TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/TX-84/10+325-1F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Estimating the Remaining Service Life of Flexible Pavements		5. Report Date January 1984
		6. Performing Organization Code
7. Author(s) Alberto Garcia-Diaz and Jack T. Allison		8. Performing Organization Report No. Research Report 325-1F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843		10. Work Unit No.
		11. Contract or Grant No. Study No. 2-8-82-325
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation P. O. Box 5051 Austin, Texas 78763		13. Type of Report and Period Covered Final - September 1981 August 1982
		14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with DOT, FHWA.
Research Study Title: Estimating the Remaining Service Life of Flexible Pavements.

16. Abstract

A procedure is developed to estimate the remaining service life of flexible pavements based upon predicted ride and distress conditions. These conditions are forecast using equations that involve measurable values of material properties, climatic conditions, and design factors. In particular, life predictive models are developed for the Texas flexible pavement network. Predicted pavement lives are correlated with actual Texas data and acceptable results are obtained.

The most significant distress types affecting pavement service life were identified using a discriminant analysis approach. For each of the prevalent Texas flexible pavements the probability of needing rehabilitation is assessed for different levels of ride and distress, using discriminant functions.

A second method for estimating the remaining service life in terms of maximum likelihood estimators is also developed. Curves for estimating service life are constructed for different categories within each of the following three prevalent flexible pavement types: asphalt concrete, overlaid and surface treated.

Present worth and savings/cost analyses are provided to assess the economic impact of delaying rehabilitation decisions once the predicted life is reached. This analysis considers maintenance, user and rehabilitation costs.

17. Key Words Flexible pavements, maintenance, rehabilitation, estimation of service life, computer program.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	187	

Form DOT F 1700.7 (8-69)

ESTIMATING THE REMAINING SERVICE LIFE OF FLEXIBLE PAVEMENTS

by

Alberto Garcia-Diaz and Jack T. Allison

of the

Texas Transportation Institute

Research Report 325-1F

Research Study No. 2-8-82-325

Estimating the Remaining Service Life of

Flexible Pavements

Conducted for the

State Department of Highways and Public Transportation
in cooperation with the U. S. Department
of Transportation, Federal Highway Administration

by the

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

January 1984

ACKNOWLEDGEMENT

This project was sponsored by the Texas State Department of Highways and Public Transportation (SDHPT) through its Cooperative Research Program. Alberto Garcia-Diaz served as Principal Investigator and Jack T. Allison as Research Assistant. Mr. Robert Mikulin and Mr. Robert Guinn were the SDHPT Contact Representatives. Their outstanding cooperation and interest in the project is sincerely appreciated. Proper acknowledgment is extended to Robert L. Lytton for his excellent guidance and valuable suggestions in the development of this effort.

DISCLAIMER

ABSTRACT

A procedure is developed to estimate the remaining service life of flexible pavements based upon predicted ride and distress conditions. These conditions are forecast using equations that involve measurable values of material properties, climatic conditions, and design factors. In particular, life predictive models are developed for the Texas flexible pavement network. Predicted pavement lives are correlated with actual Texas data and acceptable results are obtained.

The most significant distress types affecting pavement service life were identified using a discriminant analysis approach. For each of the prevalent Texas flexible pavements the probability of needing rehabilitation is assessed for different levels of ride and distress, using discriminant functions.

A second method for estimating the remaining service life in terms of maximum likelihood estimators is also developed. Curves for estimating service life are constructed for different categories within each of the following three prevalent flexible pavement types: asphalt concrete, overlaid and surface treated.

Present worth and savings/cost analyses are provided to assess the economic impact of delaying rehabilitation decisions once the predicted life is reached. This analysis considers maintenance, user and rehabilitation costs.

IMPLEMENTATION STATEMENT

The typical pavement service lives developed in this project can be immediately used to predict an average amount of money needed to rehabilitate each of several pavement types within the most important highway functional classifications of the State network. The typical remaining service life estimates combined with traffic growth rates will result in an average mileage to be rehabilitated in each year of an extended planning horizon. The mileage to be rehabilitated and typical costs of rehabilitation for specified levels of PSI or distress can be used to estimate average rehabilitation money needed each year. This money can be compared against the money that will be saved by the users of the highways, using the user cost methodology developed in the project. Each District of the entire State network can thus benefit from the results of the present project.

TABLE OF CONTENTS

LIST OF TABLES

Table		Page

LIST OF FIGURES

1. INTRODUCTION

The efficient maintenance and rehabilitation of existing pavement systems has become a critical planning aspect, due to increasing transportation demands and insufficient available funds.

During the past five years the State of Texas has spent approximately $180,000,000.00 annually in rehabilitating and/or maintaining the flexible highway system, which consists of approximately 158,000 lane miles of pavement. Budget projections for 1983 made by the Texas State Highway Department are in excess of $400,000,000.00 to help alleviate the maintenance and rehabilitation backlog accumulated over the past decade. Due to a sharp decline in the physical condition of the State highway system, funding necessary for maintaining it at acceptable levels of user serviceability by far exceeds available budgets.

In an effort to provide for maintenance and rehabilitation needs, a number of State transportation agencies are currently experiencing a shift in pavement expenditures from construction to maintenance and rehabilitation. Figure 1 illustrates the share of funds expended for capital improvements and for highway maintenance from 1962 through 1979 in the United States (1). During this period, construction funding decreased from 60% to 42%, while maintenance and rehabilitation funding increased from 23% to 33% of the total highway disbursements.

The capital allocation problem is further complicated by the difficulty in establishing priorities for pavement maintenance that maximize or significantly improve the benefits to the users of the highway system. Perhaps the most fundamental aspect in any procedure that

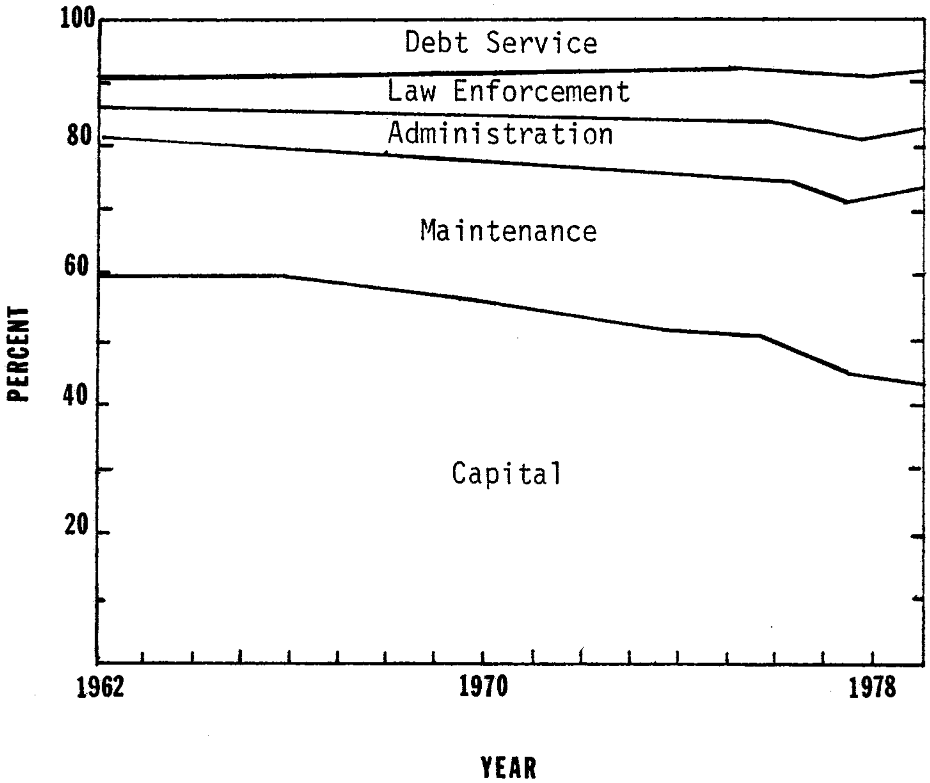

Figure 1. Distribution of Total Highway Disbursements.

allocates capital resources to achieve the previously stated goal is a reliable model for estimating remaining service life of pavements. The overall purpose of this research project is to develop a model for predicting service life for different types of Texas flexible pavements.

The specific objectives of this research project can be outlined as follows:

a. To develop systematic and reliable procedures to estimate the remaining service life of an existing flexible pavement on the basis of predicted values of serviceability and distress; input factors in this development are traffic levels, climatic conditions, material properties, design characteristics, and highway type.

b. To quantify road user cost savings resulting from pavement improvements, and to estimate the effect of delaying such improvements once the predicted life is reached. The quantification of these benefits provides a basis for a savings/cost analysis which takes into consideration rehabilitation, maintenance, vehicle operating costs, and discount rates.

c. The development of a computer program that integrates objectives (a) and (b) to provide an accessible tool for estimating the time at which a pavement should be rehabilitated.

2. LITERATURE REVIEW

2.1 Pavement Life

Many of the previous attempts in determining the remaining life of existing pavements have involved either individual judgment, or methods based upon a serviceability performance concept such as that established in the American Association of State Highway Officials (AASHO) Road Test (2) in the late 1950's. A typical example of this work was conducted by Corvi and Bullard (3). They described a method based on the performance concept established in the AASHO Road Test to predict when a pavement will need resurfacing. Whiteside et al. (4) considered the use of the AASHO performance concept to evaluate the effect of increasing truck weights and dimensions. Similarly, Hicks et al. (5) utilized this concept to measure the effect of increased truck weights on pavements that had been in service for several years. A shortcoming of these procedures is the use of the AASHO performance equations in places other than the test site.

A more systematic approach was developed for the NULOAD computer program (6) which estimates the effect of changes in truck size, weight and configuration to pavement remaining service life; this effect is measured in terms of pavement maintenance and rehabilitation costs for each period in a specified planning horizon. This approach, however, also uses the AASHO performance concept.

Other procedures not using the AASHO performance model, such as the RENU Method (7), California Method (8), Texas Method (9), Asphalt Institute Method (10), and Elastic-layered theory methods (11) are based upon some form of structural failure of the roadway.

In addition to roughness as a measure of pavement performance, signs of distress such as cracking and rutting should also be considered. To this effect, in a workshop attended by a group of top ranking pavement experts (12), the need for relating pavement distress to performance was identified as a primary research need. Smeaton, Sengupta, and Haas (13) present a suggested framework and methodology for identifying the objective relationships between pavement distress and performance. Results of this study indicate that different forms of pavement distress are interdependent through time and depend not only on variables such as traffic loads, environment, structure, structural capacity, pavement condition, and roughness, but also on their historical behavior.

In 1973, Lu, Lytton, and Moore (14) utilized data from test pavement sections in Texas to predict serviceability loss in flexible pavements. A two-step constrained regression procedure was developed to examine the effect of selected variables on the loss of serviceability. Recently, Lytton et al. (15) again used this procedure to develop a set of equations to describe the performance of flexible pavements in Texas; these equations are based upon measurable values of material properties, climatic conditions and design features. An explanation of pavement performance is proposed in terms of two basic concepts:

a. Performance as a function of the serviceability index. This is a general measure of roughness measured on a scale between 0 and 5 where a value of 5 represents a perfectly smooth surface.

b. Performance as a function of distress. Cracking, rutting, and ravelling are common types of physical distress found in a pavement.

Pavement performance is theorized in terms of an S-shaped curve, relating the serviceability index or percentage of distress to the life of the pavement as shown in Figure 2. In this figure, pavement C is stronger than B and B is stronger than A.

A function that has been proposed to describe the S-shaped curve is:

$$g(N) = e^{-(\rho/N)^{\beta}} \qquad (1)$$

where

N = number of traffic loads (18-Kip equivalent single axle loads, ESAL's) and

ρ, β = deterioration rate constants derived from a regression analysis.

Scullion, Mason and Lytton (16) utilized the Texas performance equations to predict the reduction in the service life to rural farm-to-market roads in Texas due to the increased traffic generated by oil field development.

In an attempt to construct a model similar to NULOAD applicable to conditions found in Texas the computer program RENU (6) was developed using the best features of NULOAD. One of the most important aspects of this program is the use of Texas based pavement performance equations in lieu of the AASHO performance equations.

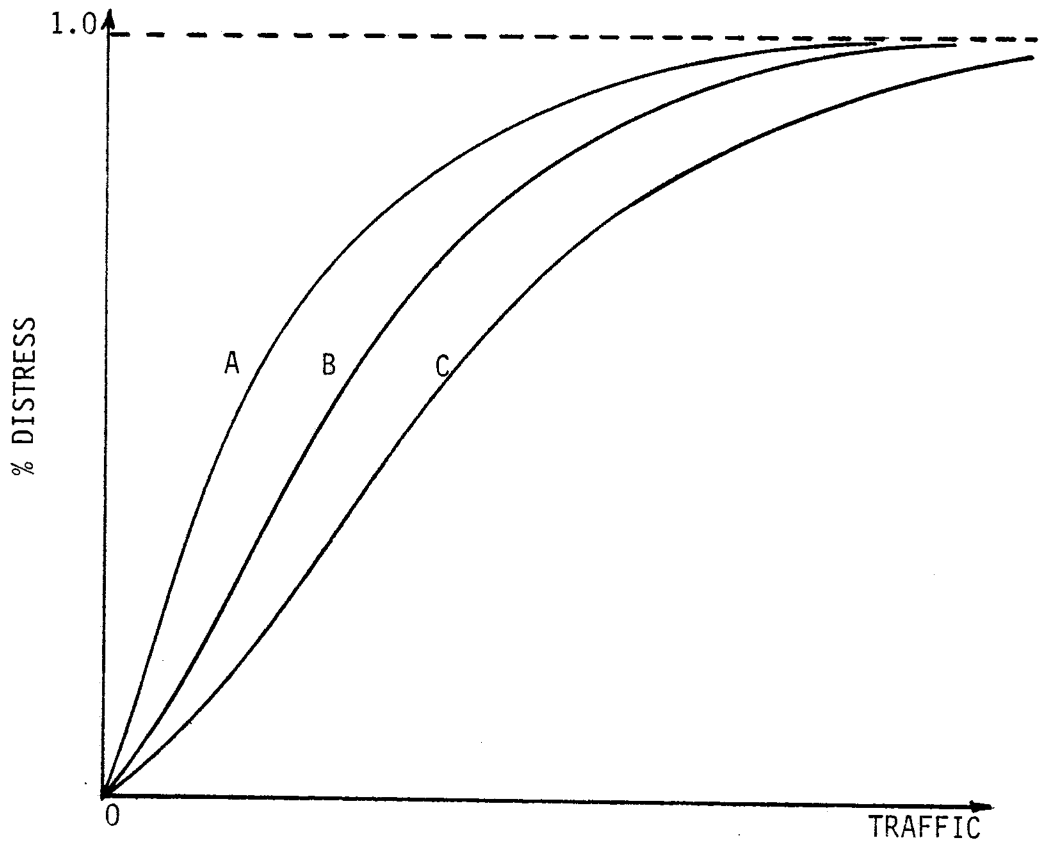

Figure 2. Typical Performance Curves.

In another related study, Noble and McCullough (17) describe an application of discriminant analysis to define a criterion based upon signs of distress for determining the need for either major rehabilitation or overlay on continuously reinforced concrete pavements in Texas. Barber (18), and Darter and Hudson (19) developed reliability models based on deterministic equations using field data related to pavement deterioration. These models provide a method of determining the probability that a pavement will last for a certain period of time or number of vehicle loadings.

In summary, the state of the art of models for predicting pavement life progressed from totally subjective methods to models that include a rideability concept, and from this stage it evolved to models considering signs of pavement distress.

2.2 Vehicle Operating Costs Related to Pavement Condition

A comprehensive study of vehicle operating costs in the United States was conducted by Claffey (20) in 1971. Winfrey (21) used the results of this and similar studies to prepare tables of vehicle operating costs. However, the costs in these tables were not related to the pavement condition expressed in terms of a serviceability concept.

In an extensive project recently sponsored by the Federal Highway Administration, Zaniewski et al. (22) updated information on the interactions between roadway characteristics and vehicle operating parameters. Over 600 references were reviewed to develop these interactions for the following vehicle operating parameters:

(a) running speed

(b) fuel consumption

(c) accidents

(d) oil consumption

(e) tire wear

(f) maintenance and repair

(g) use related depreciation

As a result of this study, comprehensive tables were produced for determining operating costs for different types of vehicles at different speeds and grades. The study also produced a means to differentiate these costs on the basis of the serviceability index (PSI). This section presents a survey of the literature reported by Zaniewski relating vehicle operating costs to pavement condition for the different vehicle cost parameters.

Two principal studies have been conducted relating pavement roughness and vehicle speed. Karan et al. (23) developed regression equations relating pavement roughness, volume capacity ratio, and speed limit to the average travel speed. The study was performed on two-lane asphalt concrete pavements in Canada. Investigations of this relationship were also conducted in Brazil by Zaniewski et al. (24) on paved and unpaved roads and regression equations were obtained for automobiles, trucks, and buses. The general trend observed in the two studies indicates that travel speed decreases with increases in pavement roughness (i.e., travel time increases).

Five studies have been performed that report the effects of roadway characteristics on fuel consumption. Claffey (20) reported an increase of 30% in fuel consumption for travel over a badly broken and patched surface compared to travel over a good paved surface. Zaniewski et al. (25), in the Brazil study, found a difference of 10% over a range of rough to smooth pavements (PSI of 1.5 and PSI of 4.5). Hide (26) in a study in Kenya found no effect of pavement roughness on fuel consumption, however, the range of roughness used was very small. In a more recent study in Wisconsin, Ross (27) reported that for a scale of 1.5 to 4.5 (serviceability index), fuel consumption is 1.5% higher on the rough section. Zaniewski et al. (22) reported no significant difference in fuel consumption on asphalt concrete pavement sections of different roughness ranging in PSI from 1.5 to 4.5. Claffey's work, being the first, has been widely used to estimate differences in fuel consumption on surfaces with different levels of serviceability. An example is the approach for selecting resurfacing projects developed by the Kentucky Bureau of Highways (28). However, the later studies cast some doubt on the validity of using Claffey's relationship, and in fact, cloud the issue such that one is obliged to choose among sometimes conflicting theories in settling this relationship.

Two studies were reported relating pavement surface condition and accident rates. Tignor and Lindley (29) studied accident rates on the two-lane rural highways before and after resurfacing (thus, increasing the PSI), and found no statistically significant relationship between accident rates and pavement improvements, but did report a trend toward an increased accident rate as pavements are improved. In Zaniewski's Federal Highway Administration study, varied results were obtained relating accident rates to PSI on a sample of Texas pavements. A small statistically significant relationship was found between PSI and accident rates, however, the direction of the relationship varied for different highway classifications. In some instances, the higher PSI roads had higher accident rates and in other instances this trend was reversed. The general conclusion of this study was that a larger and more controlled study is necessary to establish a meaningful relationship.

The only studies available to relate pavement condition to oil consumption, tire wear, vehicle maintenance and repair, and use related depreciation emanated from the Brazil study (22). Results of this study establish a set of factors for each type of operating cost, to be multiplied by the vehicle operating cost, to reflect the effect of varying the roughness of the pavement. The trend of these factors is such that an increase in roughness (decrease in PSI) reflects an increase in operating costs.

3. PAVEMENT LIFE METHODOLOGY

3.1 Introduction

Highway pavements, like many other durable goods, are designed to perform for a specific length of time. Pavement design methods prescribe materials and layer thicknesses capable of absorbing a known traffic load over a specified design period. In the past fifty years pavement design procedures have evolved from empirical approaches to the use of sophisticated mechanistic models. The common shortcoming of earlier design procedures was the lack of an adequate concept for the study of pavement performance. The performance model developed from the AASHO Road Test represented a significant contribution toward the quantification of the riding conditions of both flexible and rigid pavements; in this model, the failure of a pavement is predicted in terms of a single measure that summarizes the pavement's ability to carry out its intended function without causing user discomfort or high vehicle stress.

In order to define the scope of this research project, three basic terms are first discussed: (a) maintenance, (b) rehabilitation, and (c) reconstruction.

Maintenance operations include all those activities related to the preservation, repair, and restoration of a highway facility as nearly as possible to its original condition. Routine maintenance includes the normal day-to-day operations which keep the facility functional. Major maintenance includes activities which are more extensive in scope than routine maintenance and may involve work which overlaps with safety, betterment, and rehabilitation.

Rehabilitation generally is defined as the restoration of an existing facility to its former serviceability, capacity, or condition, including safety considerations and operational improvements. Reconstruction consists of actually rebuilding an existing facility, possibly adding structural capacity. Rehabilitation may be required more than once during the pavement's design life as illustrated in Figure 3; typical rehabilitation alternatives for flexible pavements are seal coats and asphalt overlays. According to this observation, a pavement service life is defined as the time between resurfacings or overlays.

Data on flexible highways in Texas indicate that many sections of pavement with acceptable riding serviceability have been rehabilitated during their design life due to the presence of structural distress in the form of cracking, patching, and rutting. The aim of this rehabilitation has been to strengthen the original structure thus assuring that the pavement will reach or surpass its design life without the need of a major reconstruction effort unless warranted by capacity restrictions. In order to model the performance of a pavement section that requires rehabilitation due to various distress types before reaching a terminal serviceability index, several analysts (15,30) have proposed and used the performance curve shown in Figure 4. In this figure, the P_f value represents an asymptote of the performance curve, and P_t is a specified terminal value. This specified value is never reached and one or more types of distress become serious enough to cause the need of rehabilitation.

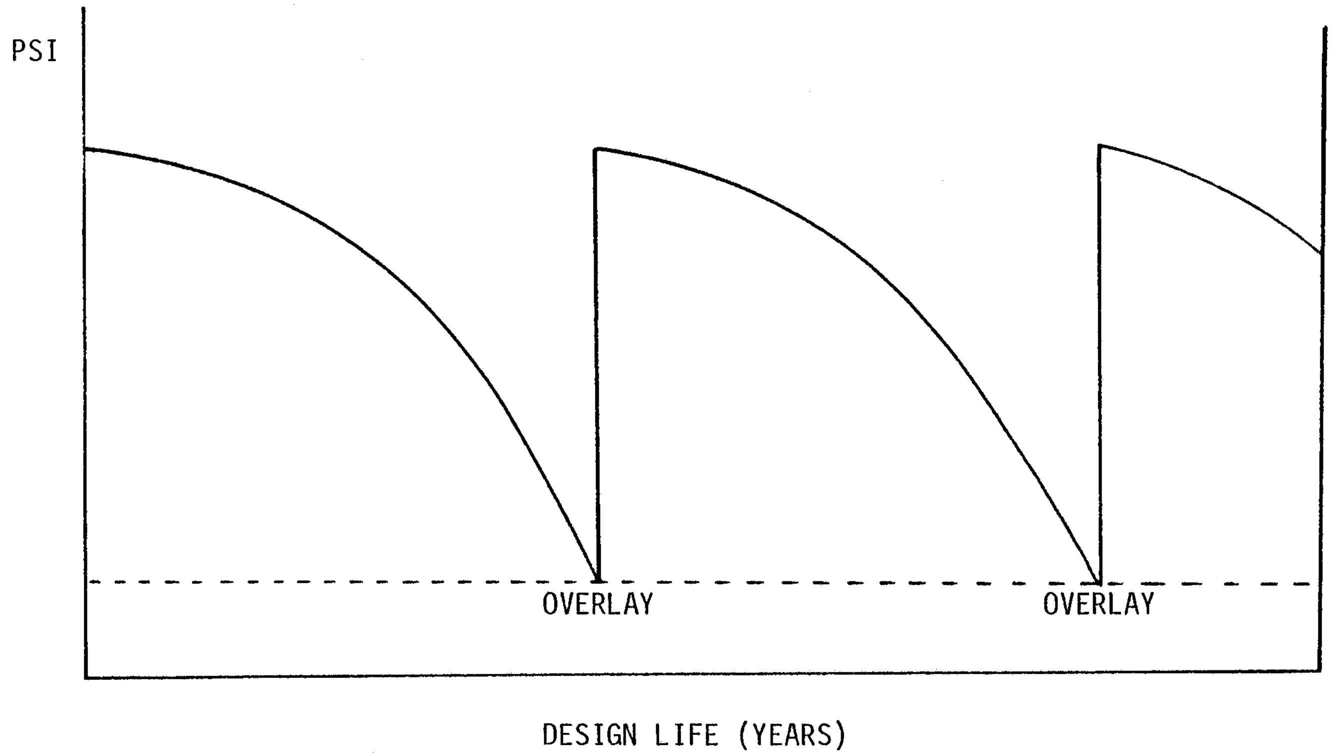

Figure 3. Rehabilitation During Pavement Design Life.

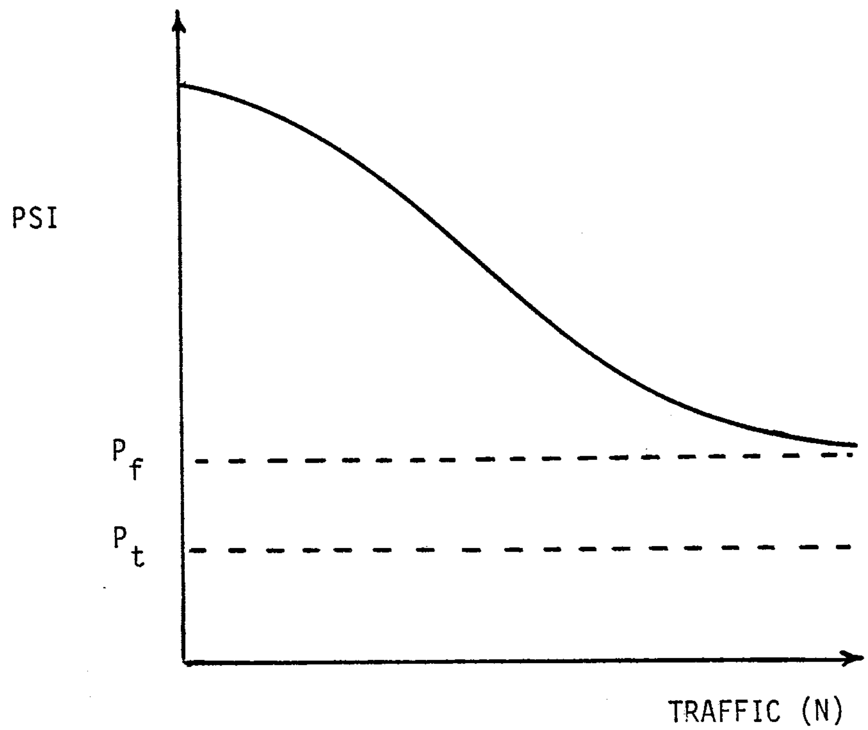

Figure 4. Serviceability Performance Curve.

A performance analysis based on the serviceability criterion is possible by defining a damage function that reflects the loss in serviceability after a given traffic load. Let P_i, P_f, and P_t be the initial asymtotic and terminal values of the serviceability index; therefore, the relative loss of serviceability can be represented by

$$g_t = \frac{P_i - P_t}{P_i - P_f} \tag{2}$$

Assuming that the above reduction in serviceability was caused by a traffic load equal to N, it is possible to provide the alternative expression for g_t given in Eq. (2); that is;

$$g_t\ (N) = e^{-(\rho/N)^{\beta}} \tag{3}$$

From Eqs. (2) and (3) it can be concluded that

$$P_t = P_i - (P_i - P_f)\ e^{-(\rho/N)^{\beta}} \tag{4}$$

This performance function is the same as that presented in Figure 4.

