., struc. cond. comb. with ride score & traffic volumes determine priority.	14,000 lane miles of PCCP and 33,000 lane miles of AC some of which is actually composite (AC over PCC) with little PCC over AC	Yes, must consider environment, soil conditions, past performance, etc.	Through latest bids, inquires to manufacturer, contractors, etc.
COLORADO	Currently devel. PMS, does not link to pvmt. selec. now but a link may be made in the future	No, will be part of PMS	Will be part of PMS similar to Ariz.	Interstate 755 mi. Pcc or 8% of Colorado 9000 mile system PCC has not been cost-effective on most other highways	Full depth HBP is gen. used in Urban traf. to avoid putting vehicles over aggregate base course.	Costs would be based on recent contract prices
CONNECTICUT	Presently under formation	No	No	Major projects 50% each type Minor projects almost 100% Bituminous.	Yes	- - -

TABLE A-4 (Continued)

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
DELAWARE	In early stages of devel. PMS. Procedure for pvmt selec. haven't been established yet.	Nothing upon which could base future decisions on.	Not yet, but probably would be included in PMS	Flex. 95%; Rigid 5%; these % would increase for Rigid and decrease for Flex. If high type roads on new location were being constructed.	Yes, but limited to subj judgement of design personnel coupled with comments from construction district	If use appear to show promise; cost is not governing criteria; no formal proc. to incorp. new matls. or methods.
FLORIDA	Developed a PMS. PMS will provide perf. input to selec. process	Yes, satellite projects PMS will allow retrieval of perf. data from hwy system in general.	Min. level set at PSI = 3.0	About 90% Flexible	Yes, narrative review No numeric quantification.	Do not account for new technology in future yrs of the anal. New tech. in current yr. subj to sensitivity anal. by changing anal period.
GEORGIA	Yes, presently being impl ('83) but not pres. used in pvmt design selection procedure	Yes, variable reliability	P_t = 2.5	75% ± asphalt; 25%±Conc.	Engineering judgement and past experience	Not considered seperately
HAWAII	Yes, just started PMS; plan to make study of Life-cycle after compiled sufficient data.	No	No	Rigid - 1%; Flexible - 99%	Yes, by adjusting the costs.	Estimate construction and maintenance costs.
IDAHO	Have PMS perf data and overlay design programs are used in combination with other factors to design pvmt. Network opt. model being developed	4 yrs perf. history. struct. roughness cracking & skid on Interstate & 2 complete yrs. on entire state hwy system.	Use 2.5 index on Interstate & primaries & 2.0 on secondaries and Urban.	Estimate: 60% Rigid; 40% Flexible in recent yrs.	The procedure is flexible enough to permit these factors to enter into the determination	Such considerations are handled outside the normal pvmt type determination.

TABLE A-4 (Continued)

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
ILLINOIS	Yes, one PMS now under consideration. would deal with new pvmt design procedure and selection procedure.	Yes	Min. serv. level 2.5 for multi-lane; future multi-lane one-way str. with a struct. design, traffic greater than 3500 ADT., All others min. 2.0	Interstate 98% rigid; 2% flexible. Supplemental fwys 79% R; 21% F. State routes 95% R; 5% F. Frontage rds 72% F; 28% R.	Const. and ease of impl. are considered in the est. costs used in the anal. proc. Maintain. is consd. by the addt. of surface corrections for flex. pvmts due to heavy traffic loads	The anal. proc. is for new pvmts. only and there is no way of incl. experimental matls. or tech., Permanent procedures such as roto milling Bit. surfaces have been built into the formulas.
INDIANA	Yes, have PMS and hopefully in the future they can provide Life-Cycle costs to aid in the Economic proced. of pvmt type selection.	No	Use TSI=to 2.0 or = to 2.5. a P_t of 2.5 used in desg. on Rigid. P_t of 2.5 used in design of Flex for State, US & Int. as well as 4 lane and larger str. & County Rds. P_t = 2.0 for others.	100% all resurfacing is done with bit. materials. Flex. pavements account for 80-90% of all new construction on a mileage basis with the balance being rigid pavement construction.	Yes, as pvmt. type selec. is gen. based on an engr. eval. considering factors contained in 1960 AASHTO Publication titled: "An Informational Guide on Project Procedures".	Based on cost data supplied by suppliers, contractors, construction engineers, etc.
IOWA	Under development (PMS) will be of value later	Yes, used in original determination in design prior to Economic Analysis.	Yes - PSI 2.5 for design purposes but actual values may vary with service life of highway.	70-80%; High % of original pvmt. is PCC; 80% High % of resurfacing restoration is ACC	No	Detailed cost anal. on all bid items. Prepared & tested by competitive bidding.
KANSAS	In process of developing.	No; however, at this stage of developmt. of PMS we have develop. a conscensus of opinions on pvmt perf.	PMS will set min. accept. perf. levels ride & distress types are used to place pvmts. in one of 3 perf. levels.	Full design 27.4; partial design 51.1; Composite 12.3; Rigid 9.2.	Yes, consider whether tech. or process is simple and whether maint. has resources to maintain a particular type of pvmt.	Make an assumption that they are equiv. to some in-use material or techniques.
KENTUCKY	In process of refining a PMS	Some	No	Not a valid question due to the wide variance of designs used.		Assumptions that new mtl. will perform like standard materials.
MARYLAND	Yes, network level PMS in final stage of devel. and not yet related to pvmt des. sel. Procedure. Anticipate impl. end of 1984.	Ongoing studies with emphasis on major projects.	Yes, serv. index of 2.5 (AASHTO) PMS when Impl. will establish accept. levels and limiting values.	Initial lane mile const. with in last 5 yrs: Flex. 80% Rigid 20%; in place pvmts. excl. resurf. Approx. 50% Flex: 50% Rigid.	Consider mtl. availability, constr. practicality, environmental infl. & maint. controls as part of econ. anal. under const. costs.	Handled as demo. and experimental proj. and then consid. as alternatives as based on performance.

TABLE A-4 (Continued)

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
MASSACHUSETTS	Beg. an Inventory of PSI's for priority program. does not directly influence design selection.	No	PSI equal to or greater than 2.5.	100% Bit. since 1965	Constr. and/ or ease of implementation.	Engineering estimates of costs.
MICHIGAN	Just starting, no tie in yet.	Not much	No	60% Bit.; 40% conc. subject to change dependent on year and project	General typical recommendations, experience.	Best Estimates.
MINNESOTA	Yes, at this not related. In future move procedure to PMS	No, not as part of procedure	No, not as part of procedure.	1983: 50% Flex; 50% Rigid 1982: 55% Flex; 45% Rigid 1981: 58% Flex; 42% Rigid	Only when alternatives within 50% of each other	Only use "Standard Designs" for selec. process.
MONTANA	Have PMS but has not been in operation long enough to have positive results in design selection procedure.	Not formally but proj. files and history data are avail. for comparison.	Interstate & Primary 2.5 serv. index. Sec. access roads 2.0 serv. index.	90% Flex; 5% Rigid; 5% grael or Bit. Surface Treatment.	Yes, usually reflects in unit costs or experience maintenance costs.	Usually reflects in unit costs.
NEBRASKA	Just now, developed one	Yes (Particularly conc. on intersate)	Suf. rating sys. Develop. a pvmt. restoration index based on cracking, spalling, effective thickness,etc.	Interstate PCC; Urban PCC Rural mostly asphalt	Field experience, value engineering.	Matls. division evaluates with some "On the road" research.
NEW HAMPSHIRE	Future plans incl. impl. a PMS.	No	- -	All asphalt, concrete pavements	Only asphalt pvmts have been spec. for many yrs. in the state*	N/A
NEW JERSEY	Recent impl. of the PMS has precluded its use in type selec.	Yes	Target PSI Value of 2.5.	Flexible 80%; Rigid 20%	Factors listed used in subjective manner	Life-cycle cost effects are estimat. by Bureaus of Geotech. Engr. and Transp. Struct. research.
NEW MEXICO	Yes, it's new and does not yet relate to pvmt design selection	No	Yes, now have a roughness & distress rating sys. and have cut-off point on it.	10% PCC; 90% AC	Yes, experience & judgement	on the basis of experience & initial cost.
NEW YORK	Developing	No, est. from maint. engr. experience.	Developing, condition level, roughness.	22% PCC, 37% AC, 41% overlaid concrete (mostly conc. pvmt. built in 1920's, 30's) 16,000 mile system.	- -	Perf. evaluation program before considered standard.

TABLE A-4 (Continued)

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
NORTH CAROLINA	PMS being established and we expect Perf. data will be important to pvmt selection process.	No	PSR = 2.5	Interstate 65% concrete, 35% Asphalt, Primary 5% Concrete, 95% AC, Secondary 100% AC	Yes	Estimate based on available info. from other agencies, other states and industry.
NORTH DAKOTA	Yes, the sys. still early, so not fully implemented as yet.	No	No	Interstate 90% Rigid Primary and Secondary 80% Flexible.	No	Not encountered this yet.
OHIO	In process of building a PMS.	Yes	2.5	90% of two lane and low volume 4 lane roads are flex. Majority of major 4 lane and Interstate are Rigid or Composite 95%.	No	By experimental or demonstration projects.
OKLAHOMA	No	Yes	- -	80% AC; 20% PC	- -	- -
OREGON	PMS is currently being developed & at present no impact on the selection process.	Yes	No	For interstate system all new const. is PCC & approx 60% for 4 R proj. are PCC Non-Interstate are AC	Yes, as seccondary factors.	We have no formal procedure. we attempt to establish cost and the effect on design life.
PENNSYLVANIA	Just beg. to use a syst. for rehab. & maint., Does not completely involve design yet.	No	No	Rigid 15%; Flexible 85%.	Yes	Include in cost of construction or repair.
RHODE ISLAND	Presently being impl.	Not at this time, research under way.	Yes, PSI=2.0 minor road PSI=2.5 on major roads.	75% Bit. Concrete, 22% Bit. Concrete Surf. PCC Base, 3% PCC	Yes, experience of senior engrs. especially the matl's engr. and history of any part. maint. or construct. problem.	This is a difficult prob. usually rely on costs experienced by other states or developed by manuf.
SOUTH CAROLINA	Yes, prioritize projects of rehab.	Yes	No	Approximately 99+% Flexible less than 1% Rigid	Yes, by characteristics of Individual Projects.	Trial or demonstration projects or alternate bids
SOUTH DAKOTA	Yes, it determines const. priority but does not relate to surfacing selection.	Yes, through detailed state-wide accounting procedures.	Yes reconstruction is scheduled at 2.5 psi.	About 50-50 for projects scheduled at construction.	Yes, subjectively.	Require same life expectancy and estimate costs similarly as for all other materials and techniques.

TABLE A-4 (Continued)

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
TENNESSEE	Yes, maint. costs are being developed through the maint. management program for the purpose of determining overall costs of pvmt life-cycle.	In some cases	No	Flexible 90%, Rigid 10%	Yes, through discussions with the construction & maintenance divisions.	N/A
UTAH	Yes	Avg history Flex. Interstate 8-12 before overlay	Interstate 3.0 or above	Interstate 60 flexible, 40 rigid using more rigid all the time.	No	Don't
VIRGINIA	PMS being developed eventually feed back will be used to modify design criteria in necessary.	Our research council has some, Charlottsville, VA.	2.5 AASHTO Approach	Interstate Flex. 60%, Rigid 40%; Primary Flex 95%, Rigid 5%; Secondary Flex 100%	Yes in initial design	Modified AASHTO Design method used. New matls. evaluated & used in procedure.
WASHINGTON	Yes, have developed a program which can be used to analize Life-Cycle costs for various overlay options.	Yes	No	BST 40%; ACP 44%; PCCP 6%	Only in original selection of alternatives.	Specific project analysis.
WEST VIRGINIA	Currently being developed no effect on design yet.	Yes, to a certain degree.	Not at present but is being considered for future use.	20% Rigid, 80% Asphalt	Maint. of traffic during const. is a predominant factor that is considered.	When a matl. has demonstrated its reliability thru usage, design values are assigned, otherwise they are used emperically.
WISCONSIN	Sucn a system is currently in the early stage of development.	Yes, PSI data collected over time	Ideally yes, 2.25-2.50 PSI depending on funct. class of the hwy Realistically this is almost impossible as the available dollars never seem to be enough.	CRCP 4%, Non reinf. PCC 16%, High type bit. conc. (Virgin & Recycled) 76%, Low type bit. (Road mix, etc.) 4%	These are definitely considered in making a final selec.for pvmt type but not a part of procedure indicated under question No.1	Cost estimate and service life are based on our best judgement.

TABLE A-4 (Continued)

STATE OR AGENCY	DO YOU HAVE A PAVEMENT MANAGEMENT SYSTEM AND HOW DOES IT RELATE TO PAVEMENT TYPE SELECTION	DO YOU HAVE PERFORMANCE HISTORIES OF DIFFERENT PAVEMENT TYPES	WHAT MINIMUM ACCEPTABLE PERFORMANCE LEVELS ARE USED	APPROXIMATE PERCENTAGE OF EACH OF THE DIFFERENT PAVEMENT TYPES	ARE FACTORS SUCH AS CONSTRUCTABILITY MAINTAINABILITY; AND EASE OF IMPLEMENTATION USED AND IF SO, HOW	HOW ARE NEW MATERIALS OR TECHNIQUES USED IN ANALYSIS PROCEDURE
WYOMING	No, but PMS is in development.	Not at the present time A data base is being built	Inst. PSI 2.5 Pri. PSI 2.0 Sec. ADT $\geq$ 750 psi 2.0 ADT $\leq$ 750 psi 1.5	Flexible 90-95%, Rigid 5-10%	Yes, normally such considerations will be manually weighed against any possible initial cost savings; often such considerations will eliminate an alternative.	Cost of new matls. or tech. are estimated and included in const. cost estimates.
ONTARIO	MTC does not have an integrated PMS current proc. concentrate on pvmt rehab. with no direct ties to pvmt select process	Yes, records are however, relatively young (5 yr avg.)	In general way so that a project is placed in the priority program (EG 50 on a scale of 1-100).	.Conventional asph. pvmt & gran. bases 95%, Deep strength & full depth pvmts 3%,Conc. & comp. pvmts. 2%	In const: Min thicknesses are estab. Impl:use of local matls. Maint: min. time period before major maint.	Equivalency factors are assigned to matls. & unit costs are obtained from est. office along with overall costs for new tech.
NORTHWEST TERRITORIES	Pavement Programme has been very limited to date PMS has not had significant impact on pvmt design selection to date.	Regular monitoring of pvmt perf. - logs of pvmt distress types (severity & frequency) also Benkelman Beam Rebound Data.	Monitor maint. costs & physical perf. characteristics.	To date: (1) surface treatment 135 km. (2) Hot mix 55 KM(AC), (3) Cold Mix 30 km (Cut back and emulsion)	Contract magnitude limited by length of const., season, limited budget, emphasis for Northern Contractors.	Paving is relatively new to N.W.T., rely heavily on other govt. jurisdictions on their past successes.
SASKATCHEWAN	Yes, PMS presently used to identify rehab. needs. No direct relationship with pvmt design selection presently exists	No	Yes, Min. acceptable riding comfort index is 5.5.	Pcc 0%, ACP 100%, 15 yr design 15%, 5 yr design 15%, < 5 yr design 70%.	Subjective factors weighed against cost.	- -
WASHINGTON DC	Yes, in-pvmt serv hist. are being I.D. to allow comparison of previously constructed pvmt designs with service life.	Yes	A dept.wide task force is currently developing standardized needs criteria for pvmt rehab and reconst.	41% composite, 52% flex,	All of these factors are consd. in selec. of matls. but not in pvmt type selection.	Lab analysis must show equiv. or sup. properties to exist. matls.

APPENDIX B

CASE STUDY: LIFE-CYCLE COST ANALYSIS OF PAVEMENTS (WORLD BANK) (*72*)

LIFE-CYCLE COST ANALYSIS OF PAVEMENTS

Case Study

Introduction

1.1 A 20 km section of a two-lane trunk road is programmed for rehabilitation. The road follows the shoreline of an old lake bed, running along a slight ridge consisting of sandy soils with low to negligible clay content. The road was constructed about 20 years ago with a 125-mm asphalt stabilized sand base and a double-surface treatment on natural subgrade with an average CBR of 20%. Although the pavement is extensively cracked, the riding quality is fair to good except for some short lengths that are badly deformed and have an occasional pothole. The existing pavement is estimated to have received over two million standard axle (18-kip) applications. Benkleman Beam deflection tests show that the pavement structure is still quite strong and an asphalt concrete (AC) overlay after repair of defective areas could serve as an effective remedial treatment to provide a serviceable pavement. A possible alternative that would measureably improve the riding quality is to reconstruct the pavement.

Pavement Management Strategies

1.2 A review of road rehabilitation possibilities resulted in three alternatives for more detailed consideration:

Alternative 1: Single-surface treatment in Year 1, followed by a 50-mm AC overlay in Year 5; this will serve as the base case or null alternative.

Alternative 2: 50-mm AC overlay in Year 1 after scarifying and leveling the existing surface.

Alternative 3: Reconstuction in Year 1 using the following design:

Sand-asphalt subbase:	125 mm
Sand-asphalt base:	150 mm
Asphalt/concrete surface:	50 mm

The traffic and pavement data needed for the life-cycle cost analysis of these alternatives are summarized in Table B-1.

1.3 Routine Maintenance. Except for the pavement area to be patched or sealed each year, the routine maintenance effort (type and frequency of operations) will be the same for the three alternatives. Hence, only the cost of patching is included under routine maintenance costs in the life-cycle cost analysis. The routine maintenance policy requires patching of all pavement areas needing repair each year.

1.4 Periodic Maintenance. Application of a single surface treatment whenever: (i) roughness (R) exceeds 3000 mm/km; or (ii) total patched and cracked pavement area (P) exceeds 10% of the pavement surface area (i.e., 730 m^2/km for a two-lane road).

However, the interval between applications should not be less than five years or more than ten years.

1.5 The theoretical framework for the analysis of pavement life-cycle costs is described in the Attachment. A 20-year life cycle was used for the engineering-economic analysis, which is summarized in Tables B-2, B-3, and B-4. A terminal (salvage) value was applied only to the remaining life of the last major operation on the pavement (e.g., last surface treatment in Alternative 2). The analysis was made using three discount rates (0%, 5%, and 10%). The life-cycle costs are presented on a unit-km basis.

Results and Conclusions

1.6 The results are summarized in Table B-5. At discount rates of 0 to 10%, the most economical alternative, considering total transport costs (i.e., agency plus user costs), is the reconstruction alternative (Alternative 3), which gives a fairly strong pavement structure with a smooth riding quality. If only agency costs (construction and maintenance costs) are considered, the most economical alternative is the overlay option; at 0 to 5% discount rates, the analysis suggests that the pavement should be overlaid in Year 1 (Alternative 2), while at a 10% discount rate, it would be even more economical to defer the application of the overlay to Year 5 (Alternative 3).

1.7 The most important conclusions are:

a. Road user costs are the dominant element in the life-cycle cost of a pavement and their exclusion from the analysis of road improvements is likely to result in suboptimal solutions.

b. Lower discount rates tend to favor improvement with longer service lives and, as expected, alternatives with a higher level of initial capitalization. Conversely, higher discount rates are likely to result in the selection of stage construction alternatives.

c. The minimum requirements for the evaluation of life-cycle costs are:

(1) An objective and quantifiable measure of pavement condition (roughness in this case study).

(2) A predictive model that relates pavement condition to time (or indirectly axle-load applications).

(3) A model that relates changes in pavement condition to user costs.

(4) A model that converts changes in pavement condition to discrete pavement maintenance needs and costs.

Acknowledgment

The data for the case study was provided by Mr. N. Okin, Director (Planning), Federal Ministry of Works, Nigeria. Mr. E. Boas, a researcher at the World Bank, assisted with developing the computer program for the analysis.

The case study for this synthesis was prepared by Asif Faiz, Senior Transport Economist, Washington, D.C. The procedures presented in this study were developed by the author and do not necessarily reflect the policies or precedures of the World Bank.

LIFE CYCLE COST ANALYSIS OF PAVEMENTS

Analytical Framework for the Case Study

A. VEHICLE OPERATING COST (VOC) RELATIONSHIPS

Generalized VOC equation: $VOC = a + bR$ (1)

where: VOC = vehicle operating cost in US$ per 1000 km;
R = road roughness as measured in mm/km by a fifth-wheel bump integrator towed at 30 km/hour; and
a,b = regression constants.

Vehicle Type	Vehicle Operating Cost Equation	R^2	
Passenger car	VOC = (66.333 + 0.0102474R) x 1.82	0.9980	(2)
Light goods vehicle	VOC = (29.425 + 0.0271176R) x 1.82	0.9994	(3)
Bus	VOC = (112.324 + 0.0144771R) x 1.82	0.9999	(4)
Medium SU truck (5t payload)	VOC = (154.533 + 0.0267481R) x 1.82	0.9999	(5)
Heavy SU truck (9t payload)	VOC = (191.164 + 0.0306191R) x 1.82	0.9999	(6)
Semitrailer (25t payload)	VOC = (512.749 + 0.0746589R) x 1.82	0.9999	(7)

The VOC equations were obtained by fitting the best curve (using R^2 as an indicator) to nine data sets of "roughness" and "VOC estimates" obtained by using TRRL Report No. 723 Tables for Estimating Vehicle Operating Costs on Rural Roads in Developing Countries by Abaynayaka et. al. (1976). The average road characteristics used for VOC estimates were: rise/fall 15 m/km; curvature 30°/km; road width 7.3 m; and altitude 350 m.

B. PAVEMENT DETERIORATION RELATIONSHIPS

Pavement structural number: $$SN = \frac{1}{25.4} \sum_{x=1}^{i} a_i D_i$$ (8)

where: SN = structural number of a pavement;
a_i = strength coefficient of the i^{th} pavement layer; and
D_i = thickness of the i^{th} pavement layer (mm).

Modified pavement structural number: $$\overline{SN} = SN + 3.51\log_{10}CBR - 0.85(\log_{10}CBR)^2 - 1.43 \quad (9)$$

where: $\overline{SN}$ = modified structural number; and
CBR = California bearing ratio of the subgrade (%).

Pavement roughness: $$R = R_o + 1250mN \quad (10)$$

where: R = predicted road roughness (mm/km);
R_o = roughness of the road when new or after an overlay or rehabilitation (mm/km); and
N = cumulative equivalent standard axles per lane since the road was new, overlaid, or rehabilitated.

$$m = \frac{1}{10^{(a^{1/3} - b^{1/3} - 1.3841)}} \quad (11)$$

where: $a = (0.20209 + 23.1318c^2)^{\frac{1}{2}} - 4.8096c$ (12)
$b = (0.20209 \pm 23.1318c^2)^{\frac{1}{2}} + 4.8096c$ (13)
$c = 2.1989 - \overline{SN}$ (14)

Pavement patching and cracking: $$P = 300\left\{(\overline{SN} - 4) + \frac{72N}{\overline{SN}^{\overline{SN}}}\right\} \quad \text{for } \overline{SN} < 3.6,\ P \geq 0 \quad (15)$$

$$= \frac{21600\ (N - 0.560)}{\overline{SN}^{\overline{SN}}} \quad \text{for } \overline{SN} \geq 3.6,\ P \geq 0 \quad (16)$$

where: P' = total cracked/patched area per lane since the road was new, overlaid, sealed, or rehabilitated (m^2/km);

$$P = P'_1 + P'_2 \tag{17}$$

where: P = total cracked/patched pavement area (Lanes "1" and "2") since the road was new, overlaid, sealed, or rehabilitated (m^2/km);
= $2 \times P'$ (for a specific 50:50 traffic distribution); and

$$dP = P_{(x+1)} - P_x \tag{18}$$

where: dP = incremental increase in patched/cracked pavement area during one maintenance period, normally one year (m^2/km);
P_x = total cracked/patched area at end of year x, (m^2/km); and
$P_{(x+1)}$ = total cracked/patched area at end of year x+1, (m^2/km).

Information on pavement deterioration relationships was obtained from TRRL Report No. 674 A Road Transport Investment Model for Developing Countries by Robinson et. al. (1975), and TRRL Supplementary Report No. 246 Revision of the Road-Transport Investment Model by Rolt and Abaynayaka (1976).

C. BASIC PARAMETERS FOR LIFE CYCLE COST ANALYSIS

1. Pavement roughness (R) is set to:

   a. 1500 mm/km for a newly-constructed road with an asphalt concrete surface;

   b. 1800 mm/km after application of an asphalt concrete overlay; and

   c. 2500 mm/km after application of a surface treatment, except where roughness is less than the respective critical values prior to application of asphalt concrete overlay or surface treatments.

2. Patched and cracked area (P) is set to zero after application of an overlay or surface treatment.

3. Traffic loads (in terms of equivalent standard axles, EAL) are accumulated from zero after a pavement is reconstructed, overlaid, or surface-treated. This assumption may not be entirely valid for surface treatments or seal coats, but is tenable in this case due to the presence of a very strong and permeable subgrade and a routine maintenance policy that provides for 100% patching of the incremental pavement area needing repair each year.

