# Development of a Methodology to Estimate Pavement Maintenance and Repair Costs for Different Ranges of Pavement Condition Index

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**This paper presents a network-level procedure for determining the best maintenance and repair alternative and its associated cost for different pavement categories at different Pavement Condition Index ranges. Data from a number of military installations in the United States were used, and the analysis was performed separately for each installation. The methodology developed included techniques for *(a)* Determining the fixed initial construction cost of each alternative based on local prices; *(b)* Determining the cost of pavement preparation before repair as a function of pavement type, condition, local prices, and installation policy for pavement preparation; *(c)* Determining the annual cost of routine maintenance of each maintenance and repair alternative as a function of pavement condition, local prices, and installation maintenance policy; *(d)* Determining pavement performance characteristics (service life and rate of serviceability deterioration) for various pavement categories; and *(e)* Conducting a life-cycle cost analysis of each alternative for all pavement categories at various Pavement Condition Index ranges using the equivalent uniform annual cost approach.**

After several decades of adequate service, pavements on military installations, like those of the rest of the other highway systems, are deteriorating at a fast rate. In recent years, maintenance and repair activities have not been able to keep pace with the rate of deterioration of highway pavements. This impending infrastructure crisis has confronted military pavement engineers with questions for which they have no ready or documented answers. The difficulty of assessing maintenance and repair needs, budget requirements, maintenance and repair alternatives and their cost-effectiveness, has resulted in the development of a systematic pavement management system (PAVER) by the U.S. Army Corps of Engineers *(1)*.

The PAVER system consists of a computerized data base and a number of programs that store, retrieve, and manipulate data, as well as perform a variety of analyses and calculations required for network and project-level decisions. PAVER's capabilities include: *(a)* data storage and retrieval, *(b)* pavement network identification, *(c)* pavement condition rating, *(d)* project priority setting, *(e)* inspection scheduling, *(f)* maintenance and repair needs determination, *(g)* resource planning, and *(h)* economic analysis and budget planning.

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The Pavement Condition Index (PCI) is the basis for the PAVER pavement management system. The PCI is a scale from 0 to 100, with 100 being excellent, and is determined based on measured distress type, severity, and amount.

The PAVER system was developed to assist installation engineers and planners with pavement management by providing an extensive data base and valuable computational and report-generating capabilities. One of its most useful and widely used network-level planning programs is its budget-planning report, or BUDPLAN. The execution of BUDPLAN and a number of other programs requires the user to input area unit costs for maintenance and repair alternatives at various pavement conditions (PCI ranges). Based on predicted pavement condition and input unit costs, PAVER computes a 5-year maintenance and repair budget. These estimates can then be used to justify present and future funding requests.

The estimation of unit costs for maintenance and repair activities at various PCI values requires that the user be familiar with the PAVER system and have complete maintenance and repair records. As the PAVER system is only now being implemented at many military installations, or at most has been on-line for a few years, it is doubtful that system users can generate valid cost estimates. Furthermore, an error in unit cost data, in relation to pavement condition, can result in erroneous estimates of budget needs.

The overall objective of this research project was to develop a rational procedure by which unit maintenance and repair costs at a given installation could be estimated as a function of pavement condition. Based on results from this study, average square yard costs for different pavement categories at various pavement condition ranges can be incorporated into the PAVER system or used as guidelines by PAVER users.

## STUDY APPROACH

In order to develop reasonable cost estimates and relate them to the PCI levels, several tasks were performed, as discussed below.

1. Development of a comprehensive data base that includes all necessary information. This was done through the modification

and screening of the PAVER data bases available through the Construction Engineering Research Laboratory (CERL) of the U.S. Army Corps of Engineers.

2. Grouping of pavements into classes based on construction type and traffic levels.
3. Grouping of maintenance and repair alternatives into a number of discrete activities, which were: annual routine maintenance, surface treatment, thin overlay, thick overlay, and reconstruction.
4. Grouping of PCI values into ranges (0–20, 20–40, 40–60, 60–80, and 80–100).
5. Analysis of life-cycle costs for each pavement class to determine the most cost-effective maintenance and repair alternative for each PCI range.
6. Development of a relationship between the PCI and maintenance and repair costs for each pavement class.

In the remainder of this paper, each of these tasks is described in detail. Results from different military installations are also presented as an example.

## DATA BASE DEVELOPMENT

The main source of the data used in this research was the PAVER data bases made available through CERL. However, several modifications were carried out to reduce and screen the available data to a form suitable for the objectives of this project. The data base included detailed information from five military installations (Fort Eustis, Fort Knox, Great Lakes, Sierra Army Facility, and Tulsa) and consisted of 2,517 records. Each record included the following main categories of information:

1. Section identification
   - Military installation code
   - Inspection number
   - Section length
   - Other items
2. Pavement rank (traffic category)
3. Pavement structure
   - Surface type, thickness, and date of construction
   - Base type, thickness, and date of construction
   - Other items
4. Pavement condition
   - Inspection date
   - Amount and severity level of each distress type and associated deduct points
   - Overall PCI

## PAVEMENT CLASSIFICATION

Pavement sections were grouped based on structure type and traffic level. Although initially it was found that there were 14 pavement structure types, it was decided to group them into four major categories: *(a)* asphalt concrete, *(b)* surface treatment, *(c)* thin overlay (less than 2 in.), and *(d)* structural overlay (more than 2 in.). Traffic level was also considered through grouping pavement sections based on their rank. Three basic pavement ranks are used in the PAVER system: primary, secondary, and tertiary, with primary being the rank with highest traffic level. Thus, pavement sections were grouped into 12 classes (four pavement structure types and three pavement ranks or traffic levels).