A similar analysis is possible when using the distress criterion; in this case, the maximum allowable loss in performance before rehabilitation can be represented as

$$g_t = \begin{cases} a_t & \text{for area} \\ s_t & \text{for severity} \end{cases} \tag{5}$$

where a_t is the maximum allowable area covered by a specified type of distress, and s_t is the maximum allowable severity level of the same type of distress. Both a_t and s_t are expressed as numbers between 0 and 1. Since g(N), as defined in Eq. (1), also varies between 0 and 1, it is therefore possible to equate g(N) to g_t and conclude that

$$a_t = e^{-(\rho/N)^{\beta}} \tag{6}$$

and

$$s_t = e^{-(\rho/N)^{\beta}} \tag{7}$$

The graphical representation of either of the above equations is given in Figure 5. As a result of the undergoing discussion, it is concluded that

$$N = \frac{\rho}{(-\ln g(N))^{1/\beta}} \tag{8}$$

More specifically,

$$N = \begin{cases} \rho\left(-\ln \dfrac{P_i - P_t}{P_i - P_f}\right)^{-1/\beta} & \text{for serviceability} \\ \rho(-\ln a_t)^{-1/\beta} & \text{for area} \\ \rho(-\ln s_t)^{-1/\beta} & \text{for severity} \end{cases} \tag{9}$$

Estimates of parameters ρ and β are required to use Eq. 3. Regression equations developed at the Texas Transportation Institute (TTI) by Lytton et al. (15) estimate these parameters for different classifications of flexible pavements. Flexible pavements in Texas

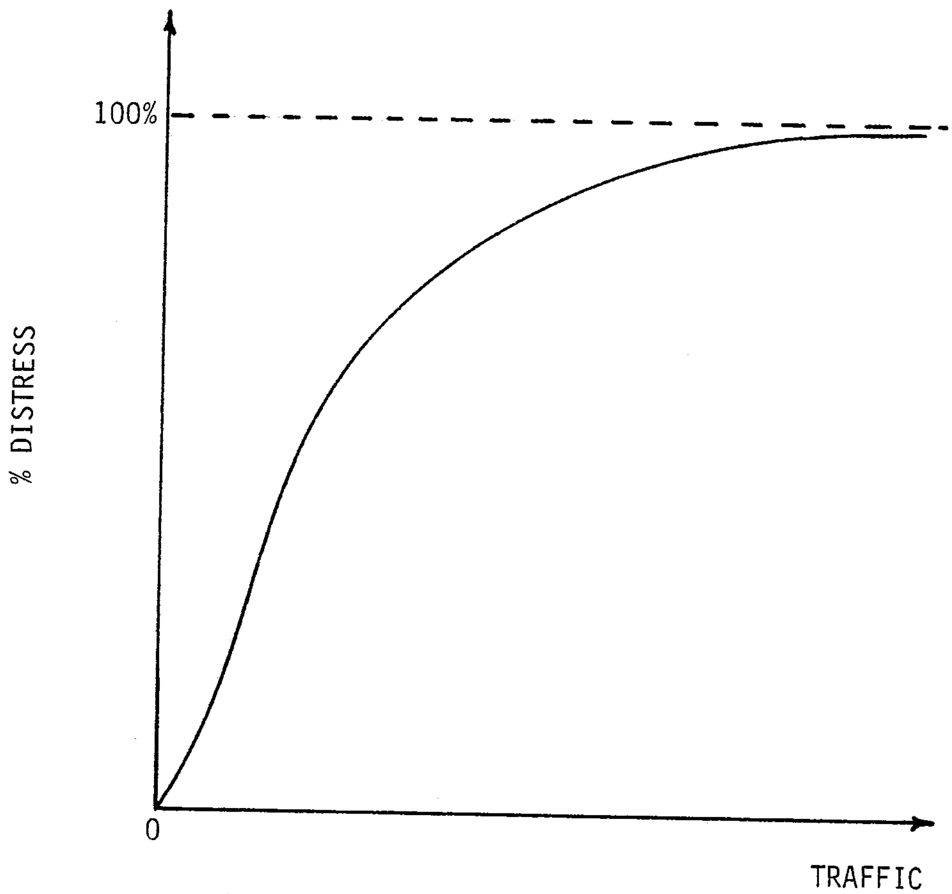

Figure 5. Performance Curve for Pavement Distress.

have been categorized as asphalt concrete, overlays, and surface treated. The performance equations, developed at TTI predict the affected area or degree of severity for each of the following types of distress: (a) rutting, (b) ravelling, (c) flushing, (d) corrugations, (e) alligator cracking, (f) longitudinal cracking, and (h) patching.

Assuming the S-shaped performance curve of Figure 4, these parameters can also be estimated using the method of maximum likelihood estimators (MLE) where ρ and β are the scale and shape parameters, respectively.

Appendix A contains a description of the use of maximum likelihood estimators to predict the service life of a pavement. This section also contains a description of a life prediction model developed using discriminant analysis in conjunction with the pavement performance equations developed for Texas. The model is based on the assumption that a combination of ride and different modes of distress determine when a pavement is to be resurfaced, and discriminant analysis is used to weight the contribution of each in determining the service life. Appendix C contains a description of discriminant analysis.

3.2 Parameter Estimation by MLE

The TTI flexible pavement data base served as a source for providing a sample of pavement service lines for each of the three pavement types predominant in Texas. Prior to utilizing the methodology described in Appendix A for estimating the parameters ρ and β, an analysis of variance was conducted in an attempt to identify any specific characteristics that might warrant grouping observations of pavement lives into subsets for each of the three pavement types. For asphaltic concrete pavements the characteristics analyzed were geographical location, thickness of the asphaltic concrete layer, and the highway classification. For surface treated pavements geographical location, number of surface treatment layers placed, and the highway classifications were tested. Similarly, characteristics analyzed for overlaid pavements included geographical location, thickness of the asphaltic concrete overlay, the highway classification, and the composition of the original pavement was also considered since a number of concrete pavement sections were included under this classification.

Due to relatively small sample sizes for each of the pavement types 30,330 and 51 for asphaltic concrete, surface treated and overlaid pavements respectively, the state was divided into two geographical areas; one included south and east Texas (the wetter and warmer part of the state) and the other including north and west Texas (the dryer, colder portion of the state). Figure 6 illustrates the two geographical areas that were used.

Highway classifications utilized included Interstate, U.S./State, and Farm-to-Market highways. Table 1 lists the results obtained from the analysis of variance performed using the generalized linear model (GLM) available in the Statistical Analysis Systems package (SAS); in this statistical test a level of significance of 0.05 was used.

These results indicate that there is no significant difference between service lives due to changes in geographical location. Highway classification did prove to be a significant factor as intuition

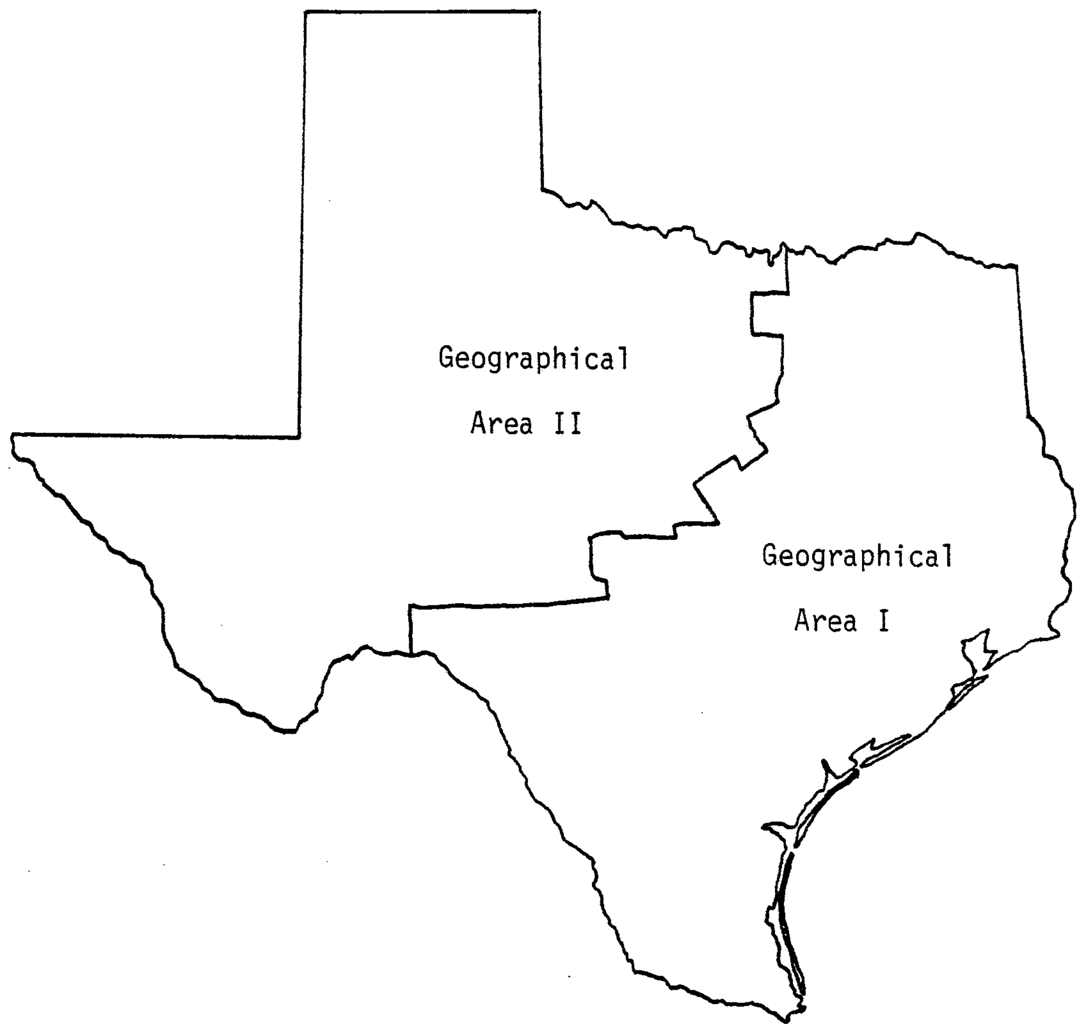

Figure 6. Two Geographical Areas of Texas Used for Analysis of Variance.

Table 1. Factors Which Cause Significant Difference in Pavement Performance as Determined by Analysis of Variance.

Factor	Asphaltic Concrete	Surface Treated	Overlaid
Geographical Location	No	No	No
Highway Classification	Yes	Yes	Yes
Thickness of Asphalt Concrete Layer	No	N/A	N/A
Number of Surface Courses	N/A	Yes	N/A
Thickness of Asphalt Concrete Overlay	N/A	N/A	No
Composition of Original Pavement	N/A	N/A	Yes

would tend to indicate; Interstate highways are usually designed for a heavier traffic load that is expected on U.S./State highways and a similar situation exists between U.S./State highways and Farm-to-Market highways. Surface layer thickness was not found significant for asphaltic concrete and overlaid pavements; the number of courses in the case of surface treated pavements, however, did prove to be significant. Maximum likelihood estimates for ρ and β were obtained for different subsets of observations as shown in Table 2.

3.3 Central Tendency Estimators

In order to obtain a good estimate of the pavement service life, several central tendency statistics were evaluated. The particular statistics considered in this analysis were:

Table 2. MLE Values of $\hat{\rho}$, $\hat{\beta}$.

Pavement Type	No. Obs.	$\hat{\rho}$	$\hat{\beta}$
Asphalt Concrete			
US/State	20	0.3259	1.3678
Interstate	10	1.0648	2.7889
Surface Treated			
US/State, IH, Single Treatment	73	0.310	0.9938
US/State, IH, Multiple Treatment	160	0.4030	1.0531
FM, Single Treatment	138	0.0056	1.1303
FM, Multiple Treatment	53	0.0050	0.9444
Overlay			
US/State on Flexible	21	0.1324	1.1100
US/State on Concrete	22	0.2262	1.4354
Interstate	7	1.2163	2.6206

(a) the sample average
(b) the MLE estimator of the population mean
(c) the MLE estimator of the population median
(d) the MLE estimator of the population mode

The sample average is calculated as $\frac{\Sigma n_i}{m}$, where n_1, n_2,....., n_m are a random sample of test sections corresponding to a specified pavement classification.

The MLE estimator $\hat{\mu}$ of the population mean can be obtained as

$$\hat{\mu} = \int_0^\infty \frac{\hat{\beta}(\hat{\rho})^{\hat{\beta}}}{n^{\hat{\beta}+1}} e^{-(\frac{\hat{\rho}}{n})^{\hat{\beta}}} dn \tag{10}$$

where $\hat{\rho}$ and $\hat{\beta}$ are the MLE estimators of the parameters ρ and β. The above integral can be found to be equal to

$$\hat{\mu} = \hat{\rho}\Gamma\left(\frac{\hat{\beta}-1}{\hat{\beta}}\right) \tag{11}$$

for $\hat{\beta} > 1$. In Eq. (10), $\Gamma(\cdot)$ is defined as

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy \text{ for } \alpha > 0 \tag{12}$$

Several estimates for the shape parameter β were less than one, thus making the expression $(\hat{\beta}-1/\hat{\beta})$ less than zero. The result of evaluating Eq. (11) for $\hat{\beta}-1/\hat{\beta} < 0$ is a negative number, therefore, the expected value of estimates for less than one will not be used.

The MLE estimator $\mu_{0.50}$ of the population median can be computed as

$$\hat{\mu}_{0.50} = \frac{\hat{\rho}}{(-\ln 0.5)^{1/\hat{\beta}}} \tag{13}$$

where $\hat{\rho}$ and $\hat{\beta}$ are MLE estimators of ρ and β.

Finally, the MLE estimator of the mode is the value $N = \mu^*$ such that

$$\frac{d}{dN}\left[\frac{\hat{\beta}(\hat{\rho})^{\hat{\beta}}}{N^{\hat{\beta}+1}} e^{-(\hat{\rho}/N)^{\hat{\beta}}}\right] = 0 \tag{14}$$

Table 3. Statistics for Pavement Types Derived from Maximum Likelihood Estimates for ρ and β (Millions 18-Kip ESALS).

Pavement Type	E(n)	Median	Arithmetic Average	Mode	Percentiles 10	90
Asphalt Concrete						
US/State	1.0940	0.4260	0.6161	0.230	0.1771	1.6889
Interstate	1.4922	1.2143	1.4458	0.950	0.7896	2.3862
Overlays						
Interstate	1.7617	1.3989	1.6552	1.08	0.8848	2.8706
US/State, (Flexible)	1.2715	0.1842	0.2742	0.07	0.0625	1.0054
US/State, (Composite)	0.6690	0.2742	0.4051	0.16	1.1265	0.0848
Surface Treated						
US/State, (Single)	****	0.0448	0.0751	0.02	0.0134	0.2984
US/State, (Multiple)	0.7783	0.0571	0.0926	0.03	0.0183	0.3415
FM (Single)	0.04591	0.0077	0.0131	0.005	0.0027	0.0410
FM (Multiple)	****	0.0074	0.0166	0.0021	0.0060	0.0542

**** Expected value not given, β < 1.

The location of the pavement distribution can be more completely described by calculating several percentiles; two meaningful percentiles are tenth percentile (P_{10}) and the ninetieth percentile (P_{90}). The P_{10} estimates the traffic load that will cause 10% of the total pavement mileage to be rehabilitated; similarly, P_{90} estimates the traffic load that will cause 90% of the mileage to fail. Any percentile can be obtained from the cumulative probability distributions given in Appendix B. A summary of results for the Texas highway system is given in Table 3.

In all cases, with the exception of those having estimates of β less than one, the expected service life was greater than the median. This is so because the probability density function is skewed to the right. For cases with $(\hat{\beta}-1)/\hat{\beta}$ values between .05 and .11, the expected service life exceeded the P_{90} percentile.

An analysis of Eq. (11) reveals that as $\hat{\beta}$ increases the gamma function of $(\hat{\beta}-1)/\hat{\beta}$ decreases, and as β approaches one the gamma function increases rapidly. Hence, the expected value of the pavement service life is very sensitive to the value of β. Table 4 gives the value of the gamma function for different values of β. The values of the gamma function were generated using the built-in function GAMMA(*) available with the FORTRAN WATFIV compiler.

Also, an examination of the probability density functions shown in Appendix B shows that as β approaches zero, the degree of peakedness (kurtosis) increases as indicated by a decrease in the percentile coefficient of kurtosis shown in Table 5; subsequently, the expected

Table 4. Relationship Between $\hat{\beta}$ and $\Gamma(\frac{\hat{\beta}-1}{\hat{\beta}})$.

$\hat{\beta}$	$\alpha = \frac{\hat{\beta}-1}{\hat{\beta}}$	$\Gamma(\alpha)$
1.0531	0.0504	19.3117
1.1100	0.0991	9.6036
1.1303	0.1153	8.1991
1.3678	0.2689	3.3570
1.4354	0.3033	2.9574
2.6206	0.6184	1.4484
2.7889	0.6414	1.4014

value is further from the median mode, and the sample average. Therefore, as β approaches one the expected value of the service life becomes less meaningful for estimation purposes. In this case, the median is a better estimate. Confidence intervals for β are obtained, since this parameter has a strong effect on the estimate of the expected value. These confidence intervals can be obtained as shown in Appendix D.

Using the methodology of Appendix D, a 95% confidence interval for β was obtained for each of the predominant pavement types. The corresponding results are given in Table 6. From the intervals shown in Table 6, it can be noted that for values of β close to one, the upper limit of the interval is also close to one. Therefore, the expected value would not significantly increase in importance for estimating the service life of a pavement.

Table 5. Percentile Coefficient of Kurtosis for Different Distributions.[a]

Distribution Defined by $\hat{\rho}$	$\hat{\beta}$	Percentile Coefficient of Kurtosis
0.0050	0.9444	0.1459
0.310	0.9938	0.1514
0.0430	1.0531	0.1578
0.1324	1.1100	0.1612
0.0056	1.1303	0.1658
0.3259	1.3678	0.1831
0.2262	1.4354	0.1871
1.2163	2.6206	0.2223
1.0648	2.7889	0.2247

[a] Coefficient of Kurtosis = $0.5 \left(\frac{P_{75} - P_{25}}{P_{90} - P_{10}}\right)$

Table 6. 95% Confidence Intervals for β.

Pavement Type	$\hat{\beta}$	Var $(\hat{\beta})$	Interval
Asphalt Concrete			
Interstate	2.7889	0.5138	(1.3839, 4.1939)
US/State	1.3678	0.0510	(0.9250, 1.8106)
Overlays			
Interstate	2.6206	0.5866	(1.1195, 4.1217)
US/State (Composite)	1.4354	0.0512	(0.9918, 1.8790)
US/State (Flexible)	1.1100	0.0299	(0.7711, 1.4489)
Surface Treatment			
US/State (Single)	0.9938	0.0070	(0.8302, 1.1574)
US/State (Multiple)	1.0531	0.0092	(0.8647, 1.2415)
FM (Single)	1.1303	0.0086	(0.9487, 1.3119)
FM (Multiple)	0.9444	0.0092	(0.7563, 1.1325)

3.4 Discriminant Analysis

A model for predicting the service life of a flexible pavement was developed based upon a combination of predicted ride and distress conditions. The technique explained in Appendix C was utilized to measure the relationships of the different contributing factors that warrant a decision concerning the rehabilitation of a pavement.

3.5 Development of Discriminant Functions

Discriminant analysis (Appendix C) was used to determine which type of distress or serviceability index causes a decision to resurface. This decision consists of assigning a particular section of pavement to the group of pavements that are in need of rehabilitation.

The variables used to calculate the discriminant functions were the serviceability index (range 0-5) and the area (range 0-3) and severity (range 0-3) of the different types of distress. The distress types considered for this analysis were:

(a) rutting area and severity

(b) longitudinal cracking area and severity

(c) ravelling area and severity

(d) alligator cracking area and severity

(e) transversal cracking area and severity

(f) patching area and severity (only for surface treated pavements.)

Other distress types usually evaluated were not considered because the associated prediction models were not found to be reliable.

Periodic pavement condition surveys have been performed on selected pavement sections in Texas to monitor the serviceability index and both the severity and extent of distress. The area of distress is rated according to the numbers 0, 1, 2, or 3, as shown in Table 7. Additionally, distress severity is rated as none, slight, moderate, and severe, corresponding to numerical ratings of 0, 1, 2, and 3, respectively. These ratings can be converted into area or severity percentages; for applications reported in this study, 16.6, 33, and 50% correspond to ratings of 1, 2, and 3, respectively. This relationship is used in the development of the service life prediction model to numerically express the extent of each type of distress.

Table 7. Definition of Ratings for Distressed Area.

Rating	Corresponding Physical Area Affected
0	None to less than one wheel path
1	One wheel path to less than two wheel paths
2	Two wheel paths
3	Area greater than two wheel paths

Once the extent of distress is estimated, the service life of a pavement can be determined from Eq. (1).

For each pavement type, the estimation procedure was based on a sample of sections with condition survey information available for the years 1973-1978. The observations in each sample were classified into two groups; those that had been resurfaced during the 1973-1978 period and those that had not. Ratings from the 1977 survey or from the years preceding a decision to rehabilitate (resurface) were used as the variable values that describe the condition of each section.

The rule for assigning test sections to either of the two groups involved in the analysis should discriminate as much as possible on the basis of observed variable values. The complexity of this rule, referred to as a "discriminant function" may be reduced by limiting the set of variables to those that contribute the most to the assignment of the observations int o two groups. A regression analogy, due to Cramer (31), applicable to linear discriminant analysis with two groups, allows the problem to be treated as a multiple regression problem with the creation of a dummy variable indicator of group membership. To accomplish this, a new variable, Y_i is defined so that

$$y_1 = \frac{N_2}{N_1 + N_2} \text{ , if } X_i \text{ is a member of group 1} \qquad (15)$$

or

$$y_2 = \frac{-N_1}{N_1 + N_2} \text{ , if } X_i \text{ is a member of group 2} \qquad (16)$$

where

y_i = dependent variable for observation i,

N_1 = number of observations in group 1, and

N_2 = number of observations in group 2.

The use of this substitute variable makes it possible to examine all of the linear regression relations among the dependent and independent variables. The model with the smallest mean square error was chosen to provide the set of variables (distress types or serviceability index) that are used in the discriminant function. An alternative approach to this one could have used a forward or backward stepwise regression model available in many standard computer software packages. However, it was believed that the procedure used here was superior to the stepwise procedure since the order that the variables enter into the model does not affect the final set of variables.

Table 8 gives the list of distress types which proved to be the best indicators of the need to resurface each of the three pavement types. The number of variables used in the model is greatly reduced for each of the pavement types. Interestingly, the serviceability index (PSI) was chosen for only the overlaid pavements. This result

Table 8. Serviceability/Distress Types by Pavement Type Selected for Use in the Discriminant Analysis.

Pavement Type		
Asphalt Concrete	Overlay	Surface Treated
Alligator Cracking Severity	Serviceability Index	Rutting Severity
Longitudinal Cracking Severity	Alligator Cracking Area	Rutting Area
Longitudinal Cracking Area	Longitudinal Cracking Severity	Longitudinal Cracking Severity
Transverse Cracking Severity	Longitudinal Cracking Area	Transverse Cracking Area
		Patching Area

corresponds to the widely held opinion that Texas pavements are rehabilitated mainly because of existing distress rather than the quality of the ride. The set of variables for each pavement type includes some of the most important distress types, such as rutting and alligator, longitudinal and transverse cracking.

Using the variables listed in Table 8, discriminant functions are developed to identify pavement sections in need of resurfacing. Hypothesis testing of the covariance matrices of the two groups (resurfaced and not resurfaced) revealed that they are not statistically equal, resulting in quadratic discriminant functions, which are more appropriately handled by a computer program. The resulting quadratic discriminant functions are listed in Appendix F. Classification is accomplished by calculating the probability of belonging to a group according to Eq. (C-2) in Appendix C. The classification performance of the models is found to be acceptable by examining the number of correct assignments made using the test data. The results of this analysis are displayed in Tables 9, 10, and 11. The apparent error rates (1 - % of correct prediction), and the maximum likelihood error estimates were evaluated. It is noted that a limited number of observations existed for cases of resurfaced pavements in the asphalt concrete and overlay categories. The resulting functions may be somewhat biased because of this fact. However, the results displayed in Tables 9, 10, and 11 demonstrate that the models are fairly good discriminators.

Table 9. Number of Observations Correctly Predicted by the Quadratic Discriminant Functions for Asphalt Concrete Pavements.

Group	Number of Cases	Number of Correct Predictions	Percent
Resurfaced	5	4	80.0
Not Resurfaced	76	71	93.4
Total	81	75	92.6
Apparent Error Rate			7.4
Maximum Likelihood Error Estimate			9.5

Table 10. Number of Observations Correctly Predicted by the Quadratic Discriminant Functions for Overlaid Pavements.

Group	Number of Cases	Number of Correct Predictions	Percent
Resurfaced	16	10	62.5
Not Resurfaced	64	58	90.6
Total	80	68	85.0
Apparent Error Rate			15.0
Maximum Likelihood Error Estimate			19.3

Table 11. Number of Observations Correctly Predicted by the Quadratic Discriminant Functions for Surface Treated Pavements.

Group	Number of Cases	Number of Correct Predictions	Percent
Resurfaced	56	39	69.6
Not Resurfaced	77	62	80.5
Total	133	101	75.9
Apparent Error Rate			24.1
Maximum Likelihood Error Estimate			17.0

3.6 Life Prediction Model

In contrast to the service life predictive method based on the MLE estimators, which is applicable to families of similar pavements, a second method was developed to predict the service life of a specific pavement section. This model predicts service life based upon physical and climatic conditions in conjunction with historical decision making policies on the timing of rehabilitation.

The serviceability/distress performance equations listed in Appendix G are used in combination with the discriminant functions of Appendix F to predict the life of a section of pavement. As aging occurs or loads accumulate, signs of distress become evident and the serviceability index may decrease. At the point where the equations predict a change in the condition rating, the overall rating for each of the corresponding distress/serviceability variables is evaluated by the corresponding discriminant function. This process continues until the probability of being assigned to the group of pavements in need of resurfacing reaches or exceeds a specified value. Since the goal of the model is to determine when a pavement is in need of rehabilitation, which may be considered a critical decision, a relatively high assignment probability is warranted. The probabilities used in the model are 0.70, 0.70, and 0.80 for asphalt concrete, overlays, and surface treated pavements, respectively. However, if the deterioration rates of two distress types reach their maximum value (3) and the probability has not been achieved, the pavement section will automatically be reassigned to the group of pavements in need of resurfacing. Figure 7 shows the overall concept of the life prediction model.

The estimated pavement life in 18-kip ESAL's is translated into time by performing as traffic analysis utilizing the current average daily traffic (AADT), estimated traffic growth, percent trucks and truck traffic axle load information for 1980 obtained from weigh stations located throughout the State and commonly known as W-4 and W-5 tables.

Rural highway axle weight distributions (W-4 Table) are shown in Appendix E for all truck types and includes each axle load group (single and tandem) with its respective percentage of the total trucks weighed. Appendix E also contains a summary of all truck combinations of each of various gross weights (W-5 Table) and lists the percent distribution of various truck types derived from the 1980 W-5 Table for all rural roads in Texas based on the five state weigh stations.

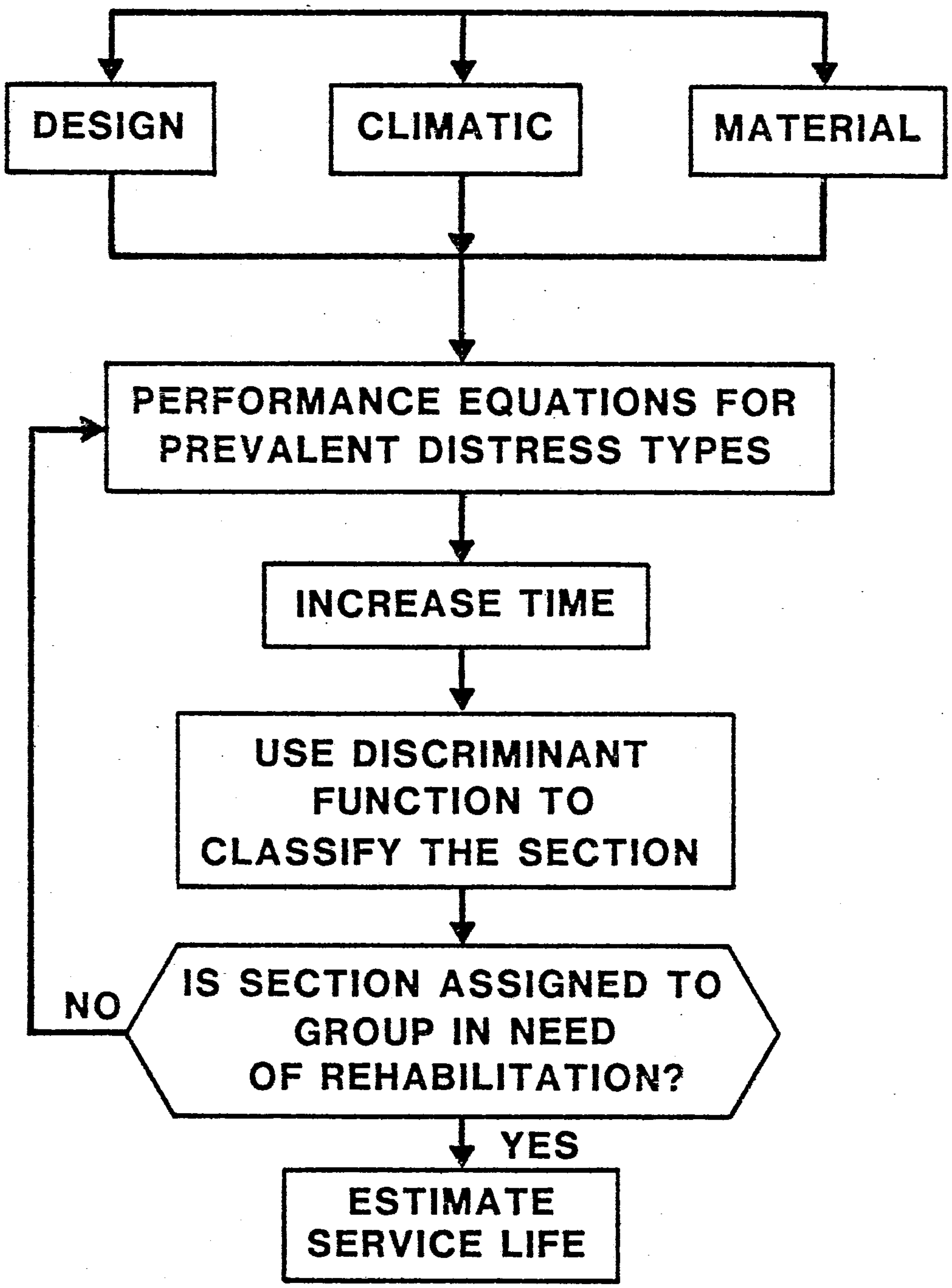

Figure 7. Conceptual Life Estimation Methodology.

Factors derived from the AASHO Road Test Data are used to convert the various weight classes into 18-kip ESAL's and are listed in Table E-4 in Appendix E.

