Life-Cycle Costing of Paved Alaskan Highways

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ABSTRACT

The development of a pavement design evaluation system (PDES), which provides a systematic, consistent, and efficient procedure to evaluate alternative initial designs for paved highways in Alaska on the basis of their total life-cycle costs, is described. The major cost components of PDES are initial cost of construction, cost of routine maintenance required to keep a pavement serviceable, possible salvage value, and user costs. PDES consists of four subsystems: pavement performance subsystem, cost subsystem, life-cycle cost procedure, and optimization subsystem. Mechanistic procedures tailored to Alaskan conditions and calibrated with empirical data and engineering judgments have been used to predict future physical characteristics of alternative pavement designs. The performance variables for which prediction models are developed are roughness caused by cumulative application of traffic loading, roughness caused by thaw settlement in permafrost regions, fatigue cracking, and major transverse cracking. Uncertainties associated with the prediction of future pavement performance are explicitly considered in PDES to calculate the total expected costs during a specified analysis period and to determine the minimum cost alternative that satisfies desired reliability constraints. As a tool for the designer and decision maker, PDES provides a means of documenting and justifying specific design selections for site-specific projects contemplated for construction in Alaska.

Recent developments in the field of pavement management indicate that the selection of an initial pavement design should consider not only the initial construction cost, but also costs incurred during a life-cycle period. Life-cycle costs should include user costs caused by increased surface roughness, routine maintenance costs for maintaining pavements in minimum acceptable condition, and inflation and interest factors.

Currently, the Alaskan road design process considers only the initial cost of the type of structure as determined by the provisions of the design manual. Alternative design choices are few and are usually a direct response to budget changes during the preconstruction period. The eventual effects of increasing or decreasing layer thickness cannot be rationalized because the trade-offs between increased initial costs and decreased life-cycle costs (user and maintenance costs) are not considered.

The primary objective of the investigation described in this paper was to develop a systematic procedure for the determination of life-cycle cost comparisons for alternative pavement designs contemplated for use in various climatic zones in Alaska. For purposes of this investigation, life cycle refers to serviceable life of original construction with provision for such maintenance activities as crack filling, seal coat, leveling, and thin overlays; however, thick overlays are not considered because they generally are not used in Alaska. Cost considerations include initial cost of construction, cost of routine maintenance required to keep the pavement serviceable, salvage value, and user costs.

To meet the objectives of the project, a pavement design evaluation system (PDES) was developed that provides a systematic, consistent, and efficient procedure to evaluate alternate designs and to select the optimum alternative for paved highways in Alaska.

The paper is organized into six major sections:

1. Research approach: An overview of the approach used in the investigation.
2. Pavement performance subsystems: The development of pavement prediction models used to estimate the future physical characteristics of alternative pavement designs.
3. Pavement cost subsystem: Cost models used to associate pavement costs with alternative design considerations.
4. Life-cycle cost calculations: Procedures and assumptions that are necessary to combine performance expectations with costs for alternative design considerations.
5. Optimization subsystem: Procedures used to determine the expected costs of feasible alternative designs.
6. Summary and conclusions: A review of results from the investigation with suggestions for implementation and periodic updating.

RESEARCH APPROACH

Figure 1 shows the basis for structuring the PDES. The major subsystems are given in this figure and show the general order and continuity of the proposed system. A brief description of each subsystem is provided in the following sections, which describe in detail the development of each subsystem.

Pavement Performance Subsystem

Two sets of pavement performance models are considered:

1. Statistical-mechanistic pavement performance prediction models used for the analysis of the normal structural pavement layers for surface environments (i.e., without considering the impact of permafrost conditions), and
2. Models that estimate the rate of development of pavement roughness for subsurface environment (i.e., roughness caused by thaw settlement for roads built over permafrost foundations).

The performance models are used to estimate the expected life cycle of the pavement (i.e., the time to reach a specified terminal condition) for two selected performance variables: roughness and fatigue cracking. In addition, an estimate of the dispersion around the expected life cycle is made