It should be noted that this study was limited to nonfamily, asphalt roadways only. Results may not be applicable to parking lots, airfields, or rigid and asphalt-overlaid rigid pavement. However, the methodology described in this paper can be used to develop similar results for any pavement type.

## PCI RANGES

Since the objective of this research was to develop relationships between unit costs and pavement condition as defined by the PCI, it was necessary to establish the PCI ranges for which unit cost information was to be developed. To comply with the BUDPLAN report's input requirements, it was decided to use the following five PCI ranges:

PCI 81–100
PCI 61–80
PCI 41–60
PCI 21–40
PCI 0–20

## MAINTENANCE AND REPAIR ACTIVITIES

In selecting maintenance and repair (M&R) activities to be included in this study, two items were considered. First, the selected M&R actions were comparable to those listed in the available data base, otherwise it would have been impossible to have obtained performance and cost information on any of the activities. Second, general groups of these maintenance and repair activities were included, rather than specific project-level activities, because the research was conducted at the network level. The following maintenance and repair actions were found to be common to all installations:

Annual maintenance only
Surface treatment
Thin overlay (< 2.0 in.)
Structural overlay (> 2.0 in.)
Reconstruction

It should be noted that in some cases reconstruction includes both the base and surface courses, while in other cases reconstruction includes only the surface course. Furthermore, although recycling was initially included as an option, installations included in this study do not consider it to be cost-effective for small-scale rehabilitation projects. Discussions with installation engineers and reviews of past contract documents indicated that each installation's definition of various M&R actions and what they consist of was somewhat different. Therefore, it was necessary that unit cost estimates be derived separately from the work items that are commonly included in each M&R alternative at each installation. As the work items for a particular M&R alternative are different at different installations, a weighted average approach was used to estimate unit activity costs by considering the percentage of times a particular work item was included in the data on the number of projects for a particular M&R alternative in an installation.

## SELECTION OF MOST COST-EFFECTIVE MAINTENANCE AND REPAIR ALTERNATIVE

The purpose of this section is to illustrate the procedure used to select the most cost-effective maintenance and repair alternative. The methodology is based on a comparison of alternatives using a life-cycle costing procedure. Life-cycle costing was based on both the cost and performance of each alternative.

### Maintenance and Repair Unit Costs

To estimate the life-cycle cost of any alternative, both its service life and its unit cost must be known. Unit costs associated with each repair alternative included initial cost and routine or annual maintenance costs during the service life of the alternative. User costs were not considered, because the role of user costs on low volume military roads is not well established. Furthermore, since the results of this project will be used for budget estimates, results in terms of agency costs only are relevant.

### Initial Costs

Initial costs of any M&R alternative are made up of both a fixed-cost component and a variable-cost component. The variable-cost component depends on the amount of pavement preparation required. The methodology used to determine both components is described below.

### Fixed Initial Cost

The fixed initial cost of an M&R alternative is a function of both the local prices and the physical layout of the installation's highway system. The total square-yard fixed-unit cost for each maintenance and repair alternative was calculated using the following simple cost formula:

$$T_k = \sum_{i=1}^{n} C_{ik} * F_{ik} \qquad (1)$$

where

$T_k$ = total square yard fixed cost for the $k$th M&R alternative,
$C_{ik}$ = average square yard unit cost for the $i$th cost item used in the $k$th M&R alternative,
$F_{ik}$ = frequency of use of the $i$th cost item in the $k$th M&R alternative, and
$n$ = total number of cost items.

Various cost items are not uniformly used every time an activity is undertaken. Unit costs along with frequencies of use of different cost items were obtained through field visits to different installations where key project information such as the project specifications, quantity estimates, and actual bid abstracts were reviewed. The frequency of use of a cost item for a specific M&R alternative was determined by dividing the number of times an item was used by the total number of projects in this alternative. The frequency of use factor was used to reflect the degree of use of different cost items, which may vary significantly from location to location.

### Cost of Pavement Surface Preparation

The second component of any M&R alternative's initial cost is the expense associated with pavement preparation before the application of the M&R alternative. Pavement preparation cost depends on two key factors: *(a)* pavement condition at repair time, and *(b)* local repair policy that determines what surface preparation is to be done before executing a specific repair activity.

Surface preparation cost was related to PCI level through the use of the distress density matrix after the identification of each installation's surface preparation policy. Distress density is defined as the percent of section area indicating a specific distress type and severity level. The density matrix of a specific pavement class summarizes the average density values for each PCI range by distress type-severity level combination. In this project a density matrix was developed for each pavement class within the five military installations. An example of the density matrix is presented in Table 1.