Assuming that all highways have the same distribution of truck configurations and weight distributions the information from Appendix E, AADT, percent trucks, and percent trucks in main traffic lane, the total ESAL's for a month can be determined. If a linear traffic growth rate is assumed, the following expression relates time in months to the accumulated load:

$$A = N_0[I + 0.5\ GI(I-1)] \tag{17}$$

where

N_0 = monthly 18-kip ESAL's at time 0,

I = number of months,

G = monthly growth rate,

A = accumulated 18-kip ESAL's

and

$$N_0 = N_c/(1 + I_sG) \tag{18}$$

where

N_c = current monthly 18-kip ESAL's

I_s = surface age in months.

Once the current monthly 18-kip ESAL's has been determined and a 18-kip ESAL life has been estimated, Eqs. (17) and (18) can be used to calculated the number of months that the pavement will last. Given the current age of the pavement, the remaining service life in months is obtained by subtracting it from the total life. This is also converted into 18-kip ESAL's by the relationship shown in Eq. (17).

Results produced from the life prediction model were correlated with actual data from Texas pavements. Sample averages for the sections used in the correlation analyses were found to be consistent with those obtained using the MLE estimators and are listed in Table 12. The statistical findings from regression and correlation analyses are shown in Figures 8, 9, 10, and 11 for asphalt concrete, overlaid flexible, overlaid composite and Farm-to-Market surface treated pavements. Estimates for other surface treated pavements did not correlated acceptably with actual data.

Table 12. Means of Estimated Service Lives for Sections Utilized in the Life Prediction Model.

Pavement Type	No. of Observations	Average
Asphalt Concrete		
Interstate	10	1.1058
US/Sate	17	0.6595
Overlays		
Interstate	7	1.1779
US/State (Flexible)	19	0.5783
US/State (Composite)	17	0.5898
Surface Treated		
US/State	25	0.1206
Farm-to-Market	31	0.0206

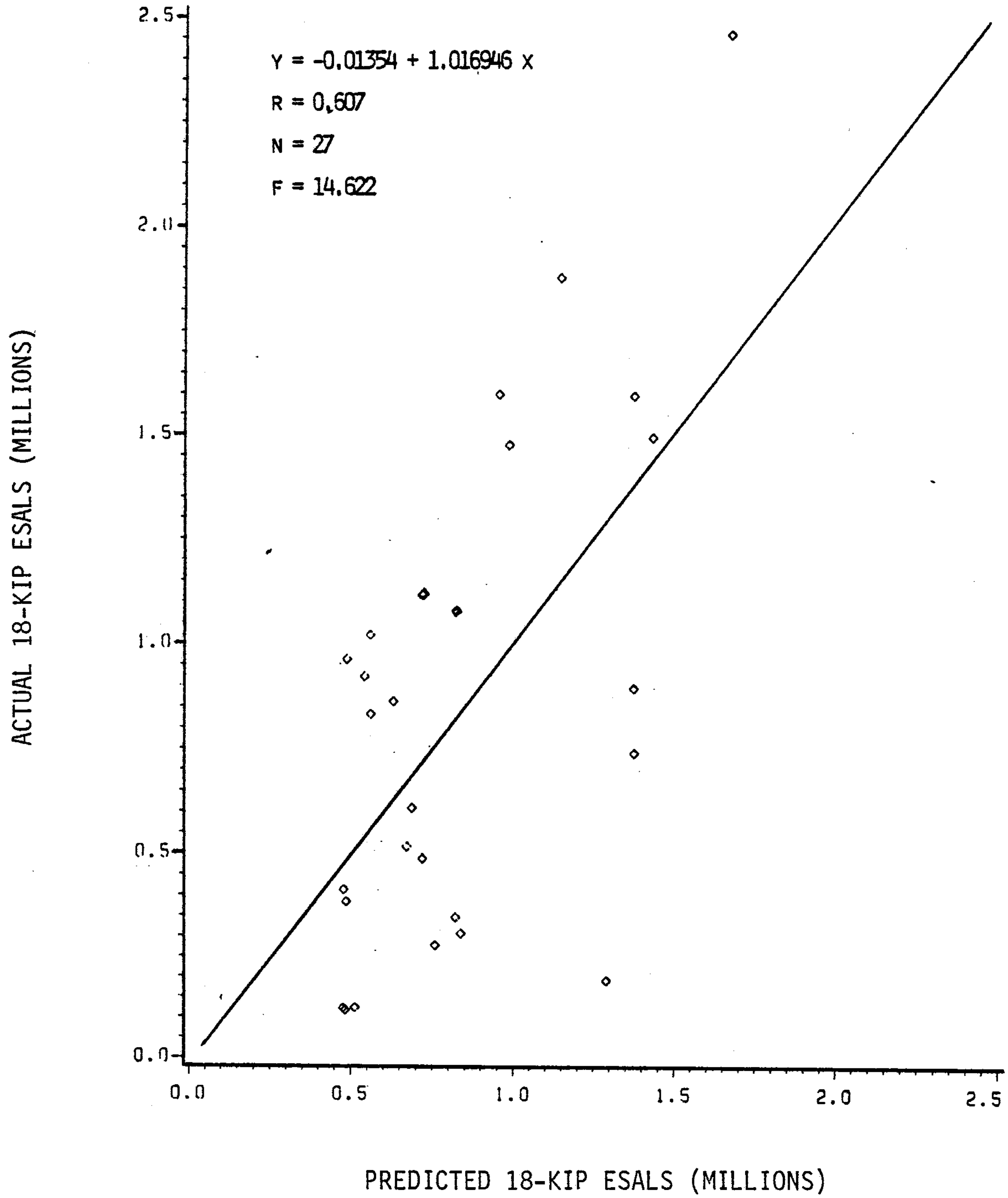

Figure 8. Actual -vs- Predicted Performance for Asphalt Concrete Pavements.

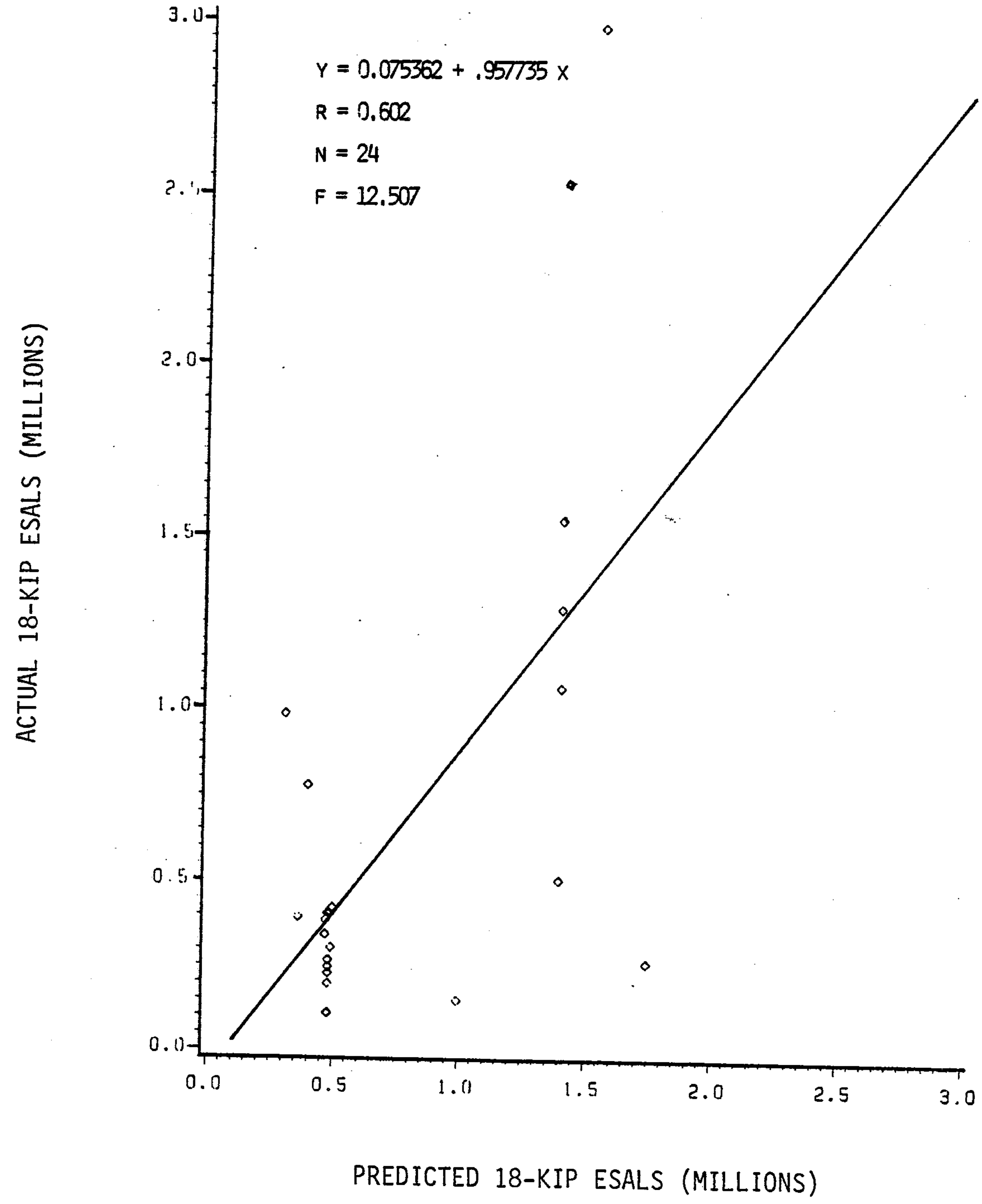

Figure 9. Actual -vs- Predicted Performance for Overlaid Flexible Pavements.

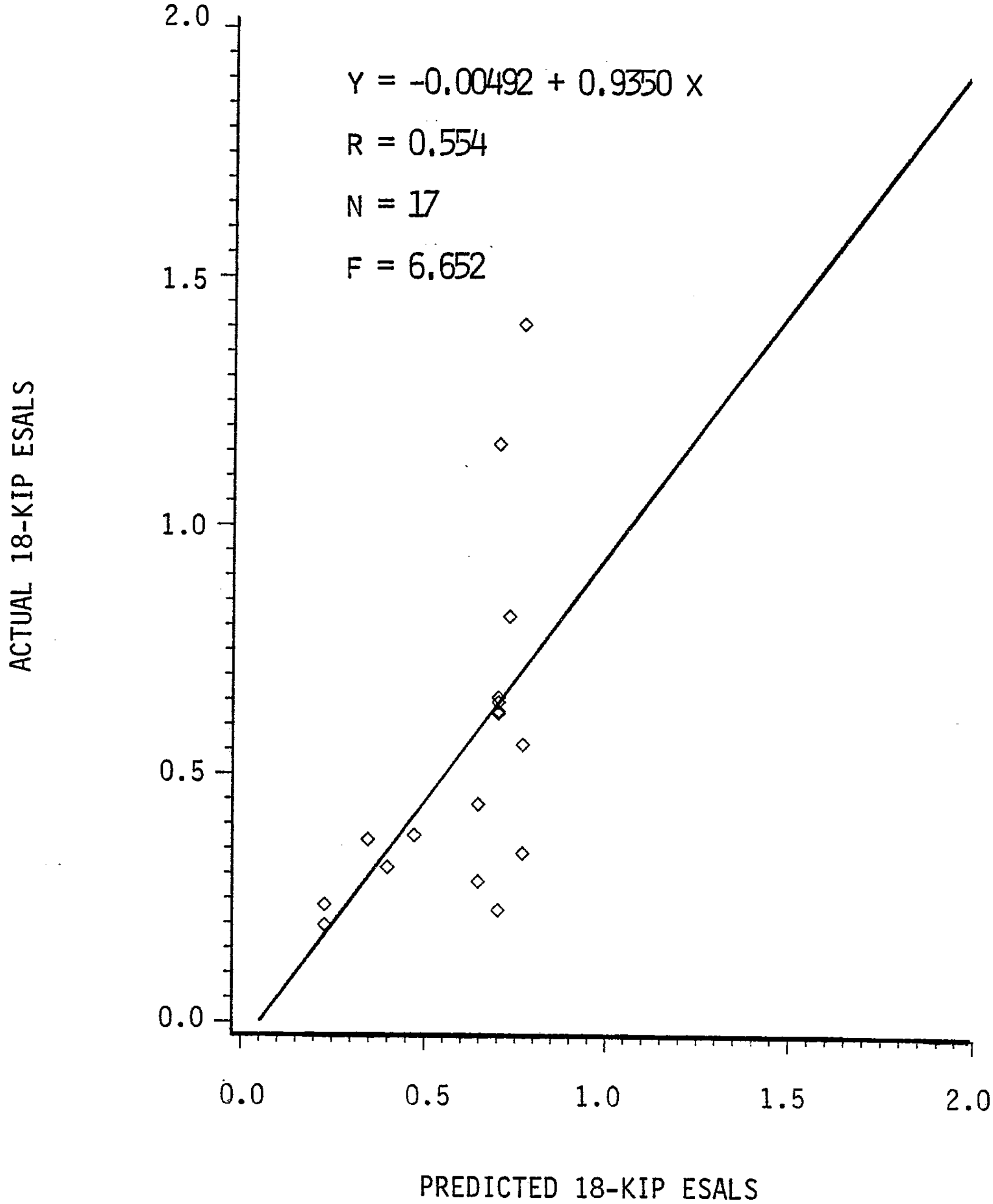

Figure 10. Actual -vs- Predicted Performance for Overlaid Composite Pavements.

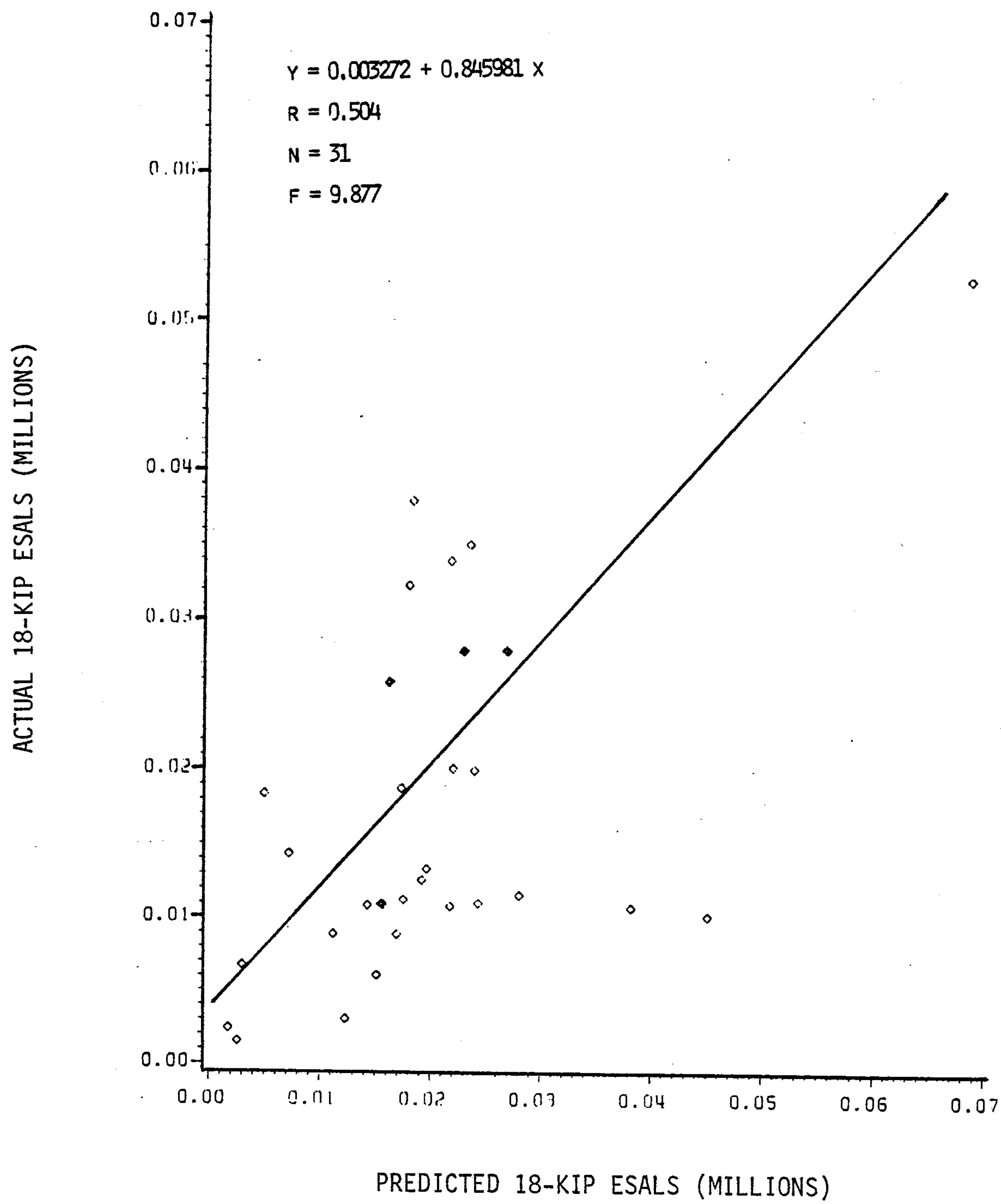

Figure 11. Actual -vs- Predicted Performance for Farm-to-Market Surface Treated Pavements.

The resulting regression lines are close to the desired 0 intercept with a slope of 1 (a 45° line on the graphs). With correlation coefficients in the .5 to .6 range, about 26-37% of the variation in the actual service life is accounted for by the linear relationship. However, an examination of the F values (6.7 - 14.6) reveals that a significant amount of the variation in the response variable (actual life) is accounted for by the linear model. Although these results may not be extremely impressive, they are promising, especially when it is realized that there has been a wide range in the decision process for determining when a pavement should be resurfaced, including the availability of funding, which may or may not have been related to the need for resurfacing.

4. USER COST METHODOLOGY

A fundamental aspect in the economic analysis of a road construction or rehabilitation policy is the quantification of the corresponding savings in user costs. The two types of variable user costs that are generally associated with the operation of a transit system are the mileage-dependent cost and the time-dependent cost. Mileage-dependent costs include the cost of power and the cost of keeping vehicles in operative condition. Time-dependent costs are related to the value of passenger travel time and the wages paid to operating personnel driving the vehicles.

One of the objectives of this study, and the purpose of this Section, is to develop a methodology to assess the savings in user costs resulting from a decision concerning the rehabilitation of a pavement. The quantification of the time delay and extra vehicle operating costs during the rehabilitation (resurfacing) activity will not be considered in this study. Only those cost items directly measurable for different levels of roughness will be studied. These items generally can be classified as (21,22):

(a) fuel consumption

(b) oil consumption

(c) tire wear

(d) repair parts and maintenance

(e) travel time

(f) depreciation

The above costs are affected by the type of road, the type of vehicle, the operator, the weather and the topographical conditions. Here, it is assumed that only the type of vehicle and the type of road are relevant. It should be mentioned that the speed of the vehicle is an important parameter since it affects the consumption rates of some other basic inputs of the mileage-dependent cost.

The following types of vehicles will be considered in the present analysis:

(a) automobiles (mid-sized)

(b) single unit 2 axle trucks (SU-2)

(c) single unit 3 axle trucks (SU-3)

(d) tandem unit 4 axle trucks (2-S2)

(e) tandem unit 5 axle trucks (3-S2)

Table 13 lists the component prices used for each vehicle type. The number of each type of vehicle traveling over a pavement section is derived using AADT estimates, percent of trucks, and the percent distribution of each truck type (Appendix E, Table E-3).

Roughness, measured in terms of PSI, will be used to describe the riding condition of a given pavement. The performance equations developed by Lytton et al. (15) to predict PSI values for different pavement types in Texas will be used to estimate the riding conditions at the time a rehabilitation decision is scheduled. Appendix G lists the equations used in this study for predicting PSI values for each of the three pavement types.

Table 13. Component Prices.

Item	Automobile (Mid-Size)	SU-2	SU-3	2-S2	2-S3
Fuel ($/gal)	1.25	1.25	1.25	1.25	1.25
Oil ($/qt)	1.00	1.00	1.00	1.00	1.00
[a]Tires* ($/tire)	68.00	194.00	465.00	465.00	465.00
[a]Maintenance and Repairs ($/1000 mi)	41.60	99.00	140.00	145.00	145.00
[a]Depreciable Value ($/veh)	7,501.00	8,673.00	45,350.00	48,687.00	51,630.00

* Truck tire cost includes 2.5 recaps per tire for all trucks except SU-2 which has 1.5.

[a] Source: Reference 22.

4.1 Fuel Consumption

Fuel costs represent the largest portion of the total outlay for vehicle operation. However, the fuel consumption rate varies little with changes in pavement condition. For automobiles, the difference between rates was found to be 1.5% when the PSI is varied from 4.5 to 1.5 (26). Figure 12 represents the relationship between fuel consumption and PSI. In this figure, it is assumed that the fuel consumption rate can be linearly reduced as a function of PSI. In this study this relationship will be used for all types of vehicles. Fuel consumption savings derived from improvements in serviceability are calculated on the basis of the concept illustrated in Figure 13 (28). This concept assumes that costs linearly increase up to a point (B) at

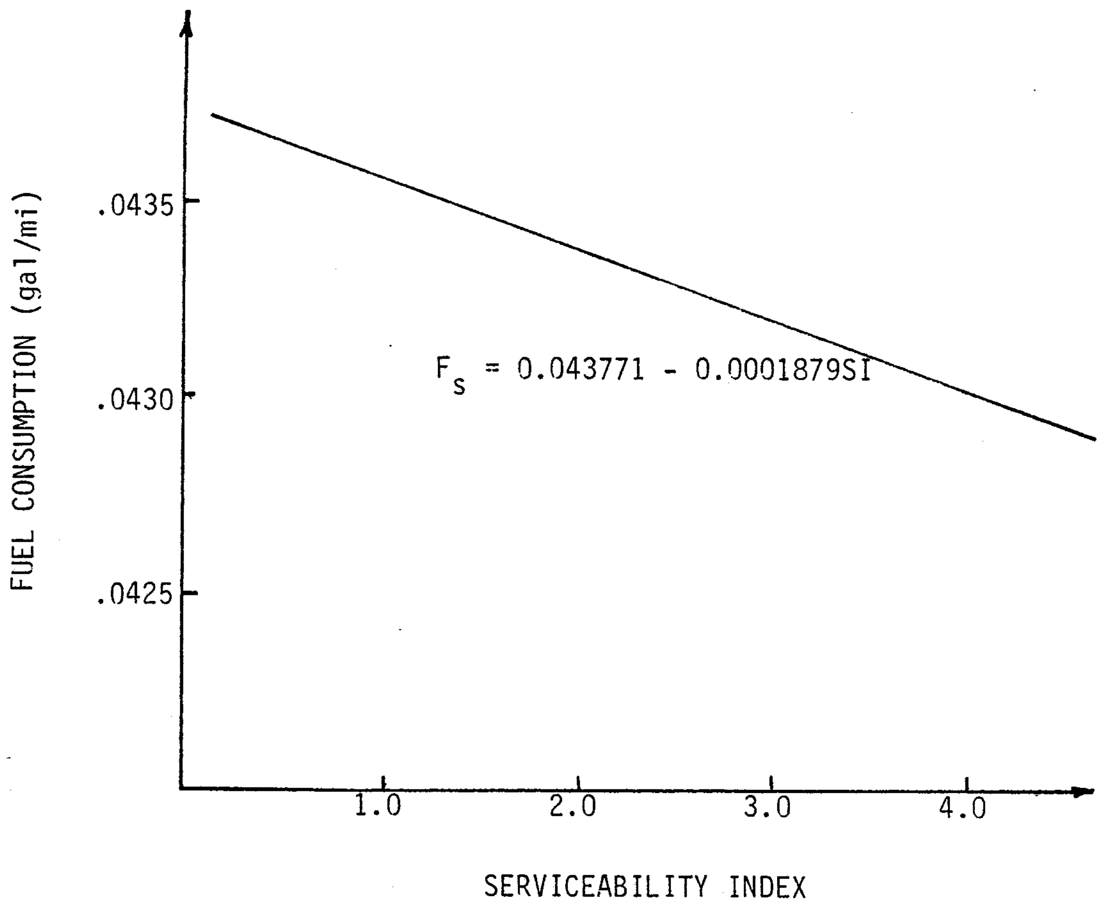

Figure 12. Fuel Consumption -vs- Serviceability Index.

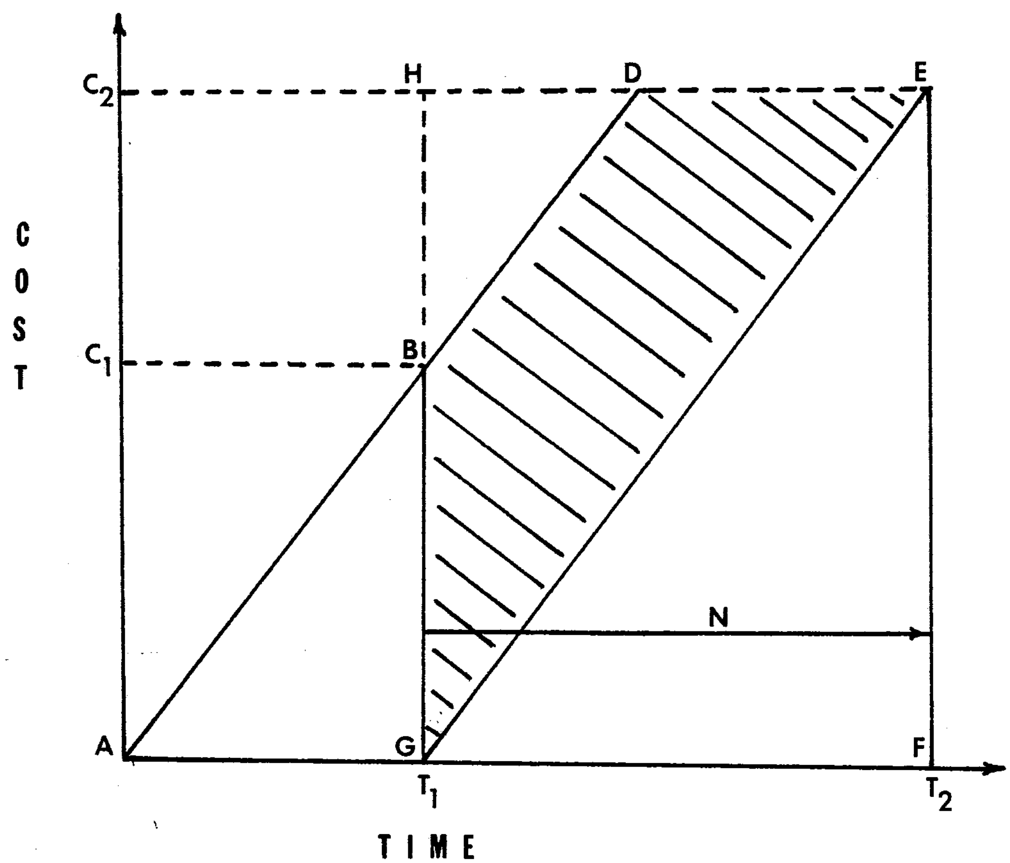

Figure 13. Time -vs- Cost Concept (28).

which they remain constant; resurfacing (G) would update the age of the road and reset the cost structure to zero. The savings associated with the rehabilitation decision are represented by the area BDEG for a service life of N years.

Using the above concept, the following equation was developed to calculate fuel consumption savings due to resurfacing:

$$S_f = 365\ [F_2 N/2 - .5\ (F_2 - F_1)\ (N - N(F_1/F_2))](AADT)\ (L_s)\ (CG)/GC/N \qquad (19)$$

where

S_f = savings from fuel savings due to resurfacing/year,

F_2 = maximum percent reduction in fuel costs (1.5%) due to resurfacing,

F_1 = percent reduction in fuel costs based on PSI before resurfacing,

N = service life,

AADT = average annual daily traffic,

GC = average miles/gallon,

CG = cost of a gallon of gasoline, and

L_s = length of section.

The percentage reduction in fuel usage is given by:

$$F_1 = 0.0001879(PSI_A - PSI_B)/(0.043771 - 0.0001879 PSI_A) \qquad (20)$$

where

PSI_A = serviceability index after resurfacing and

PSI_B = serviceability index before resurfacing.

The average number of miles per gallon of gasoline is estimated as

$$GC = 1000 \sum_{i=1}^{5} \frac{AADT + PV_i}{S_i} \qquad (21)$$

where

PV_i = percent of ith vehicle type

PV_i for automobiles = AADT(1-PCTRK)

PV_i for trucks = AADT(PCTRK)($PCTR_j$)

PCTRK = percent trucks

$PCTR_j$ = percent of jth truck of total trucks

S_i = fuel consumption (gallon/1000 mi) for a given speed. Appendix H lists fuel consumption rates for the different vehicle types.

4.2 Oil Consumption

Under normal operating conditions oil consumption costs are the least important of the non-fuel vehicle operating costs. The best available data for relating oil consumption to pavement roughness are those collected in a recent study in Brazil (22). The results from that study may not be directly applicable to the United States due to differences in design and economic conditions. Figure 14 illustrates the relationship between PSI and fuel consumption that will be used in this research project for automobiles and trucks.

Costs savings for oil consumption and all other user costs described hereafter are calculated using the concept illustrated in Figure 15 (28). This concept assumes that costs are equal to C_2 until resurfacing, at which time (T_1) they decrease to a level C, and remain constant. Although the serviceability index probably decreases with time, it can be assumed that routine maintenance will maintain it relatively constant.