TABLE B-1

DATA FOR CASE STUDY

A. Vehicle Operating Cost($/ Km)

VOC = A + (B * Roughness(mm/km)) * 0.00182

	A	B	Traffic Distribution
VOC (passenger car):	66.33	0.01	34.0%
VOC (light goods vehicle):	29.43	0.03	48.0%
VOC (bus):	112.32	0.01	1.0%
VOC (medium truck,5t pay):	154.53	0.03	7.0%
VOC (heavy truck,9t pay):	191.16	0.03	5.0%
VOC (semi-trailer,25t pay):	512.75	0.07	5.0%
VOC (weighted):	83.81	0.02	

B. Unit Costs

SS treatment($/Km):	29,290.00
50 mm AC overlay($/Km):	140,000.00
New Construction($/Km):	301,000.00
Patching($/m2):	25.50

C. Traffic

Annual Growth (ADT & EAL):	6%
ADT(vpd):	1680
Directional Distribution:	50:50
EAL(18k); Yr.1:	247000

D. Pavement Data

SN :	1.35	2.14	2.81
Subgrade CBR (%):	20	20	20
SN" (modified):	3.05	3.84	4.51
Roughness Factors - a:	8.1907	15.7780	22.2191
b:	0.0246	0.0127	0.0090
m:	0.4563	0.1287	0.0604

Structural Coefficients

Asphalt Concrete:	0.40
Sand Asphalt Base:	0.25
Sand Asphalt Subbase:	0.11
Single Surface Treatment:	0.00

TABLE B-2

ANALYSIS OF ALTERNATIVE 1

ALTERNATIVE 1

Year	ADT	EAL-18k (million)	EAL (cumul)	SN*	R (mm/km)	P (m2/km)	dP (m2/km)	VOC ($/veh-km)	Aggregate Cost($/Km): VOC	Patching	Const/Overlay/Per.Maint.	Total	Remarks
1	1680	0.247	0.247	3.05	2500	0	0	0.2607	-	-	29,290	29,290	SS Treatment
2	1781	0.262	0.509		2790	165	165	0.2733	173,566	4,202		177,768	
3	1888	0.278	0.786		2949	566	401	0.2802	190,668	10,238		200,906	
4	2001	0.294	1.081		3116	992	426	0.2874	207,263	10,852		218,115	
5	2121	0.312	0.312	3.84	1800	0	0	0.2304	200,456	0	140,000	340,456	50mm AC Overlay
6	2248	0.331	0.642		1903	20	20	0.2349	190,941	520		191,461	
7	2383	0.350	0.993		1960	107	87	0.2374	205,403	2,213		207,616	
8	2526	0.371	1.364		2019	199	92	0.2399	220,044	2,345		222,389	
9	2678	0.394	1.758		2083	297	97	0.2427	235,849	2,486		238,335	
10	2838	0.417	2.175		2150	400	103	0.2456	252,924	2,635		255,560	
11	3009	0.442	2.617		2221	510	110	0.2487	271,386	2,794		274,179	
12	3189	0.469	3.086		2296	626	116	0.2519	291,361	2,961		294,322	
13	3380	0.497	3.583		2376	749	123	0.2554	312,991	3,139		316,129	
14	3583	0.527	4.110		2461	879	130	0.2591	336,431	3,327		339,758	
15	3798	0.558	0.558	3.84	2500	0	0	0.2607	360,327	0	29,290	389,617	SS Treatment
16	4026	0.592	1.150		2685	146	146	0.2688	389,067	3,726		392,793	
17	4268	0.627	1.777		2786	302	155	0.2731	422,049	3,963		426,011	
18	4524	0.665	2.443		2893	466	165	0.2777	454,800	4,200		459,001	
19	4795	0.705	3.148		3006	641	175	0.2827	490,435	4,452		494,888	
20	5083	0.747	0.747	3.84	2500	46	(595)	0.2607	504,089	(15,160)	29,290	518,218	SS Treatment
								PV @ 10%	2,117,128	30,473	137,414	2,285,015	
								PV @ 5%	3,317,976	38,018	170,853	3,526,847	
								PV @ 0%	5,710,051	48,893	227,870	5,986,814	

TABLE B-3

ANALYSIS OF ALTERNATIVE 2

ALTERNATIVE 2

Year	ADT	EAL-18k (million)	EAL (cumul)	SN*	R (mm/km)	P (m2/km)	dP (m2/km)	VOC ($/veh-km)	Aggregate Cost($/Km) VOC	Patching	Const/Overlay/Per.Maint.	Total	Remarks
1	1680	0.247	0.247	3.84	1800	0	0	0.2304	-	-	140,000	140,000	50mm AC Overlay
2	1781	0.262	0.509		1882	0	0	0.2340	150,941	0		150,941	
3	1888	0.278	0.786		1926	56	56	0.2359	161,883	1,429		163,313	
4	2001	0.294	1.081		1974	129	73	0.2380	173,050	1,858		174,908	
5	2121	0.312	1.392		2024	206	77	0.2401	185,066	1,969		187,035	
6	2248	0.331	1.723		2077	288	82	0.2424	198,004	2,087		200,092	
7	2383	0.350	2.073		2133	375	87	0.2449	211,946	2,213		214,159	
8	2526	0.371	2.445		2193	467	92	0.2475	226,979	2,345		229,325	
9	2678	0.394	2.838		2257	564	97	0.2502	243,201	2,486		245,687	
10	2838	0.417	0.417	3.84	2324	0	0	0.2531	260,716	0	29,290	290,006	SS Treatment
11	3009	0.442	0.859		2395	74	74	0.2562	279,643	1,890		281,534	
12	3189	0.469	1.328		2470	190	116	0.2595	300,114	2,961		303,075	
13	3380	0.497	1.825		2550	313	123	0.2629	322,269	3,139		325,408	
14	3583	0.527	2.352		2635	444	130	0.2666	346,266	3,327		349,593	
15	3798	0.558	2.911		2725	582	138	0.2705	372,279	3,527		375,806	
16	4026	0.592	3.502		2820	729	147	0.2746	400,500	3,738		404,239	
17	4268	0.627	4.130		2921	884	155	0.2790	431,142	3,963		435,105	
18	4524	0.665	0.665	3.84	2500	0	0	0.2607	445,582	0	29,290	474,872	SS Treatment
19	4795	0.705	1.370		2720	201	201	0.2703	464,726	5,116		469,842	
20	5083	0.747	2.117		2841	386	185	0.2755	506,283	4,720	(11,716)	499,287	Salvage Value SST
								PV @ 10%	2,068,757	16,939	158,217	2,241,997	
								PV @ 5%	3,275,882	26,950	171,660	3,469,856	
								PV @ 0%	5,680,591	46,769	198,580	5,914,224	

TABLE B-4
ANALYSIS OF ALTERNATIVE 3

ALTERNATIVE 3

Year	ADT	EAL-18k (million)	EAL (cumul)	SN*	R (mm/km)	P (m2/km)	dP (m2/km)	VOC ($/veh-km)	Aggregate Cost($/Km) VOC	Patching	Const/Overlay/Per.Maint.	Total	Remarks
1	1680	0.247	0.247	4.51	1500	0	0	0.2175	-	-	301,000	301,000	New Construction
2	1781	0.262	0.509		1538	0	0	0.2191	141,890	0		141,890	
3	1888	0.278	0.786		1559	11	11	0.2200	151,288	281		151,569	
4	2001	0.294	1.081		1582	25	14	0.2210	161,047	365		161,412	
5	2121	0.312	1.392		1605	41	15	0.2220	171,476	387		171,863	
6	2248	0.331	1.723		1630	57	16	0.2231	182,625	410		183,035	
7	2383	0.350	2.073		1656	74	17	0.2242	194,549	435		194,984	
8	2526	0.371	2.445		1684	92	18	0.2254	207,309	461		207,770	
9	2678	0.394	2.838		1714	111	19	0.2267	220,968	489		221,457	
10	2838	0.417	0.417	4.51	1746	0	0	0.2281	235,597	0	29,290	264,887	SS Treatment
11	3009	0.442	0.859		1779	15	15	0.2295	251,274	372		251,645	
12	3189	0.469	1.328		1814	37	23	0.2311	268,082	582		268,664	
13	3380	0.497	1.825		1852	62	24	0.2327	286,113	617		286,730	
14	3583	0.527	2.352		1892	87	26	0.2344	305,466	654		306,120	
15	3798	0.558	2.911		1934	114	27	0.2362	326,250	693		326,943	
16	4026	0.592	3.502		1978	143	29	0.2382	348,585	735		349,320	
17	4268	0.627	4.130		2026	174	31	0.2402	372,601	779		373,381	
18	4524	0.665	4.795		2076	206	32	0.2424	398,442	826		399,268	
19	4795	0.705	5.500		2129	241	34	0.2447	426,264	875		427,139	
20	5083	0.747	0.747	4.51	2185	0	0	0.2471	456,238	0	29,290	485,528	SS Treatment
								PV @ 10%	1,875,764	3,319	318,211	2,197,294	
								PV @ 5%	2,956,544	5,238	331,472	3,293,254	
								PV @ 0%	5,106,062	8,964	359,580	5,474,606	

TABLE B-5
SUMMARY OF RESULTS

RESULTS

A.Total Transport Cost per Km ($ million)

	Discount Rate		
	0%	5%	10%
Alternative 1	5.987	3.527	2.285
Alternative 2	5.914	3.470	2.242
Alternative 3	5.475	3.293	2.197
Least Cost Solution	Alt.3	Alt.3	Alt.3

B.Construction and Maintenance Cost per Km ($ million)

	Discount Rate		
	0%	5%	10%
Alternative 1	0.277	0.209	0.168
Alternative 2	0.245	0.199	0.175
Alternative 3	0.369	0.337	0.322
Least Cost Solution	Alt.2	Alt.2	Alt.1

APPENDIX C

LIFE-CYCLE COSTING PROCEDURES

DESIGN OF PAVEMENT STRUCTURE - 600

GENERAL - 601

601.01 Scope and Limitations

Design of the pavement structure includes the determination of the thickness of subbases, bases and surfacing to be placed over subgrade soils. An important aspect of this design is the selection of available materials that are most suited to the intended use. Their grouping in horizontal layers under the pavement, from good to poor, should be such that the most benefit will be derived from the inherent qualities of each material. In establishing the depth of each layer, the objective is to provide a minimum thickness of overlying material that will reduce the unit stress on the next lower layer commensurate with the load carrying capacity of the material within that layer.

The design of the roadbed cross section is not an exact science. The many variables to be correlated make it impossible to reduce the problem to exact mathematical terms so commonly applied to structures. Present practice, as discussed herein, stems from empirical relationships developed from test track and other pavement experiments as well as the observation of pavements under service. Research continues on this subject, and present design methods may therefore be subject to frequent modification.

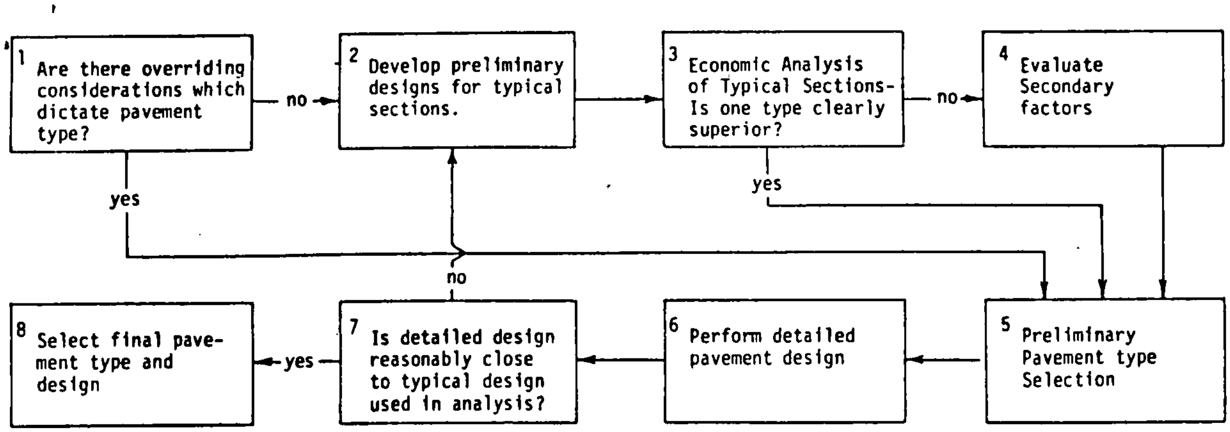
PAVEMENT TYPE SELECTION PROCEDURE - 602

602.1 Justification of Pavement Type

The two general types of pavement considered are rigid pavement, i.e., portland cement concrete, and flexible pavement as typified by hot bituminous pavement.

The six principal factors to be considered in choosing pavement type are: traffic, soils characteristics, weather, construction considerations, recycling and cost comparison. No significance is attached to the order in which they are listed. A statement should be made that they have been considered, but only those that apply to the specific project need be individually addressed. The secondary factors are: performance of similar pavements in the area, adjacent existing pavements, conservation of materials and energy, availability of local materials, contractors' capabilities, traffic safety, incorporation of experimental features, stimulation of competition and municipal preference.

PAVEMENT TYPE SELECTION PROCESS



COLORADO (35)

602.2 Procedure

A. A justifying analysis to support the pavement type selection will be prepared for all projects comparing concrete to asphalt pavements.

B. The AASHO booklet entitled, "An Informational Guide on Project Procedures," will be used for paving type determination and documentation.

C. Design life is the period of time in years for which the volume and type of traffic and the resultant wheel or axle load application are forecast, and on which the geometric pavement designs are calculated. Colorado highway projects are generally designed for 20 years. Interstate highways are also designed for 20 years.

D. Service life is the period of time the surface course of the pavement structure will serve the purpose for which it was intended. The purpose is to provide a riding surface at an acceptable serviceability condition and to provide protection for the underlying structural layers from the elements. When any type of pavement is resurfaced, the old surface course then becomes a base course and a new service life begins.

E. Economic life is the total useful life of a pavement structure including the extended service life gained when the initial pavement is supplemented by the addition of structural layers. It also means the period of time beyond which further use is not economical.

F. Analysis period is the period of time selected for making an economic analysis of pavement costs. Colorado analysis period will be 40 years.

G. Economic Cost Comparison

Base data to be used:

(1) Analysis Period - 40 years
Design Life - 20 years

Rejuvenating Periods
(Use for Cost Analysis)

CONCRETE PAVEMENT	> 750 ADT	< 750 ADT
20 years	2" overlay	--
30 years	2" overlay	2" overlay

ASPHALT PAVEMENT - FULL DEPTH	> 750 ADT	< 750 ADT
15 years	2" overlay	Seal Coat
25 years	2" overlay	Seal Coat
35 years	1" overlay	Seal Coat

ASPHALT PAVEMENT - UNTREATED BASE	> 750 ADT	< 750 ADT
10 years	2" overlay	Seal Coat
20 years	2" overlay	2" overlay
30 years	2" overlay	Seal Coat

(2) Maintenance Cost

Bituminous Pavement Concrete Pavement	Maintenance costs assumed equal unless cost differential provided by District Engineer is justified.

(3) Salvage value of either pavement will not be considered.

(4) Interest rate of 4% and a present worth system will be used for our analyses.

(5) Difference in grading quantities required by different pavement types are not to be considered except when untreated bases are used.

H. An economic analysis report will be prepared and transmitted to the District Engineer. After pavement type is selected by District Engineer and approved by the Chief Engineer, the report is to be transmitted to FHWA for approval, when required.

The choice of pavement type will be based on least life-cycle costs unless special conditions (pavement presently in place, special traffic conditions, sub-soil conditions or other unusual conditions) dictate selection of a particular pavement type. This policy will hold true for two-lane as well as for multi-lane highways. Alternate bids, which consider only initial costs, may be used where life-cycle analysis dictates comparable costs over the life of the projects, if approved by FHWA.

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ECONOMICAL ANALYSIS FOR PAVEMENT TYPE DETERMINATION

Prepared by:
Estimating Section
Office of Contracts
Highway Division
Iowa Department of Transportation

June 1976

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ECONOMICAL ANALYSIS FOR PAVEMENT TYPE DETERMINATION

The Office of Contracts prepares an economical analysis for each alternate pavement design received from the Road Design Engineer. Both flexible and rigid pavement types are considered in this analysis. Generally, this involves three alternatives -- one for asphaltic concrete with asphaltic concrete resurfacing, one for portland cement using Class I aggregate with asphaltic concrete resurfacing, and one for portland cement using Class 2 aggregate. In certain locations in Iowa, a portland cement alternate using Class 5 concrete aggregate is also economically feasible. The purpose of the analysis is to determine the most economical combination of materials, construction, and maintenance costs for each alternate. The total cost of each pavement design is then compared by using a present worth basis of evaluation over a 30-year analysis period.

MATERIALS COSTS

When a pavement determination is forwarded to the Office of Contracts by the Road Design Engineer, the Office of Materials is requested to furnish a list of probable aggregate sources for that project (Exhibits B & C). After this information is received, requests for aggregate quotations are sent to probable producers if current prices are not known (Exhibit D). Quotations are also requested for other major project materials used such as portland cement asphaltic cement, lime and reinforcing steel if current prices are not known.

After material prices are determined, they are analyzed to determine the most economical combination of sources. All material quotations are kept strictly confidential.

CONSTRUCTION COSTS

Construction costs are estimated using current prices according to the following general procedure:

A, Bid prices from previous lettings for projects involving similar work in the same general area are reviewed and applicable prices are used as a guide when calculating unit prices. Bids should be reviewed in light of similar project conditions, material availability, weather factors and competition among contractors at the time bids were received.

B. Unit prices for portland cement and asphaltic concrete pavements are then calculated by considering the following factors (Exhibit E):

1. Cost of materials delivered to jobsite - includes cements,aggregates, reinforcing steel, and curing compound.
2. Base Price - Arrived at by combining the following factors: Mobilization, all labor and equipment costs associated with the construction, job overhead, operating capital, risk and incidentals.
3. Job Haul - Cost of hauling materials from plant site to the construction area.
4. Profit - Includes profit on all labor, equipment and materials.

C. Unit prices for shoulders and other items of work are calculated using a similar approach as outlined above.

D. Estimated unit prices are then applied to typical quantities per mile to arrive at an estimated cost per mile for each pavement design (Exhibit F).

MAINTENANCE COSTS

At the present time, the only significant documented difference in maintenance costs for the various pavement alternatives is that all A. C. pavement designs, and P. C. pavement designs using Class I aggregate, will require one overlay, after approximately fifteen years, to maintain the pavement at a satisfactory level of service over the thirty year analysis period. A resurfacing thickness of 3" is used in both cases. Resurfacing costs are converted to a present worth basis using an interest factor of 7% per year (Exhibits G & H).

***

Upon completion of the economical anslysis, the recommendation of the Office of Contracts is submitted to the Director of the Development Bureau for his review and approval (Exhibit I). After a pavement type and thickness has been approved, the economical analysis is returned to the Office of Contracts for confidential filing. The Assistant Contracts Engineer then notifies the following as to the type and thickness approved:

County ______ Road No. ______ Date ______

Location:

P. C. Pav't.

Cement	bbls @	=	/36 =	x		=
Coarse Aggr.	tons @	=				
Sand	tons @	= ______	Mat'ls.			=
			Base Price			=
			Steel, Jts. etc.			=
			Haul			=
Coarse Aggr. Source ______			5% Prf. Mat'ls.			=
			10% Others			= ______
			Ded. for slipform			= ______
Sand Source ______				Total		=
				Use		=

Granular Subbase ______

* * * * *

Asph. Tr. Base

Asph.	%	@	=	Mat'ls.	=
Coarse Aggr.	tons	@	=	Move In	=
Sand	tons	@	= ______	Lay Cost	=
				Plant Cost	=
	Total		=	Profit	=
				Haul	= ______
				Total	=
Stone Source ______				Use	=

Sand Source ______

______

Type ______ A.C.

Asph.	%	@	=	Mat'ls.	=
Coarse Aggr.	tons	@	=	Move In	=
Sand	tons	@	= ______	Lay Cost	=
				Plant Cost	=
	Total		=	Profit	=
				Haul	= ______
				Total	=
Stone Source ______				Use	

Sand Source ______

Engineer's Preliminary Estimate of Cost

of
Pavement Per Mile

County ______________ Road No. ______________ Date ______________

Location:

PORTLAND CEMENT PAVEMENT		Typical Section		PCC Pav't. Paved Shoulders Class A Subbase
PCC Pavement	:		@ $	:
Class A Subbase	:		@ $	:
Paved Shoulders	:		@ $	:
Granular Surf. of Shldrs.	:		@ $	:
Earth Fill For Shldrs.	:		@ $	:
Prime & Tack & Fog Coat	:		@ $	:
Binder Bitumen	:		@ $	:
Cover Aggregate	:		@ $	: ______________
______________	:		@ $	: ______________
______________	:		@ $	: ______________
			TOTAL	

ASPHALTIC CONCRETE PAVEMENT		Typical Section		Asph. Conc. Asph. Treated Base Paved Shoulders Soil Subba
Construct Soil-lime Subbase	:	2 miles	@ $	:
Lime	:		@ $	:
Sealer Bitumen	:		@ $	:
Asph. Treated Base	:		@ $	:
A. C. Binder	:		@ $	:
A. C. Surface	:		@ $	:
Prime and Tack	:		@ $	:
Gran. Surf. of Shldr.	:		@ $	:
Earth Fill for Shldr.	:		@ $	:
Binder Bitumen	:		@ $	:
Cover Aggregate	:		@ $	:
______________	:		@ $	: ______________
______________	:		@ $	: ______________
			TOTAL	

of
Pavement Per Mile

County ______________ Road No. ______________ Date ______________

Location:

PORTLAND CEMENT PAVEMENT WIDENING		Typical Section		PCC PAVEMENT ASPH. CONC. PAVEMENT
PCC Pavement, Widening	:		@ $	:
Cleaning & Preparation of old base	:		@ $	:
Asphaltic Conc. Type	:		@ $	:
Prime & Tack	:		@ $	:
Trench Excavation	:		@ $	:
Sand Cover	:		@ $	:
Stabilized Shoulder	:		@ $	: ______________
			TOTAL	

ASPHALTIC CONCRETE PAVEMENT		Typical Section		ASPH. CONCRETE ASPH. TREATED BASE
Asphalt Treated Base-Widening	:		@ $	:
Cleaning & Preparation of old base	:		@ $	:
Asphaltic Concrete, Type	:		@ $	:
Prime and Tack	:		@ $	:
Trench Excavation	:		@ $	:
Sand Cover Aggregate	:		@ $	:
Stabilized Shoulder	:		@ $	: ______________
			TOTAL	

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**Engineer's Preliminary Estimate of Cost
of
Pavement Per Mile**

County ____________ Road No. ________ Date ____________

Location

Width ____________

Portland Cement Pavement — Typical Section ____________

P. C. Pavement	:	sq.yds.	@	=
Stabilized Shoulder Mat'l.	:	tons	@	=
		Total		____________

Asphaltic Concrete Pavement — Typical Section ______ Type Asph. Conc.
______ Asph. Treated Base
______ Soil ______ Subbase

Const. Soil ______ Subbase	:	mile	@	=
Lime	:	tons	@	=
Cement	:	bbls.	@	=
Asphalt Treated Base	:	tons	@	=
Prime & Tack Coat	:	gals.	@	=
Type Asph. Conc.	:	tons	@	=
Stabilized Shoulder Mat'l.	:	tons	@	=
		Total		____________

WORKSHEET FOR PAVEMENT MAINTENANCE COSTS

County ____________ Road No. ________ Date ____________

Location

Rigid Pavement

Resurfacing Costs

Cleaning and Preparation of Old Base	miles	@	= ______
Sand Cover	tons	@	= ______
Prime and Tack	gals	@	= ______
A C Surface	tons	@	= ______
Granular Surfacing	tons	@	= ______
Total			$______

Present Worth of Resurfacing =

Present Worth of Maintenance =

Flexible Pavement

Resurfacing Costs

Cleaning and Preparation of Old Base	miles	@	= ______
Sand Cover	tons	@	= ______
Prime and Tack	gals	@	= ______
A C Surface	tons	@	= ______
Granular Surfacing	tons	@	= ______
Total			$______

Present Worth of Resurfacing =

Present Worth of Maintenance =

SUMMATION OF PRESENT WORHT COSTS

County ____________ Road No. ____________ Date ____________

Location:

Length of Study ________ Year

Interest Rate Used ________ %

P.C.C. Resurfacing Interval Using Class 2 Agg. ________ Year

P.C.C. Resurfacing Interval Using Class 1 Agg. ________ Year

A. C. Resurfacing Interval ________ Year

P.C.C. First Cost Per Mile Using Class 2 Agg. $________

P.C.C. First Cost Per Mile Using Class 1 Agg. $________

A. C. First Cost Per Mile $________

	P.C.C. Cl.2 Agg.	P.C.C. Cl. 1 Agg.	A. C.
First Cost Per Mile	$________	$________	$________
Present Worth of Resurfacing	$________	$________	$________
Total Present Worth of Paving	$________	$________	$________

DEPARTMENT OF TRANSPORTATION

AGENDA ITEM / COMMISSION ORDER / STAFF ACTION

Division/Bureau/Office ____________ Item/Order No. ________

Submitted by ____________ Phone No. ________ Meeting Date ________

TITLE: ____________

DISCUSSION/BACKGROUND:

PROPOSAL/ACTION RECOMMENDATION:

COMMISSION ACTION / STAFF ACTION:

Moved by ____________ Seconded by ____________

Vote	Aye	Nay	Pass
Gardner	___	___	___
Garst	___	___	___
McGrath	___	___	___
Pellegreno	___	___	___
Rigler	___	___	___
Schoelerman	___	___	___
Thoms	___	___	___

________ Division Director ________ Finance (if $ involved) ________ Legal (if [illegible]) ________ State Director (if [illegible])

11.8 TYPE DETERMINATION

A present worth economic analysis shall be required for those projects involving 6000 square yards (5016.76 m²) or more of pavement construction. The economic analysis shall compare the pavement structures found on page 3 of Form D-4332. An interest rate of 6% and a service life of 40 years shall be used.

The economic analysis of each pavement type will be compared by cost per linear foot. The quantity estimates will be based upon the actual typical cross-section to be used for the project. Consideration should be given to the estimated percentage of the project in total cut, total fill and in cut and fill, in determining the subbase, subgrade and excavation quantities. Differences in earthwork quantities should be used in the economic analysis only if the project is definitely in waste or definitely in borrow.

In computing the present worth economic analysis the initial costs shall include all items related to each type of pavement structure such as Relief Joints, Terminal Joints and Approach Slabs. In addition, any cost differences in drainage, utility moves, etc., between the different pavement structures should be included.

Resurfacing costs shall include the cost of resurfacing, shoulder modifications, necessary pavement patching, drainage and guardrail adjustments, maintenance and protection of traffic, etc. On very high volume routes consideration should be given to the delay and congestion cost to motorists during the resurfacing of the project. Information concerning delay and congestion costs can be obtained from the Bureau of Highway Design as required.

It will be necessary to document the unit cost estimate for each item utilized. This may be done by averaging bid prices for a particular item on two to three adjacent projects (provided conditions affecting the unit price of the particular material are relatively constant), by a detailed computed estimate of the unit cost of the material in place or by using the Construction Cost Catalog, Bulletin # 50. ***This documentation will be required on all projects which require an economic analysis.***

For the purpose of the present worth economic analysis, the first resurfacing for rigid pavements shall be calculated for a 3" depth of bituminous surface course. The second resurfacing on a rigid pavement and all resurfacing for flexible pavements shall be calculated for a 2½" bituminous surface course.

The following data may be used in computing the present worth analysis of each pavement type:

	Rigid			***Flexible***	
	PCC	***RCC***	***CRC***	***Stone & Soil Bases***	***Other Bases***
Time to First Resurfacing (years)	20	20	20	8	10
Interval Between Resurfacing (years)	10	10	10	8	10
Annual Maintenance Cost Per Lane Mile	$325	$325	$150	$500	$400

It is to be recognized that the time to first resurfacing, interval between subsequent resurfacings, and annual maintenance cost per lane mile may vary somewhat from the above average figures for a particular project. ***It is recommended that the District Engineer review existing pavements within his jurisdiction to determine the correlation of the above estimates to conditions within his particular District.*** Once this data is available, it should be submitted to the Bureau of Highway Design for review and possible implementation for that particular District. Any study should also give consideration to differences in slab thicknesses, traffic conditions, subgrade conditions, (poor, satisfactory or good) structural number of existing pavement (flexible), type and depth of resurfacing, etc., as these parameters have an effect on the pavement life.

When the economic analysis indicates that a type of rigid pavement should be used, a second economic analysis should be performed to determine the most economical shoulder to be used adjacent to the rigid pavement. The analysis should be for 40 years at 6% interest similar to the pavement economic analysis. For the purpose of the shoulder economic analysis concrete shoulders require no maintenance. Type 1 or Type 3 shoulders require a Surface Treatment every 5 years and a 2 foot wide patch along the pavement edge every 5 years. If a particular District has had a different maintenance experience with Type 1 or Type 3 shoulders it should be reflected in the analysis as accurately as possible. When concrete shoulders are required as part of the pavement system as described in SECTIONS II.2 & II.3, the economic analysis of the shoulders for all pavement types shall be part of the economic analysis of the pavements.

In addition to the economic analysis, and for those projects with less than 6000 square yards (5016.76m²) of pavement construction, the following factors should be given proper consideration in choosing a pavement type.

I. PERFORMANCE OF SIMILAR PAVEMENT IN THE AREA:

To a large degree, the experience and judgment of the Highway Engineer is based on the performance of pavements in the immediate area of his jurisdiction. Past performance is a valuable guide, provided there is good correlation between conditions and service requirements between the reference pavements and the designs under study. This factor should not be allowed to develop into blind prejudice. Caution must be urged against reliance on short-term performance records, and on those long-term records of pavements which may have been subjected to much lighter loadings for a large portion of their present life. The need for periodic reanalysis is apparent.

II. ADJACENT EXISTING PAVEMENTS:

Provided there is no radical change in conditions, the choice of paving type on a highway may be influenced by existing sections thereof which have given adequate service. This will result in a desirable continuity of pavement and consequent simplification of maintenance operations.

III. DEPRESSED, SURFACE, OR ELEVATED DESIGN:

Depressed and surface design may involve a high water table which will influence the choice of paving type. Elevated design, as in the case of approaches to long bridges or viaducts with concrete decks, may influence the decision in favor of rigid pavement to preserve a desirable continuity of pavement surface. A depressed design, presenting some periodic possible drainage problems, may also indicate the use of one type of pavement in preference to another.

IV. HIGHWAY SYSTEM:

It is not considered good practice to let a system designation influence the choice of paving type. Merits of the individual case and economics should prevail.

V. CONSERVATION OF AGGREGATES:

This consideration may well have influence in choosing a paving type which will involve, in the total pavement structure, less of the scarce critical material than might be required by another type.

VI. STIMULATION OF COMPETITION:

It is desirable that monopoly situations be avoided, and that improvement in products and methods be encouraged through continued and healthy competition among industries involved in the production of paving materials.

VII. MUNICIPAL PREFERENCE, PARTICIPATING LOCAL GOVERNMENT PREFERENCE AND RECOGNITION OF LOCAL INDUSTRY:

While these considerations seem outside of the realm of the Highway Engineer, they cannot always be ignored by the highway administrator, especially if all other factors involved are indecisive as to the pavement type to select.