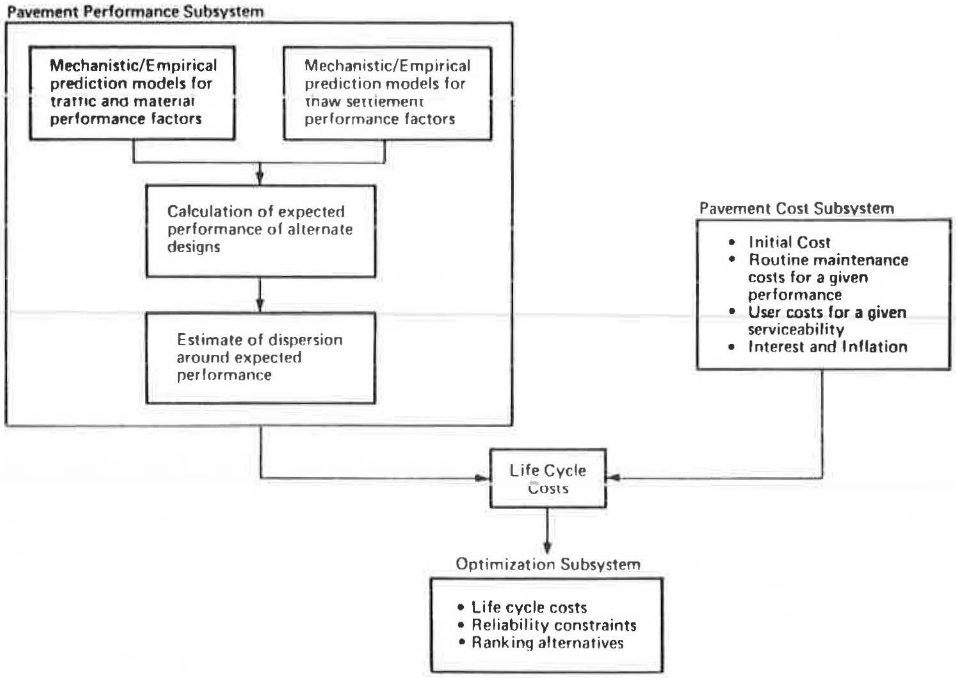

FIGURE 1 Pavement design evaluation system.

based on the analysis of available data and engineering judgment.

Cost Subsystem

The following cost components are included in the calculation of the total cost of a design alternative:

1. Initial construction and material costs (including possible salvage value);
2. Routine maintenance costs during a specified analysis period;
3. User costs, including vehicle operating costs and time delay costs; and
4. Inflation and interest factors.

Life-Cycle Cost Procedures

Computational procedures are developed to combine the performance models with the cost models in order to reflect maintenance policies and user cost considerations.

Optimization Subsystem

The total expected cost of each design alternative is calculated, and the alternative with the minimum total expected cost that satisfies specified reliability constraints is determined. A ranking of all design alternatives on the basis of their total expected costs is also produced.

PAVEMENT PERFORMANCE SUBSYSTEM

For purposes of this investigation, performance is characterized in terms of the following distresses: fatigue cracking (caused by traffic), major transverse cracks (caused by material properties and surface environment), and roughness (caused by traffic). In addition, for projects to be designed in permafrost locations, roughness caused by differential thaw settlement was also considered. A prediction model was developed to estimate the progression of each distress type with time as a function of the initial design, expected traffic, and surface and subsurface environmental conditions. Expected values of each distress, as well as the dispersion around the expected values, were characterized in the development of the performance prediction models.

Because of constraints on space, only the prediction model for fatigue cracking is described in this paper. Details regarding all of the prediction models are provided in Kulkarni et al. (1).

Prediction Model for Fatigue Cracking

Fatigue cracking is a result of cumulative damage produced by repetitive loadings applied to a pavement. Damage is believed to be associated with the deflection-induced strains that occur in the underside of the asphalt concrete layers. Fatigue cracks are usually referred to as alligator cracks because of the resemblance of the crack patterns to that of the skin of an alligator.

Fatigue cracking is influenced by a wide variety of factors, including pavement thickness, layer thicknesses, material properties, environment (temperature, rainfall, frost penetration), and traffic loadings (weight and frequency). Models to predict fatigue cracking should incorporate as many of the enumerated characteristics as appropriate.

Three general models were considered for use in predicting fatigue cracking:

1. A mechanistic-empirical model (PDMAP) developed for NCHRP (2);
2. An empirical model (OPAC) reported by Meyer et al. (3); and
3. Empirical relationships reported by McHattie et al. (4).

The PDMAP program was considered a prime candidate during the planning phases of the project; however, the model was eventually eliminated because of the lack of sufficient information relative to material properties and detailed performance information. A less sophisticated but adequate model was developed for this study based on damage models reported by McHattie et al. (4). It is pertinent to note that the PDMAP procedures can be incorporated in the PDES program once more information is available for damage models and material properties.

To take advantage of the information reported in McHattie et al. (4), two assumptions were required, as follows.

1. The majority of fatigue cracking occurs during the critical thaw weakening season (period). Observations of fatigue cracking at the AASHO Road Test (5) indicated that the majority of cracking occurred during the spring thaw period. Similar findings are reported for Alaskan highways (4).
2. Traffic during periods of thaw weakening is proportional to the total annual traffic (in terms of equivalent 18-kip single-axle loads) over a site-specific project. Consequently, the total traffic for each given project can be used as an independent variable in the regression analysis of fatigue cracking data on different projects. Because the distribution of the annual traffic by periods of the year will not be necessary, this will simplify the estimation of traffic data.

A total of 120 special study sections were available for developing a fatigue cracking prediction model (4). Only sections with fatigue cracking were included in the analysis because the timing of when fatigue cracks would develop could not be estimated for uncracked sections. Several alternative regression equations were tried with different independent variables and their combinations. The final equation selected for PDES was as follows:

$$\log(FC) = -19.05 + 5.67 \log(BB) + 2.09 \log(EAL) \qquad (1)$$

where

FC = percentage of fatigue cracking in the section for both wheelpaths (ranges from 0 to 100 percent),
BB = surface deflection in 10^{-3}-in. units under 9-kip dual wheel load as measured with the Benkelman beam and represented by the mean deflection plus two standard deviations, and
EAL = annual equivalent 18-kip single-axle loads using AASHTO equivalency factors.