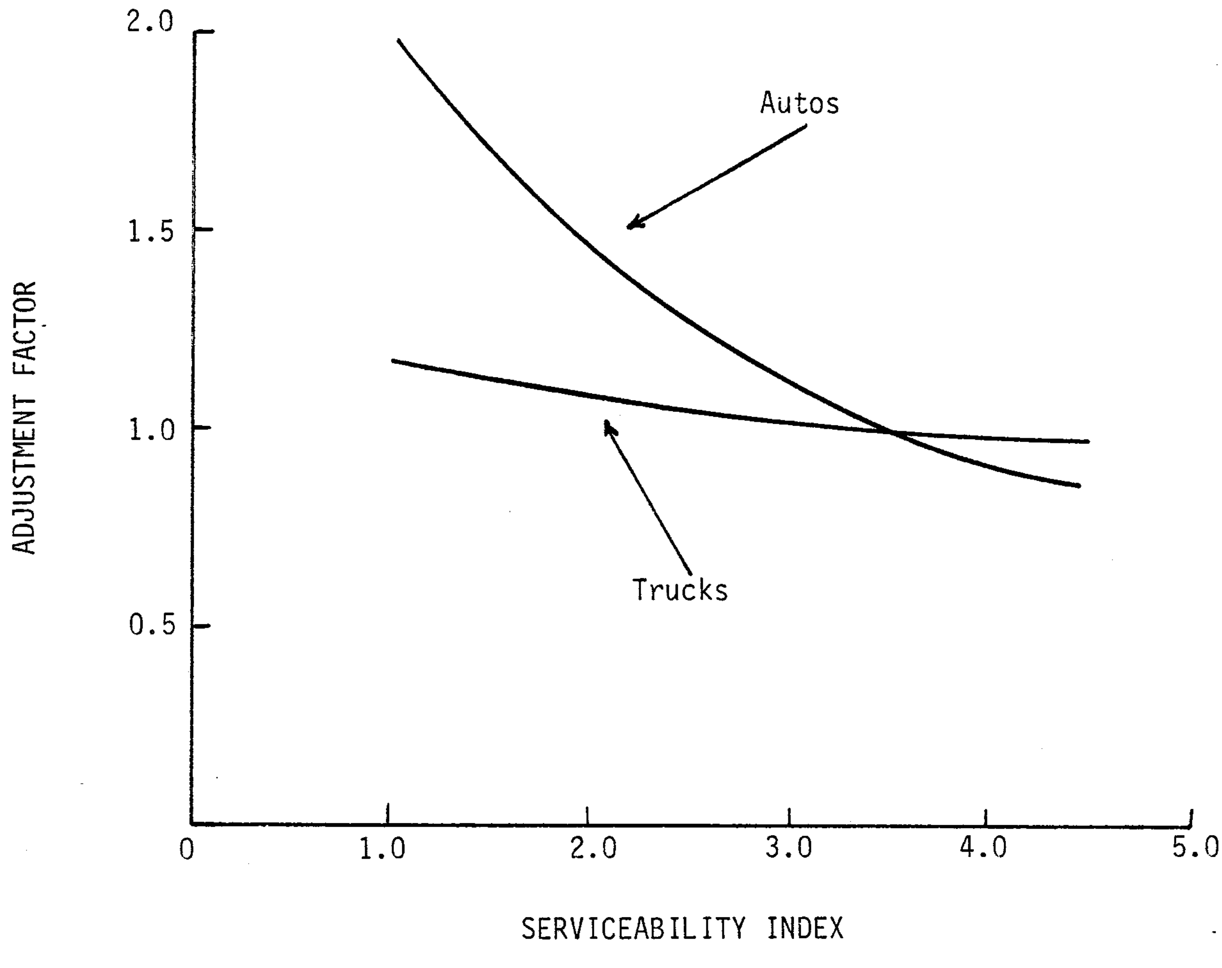

Figure 14. Influence of Pavement Condition on Oil Consumption (22).

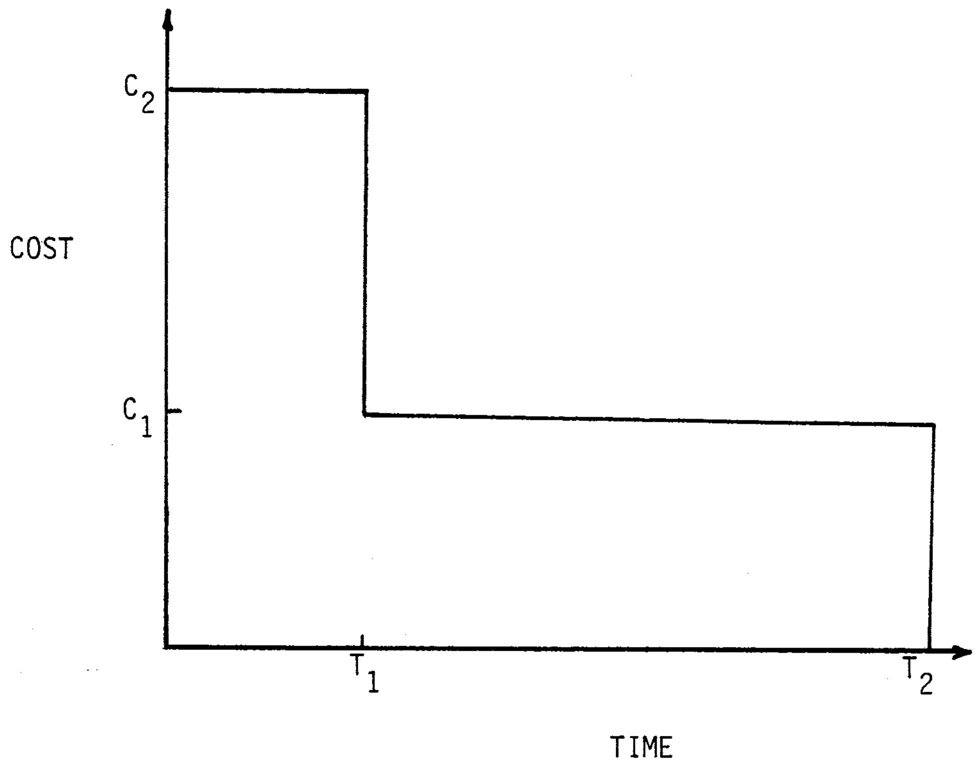

Figure 15. Time -vs- Cost Concept II (28).

Approximating the relationship shown in Figure 14 to a linear function the following equation calculates the oil consumption savings due to resurfacing:

$$S_o = 365 \; [(2.2847-0.3188(PSI_B)-0.85)(PV_1)(AADT)(OC_1) + (1.261-0.0561(PSI_B)-1.05) \sum_{i=2}^{5} PV_i (AADT) OC_i] L_s (CO) \qquad (22)$$

where S_o = oil consumption cost savings due to resurfacing/year

PSI_B = PSI before resurfacing

OC_i = oil consumption (quarts/mi) for ith vehicle type

CO = cost of a quart of oil

Appendix H summarizes the oil consumption rates for different types of vehicles and different levels of speed.

4.3 Tire wear

For each individual type of vehicle, tire wear can be measured as the percentage of the tire worn per mile. Appendix H contains the percentage worn/1000 miles as a function of speed and vehicle type. An important factor for calculating tire wear costs is the number of tires per vehicle. Automobiles, SU-2, SU-3, 2-S2 and 3-S2 trucks use 4, 6, 10, 14, and 18 tires, respectively. Roughness adjustment factors developed from the Brazil study (22) for automobiles and trucks are presented in Table 14. Subtracting the factor for the PSI after resurfacing from the factor for PSI before resurfacing, and multiplying the result by the tire cost yields the savings due to resurfacing.

Table 14. Tire Expense Adjustment Factors for Roadway Surface Condition.

Serviceability Index	Passenger Cars	Single Unit SU-2, SU-3, 2-S2 & 3-S2 Semi's
1.0	2.40	1.67
1.5	1.97	1.44
2.0	1.64	1.27
2.5	1.37	1.16
3.0	1.16	1.07
3.5	1.00	1.00
4.0	0.86	0.95
4.5	0.76	0.92

The following equation can be used to calculate the tire consumption savings associated with an increase in the serviceability index:

$$S_t = 365 \left[\sum_{i=1}^{5} NT_i (CT_i)(TC_i) TF_i (PV_i)(AADT) \right] (L_\$) \qquad (23)$$

where

S_t = tire cost savings due to resurfacing/year

NT_i = number of tires for ith vehicle

CT_i = cost of tire for ith vehicle

TC_i = % tire worn/mile for ith vehicle at a given speed

TF_i = difference in roughness adjustment factors for PSI_B-PSI_A for the ith vehicle.

4.4 Vehicle Maintenance and Repair

Maintenance and repair represent a major portion of the vehicle operating costs. This cost is composed of the cost of repair components and the cost of labor. The general vehicle components considered for the development of these costs include (21): (a) body, (b) brakes, (c) power train, (d) chassis, (e) electrical, and (f) engine. Appendix H lists the percent of the average maintenance and repair costs/1000 miles for different speeds for each vehicle type. Results from the Brazil study are used to adjust the expenditures to different levels of serviceability. The adjustment factors for each vehicle type are listed in Table 15.

The following equation describes the savings in maintenance and repair costs brought about by an increase in serviceability:

$$S_m = 365[\sum_{i=1}^{5} CM_i(MC_i)(MF_i)(PV_i)AADT](L_s) \qquad (24)$$

where

S_m = maintenance and repair cost savings due to resurfacing/year

CM_i = average yearly maintenance cost for ith vehicle

MC_i = percent of CM_i per mile at a given speed for the ith vehicle

MF_i = difference in roughness adjustment factor before and after resurfacing for the ith vehicle

Table 15. Maintenance and Repair Expense Adjustment Factors for Roadway Surface Conditions.

Serviceability Index	Passenger Cars	Single Unit	2-S2 & 3-S2 Semi Trucks
1.0	2.30	1.73	2.35
1.5	1.98	1.48	1.82
2.0	1.71	1.30	1.50
2.5	1.37	1.17	1.27
3.0	1.15	1.07	1.11
3.5	1.00	1.00	1.00
4.0	0.90	0.94	0.92
4.5	0.83	0.90	0.86

4.5 Depreciation Cost

The depreciation expense of a vehicle is related to the time and use of the vehicle. Controversy exists as what portion, if any, of this expense should be assigned to operation on the road. Appendix H contains percents of the vehicle new value for estimating the depreciation expense for different types of vehicles. These factors were developed using a procedure outlined by Daniels (32) for using vehicle survivor curves to proportion depreciation costs due to time and use. The adjustment factors of Table 16 can be used to relate surface roughness to depreciation expense. These factors were developed for the Brazil study (22).

The depreciation cost savings can be calculated by:

$$S_d = 365 \left[\sum_{i=1}^{5} VC_i(DC_i)(DF_i)(PV_i)AADT \right](LT) \qquad (25)$$

where

S_d = depreciation cost savings due to resurfacing per year

VC_i = purchase cost of ith vehicle

DC_i = percent of VC_i per mile at a given speed for the ith vehicle

DF_i = difference in roughness adjustment factor before and after resurfacing for the ith vehicle

4.6 Travel Time

Vehicle operating costs are directly influenced by the speed of the vehicle. To adjust the vehicle running speed for different levels of PSI, Hazen (33) has transformed an equation developed by Karan et al. (23). The transformed equation establishes the following relationships based on average running speeds (ARS):

(a) For ARS greater than or equal to 35 mph:

$$ARS' = ARS\,[0.8613(PSI)^{0.0928}] \qquad (26)$$

(b) For ARS between 15 and 35 mph:

$$ARS' = ARS[0.8613(PSI)^{0.0928} + (1-0.8613(PSI)^{0.0928})/(35-ARS)/20 \qquad (27)$$

(c) For ARS less than 15 mph:

$$ARS' = ARS \qquad (28)$$

Table 16. Use Related Depreciation Adjustment Factors for Roadway Surface Conditions.

Serviceability Index	Passenger Cars	Single Unit	2-S2 & 3-S2 Semi Trucks
1.0	1.14	1.33	1.32
1.5	1.09	1.23	1.22
2.0	1.06	1.15	1.14
2.5	1.04	1.09	1.09
3.0	1.02	1.04	1.04
3.5	1.00	1.00	1.00
4.0	0.99	0.97	0.97
4.5	0.98	0.94	0.94

Assuming that these relationships hold for all types of vehicles, the travel time cost savings due to resurfacing can be expressed as:

$$S_s = (365)(L_s/ARS - L_s/ARS') \, V \, (AADT) \qquad (29)$$

where

S_s = savings in cost of travel time due to resurfacing per year

V = average value of operator time ($/hr)

ARS = average running speed after resurfacing (speed limit)

ARS' = adjusted average running speed due to roughness

5. ECONOMIC ANALYSIS

The purpose of the economic analysis developed in this Section is two-fold: (a) to assess the impact of delaying rehabilitation decisions using a present worth analysis, and (b) to examine the degree of desirability associated with a given rehabilitation policy by providing the corresponding savings/cost ratio. The proposed analysis is based on the following items: initial capital costs of rehabilitation, maintenance costs, and savings in travel and maintenance costs due to resurfacing.

5.1 Rehabilitation Costs

The initial capital cost of rehabilitation depends on the specific rehabilitation strategy used to upgrade a road. The strategies used in this analysis are customized versions of those suggested by the California pavement management system (34). A summary of these strategies appears in Tables 17, 18 and 19 for asphalt, concrete, overlaid, and surface treated pavements, respectively. The use of the rehabilitation strategies summarized in Tables 17 through 19 provides realistic cost information based upon typical rehabilitation alternatives; however, these alternatives are not suggested as rehabilitation policies for specific resurfacing projects. A more detailed and fact-finding approach is needed in this case.

The costs associated with a particular rehabilitation alternative includes labor, equipment and material costs. These costs generally depend on the length, number of lanes, lane width and the presence or

Table 17. Rehabilitation Strategies for Asphalt Concrete Pavements.

Cause	Condition		
	Slight	Moderate	Severe
Alligator Cracking	Fill Cracks	1" Overlay and Local Digout	5" Overlay
Longitudinal and Transverse Cracking	Do Nothing	Fill Cracks	Chip Seal

Table 18. Rehabilitation Strategies for Overlaid Pavements.

Cause	Condition		
	Slight	Moderate	Severe
Alligator Cracking	Fill Cracks	1" Overlay and Local Digout	5" Overlay
Longitudinal Cracking	Do Nothing	Fill Cracks	Chip Seal
Serviceability Index	PSI $\leq$ 2.9	Leveling and 1" Overlay	

Table 19. Rehabilitation Strategies for Surface Treated Pavements.

Cause	Condition		
	Slight	Moderate	Severe
Rutting	Seal Coat	Double Seal Coat	Sectional Reconstruction
Longitudinal and Transverse Cracking	Do Nothing	Do Nothing	Fill Cracks
Patching	Do Nothing	Seal Coat	Double Seal Coat

absence of shoulders. Appendix I lists formulas developed for calculating the cost of several typical rehabilitation strategies for two lane, multilane, and freeway type highways. This appendix also lists labor and material costs comparable to those used in a recent budget preparation study conducted by Garcia-Diaz, et al. (35).

As part of the customizing, the alternatives have been stated in terms of the scores obtained for PSI and for each distress type from the condition survey. The alternative is matched with the predicted condition for each applicable distress type (and serviceability index, if applicable), and the most costly strategy is chosen as the cost of rehabilitation. The value of the surface is assumed to be negligible at the end of the estimated service life. If rehabilitation is delayed, the performance equations predict the pavement condition on one year intervals, thus making possible the selection of a more costly rehabilitation strategy.

5.2 Maintenance Costs

Pavement maintenance costs are assumed to increase with age. For lack of a more precise model developed for specific Texas conditions, the EAROMAR (36) equations are used. These equations were actually developed to predict maintenance work loads for multilane freeways in terms of: (a) patching, (b) crack sealing, and (c) base and surface repairs. The general form of the EAROMAR model can be formulated as follows:

$$C_t = (1100C_1 + 1000C_2 + 5C_3)/(1 + e^{-(t-10)/1.16}) \qquad (30)$$

where

C_t = annual maintenance cost in year t per lane mile,

C_1 = \$/sq yd of bituminous skin patching,

C_2 = \$/linear foot of crack sealing

C_3 = \$/cu yd of bituminous base and surface repair

Cost estimates by the SDHPT for C_1, C_2 and C_3 are \$3.47, \$0.25 and \$450, respectively. For highway types other than freeways, the EAROMAR results are appropriately modified by multiplying them by a reduction coefficient reflecting past maintenance data. Table 20 summarizes the results of this analysis after comparing maintenance costs of Farm-to-Market, and US/State highways to those on Interstate routes in Texas (7) As an illustration, Table 20 indicates that the maintenance cost on Farm-to-Market roads is 38.2% of the cost per lane mile computed by the EAROMAR equations.

Table 20. Comparison of Maintenance Costs per Lane Mile.

Highway System	Number of Observations	Average Maintenance Cost/Lane Mile	% of Interstate
Interstate	4	$1,028.00	100.0
Farm-to-Market	23	391.00	38.2
US/State	62	325.00	31.6

5.3 Discount Rate

The selection of a discount rate depends on whether estimates are made in terms of constant dollars (costs stated at price levels prevailing at a particular date in time regardless of when they occur) or current dollars (prices stated at price levels prevailing at the time the costs are incurred). A discount rate based on the market rate of return is consistent with the use of current dollars in estimating future costs. One using the real interest rate (increase in real purchasing power) is consistent with the use of constant dollars.

Erroneously, common practice has been to conduct present worth analyses using constant dollars together with the market rate of return which in turn allows for expected future inflation. If the estimation of future costs makes no provision for anticipated inflation, (a rather dangerous task, one that is not highly suggested(37)), only the real cost of capital should be represented in the discount rate (38,39).

The real long-term rate of return on capital has been between 3.7 and 4.4 percent since 1966 (38,40). Since constant dollars are to be used for estimating rehabilitation, maintenance and users costs, a discount rate of 4% will be used in the sample runs of Appendix J.

If current (inflated) dollars were to be used in the analysis, a range of 8 to 12% would be appropriate (The United States Office of Management and Budget prescribes a 10% discount rate for most federal government studies using current dollar costs (40)).

5.4 Analysis Period

The analysis period selected for this study is chosen as the estimated service life of a rehabilitation strategy. Experience has shown that overlays or seals placed upon pavements are most likely to last four to twelve years, even though many are designed to last 20 years. A 20-year analysis period would therefore require additional estimates for rehabilitation and maintenance costs during the period. Possible changes in technology and the inherent uncertainty of the events occurring when predicted may invalidate the cost analysis.

The life prediction model described in Section 3.6 will be used to estimate the service life for rehabilitated pavement. This estimate in turn will be utilized as the analysis period.

5.5 Present Worth Analysis

The present worth analysis method will be used to assess the cost of delaying rehabilitation beyond the estimated service life. This analysis focuses on the cost of the rehabilitation strategy prescribed for a pavement in a given condition and the annual maintenance cost during the analysis period. The comparison of alternatives using the present worth method requires that all alternatives be considered over the same time span, which in this case is the analysis period.

It is assumed that the service life of the rehabilitation strategy applicable at the end of the estimated life holds for rehabilitation strategies corresponding to the pavement condition after delaying rehabilitation for one or more years. It is then apparent that if the common analysis period is the service life of the rehabilitation at the end of the estimated life, a portion of the value of subsequent rehabilitations will remain unused. In order to compare the alternatives over equal time spans, the unused value of the rehabilitated pavement is taken into consideration. However, as the delay approaches the end of the analysis period, the present worth value becomes less meaningful for comparison purposes since a considerable portion of the value of the improvement remains unused.

The present worth of the rehabilitation plus maintenance at the end of the estimated service life may be expressed as:

$$PW_0 = R_c + \sum_{n=1}^{m} C_n \cdot P/F_{i,n} \quad (31)$$

where:

i = discount rate

R_c = rehabilitation cost

m = analysis period

C_n = maintenance cost in year n

$P/F_{i,n}$ = single payment present worth factor

$= {}^1/(1+i)^n$

If rehabilitation is delayed, maintenance accrued prior to resurfacing must be considered and the present worth may be represented as:

$$PW = \sum_{n=1}^{r} (C_n \cdot P/F_{i,n}) + [R_c \cdot A/P_{i,m} + \sum_{n=1}^{m} (C_n \cdot P/F_{i,n} \cdot A/P_{i,m})] \qquad (32)$$

$$(P/A_{i,m-r} \cdot P/F_{i,r})$$

where

$A/P_{i,n}$ = equal payment series capital recovery factor,

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

$P/A_{i,n}$ = equal payment series present worth factor,

$= 1/(A/P_{i,n})$

and the unused value at the end of the analysis period may be expressed as:

$$U = R_c \cdot A/P_{i,m} \cdot P/A_{i,r} \qquad (33)$$

5.6 Savings/Cost Ratio

The benefit/cost method has experienced considerable usage in the public sector and has been promoted by the American Association of State Highway Officials (41) for comparing investment alternatives. The benefit cost ratio represents the ratio of the present worth of net benefits to the present worth of net costs.

For this analysis, benefits will be measured in terms of user and state agency savings due to the improvement of the pavement surface, thus the term savings/cost ratio will be utilized.

Savings to the SDHPT are in the form of reduced maintenance costs. Maintenance costs increase with pavement age as discussed previously in Section 5.2, hence resurfacing updates the pavement age, thus reducing maintenance costs. User cost savings considered include savings in fuel consumption, oil consumption, tire wear, vehicle repairs and maintenance, depreciation, and time. Inherent in this analysis is the assumption that the responsible agency will not permit the road to completely disintegrate causing complete disruption of service to users and possibly insurmountable costs.

The savings/cost ratio may be written as:

$$S/C = \left[\frac{S_f + S_o + S_t + S_s + S_d + S_m + S_{rm}}{R_c}\right] P/A_{i,m} \tag{34}$$

where

S_{rm} = savings in road maintenance

$$= N_\ell (1100C_1 + 1000C_2 + 5C_3) \sum_{i=1}^{m} ((1/1+e^{-i/1.16}) - (1/(1+e^{-(i-10)/1.16})) \tag{35}$$

In Equation (35), N_ℓ is the number of lanes of the pavement section. Benefits derived from reduced maintenance costs are estimated by calculating the difference between maintenance costs when there is no resurfacing and when resurfacing takes place.

6. APPLICATION AND DISCUSSION OF RESULTS

The methodology for predicting remaining service life and for assessing the economic impact of delays in rehabilitation decisions will be illustrated using three typical pavement sections, one from each of the three major pavement types of the Texas highway network.

The life prediction model described in Section 3.6 and listed in Appendix J is utilized for the first part of the methodology. The first pavement section consists of a 1-1/2" asphalt concrete surface with a 14" flexible base located in the Texas panhandle. The second section is a flexible pavement consisting of a 1" overlay over 3" of asphalt concrete with a 14" flexible base located in southeast Texas. The third section is representative of a surface treated pavement with a 6" flexible base and is located in the proximity of Burleson County. Table 21 lists the climatic, design and traffic data for each of the sections under consideration.

The cost information used in the economic analysis is listed in Tables 22A and 22B. To illustrate the effect of the discount rate, the economic analysis was performed considering rates of 4% and 12%.

The distribution of the vehicle types considered in this application described in Section 3.6 and Tables E-2 - E-4 of Appendix E. This distribution is used along with the average daily traffic and the percent trucks to calculate the number of equivalent single-axle loads per month.

Table 21. Description of Sections Used in Analysis.

Variable	Pavement Type		
	Asphalt Concrete	Overlay	Surface Treatment
AADT	3290	16780	350
Percent Trucks	18.7	13.9	5.0
Percent Trucks/Lane	40.0	50.0	50.0
Percent Traffic Growth/Yr	3.5	3.5	3.5
Highway Type	US/State	Interstate	Farm-to-Market
Facility Type	Multilane	Freeway	Two-Lane
Number of Lanes	4	4	2
Section Length	1 mi	1 mi	1 mi
Speed Limit (mph)	55	55	55
Age of Surface Layer (months)	60	60	20
Thickness of Asphalt Concrete (in)	1.5	N/A	N/A
Thickness of Overlay & Original Surface	N/A	4.0	N/A
Thickness of Flexible Base	14.0	14.0	6.0
Structural Number	2.62	3.28	N/A
Subgrade Plasticity Index	27.5	38.9	23.1
Subgrade Liquid Limit	47.5	63.4	41.6
Mean Temperature - 50°F	8.2	18.3	17.4
Thornthwaite Index + 50	31.3	89.1	52.1
Average Annual Freeze Thaw Cycles	83.0	11.0	35.5
Dynaflect Maximum Deflection (mils)	N/A	N/A	1.55

Table 22A. Cost Information Used.

Rehabilitation Strategy	Rehabilitation Cost	Road Maintenance Strategy	Maintenance Cost
Overlay	$10000./in/lane mile	Patching	$3.47/sq yd
Base and Repair Patch	140000./lane mile	Base and Surface Repair	450.00/cu yd
Seal Coat	3000./lane mile	Crack Sealing	0.25/linear ft
Fill Cracks	1000./lane mile		

Table 22B. Vehicle Related Costs.

Item	Vehicle				
	Auto	SU-2	SU-3	2-S2	3-S2
Tires (ea.)	68.00	194.00	465.00	465.00	465.00
Maintenance and Repairs (/1000 mi)	41.60	99.00	140.00	145.00	145.00
Depreciable Value ($/veh)	7501.00	8673.00	45350.00	48687.00	51630.00
Gasoline ($/gal)	1.20	1.20	1.20	1.20	1.20
Oil ($/qt)	1.00	1.00	1.00	1.00	1.00
Average Value of Time ($/hr)	6.00	6.00	6.00	6.00	6.00

6.1 Results

Results for each of the sections considered are classified as follows:

(a) Service life and remaining life predictions. This information is summarized in Table 23.

(b) Predicted condition of the pavement at the end of the estimated service life, and at the end of each year thereafter if no rehabilitation occurs. This information is summarized in Tables 24, 25 and 26.

(c) Present worth and savings/cost analyses for discount rates of 4 and 12%. This information is summarized in Tables 27A, 27B, 28A, 28B, 29A, and 29B.

6.2 Analysis of Results for Asphalt Concrete Section

This pavement section has approximately three years of remaining service life; after this time a rehabilitation strategy costing $4000 is recommended. Further development of pavement distress does not trigger a more costly rehabilitation strategy until the third year; however, the PSI decreases, translating into greater potential savings to be obtained from the rehabilitation. After the third year the proposed rehabilitation costs increase significantly. Therefore, the savings/cost ratio using either a 4 or 12% discount rate indicates that the best time to rehabilitate (highest savings/cost ratio), is 2 years after the end of the estimated service life. On the other hand, rehabilitating at the end of the estimated service life gives the

Table 23. Estimated Service Life.

	Asphalt Concrete	Overlaid	Surface Treatment
Estimated Service Life (ESAL)	714,805 (100 months)	1,526,561 (48 months)	21,908 (80 months)
Remaining Life (ESAL)	303,810 (40 months)	0	16,790 (60 months)
ESAL/Month	7,411	35,120	264

Table 24. Predicted Pavement Condition for Asphalt Concrete Section.

Years After Estimated Service Life	Alligator Cracking Severity	Longitudinal Cracking		Transversal Cracking Severity	PSI
		Severity	Area		
0	1.00	1.00	2.00	1.00	2.43
1	1.00	1.00	2.00	1.00	2.37
2	1.00	1.00	2.00	2.00	2.31
3	2.00	2.00	3.00	3.00	2.26
4	2.00	2.00	3.00	3.00	2.22

Table 25. Predicted Pavement Condition for Overlaid Section.

Years After Estimated Life	PSI	Alligator Cracking Area	Longitudinal Cracking	
			Severity	Area
0	3.02	2.00	2.00	2.00
1	2.96	3.00	3.00	3.00
2	2.91	3.00	3.00	3.00

Table 26. Predicted Pavement Condition for Surface Treated Pavement.

Years After Estimated Life	Rutting		Longitudinal Cracking	Transversal Cracking Area	Patching Area	PSI
	Severity	Area				
0	1.00	0.00	1.00	1.00	0.00	3.78
1	1.00	0.00	1.00	1.00	0.00	3.74
2	2.00	1.00	1.00	1.00	0.00	3.59
3	2.00	1.00	1.00	1.00	0.00	3.44
4	3.00	2.00	2.00	2.00	1.00	3.30

lowest present worth of road rehabilitation and road maintenance costs. For the first 2 years the difference in the present worth value is due to greater road maintenance costs which in turn are a function of pavement age.

6.3 Analysis of Results for Overlaid Section

This pavement is one year past the end of the estimated service life at which time it would have been preferable to rehabilitate according to both the present worth and savings/cost ratio. The savings/cost analysis indicates that rehabilitation should not be delayed since the cost of rehabilitation increases after a one-year delay. An examination of the pavement condition reveals that each distress type considered reaches a maximum after a one-year delay, and thus the rehabilitation strategy selected is the most costly after this time. This indicates that rehabilitation should probably not be delayed further since the pavement may deteriorate to the point where a major reconstruction effort will be necessary.

6.4 Analysis of the Results for Surface Treated Section

Both the present worth and the savings/cost analyses indicate that the best time to rehabilitate is one year after the estimated service life. The effect of the discount rate is evident if we were to rank the alternatives according to the present worth value. For 4% the order of preference would be (a) in one year, (b) now, (c) in 2 years, and (d) in 3 years. For 12% the order would be (a) in one year, (b) in 3 years, (c) now, and (d) in 2 years.