VIII. TRAFFIC SAFETY:

The particular characteristics of a wearing course surface, the need for delineation through pavement and shoulder contrast, reflectivity under highway lighting, and the maintenance of a non-skid surface as affected by the available materials may each influence the paving type selection in specific locations.

IX. CONSTRUCTION CONSIDERATION:

Such considerations as speed of construction, reduction of traffic maintenance during construction, ease of replacement, anticipated future widening, need for minimum surface maintenance in highly congested locations, seasons of the year when construction must be accomplished, and perhaps other considerations may have a strong influence on paving type selections in specific cases.

X. AVAILABILITY OF AN ADAPTATION OF LOCAL MATERIALS OR OF LOCAL COMMERCIALLY PRODUCED PAVING MIXES:

The prevalence of adaptability of local materials, or the availability of commercial produced mixes particularly on small projects, may influence the selection of pavement types.

XI. GRADES, CURVATURE, UNUSUAL LOADINGS:

Slow moving vehicles, starting and stopping on steep grades and unusual loadings such as steel, coal and industrial products may effect the pavement type selection.

The recommended pavement structure shall be based on the results of the economic analysis or other governing factor. The recommended pavement structure will be designated on page 4 of Form D-4332.

11.9 PAVEMENT OVERLAYS

All pavements, after a period of services, need to be resurfaced to improve their friction values, riding quality and/or structural capacity. The following system is to be used as an engineering tool to assist Department personnel in making decisions. The system facilitates establishing priorities based upon a uniform statewide measuring and evaluation standard.

This procedural scheme considers the functional performance of the pavement (safety and riding comfort) and its service performance, which is the useful life under the given loading conditions.

The equipment currently used by the Department to monitor a pavement's adequacy are: the Single Locked Wheel Skid Tester for ***friction values,*** Mays Meter for ***riding quality*** and the Road Rater for ***structural properties*** of flexible pavements. Data obtained through such equipment is used to determine if an overlay is required, and if so, how much? The evaluation procedure to follow is illustrated by three sub-systems. The flow diagrams for these subsystems are shown in Figures 2.11.9.1, 2.11.9.2 and 2.11.9.3. These three subsystems are:

- SUB-SYSTEM 1—Evaluation of Friction
- SUB-SYSTEM 2—Evaluation of Riding Quality
- SUB-SYSTEM 3—Evaluation of Structural Capacity

Sub-System 1—Evaluation of Friction

The purpose of friction evaluation is to find the highway locations that have low friction and a disproportionate number of wet pavement accidents. The pavement surface can then be corrected to reduce the number and/or severity of traffic accidents.

The procedure for friction evaluation is illustrated in Figure 2.11.9.1. The guidelines for providing friction in bituminous wearing surfaces are described in SECTION II.6.

Sub-System 2—Evaluation of Riding Quality

The ability of a specific section of pavement to serve traffic in its existing condition defines the term "Present Serviceability". The term was developed at the AASHTO road test where the serviceability of numerous pavements were rated subjectively by a panel made up of people selected from representative groups of highway users.

Through multiple regression analysis, a mathematical index was derived and validated through which pavement ratings can be satisfactorily estimated from objective measurements taken on the pavements. In order to fulfill the requirements of the Present Serviceability Index formula for rigid and flexible pavements, it is necessary to measure the pavement roughness, cracks, patches and rut depth. These serviceability indices (or the direct ratings) always refer to the conditions existing at the time the measurements (or ratings) are made.

The PSI (Present Serviceability Index) is designated by a rating scale of 0.to 5. The descriptive scale as developed at the AASHTO Road Test is:

5	
	Very Good
4	
	Good
3	
	Fair
2	
	Poor
1	
	Very Poor
0	

The Terminal Serviceability Index (TSI) would be that level of performance or condition at which a pavement in a particular functional classification is considered to no longer adequately serve the needs of the user. In order to determine appropriate TSI values for any maintenance rehabilitation program, over 24,000 miles of highway, representative of the State Highway Network, were statistically selected and tested as part of a Research Project. The mileage was placed in 5 categories in accordance with the Maintenance Functional Code (MFC) system. These categories are:

MFC A = Interstate Highways
MFC B = Other Expressways and Principal Highways
MFC C = Minor Arterial Highways
MFC D = Collector Highways
MFC E = Local Access Highways

The average riding quality of highway in each MFC category will be different as the functions of highways in that category are different. For instance, Interstate Highways which are designed for higher maximum speed, higher volumes and longer durations of travel than Local Access

OPAC (24)

Ontario

Ministry of
Transportation and
Communications

Research and
Development
Division

OPAC Design System

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OPAC (24)

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OPAC (24)

ABSTRACT

OPAC (Ontario Pavement Analysis of Costs) is a computerized system that compares the performance and cost of hundreds of design alternatives for flexible pavements within just a few hours. Using the system, pavement design engineers can select the most effective pavement design that has the least cost.

OPAC predicts the life of a pavement. The deterioration in Riding Comfort Index (RCI) has been made a function of repeated traffic loading and annual cyclic environmental changes. The deteriorations caused by the two factors have been respectively modelled using data from the AASHTO (Illinois) Road Test and Brampton (Ontario) Road Test. Subgrade surface deflection under a standard wheel load has been used as a predictor of future behavior of a pavement. Successful thickness designs in the province were analysed using Elastic Layer Theory and several iterations of such analyses resulted in a set of modulus values which were thereafter assigned to various paving materials and six different categories of subgrades in the province. Through AASHTO Road Test data, an excellent correlation between subgrade surface deflection, traffic, and pavement performance has been developed to allow calculation of that component of pavement deterioration which is caused by traffic. The other component, caused by environment, has been modelled from the Brampton Road Test data. It is based on the difference in deterioration predicted due to traffic, as previously indicated, and actual measured deterioration of Brampton Road Test sections over a period of eight years. The two submodels for pavement deterioration are combined to predict the performance of any pavement section.

OPAC predicts pavement costs throughout the life of a pavement. Various cost components are: initial capital expenditure, subsequent resurfacing and maintenance expenditures and salvage return. OPAC is so comprehensive that it also includes road user delay cost in its economic analysis of design alternatives. OPAC provides an evaluation of the various cost components of a pavement on the one hand and various possible consequent costs to the users on the other and makes it possible to examine design trade-offs. The final decision regarding the selection of a design remains with the pavement design engineer who must also consider such location information as construction problems, aggregate depletion and traffic safety.

OPAC is very accessible, simple to use. Communication between the pavement design engineer and OPAC is achieved through a terminal which is linked by telephone to an IBM 360 computer. A question and answer dialogue is established between the computer and the engineer using the keyboard of the terminal. In response to questions posed by the computer, the pavement design engineer enters basic design specifications such as subgrade condition, performance requirements, traffic projections, available material and their costs. Within seconds the computer returns its analysis to the terminal, printing out various design alternatives to meet the engineer's specifications.

In operation since March 1974, OPAC's ability to analyze and predict cost and performance provides the basis for effective pavement management, and for assisting planners in providing, within the available budget, an economically designed road system that considers the needs of the province's travelling public.

THE SYSTEM

The Ontario Pavement Analysis of Costs (OPAC) Design System is a computerized system that enables a pavement designer within a few hours to compare the performance and costs of a great many different flexible pavement designs. Using the system, pavement design engineers can select the most effective pavement design that has the least cost.

The designer establishes a dialogue with OPAC through a remote computer terminal, entering the specifications for the designs he wishes considered, in response to questions posed by the computer. Within seconds, the computer returns its analysis to the terminal, a list of designs arranged in ascending order of costs. Details of material arrangement and thicknesses, predicted life history, and costs, are provided for each design listed. The designer can specify conventional granular base and subbase or treated base designs, deep strength and full depth asphalt designs. The designer can also examine designer changes needed for better or worse subgrade conditions,

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**Head, Pavement Research, Ministry of Transportation & Communications, Ontario

OPAC (24)

Table 1, Structural Design Guidelines for Flexible Pavements

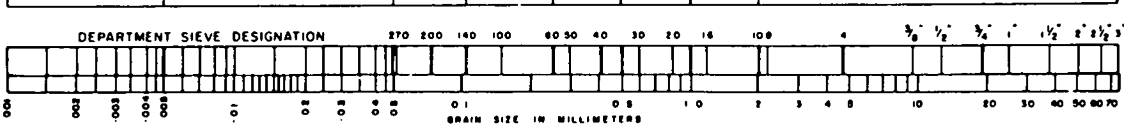
TRAFFIC CLASSIFICATION RURAL OR URBAN \ SUBGRADE MATERIAL		GRAN. TYPE MATERIALS SUITABLE AS GRAN. BORROW	SANDY SILT AND CLAY LOAM TILL: SILT < 40 V.F. Sa and Si. < 45	SILT 40 - 50 V.F. Sa. and Si. 45 - 60	SILT > 50 V.F. Sa. and Si. > 60	LACUSTRINE CLAYS	VARVED AND LEDA CLAYS
		1	2	3	4	5	6
MULTI-LANE	HM	5½"	5½"	5½"	5½"	5½"	5½"
	B	6" - 9"	6"	6"	6"	6"	6"
	SB	–	12" - 18"	18" - 24"	24" - 30"	18"	18" - 42"
	GBE	(17" - 20")	(25" - 29")	(29" - 33")	(33" - 37")	(29")	(29" - 45")
2 LANES > 2000 AADT	HM	4½"	4½"	4½"	4½"	4½"	4½"
	B	6" - 9"	6"	6"	6"	6"	6"
	SB	–	12" - 18"	18" - 24"	24" - 30"	18"	18" - 42"
	GBE	(15" - 18")	(23" - 27")	(27" - 31")	(31" - 35")	(27")	(27" - 43")
2 LANES < 2000 AADT	HM	3½"	3½"	3½"	3½"	3½"	3½"
	B	6"	6"	6"	6"	6"	6"
	SB	–	12"	12" - 18"	18" - 24"	12" - 18"	18" - 30"
	GBE	(13")	(21")	(21" - 25")	(25" - 29")	(21" - 25")	(25" - 33")
PAVED > 1000 AADT	HM	1½"	1½"	1½"	1½"	1½"	1½"
	B	6"	6"	6"	6"	6"	6"
	SB	–	6" - 12"	12"	18" - 24"	12" - 18"	18" - 30"
	GBE	(9")	(13" - 17")	(17")	(21" - 27")	(17" - 21")	(21" - 29")
UNPAVED < 1000 AADT	HM	–	–	–	–	–	–
	B	6"	6"	6"	6"	6"	6"
	SB	–	6"	6" - 12"	18"	12"	18"
	GBE	(6")	(10")	(10" - 14")	(18")	(14")	(18")
PAVED > 200 AADT	HM	1½"	1½"	1½"	1½"	1½"	1½"
	B	4" - 6"	6"	6"	6"	6"	6"
	SB	–	6"	6"	6" - 12"	6" - 12"	12" - 18"
	GBE	(7" - 9")	(13")	(13")	(13" - 17")	(13" - 17")	(17" - 21")
UNPAVED < 200 AADT	HM	–	–	–	–	–	–
	B	4" - 6"	6"	6"	6"	6"	6"
	SB	–	6"	6" - 12"	12" - 18"	12"	12" - 18"
	GBE	(4" - 6")	(10")	(10" - 14")	(14" - 18")	(14")	(14" - 18")
MINING & ACCESS	HM	–	–	–	–	–	–
	B	4" - 6"	6"	6"	6"	6"	6"
	SB	–	6"	6"	6" - 12"	6" - 12"	12" - 18"
	GBE	(4" - 6")	(10")	(10")	(10" - 14")	(10" - 14")	(14" - 18")

HM - HOT-MIX ASPHALT THICKNESS
B - BASE THICKNESS
SB - SUB-BASE THICKNESS

GBE - GRANULAR BASE EQUIVALENCY THICKNESS (1" HM ≈ 1" TREATED B. ≈ 2" GRAN. B. ≈ 3" SB)
**U.S. BUREAU OF SOILS CLASSIFICATION*

NOTE: THE RANGE IN TOTAL THICKNESS SHOWN IN THE ABOVE TABLE ARE DEPENDENT UPON THE MOISTURE CONTENT OF THE SUBGRADE.

U. S. BUREAU OF SOILS CLASSIFICATION							
Clay	Silt	Very Fine Sand	Fine Sand	Medium Sand	Coarse Sand	Fine Gravel	Gravel



1 in. = 2.54 cm

lower or higher traffic, and various levels of initial and terminal serviceability, all within hours and all at reasonable design cost. Final design selection is not wholly based on cost; location factors such as depletion of aggregate sources, ease and practicality of construction, safety and disruption of traffic, past experience, and engineering judgement also influence the design selection.

OPAC replaces a design method in which past experience is embodied in a table (Table 1) of design thicknesses suitable for various subgrades and traffic (1). OPAC, in operation since March 1974, is now used routinely in all five regions of the Province.

SYSTEM OUTLINE

OPAC generates all possible pavement designs within the thickness limitations prescribed by the designer, by combining the given materials in different layers and in various increments of thicknesses, 1, 2, or 3 inches (1 inch = 2.54 cm). Each of these pavement designs is then examined by the pavement life prediction model. The pavement life prediction model utilizes the subgrade and the equivalent granular pavement structure to define the response to a standard load. (Granular equivalents for various materials are designer specified). This response, the deflection of the subgrade surface, is indicative of the future performance of the pavement. Predictive models within OPAC for loss of Riding Comfort Index (RCI) with the number of standard load repetitions up to any desired time, and for loss of RCI with the corresponding number of seasonal cycles (years), then predict the RCI at any time after initial construction. For a given (designer specified) terminal RCI, the useful life of the pavement is determined. If a design satisfies the minimum predicted life criterion set by the designer, OPAC then proceeds to examine the overlays needed to recapture RCI loss so that the pavement can continue to be serviceable during the analysis period.

The designer specifies the materials and thicknesses of lifts for future overlay that he wants to consider and inputs quantity estimates for isolated padding. OPAC calculates the costs of future overlays and uses the life prediction model to determine the life of each. If the first overlay does not carry the design beyond the end of the analysis period, another similar overlay is added, and so forth, until the whole analysis period is covered. The present value of costs of each of these overlay strategies is determined and the least cost strategy adopted. For each initial design alternative considered, OPAC determines the optimal overlay strategy.

OPAC calculates material volumes per mile for designer specified widths for each combination of material thickness under consideration, and determines structure costs from unit weight and unit cost figures. Overlay costs for each combination is determined. Additionally, the cost to the user of traffic delays caused by construction of overlays is determined, and the salvage value of the pavement structure at the end of the analysis period. The cost of future pavement maintenance is estimated from average cost curves. All future costs are discounted at a recommended rate (often 6 percent) back to their present values, in order to permit fair comparison of different initial designs by also taking account of their future needs. This is illustrated in Figure 1. The procedures for cost calculation are fully described in Ref. 2. The total cost of each design considered after the first 24 is compared with the total cost of the lowest 24 so far considered, and is either rejected as higher or if lower than any in the group it replaces the one in the 24 with the highest cost.

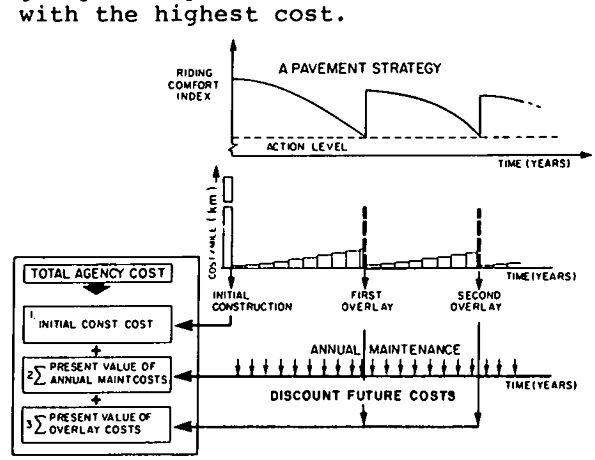


Figure 1. Future Costs are Discounted to Compare Strategies

A typical computer output is shown in Figure 2. Subsequent versions of OPAC will extend the engineering analysis to provide checks of these 24 designs against criteria for fatigue and rutting deformation.

THE PREDICTION MODEL

The basis of life prediction are the models which relate losses in Riding Comfort Index (RCI) with the passage of traffic and environmental cycles, and the limits of tolerable

RCI (3,4).

Riding Comfort Index is the number between 0 and 10 which represents the acceptability of ride comfort of a section of road. A very smooth road which provides a highly acceptable ride is given a maximum value of 10. This scale is directly comparable to the Present Serviceability Rating (PSR) scale of 0-5 used at the AASHTO Road Test (5).

Ministry of Transportation and Communications
Flexible Pavement Design System, OPAC

Prob	Dist	Work Project	Highway	Date	Page
1	3	118 68 01	6N	2/20/73	10

Summary of the Best Design Strategies
in order of Increasing Total Cost

	1	2	3	7	8
Material Arrangement	ABCE	ABCE	ABCE	ABC	ABC
Init Const Cost	144057	138476	147716	159466	153981
Overlay Const Cost	42774	48874	41188	43659	52395
User Cost	445	512	433	454	567
Routine Maint Cost	17771	17572	18066	17572	17572
Salvage Value	-3067	-3312	-3094	-3432	-4041
Total Cost	201981	202122	204310	217720	220475
Layer Depth (Inches)					
D(1)	1 50	1 50	1 50	1 50	1 50
D(2)	4 00	4 00	4 00	7 00	7 00
D(3)	7 00	6 00	6 00	7 00	6 00
D(4)	9 00	9 00	12 00		
Perf Time (Years)					
T(1)	10 4	10 0	10 8	10 4	10 0
T(2)	20 5	19 9	21 1	20 3	19 7
T(3)	30 7	30 1	31 5	30 4	29 6
T(4)					39 5
Overlay + Level Up					
O(1)	3 0	3 0	3 0	3 0	3 0
O(2)	3 0	4 0	3 0	3 0	3 0
O(3)					3 0

A = Surface; B = Binder; C = Gran. Base; D = Gran. Subbase

Figure 2. Typical OPAC Output

A comprehensive elastic layer analysis of existing pavement design experience in Ontario, as represented by Table 1, has revealed that elastic deformation at the top of the subgrade is the best indicator of pavement performance. The underlying hypothesis is that repeated subgrade deflections result in permanent deformations of the subgrade surface which reflect through on the pavement surface and decrease riding quality (6).

Subgrade deflections may be calculated by using the procedure developed by Odemark (7) whereby an elastic layer system can be transformed into an equivalent granular thickness system by means of equivalency factors. The computed equivalent thickness H_e is then used to calculate the deflection w at the top of the subgrade as shown in Figure 3. Layer equivalency factors for determining equivalent granular thickness as shown in this figure have been obtained from experience gained at the Brampton Road Test.

As per the Odemark method, certain properties of layer materials named elastic moduli, are required for calculating subgrade deflections (7). As described in Reference (6), a specific set of these properties was arrived at through a comprehensive analysis of experiences on various classes of roads in Ontario. These are given in Figure 3. Layer equivalency factors as determined at the Brampton Road Test helped to establish the ratios among the values of these layer moduli (Figure 3). Since a fixed value of layer modulus is assigned to each layer, henceforth, these values will be called "layer coefficients" to avoid confusion with the traditional definition of a modulus. A close scrutiny of the deflection equation using various other sets of "layer coefficients" has revealed that absolute values of layer coefficients are immaterial as long as their "ratios" remain constant (since ratios determine layer equivalency factors).

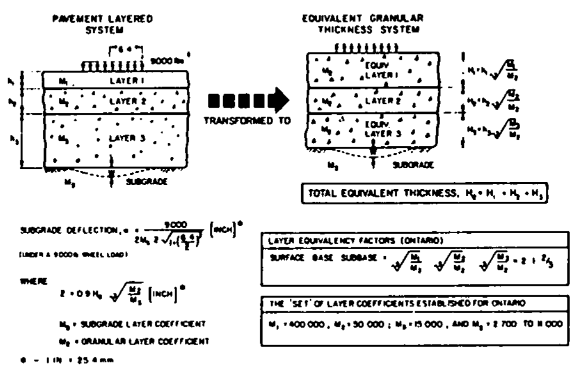


Figure 3. Transformation of Pavement Layered System into Equivalent Granular System, and Calculation of Subgrade Deflection

The hypothesis that subgrade deflection is a good indicator of pavement performance and that this deflection can be determined adequately by the set of layer coefficients as given in Figure 3, is substantiated in Figures 4 and 5. Figure 4 shows an excellent correlation between Odemark subgrade deflection calculated for AASHTO Road Test sections (using the set of layer coefficients in Figure 3) and the number of 18-kip (80kN) equivalent applications successfully carried on these test sections to a terminal performance level of 2.5. Figure 5 shows a correlation that was observed at the Brampton Road Test between calculated Odemark subgrade deflections (using the same set of layer coefficients) and the measured Benkelman Beam surface deflections - the response which, from Canadian experience, is considered to be a good indicator of pavement performance (8).

By using the established set of layer coefficients, Figure 6 has been drawn to give a graphical representation of the Odemark subgrade deflection due to a standard 9000-lb. (40 kN) wheel load and for various subgrade layer coefficient values. Inherent in the curves of the figure are the following layer equivalency factors of Surface: Base:Subbase = 2:1 : 2/3. The deflection w is obtained from this figure after selecting a value for the subgrade layer coefficient (from the table in the figure determined on the basis of Ontario pavement performance experience on a variety of subgrades in the province) and after calculating the value of the total equivalent granular thickness H_e for a pavement structure by using the above layer equivalency factors. Also shown (on the righthand side of the figure) is a scale from which corresponding peak Benkelman Beam surface deflections can be predicted as determined from the correlation established in Figure 5.

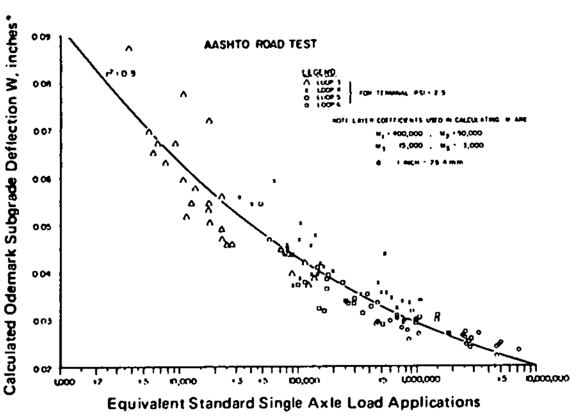
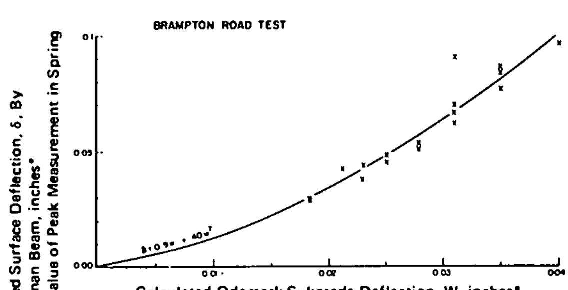


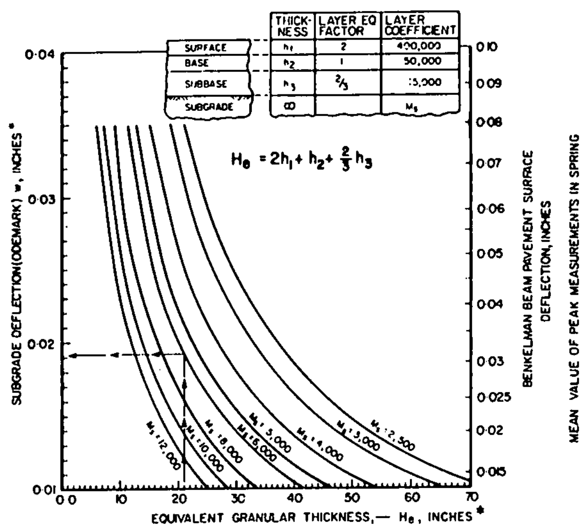
Figure 4. Calculated Odemark Subgrade Deflection Versus Load Repetition at the AASHTO Road Test (After Reference 6)



Note: Layer Coefficients Used in Calculating W are:
M_1 = 400,000 M_2 = 50,000
M_3 = 15,000 M_5 = 4,000

* 1 inch = 25.4 mm

Figure 5. Calculated Odemark Subgrade Deflection Versus Largest Benkelman Beam Deflection in Spring, Brampton Road Test



TYPICAL SUBGRADE LAYER COEFFICIENTS M_s IN ONTARIO

SUBGRADE / CONDITION	GRAN TYPE MATERIALS SUITABLE AS GRAN BORROW	SANDY SILT AND CLAY LOAM TILL: SILT<40 V F Sa and Si <45	SILT 40-50 V F Sa and Si 45-60	SILT >50 V F Sa and Si >60	LACUSTRINE CLAYS	VARVED AND LEDA CLAYS
GOOD	11,500	7,000	6,000	4,500	5,500	4,500
FAIR	10,500	6,000	5,000	4,000	5,000	3,500
POOR	9,000	5,500	4,500	3,500	4,000	2,500

* 1 INCH = 25.4 mm

Figure 6. Odemark Subgrade Surface Deflections for Different Equivalent Granular Thicknesses and Subgrade Layer Coefficients

The method presented in the following sections shows how the Odemark subgrade deflection w is used to predict performance of a pavement structure.

The structure prediction model presented in this report is composed of:

a/ a traffic input model which establishes the amount of traffic during the analysis time period.
b/ a model for predicting the performance loss p_T due to traffic loads.
c/ a model for predicting the performance loss p_E due to geographic or environmental influences and,
d/ a method for combining p_T and p_E.

Immediately after construction, the Riding Comfort Index p_o of a pavement is relatively high and depends largely on the conditions during construction. From this value, the losses p_T and p_E must be subtracted to obtain the Riding Comfort Index p at any particular time. Thus,

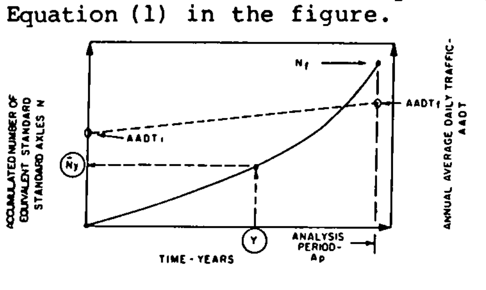
$$p = p_O - p_T - p_E$$

The traffic loss p_T is a function of the number of equivalent standard axle load applications, N. The environmental loss p_E is a function of the number of years or seasons passed, Y. The number N is a function of Y as established by the traffic input model.

Traffic Input Model

The traffic input model is basically a functional relationship between traffic load N and time Y. The relationship can be established from traffic data as proposed and discussed in Reference (9). The following method is being used in Ontario.

Each project to be designed has a traffic estimate; usually an annual average daily traffic (AADT) in the design (first) year and a predicted AADT at the end of 20 years. First, the total equivalent 18-kip (80 kN) single axle load applications, N_f expected during the analysis period A_p are determined by using an average of initial and final estimates of the number of 18-kip (80 kN) axles per day in the design lane as described by Equation (2) in Figure 7. Subsequently, at any number of years Y, the number of corresponding standard load applications N are determined by using Equation (1) in the figure.



$$N = \frac{N_f}{A_p}\left[\frac{2AADT_i}{(AADT_i + AADT_f)}Y + \frac{AADT_f - AADT_i}{A_p(AADT_i + AADT_f)}Y^2\right] \text{——} (1)$$

$$N_f = \frac{A_p}{2}\left\{\left(\frac{AADT_i}{2} \times DAYS \times T_i \times LDF_i \times TF_i\right) + \left(\frac{AADT_f}{2} \times DAYS \times LDF_f \times TF_f\right)\right\} - (2)$$

WHERE T = PERCENT OF TRUCKS

$\frac{AADT}{2}$ = ONE DIRECTIONAL AVERAGE ANNUAL DAILY TRAFFIC

LDF = LANE DISTRIBUTION FACTOR (1.0 FOR TWO LANE ROADS; 0.8 FOR MOST FOUR LANE ROADS)

TF = TRUCK FACTOR = EQUIVALENT STANDARD AXLES PER TRUCK (18 kip or 80 kN)

DAYS = No. OF DAYS PER YEAR FOR TRUCK TRAFFIC (GENERALLY = 300)

i AND f DENOTE "INITIAL" AND "FINAL" RESPECTIVELY

Figure 7. Traffic Input Model

Traffic Related Deterioration

The calculated Odemark subgrade deflection w is used to derive a performance prediction equation based on the main factorial test data of the AASHTO Road Test (5). The equation (Equation (11) in Reference (6) has been rescaled from a 5-point index (Present Serviceability Index (PSI) to a 10-point index (Riding Comfort Index (RCI)). The modified equation is given below and is plotted in Figure 8.

$$p_T = 2.4455\ \psi + 8.805\ \psi^3$$

where:

ψ = $1000w^6N$*
p_T = loss in Riding Comfort Index due to traffic
w = calculated Odemark subgrade deflection in inches
N = number of standard (18-kip or 80 kN) single axle load applications

It should be noted that AASHTO Road Test data did not include sections giving Odemark subgrade deflections of less than 0.025 inches (0.635 mm) (i.e. very thick pavements), however, the model can be extrapolated for designs in this range.