The square of multiple correlation coefficient for Equation 1 was 0.54.

Estimation of Inputs to Fatigue Cracking Prediction Model

In order for the designer to use the fatigue cracking prediction model, it will be necessary to estimate traffic and deflection for each design alternative. Traffic can be estimated based on available traffic count data for adjacent projects and the expected use of the new roadway. The deflection for each alternative design section is estimated by means of an elastic-layered structural analysis. The specific program incorporated into PDES is the N-LAYER program described by Schiffman (6).

The required inputs for the N-LAYER program to predict surface deflection under a standard 18-kip axle load are (a) elastic modulus of each layer of pavement, including foundation materials, during the critical period when most fatigue cracking occurs; and (b) thickness of each pavement layer. The data for the development of modular information were available from two sources: backup reports in McHattie et al. (4), as provided by Alaska Department of Transportation and Public Facilities (ADOTPF) staff; and information from Dynatest Consulting, Inc. (7).

Studies by ADOTPF research personnel have indicated that the occurrence of fatigue cracking is related to the percentage of fines in the aggregate. Information from Dynatest Consulting, Inc., provided data relative to the in situ moduli of asphalt concrete, aggregate base, and the supporting materials to a depth of 48 in. below the base. Thus an effort was made to predict the moduli of granular layers based on the percentage passing the No. 200 sieve. The moduli values used in developing the prediction model were the spring values reported by Dynatest Consulting, Inc.

The general form of the model was

$$MR = f(-200 \text{ in each layer}) \qquad (2)$$

where MR is the resilient modulus, equivalent to modulus of elasticity; and -200 is the percentage of fines passing the No. 200 sieve.

Specific regression equations were developed for the base course (usually the first 6 in. below the surface layer) and the granular layers below the base course. The development of these equations is described in Kulkarni et al. (1).

The modulus of the asphalt concrete layer has been set at 1.1×10^6 psi, which is representative of values used by Dynatest Consulting, Inc., during field testing with the falling weight deflectometer. This value is included as a default value in the N-LAYER program.

PAVEMENT COST SUBSYSTEM

The principal elements in the cost subsystem include

1. Initial and stage construction (including possible salvage value),
2. Routine maintenance,
3. Excess road user costs, and
4. Considerations of interest and inflation.

Each of these elements is responsive to a combination of designer inputs and prediction model outputs.

Estimation of Initial Costs

The cost subsystem can accommodate the initial and stage construction costs for two general cases: a roadway section that traverses an area where no permafrost is present, and a section that traverses an area where permafrost is present. For cost comparisons, mass grading is excluded. It is assumed that mass grading will be essentially the same for all alternatives.

The roadway section that traverses a nonpermafrost subgrade would consist of a non- or low-frost-susceptible borrow on which the pavement section is constructed. For those sections that traverse a subgrade with permafrost, additional embankment would be constructed before the borrow layer. The installation of insulation and the construction of thermal berms could also be accommodated.

Designer inputs would include those items necessary to establish the geometry of the section such as paved width, roadway width, fill slopes, thickness of pavement layers (asphalt concrete, aggregate base, aggregate subbase), thickness of borrow, thickness of insulation, thickness of unclassified fill, and the dimensions of the thermal berms. Stage construction is assumed to be the construction of bituminous surface treatment (BST) on aggregate base before construction of the asphalt concrete surface. For the stage construction alternate, the width of the BST would be required.

The designer would also be required to input unit costs for the various materials of construction in the units included in the following table:

Item	Unit
Asphalt concrete	\$/ton
Aggregate base	\$/ton
BST	\$/yd^2
Aggregate subbase	\$/ton
Borrow	\$/ton
Insulation	\$/yd^2/2-in. thickness
Unclassified fill	\$/yd^3

If some salvage value is associated with certain materials for a specified design alternative at the end of a selected analysis period, the unit costs for initial construction should be reduced by the present worth of the salvage value.

Estimation of Routine Maintenance Costs

Maintenance cost records from 1977 through 1980 were provided by the Information Systems Division of ADOTPF in Juneau. These data consisted of the annual cost per mile for those activities associated with maintenance of the pavement surface. The information was provided for selected major paved routes in the state's highway system. The activities currently reported for surface maintenance include pothole repair (Activity 002), skin patching and thin overlays (Activity 004), crack sealing (Activity 011), and seal coats (Activity 012). The paved highway performance evaluation data for 1978, 1979, and 1980 were used to establish relationships between performance and routine maintenance costs.

Information on the suspected locations of permafrost was obtained by examining the raw data printouts from the Mays meter. There is a characteristic signature produced by the Mays meter graph that has been correlated with areas where permafrost is known to exist. The Mays meter records for all of the major routes were examined and the limits of suspected permafrost were identified. In almost all cases section lengths were less than 0.2 mile.

