

Economic Evaluation of Concrete Pavement Rehabilitation

Daren L. Coudriet, Keystone Management Systems
David R. Luhr, Keystone Management Systems
Walter P. Kilareski, Pennsylvania State University

I. Background

Introduction

Today, transportation agencies face the increasingly difficult task of managing a deteriorating infrastructure in an inflationary environment with declining revenues and significant increases in traffic volumes. The estimated cost of maintenance and construction on U.S. roadways alone is approximately 15 billion dollars per year. In an effort to maximize the benefits from such a large investment, Pavement Management Systems (PMS) are being implemented to help better manage the nation's highway system.

A PMS examines roadways on both a 'macro' and 'micro' level, consisting of a Network and Project level analysis, respectively. The basis for decision making at both levels ultimately depends on the costs of maintenance and rehabilitation and the benefits received from each, in conjunction with the funds available to perform these tasks. Because

decision criteria related to pavement management are primarily influenced by economics, the term "Pavement Economics" becomes an adequate description of the most critical element in pavement management. However, current pavement design procedures may not include in a direct manner the consideration of pavement economics in determining the optimum design period and level of service for a given set of conditions.

Pavement economics at the network level is difficult because it often requires the evaluation of a large number of roadway segments. It is however, necessary to group at the network level maintenance and rehabilitation alternatives for roadway segments so that cost estimates can be obtained. A common approach to this problem is to use a "decision tree," where the pavement condition automatically dictates what will be programmed for the road segment without consideration of other factors. This provides a rough estimate to personnel for the purposes of determining cost, materials, and other

future resource requirements for the road network, and to plan for future rehabilitation projects.

Project level analysis, however, relies heavily on pavement economics in determining the proper rehabilitation alternative. Many alternative strategies must be evaluated, and all factors that relate to cost must be considered. For example, to determine the most cost effective rehabilitation alternative for a particular roadway segment, not only would the condition of the pavement be a factor (as in a structural analysis), but the unit cost of construction for each alternative would also be considered. It is the objective of project-level pavement management to determine the type of rehabilitation that performs satisfactorily at the least cost.

In this paper, an overview of pavement economics is presented, followed by an analysis of the factors that affect the economic analysis, particularly as they relate to network level analysis and economic life. Also, the importance of proper economic comparisons relative to the decision making process is presented, with information on project cost sensitivity.

Pavement Economics

Pavement economics centers on the cash flow evaluation of 1) initial construction, 2) rehabilitation, 3) maintenance, 4) user costs, and 5) salvage value over the "life" of the pavement, which is termed a "life-cycle cost" analysis (1). Life-cycle cost analysis is a technique that discounts future costs according to a specified interest rate, allowing cost comparisons of different strategies and alternatives on the basis of a present

worth or an equivalent uniform annual cost (EUAC). Some frequently used economic terms are reviewed below.

Initial Construction Cost. The cost of initial construction includes the cost of transportation and placement of materials and also the cost for the material in the pavement structure. Initial construction takes place in year "zero" of the performance period.

Rehabilitation Cost. Rehabilitation cost is the cost of rehabilitating the pavement after failure. The analysis of this paper is based on a single performance period which is assumed to begin at the time of initial construction and end prior to rehabilitation. The rehabilitation represents the beginning of a second performance period.

Maintenance Cost. Maintenance encompasses all activities that do not add to the structural capacity of the pavement, but instead, prolong pavement performance. This would include patching, joint and crack sealing and other miscellaneous activities. These costs depend on the type and level of maintenance (preventative, responsive, deferred), and the current condition of the pavement.

User Cost. User cost can be broken into two categories, vehicle delay and vehicle operating. Vehicle delay is defined as the cost of lost time due to some type of rehabilitation. Vehicle operating refers to the additional cost the user must pay in vehicle operating expenses because the road is not in excellent condition. For this paper, the levels of user cost were assumed using PSI values ranging from 1.5 to 3.0, a 0% grade, and a constant speed of 55 mph, and a medium sized car (2).

Salvage Value. The monetary value of a pavement structure at the end of the analysis period is called the salvage value.

Because this study examines only a fixed performance period and not the entire analysis period, the salvage value is not considered as a factor.