Environment Related Deterioration

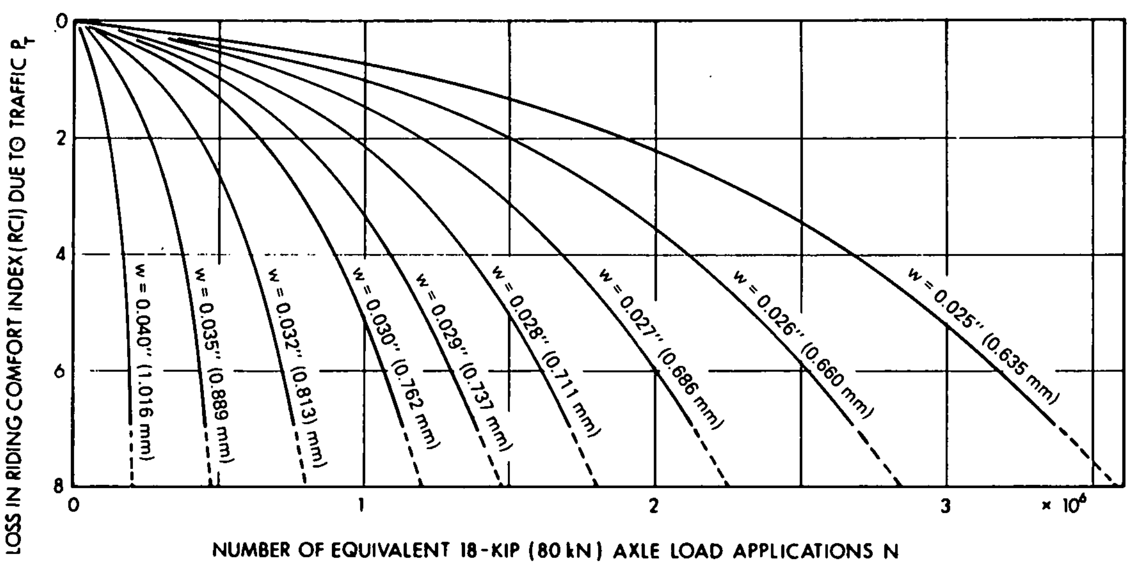
Since the AASHTO Road Test was carried out with accelerated loading and relatively underdesigned pavement thicknesses, results are not readily applicable to real-life pavements even if such pavements are influenced by similar geographical and environmental conditions. Due to exposure to climatic cycles, the real-life pavements suffer deterioration over a period of time, even under low traffic volumes, due to differential heaving and settling from frost, freeze-thaw cycles, swelling subgrades or other such influences. Since the AASHTO Road Test sections survived only one or two winter seasons, the test results do not adequately indicate the effect of these influences. This became apparent in Ontario when the traffic related performance model derived from AASHTO Road Test data was applied to the Brampton Road Test over a period of eight years of its performance. The traffic performance model could not reproduce the Brampton results even by applying a proportionality factor and the characteristics of the difference suggested a different kind of functional relationship.

A flexible pavement attains its highest level of serviceability of riding comfort immediately after

*$\psi = 3.7238 \times 10^{-6}\ w^6N$
where w is in millimetres

construction. During its lifetime, the pavement is exposed to forces from axle weights, temperature changes which cause restrained expansion or contraction, and changes of subgrade conditions which cause swelling, shrinkage, freezing - thawing, and heaving - settlement. These forces or influences act in various combinations and proportions on a pavement, causing loss in Riding Comfort Index.

decreasing exponentially with each year or season passed. A similar function has been suggested by Kher et al (10) in the development of pavement performance equations for swelling clay subgrades in Texas, a condition which produces similar volume changes as those produced by low-temperature frost effects. The function is shown in Figure 9 and shows that the rate of decrease in p due to



Performance Prediction Model: $P = P_O - P_T - P_E$ $P_T = 2.4455\,\psi + 8.805\,\psi^3$ Where $\psi = 1000\,w^6\,N$ (for w in inches)*

* 1 inch = 25.4 mm $\psi = 3.7238 \times 10^{-6}\,w^6\,N$ (for w in millimetres)

Figure 8. Performance Prediction Model - Traffic Related Contribution (p_T)

The combination of axle weights with soft subgrade conditions in the spring, and the upward migration of water in the subsoils due to freezing (which results in heave or upward expansion in conjunction with subsequent re-consolidation) are noteworthy distress mechanisms. The influence of spring softening observed in the AASHTO Road Test was the reason why the number of axle repetitions were "weighted". The effect of water migration and freezing is a function of the increasing number of years through which a pavement survives. Also, deterioration due to temperature changes (such as transverse cracking) is a function of the number of winter-spring seasons. In light of this time-dependent part of pavement deterioration, it becomes necessary that a loss model, in addition to a traffic loss model, should be developed as a function of number of years or winter-spring cycles.

The function which best represents this additional loss term is conceived to have the specific characteristic of environmental forces is at a maximum in the initial years and reduces with time as p reaches a hypothetical ultimate value of p_∞, at infinite time. In other words, the more a pavement deteriorates from its initial smoothness towards its ultimate roughness value of p_∞, the less is the annual rate of "roughening". For regions where a different type of environmental deterioration is observed, the loss function may assume a different form such as, for example a linear relationship which should be used where the same average amount of environmental deterioration is observed in each year of pavement life.

It is also conceived that the level of p_∞ is larger for stronger pavements, i.e., stronger (thicker) pavements will be less affected by environmental deterioration than weaker pavements. Since the strength of a pavement has been established in the previous section by the subgrade surface deflection criterion, the same response value can be used to establish the resistance of pavements to environmental forces. In other words, p_{∞} can be made a function of the Odemark subgrade deflection.

correlates highly with the strength of the section represented by the Odemark

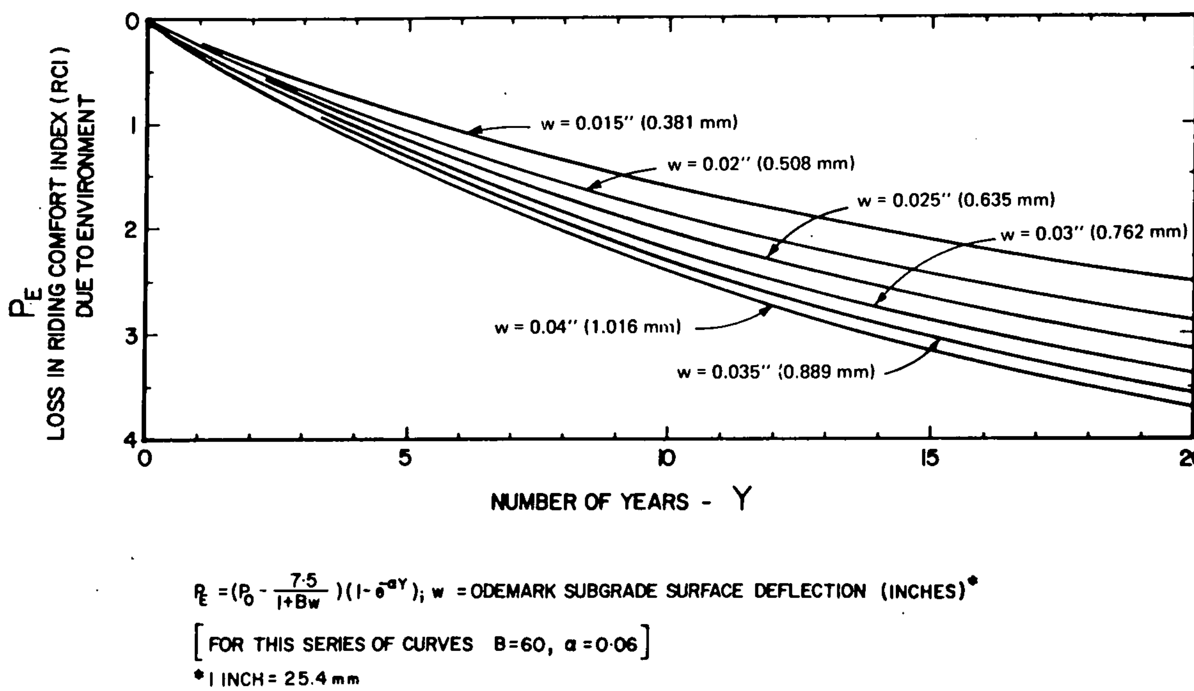


Figure 9. Performance Prediction Model - Environmental Related Contribution (p_E)

To establish the constants of the exponential deterioration function, it is necessary to obtain experimental data or other experience on real pavements in a particular region. In Ontario, the Brampton Road Test was used for this purpose. The methodology adopted to establish this function is described below. However, it is obvious that each region must rely on local experience to obtain a relevant function with different constants.

For each section of the Brampton Road Test, the best fit curves were drawn through the observed data as well as the curve predicted by the traffic performance model. The two curves did not coincide due to the differences contributed by the environmental factors. When the differences were examined for all the sections of the Brampton Road Test, the following three inferences were drawn:

1/ Environmental deterioration is an exponential curve of RCI versus the number of years;
2/ Exponential deterioration rate equal to 0.06 applies to all sections of the Brampton Road Test; and
3/ The asymptotic value of p_{∞} varies for each section and

subgrade deflection, w. The correlation is expressed as follows:

$$p_{\infty} = \frac{p_o}{1 + Bw}$$

where:

p_o = Initial Riding Comfort Index of Pavement
B = 100

Figure 10 gives the basic performance data on some of the Brampton Road Test sections, ranging from very weak to very strong pavements. The curves calculated by the equations of the final model which combine deterioration resulting from both traffic and environmental influences (using the above constants) are also shown. These curves demonstrate that the final model predicts the riding comfort measurements of the Brampton Road Test over the entire range of conventional pavements tested. Also shown in these figures are the curves resulting from only the traffic deterioration model.

Data on the values of RCI taken immediately after construction indicated that average p_o for the

OPAC (24)

pavements can be assumed to be equal to 7.5. With p_o at a constant value, the model was tested on a variety of past pavement design experiences in the province. The analysis showed that for B equal to 60, pavement lives matched the province-wide experience.

The first step in the procedure is to calculate the total granular equivalent thickness H_e of the pavement structure. This is (3½ x 2) + (6 x 1) + (12 x 2/3) = 21 inches (533.4 mm) when appropriate layer equivalency values are applied to each

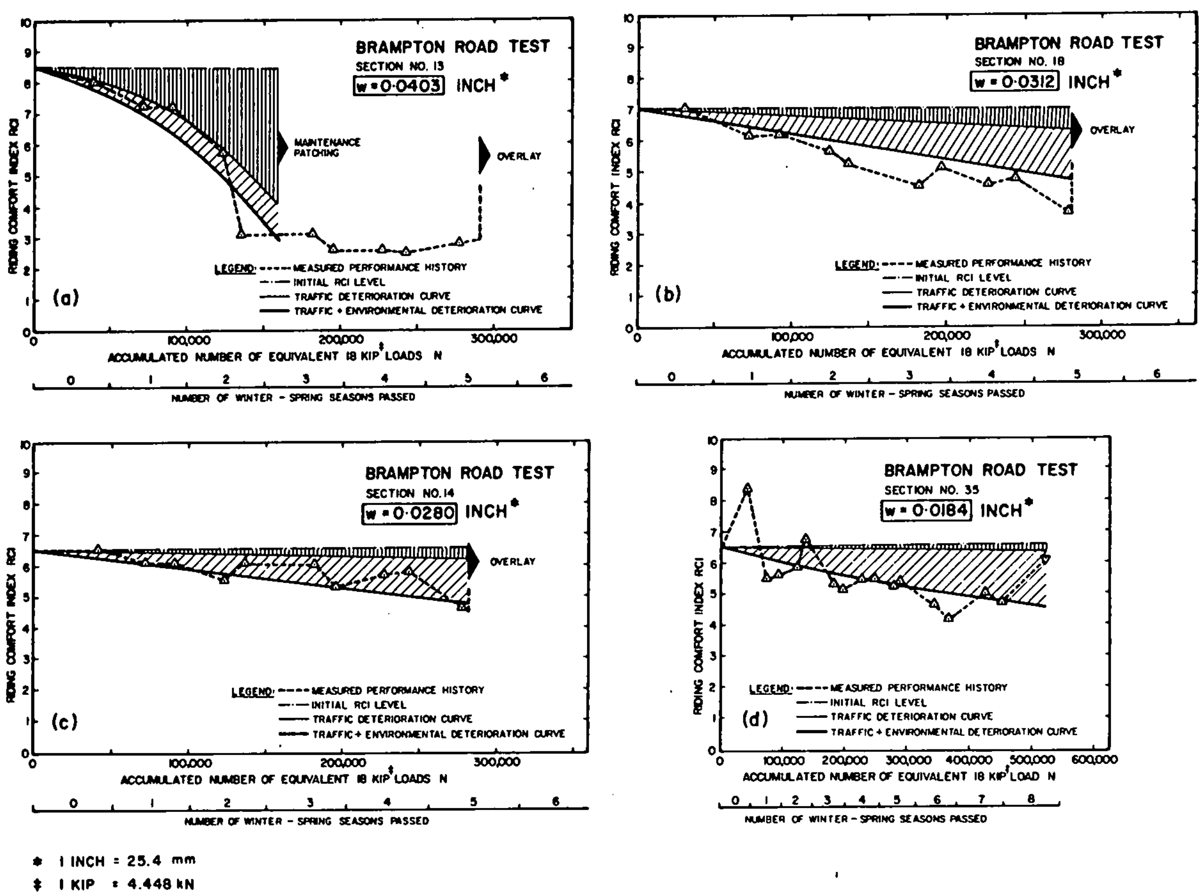


Figure 10. Brampton Road Test Performance Data Versus the Predicted Performance Using the Prediction Model (Traffic Plus Environmental Deterioration)

EXAMPLE OF APPLICATION OF THE MODEL

The following example is presented to demonstrate how the effects of traffic and environmental loss in RCI are combined and used to predict the age at which terminal performance is attained.

1/ Assume a pavement with a 3½-inch (88.9 mm) asphalt surfacing, a 6-inch (152.4 mm) granular base and a 12-inch (304.8 mm) granular subbase constructed on a soft clay subgrade.

2/ The estimated number of standard 18-kip (80 kN) axle load repetitions at 12 years is 300,000.

layer.

For the second step, the subgrade layer coefficient which is selected from the table in Figure 6 as being consistent with the description of the material is M_s = 2,700. The Odemark subgrade surface deflection w for this pavement under the standard 9-kip (50 kN) wheel load P (contact radius, a = 6.4 inches (162.6 mm) is either calculated by:

$$w = \frac{9000}{2\,M_s\,Z} \times \frac{1}{\sqrt{1 + \left(\frac{a}{z}\right)^2}}$$

where:

$$Z = 0.9 \sqrt[3]{\frac{M_2}{M_s}^2 \times H_e}$$

or may be read directly from the graph in Figure 6.

For this example M_s = 2,700; M_2 = 50,000 (adopted for the subsystem and H_e = 21 inches (533.4 mm). Z is calculated as 50 inches (1270 mm) and w is calculated as 0.03306 inches (0.84 mm).

For the third step, the number of standard axles N at any time Y must be known. For the example N = 300,000 at Y = 12 years. The loss in RCI, p_T, due to traffic is determined from the following equations:

$$p_T = 2.4455\ \psi + 8.805\ \psi^3$$

where:

$$\psi = 1000\ w^6 \times N^*$$

In this example ψ = 0.3917 and p_T = 1.487. The RCI loss may also be read from the curves in Figure 8.

For the fourth step, the loss in RCI due to environmental influences p_E, is calculated by the following formula:

$$p_E = (p_o - p_\infty)\ (1 - e^{-\alpha Y})$$

where:

$$p_\infty = \frac{A}{1 + Bw}$$

For this example, as is the case with most new construction, the initial RCI value p_o is taken as 7.5. The constants in these equations are taken as:

p_o = 7.5 = A
B = 60
α = 0.06

use of these values for southern Ontario appears to predict lives which fit experience

For this example p_∞ = 2.514 and p_E = 2.559. This may also be found from Figure 9.

For the next step, the RCI losses p_T and p_E are deducted from the initial RCI (p_o) to determine the RCI at 12 years, or $p_{12} = p_o - p_T - p_E$ = 7.5 - 1.487 - 2.559 = 3.454. This predicted RCI at 12 years forms one point on the performance curve for this pavement structure. Other points are similarly calculated for different times Y and their corresponding traffic loads N so that the performance curve may be defined. When this is done as is illustrated in Figure 11, the age of the pavement may be determined for any value of RCI which is considered to be the terminal value or the value at which rehabilitation becomes necessary. For example, at a terminal RCI of 4.0, the corresponding predicted age taken from the performance curve is 10.8 years.

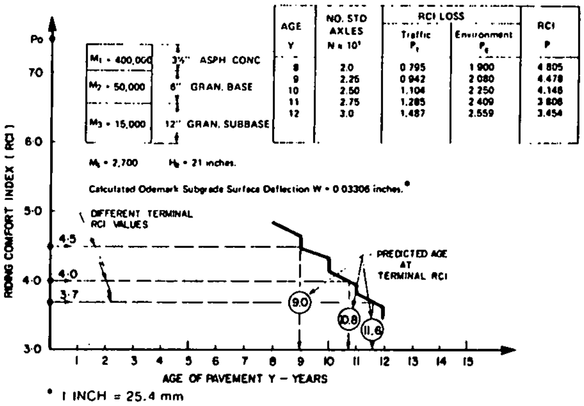


Figure 11. Example Showing Predicted Performance Curve and Predicted Ages at Different Terminal RCI Values

OVERLAYS

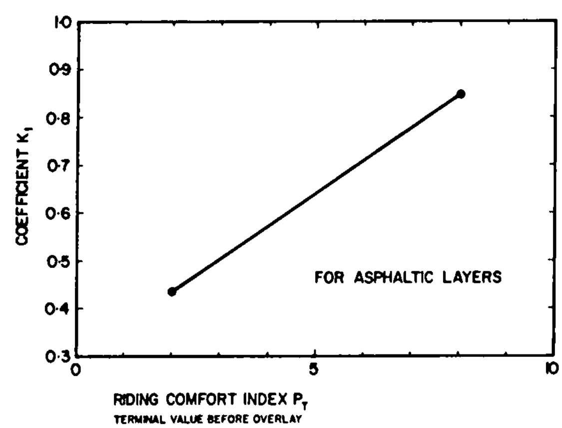
Repeated traffic loads and environmental influences result in gradual deterioration of pavement layers. Cracks develop in the asphaltic layers and increase in number over the years; concurrently, the granular layers are weakened by various mechanisms such as aggregate degradation and contamination.

Thus, although the life of a newly constructed pavement is predicted based on its initial value of calculated subgrade deflection w, this deflection value does not remain constant but increases as the strength of the pavement layers decreases. This increase in deflection was observed at the Brampton Road Test (11) and demonstrated by Lister in his observations on deflection of more than 300 experimental sections (12). For the design of an overlay, the reduction in the strength of the existing layers can be accounted for by reducing their layer equivalency factors. The reduction coefficients which are used at present in the subsystem are given in Figure 12.

The premise underlying the use of layer equivalency reduction coefficient K_1 for asphaltic layers is that repeated

$^*\psi = 3.7238 \times 10^{-6}\ w^6 N$
where w is in millimetres

loading decreases stiffness (13) thus, the coefficient K_1 decreases as RCI decreases to values slightly below that of poor gravel. A straight line relationship was considered most suitable. Figure 12 similarly presents layer equivalency reduction coefficients K_2 and K_3 for granular base and subbase materials. The coefficients are larger for stronger pavements because such pavements are designed to withstand heavier traffic loads and/or more seasonal cycles. The layer equivalency reduction coefficients, while based on limited data, serve not only as indicators of how the modelling of the overlay problem is approached, but their usage results in overlay lives which are acceptable to practicing design engineers in Ontario.



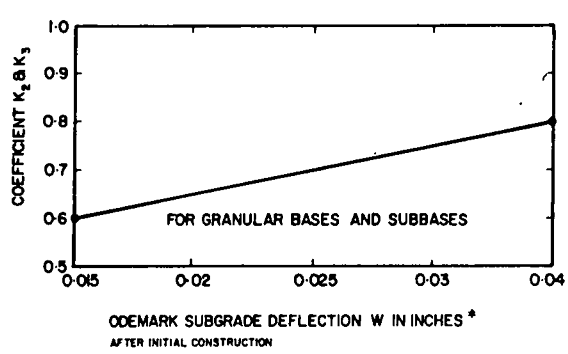


Figure 12. Reduction Coefficient for Layer Equivalency Factor

An overlay rehabilitates the pavement in two respects. First, it raises the riding quality to a more comfortable level and, secondly, it re-establishes the strength of the pavement. As a general guideline, overlay thickness provided should compensate for some of the loss in strength of the old pavement so that the total granular equivalent thickness after the overlay is comparable with the thickness of the initial construction. The equivalent thickness after overlay is determined is determined as follows:

$$H_e = a_1h_o + k_1a_1h_1 + k_2a_2h_2 + k_3a_3h_3$$

where:

h_o	=	overlay thickness
a_1, a_2, a_3	=	layer equivalency factors for asphalt surfacing, base and subbase, respectively
h_1, h_2, h_3	=	layer thicknesses of surfacing, base and subbase of initial pavement, respectively
k_1, k_2, k_3	=	layer equivalency reduction factors (Figure 12) for surfacing, base and subbase, respectively

To predict the life span of an overlaid pavement, the new equivalent thickness value replaces the initial equivalent thickness value and performance prediction procedure is repeated.

SYSTEM VALIDITY

The validity of the OPAC Design System hinges on how well the performance model predicts a pavement's Riding Comfort Index as a function of its age. Though the model predicts fairly well the RCI versus age of the Brampton Road Test sections, historical RCI data on actual pavements is relatively scarce. However, records of pavement ages i.e., time from new construction to resurfacing, is available and will be used here for comparison.

Data on 2680 km of equivalent two lane pavements resurfaced between 1965 and 1971 is presented in Figure 13 where accumulated percentage of miles versus pavement age at resurfacing is plotted. An average age of 11.5 years is observed, but since the survey included many stage paving projects, average age to resurfacing of about 12 to 13 years will be more representative of actual pavements. For comparison, pavement designs from the top 3 rows of Table 1 (successful experience) were analyzed for life predictions using OPAC. The results are shown in Table 2. The lives to resurfacing are found to vary between 11 to 13 years, closely matching those observed in the Survey above.

Further validation is attempted through a review of 20 actual projects designed in the Province in 1975-6 using OPAC. Total granular equivalences selected after analysis by OPAC and those given by Table 1 (successful experience) are listed in Table 3. The designs selected using OPAC do not deviate a great deal from the design ranges given in Table 1. The variations are explained by the fact that many other factors are taken into consideration by the designers for selecting a pavement design than consideration of cost alone (as per OPAC). Conservation of aggregates, stimulation of competition, practicality of construction and adaptions of local materials are some of the many factors considered in the selection process.

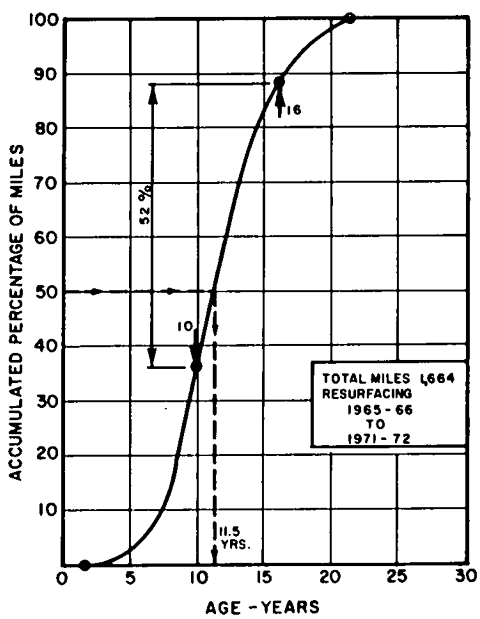


Figure 13. Age of Resurfaced Pavements in Ontario (1664 Miles - Period 1966 To 1972)

Subgrade Material / Traffic Classification Rural or Urban	Gran Type Materials Suitable As Gran Borrow	Sandy Silt and Clay Loam Till: Silt < 40 V F Sa and Si < 45	Silt 40 50 V.F Sa and Si 45 - 60	Silt > 50 V F Sa. and Si. > 60	Lacustrine Clays	Varved and Leda Clays	Avg 20 - Year 18 Kip Axles (Millions)
	1	2	3	4	5	6	
Multi Lane	12** (17 20)*	12 (25 29)	12 (29 33)	12 (33 37)	11 5 (29)	11 5 (29 45)	6.00
2 Lanes 2000 AADT	12 5 (15 18)	12.5 (23 27)	13 (27 31)	12 5 (31 35)	12 (27)	12 (27-43)	4.50
2 Lanes 2000 AADT	11 (13)	12 (21)	11 5 (21 25)	12 (25 29)	11 5 (21 25)	11.5 (25 33)	3 00

* Range of Granular Equivalencies Successful Experience Designs
** Life Predicted by Performance Model for Mid Range Granular Equivalency

Table 2. Lives Predicted by Pavement Performance Model for Designs in Table 1.

Traffic is another major source of difference between Table 1 designs and OPAC predictions. Table 1 lists 2 - lane designs with traffic greater than 2000 AADT in one (same) category and all multilane designs in another, but OPAC will design for the actual traffic and actual total 20 - year 18 kip axles. For the twelve 2 - lane (AADT > 2000 as per Table 1) highway projects shown in Table 3, actual traffic (AADT) varies from 3,300 to 6,500 and total 20 - year 18 kip axles from 1.91 to 10.00 millions. For eight multilane highway projects, AADT varies from 6,750 to 15,500 and total 18 kip axles from 3.24 to 8.0 millions. Since actual traffic on each project is different than the average shown in Table 2, designs different than those in (successful experience) Table 1 results. However, initial lives of those twenty projects plotted in Figure 14 are still within the ranges obtained in the Provincial Survey (Figure 13).

Project No.	Highway Type: 2/M*-Lane	Highway Type: AADT	20-Year 18-Kip Axles ($X10^6$)	Granular Equivalency (Inches): Range by Successful Design Table	Granular Equivalency (Inches): Actual Design by OPAC
1	2	3,300	3.11	23–27	29
2	2	4,550	3.29	23–27	28
3	2	4,600	2.32	23–27	24
4	2	3,500	1.91	23–27	22
5	2	5,000	3.80	23–27	24
6	2	6,500	4.50	27	30
7	2	5,400	4.74	27	27
8	2	4,050	5.15	31–35	37
9	2	6,000	6.75	27–31	29
10	2	5,250	7.13	15–18	21
11	2	5,250	7.13	27–31	27
12	2	6,040	10.00	23–27	29
13	M	11,375	4.78	23–27	28
14	M	7,500	3.24	25–29	25
15	M	6,750	5.00	25–29	26
16	M	10,000	8.00	17–20	21
17	M	9,350	7.53	17–20	21
18	M	9,350	7.53	29–33	32
19	M	9,870	7.30	29	33
20	M	15,500	7.33	25–29	28

M = Multilane, 4 or 6 lanes

Table 3. Comparison of Pavement Design Thicknesses (Granular Equivalencies) From Successful Experience Design Table 1 Versus OPAC Design Selections for 20 Actual Projects in 1975 - 76

OPAC (24)

SYSTEM IMPLEMENTATION

OPAC is now fully implemented into the day to day operations of the Ministry. The Ministry has five regions in the Province responsible for pavement design. For any new project, regional design offices submit pavement design recommendations to the Head Office where they are reviewed before a Pavement Selection Committee for cost and other factors. This Committee approves a particular design.