An installation's surface preparation policy was obtained through interviews with facility engineers. From these interviews, both the installation policy in terms of actions taken to prepare pavement surface before repair and the associated unit cost were obtained. For example, considering the average of all installations, it was found that pavements with high-severity alligator cracking are usually maintained or the surface prepared with deep patches at an average cost of $3.60/yd$^2$. A surface preparation policy was identified for each installation to indicate the action and associated unit cost for different distress type-severity conditions. An example is shown in Table 2.

### Calculation of Surface Preparation Costs

The average density values obtained from the density matrix were combined with the installation surface preparation policy to arrive at a total surface preparation cost by PCI range as follows:

$$PC_{kl} = .09 - \sum_{i=1}^{19} \sum_{j=1}^{3} * D_{ij} * C_{ij} \qquad (2)$$

where

$PC_{kl}$ = total surface preparation cost for the $k$th surface type at the $l$th PCI range;
$i$ = distress type (1, . . . , 19);
$j$ = distress severity levels (1, 2, 3);
$D_{ij}$ = average density (percent) of the $i$th distress type with $j$th severity-level combination for a PCI range;

$C_{ij}$ = unit cost of surface preparation required for the $i$th distress type with $j$th severity-level combination; and

.09 = constant to convert $ft^2$ to $yd^2$ costs and to change density from a percent value to a ratio.

A sample calculation is illustrated in Table 3. Assume a pavement has only three distress type-severity level combinations for a PCI range of 61 to 80, and that unit surface preparation costs are as shown.

### Determining Total Initial Costs

Finally, total initial cost (fixed + surface preparation) was calculated for each M&R alternative for all pavement classes by PCI range for each installation.

### Annual Routine Maintenance Costs

Annual routine maintenance costs, like surface preparation costs, are a function of pavement condition, local prices, and local installation policy. Each factor was determined using the same procedure as outlined for surface preparation cost. Total unit costs were calculated using Equation 2. Although the same density matrices were used, routine maintenance policy differed substantially from surface preparation policy, and thus the unit cost values for each distress type ($C_{ij}$) would be markedly different. An example of annual maintenance policy is shown in Table 4.

### Pavement Performance

Life-cycle costing requires the determination of pavement service life and rate of performance deterioration. Therefore, a substantial effort was made in the development of PCI versus age relationship for each pavement class. The expected life of an M&R alternative is usually based on engineering judgment and experience, with consideration given to local materials, environmental factors, and traffic levels. However, this subjective evaluation usually leads to wide variation in estimated service life. Additionally, most definitions of service life and deterioration rates in the literature are usually not explicit and certainly not in terms of PCI values. In addition, as performance is so dependent on local materials and environmental factors, it would be difficult to relate service life for pavements from different locations. For this research project, it was decided to use the available data base to develop aggregate estimates of pavement performance.

To model pavement performance, both the graphical capabilities of the microcomputer data base manager, KMAN *(2)*, and the statistical procedures of the package SPSS *(3)* were used to test a large number of models. The best model was in the following form:

$$C = 100 - b\,x^m$$

where

$C$ = pavement condition expressed in terms of PCI,
$b$ = slope coefficient,
$m$ = parameter whose value controls the degree of curvature of the performance curve, and
$x$ = pavement age (months).