Although clear relationships between distress (as reported in the road inventory) and maintenance costs could not be identified, examination of the data did reveal general trends. By using these trends and engineering judgments, relationships were developed between fatigue cracking, traffic roughness, and thaw settlement roughness observed for a given year and routine maintenance costs for that year based on 1980 dollars. Only the relationship between fatigue cracking and routine maintenance costs is summarized in this paper. Details regarding all the relationships can be found in Kulkarni et al. (1).

For fatigue crack sealing (Figure 2), the first portion of the curve represents repair by crack filling, which might occur during the early stages of fatigue crack development. It was estimated that when more than 30 percent of the road section length has fatigue cracking, the choice would be the construction of a seal coat, which is represented by the linear portion of the curve.

Estimation of Excess Road User Costs

The roughness of a pavement can contribute to road user cost by increasing running time and operating cost. In considering excess road user cost (i.e., those road user cost differentials that are caused by pavement roughness only), it was decided to limit

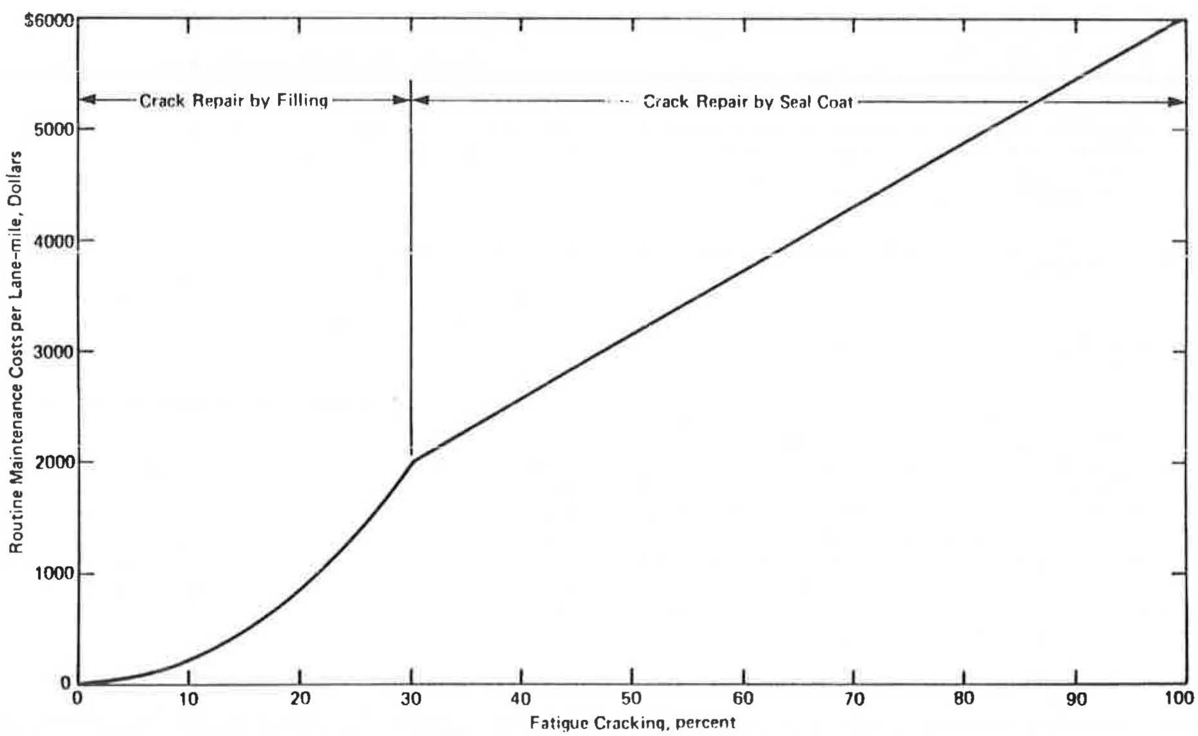

FIGURE 2 Relationship between routine maintenance cost and fatigue cracking.

the analysis to the estimation of excess cost experienced by commercial vehicles. Not included are excess road user costs associated with the operation of private vehicles. The differential operating costs are probably quite small, and noncommercial driver time may not have a significant dollar value.

A relationship was developed from information contained in the literature and from interviews with two trucking companies, which allowed the estimation of excess user costs as discussed in the following sections.

Differential Running Time

Zaniewski et al. (8) reported on a relationship that was developed between riding comfort and speed and includes such factors as volume/capacity ratio and speed limit. With riding comfort converted to present serviceability index (PSI) and speed to miles per hour, this relation becomes:

$$S = 2.404\,(PSI)^{0.0928}\,(v/c)^{-0.0275}\,(SL)^{0.704} \qquad (3)$$

where

S = speed (mph),
v/c = volume/capacity ratio, and
SL = speed limit (mph).

The Mays meter used for roughness measurements on Alaskan highways has not been correlated to PSI as of this date. A method of correlating PSI with Mays meter readings is contained in Walker and Hudson (9). McHattie et al. (4) indicated that the average PSI for paved Alaskan highways was 2.2. The average Mays meter reading for the 1,200 miles of paved highway in the sample included in this study was 91 in 1980. Using this information, the following relationship was developed:

$$PSI = 5\,\exp[-(\ln M/4.7)^5] \qquad (4)$$

where exp is the base of the natural logarithms, and M is the Mays meter readings (in./mile).