The first implementation stage conducted by the developers included redesign by OPAC of many previously designed projects. Encouraging results and considerable potential savings led to a more general second implementation stage. This stage ongoing at present, requires input to be prepared by the regional designer and entered into OPAC system. Communication between the pavement design engineer and OPAC is established through a remote terminal located in each region and linked to an IBM 360 computer located at the Head Office. The program is interactive, that is, questions are posed by the computer for obtaining designer inputs. Once all input is completed, computer returns its analysis to the terminal within seconds, printing out various design alternatives. These outputs are then submitted to the Head Office along with regional recommendations.

During this stage, OPAC developers in the Research and Development Division have been monitoring usage of the system. All OPAC outputs are reviewed and revisions are often made before the outputs are presented to the Pavement Selection Committee. Similarly, the design finally approved by the Committee and the factors leading to the choice are noted by the researchers. This interaction is leading to revisions of the system desired by the regional designers and the Committee.

A preliminary version of a User's Guideline Manual has been written and will be finalized and published at the end of the second stage implementation. Many OPAC workshops have been held to teach the usage of OPAC to the design engineers. Training on individual basis has also been conducted by the Research & Development Division.

It is anticipated that 30 to 40 pavement projects will be designed every year using the OPAC system. In addition to the design of new pavements, OPAC is being used for other studies, such as evaluating conventional resurfacing versus recycling of pavements for areas where reflection of transverse low temperature cracking is a major problem.

The ability to analyze and predict cost and performance of numerous designs and the more comprehensive output information provides the basis for effective pavement management, that is planning for road resurfacings and maintenance well into the future. The financial consequences of smoother initial construction, implications of different future action levels for resurfacings, and lesser initial life requirements are among other facets which are being studied through OPAC. For example, an analysis of past pavement design selection practices as revealed in Figure 14 has resulted in a policy that initial lives of 10 to 11 years as predicted by OPAC, should be uniformly applied for more cost effective designs.

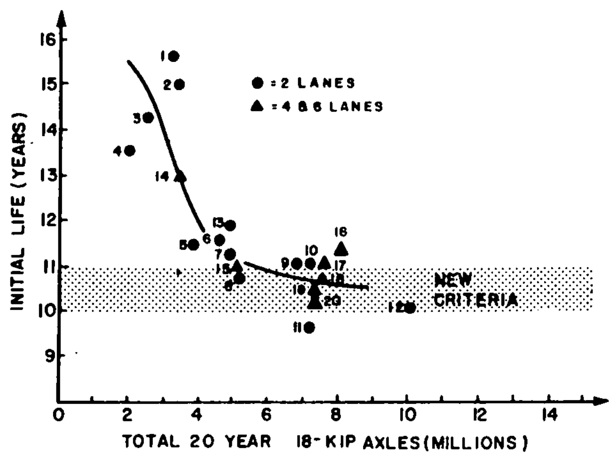


Figure 14. Lives of 20 Actual Projects Designed in Ontario Using OPAC in 1975-76

Though the first version of OPAC has been successfully implemented, further improvements are also underway. In a subsequent implementation phase it is envisaged that more comprehensive user cost analysis, improved capability of analyzing many more different pavement cross sections, upgrading of maintenance cost subsystem and incorporation of some other factors in the optimization process will result in a much improved second generation, OPAC. As shown in Figure 15, these improvements will result from generated research, feedback from monitoring use, research findings from the Ministry's pavement data system, and research by other agencies.

A preliminary evaluation during this implementation phase has revealed that through the use of OPAC, a saving of about $1 million per year can be realized over the previous design processes by saving in design manpower and by avoiding unnecessary overdesigns. As a result, there has been a high degree of acceptability of the OPAC system at all levels of the Ministry.

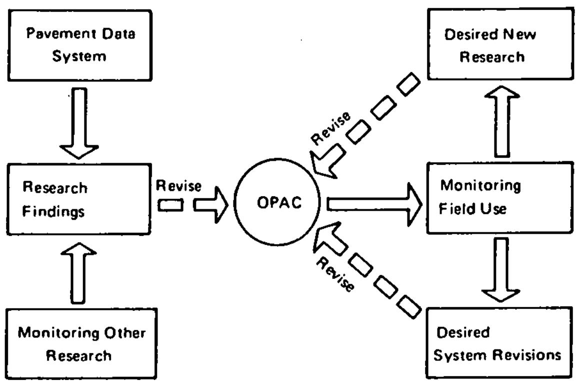


Figure 15. Revising OPAC Through Implementation and Research Feedback

REFERENCES

1. Phang, W. A., "Flexible Pavement Design in Ontario", Transportation Research Record 512, 1974, pp. 28-43.
2. Kher, Ramesh and Phang, W. A., "Economic Analysis Elements", presented at the Transportation Research Board, Washington, Jan. 1975.
3. Wilkins, E.B., "Pavement Evaluation Studies in Canada", International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, Michigan, 1962.
4. Wilkins, E. B., "Outline of a Proposed Management System for the CGRA Pavement Design and Evaluation Committee", Proc., Canadian Good Roads Association, 1968.
5. The AASHTO Road Test, Report 5, Pavement Research Publication 954, Transportation Research Board, Washington, 1962.
6. Jung, F. W., and Phang, W. A., "Elastic Layer Analysis Related to Performance in Flexible Pavement Design", Transportation Research Board Record No. 521, 1974, pp. 14-29.
7. Odemark, N., "Investigations as to the Elastic Properties of Soils and Design of Pavements According to the Theory of Elasticity", Status Vaeginstitut, Stockholm, Sweden, 1949.
8. "A Guide to Structural Design of Flexible Pavements in Canada" Canadian Good Roads Association, 1965.
9. "Evaluation of AASHTO Interim Guides for Design of Pavement Structures", NCHRP Report 128, Transportation Research Board, Washington, 1972.
10. Kher, R. K., Hudson, W. R., and McCullough, B. F., "A Working Systems Model for Rigid Pavement Design", Highway Research Record No. 407, Transportation Research Board, Washington, 1972.
11. Phang, W. A., "The Effect of Seasonal Strength Variation on the Performance of Selected Base Materials", IR39, Ministry of Transportation and Communications, Downsview, Ontario, April 1971.
12. Lister, N. W., "Deflection Criteria for Flexible Pavements and the Design of Overlays",Proc. of the 3rd International Conference on the Structural Design of Flexible Pavement, London, England, 1972.
13. Kallas, B. F., and Puzinauskas, V. P., "Flexure Fatigue Tests on Asphalt Paving Mixtures", Fatigue of Compacted Bituminous Aggregate Mixtures, ASTM STP 508, American Society for Testing and Materials, 1972.

MINNESOTA DOT (33)

ENGINEERING STANDARDS

Minnesota Department Of Transportation

METHOD OF PAVEMENT SELECTION

1983 Edition

VI. PAVEMENT SELECTION REPORT

This section of the report describes the factors that are the necessary inputs that the Task Force(s) have felt are the important costs involved in the pavement selection process. Each of the factors that the Task Force(s) investigated is addressed and has a recommendation as to its use in the economic model at the end of this section.

A. Service Life

The service life of a project indicates the span of years for which the surface pavement services traffic without major interim expenditures for rehabilitation. Minnesota is presently using a service life of 35 years as a basis of pavement performance. This service life corresponds to the analysis period which is the length of time in years for which comparable economical analyses are made for the alternative pavement types. The Task Force has examined the basis of 35 years of service life and has determined that it is still valid to be used for economic analysis. Following are comments and discussion regarding the specifics of the design criteria involved in 35 years of service life.

To design a roadway we use traffic data to determine the geometric characteristics of the roadway and the structural characteristics of the roadway. Presently our capability for traffic projections appears to be about 20 years in the future. Beyond 20 years the accuracy of the predictions is difficult to estimate. By using a 20 year design and a 35 year service life we must accept the fact that a part of our system has always been obsolete in terms of the newest and latest design criteria. Historically a major part of our system serves well beyond the time that design obsolescence sets in. Even though the geometrics may be inadequate and the traffic handling capability may be inadequate after 20 years of service, it would be short-sighted not to design the structural part of the pavement to last at least 35 years if we are capable of doing so. Another strong argument for the 35 year service life is the current resistance from all quarters in relocating existing highways or building new highways on new locations. Environmental concerns, State and Federal regulations, and property owners' opposition all point to the "freezing" of major highways into existing corridors. Even small shifts in roadway alignment or the taking of additional right of way along an existing corridor to expand highway capacity capabilities meets with determined resistance in many areas. Therefore, most all future highway improvements will consist of the upgrading of existing roadways. Long lasting surfaces with a service life of 35 years must be incorporated into such improvements.

During these studies both rural and urban roadway sections were reviewed. Presently, the DOT designs concrete pavements based on the 20 year traffic projections using the semi-tractor trailer components of the estimated heavy commercial traffic. The review indicated that on the average concrete pavements in Minnesota have performed at a satisfactory level of service for 35 years. From 1966 through 1968 Minnesota constructed some roadways using the continuously reinforced concrete pavement (CRCP). Experience has found that in this climate approximately 20% of the inplace CRCP has ruptured steel and/or bridge deck type spalling. These particular roadways will necessitate reconstruction or rehabilitation earlier than the 35 year projected service life.

The original Task Force also reviewed the 40' panel concrete pavements that were constructed in the late 1950's through 1967. Some of these roadways have an abnormally high maintenance level due to the intrusion of incompressibles in the joints. This was caused by the unsatisfactory performance of the joint seal material, midpanel cracks, and joint spalling. Another problem with the 40' panel pavements was the premature failure caused by "D" cracking, a phenomenon that has been traced to the aggregate used and consequently, its use has been prohibited by specification changes on all future projects. Many miles of this 40' concrete panel pavements are now 20 years old and are still carrying heavy traffic volumes. The Department, in analyzing the problems with the 40' panels, re-designed the pavement and now uses 27' skewed joint spacings on reinforced concrete pavement or the 15 foot effective panel spacing (13', 16', 14', 17') on plain concrete pavement. The 27' skewed joint spacing has been used in Minnesota since 1970 with no apparent design or performance problems to date. We have every reason to believe that these will perform satisfactorily for the 35 year service life.

The present design of flexible pavements in Minnesota is based on the summation of equivalent 18,000 pound axle load repetitions based on 20 year traffic volume projections and soil support values ("R-Values") as provided in the Departments Road Design Manual. This design does not differentiate between urban and rural traffic volumes. However, this study indicated that there is a difference between rural and urban flexible pavement longevity. Of the five trunk highway flexible pavement sections investigated in the urban area it was concluded that the design provides structural integrity but that the wearing surface has deteriorated or is deteriorating to a level that would require some type of rehabilitation at the 12th year. For this reason, a plant mix seal coat should be included in the surface determination formula and should be provided in the 12th year. This would restore the design cross section, rideability, repair surface irregularities, and restore skid resistance. At the 20th year an overlay or removal and replacement of a portion of the surface thickness should be provided based upon future projected traffic volumes; this should be included in the surface determination formula. Present practice indicates that we use an arbitrary leveling and surface wearing course; the advantages of designing the overlay would be to provide an overlay thickness commensurate with the traffic volume. It also will eliminate another thin overlay or plant mix seal coat prior to the end of the 35 year service life. Therefore, it is recommended that in urban areas and in any other area where projected traffic volumes exceed 10,000 AADT in the design lane, that the formula should incorporate the plant mix seal coat at the 12th year and a designed overlay at the 20th year. On other roadways with less than a projected design lane traffic volume of 10,000 ADT, the 20th year design life is appropriate for both urban and rural roadway.

A valid road cost comparison between alternatives should relate all increments for alternate designs assuming equal traffic service and service life. Somewhat over-simplified, this would basically include purchase of right of way, initial construction cost, maintenance expense, further supplemental work, and engineering overhead required to keep the road serviceable for a given number of years. For purposes of comparison the unit of measurement adopted for road life economic studies is the average annual road cost per mile. The annual cost of the road may be expressed as the total yearly expenditure that is necessary to construct, replace, and maintain in serviceable condition any existing road under existing traffic and climatic conditions. However, it is the practice of pavement selection procedures to consider only those costs associated with the base, surfacing and shoulder elements. Other costs such as right of way, grading and appurtenances are considered non-influencing as far as the pavement selection procedure is concerned. They are considered equal for the different alternatives.

B. Economic Factors

This portion of the report will be concerned with the economic model to be used for pavement selection and the interest and inflation factors as they apply to the analysis.

The economic model relates all increments of costs for alternate designs assuming equal traffic service and equal service life. For purposes of comparison of the alternates, the unit of measurement adopted is the average annual road cost per mile. This may be expressed as the total yearly expenditure that will construct, replace and maintain in standard serviceable condition any exsiting road under existing traffic and climatic conditions. For simplification, it is the practice in the pavement selection procedure to consider only those costs associated with the base, surfacing and shoulder elements. Right of way costs, grading and appurtenances are considered non-influencing as far as the pavement selection procedure is concerned.

The interest rate is often defined as the money paid for the use of money borrowed. In economic analysis, interest is also defined as the minimum attractive return on an investment. The report "A Critical Review of the Pavement Selection Process"(1) prepared in 1977 by the Research and Standards Section, quotes Clarkson H. Oglesby(2) who refers to both of these practices being used in establishing the interest rate of highway economic studies. It is necessary in economic analysis to base consideration of alternatives which have different costs in different time periods to an equal base. The equal base is either the present worth of the alternative for the equal period time or the annual cost of each alternative for a given interest rate.

Highway capital improvement projects are financed almost entirely from tax dollars. Inherent in public works programs is the concept that these tax dollars are spent effectively and that benefits will accrue to the taxpayer which are equal to or greater than the cost of the programs. When funds are collected in the form of taxes for public works programs, an opportunity for the tax payer to use these funds for other purposes is foregone. The value of these foregone opportunities creates the opportunity rate for the minimum attractive rate of return on an investment from the taxpayer's viewpoint.

In establishing the opportunity rate which the individual taxpayer could expect, it is possible to consider a rather wide range of interest rates. The amounts of money available annually to an individual taxpayer, if taxes for highways were not collected, are relatively small. The risk involved in any investment he might make should be relatively small in keeping with the low risk assumed for any highway improvement failing to be cost effective. In theory, the taxpayer would have the option of placing the uncollected taxes in a savings account, of making additional payments on his home mortgage, of buying certificates of deposit, or any number of other uses which could yield varying amounts of interest up to 18 percent which may be charged for time purchases.

The actual rate of interest, also referred to as a discount rate in economic analysis, applied to future costs in arriving at an equivalent cost base for alternates can be quite significant if the future costs anticipated for the several alternates are quite different. The use of a relatively high interest factor favors the selection of the alternate with the lower initial cost even though future expenditures throughout the maintained life of the facility may be considerably higher than those for the higher initial cost alternates. Conversely, the absence of an interest factor, or the use of an unrealistically low interest factor in the analysis will tend to result in the selection of the more capital intensive alternate based on first cost. The sensitivity of the analysis model to the interest factor used can only be determined after all elements of annual cost have been established.

The December, 1978, Mn/DOT report, "Pavement Selection Method" recommended that the interest for the economic analysis for pavement type determination be ". . .equal to one percentage point less than the current index for long term U.S. Government Bonds. . .". It also recommended that ". . .a separate inflation factor not be incorporated into the analysis. . .". Most of the justification for these recommendations were obtained from Professor Huber and are included on Pages 23-30 of the 1978 report.

In May, 1978, Professor Huber made a presentation to the Pavement Selection Task Force during which he cited several reasons for not using an inflation factor in determining deferred costs during the economic analysis for pavement selection.

Basically, these reasons were taken from a paper presented at the 1965 HRB meeting by Lee and Grant[5] and can be summarized as follows:

1. Long term inflation is difficult to forecast.

2. The Federal Government is committed to price stabilization.

3. Future revenues to pay for future expenses will likewise be inflated.

In their presentation, Lee and Grant further suggested that a long-term rate of inflation of "2 percent per year" was a "reasonable figure". As inflation rates over the past several years have been considerable greater than the 2 percent figure, the Task Force feels it is appropriate to reconsider the recommendations on inflation and interest.

Recently, Professor Huber and the Task Force further researched the issue and found several important references[6, 7, 10, 11], that were not considered in 1978. These recent works suggest the need for considering an inflation factor in engineering economic analyses if "market interest rates" are used. The interest actually charged is commonly called the "market interest rate".

Recent literature[6], however, suggests a method of taking the rate of inflation into account, without forecasting what it is going to be. This method recognizes that the market interest rate is made up of the anticipated rise in prices (inflation) plus an amount to add a real increase in the purchasing power of the investment. As an example: Assume a friend asks to borrow $100 for one year. You agree, but want to be compensated for not having the use of the $100 for the coming year. You decide that you will charge an interest rate that, one year from now, will enable you to buy $104 worth of goods in today's dollars. That rate would be 4 percent if prices do not rise. However, suppose you anticipate prices to rise 6 percent due to inflation during the year. Then to ensure that you can buy $104 worth of goods (which would cost $104 x 1.06 = $110) you must adjust the interest rate to account for the expected inflation. You would have to charge 4% + 6% = 10% interest.*

The interest rate actually charged (10% in the example) is commonly called the "market interest rate". The percentage real increase in purchasing power (4 percent in the example) is referred to as the "real interest rate", the "real cost of capital" or the "real cost of money". The percentage increase in prices is the "inflation rate". The "real interest rate" is nominally equal to the "market interest rate" minus the "inflation rate".

AASHTO, in a 1977 report entitled, A Manual on User Benefits Analysis of Highway and Bus Transit Improvement[6] recommends using the real cost of money in economic analysis. That report states:

*The actual rate would be (.04 x .06) + .10 = .1024 (10.24%). The less accurate formula is used to simplify the example.

"...the common practice of calculating benefits in constant dollars* (usually at prices prevailing when the economic study is made) and discounting benefits at market rates of interest is in error, because the market or nominal rate of return includes (1) an allowance for expected inflation, as well as, (2) a return that represents the real cost of capital. Thus if future benefits or costs are in constant dollars, only the real cost of capital should be represented in the discount rate used."

Cassidy and Shirra[7] support the above reasoning by stating that current and not inflated costs should be used "...provided that the real cost of money is used in the analysis..."

They further state that the real cost of money is a function of the "riskiness" of the investment and "the inflation adjustment is the investor's expectations as to the long term outlook for inflation."

"If the investor's expectation for inflation was always accurate, then the real cost of money should be virtually constant for investments of the same riskiness. However, because estimates of future inflation are not always accurate, the real cost of money does in fact, vary somewhat. Fortunately, this variation appears to be relatively small over the long term.[8]

Economics textbooks[8] and recent engineering reports[6, 7, 8, 11] suggest that it is justifiable to use a constant "real interest rate" for economic analyses of investments of a given and constant risk. Pavement surfacing is undoubtedly such an investment. What that interest rate should be is discussed in several references.

Hirshleifer and Shapiro[10] state that "...the anticipated real rate of return that enters into investor's calculations has remained in the neighborhood of 4 percent." AASHTO[6] states "...a rate of about 4 to 5 percent seems appropriate for projects of average risk evaluated in constant dollars." Professor Huber[12] likewise recommends 4 to 5 percent.

*AASHTO[6] states that "Constant dollars refers to an expression of costs stated at price levels prevailing at a particular constant date in time..." Mn/DOT's economic analysis for pavement selection is done in constant dollars.

The Task Force, therefore, recommends that the Interest Rate used in the economic formula for pavement selection be the "real interest rate" of 4.5 percent, and that future costs be expressed in constant dollars, that is, those prices prevailing at the time of the economic study.

Eugene L. Grant[3] in his discussion of forecasting change in general price levels for economic studies indicates that a deterrent to making long range forecasts of price level changes is the evident fact that good long-run forecasts have been realtively rare in the past. He also indicates that short-run forecasts of price level changes often are made with considerable confidence and with considerable success. This would support the use of a price level forecast for short range capital improvement programs but discourage their use in long range economic studies.

Inflation affects the entire economic structure so that in general, inflated revenues are available to pay inflated costs of future work. Road user revenues at the present time are only partially responsive to the effects of inflation. Motor vehicle license fees for automobiles are based on the price of the vehicle. Gasoline taxes, however, are levied at a fixed rate per gallon, which if not adjusted periodically, are not responsive to inflation. It has been the experience in Minnesota that the legislature has taken action periodically to adjust revenues by increasing the tax rate per gallon of gasoline and to a degree revenues have increased although at a much slower rate than the rate of inflation over the past several years. Predictions of what actions the legislature might take to provide revenues to compensate for the effects of inflation in the future are not possible, however, it is assumed that presented with proper documentation of needs, the legislature will act in a responsible manner and make revenues available.

Professor Huber, in his presentation to the Pavement Selection Task Force, refers to Highway Research Record No. 100 and to Robley Winfrey, a recognized authority on economic analysis, in support of his contention that a separate inflation factor should not enter into the calculation of costs.

R. H. Baldock[4] in listing factors as being necessary inputs to the annual cost of highways ignores inflation as a factor.

In summary, reliable forecasts of future price changes over long periods of time are not available and incorrect assumptions can result in erroneous decisions. Also, there is the general tendency of inflationary forces to affect revenues as well as costs resulting in a diminishing of the impact of inflation on deferred costs. If future price changes due to material shortages or technological changes can be identified they should be considered separately from inflation.

It is the recommendation of this Task Force that a separate inflation factor not be incorporated into the economic analysis for pavement type determination in as much as it is reflected to a great extent in the use of the recommended "real interest" rate.

C. Design Factors

The economic model to be used to determine the cost per mile of the different current designs for roadways represents the relative difference in the cost of the alternative designs. Since alternative pavement types require different initial designs and different interim treatments during the projected service life, it is necessary to determine these costs in a way that keeps the annual cost comparable. The means to do this is to identify the annual cost of the initial investment and to combine that with the incremental costs necessary for each alternative throughout the service life of the project. The pavement selection policy as outlined in the attached Mn/DOT Policy and Procedure requires the Department to develop comparable designs for rigid and flexible pavement types. These designs are developed using appropriate soils data, traffic data and aggregate data and are in conformance with the standard designs and procedures found in the Road Design Manual. This procedure insures the comparison of pavement structures designed having a similar service life. It is the policy of the Department to use only current standard pavement designs during the pavement selection process. This is necessary to provide assurance that the pavement structures being considered as alternatives are comparable from a performance and service life concept.

Currently, Mn/DOT is considering several new designs and design procedures. Some of these include:

1. Partial or full concrete shoulders which could result in a reduction of the design thickness of the concrete mainline.

2. A change in the design of bituminous shoulders which would result in increased shoulder thickness adjacent to concrete and full depth bituminous pavement on poor soils.

3. Increasing concrete pavement thickness to enable the elimination of dowels and reinforcing.

Any of these proposed changes would have a significant affect on pavement selection. However, before they can be considered, they, along with any other proposed changes, will have to pass vigorous testing and evaluation by our Materials Engineering and Research and Development Offices and be approved by the staff as a standard. Until any proposal is approved as a standard it should not be considered in the development of new pavement designs for the pavement selection process.

1. Rigid Pavements

The estimated service life for rigid pavements is 35 years. The standard design of the concrete pavement that is presently being used will be considered in this economic model[13]. There are two different joint designs that are currently being used for the concrete alternate. Details for these designs are contained in Mn/DOT's Standard Plates Manual and also on Standard Plan Sheets.

a. Roads that have concrete mainline and bituminous shoulders with 27' joint spacing. This pavement reinforced, has dowels, and skew joints. This is presently called Design "A".

b. Roads that have concrete mainline and bituminous shoulders with 15.0' effective spacing (13', 16', 14', 17'). This pavement is non-reinforced, without dowels, and has skewed joints. This is Design "B".

Both of these concrete pavement designs require the transverse joints to be resealed at 17-1/2 years; they also require the placing of a two-foot-wide bituminous shoulder wedge next to the pavement at 5 years on both sides of 2-lane, 2-way and on the outside only of multiple lane roadways.

2. Flexible Pavements

The estimated service life for flexible pavements is 35 years. The two basic designs are:

a. Roads that have a gravel base and a bituminous surface[14].

b. Roads that have a bituminous base and a bituminous surface[14].

Both of these designs require additional overlays to extend the design life of 20 years to a service life of 35 years. These overlays will be included in the economic model.

The schedule for the overlays is as follows:

a. On roadways that have a projected 20 year design lane traffic of 10,000 AADT or more, a 3/4" plant mix seal coat will be placed at the 12th year and an overlay designed for traffic conditions forecasted for the period of the 20th year through the 35th year will be placed at the 20 year.

b. On roadways that have a projected 20 year design lane traffic of less than 10,000 AADT an overlay designed for the traffic conditions forecasted for the period of the 20th year through the 35th year will be placed at the 20th year.

c. Bituminous shoulders shall be overlayed at the same time as the roadway and should be compatible with the mainline roadway thickness.

D. Timing of Surface Selection

The timing of the surface selection, though not a factor in the economic formula, could have an influence on the outcome of the pavement selection process in times of rapidly changing prices for one or both types of cementing materials used for roadway surfaces. This is one of the six items included in the 1981-82 Task Force's review and investigation of factors that influence the results obtained with the Department's pavement selection method.

The present policy of the Department of Transportation is to select the pavement surface type to be used on a project prior to the completion of the Design Study Report. This action is identified in the Department's project development process flow charts for Moderate and Major level projects as occurring approximately 18 months prior to contract letting.

The Federal Highway Administration's (FHWA) design approval is based on the Design Study Report; design approval by the FHWA is necessary to get Federal authorization (in most cases) to proceed with making direct purchase offers for any new right-of-way necessary for the project. Direct purchase offers are then made approximately 1-1/2 years in advance of the proposed contract letting; this time frame can be critical whenever the purchases require relocations.

The Task Force, based on its analysis of the project development process, recommends that the Department's current policy should be continued and that the pavement selection element of the development process remain as is presently indicated on the project development flow charts; approximately 18 months prior to the projects scheduled construction letting.

E. Alternate Bids

The Department has had discussions with both the industry and contractor representatives concerning the use of alternate bids for the surface types used in Minnesota in lieu of its present policy of pre-determining the surface type at a point in the project development process. The use of alternate bids on acceptable alternate surface types has been promoted by some factions as providing possible economic benefit to the Deparment.

The Department's present pavement selection policy and procedure evaluates three basic designs: portland cement concrete pavement, full-depth bituminous pavement and bituminous pavement with aggregate base. Estimates are prepared for each of the three basic designs using either entirely virgin aggregates and/or recycled bituminous or concrete from the existing roadway surface and surfaced shoulders (plus any virgin aggregates necessary to obtain the product desired). This in effect, on most projects, provides six alternates to be considered in arriving at the lowest annual cost for the surfacing based on a life cycle analysis. Additionally, there are acceptable alternates for shoulder surfacing with each of the different base and surface designs.

The three basic designs have different thicknesses of base and surface structure which affect the grading quantities, structure elevations and right of way requirements. In investigating various ways to prepare alternate plans, it appears that only completely separate designs would give true competitive cost bids for each of the three basic alternates; this could provide up to six different bids to consider if recycled materials are also considered.

Our present pavement selection procedure also recognizes that additional work on the pavement surface is required during the planned 35 year pavement life; because the cost of this future work is not the same for the alternate surface types, this cost differential would have to be considered in determining the low bid on a life cycle basis. However, FHWA policy[15, 16] does not permit the use of adjustment facaors for the cost differences of future work in the determination of the low bidder.

Another approach to the alternate bid question that was investigated by the Task Force was to prepare alternate plans, make the surface selection just prior to preparing the PS & E package, prepare the PS & E package for FHWA approvals of the plans for the surface type selected. This approach would permit using unit prices for the selection that would be approximately 5 months old rather than 18 months old under the Department's present system. However, this would require two sets of plans which would increase design costs from 20 to 60 percent depending on the type of project. While the design costs are a minor part of the total project cost, the increased design costs in terms of man-hours is significant; we could not absorb this additional workload with our currently approved design staff.