Present Worth. Present worth is a method of comparing alternatives costs by discounting future costs into equivalent values in "today's" dollars. This method requires the analysis periods of different rehabilitation alternatives to be equal for comparison (3).

Equivalent Uniform Annual Cost (EUAC). EUAC is a method of comparing alternatives by converting costs to an equivalent year end amount that is the same each year of the analysis period. The advantage of this method is that it can be used when the analysis periods are different between alternatives, since it does not require making the comparison over the same number of years (3).

Structural Performance Period. The definition of structural performance period is a predetermined number of years that a pavement is predicted of providing an adequate and safe level of service, based on the pavement design. The structural performance period relates to a design period. For example, AASHTO pavement design procedures require a predetermined design life, without consideration to the economics of that design life.

The definitions of construction, user, and maintenance costs are combined in Figure 1 to define total cost (4). For a road of low quality, the initial construction cost is often low. However, the low quality road may incur high maintenance and user costs, resulting in a higher total cost than for constructing a higher quality road. Considering the opposite situation, where a road may be built to extremely high standards, the fact that low maintenance and user costs occur does not compensate for

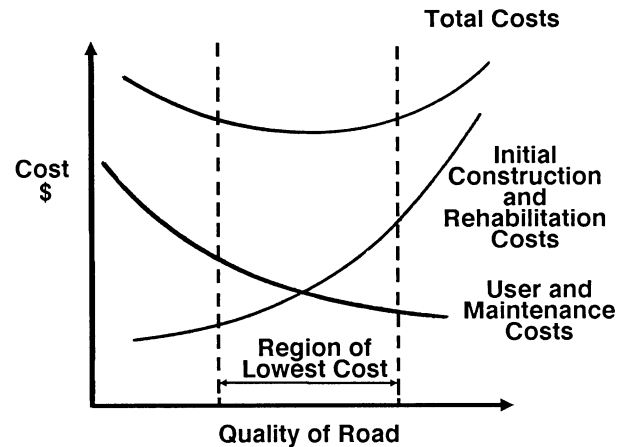


Figure 1. Cost vs. Road Quality

the very high construction costs. This situation also leads to high total costs. The lowest total cost occurs when the road is properly designed for the appropriate traffic, materials, and climate conditions.

The total cost curve is needed to compare various rehabilitation strategies and to determine the "economic life" of the pavement (see Figure 2). Economic life is the time point in a pavement economic analysis when the annualized costs are minimum (5). For example, when constructing a new roadway initial annual costs are high, because the capital costs of construction are only spread over the first few years. As the pavement age increases the initial construction and maintenance costs are distributed over more years, reducing the total annual cost. Eventually, the annual costs will reach a minimum (the economic life), and when the maintenance and user costs start to increase as the quality of the road decreases,

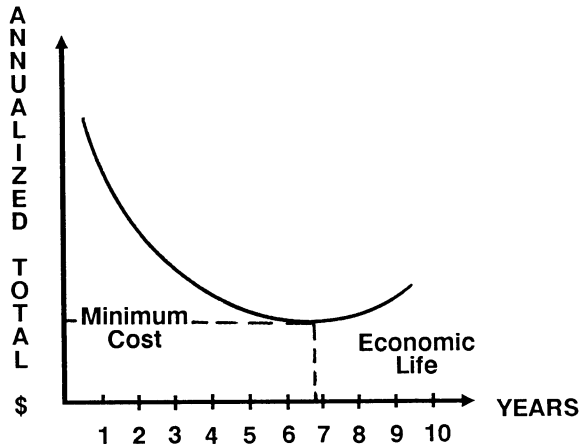


Figure 2. Definition of Economic Life

the annual cost will increase. The economic life can be used to define the optimum time of pavement rehabilitation. Minimum EUAC and EUAC at Economic Life will be used interchangeably throughout this paper.

ROADCOST

The microcomputer program, ROADCOST, was used to analyze cost data and provide life-cycle cost and sensitivity analysis information. ROADCOST was initially developed and used for long-term economic evaluations of different pavement rehabilitation strategies for over 100 miles of con-

crete pavement rehabilitation in four counties near Philadelphia, Pennsylvania.