Table 27A. Cost Analysis Results for Asphalt Concrete Section Using 4% Discount Rate.

Analysis Period = 7 yrs										
			Present Worth of Savings							
Delay Yrs.	Present Worth (R+M)	Rehab Cost	Fuel Consumption	Oil Consumption	Tire Wear	Vehicle Repair	Depreciation	Travel Time	Road Maintenance Savings	Savings Cost Ratio
0	4934.	4000.	1280.	5113.	13695.	157751.	24300.	21778.	41328.	66.31
1	6468.	4000.	1295.	5254.	13695.	157751.	24300.	22484.	47447.	68.06
2	10088.	4000.	1312.	5425.	13695.	157751.	24300.	23365.	51873.	69.43
3	65746.	97560.	1325.	5551.	13695.	157751.	24300.	24033.	54526.	2.88
4	58824.	97560.	1333.	5646.	19894.	252606.	32469.	24548.	55885.	4.02

Table 27B. Cost Analysis Results for Asphalt Concrete Section Using 12% Discount Rate.

Analysis Period = 7 yrs

			Present Worth of Savings							
Delay Yrs.	Present Worth (R+M)	Rehab Cost	Fuel Consumption	Oil Consumption	Tire Wear	Vehicle Repair	Depreciation	Travel Time	Road Maintenance Savings	Savings Cost Ratio
0	4592.	4000.	973.	3888.	10413.	119949.	18477.	16559.	29992.	50.06
1	6006.	4000.	985.	3995.	10413.	119949.	18477.	17096.	35138.	51.51
2	9010.	4000.	998.	4125.	10413.	119949.	18477.	17766.	38955.	52.67
3	57482.	97560.	1007.	4221.	10413.	119949.	18477.	18274.	41276.	2.19
4	49082.	97560.	1014.	4293.	15127.	192073.	24688.	18665.	42473.	3.06

Table 28A. Cost Analysis Results for Overlaid Section Using 4% Discount Rate.

Analysis Period = 4 yrs

			Present Worth of Savings								
Delay Yrs.	Present Worth (R+M)	Rehab Cost	Fuel Consumption	Oil Consumption	Tire Wear	Vehicle Repair	Depreciation	Travel Time	Road Maintenance Savings	Savings Cost Ratio
0	109769.	109560.	3966.	11479.	23141.	274023.	47244.	58223.	5674.	3.87
1	279534.	379739.	4059.	11964.	23141.	274023.	47244.	60579.	11988.	1.14
2	279534.	379739.	4059.	11964.	23141.	274023.	47244.	60579.	11988.	1.14

Table 28B. Cost Analysis Results for Overlaid Section Using 12% Discount Rate.

Analysis Period = 4 yrs

			Present Worth of Savings							
Delay Yrs.	Present Worth (R+M)	Rehab Cost	Fuel Consumption	Oil Consumption	Tire Wear	Vehicle Repair	Depreciation	Travel Time	Road Maintenance Savings	Savings Cost Ratio
0	109723.	109560.	3319.	9606.	19363.	229292.	39532.	48718.	4446.	3.23
1	268461.	379739.	3397.	10011.	19363.	229292.	39532.	50690.	9432.	0.95
2	169376.	379739.	3451.	10305.	19363.	229292.	39532.	52146.	17834.	0.98

Table 29A. Cost Analysis Results for Surface Treated Section Using 4% Discount Rate.

Analysis Period = 6 yrs

Delay Yrs.	Present Worth (R+M)	Rehab Cost	Present Worth of Savings: Fuel Consumption	Oil Consumption	Tire Wear	Vehicle Repair	Depreciation	Travel Time	Road Maintenance Savings	Savings Cost Ratio
0	7374.	7200.	70.	174.	115.	1607.	325.	956.	8399.	1.62
1	6211.	7200.	73.	186.	284.	3886.	650.	1000.	11396.	2.43
2	8685.	12240.	82.	223.	284.	3886.	650.	1140.	14313.	1.68
3	7648.	12240.	90.	260.	284.	3886.	650.	1284.	16820.	1.90
4	12447.	28800.	97.	295.	284.	3886.	650.	1430.	18641.	0.88

Table 29B. Cost Analysis Results for Surface Treated Section Using 12% Discount Rate.

Analysis Period = 6 yrs

			Present Worth of Savings								
Delay Yrs.	Present Worth (R+M)	Rehab Cost	Fuel Consumption	Oil Consumption	Tire Wear	Vehicle Repair	Depreciation	Travel Time	Road Maintenance Savings	Savings Cost Ratio
0	7318.	7200.	55.	137.	90.	1260.	255.	750.	6035.	1.19
1	5930.	7200.	57.	146.	223.	3048.	510.	784.	8374.	1.83
2	7955.	12240.	64.	175.	223.	3048.	510.	894.	10750.	1.28
3	6669.	12240.	70.	204.	223.	3048.	510.	1007.	12864.	1.46
4	10369.	28800.	76.	232.	223.	3048.	510.	1122.	14437.	0.68

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This report presents a complete methodology to aid in making decisions concerning the selection and scheduling of alternative rehabilitation projects.

The principal objectives of this study were: (a) to develop procedures to estimate the remaining service life of an existing flexible pavement; (b) to quantify savings in user costs associated with delaying rehabilitation beyond the predicted service life; and (c) to develop a computerized procedure integrating the two previously stated objectives to provide an accessible method for estimating the time at which a pavement should be rehabilitated.

Two methodologies were presented for estimating the service life of a flexible pavement from which the remaining life can be determined: (a) using maximum likelihood estimators, and (b) a prediction model based upon ride and distress conditions. The first method uses maximum likelihood estimators for the parameters of performance equations for three main highway types (Interstates, US/State, Farm-to-Market) and three types of pavements (asphalt concrete, overlaid, surface treated).

The second method is based on a set of serviceability and distress performance equations and a discriminant analysis approach. The purpose of the discriminant analysis was to identify the distress types that most significantly affect the life of a pavement and to identify the combination of effects of these distress types that produce a need for pavement rehabilitation. Both methods were in general agreement in estimating the service life of similar pavement sections.

Using truck traffic data from axle distribution data (W-4, W-5 Tables) and traffic count data, service life estimates in equivalent single-axle loads were translated into time estimates.

Delays in rehabilitation decisions were assessed using present worth and savings/cost analyses. The present worth analysis includes rehabilitation costs, road maintenance costs, and the value of the unused portion of the rehabilitated pavement. User savings were quantified for different pavement conditions measured in terms of roughness or serviceability index as predicted by the pavement performance equation.

7.1 Summary

A summary of the results obtained in this research project is given as follows:

(a) Using the maximum likelihood estimates method, service life estimates were provided for the following types of highways:

(1)	Asphalt concrete, Interstate:	1,214,300 18-Kip ESALS
(2)	Asphalt concrete, US/State:	426,000 18-Kip ESALS
(3)	Overlaid, Interstate:	1,398,900 18-Kip ESALS
(4)	Overlaid flexible, US/State:	184,200 18-Kip ESALS
(5)	Overlaid composite, US/State:	274,200 18-Kip ESALS
(6)	Multiple surface treatment, US/State:	57,100 18-Kip ESALS
(7)	Multiple surface treatment, Farm-to-Market:	7,400 18-Kip ESALS

(8) Single surface treatment,

Farm-to-Market: 7,700 18-Kip ESALS

(b) Alligator, longitudinal and transverse cracking were identified as the major cause of the rehabilitation of asphalt concrete pavements.

(c) A reduction in the serviceability index was found to be significant in causing the need for rehabilitation of overlaid pavements.

(d) Rutting and patching were identified as significant factors for identifying surface treated pavements in need of rehabilitation.

(e) Results from the life prediction model were correlated acceptably well with actual service lives.

(f) In general, results from the present worth and savings cost analyses indicate that pavements should be rehabilitated some time after the end of the predicted service life before a more costly rehabilitation alternative is needed.

Appendix J lists the computer program which was developed to integrate the life prediction model and the cost analysis. The program consists of approximately 825 lines of Fortran Code and can be executed in about 1/3 of a second for five pavement sections using the WATFIV compiler.

7.2 Conclusions

1. The method developed is very useful in estimating the remaining life of flexible pavements in Texas.

2. The decision rules for rehabilitation which were discovered

by discriminant analysis showed that distress is the primary determining factor in decisions to rehabilitate. In asphalt concrete pavements, various types of cracking were the principal factors, whereas with surface treated pavements, rutting and patching dominated.

3. The technique developed in this report should be used for evaluating and improving the utility decision rules that are presently used in the Pavement Evaluation System.

4. The performance and distress equations and the decision rules developed in this report would measurably improve and should be incorporated into the latest version of the RENU program (RENU2).

7.3 Recommendations

The following recommendations are made for further work in this area.

(a) Modification of Discriminant Functions.

Discriminant functions were developed for each of the prevalent Texas flexible pavements to determine if a pavement should be rehabilitated based upon calculated ride and distress values. In this development, the number of asphalt concrete and overlaid pavement sections rehabilitated between 1974-79 played a fundamental role. This number, however, is believed to be particularly low. More test sections and thus more data will probably change the discriminant function developed in this report. Also, both linear and quadratic discriminant functions should be evaluated.

(b) Validation of User Costs-Pavement Condition Relationships.

User costs due to fuel and oil consumption, tire wear, depreciation, vehicle maintenance and repair, and travel time, were derived based upon techniques directly applicable to prevailing conditions in the United States. However, the relationships between these costs and pavement roughness were taken from a study recently conducted in Brazil. Basic research is necessary in this area to validate the results derived from the Brazil study to assure that they are applicable to Texas conditions.

(c) Development of a Model for Predicting Road Maintenance Costs.

Inherent to most economic studies performed on highways is the inclusion of routine maintenance costs. The EAROMAR equations for predicting these costs based on pavement age were used in the development of this model. A more realistic analysis would be possible if maintenance costs were expressed as a function of pavement condition in terms of ride and different distress types.

(d) Calibration of Performance and Distress Equations.

Statistical estimates developed by the methods in this report can be used to calibrate the performance curves obtained by regression analysis as functions of material, climatic and design properties. Ideally, statistical estimates for the parameters of the performance curve should be approximately equal to those obtained by regression analysis. An analysis of any significant differences between the two methods for estimating parameters will be a topic worthy of future research efforts.

(e) Determination of Decision Rules for Pavement Rehabilitation. The methods developed in this report may be used with the pavement condition data in the Pavement Evaluation System and the record of rehabilitation decisions that were actually made to update and refine the utility decision rules that are presently used in the Pavement Evaluation System.

REFERENCES

1. U. S. Department of Transportation. The Status of the Nation's Highways: Conditions and Performance. Report of the Secretary of Transportation to the United States Congress, January, 1981.

2. Highway Research Board. The AASHO Road Test: Report No. 5--Pavement Research. Special Report 61E, 1962.

3. I. E. Corvi, B. G. Bullard. A System for Estimating Present Surface Condition and Remaining Service Life of Existing Pavement Sections. Public Roads, Vol. 36, No. 5, 1970, pp. 93-118.

4. R. E. Whiteside, T. Y. Chu, J. C. Cosby, R. L. Whitaker, and R. Winfrey. Changes in Legal Vehicle Weights and Dimensions: Some Economic Effects on Highways. National Cooperative Highway Research Program, Report 141, 1973.

5. R. G. Hicks, R. D. Layton, and S. Glover. Evaluation of Increased Truck Size and Mass on Pavement Life and Design Thickness. Transportation Research Board, Transportation Research Record 671, 1978.

6. R. F. Carmichael, P. Roberts, P. Jordahl, H. Treybig, and F. Finn. Effects of Changes in Legal Load Limits on Pavement Costs: Volumes 1 and 2. Federal Highway Administration, U. S. Department of Transportation, Report FHWA-RD-79-73 and FHWA-RD-79-74, July, 1974.

7. A. Garcia-Diaz, R. L. Lytton, D. Burke, B. F. McCullough, and C. M. Walton. Computerized Method of Projecting Rehabilitation and Maintenance Requirements Due to Vehicle Loadings. Texas Transportation Institute--Center for Transportation Research Report 298-312-5F, Volume 5F, August, 1981.

8. E. J. Yoder and M. W. Witczak. Principles of Pavement Design. John Wiley, New York, 2nd Ed., 1973.

9. F. H. Scrivner, W. F. McFarland, and G. R. Carey. A Systems Approach to the Flexible Pavement Design Problem. Research Report 32-11, Texas Transportation Institute, Texas A&M University, 1968.

10. The Asphalt Institute. Thickness Design-Full Depth Asphalt Structures for Highways and Streets. Manual Series No. 1 (MS-1), Eighth Edition, College Park, Maryland, 1970.

11. G. M. Dorman and C. T. Metcalf. Design Curves for Flexible Pavements Based on Layered Systems Theory. Highway Research Record 71, Highway Research Board, 1965.

12. Highway Research Board. Structural Design of Asphalt Concrete Pavement Systems. Special Report 126, 1971.

13. W. K. Smeaton, S. S. Sengupta, and R. Haas. Interactive Pavement Behavior Modelling: A Clue to the Distress-Performance Problem. Transportation Research Board, Transportation Research Record 766, 1979, pp. 17-25.

14. D. Y. Lu, R. L. Lytton, and W. M. Moore. Forecasting Serviceability Loss of Flexible Pavements. Research Report No. 57-1F, Texas Transportation Institute, College Station, Texas, Nov. 1974.

15. R. L. Lytton, C. Michalak, and T. Scullion. Texas Flexible Pavement Design System. Proceedings from the Fifth International Conference on the Structural Design of Asphalt Pavements, Vol. 1, Arkem. The Netherlands, August, 1982.

16. T. Scullion, J. M. Mason, and R. L. Lytton. Predicting Reductions in Service Life of Surface Treated Pavements Under Oil Field Traffic: Paper Prepared for Presentation at Transportation Research Board, Jan. 1983.

17. C. S. Noble, and B. E. McCullough. Distress Prediction Models for CRCP. Center for Transportation Research, University of Texas, Austin, Report No. 177-21, March 1981.

18. V. C. Barber, E. C. Odom, and R. W. Patrick. The Deterioration and Reliability of Pavements. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi, July, 1978.

19. M. I. Darter, and W. R. Hudson. Probabilistic Design Concepts Applied to Flexible Pavement System Design. Center for Transportation Research, University of Texas, Austin, Report 123-18, May, 1973.

20. P. J. Claffey and Associates. Running Costs of Motor Vehicles as Affected by Road Design and Traffic. NCHRP Report 111, Highway Research Board, National Research Council, Division of Engineering, 1971.

21. R. Winfrey. Economic Analysis for Highways. Scranton, Pennsylvania, International Textbook Co., 1969.

22. J. P. Zaniewski, B. C. Butler, G. Cunningham, G. E. Elkins, M. S. Paggi, and R. Machemehl. Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors. Federal Highway Administration, U. S. Department of Transportation, March 1982.

23. M. A. Karan, R. Haas, and R. Kher. Effects of Pavement Roughness on Vehicle Speeds. Transportation Research Record 602, NAS, Washington, D. C., 1976.

24. J. P. Zaniewski, B. K. Moses, and J. D. Swait. Predicting Travel Time and Fuel Consumption for Vehicles on Low-Volume Roads. Transportation Research Record 702, TRB, 1979.

25. J. P. Zaniewski, B. K. Moses, P. J. de Morais, and R. L. Kaesechagen. Fuel Consumption Related to Vehicle Type and Road Conditions. Transportation Research Record 702, TRB, 1979.

26. H. Hide. An Improved Data Base for Estimating Vehicle Operating Costs in Developing Countries. TRRL Supplementary Report 223 UC, Transport and Land Research Laboratory, Department of the Environment.

27. F. R. Ross. The Effects of Pavement Roughness on Vehicle Fuel Consumption. Research Unit, Materials Section, Division of Highways and Transportation Facilities, Wisconsin Department of Transportation, June 1981.

28. C. V. Zegeer et al. Use of Economic Analysis and Dynamic Programming in the Selection of Projects for Resurfacing. Kentucky Bureau of Highways, Lexington Division of Research, February, 1979.

29. S. C. Tignor and J. A. Lindley. Accident Rates on Two Lane Rural Highways Before and After Resurfacing. Public Roads, Vol. 44, No. 4.

30. M. S. Darter, M. B. Snyder, and R. E. Smith. Development of a Nationwide Concrete Pavement Evaluation System. Final Report, National Cooperative Highway Research Program Project 1-19, University of Illinois, Urbana, Illinois, 1980.

31. E. M. Cramer. Equivalence of Two Methods of Computing Discriminant Function Coefficients. Biometrics, Vol. 23, 1967.

32. C. Daniels. Vehicle Operating Costs in Transportation Studies. E. S. U. Technical Series No. 1, London: Spencer House, 1974.

33. P. I. Hazen. Speed and Pavement Condition Relationship. Highway Performance Monitoring System, Technical Report No. 4, February 1980.

34. C. Bartell, et al. Development of the California Pavement Management System. Vol. 1, System Description (Final Report), California State Department of Transportation, Sacramento Division of Maintenance, Oct. 1978.

35. A. Garcia, R. L. Lytton, J. Allison. Estimation of Network Rehabilitation and Maintenance Costs Over an Extended Planning Horizon. Paper to be presented at Transportation Research Board Annual Conference, January 1983.

36. B. D. Butler, Jr. Economic Analysis of Roadway Occupancy for Freeway Pavement Maintenance and Rehabilitation. Vols. I, II, and III, Report Nos. FHWA-RD-76-14 and FHWA-RD-76-15, 1974.

37. R. L. Lee and E. L. Grant. Inflation and Highway Economic Studies. Highway Research Record No. 100, 1965.

38. American Association of State Highway and Transportation Officials. A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements. AASHTO, 1977.

39. W. F. McFarland and J. B. Rollins. Sensitivity Analysis of Improved Cost-Effectiveness Techniques. Federal Highway Administration, Interim Report, June 1981.

40. Discount Rates to be Used in Evaluating Time-Distributed Costs and Benefits. Circular A-94, Revised, Executive Office of the President, Bureau of Budget, March 1972.

41. American Association of State Highway Officials. Road User Benefit Analyses for Highway Improvements. Washington, D. C., AASHO, 1960.

42. P. A. Stark. Introduction to Numerical Methods. McMillan Publishing Co., Inc., New York, 1970.

43. P. A. Lachenbruch. Discriminant Analysis. Hafner Press, New York, 1st Ed., 1975.

44. R. A. Fisher. The Use of Multiple Measurement in Taxonomic Problems. Ann Eugen, Vol. 7, 1938, pp. 179-188.

45. R. A. Eisenbeis, and R. B. Avery. Discriminant Analysis and Classification Procedures. Lexington Books, Mass., 1972.

46. T. W. Anderson. An Introduction to Multivariate Statistical Analysis. John Wiley and Sons, Inc., New York, 1958.

47. P. A. Lachenbruch and M. R. Mickey. Estimation of Error Rates in Discriminant Analysis. Technometrics, 10, 1968.

48. P. A. Lachenbruch. Estimation of Error Rates in Discriminant Analysis. Ph.D. Dissertation, University of California at Los Angeles, 1965.

49. A. C. Cohen. Maximum Likelihood Estimation in the Weibull Distribution Based on Complete and Censored Samples. Technometrics, Vol. 7, 1965, pp. 579-588.

50. H. L. Hunter and A. H. Moore. Maximum Likelihood Estimation of the Parameters of Gamma and Weibull Populations from Complete and from Censored Samples. Technometrics, Vol. 7, No. 4, 1965, pp. 639-643.

APPENDICES

APPENDIX A

MAXIMUM LIKELIHOOD ESTIMATORS

A very useful technique for deriving point estimators is the method of maximum likelihood. In general, these estimators are attractive because they possess many very desirable statistical properties.

One of these properties is that of consistency which implies that as the sample size increases the estimator $\hat{\theta}$ approaches the parameter to be estimated θ. A second desirable property is that of being asymptotically efficient, implying that for a large m, $\sqrt{m}\ \hat{\theta}$ has a variance that approaches the lower bound of the variance of all unbiased estimators of θ. This lower bound is defined as the Cramer-Rao Inequality.

A third desirable property of a maximum likelihood estimator is that of being asymptotically normally distributed. An estimator is said to be asymptotically normally distributed if for a large sample size m, the random variable $\sqrt{m}(\hat{\theta} - \theta)$ approaches the distribution of a normally distributed random variable with zero mean and variance equal to:

$$\hat{\sigma}^2 = \sum_{i=1}^{n} \frac{(X_i - \overline{X})}{m} \qquad \text{(A-1)}$$

In this application, the method of maximum likelihood consists of selecting the values of ρ and β for which $f(n,\ n_2, \ldots, n_m; \rho, \beta)$, the probability of obtaining the sample values $(n_1, n_2,...,n_m)$, is a maximum.

Assuming that $n_1, n_2...n_m$ are values of service lives from a random sample taken from the population described by Eq. 1, (which is a cumulative density function) the density function is given by

$$f(n,\rho,\beta) = \frac{\rho^{\beta}\,\beta}{n^{\beta+1}} \quad e^{-(\rho/n)^{\beta}} \tag{A-2}$$

and the likelihood function is given by

$$L(\rho,\beta) = \prod_{i=1}^{m} f(n_i) = \frac{\rho^{\beta m}\,\beta^{m}}{\sum_{i=1}^{m} n_i^{\beta+1}} \exp\left(\sum_{i=1}^{m} -(\rho/n_i)^{\beta}\right) \tag{A-3}$$

The values of ρ and β which maximize L will also maximize the natural log of likelihood function and is given by

$$\mathcal{L}(\rho,\beta) = [\beta m \ln\rho + m\ln\beta - (\beta+1)\sum_{i=1}^{m} \ln n_i] + \sum_{i=1}^{m} -(\rho/n_i)^{\beta} \tag{A-4}$$

Differentiating Eq. A-4 with respect to β, equating the derivative to zero and simplifying yields

$$m\ln\hat{\rho} + m/\hat{\beta} - \sum_{i=1}^{m} \ln n_i + \sum_{i=1}^{m} \left(-(\hat{\rho}/n_i)^{\hat{\beta}} \ln\hat{\rho}/n_i\right) = 0. \tag{A-5}$$

Differentiating Eq. A-4 with respect to ρ, equating the derivative to zero and simplifying yields

$$\hat{\rho} = \frac{m^{1/\hat{\beta}}}{\sum_{i=1}^{m} \frac{1}{n_i}} \tag{A-6}$$

The second derivatives of $\mathcal{L}(\rho,\beta)$ with respect to ρ and also with respect to β are less than zero thus proving that indeed maximums have been obtained.

An explicit function for $\hat{\rho}$ and $\hat{\beta}$ cannot be obtained from Eqs. (A-5) and (A-6), therefore suggesting the use of a numerical method for their approximation. The roots of Eqs. (A-5) and (A-6) were found using an iterative process (42). Assuming initial estimates of the parameters, and iterating through the following relationship yields the values of $\hat{\rho}$ and $\hat{\beta}$:

$$n_{i+1} = f(n_i) \qquad \text{(A-7)}$$

Convergence of this method is met by satisfying the following criteria:

$$\lim_{i \to \infty} (n_{i+1} - n_i) = 0 \qquad \text{(A-8)}$$

APPENDIX B

PROBABILITY AND CUMULATIVE DENSITY FUNCTION

CURVES USING MLE'S FOR ρ AND β.

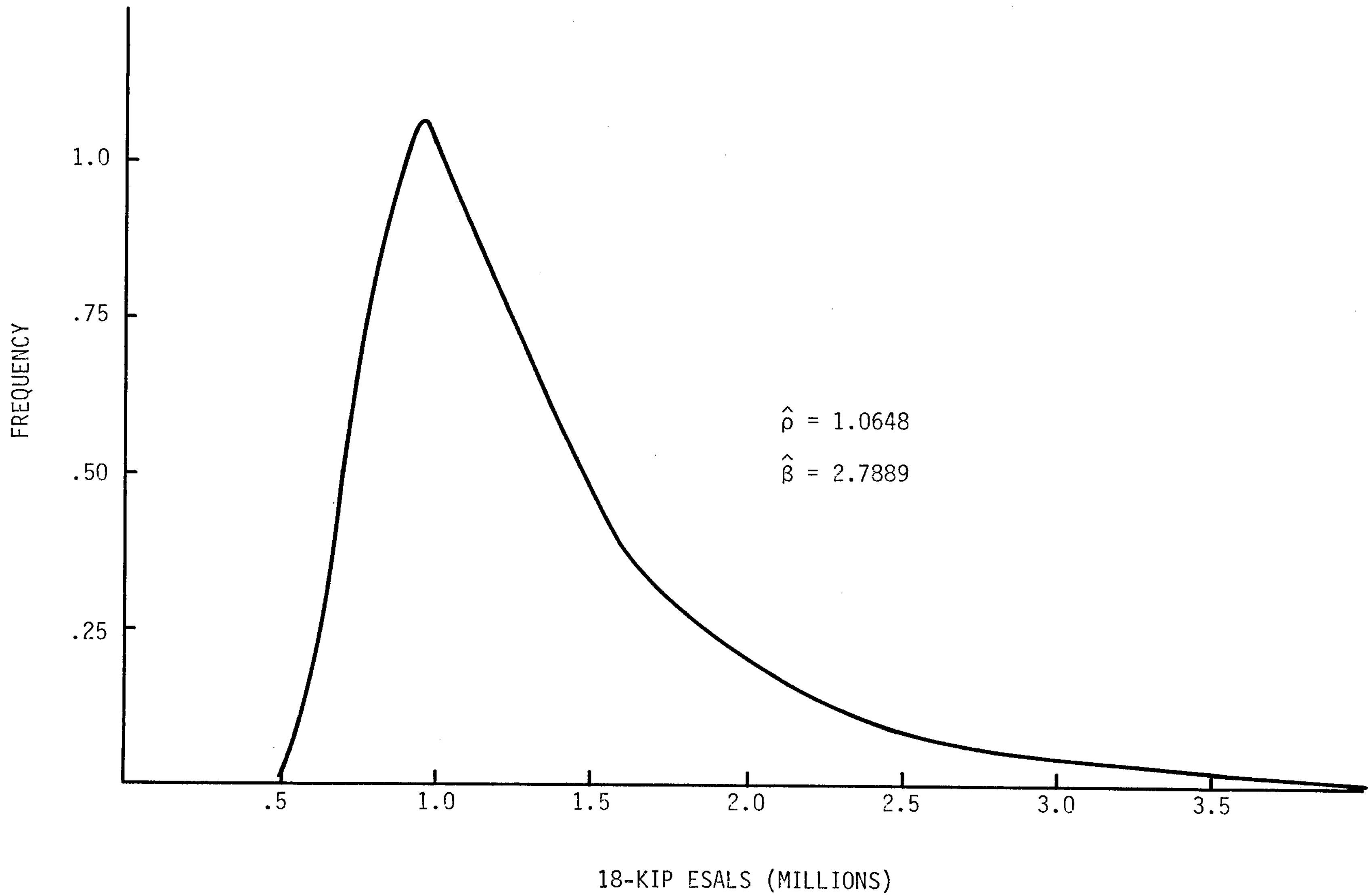

Figure B-1. Probability Density Function for Asphalt Concrete Interstates.

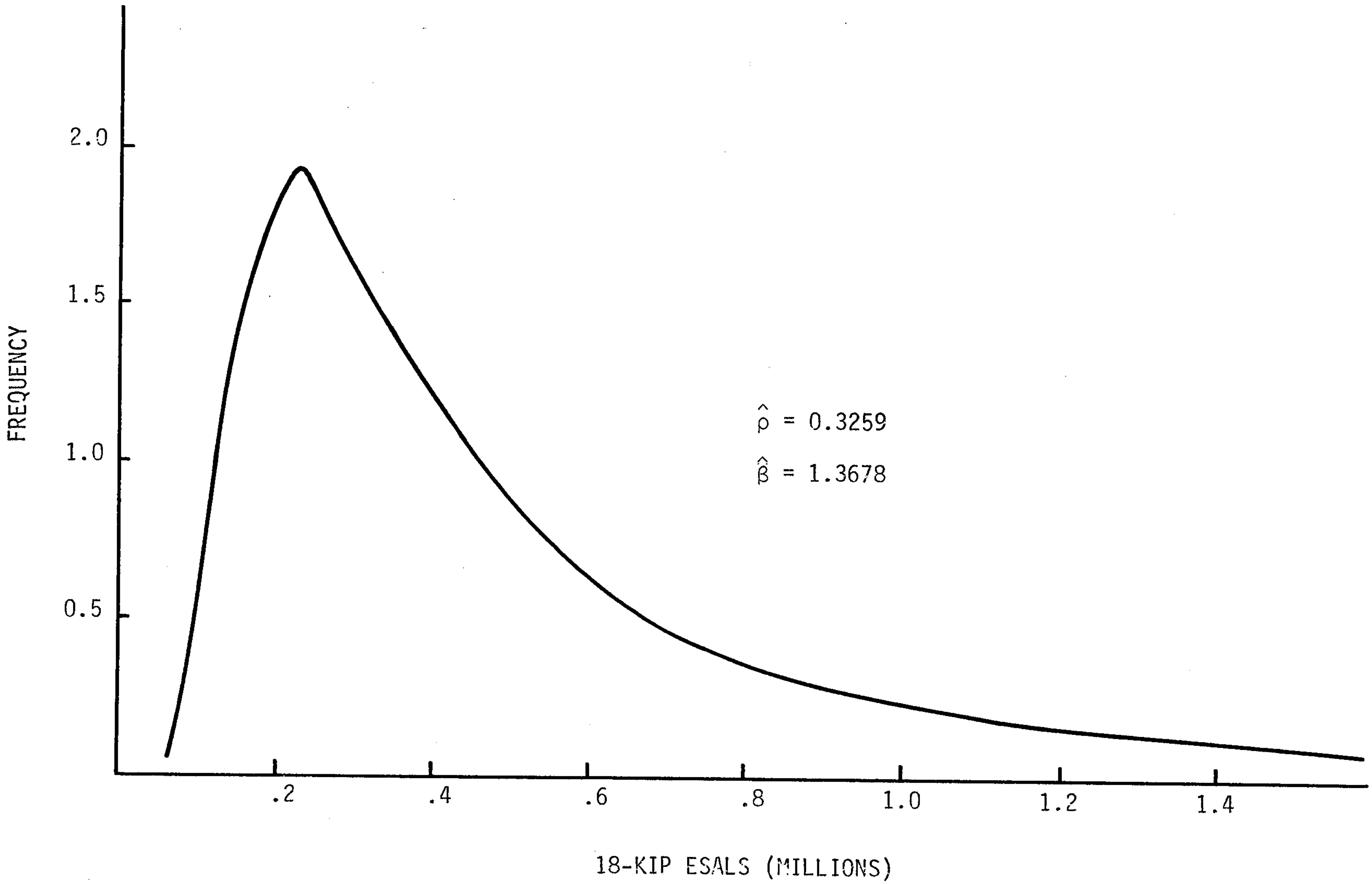

Figure B-2. Probability Density Function for Asphalt Concrete US/State Highways.