The Task Force feels that the Departments present policy of predetermining the surface type to be used 12 to 18 months in advance of the letting date by an economic and engineering analysis based on 35-year life cycle costs is a valid approach.

F. Salvage Value

With the increased emphasis on conservation of materials and the development of methods to re-utilize the materials contained in our roadway surfaces and surfaced shoulder, it was suggested that further consideration be made of including some means of incorporating salvage value in the pavement selection process. However, the value of these materials at the end of the roads planned, useful service life (35 years) remains quite conjectural at this time depending on assumptions and/or factors both known and unknown at the time of the pavement determination. Several of these are:

* The road's condition or usefulness at the end of 35 years.
* Can the present roadway materials be left inplace with minor corrective action(s) taken to prolong their useful life, or must they be removed and recycled or discarded?
* What materials, technologies, and/or equipment will be available in 35 years to re-utilize or prolong the utility of the materials in the existing facility?
* Will the road in its present form be needed to continue to provide for vehicular transportation?

The Task Force recognizes that there will be a residual value of the roadway structure and the materials contained therein; however, these values may be approximately equal or vary markedly depending on future decisions and technologies. Therefore, the Task Force is of the opinion that, because of the magnitude of the unknowns, the residual value should not be considered in the economic model used in the pavement selection process at this time.

G. Operational Maintenance

At the present time the proposed economic model[1] neglects operational maintenance costs. The assumption is made that repair costs for bituminous roadways are approximately equivalent to the repair costs for concrete roadways. Presently there is not sufficient data available in the cost accounting system to determine with good reliability if there is any difference. It is proposed that selected pavement type roadway segments be identified and monitored for operational cost experience. From these sections actual maintenance costs of individual activities necessary to maintain the prescribed levels of service can be developed for consideration for use in future determinations of pavement alternatives.

Repair of roadways in heavy traffic areas is very much a concern to the Department's maintenance personnel and to the motorists who have to use the roadway during repair operations. There are claims made by many as to the relative merits of one pavement type versus the other in terms of less exposure and hazard during routine maintenance operations. There is definitely a need to monitor this question and the Task Force recommends that data also be collected on the selected roadways to determine if this factor should be included in the economic model.

H. Other Factors

Several other factors have been studied for consideration for use in the economic model. In general the support of data presented for these other factors has been somewhat prejudiced depending on whose "experts" were used as a source of information. As the Task Force studied these other factors it was felt that their significance should be monitored through a continuing program of surveillance. This should include surveillance of the existing pavement selection procedure and also surveillance of changes in technology and materials. If it is indicated that a change should be made in the pavement selection procedure, a Task Force should be designated to research and prepare the change and submit it to the DOT staff for consideration. However, at the present time these other factors should not be included in the economic model but rather should be used as additional information for the Pavement Selection Committee.

A brief discussion of other factors is as follows:

1. Conservation of Aggregates

Deep strength asphalt and rigid pavement designs are nearly equal in amounts of aggregate required. On this basis the difference in the quantity of aggregates should not be considered in the economic model.

2. Energy Savings

The future related to energy doesn't present a clear-cut picture for making decisions on surface type. Research reports were presented to the 1978 Task Force to support points of view for both pavement types. The 1978 Task Force recommended that we continue to monitor any new developments in technology related to energy use and if it appears that there is some significant difference, the economic model should be reviewed for updating.

3. Skid Resistance

Present technology and design criteria currently provide adequate skid resistance for either surface type.

4. Noise

There are claims from both industries to support their product as having a quieter surface texture. However, research to date indicates that the texture of the surface determines the noise generated by the pavement material. Presently experiments are being conducted by Mn/DOT and by other agencies to determine surface textures that provide the maximum skid resistance and the minimum noise generation. Measured noise of vehicles traveling on various different pavement textures indicates that automobile noise varies considerably. However, heavy trucks traveling on the same various pavement textures indicate that the noise has small variations. As new heavy commercial vehicles meeting the Environmental Protection Agency's standards for engine and exhaust noise appear on our roadways, pavement texture will play an important role in reducing the total noise generation. It appears that the engine and exhaust noise for the heavy commercial vehicles is the major contributor to noise. It has also been shown that different types of road surfaces can reverse the noise level ranking when two different tires are used for the test. The economic benefits derived from noise reduction are tied to health and welfare of the people affected. In other words, annoyance with the noise is related to whatever activities are being disturbed along with the source of the noise. Noise generated by waterfalls, traffic, animals, etc., is based on the personal values as to whether it is an annoyance. At this time the 1978 Task Force did not feel that there was adequate data available to indicate that a noise factor should be involved in the economic analysis.

5. Labor Intensity

The amount of labor in a project becomes a concern if the goal is to provide jobs. There have been claims from industry that particular products provide more work for the area labor markets. This claim is not supported by data available and consequently this factor is not included in the economic model.

6. Local Preference

In the past there have been examples of local government selecting pavement type on personal preference rather than engineering economics. The limited amount of construction funds and the close scrutiny of taxpayer associations eliminate this factor as an economic consideration of pavement type.

7. "Balancing of Business"

The 1978 Task Force during their study based its decision upon the economic analysis of the pavement types available for use in Minnesota. Basically the surface type selection process is employing an economic model to determine the surface type based upon sound economic judgment and engineering expertise. The 1978 Task Force did not incorporate any factors into the process that would subsidize an industry by attempting to balance the decisions between the competing products.

8. Continuity of Roadway

Requests for certain roadway types for projects based upon the continuity of the roadway should not be considered. The economic model should be used which provides the taxpayers with the best project for the money.

9. Rideability

Rideability factors of different types of pavements were reviewed and discussed by the 1978 Task Force. There are many opinions as to the surface type providing different levels of rideability and comfort to motorists. The 1978 Task Force could not find evidence that the rideability of one particular roadway surface is inherently better than other. Therefore, rideability is not a part of the economic analysis model.

10. Driver Visibility

Many arguments have been presented that indicate visibility of certain roadways is inherently superior to others. Comments reflect the feelings of some persons that bituminous pavements have less glare during the day but are too dark at night. Conversely, comments are that concrete pavements reflect the light better at night and are susceptible to the glare of the sun during the day. It appears that this issue is more of an operational issue concerning roadway pavement markings and a design issue concerning material specifications. Therefore, this factor should not be considered in the economic analysis model.

11. Soils

The pavement design alternates take into account the subgrade soils in the design of the roadway. Soils, therefore, are accounted for in the economic model as a part of the initial cost of the roadway.

12. Engineering and Overhead Costs

Engineering and overhead costs for all of the pavement alternatives appear to be approximately equal. To determine more detailed data to validate this assumption would necessitate establishing detailed cost accounting on all projects through the design and construction phases. Currently the Department is developing a sophisticated accounting system to provide this data. Upon impelmentation of the new system, differences, if significant, will be taken into account in the economic model. However, until this type of information is available these costs are considered offsetting and will not be included in the analysis.

13. Price Fluctuations

The 1981-82 Task Force in its deliberations also reviewed the price trends and fluctuations for the two surfacing materials between 1967 and the present time. The effect of the oil shortages are clearly seen in the asphalt price index showing a quick response; however, the portland cement concrete index showed the same general trend. From this, the Task Force concluded that a specific treatment to account for price fluctuations of the two materials was not warranted to be included in the pavement selection method.

I. Economic Formulas

The foregoing factors describing inputs used to make the economic comparisons of pavement alternatives involve much study as to their relative importance in arriving at a decision. The method of annual cost formerly used by the Department failed to fully recognize the time value of money and fails to convert interim improvement expenditures to present worth as part of the "capital" worth. Present worth is merely a means for converting a future cost to current dollars on the basis that money set aside today plus interest earnings would provide the money for the future expenditure. Since alternative pavement types require different interim improvement expenditure at different points along the project life time scale to keep them serviceable, the incremental costs for each pavement type must be accumulated in a way that keeps the annual cost truly comparable. The method which best accomplishes this is the method in which the annual cost of the initial investment is combined with the present worth of future expenditures modified to fit Minnesota's concepts and assumptions. Therefore, the following equations have been developed for use in making economic comparisons of the pavement alternatives.

For Bituminous Alternates

$$C = CRF_n\ [A+(E_{b1})(PWF_{nb1}) + (E_{b2})(PWF_{nb2})]$$

For Concrete Alternate

$$C = CRF_n\ [A+(E_{c1})(PWF_{nc1}) + (E_{c2})(PWF_{nc2})]$$

Where:

- C = Comparative Annual Cost Per Mile
- CRF = Capital Recovery Factor = $\frac{r(1+r)^n}{(1+r)^n-1}$
- r = Interest Rate
- n = Analysis Period in Years (35 years)
- A = Construction Cost Per Mile
- E_{b1} = Cost Per Mile for Pavement and Shoulder Resurfacing
- E_{b2} = Cost Per Mile for Plant Mix Seal Coat (2361). This factor is included only when the 20 year design lane AADT exceeds 10,000
- E_{c1} = Cost Per Mile for Resealing Pavement Joints.
- E_{c2} = Cost Per Mile for Placing two-foot bituminous wedge.
- nb1 = Years to resurfacing (20 years).
- nb2 = Years to placement of plant mix seal. (12 years for 20 year design lane AADT exceeding 10,000. Not used for less traffic.)
- nc1 = Years to resealing transverse joints (17-1/2 years).
- nc2 = Years to placement of bituminous wedge on shoulders (5 years).
- PWF = Present Worth Factor = $\frac{1}{(1+r)^n}$

  n = nb1, nb2, nc1, or nc2

J. Pavement Selection Committee

As the Task Force, both in 1978 and in 1981-82 studied literature, listened to industry testimony, and listened to Department experts, it became very apparent that pavement selection is a very sensitive and important function of the DOT. The many factors that are inherent in pavement design and pavement function have to be identified and evaluated as to their relative economic and engineering values for each particular roadway. It also became apparent that the preciseness of present technology and the preciseness of available data added confusion to the selection process. Therefore, it is recommended that the choice not be a single individual's choice but it should be a Committee recommendation to the Assistant Commissioner, Technical Services, the Assistant Commissioner, Operations, and the Deputy Commissioner, for approval of the surface type selected.

It is recommended that the Committee shall consist of the following members:

Assistant Division Director - Engineering Development (Chairman)
Assistant Division Director - Engineering Services
Assistant Division Director - Operations
Director, Office of Engineering Standards
District Engineer (for the subject project)

These five members shall be responsible for the Department's implementation and adherence to the Pavement Selection Policies and Procedures (2-013) or its subsequent replacement (Appendix C). This directive describes in detail the Department's policy concerning pavement selection, the procedures and responsibilities involved in requesting and preparing recommendations, and specifics as to final approval and implementation of the selection. This directive also permits the Pavement Selection Committee to consider other factors in the selection process if the final road cost of any alternate submitted is within five percent of the lowest alternate. Basically the alternates within five percent based on the economic model, are considered equal. The Pavement Selection Committee then has the latitude to consider the significance of other factors as additional information in making their decision. These other factors are as follows:

Conservation of Aggregates	Construction and Maintenance Considerations
Energy Savings	Pavement Surface Continuity
Skid Resistance	Rideability
Noise Sensitivities	Driver Visibility
Labor Intensity	Engineering and Overhead Costs.

APPENDIX D

ECONOMIC TABLES

2% Interest Factors

Year Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.020	.9804	1.000	1.000	1.020	0.980
2	1.040	.9612	2.020	.4951	.5151	1.942
3	1.061	.9423	3.060	.3268	.3468	2.884
4	1.082	.9238	4.122	.2426	.2626	3.808
5	1.104	.9057	5.204	.1922	.2122	4.713
6	1.126	.8880	6.308	.1585	.1785	5.601
7	1.149	.8706	7.434	.1345	.1545	6.472
8	1.172	.8535	8.583	.1165	.1365	7.325
9	1.195	.8368	9.755	.1025	.1225	8.162
10	1.219	.8203	10.95	.0913	.1113	8.983
11	1.243	.8043	12.17	.0822	.1022	9.787
12	1.268	.7885	13.41	.0746	.0946	10.58
13	1.294	.7730	14.68	.0681	.0881	11.35
14	1.319	.7579	15.97	.0626	.0826	12.11
15	1.346	.7430	17.29	.0578	.0778	12.85
16	1.373	.7284	18.64	.0537	.0737	13.58
17	1.400	.7142	20.01	.0500	.0700	14.29
18	1.428	.7002	21.41	.0467	.0667	14.99
19	1.457	.6864	22.84	.0438	.0638	15.68
20	1.486	.6730	24.30	.0412	.0612	16.35
21	1.516	.6600	25.78	.0388	.0588	17.01
22	1.546	.6468	27.30	.0366	.0566	17.66
23	1.577	.6342	28.85	.0347	.0547	18.29
24	1.608	.6217	30.42	.0329	.0529	18.91
25	1.641	.6100	32.03	.0312	.0512	19.52
30	1.811	.5521	40.57	.0247	.0447	22.40
35	2.000	.5000	49.99	.0200	.0400	25.00
40	2.208	.4529	60.40	.0166	.0366	27.36
45	2.438	.4102	71.89	.0139	.0339	29.49
50	2.692	.3715	84.58	.0118	.0318	31.42
60	3.281	.3048	114.1	.0088	.0288	34.76
70	4.000	.2500	150.0	.0067	.0267	37.50
80	4.875	.2051	193.8	.0052	.0252	39.75
90	5.943	.1683	247.2	.0041	.0241	41.59
100	7.245	.1380	312.2	.0032	.0232	43.10

4% Interest Factors

Year Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.040	.9615	1.000	1.000	1.040	0.962
2	1.082	.9246	2.040	.4902	.5302	1.886
3	1.125	.8890	3.122	.3204	.3604	2.775
4	1.170	.8548	4.246	.2355	.2755	3.630
5	1.217	.8219	5.416	.1846	.2246	4.452
6	1.265	.7903	6.633	.1508	.1908	5.242
7	1.316	.7599	7.898	.1266	.1666	6.002
8	1.369	.7307	9.214	.1085	.1485	6.733
9	1.423	.7026	10.58	.0945	.1345	7.435
10	1.480	.6756	12.01	.0833	.1233	8.111
11	1.539	.6496	13.49	.0742	.1142	8.760
12	1.601	.6246	15.03	.0666	.1066	9.385
13	1.665	.6006	16.63	.0601	.1001	9.956
14	1.732	.5775	18.29	.0547	.0947	10.56
15	1.801	.5553	20.02	.0499	.0899	11.12
16	1.873	.5339	21.83	.0458	.0858	11.65
17	1.946	.5134	23.70	.0422	.0822	12.17
18	2.026	.4936	25.65	.0390	.0790	12.66
19	2.107	.4746	27.67	.0361	.0761	13.13
20	2.191	.4564	29.78	.0336	.0736	13.59
21	2.279	.4388	31.97	.0313	.0713	14.03
22	2.370	.4220	34.25	.0292	.0692	14.45
23	2.465	.4057	36.67	.0273	.0673	14.86
24	2.563	.3901	39.08	.0256	.0656	15.25
25	2.666	.3751	41.65	.0240	.0640	15.62
30	3.243	.0308	56.09	.0178	.0578	17.29
35	3.946	.2534	73.65	.0136	.0536	18.67
40	4.801	.2083	95.03	.0105	.0505	19.79
45	5.841	.1712	121.0	.0083	.0453	20.72
50	7.107	.1407	152.7	.0065	.0466	21.48
60	10.52	.0951	238.0	.0042	.0442	22.62
70	15.57	.0642	364.3	.0028	.0428	23.40
80	23.05	.0434	551.2	.0018	.0418	23.32
90	34.12	.0293	828.0	.0012	.0412	24.27
100	50.51	.0198	1238.	.0008	.0409	24.51

6% Interest Factors

Year Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.060	.9434	1.000	1.000	1.060	0.943
2	1.124	.8900	2.060	.4854	.5454	1.833
3	1.191	.8400	3.184	.3141	.3741	2.673
4	1.262	.7921	4.375	.2286	.2886	3.465
5	1.338	.7473	5.637	.1774	.2374	4.212
6	1.419	.7050	6.975	.1434	.2034	4.917
7	1.504	.6651	8.394	.1191	.1791	5.582
8	1.594	.6274	9.897	.1010	.1610	6.210
9	1.689	.5919	11.49	.0870	.1470	6.802
10	1.791	.5584	13.18	.0759	.1359	7.360
11	1.898	.5268	14.97	.0668	.1268	7.887
12	2.012	.4970	16.87	.0593	.1193	8.384
13	2.133	.4688	18.88	.0530	.1130	8.853
14	2.261	.4423	21.02	.0476	.1076	9.295
15	2.397	.4173	23.28	.0430	.1030	9.712
16	2.540	.3936	25.67	.0390	.0990	10.11
17	2.693	.3714	28.21	.0354	.0954	10.48
18	2.854	.3503	30.91	.0324	.0924	10.83
19	3.026	.3305	33.76	.0296	.0896	11.16
20	3.207	.3118	36.79	.0272	.0872	11.47
21	3.400	.2942	39.99	.0250	.0850	11.76
22	3.604	.2775	43.40	.0231	.0831	12.04
23	3.820	.2618	47.00	.0213	.0813	12.30
24	4.049	.2470	50.82	.0197	.0797	12.55
25	4.292	.2330	54.87	.0182	.0782	12.78
30	5.743	.1741	79.06	.0127	.0727	13.77
35	7.686	.1301	111.4	.0090	.0690	14.50
40	10.29	.0972	154.8	.0065	.0665	15.05
45	13.77	.0727	212.7	.0047	.0647	15.46
50	18.42	.0543	290.3	.0034	.0634	15.76
60	32.99	.0303	533.1	.0019	.0619	16.16
70	59.08	.0169	967.9	.0010	.0610	16.39
80	105.8	.0095	1747.	.0006	.0606	16.51
90	189.5	.0053	3141.	.0003	.0603	16.58
100	339.3	.0029	5638.	.0002	.0602	16.62

8% Interest Factors

Year Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.080	.9259	1.000	1.000	1.080	0.926
2	1.166	.8573	2.080	.4808	.5608	1.783
3	1.260	.7938	3.246	.3080	.3880	2.577
4	1.360	.7350	4.506	.2219	.3019	3.312
5	1.469	.6806	5.867	.1705	.2505	3.993
6	1.587	.6302	7.336	.1363	.2163	4.623
7	1.714	.5835	8.923	.1121	.1921	5.206
8	1.851	.5403	10.64	.0940	.1740	5.747
9	1.999	.5002	12.49	.0801	.1601	6.247
10	2.159	.4632	14.49	.0690	.1490	6.710
11	2.332	.4289	16.65	.0601	.1401	7.139
12	2.518	.3971	18.98	.0527	.1327	7.536
13	2.720	.3677	21.50	.0465	.1265	7.904
14	2.937	.3405	24.22	.0413	.1213	8.244
15	3.172	.3152	27.15	.0368	.1168	8.559
16	3.426	.2919	30.32	.0330	.1130	8.851
17	3.700	.2703	33.75	.0396	.1096	9.122
18	3.996	.2502	37.45	.0267	.1067	9.372
19	4.316	.2317	41.45	.0241	.1041	9.604
20	4.661	.2145	45.76	.0219	.1019	9.818
21	5.034	.1987	50.42	.0198	.0998	10.02
22	5.437	.1839	55.46	.0180	.0980	10.20
23	5.871	.1703	60.89	.0164	.0964	10.37
24	6.341	.1577	66.77	.0150	.0950	10.53
25	6.848	.1460	73.11	.0137	.0937	10.68
30	10.06	.0994	113.3	.0088	.0888	11.26
35	14.79	.0676	172.3	.0058	.0858	11.56
40	21.73	.0460	259.1	.0039	.0839	11.93
45	31.92	.0313	386.5	.0025	.0826	12.11
50	46.90	.0213	573.7	.0017	.0817	12.23
60	101.3	.0099	1253.	.0008	.0808	12.38
70	218.6	.0046	2720.	.0004	.0804	12.44
80	472.0	.0021	5887.	.0002	.0802	12.47
90	1019.	.0010	12724.	.0001	.0801	12.49
100	2200.	.0005	27485.	.0000	.0800	12.49

10% Interest Factors

Year Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.100	.9091	1.000	1.000	1.100	0.909
2	1.210	.8264	2.100	.4762	.5762	1.736
3	1.331	.7513	3.310	.3021	.4021	2.487
4	1.464	.6830	4.641	.2155	.3155	3.170
5	1.611	.6209	6.105	.1638	.2638	3.791
6	1.772	.5645	7.716	.1296	.2296	4.355
7	1.949	.5132	9.487	.1054	.2054	4.868
8	2.144	.4665	11.44	.0874	.1874	5.335
9	2.358	.4241	13.58	.0736	.1736	5.759
10	2.594	.3855	15.94	.0628	.1628	6.144
11	2.853	.3505	18.53	.0540	.1540	6.500
12	3.138	.3186	21.38	.0468	.1468	6.814
13	3.452	.2897	24.52	.0408	.1408	7.103
14	3.797	.2633	27.98	.0358	.1358	7.367
15	4.177	.2394	31.77	.0315	.1315	7.606
16	4.595	.2176	35.95	.0278	.1278	7.824
17	5.054	.1978	40.54	.0247	.1247	8.022
18	5.560	.1799	45.60	.0219	.1219	8.201
19	6.116	.1635	51.16	.0196	.1196	8.365
20	6.727	.1486	57.28	.0175	.1175	8.514
21	7.400	.1351	64.00	.0156	.1156	8.649
22	8.140	.1228	71.40	.0140	.1140	8.772
23	8.954	.1117	79.54	.0126	.1126	8.883
24	9.850	.1015	88.50	.0113	.1113	8.985
25	10.84	.0923	98.35	.0102	.1102	9.077
30	17.50	.0573	164.5	.0061	.1061	9.427
35	28.10	.0356	271.0	.0037	.1037	9.644
40	45.26	.0221	442.6	.0023	.1023	9.779
45	72.89	.0137	718.9	.0014	.1014	9.863
50	117.4	.0085	1164.	.0009	.1009	9.915
60	304.5	.0033	3035.	.0003	.1003	9.967
70	789.7	.0013	7887.	.0001	.1001	9.987
80	2048.	.0005	20474.	.0001	.1001	9.995
90	5313.	.0002	53120.	.0000	.1000	9.999

12% Interest Factors

YEAR Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.120	.8929	1.000	1.000	1.120	0.893
2	1.254	.7972	2.120	.4717	.5917	1.690
3	1.405	.7118	3.374	.2963	.4164	2.402
4	1.574	.6355	4.779	.2092	.3292	3.037
5	1.762	.5674	6.353	.1574	.2774	3.605
6	1.974	.5066	8.115	.1232	.2432	4.111
7	2.211	.4523	10.09	.0991	.2191	4.564
8	2.476	.4039	12.30	.0813	.2013	4.968
9	2.773	.3606	14.78	.0677	.1877	5.328
10	3.106	.3220	17.55	.0570	.1770	5.650
11	3.479	.2875	20.66	.0484	.1684	5.938
12	3.896	.2567	24.13	.0414	.1614	6.194
13	4.363	.2292	28.03	.0357	.1557	6.424
14	4.887	.2046	32.40	.0309	.1509	6.628
15	5.474	.1827	37.28	.0269	.1469	6.811
16	6.130	.1631	42.75	.0234	.1434	6.974
17	6.866	.1456	48.88	.0205	.1405	7.120
18	7.690	.1300	55.75	.0179	.1379	7.250
19	8.613	.1161	63.44	.0158	.1358	7.366
20	9.646	.1037	72.05	.0139	.1339	7.469
21	10.80	.0926	81.70	.0122	.1322	7.562
22	12.10	.0826	92.50	.0108	.1308	7.645
23	13.55	.0738	104.6	.0096	.1296	7.718
24	15.18	.0659	118.2	.0085	.1285	7.784
25	17.00	.0588	133.3	.0075	.1275	7.843
30	29.96	.0334	241.3	.0041	.1241	8.055
35	52.80	.0189	431.7	.0023	.1223	8.176
40	93.05	.0107	767.1	.0013	.1213	8.244
45	164.0	.0061	1358.	.0007	.1207	8.283
50	289.0	.0035	2400.	.0004	.1204	8.304
60	897.6	.0011	7472.	.0001	.1201	8.324
70	2788.	.0004	23223.	.0000	.1200	8.330

15% Interest Factors

Year Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.150	.8696	1.000	1.000	1.150	0.870
2	1.322	.7561	2.150	.4651	.6151	1.626
3	1.521	.6575	3.472	.2880	.4380	2.283
4	1.749	.5718	4.993	.2003	.3503	2.855
5	2.011	.4972	6.742	.1483	.2983	3.352
6	2.313	.4323	8.754	.1142	.2642	3.784
7	2.660	.3759	11.07	.0904	.2404	4.160
8	3.059	.3269	13.73	.0729	.2229	4.487
9	3.518	.2843	16.79	.0596	.2096	4.772
10	4.046	.2472	20.30	.0493	.1993	5.019
11	4.652	.2149	24.35	.0411	.1911	5.234
12	5.350	.1869	29.00	.0345	.1845	5.421
13	6.153	.1625	34.35	.0291	.1791	5.583
14	7.076	.1413	40.51	.0247	.1747	5.724
15	8.137	.1229	47.58	.0210	.1710	5.847
16	9.358	.1069	55.72	.0180	.1680	5.954
17	10.76	.0929	65.08	.0154	.1654	6.047
18	12.38	.0808	75.84	.0132	.1632	6.128
19	14.23	.0703	88.21	.0113	.1613	6.198
20	16.37	.0611	102.4	.0098	.1598	6.259
21	18.82	.0531	118.8	.0084	.1584	6.312
22	21.65	.0462	137.6	.0073	.1573	6.359
23	24.89	.0402	159.3	.0063	.1563	6.399
24	28.63	.0349	184.2	.0054	.1554	6.434
25	32.92	.0304	212.8	.0047	.1547	6.464
30	66.21	.0151	434.7	.0023	.1523	6.566
35	133.2	.0075	881.2	.0011	.1511	6.617
40	267.9	.0037	1779.	.0006	.1506	6.642
45	538.8	.0019	3585.	.0003	.1503	6.654
50	1083.	.0009	7218.	.0001	.1501	6.661
60	4384.	.0002	29219.	.0000	.1500	6.665

20% Interest Factors

YEAR Y	SCA P-F	SPW F-P	UCA A-F	USF F-A	UCR P-A	UPW A-P
1	1.200	.8333	1.000	1.000	1.200	0.833
2	1.400	.6944	2.200	.4546	.6546	1.528
3	1.728	.5787	3.640	.2747	.4747	2.106
4	2.074	.4823	5.368	.1863	.3863	2.599
5	2.488	.4019	7.442	.1344	.3344	2.991
6	2.986	.3349	9.930	.1007	.3007	3.326
7	3.583	.2791	12.92	.0774	.2774	3.605
8	4.300	.2326	16.50	.0606	.2606	3.837
9	5.160	.1938	20.80	.0481	.2481	4.031
10	6.192	.1615	25.96	.0385	.2385	4.192
11	7.430	.1346	23.15	.0311	.2311	4.327
12	8.916	.1122	39.58	.0253	.2253	4.439
13	10.70	.0935	48.50	.0206	.2206	4.533
14	12.84	.0779	59.20	.0169	.2169	4.611
15	15.41	.0650	72.04	.0139	.2139	4.675
16	18.49	.0541	87.44	.0114	.2114	4.730
17	22.19	.0451	105.9	.0094	.2094	4.775
18	26.62	.0376	128.1	.0078	.2078	4.812
19	31.95	.0313	154.7	.0065	.2065	4.843
20	38.39	.0261	186.7	.0054	.2054	4.870
21	46.01	.0217	225.0	.0044	.2044	4.891
22	55.21	.0181	271.0	.0037	.2037	4.909
23	66.25	.0151	326.2	.0031	.2031	4.925
24	79.50	.0126	392.5	.0026	.2026	4.937
25	95.40	.0105	472.0	.0021	.2021	4.948
30	237.4	.0042	1182.	.0009	.2009	4.979
35	590.7	.0017	2948.	.0003	.2003	4.992
40	1470.	.0007	7344.	.0001	.2001	4.997
45	3657.	.0003	18281.	.0001	.2001	4.999
50	9100.	.0001	45497.	.0000	.2000	4.999

APPENDIX E

COST DATA

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PRICE DATA

Data are included in this manual which define prices associated with pavement construction, reconstruction, recycling and maintenance operations. These prices are intended to be representative only and are updated prices for the year 1980 based on data given in References 23 and 55. If prices for these operations are available from local agencies' historical records or local contractors, they should be substituted appropriately because a large price variation can be expected depending on the location of the project and the time of construction.