TABLE 1 DENSITY MATRIX FOR ALL CLASSES

| Distress Code | Severity No. | Average 81–100 | Density 61–80 | (Percent) 41–60 | By PCI Range 21–40 | 0–20 |
|---|---|---|---|---|---|---|
| 1 | 1 | 0.32 | 1.15 | 5.54 | 11.36 | 9.46 |
| 1 | 2 | 0.13 | 0.20 | 1.80 | 10.24 | 14.09 |
| 1 | 3 | 0.03 | 0.04 | 0.39 | 1.05 | 14.02 |
| 2 | 1 | 0.30 | 0.89 | 1.04 | 1.02 | 1.25 |
| 2 | 2 | 0.02 | 0.17 | 0.37 | 1.08 | 0.56 |
| 2 | 3 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| 3 | 1 | 0.57 | 11.45 | 6.90 | 5.46 | 3.23 |
| 3 | 2 | 0.06 | 0.93 | 5.80 | 8.01 | 7.42 |
| 3 | 3 | 0 | 0.01 | 0.13 | 0.59 | 2.58 |
| 4 | 1 | 0.01 | 0.01 | 0.03 | 0.02 | 0.01 |
| 4 | 2 | 0.00 | 0.00 | 0.00 | 0.01 | 0.05 |
| 4 | 3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 |
| 5 | 1 | 0.01 | 0.17 | 0.15 | 0.03 | 0.07 |
| 5 | 2 | 0.00 | 0.00 | 0.01 | 0 | 0.19 |
| 5 | 3 | 0 | 0.00 | 0.00 | 0 | 0 |
| 6 | 1 | 0.05 | 0.11 | 0.25 | 0.26 | 0.28 |
| 6 | 2 | 0.01 | 0.03 | 0.15 | 0.17 | 0.47 |
| 6 | 3 | 0.00 | 0.00 | 0.03 | 0.05 | 0.16 |
| 7 | 1 | 0.53 | 0.66 | 0.72 | 0.70 | 0.48 |
| 7 | 2 | 0.22 | 0.88 | 1.51 | 1.26 | 1.10 |
| 7 | 3 | 0.04 | 0.20 | 0.50 | 0.81 | 2.25 |
| 8 | 1 | 0.13 | 0.23 | 0.23 | 0.03 | 0 |
| 8 | 2 | 0.06 | 0.25 | 0.30 | 0.18 | 0 |
| 8 | 3 | 0.01 | 0.02 | 0.03 | 0.02 | 0.01 |
| 9 | 1 | 0.27 | 0.15 | 0.13 | 0.11 | 0.13 |
| 9 | 2 | 0.31 | 0.44 | 0.22 | 0.22 | 0.10 |
| 9 | 3 | 0.14 | 0.26 | 0.34 | 0.21 | 0.05 |
| 10 | 1 | 1.53 | 2.83 | 2.50 | 1.57 | 0.86 |
| 10 | 2 | 0.30 | 0.82 | 1.41 | 1.78 | 1.05 |
| 10 | 3 | 0.01 | 0.03 | 0.08 | 0.16 | 0.16 |
| 11 | 1 | 0.32 | 0.74 | 1.19 | 1.67 | 0.79 |
| 11 | 2 | 0.09 | 0.20 | 0.84 | 1.15 | 2.44 |
| 11 | 3 | 0.00 | 0.02 | 0.14 | 0.44 | 1.13 |
| 12 | 1 | 0 | 0 | 0 | 0 | 0 |
| 12 | 2 | 0 | 0 | 0 | 0 | 0 |
| 12 | 3 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1 | 0.00 | 0.00 | 0.01 | 0.03 | 0.28 |
| 13 | 2 | 0.00 | 0.00 | 0.01 | 0.02 | 0.19 |
| 13 | 3 | 0.00 | 0.00 | 0.01 | 0.02 | 0.37 |
| 14 | 1 | 0.10 | 0.02 | 0.01 | 0.11 | 0 |
| 14 | 2 | 0.01 | 0.02 | 0.00 | 0.06 | 0.09 |
| 14 | 3 | 0.04 | 0 | 0 | 0.08 | 0.36 |
| 15 | 1 | 0.11 | 0.36 | 1.17 | 1.80 | 2.39 |
| 15 | 2 | 0.04 | 0.10 | 0.73 | 0.80 | 1.66 |
| 15 | 3 | 0.07 | 0.05 | 0.18 | 0.45 | 2.02 |
| 16 | 1 | 0.01 | 0.05 | 0.01 | 0.01 | |
| 16 | 2 | 0.00 | 0.00 | 0.05 | 0.00 | |
| 16 | 3 | 0.00 | 0.00 | 0.00 | 0 | 0 |
| 17 | 1 | 0.00 | 0.00 | 0.01 | 0.04 | 0.00 |
| 17 | 2 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| 17 | 3 | 0 | 0 | 0 | 0.00 | 0.02 |
| 18 | 1 | 0.00 | 0.00 | 0 | 0 | 0.00 |
| 18 | 2 | 0 | 0.00 | 0 | 0.00 | 0.01 |
| 18 | 3 | 0 | 0 | 0 | 0 | 0 |
| 19 | 1 | 4.49 | 12.44 | 17.15 | 19.57 | 11.25 |
| 19 | 2 | 0.56 | 1.18 | 6.60 | 10.84 | 17.31 |
| 19 | 3 | 0.06 | 0.08 | 0.42 | 6.04 | 23.74 |

TABLE 2 IDEAL SURFACE PREPARATION POLICY: FORT KNOX

| Distress Type | Severity | Method | Unit | Unit Cost ($) |
|---|---|---|---|---|
| Alligator cracking | H | Deep patch | SF | 2.98 |
| | M | Shallow patch | SF | 1.78 |
| | L | Seal coat | SF | 0.12 |
| Bleeding | H | Seal coat | SF | 0.12 |
| | M | Seal coat | SF | 0.12 |
| Block cracking | H | Shallow patch | SF | 1.70 |
| | M | Seal coat | SF | 0.12 |
| Bumps/sags | H | Shallow patch | SF | 1.78 |
| | M | Skin patch | SF | 1.01 |
| Corrugation | H | Shallow patch | SF | 1.78 |
| | M | Skin patch | SF | 1.01 |
| Depressions | H | Shallow patch | SF | 1.78 |
| | M | Skin patch | SF | 1.01 |
| Edge cracking | H | Deep patch | LF | 4.47 |
| | M | Shallow patch | LF | 2.23 |
| Lane/shoulder dropoff | H | Grade and add gravel | LF | 0.38 |
| | M | Grade and add gravel | LF | 0.28 |
| Longitudinal transverse cracking | H | Crack seal | LF | 1.42 |
| | M | Crack seal | LF | 1.01 |
| | L | Crack seal | LF | 0.31 |
| Patching and utility cut patching | H | Replace patch | SF | 2.98 |
| | M | Crack seal | SF | 1.68 |
| Potholes | H | Deep patch | Each | 9.36 |
| | M | Deep patch | Each | 2.32 |
| | L | Shallow patch | Each | 1.39 |
| Rutting | H | Deep patch | SF | 2.98 |
| | M | Shallow patch | SF | 1.78 |
| | L | Skin patch | SF | 1.01 |
| Shoving | H | Shallow patch | SF | 1.78 |
| | M | Shallow patch | SF | 1.78 |
| Slippage crack | H | Shallow patch | SF | 1.78 |
| | M | Shallow patch | SF | 1.78 |
| Swell | H | Shallow patch | SF | 1.78 |
| | M | Shallow patch | SF | 1.78 |
| Weathering and raveling | H | Seal coat | SF | 0.12 |
| | M | Seal coat | SF | 0.12 |
| | L | Seal coat | SF | 0.12 |