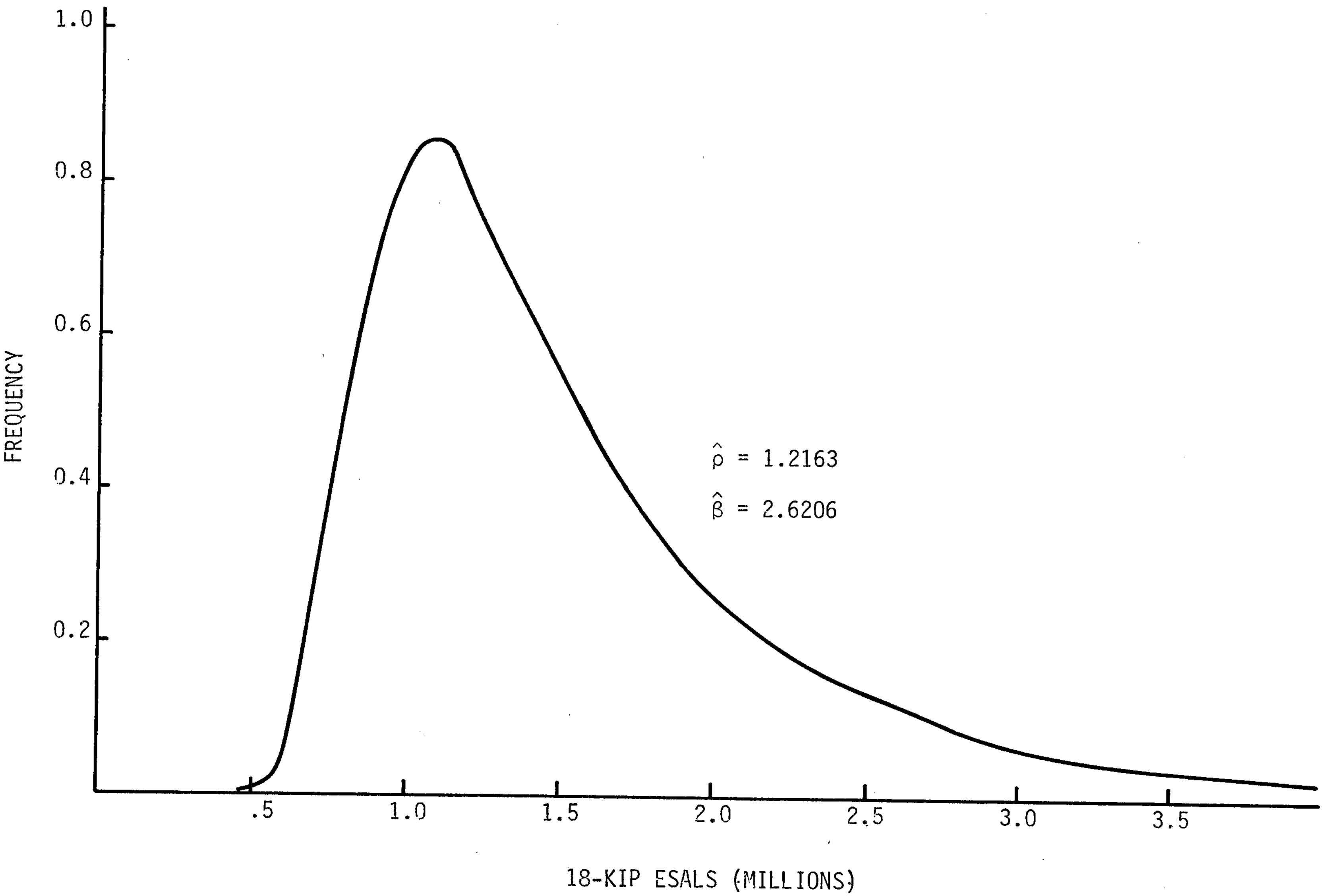

Figure B-3. Probability Density Function for Overlaid Interstate Highways.

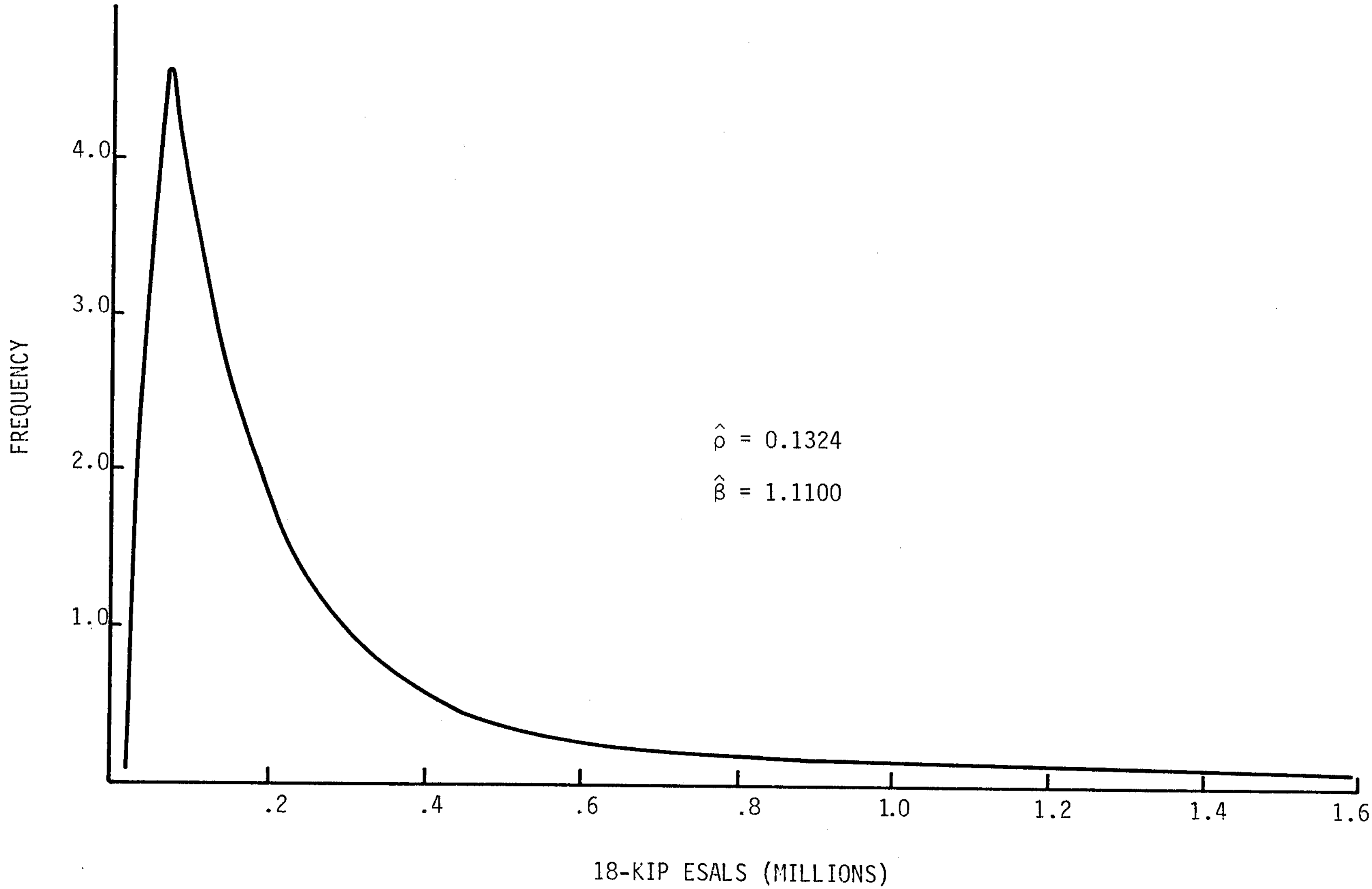

Figure B-4. Probability Density Function for Flexible Overlaid US/State Highways.

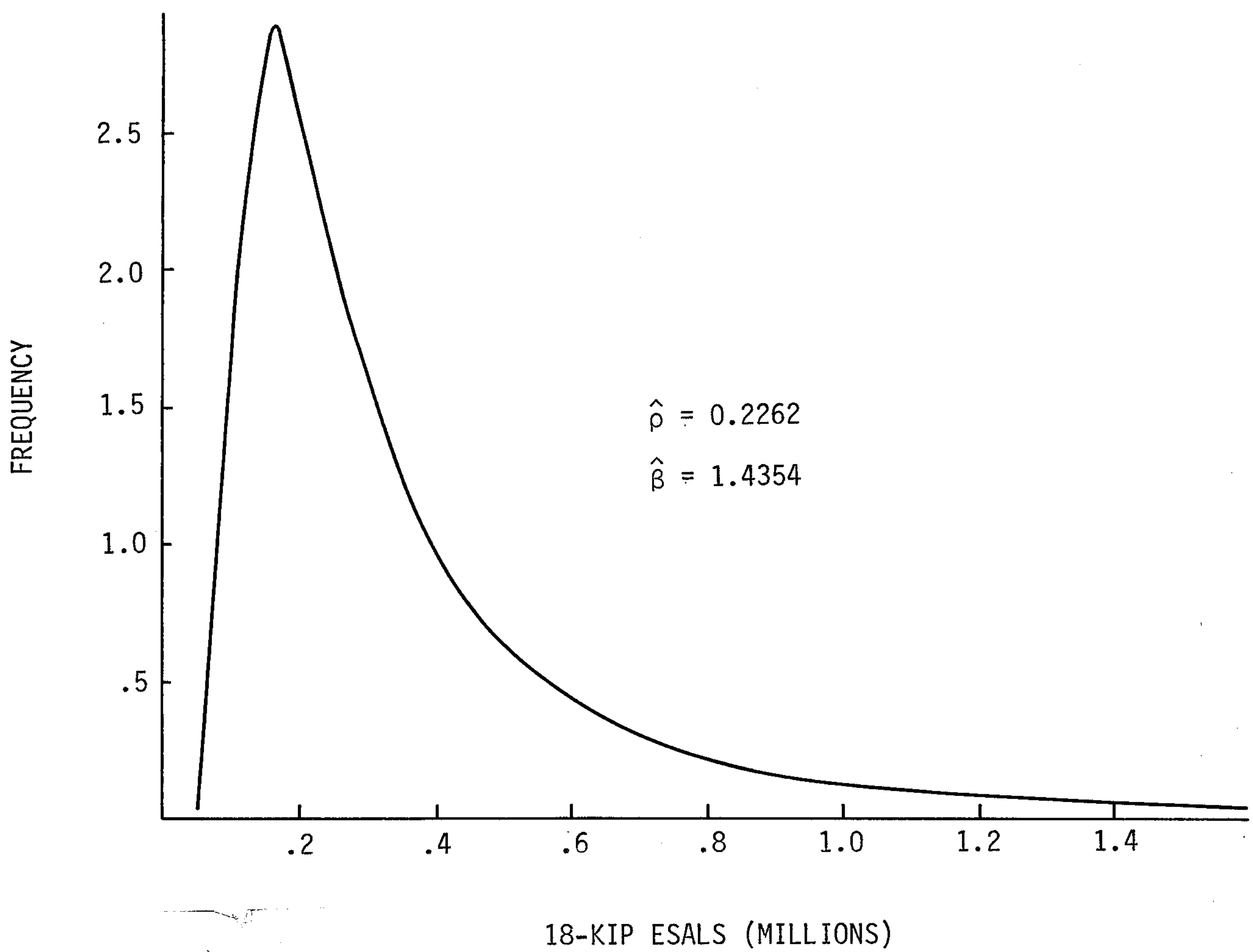

Figure B-5. Probability Density Function for Composite Overlaid US/State Highways.

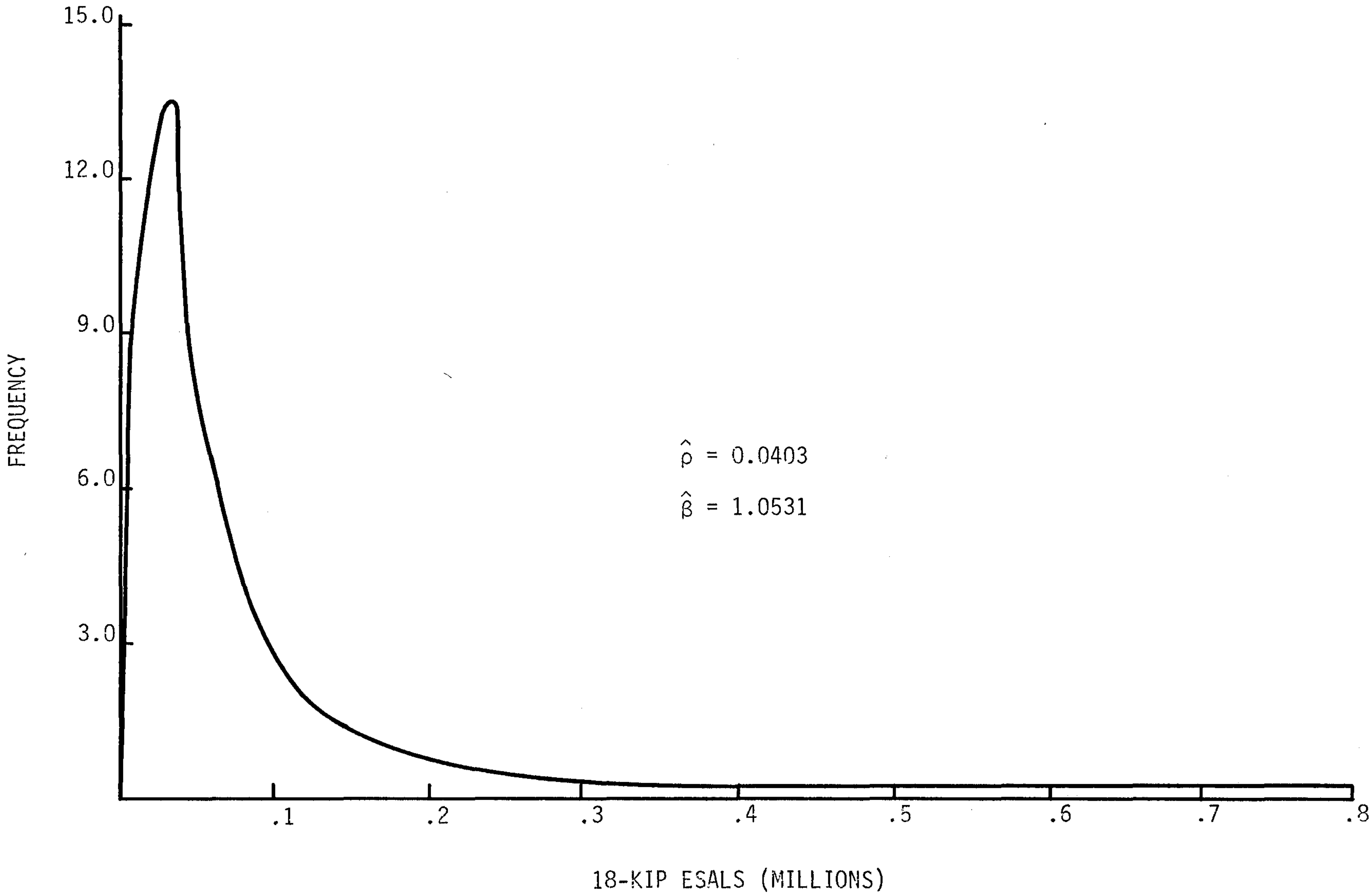

Figure B-6. Probability Density Function for Multiple Treatment Surface Treated US/State Highways.

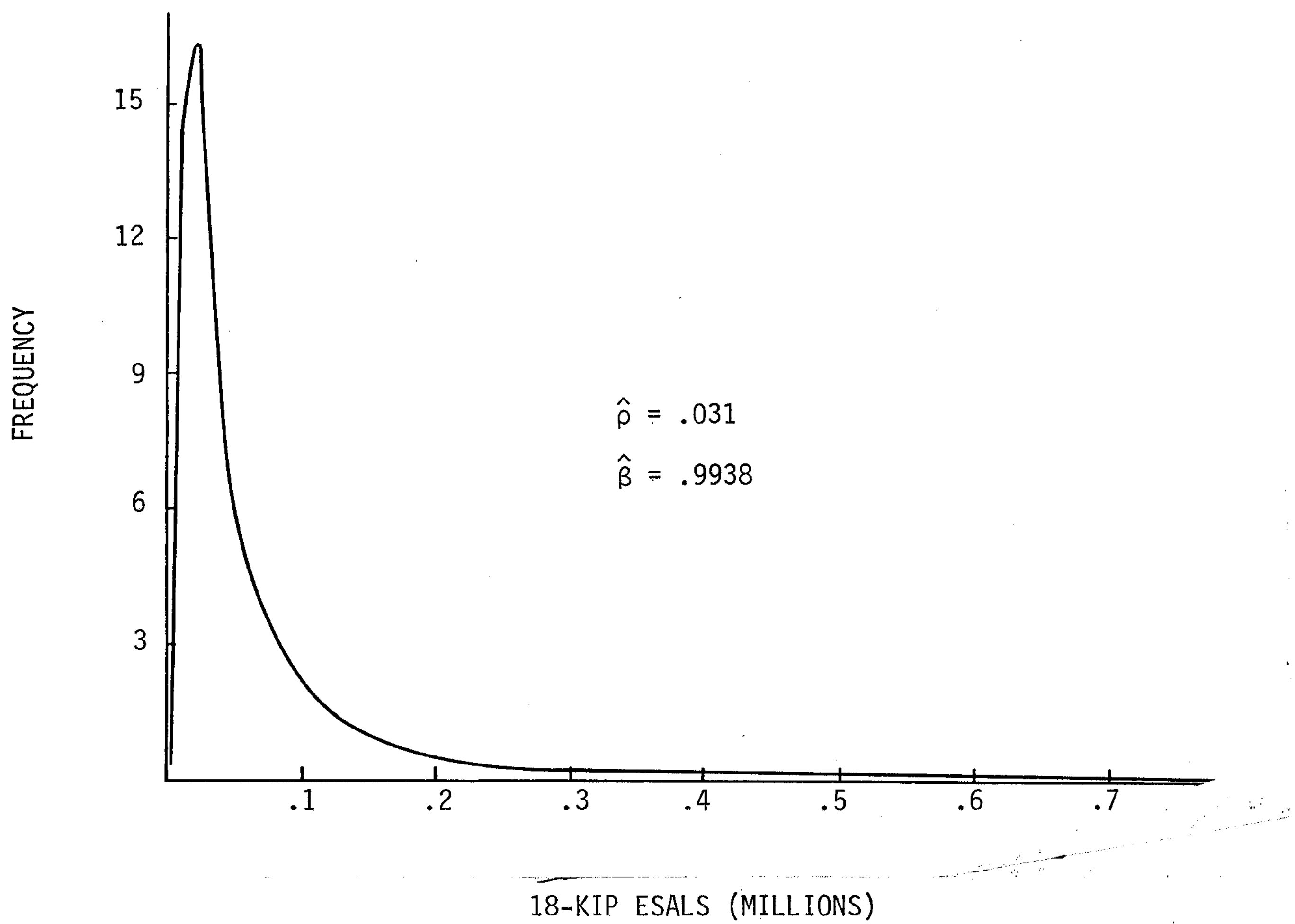

Figure B-7. Probability Density Function for Single Treatment Surface Treated US/State Highways.

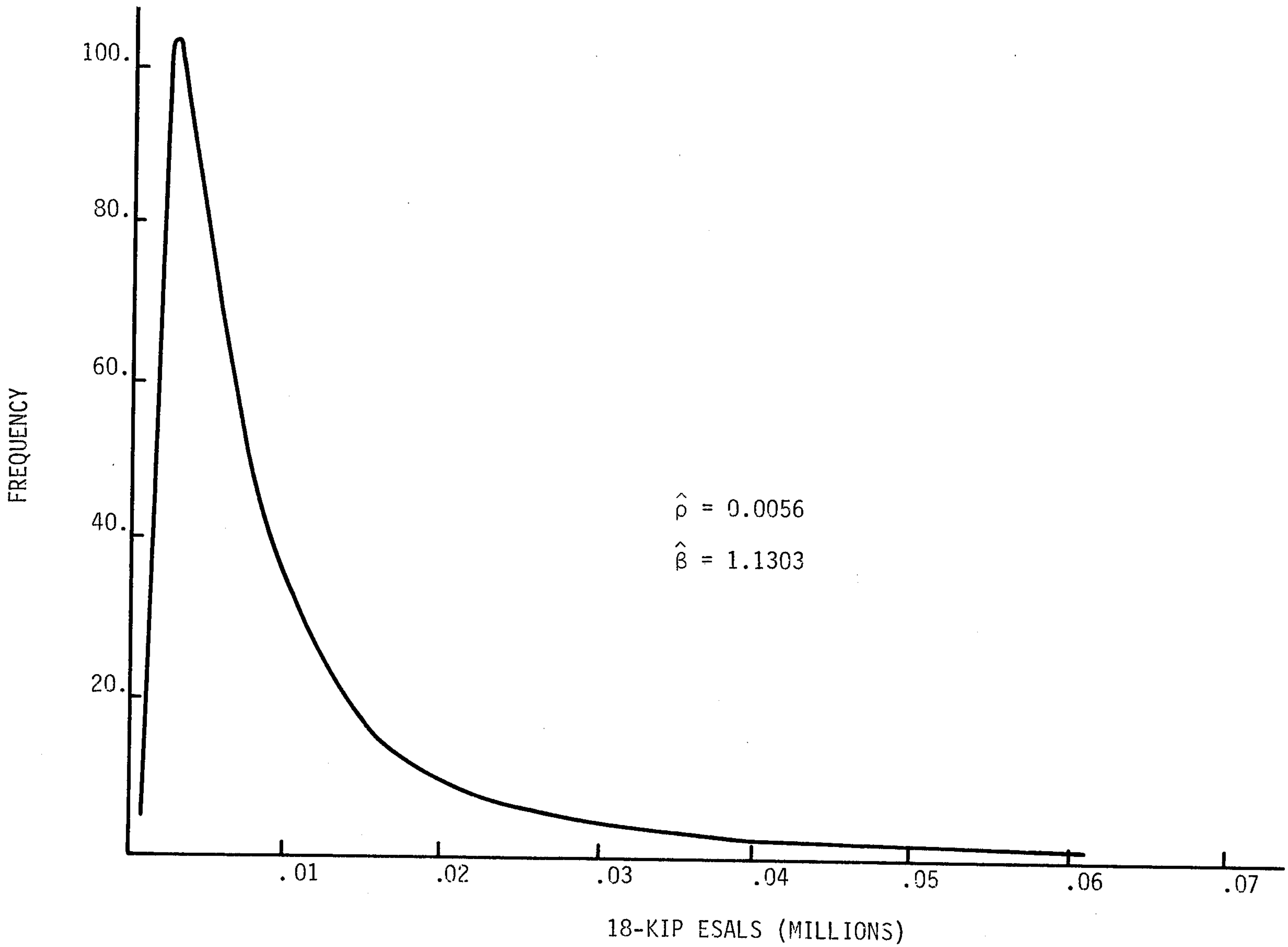

Figure B-8: Probability Density Function for Single Treatment Surface Treated Farm to Market Highways.

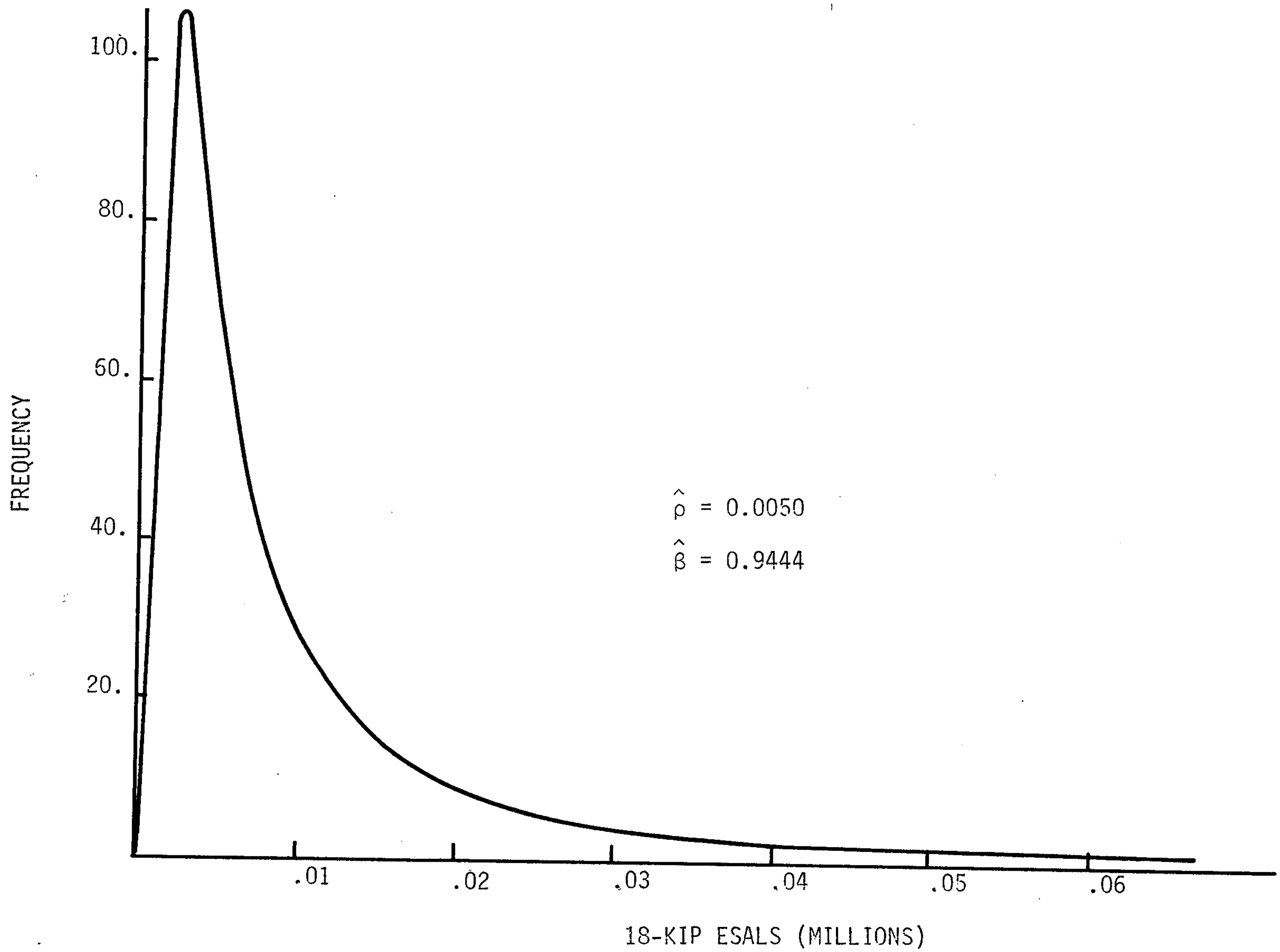

Figure B-9. Probability Density Function for Multiple Treatment Surface Treated Farm to Market Highways.