Combining Equations 3 and 4 results in the following relationship between speed and Mays meter reading:

$$S = 50\,(v/c)^{-0.0275}\,\exp[-(\ln M/4.7)^5] \times 0.0928 \qquad (5)$$

This equation uses a speed limit of 60 mph. Although this is not the speed limit in the state, the use of 60 mph provides calculated average speeds that correspond more closely to the relationship between average speed and roughness obtained from interviews with trucking companies. For an average driver cost of $33/hr, the average cost per Mays meter inch per mile over a wide range of roughness is $0.00055.

Differential Operating Costs

The estimated average cost per mile for operating a four-axle tractor and multiaxle semitrailer on Alaskan highways is $0.92. Included in this cost are fuel and oil, tires, depreciation, and maintenance and repair. In response to questions to trucking companies regarding an increase in costs when operating on extremely rough roads, it is estimated that the operating cost increase is $0.00125 per Mays meter inch per mile.

Total Excess Road User Costs

Combining driver cost and operating cost, the total excess road user cost for large long-haul vehicles is estimated to be $0.0018 per Mays meter inch per mile per truck. With the lowest Mays meter reading observed of about 30 in./mile, the excess road user cost then becomes $0.0018 (M - 30).

A relationship was developed between equivalent axle loads (EALs) and excess road user cost. Using EAL constants developed for California and taking into consideration the greater axle load limit in Alaska, it is estimated that the heavy truck-trailer combination for which the excess road user costs were developed has an EAL equivalent of 3.25. The excess road user cost caused by roughness can be expressed as follows:

$$\begin{aligned}\text{Excess road user cost} &= \$0.0018/3.25\\ &= \$0.00055\,(M-30)\ \text{per EAL per mile}\end{aligned} \qquad (6)$$

Estimation of Interest and Inflation Factors

Epps and Wootan (10) recommend that the interest rate to be used in economic studies of this type should represent the real cost of capital. That is, it should be the actual rate of return on assets after inflation. They report that since 1966 the inflation-free interest rate has ranged from 3.7 to 4.4 percent. This represents approximately the difference between interest and inflation. It is interesting to note that although interest and inflation rates have varied considerably since 1966, the differential has remained nearly constant.

Because maintenance is labor intensive, the largest contributor to inflation of maintenance costs would be salary increases. It is reported that this has been at a rate of 8.5 percent during the past few years. The Planning and Programming Division of ADOTPF recommends an interest rate of 10.5 percent for studies of this type. Although this rate may be artificially low, it is used to provide uniformity throughout the state. An interest rate around 15 percent may be more realistic. Because the rates of inflation for construction costs, maintenance costs, and user costs may be different, PDES allows the user to input different rates of inflation for these cost components. A common interest rate is then used to convert the inflated costs incurred at different times into their present worth.

LIFE-CYCLE COST PROCEDURES

Figure 3 shows the logic used in calculating life-cycle costs. Input parameters shown in Figure 3 are used to develop prediction models for the relevant pavement performance variables. Various cost components are then estimated as a function of the performance variables.

The procedures used to incorporate uncertainties in pavement performance and to calculate different life-cycle cost components are described in the following sections.

Treatment of Uncertainties

Because of the uncertainties in predicting roughness and fatigue cracking, exact routine maintenance costs or user costs cannot be estimated for any one year. However, the probability that roughness or fatigue cracking would be equal to a specific value can be estimated. For given values of the two performance variables, costs could then be estimated.

The continuous probability distributions of roughness and fatigue cracking at any given time were discretized into 10 intervals, each with a probability of 0.10, and the median value for that interval was assumed to represent that interval. For a variable X, the 10 intervals and their representa-