NOTE: H = high, M = medium, L = low; SF = square ft, LF = linear ft.

TABLE 3 SAMPLE CALCULATION OF SURFACE PREPARATION COSTS

| Density | Distress Type | Severity | Preparation Method | Unit | Unit Cost ($) |
|---|---|---|---|---|---|
| 0.55 | Alligator cracking | Medium | Deep patch | SF | 3.80 |
| 0.12 | Alligator cracking | High | Deep patch | SF | 3.80 |
| 1.25 | Longitudinal/transverse cracking | High | Crack seal | LF | 1.15 |

The surface preparation unit cost ($) can then be calculated as follows:

| | | |
|---|---|---|
| Medium alligator cracking | = $0.55 \times 0.09 \times 3.80 =$ | 0.19 $yd^2$ |
| High alligator cracking | = $0.12 \times 0.09 \times 3.80 =$ | 0.04 $yd^2$ |
| High longitudinal/transverse cracking | = $1.25 \times 0.09 \times 1.15 =$ | 0.13 $yd^2$ |
| Total surface preparation cost | | $0.36 $yd^2$ |

TABLE 4 ANNUAL MAINTENANCE POLICY: FORT KNOX

| Distress Type | Severity | Method | Unit | Unit Cost ($) |
|---|---|---|---|---|
| Alligator cracking | H | Deep patch | SF | 2.98 |
| | M | Skin patch | SF | 1.01 |
| Block cracking | H | Shallow patch | SF | 1.70 |
| Bumps/sags | H | Shallow patch | SF | 1.78 |
| Corrugation | H | Shallow patch | SF | 1.78 |
| Depressions | H | Shallow patch | SF | 1.78 |
| Edge cracking | H | Deep patch | LF | 4.47 |
| Lane/shoulder dropoff | H | Grade and add gravel | LF | 0.38 |
| Longitudinal/transverse cracking | H | Crack seal | LF | 1.42 |
| | M | Crack seal | LF | 1.01 |
| Patching and utility cut patching | H | Replace patch | SF | 2.98 |
| | M | Crack seal | SF | 1.68 |
| Potholes | H | Deep patch | Each | 9.36 |
| | M | Deep patch | Each | 2.32 |
| Rutting | H | Skin patch | SF | 1.01 |
| Shoving | H | Skin patch | SF | 1.01 |
| Slippage crack | H | Skin patch | SF | 1.01 |
| Swell | H | Skin patch | SF | 1.01 |

NOTE: H = high, M = medium, L = low; SF = square ft, LF = linear ft.

TABLE 5 COST AND PERFORMANCE DATA FOR DIFFERENT M&R ALTERNATIVES ON THIN OVERLAY PAVEMENT: FORT EUSTIS

COST DATA

Initial Cost (Fixed) of Different M & R Alternatives

| M & R Activity: | Surface Treatment | Thin Overlay | Thick Overlay | Reconstruction |
|---|---|---|---|---|
| Unit cost ($/sy): | 1.58 | 3.76 | 5.07 | 20.70 |

Initial Cost (Surface Preparation at the Time of Repair)

| PCI Range: | 0-20 | 21-40 | 41-60 | 61-80 | 81-100 |
|---|---|---|---|---|---|
| Unit Cost ($/sy): | 18.50 | 8.50 | 5.20 | 0.51 | 0.15 |

Annual Maintenance Cost of Different M & R Activities

| PCI Range: | 0-20 | 21-40 | 41-60 | 61-80 | 81-100 |
|---|---|---|---|---|---|
| Unit Cost ($/sy) for: | | | | | |
| - Surface Treatment | 7.7 | 2.2 | 0.80 | 0.50 | 0.13 |
| - Thin Overlay | 7.0 | 2.0 | 0.70 | 0.35 | 0.13 |
| - Thick Overlay | 4.0 | 1.0 | 0.60 | 0.30 | 0.07 |
| - Reconstruction | 4.4 | 1.3 | 0.65 | 0.33 | 0.07 |