The program provides the user with the flexibility to analyze any number of pavement rehabilitation strategies, and to select the one which is most economical. The program inputs are: data on traffic volumes and user unit costs, selection of items that are part of the rehabilitation strategy, the year(s) the rehabilitation items will occur, and the quantity and unit cost of the items. With this information, the program constructs the life-cycle cash flow, discounts future values to present worth, and converts the present worth to a uniform annual cost, allowing comparisons between rehabilitation alternatives with different analysis periods.

The ROADCOST program, therefore, evaluates the pavement economics, including the economic life, of various pavement rehabilitation alternatives. The following sections of this paper include an analytical evaluation of the various factors relating to pavement economics for rigid pavements.

II. ANALYSIS OF ECONOMIC FACTORS

Objective

The objective of this study was to examine how economic life compared to design life in evaluating maintenance and rehabilitation alternatives, and to determine the effect of each of the economic factors on economic life and project cost.

Procedure

The analysis was conducted by performing a full-factorial sensitivity analysis of the ROADCOST program for various input variables. The factors used in the analysis were chosen because they represented the major economic elements that combine to determine the total life-cycle cost for a rigid pavement. These factors are: interest rate, structural performance period, initial construction cost, maintenance cost, vehicle operating cost and traffic level. Three levels of each of these factors, associated with low, medium and high values were determined to include a broad range of conditions (Table 1).

The possible combinations generated from all the factors and each of these levels (full-factorial) was 3^6 , or 729 observations. For all of the combinations, a variety of dependent variables, including the Present Worth (PW), Equivalent Uniform Annual Cost (EUAC), Minimum EUAC (EUAC at Economic Life), Annual Cost per Vehicle per Mile, and a breakdown of project costs into percentages of the total cost were calculated. The following discussion will focus on economic life, the importance of proper economic comparisons, and a sensitivity analysis of project costs.

Predictive Equations

The generation of the 729 observations in the above analysis, using a designed full-factorial of 6 terms at 3 levels, provides an excellent source of data for developing predictive equations regarding pavement economic analyses. From the wide range of variable levels, a good indication can be developed of what factors most significantly affect the economic-based dependent variables.

Table 1. Levels of Variables Used in the Analysis

Variable	Level	Unit
Interest Rate	3;5;7	%
Structure Performance	10;25;40	Years
Initial Construction	30;50;70	\$/sy
Maintenance	5;10;15	\$/sy
Traffic Level	5000;25000;45000	ADT
Vehicle Operating	.03;.09;.15	\$/vehicle/mile

Using multiple regression analysis, predictive equations were developed for 1) economic life (the optimum year to rehabilitate), 2) the annual cost (EUAC) at the economic life, 3) the slope of the annualized cost curve after the economic life, and 4) the PSI at economic life.

Economic Life. To perform an accurate economic analysis to determine the economic life of a pavement section, a program such as ROADCOST should be used; however, this is not practical for thousands of sections at the network level. A regression equation to predict the economic life of a pavement can be very useful in a network level pavement management analysis. The economic life equation can be used to determine which sections will reach their optimum time to rehabilitation in the next year, next 3 years, etc.

The equation developed through the regression analysis is:

$$\text{Economic Life} = 8.54 + .439(\text{Struct. Perf.}) + .0890(\text{Init. Const.}) - .186(\text{Maintenance}) - .00014(\text{Traf- fic}) - 34.3(\text{Veh. Oper.})$$

$r^2 = 94.7\%$ standard error = 1.54
The units are the same as defined in Table 1, the Economic Life is defined in years.

Note that the economic life is reduced with higher maintenance costs, increased traffic levels, and higher vehicle operating cost; and increases with higher initial construction cost and a longer performance period.

EUAC at Economic Life. This equation allows for the network-level prediction of the equivalent uniform annual cost (EUAC) at the time the economic life is reached (optimum time to rehabilitate), also termed minimum EUAC.

$$\begin{aligned} \text{Min. EUAC} = & 7.67 + .290(\text{Int. Rate}) - .650(\text{Struct. Perf.}) \\ & + .109(\text{Init. Const.}) + .0252(\text{Maintenance}) \\ & + .000046(\text{Traffic}) + 13.6(\text{Veh. Oper.}) + \\ & .00855(\text{Struct. Perf.})^2 \end{aligned}$$

$r^2 = 94.3\%$ standard error = .89
The units are the same as defined in Table 1, the Minimum EUAC is defined in terms of \$/square yard/year.