The engineer should be aware that the term "pavement price" refers to the total amount of monies that an agency, or the public, must spend to have a pavement structure constructed, rehabilitated or maintained. Pavement price includes pavement cost, general contractor overhead and contractor profit. Pavement cost is defined as the amount of monies that a contractor must spend for labor, materials, equipment, subcontracts and overhead to construct, rehabilitate or maintain a pavement structure.

Construction Prices

Prices of common pavement construction operations are shown in Table 3. These prices are considered representative of average in-place prices in the United States. Prices are based on pavement layers in the range of 4 to 8 inches for untreated base and stabilized layers. Asphalt concrete prices are typical of 1.5 to 3 inch lifts while portland cement concrete prices are typical for pavements 8 to 10 inches in thickness. These thicknesses are typical of those found on general aviation airports and highway pavements.

Rehabilitation and Pavement Recycling Prices

Prices associated with selected rehabilitation and pavement recycling operation prices are shown in Tables 4, 5 and 6. The common rehabilitation activities of asphalt concrete overlays, chip seal costs, etc. can be found in Table 4. Recycling prices are shown in Tables 5 and 6.

Maintenance Costs

Costs associated with flexible pavement maintenance operations are shown in Table 7 and with rigid pavement maintenance operations in Table 8. Costs were obtained from the states of California, Florida, Iowa, Louisiana, Nevada, New Jersey and North Dakota and are representative of costs in 1980.

A general description for each maintenance activity has been prepared and is shown in the tables together with the average, low and high unit costs for these activities. The reported suggested costs are the author's best estimate of representative unit costs for the stated maintenance activity. The wide range of reported unit costs for this condensed list of activities is due in part to:

1. Different crew sizes utilized in the various areas
2. Different equipment requirements for various areas
3. Differences in maintenance work activity as defined by various agencies
4. Variety of traffic conditions under which maintenance is performed
5. Type of facility on which maintenance activities are performed
6. Amount of work performed per square yard or other unit of measurement

Maintenance unit cost information has been converted to costs per square yard of total pavement surface area treated (Table 9). In order to develop these costs, assumptions were made as to the thickness and extent of the area treated. Costs associated with maintenance activities of different thicknesses and extent can be calculated from Tables 7 and 8.

The summary of maintenance information contained in the previous tables is for 11 flexible and 5 rigid highway pavement activities. Costs representative of airport pavement maintenance operations are not available in summary form. As a first approximation, highway maintenance costs can be used to represent airport maintenance costs. If there is a need for determining maintenance costs for activities other than those listed in Tables 7, 8 and 9, it will be necessary to obtain data from local state, county, or city governments or contractors that perform those activities.

Airport Versus Highway Prices

Price data reported in this manual are based primarily on information obtained from highway construction projects. Highway prices and costs are readily available to the engineer in summary form. Price data for airport construction, rehabilitation, recycling and maintenance operations are not available in summary form. Bid tabulation forms from 25 reconstruction and rehabilitation projects have been obtained however, and are summarized in Tables 10 and 11. The variability in prices associated with highway and airport projects is so large when defining national average prices that, in all probability, a statistically significant difference could not be ascertained between prices for these two types of pavements (46).

PRICE UPDATING PROCEDURES

As price information is obtained from various sources at various times, it is necessary to bring these prices to a common time frame. In order to convert price figures contained in this manual to a current date, the price or cost index method is suggested. The following equation can be used.

$$C_c = C_o \left(\frac{I_c}{I_o}\right)$$

where: C_c = Current estimated cost

C_o = Cost at other time "0"

I_c = Current index number

I_o = Index number at other time "0"

The index number to use depends upon the type of cost being estimated. Four indices are commonly available and can be used.

1. The ENR Construction Cost Index (56)
2. Bid Price Trends on Federal-Aid Highway Contracts (57)
3. The ENR Equipment Price Index (56)
4. The Cost Trends on Highway Maintenance and Operations (58)

The ENR Construction Cost Index (Table 12) was designed as a general purpose construction cost index to chart basic costs with time. It is a weighted index of constant quantities of structural steel,

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portland cement, lumber and common labor, valued at $100 in 1913.

The Bid Price Trends on Federal-Aid Highway Contracts is compiled by the Federal Highway Administration as reported by state transportation agencies (Table 13). The base year for this index is 1967.

The ENR Equipment Price Index is compiled from Bureau of Labor statistics and is published periodically by Engineering News Record (for a base year of 1967).

The Cost Trends for Highway Maintenance and Operations (Table 14) are given through 1979 (the latest year available).

For price and cost data presented in this manual the following 1980 index numbers are suggested:

1. ENR Construction Cost Index (1980), I_c = 3237.
2. Highway Bid Price Trends on Federal-Aid Highway Contracts (1980), I_c = 347.9
3. Cost Trends on Highway Maintenance and Operations (1979), I_c = 239.79

Future Price Trends

The information contained in Tables 12-14 can be supplemented and used to project future price trends associated with materials used for construction, rehabilitation and maintenance. Figures 2 and 3 illustrate the rate of increase in costs since 1967 (59). The rapid increases in prices between 1973 and 1974 were a result of ending federal price controls and of the Arab oil embargo. Highway price moderations during the period 1974 to 1977 were a result of a general decrease in highway construction work (more competition for the same projects) and moderation of the general rate of inflation and crude oil prices.

It is important to realize that considerable regional and local price differences exist throughout the United States. Figure 4 illustrates the differences among the prices of asphalt concrete in Texas, Region 6 of the FHWA (Texas, Oklahoma, New Mexico, Arkansas and Louisiana) and the average price for the United States. Similar differences are noted in Figures 5-9 for common excavation, portland cement concrete pavement, reinforcing steel, structural steel and structural concrete (57).

Three primary reasons which are responsible for price increases for pavement construction, rehabilitation, recycling and maintenance activities are the prices of crude oil, asphalt cement and the cost of transportation. Figure 10 illustrates the price of imported crude oil from 1973 to present (60). (The United States presently imports about 45 percent of its crude oil.) Figure 11 shows the price increases associated with asphalt cement in Texas (61). Similar price increases are noted throughout the United States. The present posted price of asphalt cement is about 175 dollars F.O.B. refinery. Transportation cost increases closely follow the price increases associated with crude oil (Figure 12) (62).

A review of the attached cost trends indicates the following annual rates of inflation for the various items during the period 1973-1980 in the United States (see Table 1 for a more complete list).

Item or Index	Annual Rate of Inflation, Percent
Building cost index	8.0
Construction cost index	8.0
Highway bid price index	12.5
Highway maintenance cost index	8.9
Asphalt concrete	14.1
Portland cement concrete	11.5
Excavation	12.5
Mideastern crude oil	45.7
Asphalt cement	25.8
Rail transportation (Figure 11)	13.0

The expected rate of cost increases for many construction related items in the 1980 to 1981 period are expected to be approximately 15-20 percent. The expected price increases associated with consumer goods for the years 1981 to 1990 are shown in Table 15 (63).

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Table 3. Price of Common Pavement Construction Operations - 1980.

Construction Operation	Representative Price Dollars - Per Square Yard - Inch	
	Average	Range
Crushed Stone Base	0.65	0.35 - 0.85
Gravel Base	0.55	0.25 - 0.85
Lime Stabilized Subgrade	0.35	0.20 - 0.55
Cement Stabilized Subgrade	0.45	0.25 - 0.60
Cement Treated Base	1.10	0.70 - 1.60
Asphalt Treated Base	1.40	0.75 - 1.90
Lime--Fly Ash--Aggregate Base	1.00	0.65 - 1.25
Chip Seal	0.60*	0.40 - 0.90*
Asphalt Concrete	1.65	0.90 - 2.50
Portland Cement Concrete	1.85	1.00 - 2.75

*Price per square yard of surface

$1\ yd^2 = 8.361 \times 10^{-1}\ m^2$

$1\ in. = 2.54 \times 10^{-2}\ m$

Table 4. Price of Pavement Rehabilitation Operations - 1980.

Rehabilitation Operation	Approximate Thickness, Inch	Representative Price Dollars - Per Square Yard	
		Average	Range
Chip Seal Coat	1/2	0.60	0.40 - 0.90
Fabric Interlayers	1/4	1.20	0.75 - 1.75
Asphalt-Rubber Interlayer	1/2	1.25	0.90 - 1.50
Open Graded Friction Course	5/8	1.50	1.00 - 2.50
Asphalt Concrete (Dense Graded)	1	1.65	0.90 - 2.50
Asphalt Concrete (Dense Graded)	2	3.15	1.80 - 4.75
Asphalt Concrete (Dense Graded)	3	4.75	2.60 - 7.00

$1\ yd^2 = 8.361 \times 10^{-1}\ m^2$

$1\ in. = 2.54 \times 10^{-2}\ m$

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Table 5. Price of Common Recycling Operations - 1980.

Recycling Operation	Representative Price Dollars - Per Square Yard - Inch*	
	Average	Range
Heat and Plane Pavement - 3/4 inch depth	0.40	0.20 - 0.70
Heat and Scarify Pavement - 3/4 inch depth	0.50	0.20 - 0.90
Cold Mill Pavement	0.85	0.30 - 1.25
Rip, Pulverize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.30	0.20 - 0.50
Rip, Pulverize, Stabilize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.50	0.25 - 0.70
Rip, Pulverize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.35	0.15 - 0.50
Rip, Pulverize, Stabilize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.55	0.30 - 1.00
Remove and Crush Portland Cement Concrete	0.70	0.40 1.10
Remove and Crush Asphalt Concrete	0.50	0.25 1.00
Cold Process - Remove, Crush, Place, Compact, Traffic Control - (Cold Process) without Stabilizer	0.55	0.30 - 0.90
Cold Process - Remove, Crush, Mix, Place Compact, Traffic Control - (Cold Process) with Stabilizer	0.65	0.40 1.00
Hot Process - Remove, Crush, Place Compact. Traffic Control - without Stabilizer	0.80	0.50 - 1.40
Hot Process - Remove, Crush, Mix, Place Compact, Traffic Control - with Stabilizer	1.10	0.75 - 1.65

*Costs are for a square yard inch except where listed.

1 yd = 8.361×10^{-1} m^2 1 in. = 2.54×10^{-2} m

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Table 6. Representative Price for Asphalt Pavement Recycling Operations - 1980.

Type	Operation	Option or Expected Results		Representative Price Per Square Yard		Assumptions
				Average	Range	
A. Surface	Heater Planer	Without additional aggregate	A1	0.40	0.35 - 0.90	Heat, plane, clean-up, haul, traffic control.
		With additional aggregate	A2	0.55	0.30 - 0.80	Spread aggregate, heat, roll, traffic control and clean-up.
	Heater Scarify	Heater scarify only	A3	0.40	0.25 - 0.90	Heat, scarify, recompact, traffic control (3/4 inch scarification).
		Heater scarify plus thin overlay of asphalt concrete	A4	1.25	0.80 - 1.50	Heat, scarify, recompact, add 50 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
		Heater scarify plus chip seal or slurry seal	A5	1.00	0.60 - 1.50	Heat, scarify, recompact, place slurry seal or chip seal and traffic control (3/4 inch scarification).
		Heater scarify plus thick overlay	A6	5.00	3.00 - 6.50	Heat, scarify, recompact, add 300 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
	Surface Milling or Grinding	Surface milling only	A7	0.85	0.30 - 1.50	Milling, cleaning, hauling, traffic control (one inch removal).
		Surface milling plus thin overlay	A8	4.00	2.50 - 5.00	Milling, cleaning, hauling, 200 lbs. of asphalt concrete, traffic control (one inch removal).
		Surface milling plus thick overlay	A9	6.85	4.25 - 8.00	Milling, cleaning, hauling, 400 lbs. of asphalt concrete, traffic control (one inch removal).
B. In-Place	Asphalt Concrete Surface Less Than 5 Inches	Minor structural improvement without new binder	B1	4.40	2.50 - 6.00	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B2	3.65	2.10 - 4.10	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement	B3	8.10	5.00 - 10.00	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B4	6.25	4.00 - 8.00	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement without new binder	B5	3.50	2.50 - 4.50	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B6	3.80	2.50 - 4.75	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	B7	6.25	5.00 - 7.50	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B8	6.40	5.00 - 7.50	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.
C. Central Plant	Cold Mix Process	Minor structural improvement without new binder	C1	4.60	4.00 - 5.25	Remove, crush and replace to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C2	3.90	2.75 - 5.00	Remove, crush, mix and replace to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C3	8.00	6.00 - 10.00	Remove, crush and replace to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C4	6.50	5.00 - 8.00	Remove, crush, mix and replace to 6 inch depth with 2 inches of asphalt concrete, traffic control.
	Hot Mix Process	Minor structural improvement without new binder	C5	6.25	5.00 - 8.00	Remove, crush and replace to 4 inch depth with 1.5 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C6	6.20	5.00 - 8.00	Remove, crush, mix and replace to 4 inch depth with 1/2 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C7	8.75	7.00 - 10.00	Remove, crush and replace to 6 inch depth with 3 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C8	10.00	8.00 - 12.00	Remove, crush, mix and replace to 6 inch depth with 1 inch of asphalt concrete.

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Table 7. Unit Costs for Flexible Pavement Maintenance Operations - 1980.

Descriptive Title	General Description	State	Activity No.*	Reported Average Unit Cost, Dollars	Suggested Cost, Dollars				Adjusted Average Unit Cost, Dollars
					Average	Low	High	Unit Measured	
Fog Seal - Full Width	Light application of diluted emulsion or a proprietary material over a full lane width in a continuous section.	CAL	01-983	126.35/ton					0.063/yd^2
		NEV	101.06	0.08/yd^2	0.12	0.06	0.21	yd^2	0.08/yd^2
		ND	435	0.21/yd^2					0.21/yd^2
Chip Seal - Partial Width	Application of asphalt and cover aggregate to a limited area.	CAL	01-050	36.15/ton					0.45/yd^2
		CAL	01-051	46.41/ton					0.57/yd^2
		CAL	01-052	48.93/ton					0.61/yd^2
		CAL	01-053	47.73/ton	0.47	0.24	1.91	yd^2	0.59/yd^2
		CAL	01-083	153.98/ton					1.91/yd^2
		LA	411	48.86/yd^2					0.41/yd^2
		NEV	101.04	0.24/yd^2					0.24/yd^2
		ND	412	0.42/yd^2					0.42/yd^2
Chip Seal - Full Width	Application of asphalt and cover aggregate to a full lane width in a continuous section.	CAL	01-054	45.74/ton					0.57/yd^2
		IWA	614	0.45/yd^2					0.45/yd^2
		LA	415	3179/mile	0.40	0.23	0.57	yd^2	0.23/yd^2
		NEV	101.09	0.31/yd^2					0.31/yd^2
		ND	422	0.44/yd^2					0.44/yd^2
Surface Patch Hand Method, Pothole Type	Application of a Premix to fill small depressions.	CAL	01-131	142.59/ton					269.50/yd^3
		FLA	411	181.67/ton	250.00	144.00	343.00	yd^3	343.35/yd^3
		LA	412	76.33/ton					144.25/yd^3
Surface Patch - Hand Method	Application of a Premix material to the surface of the pavement by hand method.	FLA	413	65.39/ton					123.60/yd^3
		LA	417	47.86/ton	150.00	90.45	295.60	yd^3	90.45/yd^3
		LA	414	54.71/ton					103.40/yd^3
		NEV	101.02	156.39/yd^3					295.60/yd^3
Surface Patch - Machine Method	Application of a Premix material to the surface of the pavement with machine.	CAL	01-021	49.16/ton					92.90/yd^3
		CAL	01-022	34.97/ton					66.10/yd^3
		CAL	01-023	23.41/ton					44.25/yd^3
		CAL	01-024	30.20/ton					57.10/yd^3
		CAL	01-025	29.16/ton					55.10/yd^3
		FLA	412	60.48/ton	60.00	30.27	114.30	yd^3	114.30/yd^3
		IA	611	20/05/ton					37.90/yd^3
		LA	416	32.82/ton					62.00/yd^2
		NEV	101.03	30.27/yd^3					30.27/yd^3
		NJ	071	25.25/ton					47.70/yd^3
		ND	421	35.28/yd^3					35.28/yd^3
Digout and Repair - Hand Method	Removal and repair of limited areas by use of hand tools.	CAL	01-034	130.75/ton					238.30/yd^3
		FLA	414	60.11/ton	160.00	109.55	238.30	yd^3	109.50/yd^3
		ND	411	127.52/yd^3					127.62/yd^3
Digout and Repair - Machine Method	Removal and repair of limited areas by use of mechanized equipment.	CAL	01-111	44.94/ton					81.90/yd^3
		CAL	01-012	40.81/ton					74.40/yd^3
		FLA	414	60.11/ton					109.55/yd^3
		LA	413	31.41/yd^3	90.00	26.11	151.05	yd^3	31.41/yd^3
		NEV	101.01	26.11/yd^3					26.11/yd^3
		NJ	066	77.41/ton					141.10/yd^3
		NJ	067	82.89/ton					151.05/yd^3
Crack Pouring	Pouring cracks in flexible pavement with asphalt material (may include cleaning with compressed air and covering with sand.	CAL	01-041	6.71/gal					6.71/gal
		CAL	01-042	10.03/gal	6.25	2.37	10.03	gal	10.03/gal
		NEV	101.07	0.73/lb					6.10/gal
		NJ	068	314.91/ln mi					6.00/gal
		ND	414	2.37/gal					2.37/gal
Slurry Seal	Sealing the roadway with a mixture of emulsion, cement and aggregate and placed by machine.	IA	617	0.24/yd^3	0.25			yd^2	0.24/yd^2
Heater Planing	Heating and planing the surface to remove bumps, ripples, wheel ruts, etc.	IA	619	0.90/yd^2					0.90/yd^2
		LA	418	34.60 each	0.70	0.28	0.90	yd^2	0.85/yd^2
		NEV	111.08	0.28/yd^2					0.28/yd^2

*A number which defines the maintenance operation and used in the states' maintenance management system.

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Table 8. Unit Costs for Rigid Pavement Maintenance Operations - 1980.

Descriptive Title	General Description	State	Activity No.*	Reported Average Unit Cost, Dollars	Suggested Cost, Dollars: Average	Low	High	Unit Measured	Adjusted Average Unit Cost, Dollars
Mudjacking	Drilling holes and pumping concrete slurry under slab to fill the voids and raise the slab to grade.	CAL	02-011	370.50/yd^2					370.50/yd^2
		FLA	421	256.13/Slab	6.00	4.00	370.60	yd^2	8.70/yd^2
		FLA	422	144/ft^3					-
		IA	621	82.23/yd^3					
		NJ	074	117.73/Slab					4.00/yd^2
Temporary Patching	Patch with bituminous material	CAL	02-021	172.26/ton					325.55/yd^3
		CAL	02-022	38.23/ton	180.00	72.25	325.55	yd^3	72.25/yd^3
		IA	609	126.77/ton					238.60/yd^3
		IA	610	78.72/ton					148.00/yd^3
		NEV	111.01	123.44/yd^3					123.45/yd^3
Permanent Patching	Patch with P.C.C.	IA	613	33.54/yd^2					123.15/yd^3
		NEV	111.02	402.24/yd^3	270.00	134.15	402.24	yd^3	402.24/yd^3
Joint Sealing	Cleaning joint, pour joint and apply sand as required.	CAL	02-042	7.91/gal					7.91/gal
		CAL	02-043	6.50/gal					6.50/gal
		FLA	423	318.00/mile	7.50	3.06	12.40	gal	-
		IA	612	3.06/gal					3.06/gal
		NEV	111.05	1.49/lb					12.40/gal
		NJ	070	187.61/unit					
Expansion Joint Repair	Cut along distresses area, clean out area, place filler material.	NEV	111.06	23.91/lin ft	24.00			lin ft	23.91/lin ft

*A number which defines the maintenance operation and used in the states' maintenance management system.

Table 9. Representative Costs for Flexible Pavement Maintenance and Rehabilitation Activities - 1980.

Maintenance Activity	Cost Dollars* Per Square Yard	Cost Dollars* Per Lane Mile	Cost Dollars Per Square Yard of Maintenance Performed	Total Pavement Area Treated
Fog Seal - Partial Width	0.09	640	0.18	50 percent
Fog Seal Full Width	0.12	845	0.12	100 percent
Chip Seal - Partial Width	0.07	500	0.47	15 percent
Chip Seal - Full Width	0.40	2,820	0.40	100 percent
Surface Patch - Hand Method Pothole Type	0.14	1,000	13.90	100 percent 2 inch thick
Surface Patch - Hand Method	0.10	730	4.20	2.5 percent 1 inch thick
Surface Patch - Machine Method	0.17	1,170	1.70	10 percent 1 inch thick
Digout and Repair - Hand Method	0.36	2,500	17.80	2 percent 4 miles thick
Digout and Repair - Machine Method	0.75	5,280	15.00	5 percent 6 inch thick
Crack Pouring	0.23	1,630	-	250 lin ft per station

*Costs are for square yards of total pavement surface maintained. For example surface patching by the hand method may have been applied over only 5 percent of total pavement surface area, yet costs reported are for the total pavement.

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Table 10. 1980 Bid Prices on FAA Projects.

Item	Description	Location*	Unit	Quantity	Unit Price, $
P-151	Removal of AC Pavement	West-O	yd^2	111,940	0.50
	Removal of PCC Pavement	West-O	yd^2	46,060	1.90
	Removal of Pavements	West-O	yd^2	24,100	0.35
	Removal of AC Pavement	West-M	yd^2	19,300	1.00
	Removal of AC Pavement	West-S	yd^2	4,300	4.60
	Demolition of PCC Pavement	South-D	yd^2	14,500	3.00
	Demolition of AC Pavement	South-D	yd^2	16,500	1.00
	Removal of PCC Pavement	South-J	yd^2	24,000	7.50
	Removal of Existing Pavement	East-W	yd^2	2,236	4.00
	Removal of 8"Non-Reinforced PCC	West-D	yd^2	7,526	5.00
	Removal of PCC Pavement	West-P	yd^2	4,681	5.40
	Removal of AC Pavement	West-P	yd^2	954	2.00
	Removal of Pavement	West-PO	yd^2	3,860	4.75
P-152	Unclassified Excavation	West-O	yd^3	565,000	1.80
	Unclassified Excavation	South-T	yd^3	77,500	2.05
	Pavement and Base Removal - 3" and 8"	South-P	yd^2	250	8.00
P-154	Subbase Course	West-O	yd^3	8,000	3.30
	Work Platform - 8" Limerock	South-D	yd^2	125,340	1.72
P-155	Lime Treated Subgrade - 6"	West-G	yd^2	35,400	2.47
	Lime Treated Subgrade - 6"	West-D	yd^2	8,063	2.72
	Lime Treated Subgrade - 18"	West-D	yd^2	4,484	5.70
P-150	Pavement Milling 0-1.5"	South-M	yd^2	4,200	3.00
	Pavement Milling 0-1.5"	South-M	yd^2	800	14.00
	Pavement Milling 0-1.5"	South-SA	yd^2	13,542	2.50
	Pavement Milling	West-N	yd^3	6,443	17.00
	Pavement Pulverization	West-O	yd^2	48,000	0.80
	Pavement Pulverization	West-OA	yd^2	51,000	1.25

Item	Description	Location*	Unit	Quantity	Unit Price, $
P-201	Bituminous Base Course - Aggregate	South-M	Ton	1,512	38.43
	Bituminous Base Course - Sand	South-M	Ton	235	38.44
	Bituminous Base Course - Aggregate	South-M	Ton	10,205	47.08
	Bituminous Base Course - Sand	South-M	Ton	1,290	50.33
	Bituminous Base Course	South-P	Ton	13,735	29.16
	Bituminous Base Course	West-W	Ton	250	30.45
P-209	Crushed Aggregate Base	West-O	yd^3	49,200	11.00
	Aggregate Base	West-M	Ton	9,000	8.00
	Aggregate Base	West-F	Ton	1,065	11.00
	Aggregate Base	South-D	yd^3	3,500	11.00
	Aggregate Base	West-G	yd^3	5,900	13.70
	Crushed Limestone Aggregate	West-R	yd^3	5,000	20.00
	Crushed Rock Base	West-P	Ton	3,696	9.00
	Aggregate Base	West-OA	Ton	4,300	7.40
	Crushed Aggregate Base	West-PO	yd^3	3,630	16.20
P-211	Lime Rock Base Course	South-T	yd^3	27,500	32.00
	Lime Rock Base Course - 18"	South-D	yd^2	81,158	6.44
	Lime Rock Base Course - 12"	South-D	yd^2	33,800	4.00
	Lime Rock Base Course - 6"	South-D	yd^2	18,860	3.00
	Lime Rock Base Course - 18"	South-M	yd^2	110,730	6.50
	Lime Rock Base Course - 12"	South-M	yd^2	21,460	3.75
	Lime Rock Base Course - 6"	South-M	yd^2	19,560	3.00
	Lime Rock Work Platform - 3"	South-M	yd^2	132,370	2.00
	Lime Rock Base Course - 18"	South-M	yd^2	34,250	7.50
	Lime Rock Base Course - 6"	South-M	yd^2	15,010	3.20
	Lime Rock Work Platform - 3"	South-M	yd^2	23,310	2.80
	Lime Rock Base Course - 8"	South-R	yd^2	31,250	5.65
P-212	Shell Base Course	South-T	yd^3	687,500	25.00

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Item	Description	Location*	Unit	Quantity	Unit Price, $
P-213	Sand/Clay Base Course - 6"	South-P	yd^2	12,750	1.90
	Soil Cement Base	West-O	yd^3	52,600	16.10
P-301	Soil Cement Base - 4"	South-A	yd^2	11,450	2.[illegible]5
	Soil Cement Base - 6"	South-A	yd^2	11,450	2.99
	Econocrete Base Course	South-J	yd^2	26,375	11.27
P-304	Recycled Econocrete Course	South-J	yd^2	26,375	11.65
	Cement Treated Base Course - 8"	West-W	yd^2	18,265	11.67
	Asphalt Concrete Surface	West-O	Ton	44,410	22.93
	Asphalt Concrete Surface	West-M	Ton	2,350	28.00
	Asphalt Concrete Surface	West-F	Ton	4,720	29.00
	Asphalt Concrete Surface	West-S	Ton	106,400	34.31
	Asphalt Concrete Surface	South-T	Ton	39,400	33.60
	Asphalt Concrete Surface	South-D	Ton	13,800	32.46
	Asphalt Concrete Surface	South-M	Ton	21,153	41.00
	Asphalt Concrete Surface	South-M	Ton	14,260	50.29
	Asphalt Concrete Surface	South-R	Ton	1,731	34.26
	Asphalt Concrete Surface	South-P	Ton	6,160	29.16
	Asphalt Concrete Surface	South-C	Ton	3,035	26.75
	Asphalt Concrete Surface	South-SM	Ton	7,180	28.20
P-401	Asphalt Concrete Surface	South-S	Ton	1,150	29.37
	Asphalt Concrete Surface	South-RD	Ton	4,700	27.50
	Asphalt Concrete Surface	South-SA	Ton	41,500	27.25
	Asphalt Concrete Surface - 2"	South-A	yd^2	11,450	4.20
	Asphalt Concrete Surface Course	East-W	Ton	2,622	37.00
	Asphalt Concrete Surface - Type B	West-W	Ton	65	30.45
	Asphalt Concrete Surface	West-P	yd^2	3,222	5.00
	Asphalt Concrete - Class B	West-O	Ton	20,500	25.00
	Asphalt Concrete Surface	West-OA	Ton	7,750	28.45
	Asphalt Concrete Surface - Class B	West PO	Ton	10,950	32.70
	Asphalt Concrete Surface - Class D	West PO	Ton	1,900	35.60
	Recycled Asphalt Concrete	West-N	Ton	12,927	25.55

Item	Description	Location*	Unit	Quantity	Unit Price, $
	PCC Pavement	West-O	yd^3	97,310	56.82
	PCC Pavement - 14"	South-D	yd^2	33,800	25.20
	PCC Pavement - 14"	South-M	yd^2	17,380	37.00
	PCC Pavement - 16"	South-J	yd^2	26,375	30.00
	PCC Pavement - 10"	South-J	yd^2	520	22.00
P-501	PCC Pavement - 6"	South-A	yd^2	11,450	12.43
	PCC Pavement - 16" Non-Reinforced	West-W	yd^2	16,383	32.30
	PCC Pavement - 16" Reinforced	West-W	yd^2	1,018	35.45
	PCC Pavement - 9" Reinforced	West-D	yd^2	8,031	33.00
	PCC Pavement - 14" Reinforced	West-D	yd^2	5,269	47.00
	PCC Pavement - 19" Reinforced	West-D	yd^2	4,651	54.00
	PCC Pavement	West-P	ft^2	42,125	5.50
	Bituminous Prime Coat	West-O	Ton	374	190.00
	Bituminous Prime Coat	West-M	Ton	19	300.00
	Bituminous Prime Coat	West-S	Ton	315	265.00
	Bituminous Tack Coat	West-S	Ton	344	220.00
	Bituminous Prime Coat	South-T	gal	53,000	1.40
	Bituminous Tack Coat	South-T	gal	7,500	2.80
	Bituminous Prime Coat	South-D	gal	15,000	2.00
	Bituminous Tack Coat	South-D	gal	8,000	1.00
	Bituminous Prime Coat	South-M	gal	22,800	3.15
P-602	Bituminous Tack Coat	South-M	gal	13,325	1.05
	Bituminous Prime Coat	South-M	gal	7,400	3.47
	Bituminous Tack Coat	South-M	gal	6,980	1.16
	Bituminous Prime Coat	South-R	gal	6,250	1.30
	Bituminous Tack Coat	South-R	gal	3,100	1.15
	Bituminous Prime Coat	South-P	gal	5,100	1.08
	Bituminous Tack Coat	South-P	gal	7,185	0.75
	Bituminous Tack Coat	South-C	gal	3,680	0.85
	Bituminous Tack Coat	South-SM	gal	8,700	0.88
	Bituminous Prime Coat	South-RD	gal	5,200	1.00
	Bituminous Tack Coat	South-RD	gal	1,050	1.00

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Item	Description	Location*	Unit	Quantity	Unit Price, $
	Bituminous Tack Coat	South-SA	gal	22,000	1.22
	Bituminous Prime Coat	South-A	gal	5,700	1.33
	Bituminous Tack Coat	West-N	gal	18,409	1.60
P-602	Bituminous Prime Coat	West-G	gal	9,000	0.94
	Bituminous Prime Coat	West-W	gal	3,655	1.15
	Bituminous Tack Coat	West-W	gal	125	1.15
	Bituminous Tack Coat	West-O	gal	15,000	0.70
	Bituminous Prime Coat	West-OA	Ton	75	2.82
	Bituminous Tack Coat	West-OA	Ton	2	3.10
	Chip Seal	West-S	yd^2	20,400	3.95
	Chip Seal	South-D	yd^2	825,000	0.90
	Chip Seal	South-M	yd^2	100,000	1.42
P-609	Chip Seal	South-SM	yd^2	3,940	0.85
	Chip Seal	South-S	yd^2	40,000	1.42
	Chip Seal	West-N	yd^2	46,000	1.18
	Slurry Seal	West-S	yd^2	309,600	1.05
	Slurry Seal	West-O	yd^2	2,200	2.00
	Fabric	South-S	yd^2	32,040	1.43
P-640	Fabric	South-P	yd^2	670	2.25
	Fabric	South-SA	yd^2	83,500	1.00

*Codes used to designate specific airports.