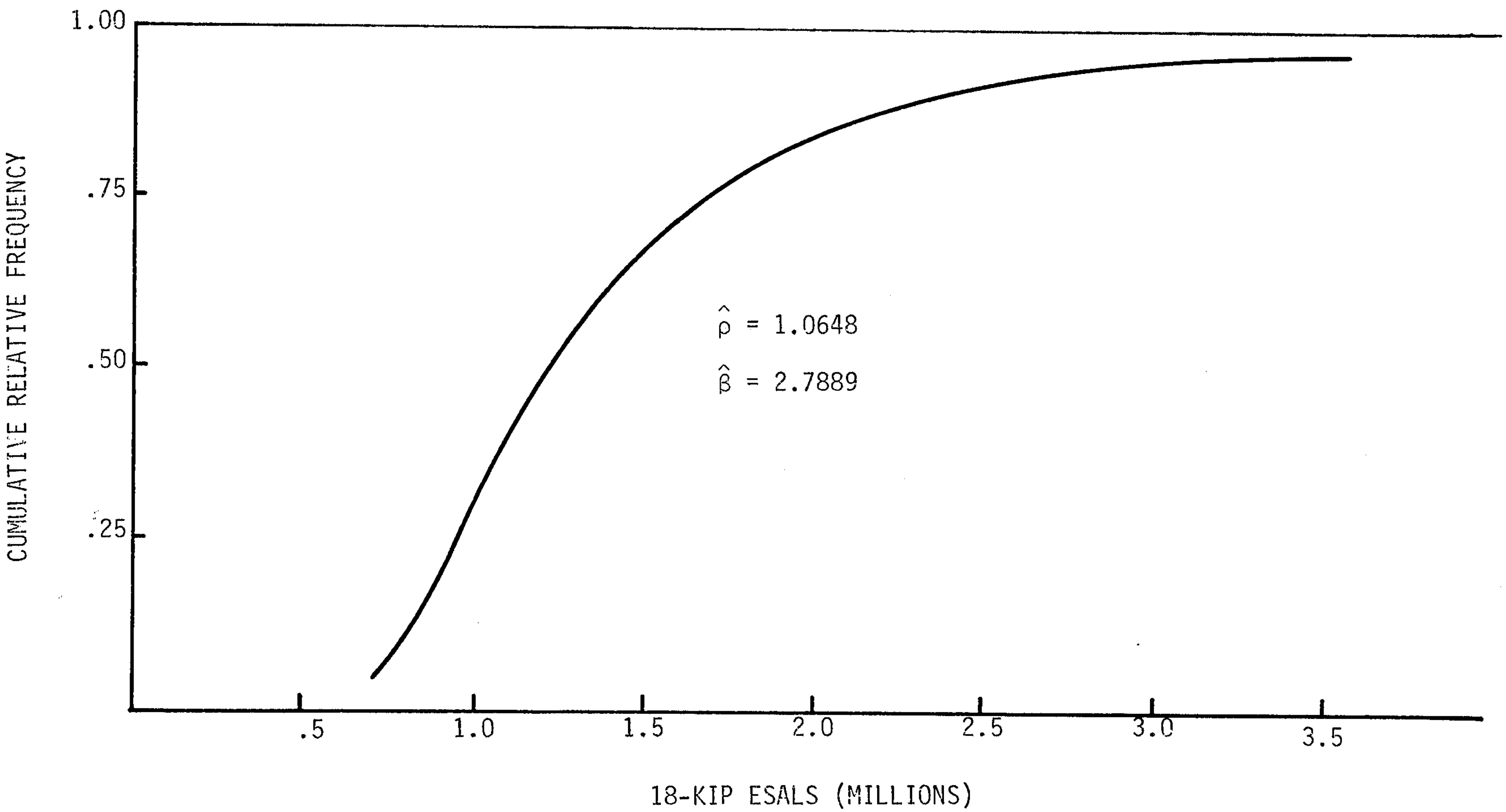

Figure B-10. Cumulative Density Function for Asphalt Concrete Interstates.

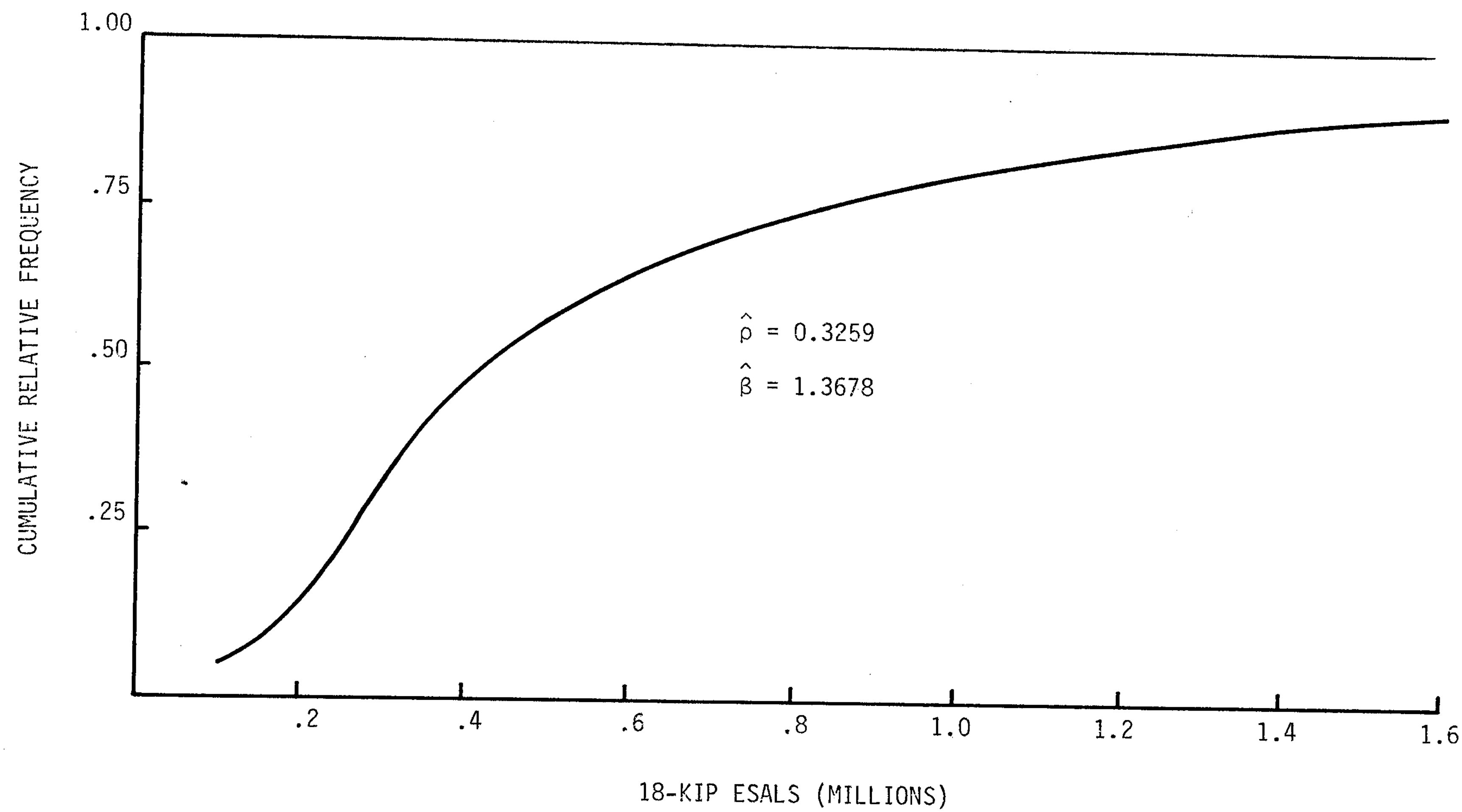

Figure B-11. Cumulative Density Function for Asphalt Concrete US/State Highways.

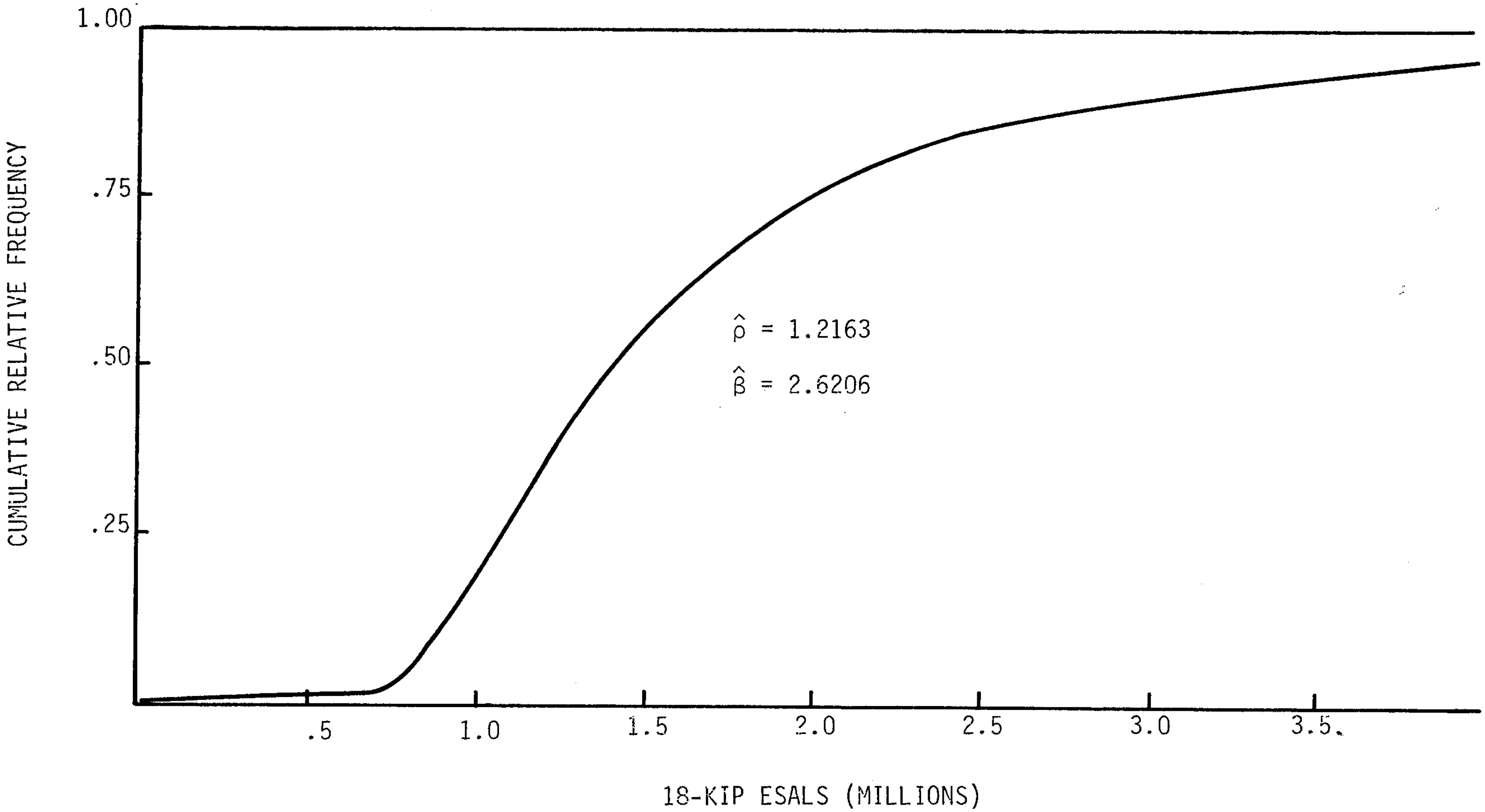

Figure B-12. Cumulative Density Function for Overlaid Interstate Highways.

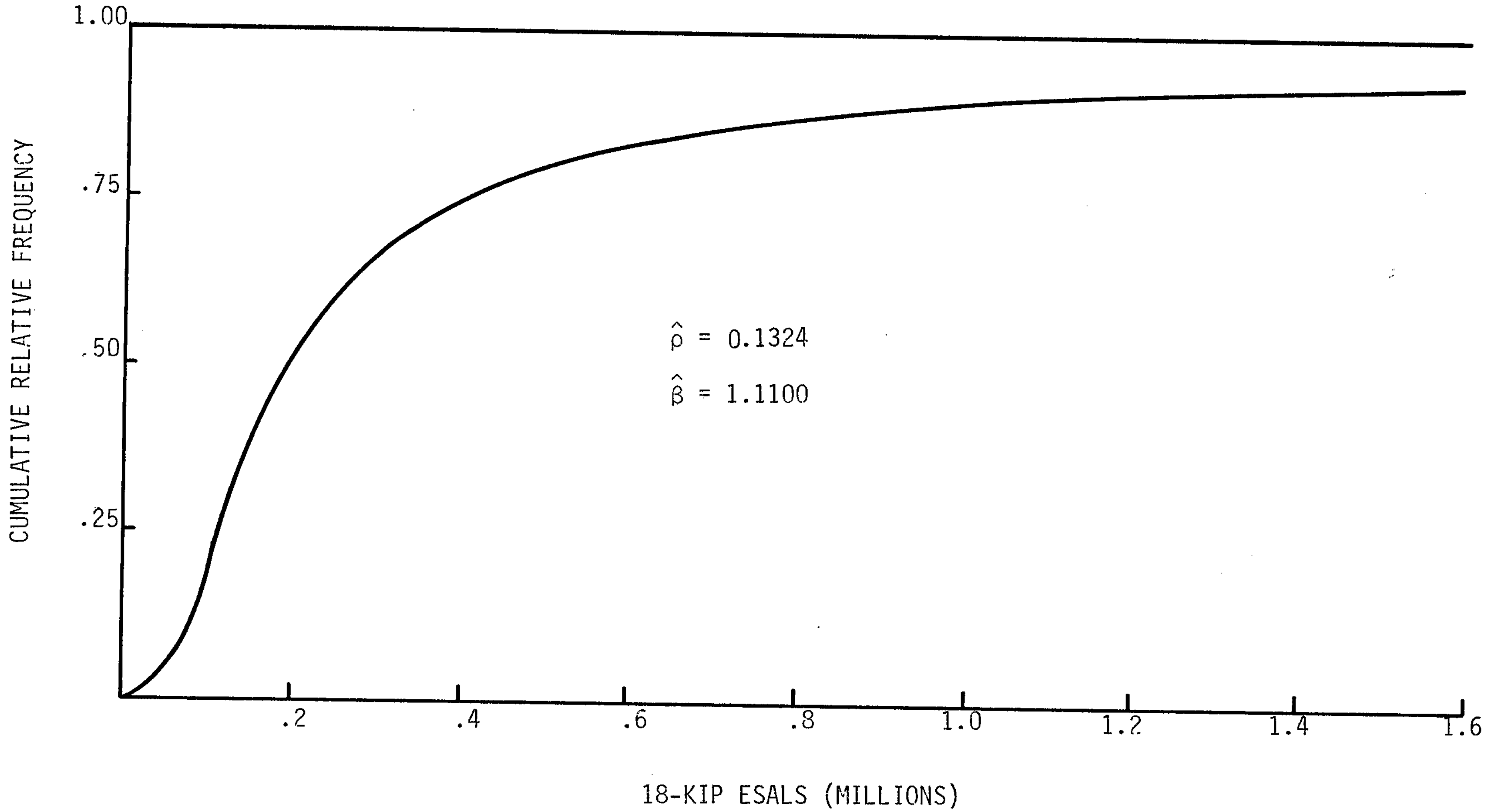

Figure B-13. Cumulative Density Function for Flexible Overlaid US/State Highways.

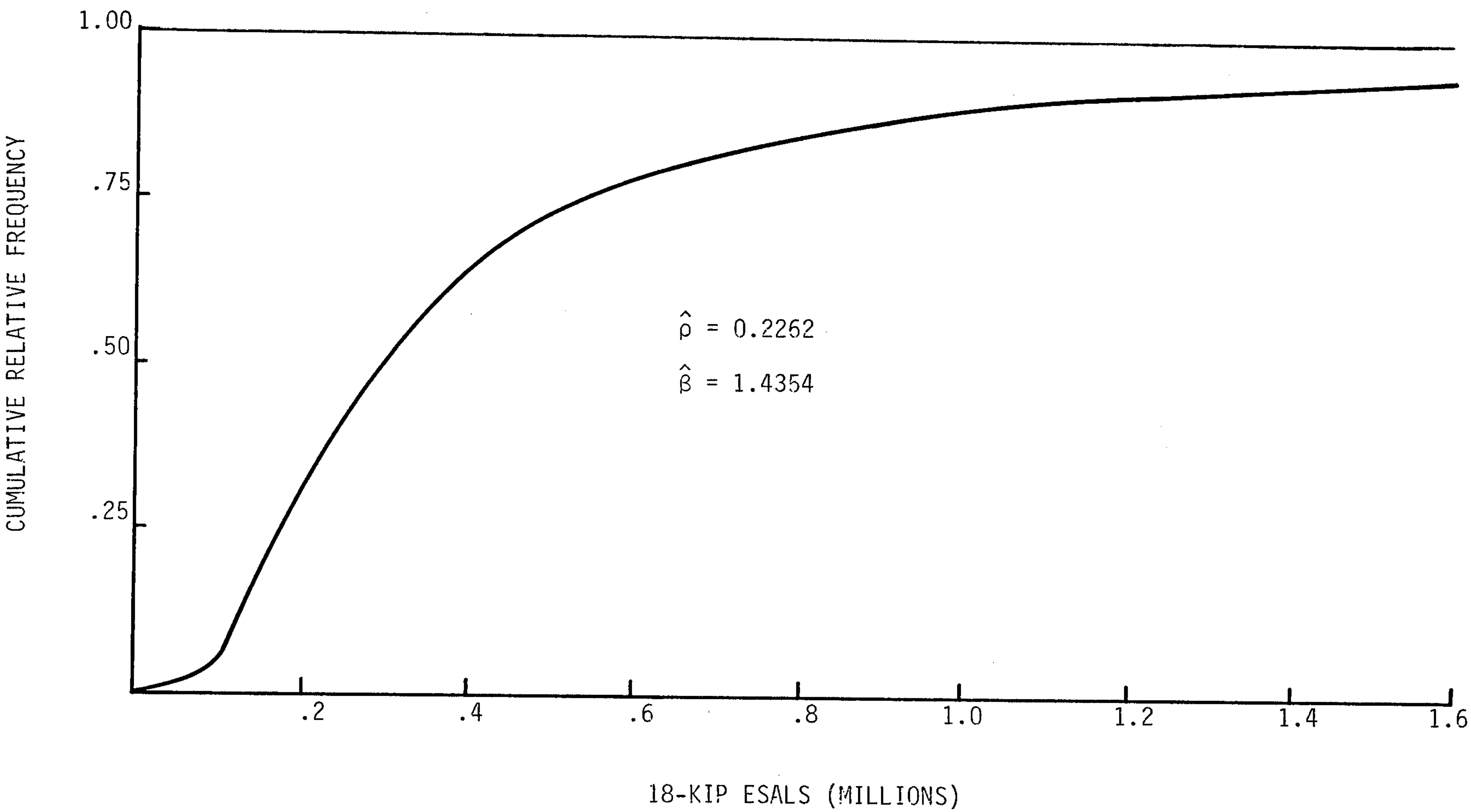

Figure B-14. Cumulative Density Function for Composite Overlaid US/State Highways.

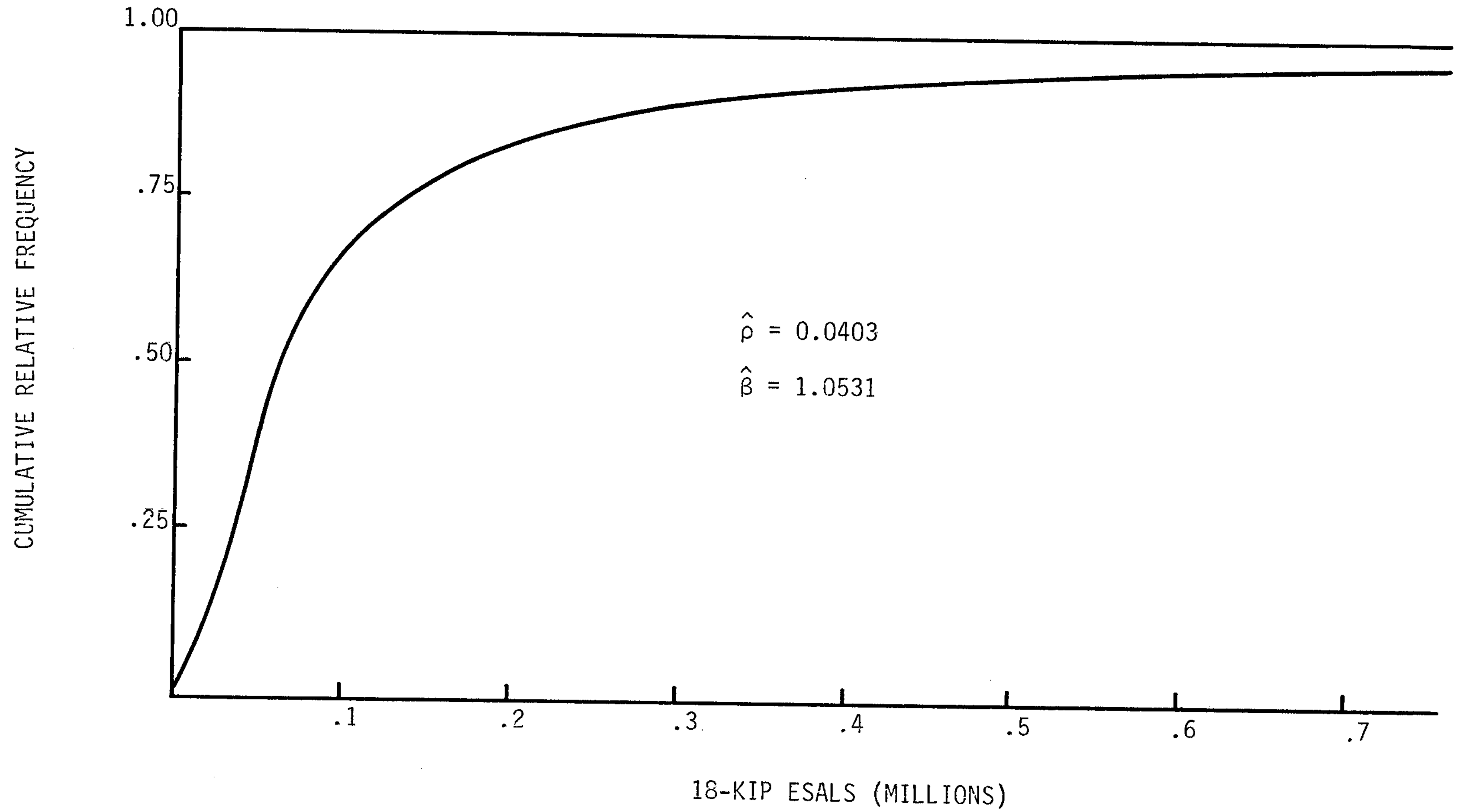

Figure B-15. Cumulative Density Function for Multiple Treatment Surface Treated US/State Highways.

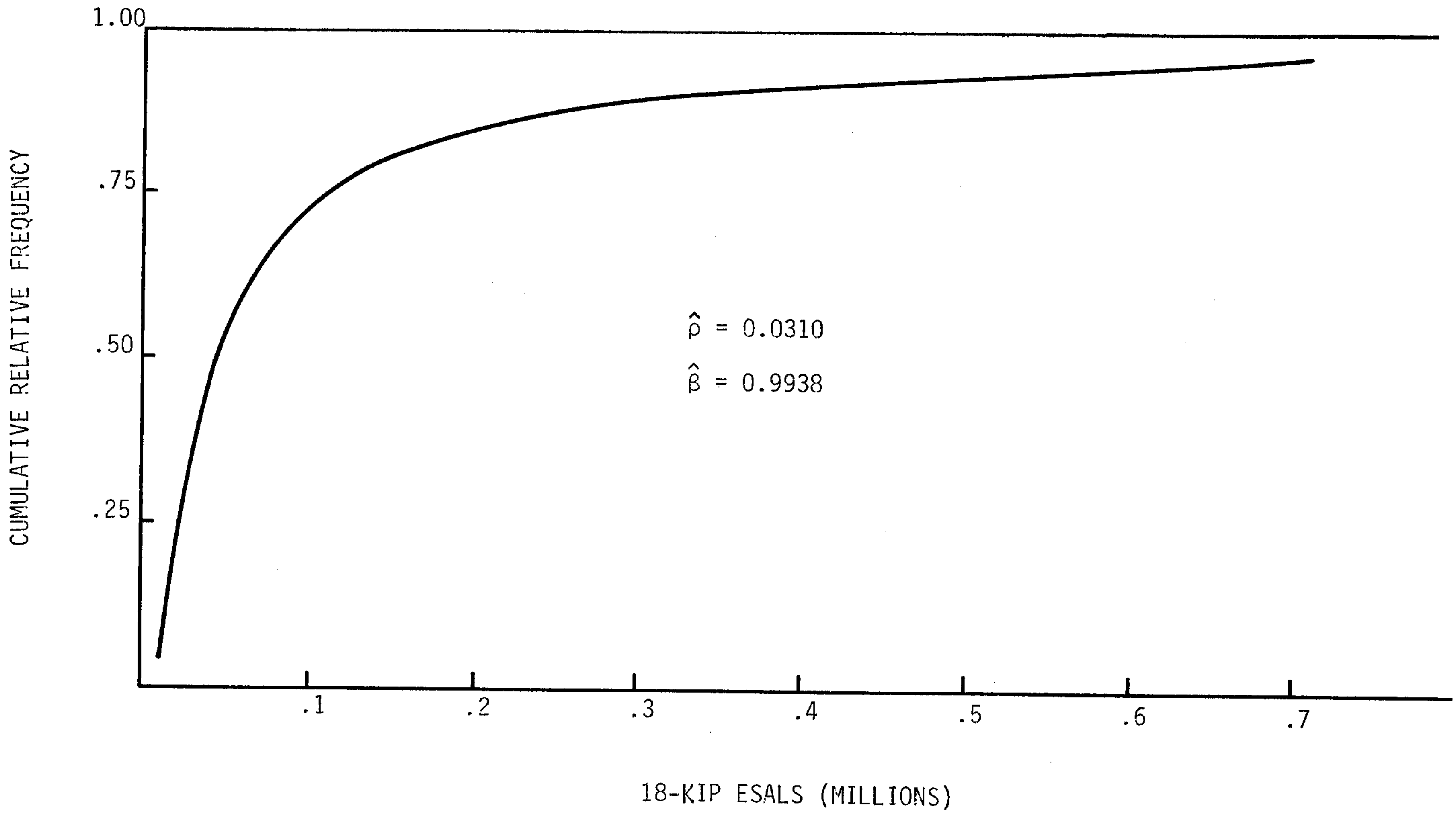

Figure B-16. Cumulative Density Function for Single Treatment Surface Treated US/State Highways.

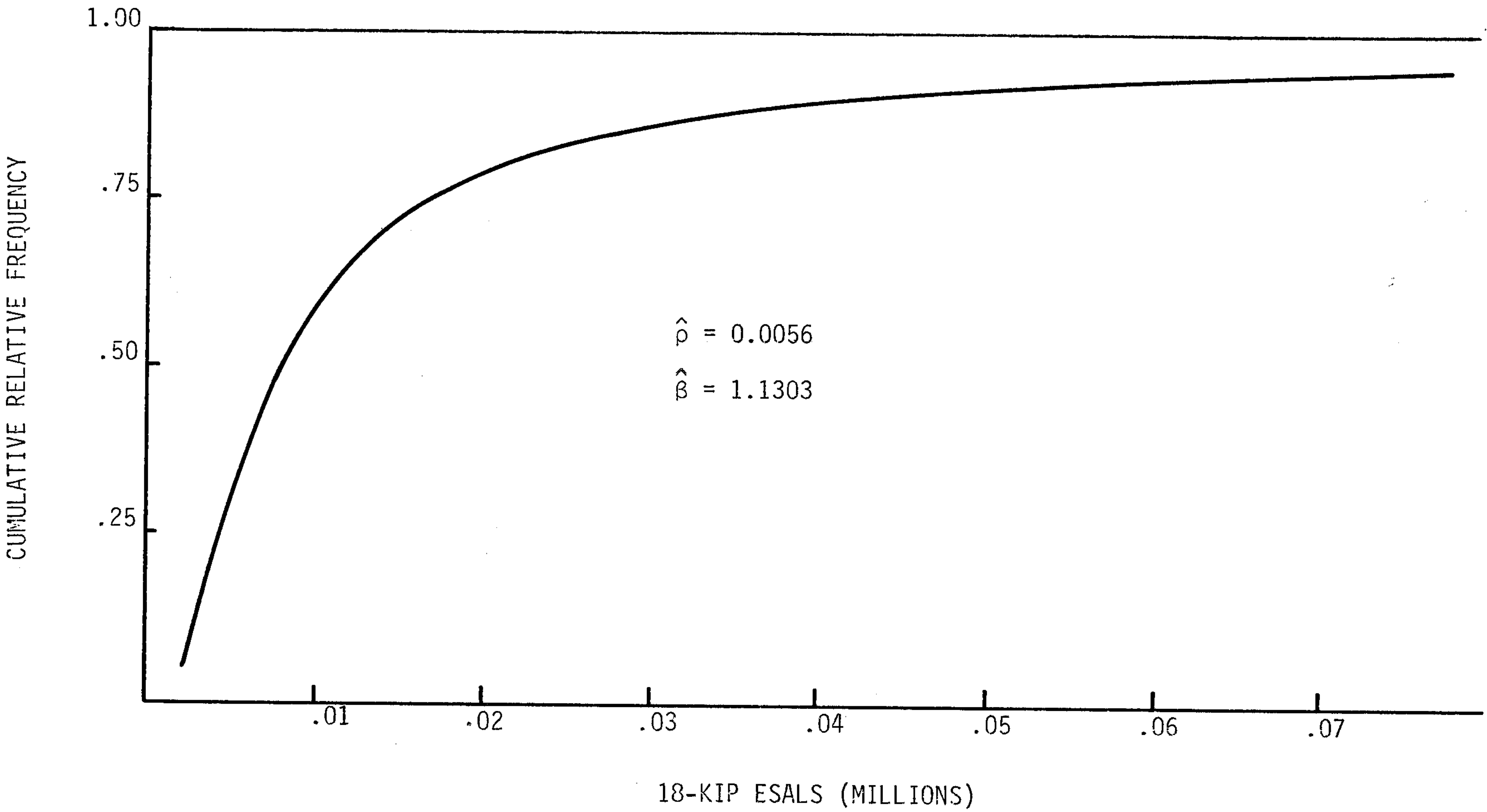

Figure B-17. Cumulative Density Function for Single Treatment Surface Treated Farm to Market Highways.