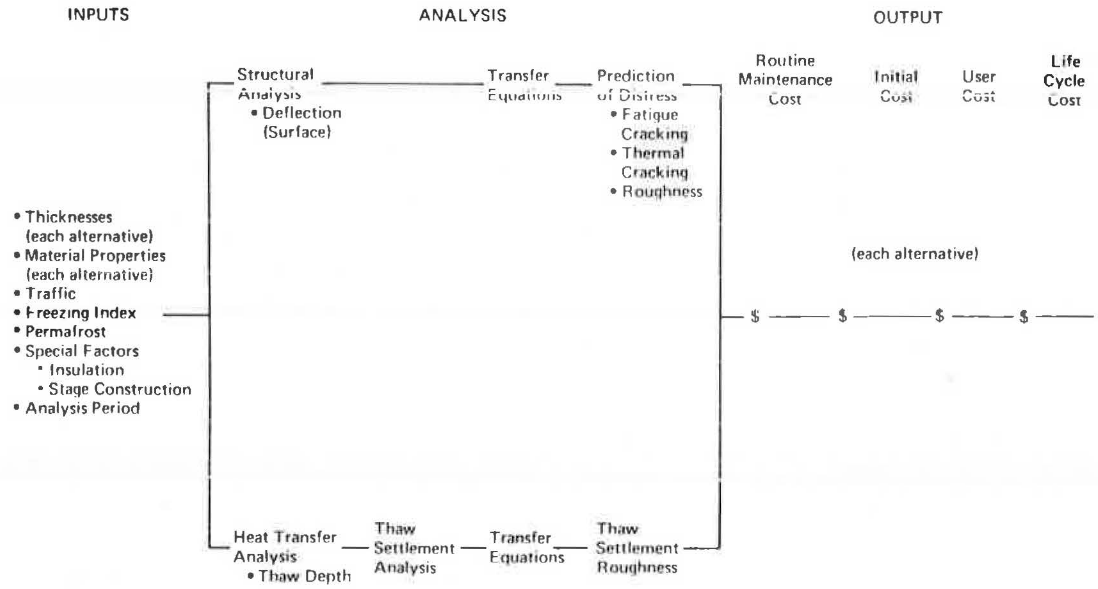

FIGURE 3 Life-cycle cost logic.

tive values were as follows (X_p denotes the value of X such that the probability of being less than or equal to X_p is p):

Interval	Representative Value
$X_{0.9} - X_{1.0}$	$X_{0.95}$
$X_{0.8} - X_{0.9}$	$X_{0.85}$
$X_{0.7} - X_{0.8}$	$X_{0.75}$
$X_{0.6} - X_{0.7}$	$X_{0.65}$
$X_{0.5} - X_{0.6}$	$X_{0.55}$
$X_{0.4} - X_{0.5}$	$X_{0.45}$
$X_{0.3} - X_{0.4}$	$X_{0.35}$
$X_{0.2} - X_{0.3}$	$X_{0.25}$
$X_{0.1} - X_{0.2}$	$X_{0.15}$
$X_{0} - X_{0.1}$	$X_{0.05}$

If X is normally distributed with mean μ and standard deviation σ (or coefficient of variation $c = \sigma/\mu$), then X_p can be calculated from $X_p = \mu + k_p\sigma$, where k_p is a value from normal probability tables that corresponds to the cumulative probability of p.

It was assumed that if a pavement performs worse or better than the average at one time, it would continue to perform the same way at any other time. This is a reasonable assumption, because for a given project traffic and environmental conditions are fixed, and future pavement performance would depend on factors such as initial design and quality of construction that are determined at the time of construction. With this assumption, the performance values (X_p) at different time periods were connected to obtain a performance curve such that the probability of being less than or equal to the value on this curve at any given time would be p. Corresponding to 10 values of p, 10 different performance curves were thus defined for fatigue cracking and total roughness. This is shown schematically in Figure 4.

For each performance curve, maintenance cost and user cost were calculated by using the procedures described in the following sections. The expected costs at time t were then calculated by averaging the 10 values of the cost at that time. A standard deviation of the cost was also calculated by considering the deviations from the expected cost.

Initial Costs

The initial costs of each design alternative are calculated from the specification of the cross section of the design and properties of different layers (thickness, density, material, insulation), and unit construction costs. Volumes, weights, or areas of different quantities are calculated, multiplied by the appropriate unit costs, and summed to obtain cost per lane-mile.

For stage construction, the construction cost of the first stage is combined with the present worth cost of the second stage to obtain the total initial cost.

If some salvage value is appropriate to consider for a particular design alternative at the end of the analysis period, the unit costs should be reduced by the amount of the present worth of the salvage value of different materials (asphalt concrete, aggregate, and so forth).

Maintenance Costs for Fatigue Cracking

The maintenance policy used to estimate costs for fatigue cracking is shown in Figure 5. The basic fatigue cracking model estimates, with some uncertainty (not shown), that the amount of fatigue cracking will first reach 10 percent at year t_1. Maintenance will then be initiated that will correct the condition, bringing fatigue cracking to zero. Fatigue cracking will continue to develop according to the initial prediction curve. When the 10 percent cracking level is exceeded again at year t_2, maintenance will again be initiated to correct the condition. The maintenance cost is estimated as a function of the percentage of fatigue cracking in the year of maintenance. The process is repeated to time T for which the comparisons of alternate designs are to be made. Time T should be equal to or greater than the time required to develop 10 percent cracking in the most effective design. Alternatively, the user may specify an analysis period that is greater than the maximum design life of the strongest section. It is recommended that the user use an analysis period of 15 to 20 years. The program is currently limited to a maximum 25-year analysis period.