Slope of Annual Cost Curve after Economic Life. A third equation defines the dependent variable Slope as the line representing the change in the EUAC between the economic life and the design period, divided by the number of years that separate them.

$$\text{Slope} = \frac{\text{EUAC at Design Period} - \text{EUAC at Economic Life}}{\text{Structural Performance Period} - \text{Economic Life}}$$

This can be incorporated to indicate how critical the rehabilitation decision is with regard to time. This concept is

illustrated in Figure 3 which contains two annual cost curves, one of which increases sharply after reaching the economic life, demonstrating the importance of timely rehabilitation. The other has a small slope (S2) which is an indication that rehabilitation could be postponed without severe penalty. This illustrates the fact that time period defined by the economic life can be significantly different than the design period, and that if an arbitrary design period is selected by the designer without considering the economic effects, extra expense to the agency will result.

Economic Terminal Serviceability Index. To determine Present Serviceability Index (PSI) in the year defined by economic life, the PSI level at the beginning and end of the structural performance design period were assumed as 4.2 and 1.5, respectively. A simplified linear performance vs. time relationship was used for demonstration purposes.

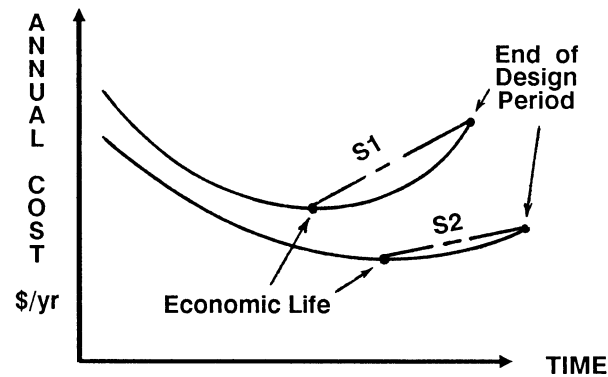


Figure 3. Illustration of Slope and Importance of Timely Rehabilitation

The resulting regression equation was:

$$\text{PSI at Economic Life} = 1.96 - .0242(\text{Int. Rate}) + .0141(\text{Struct. Perf}) - .0078(\text{Init. Const.}) + .0151(\text{Maintenance}) + .000012(\text{Traf- fic}) + 2.92(\text{Veh. Oper.})$$

It was determined that the mean value of PSI corresponding to the economic life was 2.60, with a standard deviation of 0.29. This value seems reasonable as a typical Terminal Serviceability Index (TSI) for rigid pavements; however, the PSI at the economic life ranged from a low of 1.8 to a high of 3.2, meaning that conditions can significantly change the optimum value of the TSI, and that it should not be simply assumed. Instead, it should be determined through an economic evaluation.

Importance of Proper Economic Evaluation

An integral part of a PMS is an economic analysis of various rehabilitation alternatives. This typically involves applying life cycle cost analysis and choosing the strategy with the lowest **final cost** over a predefined analysis period (6). However, data obtained from this study suggests that the minimum EUAC (at economic life) should serve as the value of comparison, rather than the Final EUAC (EUAC over the design period).

For example, Table 2 summarizes the calculations of two possible combinations of the economic factors. Note that if the design period costs were used as a basis of comparison the choice would be Case B, with a cost of \$5.53/sy/yr. But if the

Table 2. A Comparison Summary of Two Possible Combinations of Economic Factors

Variable	Case A	Case B
Interest Rate	3	3
Structural Performance	40	40
Initial Construction	50	70
Maintenance	15	5
Traffic level	25000	25000
Vehicle Operation	.03	.03
Final EUAC	6.58	6.23
Economic Life EUAC	3.60	5.53