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Table 11. Summary of Selected 1980 FAA Bid Prices.*

Item	Description	Unit	Price, Dollars Low	High	Representative	No. of Projects
P-150	Pavement Milling 0-1.5"	yd^2	2.50	14.00	3.00	3
	Pavement Pulverization	yd^2	0.80	1.25	1.00	2
P-151	Removal of AC Pavement	yd^2	0.50	4.60	2.00	5
	Removal of PCC Pavement	yd^2	1.90	7.50	4.00	4
	Removal of Pavement	yd^2	0.35	4.75	2.00	3
P-154	Subbase Course	yd^2-in	0.10	0.57		2
P-155	Lime Treated Subgrade	yd^2-in	0.32	0.45	0.40	3
P-201	Bituminous Base Course	yd^2-in	1.53	2.47	2.05	6
P-209	Aggregate Base Course	yd^2-in	0.31	0.56	0.42	9
P-211	Lime Rock Base Course	yd^2-in	0.31	0.93	0.55	12
P-212	Shell Base Course	yd^2-in			0.70	[illegible]
P-213	Sand/Clay Base Course	yd^2-in			0.32	1
P-301	Soil Cement Base	yd^2-in	0.45	0.53	0.50	3
P-304	Cement Treated Base	yd^2-in			1.45	1
P-401	Asphalt Concrete Surface	yd^2-in	1.20	2.64	1.70	22
	Recycled Asphalt Concrete	yd^2-in			1.35	1
P-501	PCC Pavement - Non-Reinforced	yd^2-in	1.58	2.64	2.00	7
	PCC Pavement - Reinforced	yd^2-in	2.22	3.67	3.00	4
P-602	Bituminous Prime Coat	yd^2	0.16	0.69	0.22	13
	Bituminous Tack Coat	yd^2	0.04	0.14	0.06	13
P-609	Chip Seal	yd^2	0.85	3.95	1.10	6
	Slurry Seal	yd^2	1.05	2.00	1.25	2
P-640	Fabric Interlayers	yd^2	1.00	2.25	1.50	3

*Based on Table 10.

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Table 12. ENR Construction Cost Index History 1960-1981.*

	Monthly												Annual Average
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
1960	812	813	813	815	823	827	829	830	831	830	830	831	824
1961	834	834	834	838	847	850	854	854	854	854	855	855	847
1962	855	858	861	863	872	873	877	881	881	880	880	880	872
1963	883	883	884	885	894	899	909	914	914	916	914	915	901
1964	918	920	922	926	930	935	945	948	947	948	948	948	936
1965	948	957	958	957	958	969	977	984	986	986	986	988	971
1966	988	997	998	1006	1014	1029	1031	1033	1034	1032	1033	1034	1019
1967	1039	1041	1043	1044	1059	1068	1078	1089	1092	1096	1097	1098	1070
1968	1107	1114	1117	1124	1142	1154	1158	1171	1186	1190	1191	1201	1155
1969	1216	1229	1238	1249	1258	1270	1283	1292	1285	1299	1305	1305	1269
1970	1309	1311	1314	1329	1351	1375	1414	1418	1421	1434	1445	1445	1385
1971	1465	1467	1496	1513	1551	1589	1618	1629	1654	1657	1665	1672	1581
1972	1686	1691	1697	1707	1735	1761	1772	1777	1786	1794	1808	1816	1753
1973	1838	1850	1859	1874	1880	1896	1901	1902	1929	1933	1935	1938	1895
1974	1940	1940	1940	1961	1961	1993	2040	2076	2089	2100	2094	2101	2020
1975	2103	2128	2128	2135	2164	2205	2248	2274	2275	2293	2292	2297	2212
1976	2305	2314	2322	2327	2357	2410	2414	2445	2465	2478	2486	2490	2401
1977	2494	2505	2513	2514	2515	2541	2579	2611	2644	2675	2659	2669	2577
1978	2672	2681	2693	2698	2733	2753	2821	2829	2851	2851	2861	2869	2776
1979	2872	2877	2886	2886	2889	2984	3052	3071	3120	3122	3131	3140	3003
1980	3132	3134	3159	3143	3139	3198	3260	3304	3319	3327	3357	3376	3237
1981	3372	3373	3384										

How ENR builds the Index: 200 hours of common labor at the 20-cities average rate, plus 25 cwt of standard structural steel shapes at the mill price, plus 22.56 cwt (1.128 tons) of portland cement at the 20-cities average price, plus 1,088 board feet of 2 x 4 lumber at the 20-cities average price.

*1913 Base Year

Federal Aviation Administration (16)

Table 13. Bid Price Trends on Federal Aid Highway Contracts.

			Surfacing			Structures					
	Excavation Price (y^3)	Index*	PCC Price (y^2)	Bit. Conc. Price (t)	Combined Index	Rein. Steel Price (lb)	Struc. Steel Price (lb)	Struc. Conc. Price (y^3)	Combined Index	Highway Bid Price Index	ENR Building Cost Index**
1967	0.54	100.0	4.43	6.47	100.0	0.131	0.247	70.30	100.0	100.0	100.0
1970	0.66	121.8	5.42	8.04	123.3	0.163	0.338	92.73	132.2	125.6	124.4
1971	0.67	123.8	6.06	8.54	134.5	0.177	0.348	92.02	138.5	131.7	141.1
1972	0.72	133.4	6.25	9.22	141.9	0.181	0.342	100.17	140.6	138.2	156.0
1973 Av.	.80	147.1	6.87	9.99	154.8	0.207	0.373	111.83	156.5	152.4	169.3
Q1	0.67	124.7	6.57	9.85	150.3	0.181	0.295	109.34	141.9	137.8	
Q2	.75	138.0	6.36	9.90	148.2	0.193	0.352	113.51	153.4	145.9	
Q3	.81	149.5	7.10	9.61	154.7	0.212	0.422	110.60	152.1	155.1	
Q4	.93	172.7	7.43	10.83	167.7	0.233	0.379	113.51	152.0	167.8	
1974 Av.	1.00	184.1	8.67	14.74	211.3	0.340	0.551	136.80	214.5	201.8	191.2
Q1	.97	179.1	8.17	13.28	194.6	0.281	0.459	129.64	190.2	187.4	
Q2	.96	178.0	8.48	15.77	216.8	0.342	0.555	137.07	215.4	201.4	
Q3	1.02	187.9	8.82	14.64	212.4	0.371	0.577	152.57	233.7	209.7	
Q4	1.03	190.6	9.10	15.18	219.7	0.362	0.648	130.33	224.1	209.9	
1975 Av.	1.03	190.6	8.62	15.13	213.8	0.297	0.554	138.76	210.5	203.8	194.3
Q1	1.02	188.1	9.84	13.95	219.1	0.332	0.577	140.93	219.7	207.3	
Q2	1.00	184.9	8.22	14.35	203.2	0.320	0.542	139.85	213.1	199.3	
Q3	1.02	188.8	8.49	15.58	215.5	0.283	0.556	142.13	211.5	203.9	
Q4	1.10	202.6	9.00	16.41	227.7	0.277	0.548	131.90	207.9	209.8	
1976 Av.	1.03	191.2	8.65	15.07	213.7	0.257	0.493	138.75	198.1	200.4	212.1
Q1	1.04	192.0	7.70	16.28	212.3	0.251	0.543	133.72	199.3	200.3	
Q2	1.05	194.3	8.56	14.13	205.5	0.242	0.510	145.65	203.1	200.4	
Q3	1.03	191.1	9.18	15.12	219.4	0.264	0.438	135.28	189.6	199.0	
Q4	1.01	187.3	9.17	14.76	217.4	0.271	0.481	141.34	200.4	200.4	
1977 Av.	1.16	215.2	9.68	15.47	228.4	0.272	0.520	143.51	206.8	216.4	229.9
Q1	1.03	189.0	8.69	14.88	212.6	0.262	0.562	139.60	207.6	202.2	
Q2	1.16	214.6	9.41	15.29	224.1	0.268	0.499	149.54	208.3	215.4	
Q3	1.19	219.5	10.05	15.32	231.8	0.273	0.462	139.42	196.9	215.9	
Q4	1.29	237.7	10.32	16.94	247.1	0.285	0.536	148.34	214.1	233.0	
1978 Av.	1.54	233.7	11.49	17.15	262.3	0.315	0.603	172.41	244.4	264.9	249.1
Q1	1.13	209.1	9.68	16.10	233.3	0.283	0.563	151.43	219.4	219.5	
Q2	1.43	263.8	11.96	17.54	270.6	0.310	0.570	171.78	239.5	258.1	
Q3	1.84	339.8	12.04	17.11	268.4	0.346	0.638	198.97	258.9	296.1	
Q4	1.90	350.3	13.06	18.09	237.5	0.334	0.681	176.17	259.0	302.7	
1979 Av.(p)	1.62	298.7	13.47	21.21	315.7	0.421	0.759	220.28	313.1	308.3	270.7
Q1	1.48	278.2	11.59	18.35	272.3	0.381	0.737	195.60	286.6	277.2	
Q2	1.54	284.7	12.91	20.72	305.4	0.411	0.749	202.82	297.5	294.9	
Q3	1.81	334.9	15.09	22.08	341.1	0.429	0.755	215.41	310.1	328.8	
Q4(p)	1.86	343.6	16.85	23.67	373.6	0.489	0.804	240.14	342.6	352.1	
1980 Av.	1.83	338.3	14.69	25.29	360.5	0.483	0.941	226.68	348.0	347.9	289.1
Q1	1.84	339.7	12.34	23.89	322.5	0.472	0.894	234.32	346.7	336.9	
Q2	1.89	350.1	16.29	25.81	383.0	0.515	1.063	206.12	351.4	360.2	
Q3	1.72	317.0	15.78	26.28	380.5	0.475	0.792	250.66	347.2	345.4	
Q4	1.89	349.4	14.75	25.36	361.7	0.467	0.834	234.63	339.1	349.7	
1981 Av.											
Q1	1.73	320.4	15.10	24.75	359.3	0.455	0.847	245.17	240.4	346.2	

*1967 Base Year

**1967 Base Year

Federal Aviation Administration (16)

Table 14. Cost Trends - Highway Maintenance and Operations[1].

Year	Labor	Material	Equipment	Overhead	Total
1950	43.58	74.53	57.66	57.07	51.31
1951	47.76	81.07	64.34	62.23	56.41
1952	51.15	81.99	66.86	65.05	59.28
1953	52.00	82.54	68.76	65.73	60.33
1954	54.89	83.49	70.40	66.42	62.55
1955	55.94	82.80	74.24	67.71	64.09
1956	58.70	86.91	74.06	70.55	66.31
1957	63.20	60.86	75.66	78.22	70.28
1958	65.74	92.27	78.91	81.21	72.90
1959	67.82	92.40	83.15	81.88	75.17
1960	71.02	94.68	86.98	84.19	78.35
1961	73.25	95.18	87.19	85.08	79.82
1962	76.06	96.66	88.76	86.47	82.09
1963	79.46	96.87	89.25	88.05	84.32
1964	81.79	97.48	91.25	89.98	86.35
1965	85.69	99.23	94.23	92.31	89.66
1966	98.02	99.68	96.70	96.28	97.76
1967	100.00	100.00	100.00	100.00	100.00
1968	103.63	102.03	100.42	105.03	102.79
1969	113.71	106.24	104.24	110.24	110.44
1970	122.02	111.03	106.56	116.81	116.78
1971	129.67	117.37	107.93	122.76	122.68
1972	138.21	124.27	119.98	128.71	131.68
1973	148.04	130.42	133.70	134.66	141.75
1974	160.67	170.41	153.50	140.61	158.65
1975	173.15	198.74	170.58	145.56	172.97
1976	192.99	192.74	184.37	152.51	188.08
1977	211.89	202.66	194.17	158.51	202.92
1978	226.70	233.41	208.63	164.41	218.80
1979	242.63	276.14	234.64	170.37	239.79

[1]These data are prepared for the unit cost information submitted each year by State highway departments, and cover both physical maintenance and major traffic service items including snow and ice control.

1967 = Base Year

Portland Cement Association (51)

PAVEMENT PRICES

Based on FHWA "Price Trends for Federal-aid Highway Construction"

Year	Pavement PCC (sq yd) (9 in. thick)	Asphalt $ per ton	Asphalt $ per sq yd (12 in. thick)
1972	$ 6.42	$ 9.23	$ 6.08
1973	7.00	10.02	6.61
1974	8.88	14.74	9.73
1975	8.88	15.13	10.00
1976	8.92	14.83	9.80
1977	9.95	15.47	10.20
1978	11.90	17.16	11.30
1979	14.02	21.21	13.98
1980	14.92	25.29	16.65
1981	14.17	25.63	16.92
1982	13.03	24.33	16.06
Ratio '82/72	2.03	2.64	

Price trends obtained from contracts greater than $500,000 for federal-aid highway projects (other than on the secondary system).

Florida Department of Transportation (8)

EXHIBIT B

INTERSTATE ASPHALT PAVEMENT

1983 Cost Per 4 Lane Mile

20 Year Design*

ROADWAY ITEMS

DESCRIPTION	QUANTITY	UNIT PRICE	AMOUNT
Stabilized Subbase (12")	49,280 SY	$ 0.40	$19,712
Comm. Stab. Material	5,475 CY	7.75	42,431
Opt. Base Gr. 9 (12" Limerock)	28,747 SY	5.50	158,109
Opt. Base Gr. 1 (4" Limerock)	17,013 SY	2.40	40,831
Bit. Material (Tack Coat)	6,758 GA	0.80	5,406
Bit. Mat. (Plant Mix, "S")	158,814 GA	0.70	111,170
Bit. Mat. (Plant Mix, FC-2)	15,099 GA	0.72	10,871
ACSC Type "S" (6½" Thick)	28,160 SY	7.00	197,120
ACSC Type "S" (1½" Avg.)	16,427 SY	1.50	24,641
Asph. Conc. Fric. Crse. (FC-2)	32,853 SY	0.80	26,282
COST OF ASPHALT PAVEMENT (20 YEAR DESIGN)			$636,573

*This design was not used in the analysis and is provided for informational purposes only.

EXHIBIT C

INTERSTATE ASPHALT PAVEMENT

1983 Cost Per 4 Lane Mile (STAGE I)

DESCRIPTION	QUANTITY	UNIT PRICE	AMOUNT
Stabilized Subbase (12")	49,280 SY	$ 0.40	$ 19,712
Commercial Stab. Material	5,475 CY	7.75	42,431
Opt. Base Gr. 9 (12" LR Base)	28,747 SY	5.50	158,109
Opt. Base Gr. 1 (4" LR Base)	17,013 SY	2.40	40,831
Bit. Material (Tack)	5,632 GA	0.80	4,506
Bit. Mat. (Plant Mix) "S"	115,746 GA	0.70	81,022
Bit. Mat. (Plant Mix) FC-2	15,099 GA	0.72	10,871
ACSC Type "S" (1½" Avg/Thk)	16,427 SY	1.50	24,641
ACSC Type"S"(4½"thk)(3 Crses)	28,160 SY	4.85	136,576
Asph. Conc. Fric. Crse. (FC-2)	32,853 SY	0.80	$ 26,282
(STAGE I) COST OF ASPHALT PAVEMENT (PER 4 LANE MILE)=			$544,981

STAGE II AND 2" OVERLAY

1983 Cost Per 4 Lane Mile

Bit. Material (Tack)	4,881 GA	0.80	$ 3,905*
Bit. Mat. (Plant Mix "S"&III")	84,377 GA	0.70	59,064*
Bit. Mat. (Plant Mix) FC-2	15,099 GA	0.72	10,871*
ACSC Type "S" (2")	40,480 SY	2.15	87,032
ACSC Type III Leveling	1,364 TN	24.00	32,736
Asph. Conc. Fric. Course (FC-2)	32,853 SY	0.80	$ 26,282
(STAGE II) COST OF ASPHALT PAVEMENT (PER 4 LANE MILE)=			$219,890

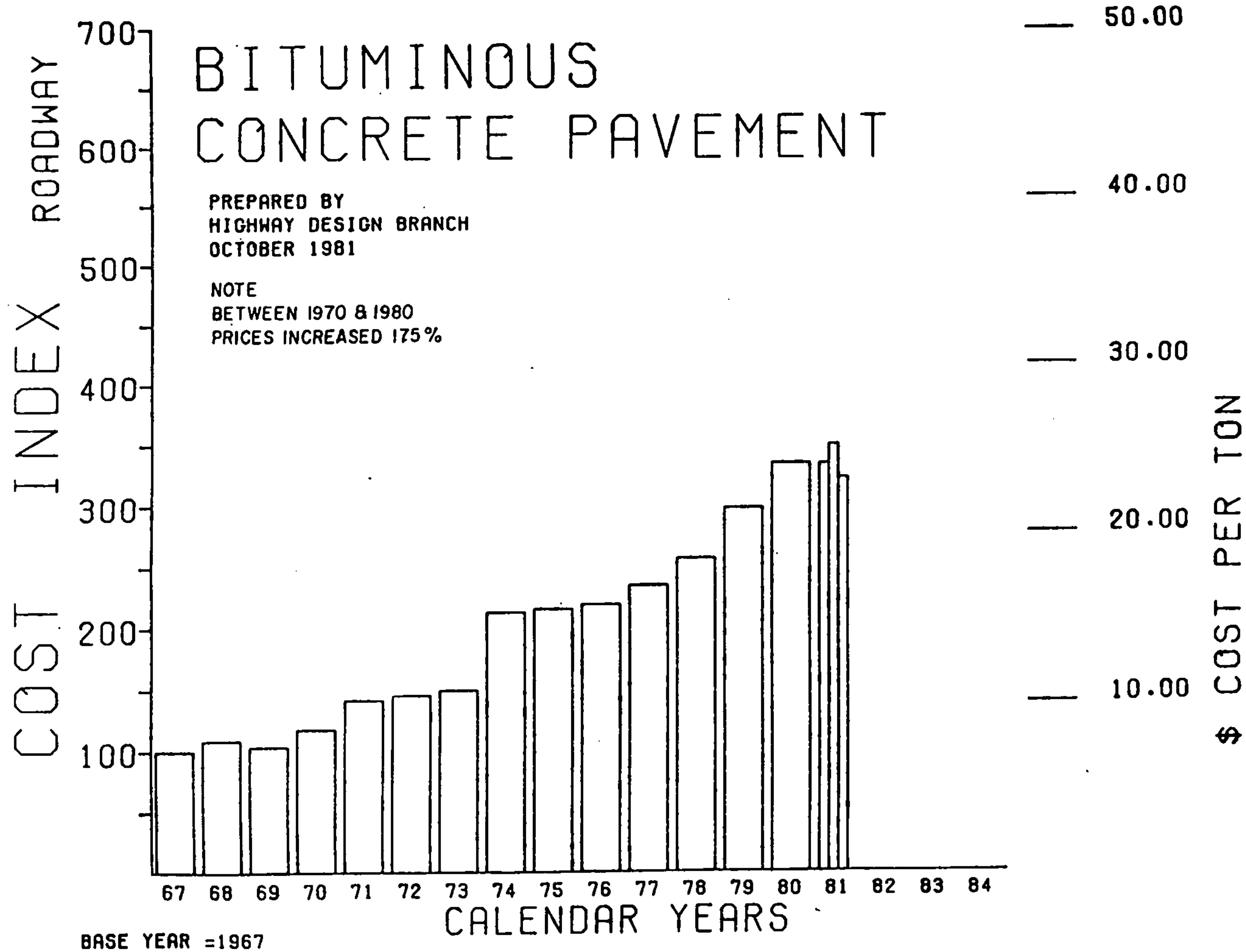
INTERSTATE ASPHALT PAVEMENT RECYCLING

The following estimated 1983 costs are for recycling of one mile of four lane Interstate asphalt pavement. These quantities are based on milling 3" of the roadway and adding 4" of recycled asphaltic concrete to the roadway and 1" to the shoulders.

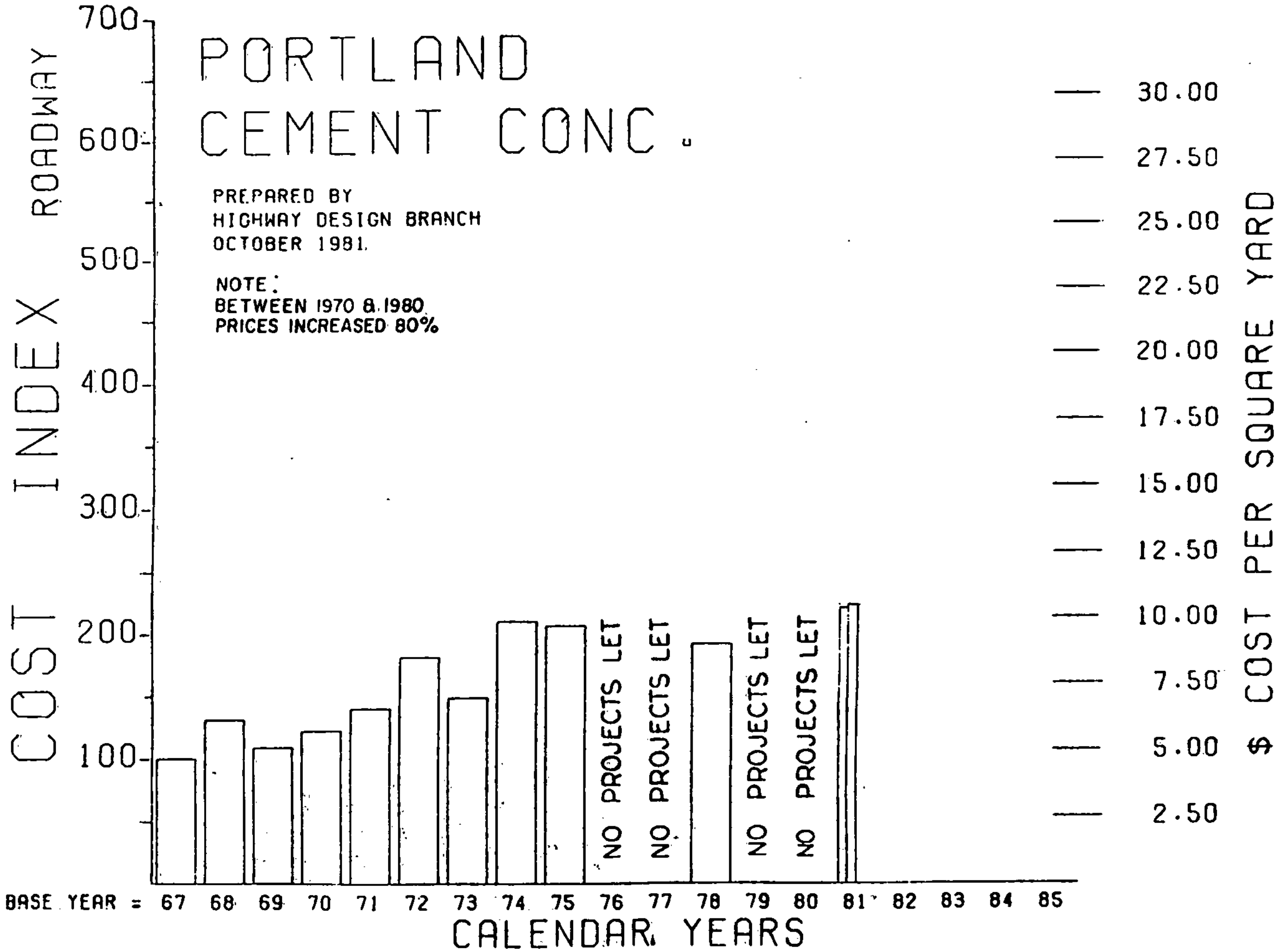
DESCRIPTION	QUANTITY	UNIT PRICE	AMOUNT
Bit. Material (Tack)	4,224 GA	$ 0.80	$ 3,379*
Bit. Mat. (Plant Mix) FC-2	15,099 GA	0.72	10,871*
Asph. Concrete FC-2	32,853 SY	0.80	26,282
Milling Exist. Asphalt Pavt.	28,160 SY	0.45	12,672
Recycled Asphalt Pavt.	6,452 TN	19.50	125,814
TOTAL COST OF RECYCLING (Per 4 Lane Mile) =			$179,018

Routine Annual Pavement Related
Maintenance Cost $528/year/4 lane mile
Salvage Value (7½" @ 30 yrs. x $14.73/Ton)= $173,696/4 lane mile
Salvage Value (8½" @ 40 yrs. x $14.73/Ton)= $194,436/4 lane mile

*Asph. mat'l. cost used in sensitivity analysis with 2.6% & 3.3% escalator.



North Carolina Department of Transportation (39)



North Carolina Department of Transportation (39)

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