PERFORMANCE

| | |
|---|---|
| Surface Treatment | $PCI = 100 - 0.0319\ (age)^{1.5}$ |
| Thin Overlay | $PCI = 100 - 0.0158\ (age)^{1.5}$ |
| Thick Overlay | $PCI = 100 - 0.0129\ (age)^{1.5}$ |
| Reconstruction (new Asphalt Pavement) | $PCI = 100 - 0.0104\ (age)^{1.5}$ |

The SPSS software *(3)* was used to develop regression equations for each pavement class. The following five variations of the general form of the performance equation were analyzed:

$$\text{PCI} = 100 - b * \text{Age}^{1.5}$$
$$\text{PCI} = 100 - b * \text{Age}^{2.0}$$
$$\text{PCI} = 100 - b * \text{Age}^{2.5}$$
$$\text{PCI} = 100 - b * \text{Age}^{3.0}$$
$$\text{PCI} = 100 - b * \text{Age}^{4.0}$$

The best fit was determined by the highest $r^2$ value (coefficient of determination) using the least-squares method. For all pavement classes at all installations, an exponent ($m$) of 1.5 resulted in the highest $r^2$ values. In this study, pavements were considered to have reached the end of their service life at the PCI level of 70. This value was chosen as the existing data base indicated that most installations were performing some form of repair activity on a pavement once it dropped below that level. In some instances, there were insufficient data samples to generate performance curves for all pavement classes. For pavements lacking regression equations, the general form of the equation was used with an exponent of 1.5. Next, the pavement service life, or age to PCI 70, was estimated. The regression equation's slope coefficient ($b$) could then be back calculated. Performance curves, regression equations, and $r^2$ values for each pavement class at all installations were calculated. The procedure to generate performance curves has now been automated *(4)*.

## LIFE-CYCLE COST ANALYSIS

An economic cost comparison among M&R alternatives was performed by determining the overall life-cycle cost of each alternative. Life-cycle costs can be expressed as a present worth or equivalent uniform annual cost. If alternatives are to be compared using the present worth method, all alternatives must be evaluated over the same analysis period. If an alternative's service life exceeded the analysis period, then the worth of that remaining life (salvage value) has to be determined. The equivalent uniform annual cost method (EUAC) allows the comparison of alternatives over different analysis periods. The EUAC method combines all investment costs and all annual expenses into a single annual sum that is equivalent to all disbursements during the pavement's service life, if spread uniformly over that period. When alternatives are compared, the one with the lowest equivalent uniform annual cost is considered the most economical.

The procedure used for determining the equivalent uniform annual cost of different M&R activities is best illustrated through the use of an example. In Table 5, an example problem is presented along with the necessary cost and performance data. The selection of the best alternative procedure is presented as follows in a step-by-step format.

### *Step 1*

Determine total initial cost of each M&R alternative as the sum of initial fixed cost and surface preparation cost. Surface preparation cost is a function of the PCI value at the time of repair and the installation surface preparation policy. For example, the total initial cost for surface treatment is equal to \$1.58 (fixed cost) + \$0.51 (surface preparation) = \$2.09/yd². Similarly, the total initial cost for a thin overlay, structural overlay, and reconstruction are \$4.27, \$5.58, and \$20.70/yd², respectively.

### *Step 2*

Determine service life (number of years to reach a PCI value of 70) for each M&R alternative. Using the performance models given in Table 5, and solving for age at PCI = 70, the required service life is determined. For instance, in the case of surface treatment a period of approximately 96 months or 8 yr is required to reach a PCI of 70. Similarly, service lives for thin overlay, thick overlay, and reconstruction are 13, 15, and 17 yr, respectively.

### *Step 3*

Determine Equivalent Uniform Annual Cost (EUAC) of initial cost of each maintenance alternative as follows:

$$\text{EUAC} = \text{IC} * (\text{CRF}, i, n)$$

where

- IC = initial cost as determined in Step 1,
- CRF = capital recovery factor = $\dfrac{i(1 + i)^n}{(1 + i)^n - 1}$,
- $i$ = inflation-adjusted discount rate (6 percent), and
- $n$ = service life as determined in Step 2.

Thus, the EUAC of initial cost of different maintenance alternatives is

Surface treatment = 2.09 (0.1610) = \$0.34/yd²
1.5-in. overlay = 4.27 (0.1130) = \$0.48/yd²
2.0-in. overlay = 5.58 (0.1030) = \$0.57/yd²
Reconstruction = 20.70 (0.0954) = \$1.97/yd²

### *Step 4*

Determine the EUAC of annual maintenance through the service life of each M&R alternative. This is done by taking the following steps.

(*a*) Determine the PCI value at each year of the service life of an alternative. For example, it is required to know the 8 PCI values corresponding to each of the 8 years of the surface treatment service life. These values are obtained by using the performance models shown in Table 4. Using the performance model of surface treatment results in a PCI value of 93 at the third year of the service life (age = 36 months) and a PCI value of 75 at the 7th year (age = 85 months).

(*b*) For each year's PCI, as calculated in Step 4(*a*) determine the corresponding PCI range and the corresponding annual maintenance cost. For example, in the case of surface treatments, at the third year the PCI value is 93 and the corresponding PCI range is 81 to 100. Thus, the annual maintenance cost is \$0.13/yd², as indicated in Table 4.