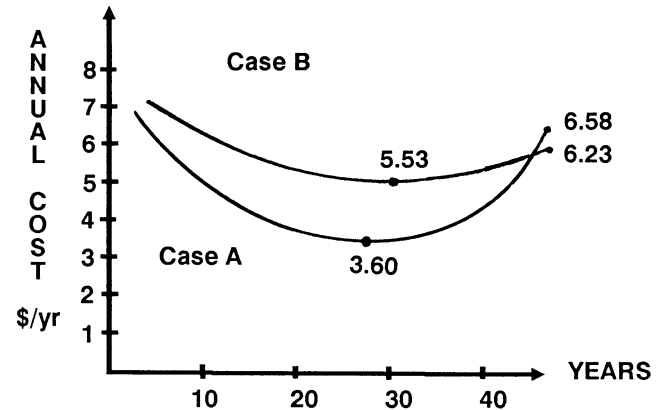


Figure 4. Graphical Comparison of Economic Life EUAC vs. Final EUAC

EUAC of the economic lives were compared the optimal solution would be Case A, with a cost of \$3.60/sy/yr, resulting in a savings of \$1.93/sy/yr. Figure 4 gives a graphical representation of the alternatives. The fact that Case A requires

Table 3. Statistical Summary of the Economic Life EUAC and the Final EUAC

Statistics	Economic Life EUAC	Final EUAC
Mean	6.74	9.41
Maximum	19.67	22.50
Minimum	2.03	2.33

rehabilitation sooner, resulting in a shorter performance period, is taken into consideration in the analysis since the EUAC comparison is made in terms of dollars per year.

To reinforce this concept, Table 3 gives a statistical summary of the economic life EUAC and final EUAC for all the possible combinations from the full-factorial. The mean is considerably lower for the EUAC at economic life, indicating that the solution strategies resulting from comparing the costs associated with economic life produced a 28% cost savings of \$2.67/sy/yr over the method of using EUAC for the design period. Another interesting comparison is seen with the standardized regression coefficients for each of the independent variables used in calculating the EUAC at economic life and the design period EUAC. Table 4 shows that the three most important factors in determining the EUAC at economic life are Structural Performance, Initial Construction, and the squared term of Structural Performance. While

Table 4. Comparison of Coefficients for the Equations of Economic Life EUAC and Final EUAC

Economic Factor	Economic Life EUAC Coeff.	Final EUAC Coeff.
Interest Rate	.5797	-.0362
Structural Performance	-.4353	1.916
Initial Construction	2.175	1.733
Maintenance	.1259	.6070
Traffic Level	.9278	3.039
Vehicle Operating	.8181	2.533
(Structural Performance) ²	1.923	----

the main economic factors in determining the design period EUAC are Traffic Level, Vehicle Operating Cost, and Structural Performance. This exemplifies the fact that the design period EUAC and minimum EUAC methods will not likely generate similar solutions.

As a final comparison of economic life EUAC and final EUAC, the sensitivity of each of these dependent variables to the independent economic factors are shown in Figures 5 and 6. The sensitivity bars are an indication of the effects that each independent variable has on the dependent variable. The independent variables were varied from low to high levels, while the other independent variables were kept at low, middle, and high levels, successively. Notice that the "middle" sensitivity bars agree with the relative sizes of the coefficients in Table 4.

Components of Total Cost

Once the rehabilitation strategy with the least cost has been determined, it is important to break down the total cost into its various components. The values of the economic components (e.g. initial construction, user operating, maintenance

cost) may change over time, making it necessary to re-evaluate the rehabilitation alternatives.

Knowing the percent contribution (to total cost) of each of the components gives an indication of how the change in the