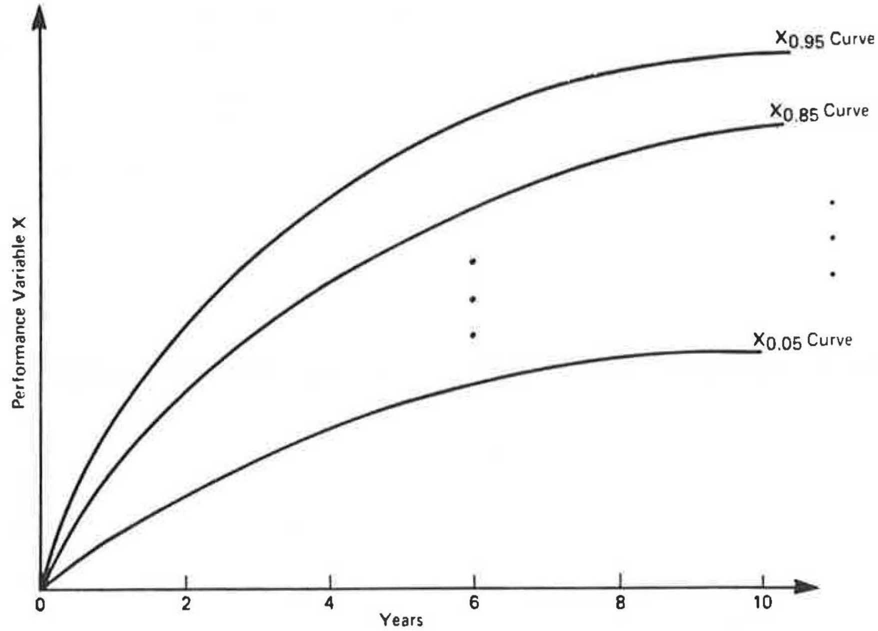

FIGURE 4 Treatment of uncertainties in performance prediction.

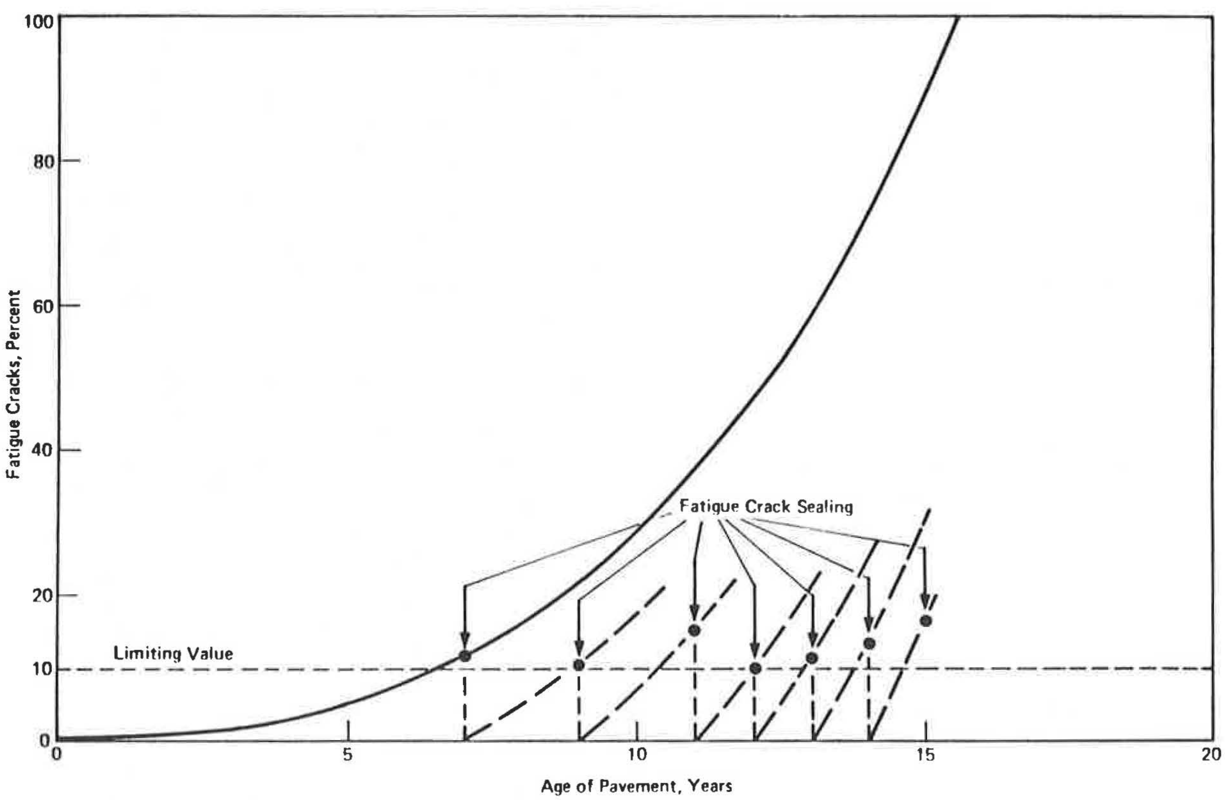

FIGURE 5 Fatigue crack sealing policy.

The expected maintenance cost for fatigue cracking in ith year [EMCF(i)] is given by

$$EMCF(i) = \Sigma\, MCF(i,FC_p)\, P(FC_p) \quad (7)$$

where $MCF(i,FC_p)$ is the maintenance cost for fatigue cracking in the ith year if the performance FC_p is followed, and $P(FC_p)$ is the probability of the performance curve FC_p.