Similarly, at the 7th year, PCI value is 75 and the PCI range is 61 to 80 and the associated annual maintenance cost is $0.50/yd$^2$.

(*c*) Determine the present worth value (PWV) of all annual maintenance costs determined in Step 4(*b*) as follows:

$$PWV = \sum_{j=1}^{n} AMC_j * (SPPWF, i, j)$$

where

PWV = present worth value of all annual maintenance costs during the service life of an alternative,

$AMC_j$ = annual maintenance cost at the *j*th year of the alternative's service life,

(SPPWF, *i*, *j*) = $\frac{1}{(1+i)^j}$ equals single payment present worth factor,

*i* = inflation-adjusted discount rate (6 percent), and

*n* = service life (yr) of the alternative under consideration, as determined in Step 2.

(*d*) Convert the PWV obtained in Step 4(*c*) to its EUAC as follows:

$$EUAC = PWV * (CRF, i, n)$$

where

EUAC = equivalent uniform annual cost ($/yd$^2$/yr) of the maintenance alternative under consideration,

PWV = present worth value as defined in Step 4(*c*), and

(CRF, *i*, *n*) = capital recovery factor, as defined in Step 3.

Executing calculations in Steps 4(*a*) through 4(*d*) for different maintenance alternatives results in EUAC of annual maintenance of $0.21, $0.18, $0.11, and $0.13/yd$^2$ for surface treatment, thin overlay, structural overlay, and reconstruction, respectively.

*Step 5*

Determine the total EUAC of each alternative by adding values from Steps 3 and 4.

EUAC (Surface treatment) = $0.34 + $0.21 = $0.55/yd$^2$
EUAC (Thin overlay) = $0.48 + $0.18 = $0.66/yd$^2$
EUAC (Structural overlay) = $0.57 + $0.11 = $0.68/yd$^2$
EUAC (Reconstruction) = $1.97 + $0.13 = $2.10/yd$^2$

*Step 6*

Select the repair alternative with the least equivalent uniform annual cost.

The life-cycle cost analysis of the example problem has shown that alternative No. 1 (surface treatment) has the least equivalent uniform annual cost. This alternative would cost Fort Eustis the equivalent of a yearly payment of $0.55/yd$^2$ over an 8-yr period at the assumed interest and inflation rates. It should be noted that the user costs associated with pavement conditions and lane closures were not included in the analysis, but would probably not affect the results much as traffic levels are relatively light.

The procedure presented above was repeated for different PCI ranges and the results are summarized in Figure 1. For

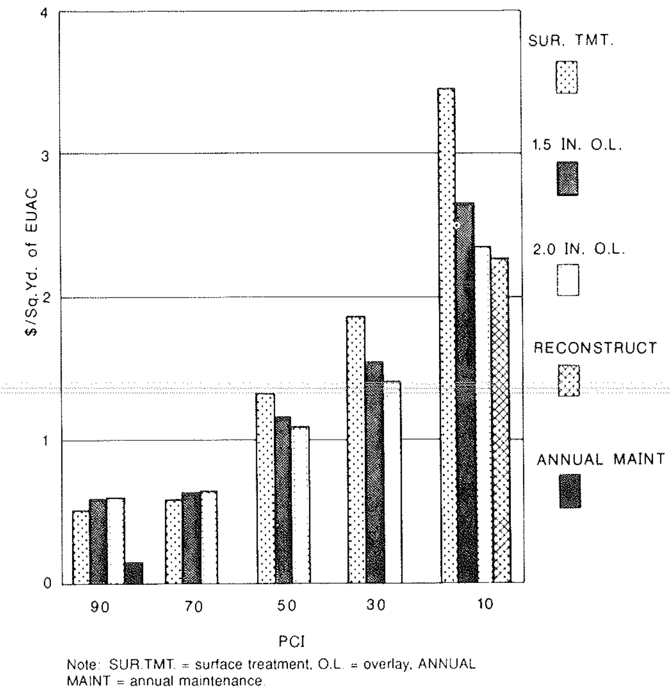


**FIGURE 1 Equivalent uniform annual costs of different M&R alternatives for thin overlay pavement by PCI range: Fort Eustis.**