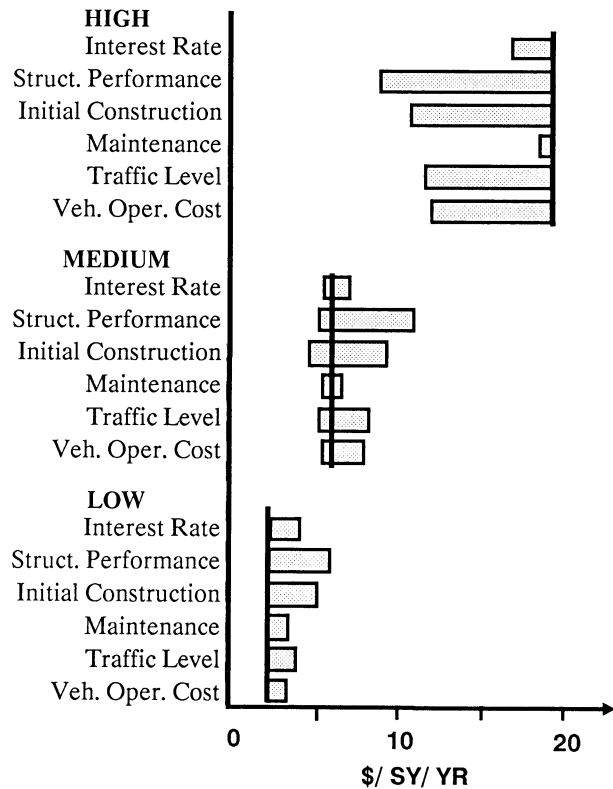


Figure 5. Economic Life EUAC Sensitivity

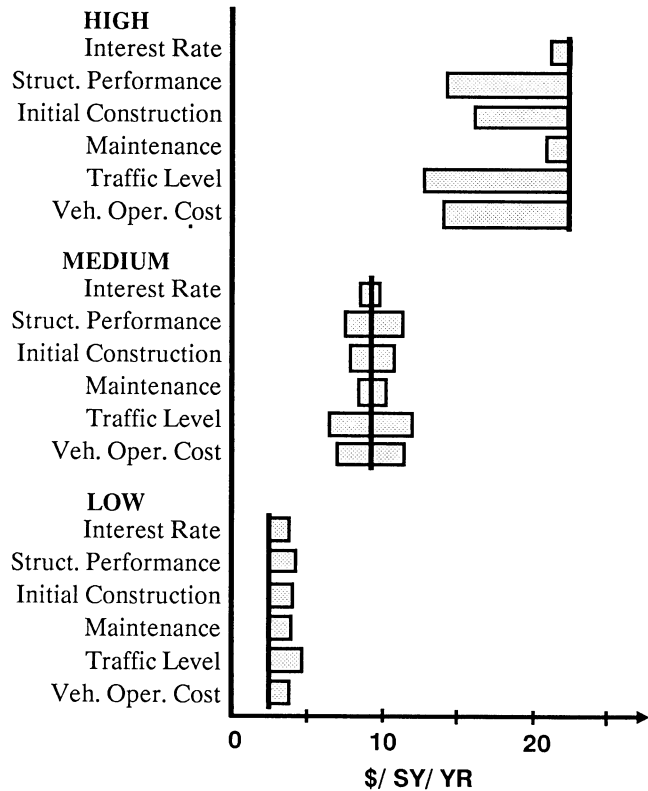


Figure 6. Final EUAC Sensitivity

economic component will affect the overall cost of the strategy. The pie chart (Figure 7), produced from ROADCOST, gives an example of a project's total cost distribution. This chart serves a purpose similar to a sensitivity analysis in that the

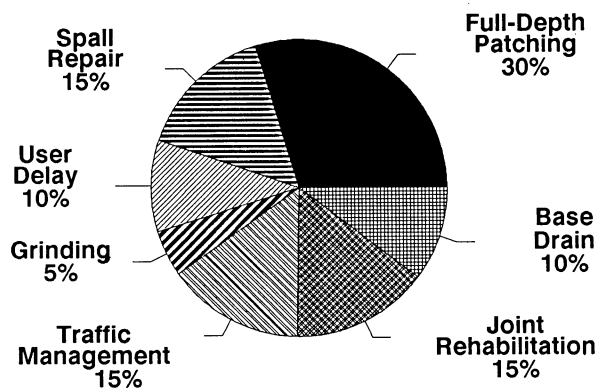


Figure 7. Cost Distribution of Concrete Pavement Rehabilitation

percentages represent the degree to which the total cost is sensitive to each item. The example in Figure 7 shows that a change in the cost of Full-Depth Patching will result in a significant change in the total cost of the project due to its large percentage, and this could affect the choice among rehabilitation alternatives.

The factorial used in this study provided a wide range of economic combinations from which a range of cost percentages for each of the analysis variables (Initial Construction, Maintenance, User Operating and User Delay) was deter-

mined. This information was used to provide the sensitivity analysis information shown in Figure 8. The sensitivity bars give an indication of the effect that each of the components have on total cost with all other variables at either high, medium or low levels. The tick marks on each bar represent the high, medium, and low levels. The component that had the lowest effect is user delay. This means that there is little need for special time and effort to develop models that predict user delay values.