Because 10 equiprobable performance curves are generated in the program, Equation 7 can be simplified to

$$EMCF(i) = (1/10)\, \Sigma\, MCF(i,FC_p) \quad (8)$$

The present worth of the total expected maintenance cost for fatigue cracking (TMCF) during an analysis period of T years is calculated from

$$TMCF = \sum_{i=1}^{T} \alpha_i \, EMCF(i) \quad (9)$$

where

α_i = present worth factor = $[(1 + I_m)/(1 + I_d)]^i$,
I_m = inflation rate for maintenance activities, and
I_d = interest rate for discounting.

Maintenance Costs for Total Roughness

The process here is similar to the one described for fatigue cracking. The limiting value of roughness is assumed to be 160, and maintenance is assumed to reduce roughness to 130. Maintenance cost is a function of the percentage reduction in the roughness at the year in which maintenance takes place.

For stage construction, the second stage is assumed to reduce roughness to a mean value of 35 and a coefficient of variation equal to that assumed for roughness at any other time.

Equations for calculating the expected maintenance cost for roughness in ith year [EMCR(i)] and the present worth of the total expected maintenance cost for roughness (TMCR) during T years are similar to Equations 8 and 9, respectively. Thus,

$$EMCR(i) = (1/10) \sum MCR(i,R_p) \quad (10)$$

and

$$TMCR = \sum_{i=1}^{T} \alpha_i \, EMCR(i) \quad (11)$$

User Costs

Expected user costs for year i [EUC(i)] are calculated as a function of unit user cost in dollars per inch of roughness per EAL, total estimated roughness in a given year, and the number of EALs for that year. Thus

$$EUC(i) = (1/10) \sum UC(i,R_p) \times EAL(i) \quad (12)$$

where $UC(i,R_p)$ is the user cost ($/EAL) in the ith year if the total roughness curve R_p is followed, and EAL(i) is the number of EALs during the ith year.

The present worth of the total expected user costs (TUC) for T years is obtained from

$$TUC = \sum_{i=1}^{T} \beta_i \, EUC(i) \quad (13)$$

where

$$\beta_i = [(1 + I_u)/(1 + I_d)]^i \quad (14)$$

and I_u is the inflation rate for user costs.

Total Cost

The present worth of the total expected cost (TEC) during an analysis period of T years is the sum of individual cost components during T years. Thus

$$TEC = I_o + TMCF + TMCR + TUC \quad (15)$$

where I_o is the initial construction cost.

OPTIMIZATION SUBSYSTEM

The primary objective of PDES is to rank design alternatives on the basis of their minimum total expected costs. Because of the uncertainties in the prediction of pavement performance, consideration should be given to achieving some minimum reliability of satisfactory performance in addition to minimizing total expected cost. Reliability is defined here as the probability that a pavement would not reach a limiting condition within a specified time period. Mathematically, the reliability constraints can be stated as follows:

$$P\,[X > X^* \text{ in time } t^*] \leq \alpha \quad (16)$$

This constraint states that the probability that the performance variable X exceeds a limiting value X* in time t* should be less than or equal to α. The reliability level associated with this specification will be $1 - \alpha$. The values of X*, t*, and α are provided by the user. This constraint is used both for fatigue cracking and total roughness in PDES. If a design alternative does not satisfy the reliability constraint for both fatigue cracking and total roughness, that alternative is considered infeasible and is not included further in the cost calculations. Only feasible design alternatives are ranked on the basis of their total expected cost.

SUMMARY AND CONCLUSIONS

The development of a PDES to rank alternative pavement designs in Alaska on the basis of life-cycle costs is described. Two main components of this system are pavement performance models and cost models. The performance variables for which prediction models were developed are roughness caused by cumulative application of traffic loading, roughness caused by thaw settlement in permafrost regions, fatigue cracking, and major transverse cracking. The major cost components of PDES are initial cost of construction, cost of routine maintenance, possible salvage value, and user costs.

Recommendations for future improvements in PDES include

1. Systematic and continuing collection of pavement performance data and adjustment of performance prediction models based on these data,
2. Accumulation of materials information necessary for mechanistic analysis of multilayered pavement systems and incorporation of more comprehensive mechanistic prediction models,
3. Development of improved modular values for the granular materials based on both field (falling weight deflectometer) and laboratory studies, and
4. Special studies (with somewhat limited scope) to obtain data on routine maintenance costs and excess user costs.

Although PDES is a stand-alone system for estimating life-cycle costs of alternative initial designs and selecting the minimum cost design, it can be expanded to fit into a broader pavement management system (PMS). This would involve the evaluation of combinations of initial designs and subsequent rehabilitation strategies such as overlays or possibly reconstruction. Most of the present structure of PDES, including the cost and performance prediction models, can be used in the development of a PMS suitable for Alaskan conditions.

In summary, PDES is a comprehensive procedure for ranking alternate pavement designs based on performance and cost expectations, while recognizing the uncertainty associated with each consideration. As a tool for the designer and decision maker, PDES will provide a means of documenting and justifying specific design selections for site-specific projects contemplated for construction in Alaska.

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