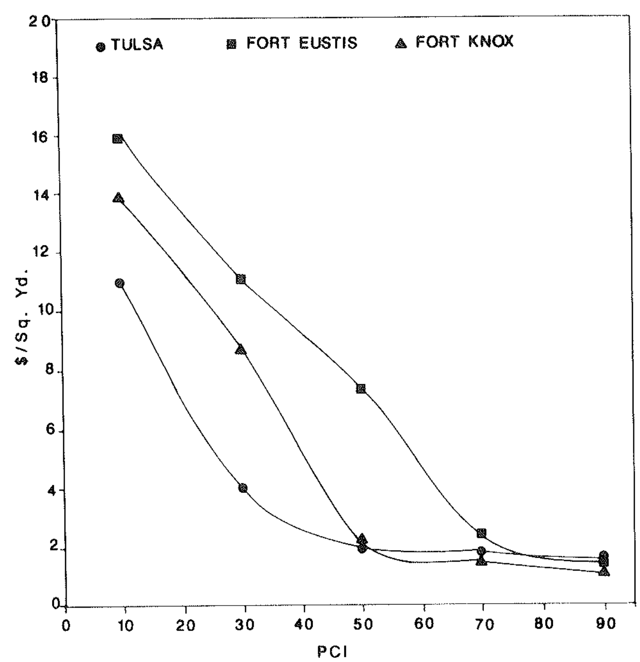


**FIGURE 2 Initial costs of least-cost M&R alternatives for asphalt concrete roads.**

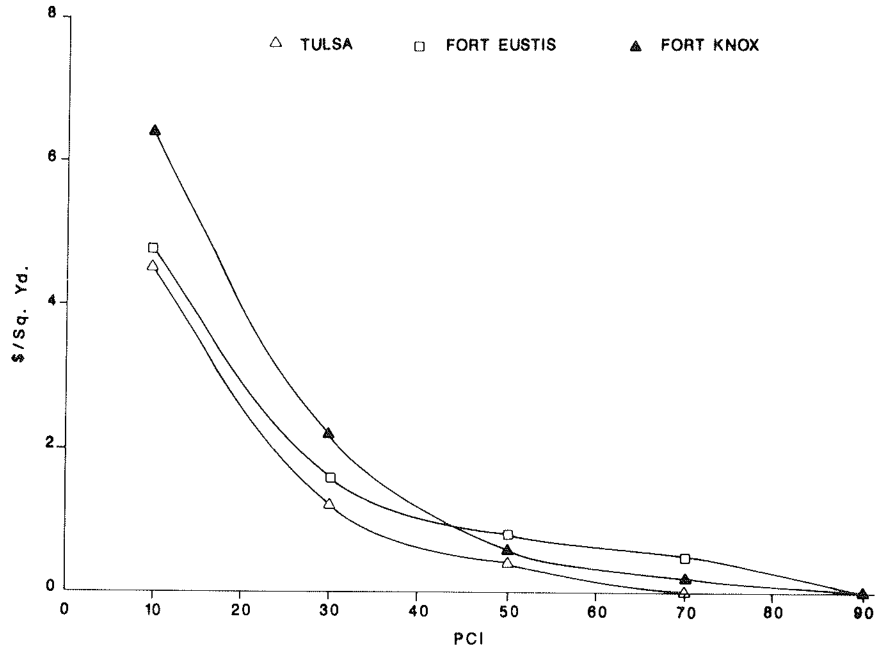


**FIGURE 3 Annual routine maintenance costs of least-cost M&R alternatives for asphalt concrete roads.**

TABLE 6 RESULTS OF SENSITIVITY ANALYSIS

| Analysis Parameter | Percent Change in EUAC due to One Percent Change in Analysis Parameter | | | |
|---|---|---|---|---|
| | Surface Treatment | Thin Overlay | Thick Overlay | Recon-struction |
| Service Life | 0.50 | 0.60 | 0.60 | 0.60 |
| Discount Rate | 0.20 | 0.25 | 0.40 | 0.40 |
| Initial Cost | 0.60 | 0.80 | 0.90 | 1.00 |
| Annual Maint. Cost | 0.40 | 0.25 | 0.16 | 0.04 |

instance, although surface treatment is the most cost-effective maintenance alternative at the PCI range of 61 to 80, structural overlay is the most cost effective at the PCI range of 41 to 60 and reconstruction is the best alternative at the PCI range of 0 to 20. Similar computations were done for all pavement classes and for all PCI ranges for each of the five installations, and the best economic repair alternatives under various conditions were determined. Figures 2 and 3 present the initial costs and annual routine maintenance costs, respectively, associated with the least cost alternatives at various PCI ranges for three installations.

### Sensitivity Analysis

The results of the above example are only as good as the estimates of service life, initial cost, annual maintenance expenses, and effective discount rate used. A sensitivity analysis was included to gauge what effect each of these estimates would have on life-cycle costs. Estimates were made with different values for each of the parameters associated with various alternatives. The effect is presented in Table 6 as the percent change in EUAC due to 1 percent change in an analysis parameter. For example, 1 percent change or error in estimating the service life of a surface treatment results in, on the average, 0.5 percent change in the overall EUAC. Similarly, 1 percent difference in the initial cost of reconstruction results in, on the average, 1 percent difference in the overall EUAC.

The results of this sensitivity analysis indicate that the accuracy of the calculated equivalent uniform annual costs of M&R alternatives is very sensitive to errors in input initial cost and expected service life. Incorrect estimation of annual maintenance expenses would not greatly affect the final EUAC values. Also, variations in discount rates did not seem to be as critical as a miscalculation of initial cost or service life.

## CONCLUSION

The paper presented a methodology for determining the least-cost maintenance and repair alternative for different pavement categories at various PCI ranges. The data from five military installations from across the United States were used. Although the case study results suggest that the methodology is reasonable, further work is necessary with an expanded data base from geographically representative military installations.

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