The two components that had the largest effect are initial construction and operating cost. The sensitivity bars for these items indicate the relative magnitude of importance for each factor in determining the total cost of a project, and emphasizes that they should be given considerable attention.

Maintenance can also be important, depending on the conditions. While other factors are at low levels, maintenance is nearly 60% of total cost. This is why it is important to perform a Project-Level Analysis with a program similar to ROADCOST, so that all the appropriate factors are taken into consideration.

III. Summary and Conclusions

Pavement Management Systems are being implemented in transportation agencies throughout the United States to help manage their vast highway systems. An integral part of a PMS is pavement economics which serves as a basis for evaluating expenditures. The procedure that is used in choosing the proper (most economical) rehabilitation alternative is life-cycle economic analysis, thus allowing comparisons to be made on the basis of cash flow. As part of the economic analysis, the

economic life of a pavement is calculated, which defines the optimum time for rehabilitation based on the economic components of the life-cycle pavement analysis. This method is superior to the designer assigning an arbitrary design period and performance failure level.

Results from the economic analysis can be very useful at the network-level. Equations for economic life, EUAC at economic life, and slope after economic life can be used to provide estimates of the number of pavement sections requiring pavement rehabilitation, a prioritization by EUAC, and a

quantification of timely importance of rehabilitation, respectively.

The importance of timely rehabilitation was illustrated by the comparison of design period and economic life as scheduled times for rehabilitation. When rehabilitation strategies were chosen based on economic life, the result was a substantial cost savings.

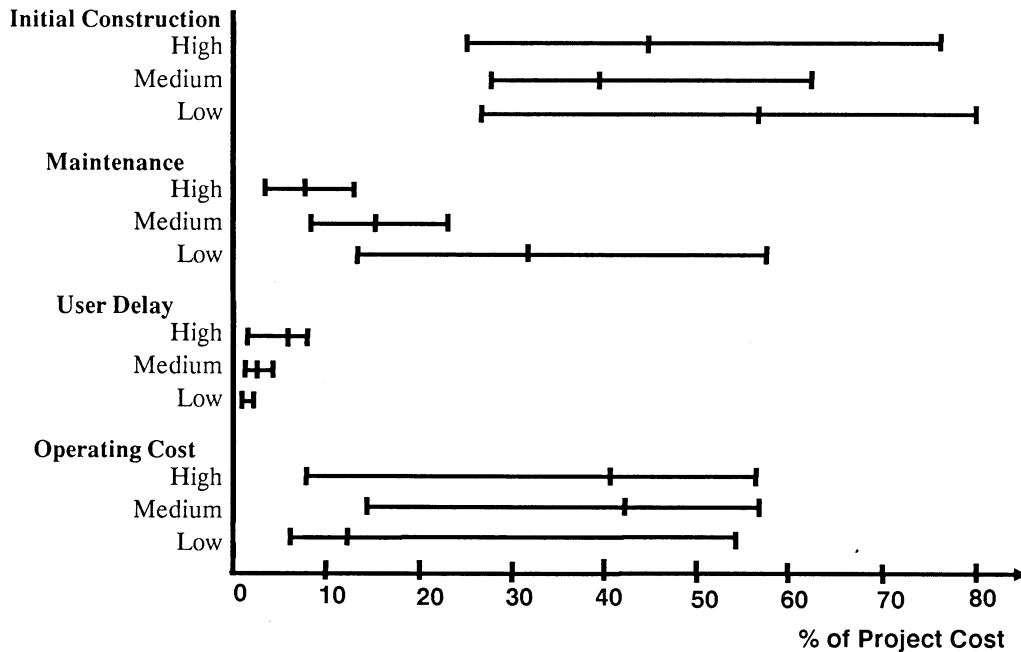


Figure 8. Sensitivity Analysis of Individual Cost Items

When a rehabilitation strategy is chosen, the cost components should be examined to determine how sensitive the total project cost is to each factor. User delay was shown to have little effect on total cost while initial construction, maintenance, and user operating costs were most often of primary importance.

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