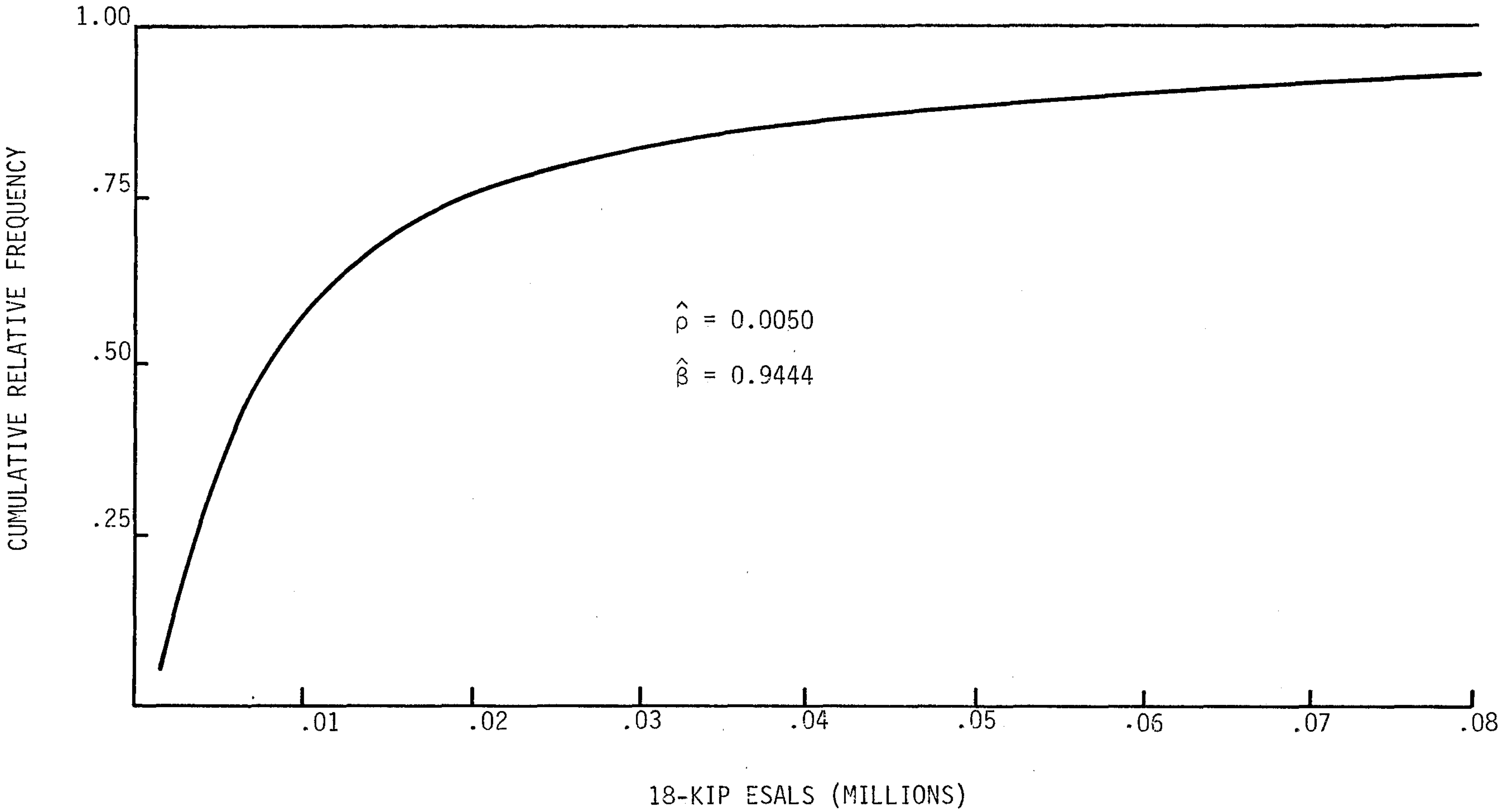

Figure B-18. Cumulative Density Function for Multiple Treatment Surface Treated Farm to Market Highways.

APPENDIX C

DISCRIMINANT ANALYSIS

Discriminant analysis is a statistical technique concerned with the problem of assigning an observation of unknown origin to one or more distinct groups, based on the value of the observation (43). The linear discriminant factor first introduced by Fisher (44) discriminates among groups using a linear combination of the observations. The coefficients of this linear relation are chosen to maximize the difference in the means of the linear combination of each of the two groups to its variance.

The general assumptions that are inherent to the use of discriminant analysis in general may be stated as:

a. The groups being investigated are discrete and identifiable.

b. Each observation in each group can be described by a set of measurements on each discriminating variable.

c. The discriminating variables in each group are assumed to have a multivariate normal distribution.

In addition to these assumptions the linear discriminant function also requires equal covariance matrices for the variables in each group. If this assumption is violated the result is a quadratic discriminant function.

In essence, the purposes of discriminant analysis are to test for mean group differences and to describe the overlaps among groups and then to construct classification schemes based upon a set of discrimination variables in order to assign unclassified observations to appropriate groups. This classification scheme is referred to as a discriminant function which defines a boundary such that the observation of each group can be separated and the function can ultimately serve to assign new observations into one of the predetermined groups.

Frequently, the distance from each individual observation to each of the group centroids, commonly known as Mahalanobis' D^2 statistic (45), is used as the criterion for assigning observations to a particular group. The smallest distance dictates the assignment rule and this distance may be stated as:

$$D_j^2(x) = (x-\bar{x}_j)^T S_j^{-1} (x-\bar{x}_j) + \ln |S_j| - 2 \ln (r_j) \qquad \text{(C-1)}$$

where

$D_j^2(x)$ = the generalized squared distance from observation x to the centroid of group j,

x = vector of the variables in an individual observation,

$\bar{x}_j$ = vector of the means of variables in group j,

S_j^{-1} = inverse of the covariance matrix for group j,

$|S_j|$ = determinant of the covariance matrix for group j, and

r_j = the prior probability of assignment to group j (the proportion of observations in group j to the total numbr of observations in all groups.

When the covariance matrices are equal, the quadratic terms cancel because of symmetry and the resulting discriminant function is linear.

Akin to the smallest distance rule is one which assigns observations based on the probability of the observation belonging to a particular group. This rule utilizes the Mahalanobis distance measures and yields the same classification results as the smallest distance rule. The probability of assigning an observation to a group as described by Eisenbers and Avery (45) is given by:

$$P[j/x] = \exp[-0.5\ D_j^2\ (x)]/\sum_K \exp[-0.5\ D_K^2\ (x)] \qquad (C\text{-}2)$$

Where P(j/x) is the posterior probability of observation x belonging to group j.

After a discriminant function has been calculated, its performance should be evaluated. A good or useful classification scheme is one that minimizes the expected probability of misclassification. Even when the error rate is minimized it may be quite large. This would occur when the group means are close together relative to the group dispersions so that the groups overlap significantly. The evaluation of a discriminant function's usefulness requires the estimation of the associated error rates.

Anderson (46) demonstrated that when the population parameters and probability density functions are known it is possible to construct discriminant functions which minimize the expected classification errors and the errors themselves are relatively easy to calculate. However, when the parameters are estimated from samples, the classification errors themselves are subject to error inherent in the sampling process. Calculating the classification error rates is not trivial, although various techniques have been proposed for these estimating error rates.

Lachenbruch and Mickey (47) discuss a number of methods for estimating the expected error rates. Among those discussed were the apparent error rate, the maximum likelihood estimate and the leaving one out method. The apparent error rate is that obtained by reclassifying the data utilized to form the discriminant function and noting the number of misclassifications. The maximum likelihood estimate for the error rate is given by

$$E = \phi(-^{D}/2) \qquad \text{(C-3)}$$

where

ϕ = cumulative normal distribution function

D = Mahalanobis' distance between the two groups (for the two-group case)

This estimate is consistent and asymptotically efficient, however, it is not unbiased and has been found poor for use with small samples. The leaving-one-out method originally proposed by Lachenbruch (48) involves eliminating the discriminant function, omitting one observation, and then using that function to classify the remainder of the observations. This is done for all observations and the number of misclassifications is tallied.

The apparent error rate and the MLE produce biased estimates, especially for small samples. For variables that are not normally distributed, Lachenbruch and Mickey concluded that the apparent error rate and the leaving-one-out method were viable candidates for estimating the error rate with the latter being preferable for small sample sizes.

APPENDIX D

CONFIDENCE INTERVALS

Let T = 1/N. It can be shown that the transformed variable has a Weibull distribution; that is:

$$f(t) = \beta\rho^{\beta}t^{\beta-1}\, e^{-(\rho t)^{\beta}} \quad \text{for } t \geq 0,\ \beta > 0,\ \rho > 0 \tag{D-1}$$

Cohen (49) and Hunter and Moore (50) proposed MLE estimators for the Weibull distribution with results consistent to those presented previously in Appendix A. An approximate value of the variance of $\hat{\beta}$ may be determined by

$$\begin{bmatrix} \mathrm{Var}\,(\hat{\beta}) & \mathrm{Cov}\,(\hat{\beta},\, \hat{\rho}^{-\hat{\beta}}) \\ \mathrm{Cov}\,(\hat{\beta},\, \hat{\rho}^{-\hat{\beta}}) & \mathrm{Var}\,(\hat{\rho}^{-\hat{\beta}}) \end{bmatrix} \simeq \begin{bmatrix} A & C \\ C & B \end{bmatrix}^{-1} \tag{D-2}$$

where

$$A = \frac{m}{\hat{\beta}^2} + \hat{\rho}^{\hat{\beta}} \sum_{i=1}^{m} t_i^{\hat{\beta}} (\ln t_i)^2 \tag{D-3}$$

$$B = -m\,(\hat{\rho}^{\hat{\beta}})^2 + 2(\hat{\rho}^{\hat{\beta}})^3 \sum_{i=1}^{m} t_i^{\hat{\beta}} \tag{D-4}$$

$$C = -(\hat{\rho}^{\hat{\beta}})^2 \sum_{i=1}^{m} t_i^{\hat{\beta}} \ln t_i \tag{D-5}$$

For a large sample the distribution of $\beta, \rho^{-\beta}$ is approximately bivariate normal with mean $(\beta, \rho^{-\beta})$ and variance as given in Eq. (D-3). The approximate 100 $(1-\alpha)$ percent confidence interval for β is:

$$\hat{\beta} - Z_{\alpha/2}\sqrt{\mathrm{Var}(\hat{\beta})} < \beta < \hat{\beta} + Z_{\alpha/2}\sqrt{\mathrm{Var}(\hat{\beta})} \tag{D-6}$$

APPENDIX E

TRAFFIC TABLES

Table E-1. W-4 Table for 1980
State of Texas, All Rural, Includes 5 Stations

Axle Loads in Pounds	Single-Unit Trucks: 2 Axle, 6 Tire — Single Axle	2 Axle, 6 Tire — Percent	3 Axle or More — Single Axle	3 Axle or More — Percent
Under 3,000	62	6	0	-
3,000 - 6,999	690	64	27	20
7,000 - 7,999	92	9	9	6
8,000 - 11,999	121	11	85	61
12,000 - 15,999	45	4	16	12
16,000 - 18,000	29	3	2	1
18,001 - 18,500	7	1	0	-
18,501 - 20,000	13	1	0	-
20,001 - 21,999	6	1	0	-
22,000 - 23,999	3	-	0	-
24,000 - 25,999	2	-	0	-
26,000 - 29,999	0	-	0	-
30,000 or over	0	-	0	-
Total Single Axles Weighed	1070	100	139	100
Tandem Axle Groups				
Under 6,000	0	-	0	-
6,000 - 11,999	0	-	25	18
12,000 - 17,999	0	-	29	21
18,000 - 23,999	0	-	21	15
24,000 - 29,999	0	-	17	12
30,000 - 32,000	0	-	7	5
32,001 - 32,500	0	-	4	3
32,501 - 33,999	0	-	1	1
34,000 - 35,999	0	-	13	10
36,000 - 37,999	0	-	7	5
38,000 - 39,999	0	-	4	3
40,000 - 41,999	0	-	3	2
42,000 - 43,999	0	-	3	2
44,000 - 45,999	0	-	3	2
46,000 - 49,999	0	-	2	1
50,000 or Over	0	-	0	-
Total Tandem Axles Weghed	0	-	139	100

Table E-1. Cont.

Axle Loads in Pounds	Tractor Semi-Trailer					
	3 Axle	Percent	4 Axle	Percent	5 Axle or Over	Percent
Under 3,000	0	-	0	-	1	0
3,000 - 6,999	17	13	35	9	45	2
7,000 - 7,999	13	10	30	8	193	7
8,000 - 11,999	46	36	176	46	2353	88
12,000 - 15,999	30	23	52	14	69	4
16,000 - 18,000	15	12	30	8	5	-
18,001 - 18,500	0	-	7	2	0	-
18,501 - 20,000	3	2	22	6	1	-
20,001 - 21,999	2	2	13	3	0	-
22,000 - 23,999	3	2	14	4	0	-
24,000 - 25,999	0	-	1	-	0	-
26,000 - 29,999	0	-	2	-	0	-
30,000 or over	0	-	0	-	0	-
Total Single Axles Weighed	129	100	382	100	2667	100
			Tandem Axle Groups			
Under 6,000	0	-	0	-	3	-
6,000 - 11,999	0	-	31	16	616	12
12,000 - 17,999	0	-	67	35	841	16
18,000 - 23,999	0	-	58	30	695	13
24,000 - 29,999	0	-	26	13	1041	19
30,000 - 32,000	0	-	2	1	511	10
32,001 - 32,500	0	-	1	1	139	3
32,501 - 33,999	0	-	5	3	373	7
34,000 - 35,999	0	-	0	-	453	9
36,000 - 37,999	0	-	0	-	286	5
38,000 - 39,999	0	-	0	-	185	3
40,000 - 41,999	0	-	1	1	90	2
42,000 - 43,999	0	-	0	-	34	1
44,000 - 45,999	0	-	0	-	11	-
46,000 - 49,999	0	-	0	-	8	-
50,000 or Over	0	-	0	-	2	-
Total Tandem Axles Weighed	0	-	191	100	5288	100

Table E-1 Cont.

Axle Loads in Pounds	Semi-Trailer - Trailer			
	Single Axle Groups			
	5 Axle	Percent	6 Axle or more	Percent
Under 3,000	0	-	0	-
3,000 - 6,999	38	8	0	-
7,000 - 7,999	20	5	0	-
8,000 - 11,999	138	31	14	44
12,000 - 15,999	111	25	11	34
16,000 - 18,000	54	12	5	16
18,001 - 18,500	12	3	0	-
18,501 - 20,000	34	8	2	6
20,001 - 21,999	20	5	0	-
22,000 - 23,999	7	2	0	-
24,000 - 25,999	5	1	0	-
26,000 - 29,999	1	-	0	-
30,000 or over	0	-	0	-
Total Single Axles Weighed	440	100	32	100
	Tandem Axle Groups			
Under 6,000	0	-	0	-
6,000 - 11,999	0	-	0	-
12,000 - 17,999	0	-	2	25
18,000 - 23,999	0	-	4	50
24,000 - 29,999	0	-	2	25
30,000 - 32,000	0	-	0	-
32,001 - 32,500	0	-	0	-
32,501 - 33,999	0	-	0	-
34,000 - 35,999	0	-	0	-
36,000 - 37,999	0	-	0	-
38,000 - 39,999	0	-	0	-
40,000 - 41,999	0	-	0	-
42,000 - 43,999	0	-	0	-
44,000 - 45,999	0	-	0	-
46,000 - 49,999	0	-	0	-
50,000 or Over	0	-	0	-
Total Tandem Axles Weghed	0	-	8	100

Table E-1. Cont.

Axle Loads in Pounds	Truck and Trailer[a]					
	Single Axle Groups					
	3 Axle	Percent	4 Axle	Percent	5 Axle or Over	Percent
Under 3,000	0	-	0	-	0	-
3,000 - 6,999	52	22	52	22	52	22
7,000 - 7,999	53	22	53	22	53	22
8,000 - 11,999	79	34	79	34	79	3
12,000 - 15,999	53	22	53	22	53	22
16,000 - 18,000	0	-	0	-	0	-
18,001 - 18,500	0	-	0	-	0	-
18,501 - 20,000	0	-	0	-	0	-
20,001 - 21,999	0	-	0	-	0	-
22,000 - 23,999	0	-	0	-	0	-
24,000 - 25,999	0	-	0	-	0	-
26,000 - 29,999	0	-	0	-	0	-
30,000 or over	0	-	0	-	0	-
Total Single Axles Weighed	237	100	237	100	237	100
	Tandem Axle Groups					
Under 6,000	0	-	0	-	0	-
6,000 - 11,999	0	-	0	-	0	-
12,000 - 17,999	0	-	26	33	52	33
18,000 - 23,999	0	-	0	-	0	-
24,000 - 29,999	0	-	53	67	106	67
30,000 - 32,000	0	-	0	-	0	-
32,001 - 32,500	0	-	0	-	0	-
32,501 - 33,999	0	-	0	-	0	-
34,000 - 35,999	0	-	0	-	0	-
36,000 - 37,999	0	-	0	-	0	-
38,000 - 39,999	0	-	0	-	0	-
40,000 - 41,999	0	-	0	-	0	-
42,000 - 43,999	0	-	0	-	0	-
44,000 - 45,999	0	-	0	-	0	-
46,000 - 49,999	0	-	0	-	0	-
50,000 or Over	0	-	0	-	0	-
Total Tandem Axles Weighed	0	0	79	100	158	100

[a] Probable number combinations used due to lack of 1980 data.

Table E-2. W-5 Table for 1980.

State of Texas, All Rural, Includes 5 Stations.

Number of Loaded and Empty Trucks and Truck Combinations of Each Type of Various Total Weights During 1980

Axle Loads in Pounds	Single-Unit Trucks			
	Panel and Pickup (Under 1 Ton)	2 Axle 4 Tire	2 Axle 6 Tire	3 Axle Or More
Under 3,999	0	0	0	0
4,000 - 9,999	0	0	205	0
10,000 - 13,499	0	0	150	3
13,500 - 19,999	0	0	101	24
20,000 - 21,999	0	0	13	8
22,000 - 23,999	0	0	23	12
24,000 - 25,999	0	0	19	7
26,000 - 27,999	0	0	9	4
28,000 - 29,999	0	0	9	5
30,000 - 31,999	0	0	5	7
32,000 - 33,999	0	0	0	5
34,000 - 35,999	0	0	1	5
36,000 - 37,999	0	0	0	2
38,000 - 39,999	0	0	0	6
40,000 - 44,999	0	0	0	17
45,000 - 49,999	0	0	0	23
50,000 - 54,999	0	0	0	8
55,000 - 59,999	0	0	0	3
60,000 - 64,999	0	0	0	0
65,000 - 69,999	0	0	0	0
70,000 - 72,000	0	0	0	0
72,001 - 74,999	0	0	0	0
75,000 - 79,99	0	0	0	0
80,000 - 84,999	0	0	0	0
85,000 - 89,999	0	0	0	0
90,000 - 94,999	0	0	0	0
95,000 - 99,999	0	0	0	0
100,000 - 104,999	0	0	0	0
105,000 - 109,999	0	0	0	0
110,000 or Over	0	0	0	0
Total Vehicles Weighed	0	0	535	139

Table E-2 Cont.

Axle Loads in Pounds	Tractor Semi-Trailer		
	3 Axle	4 Axle	5 Axle Or More
Under 3,999	0	0	0
4,000 - 9,999	0	0	0
10,000 - 13,499	0	0	0
13,500 - 19,999	1	1	0
20,000 - 21,999	1	4	0
22,000 - 23,999	6	2	5
24,000 - 25,999	1	6	12
26,000 - 27,999	1	9	45
28,000 - 29,999	4	8	74
30,000 - 31,999	1	7	84
32,000 - 33,999	5	15	107
34,000 - 35,999	2	12	96
36,000 - 37,999	7	12	76
38,000 - 39,999	4	9	58
40,000 - 44,999	5	31	147
45,000 - 49,999	4	29	159
50,000 - 54,999	1	14	159
55,000 - 59,999	0	22	138
60,000 - 64,999	0	7	210
65,000 - 69,999	0	2	247
70,000 - 72,000	0	1	137
72,001 - 74,999	0	0	193
75,000 - 79,999	0	0	337
80,000 - 84,999	0	0	226
85,000 - 89,999	0	0	99
90,000 - 94,999	0	0	27
95,000 - 99,999	0	0	5
100,000 - 104,999	0	0	1
105,000 - 109,999	0	0	1
110,000 or Over	0	0	3
Total Vehicles Weighed	43	191	2646

Table E-2 Cont.

Axle Loads in Pounds	Semi-Trailer - Trailer	
	5 Axle	6 Axle Or More
Under 3,999	0	0
4,000 - 9,999	0	0
10,000 - 13,499	0	0
13,500 - 19,999	0	0
20,000 - 21,999	0	0
22,000 - 23,999	1	0
24,000 - 25,999	1	0
26,000 - 27,999	2	0
28,000 - 29,999	3	0
30,000 - 31,999	2	0
32,000 - 33,999	0	0
34,000 - 35,999	0	0
36,000 - 37,999	1	0
38,000 - 39,999	0	0
40,000 - 44,999	2	0
45,000 - 49,999	2	0
50,000 - 54,999	5	0
55,000 - 59,999	6	0
60,000 - 64,999	8	0
65,000 - 69,999	11	4
70,000 - 72,000	3	0
72,001 - 74,999	9	1
75,000 - 79,99	16	2
80,000 - 84,999	9	0
85,000 - 89,999	4	1
90,000 - 94,999	2	0
95,000 - 99,999	1	0
100,000 - 104,999	0	0
105,000 - 109,999	0	0
110,000 or Over	0	0
Total Vehicles Weighed	88	8

Table E-2 Cont.

Axle Loads in Pounds	Truck and Trailer[a]		
	3 Axle	4 Axle	5 Axle Or More
Under 3,999	0	0	0
4,000 - 9,999	0	0	0
10,000 - 13,499	0	0	0
13,500 - 19,999	0	0	0
20,000 - 21,999	0	0	0
22,000 - 23,999	0	0	0
24,000 - 25,999	0	0	0
26,000 - 27,999	0	0	0
28,000 - 29,999	0	0	0
30,000 - 31,999	0	0	0
32,000 - 33,999	0	0	0
34,000 - 35,999	0	0	0
36,000 - 37,999	0	0	0
38,000 - 39,999	0	0	0
40,000 - 44,999	27	27	27
45,000 - 49,999	26	26	26
50,000 - 54,999	0	0	0
55,000 - 59,999	0	0	0
60,000 - 64,999	26	26	26
65,000 - 69,999	0	0	0
70,000 - 72,000	0	0	0
72,001 - 74,999	0	0	0
75,000 - 79,99	0	0	0
80,000 - 84,999	0	0	0
85,000 - 89,999	0	0	0
90,000 - 94,999	0	0	0
95,000 - 99,999	0	0	0
100,000 - 104,999	0	0	0
105,000 - 109,999	0	0	0
110,000 or Over	0	0	0
Total Vehicles Weighed	79	79	79

[a] Probable number combinations used due to lack of 1980 data.

Table E-3. Percentages of Trucks for 1980 on Rural Texas Highways.

Truck Types	Total Trucks Weighed[a]	Percent (Rounded)
Single-Unit		
2 Axle, 6 Tires	535	14
3 Axle or More	139	4
Tractor-Semi-Trailer		
3 Axle	43	1
4 Axle	191	5
5 Axle or More	2646	68
Semi-Trailer-Trailer		
5 Axle	88	2
6 Axle or More	8	-
Truck and Trailer[b]		
3 Axle	79	2
4 Axle	79	2
5 Axle or More	79	2
Total Vehicles Weighed	3887	100

[a] From W-5 Tables for 1980

[b] Probable number combinations

Table E-4. Summary of Developed Equivalency Factors for Flexible Pavements for a Terminal Serviceability Index of 1.5.[a]

Total Axle Load, Kips	Single Axle	Tandem Axle
2	--	--
4	.002	--
6	.008	--
8	.03	--
10	.07	.006
12	.16	.01
14	.32	.02
16	.59	.04
18	1.00	.05
20	1.57	.09
22	2.39	.13
24	2.95	.21
26	4.47	.30
28	7.70	.42
30	10.38	.58
32	14.26	.76
34	19.56	.98
36	25.98	1.30
38	33.54	1.64
40	42.79	2.11
42	--	2.76
44	--	3.48
46	--	4.24
48	--	5.13
50	--	--

[a] Compiled from reference (6) page 120.

APPENDIX F

DISCRIMINANT FUNCTIONS

Table F-1. Discriminant Functions for Asphalt Concrete Pavements.

Group Not Resurfaced

$$D_0^2(X) = \begin{bmatrix} X_1 - 0.632 \\ X_2 - 0.843 \\ X_3 - 0.539 \\ X_4 - 0.829 \end{bmatrix}^T \begin{bmatrix} 1.466 & 0.428 & -0.366 & -0.663 \\ 0.428 & 7.286 & -6.830 & -2.997 \\ -0.366 & -6.830 & 10.818 & 0.988 \\ -0.663 & -2.997 & 0.988 & 3.199 \end{bmatrix} \begin{bmatrix} X_1 - 0.632 \\ X_2 - 0.843 \\ X_3 - 0.539 \\ X_4 - 0.829 \end{bmatrix} - 3.767 \quad \text{(F-1)}$$

and for Resurfaced Group

$$D_1^2(X) = \begin{bmatrix} X_1 - 2.2 \\ X_2 - 1.0 \\ X_3 - 1.2 \\ X_4 - 1.8 \end{bmatrix}^T \begin{bmatrix} 1.089 & -1.325 & 0.308 & -.497 \\ -1.325 & 15.527 & -10.462 & 1.822 \\ 0.308 & -10.462 & 8.000 & -.923 \\ -0.497 & 1.822 & -0.923 & 1.183 \end{bmatrix} \begin{bmatrix} X_1 - 2.2 \\ X_2 - 1.0 \\ X_3 - 1.2 \\ X_4 - 1.8 \end{bmatrix} + 3.54623 \quad \text{(F-2)}$$

where
X_1 - alligator cracking severity
X_2 - longitudinal cracking severity
X_3 - longitudinal cracking area
X_4 - transverse cracking

Table F-2. Discriminant Function for Overlaid Pavements

Group Not Resurfaced

$$D_0^2(X) = \begin{bmatrix} X_1 & -3.777 \\ X_2 & -0.563 \\ X_3 & -0.922 \\ X_4 & -0.672 \end{bmatrix}^T \begin{bmatrix} 5.632 & 1.018 & 0.462 & -1.097 \\ 1.018 & 1.916 & -0.153 & -0.251 \\ 0.462 & -0.153 & 3.635 & -4.009 \\ -1.097 & -0.251 & -4.009 & 6.501 \end{bmatrix} \begin{bmatrix} X_1 & -3.777 \\ X_2 & -0.563 \\ X_3 & -0.922 \\ X_4 & -0.672 \end{bmatrix} -3.777 \qquad \text{(F-3)}$$

and for Group Resurfaced

$$D_1^2(X) = \begin{bmatrix} X_1 & -3.258 \\ X_2 & 0.938 \\ X_3 & -1.125 \\ X_4 & -1.375 \end{bmatrix}^T \begin{bmatrix} 4.114 & 0.846 & 0.888 & 0.089 \\ 0.846 & 1.128 & -0.761 & 1.181 \\ 0.888 & -0.761 & 4.775 & -3.852 \\ 0.089 & 1.181 & -3.852 & 4.539 \end{bmatrix} \begin{bmatrix} X_1 & -3.258 \\ X_2 & -0.938 \\ X_3 & -1.125 \\ X_4 & -1.375 \end{bmatrix} \pm 0.470 \qquad \text{(F-4)}$$

where
X_1 - Present serviceability index
X_2 - alligator cracking area
X_3 - longitudinal cracking severity
X_4 - longitudinal cracking area

Table F-3. Discriminant Functions Surface Treated Pavements

Group Not Resurfaced

$$D_0^2(X) = \begin{bmatrix} X_1 -1.013 \\ X_2 -1.662 \\ X_3 -0.351 \\ X_4 -0.260 \\ X_5 -0.766 \end{bmatrix}^T \begin{bmatrix} 11.072 & -1.657 & -0.839 & 0.884 & -1.599 \\ -1.657 & 3.134 & 0.248 & -0.706 & 0.375 \\ -0.839 & 0.248 & 3.922 & -1.183 & -0.006 \\ 0.884 & -0.706 & -1.183 & 4.164 & -0.250 \\ -1.599 & 0.375 & -0.006 & 0.250 & 1.277 \end{bmatrix} \begin{bmatrix} X_1 -1.013 \\ X_2 -1.662 \\ X_3 -0.351 \\ X_4 -0.260 \\ X_5 -0.766 \end{bmatrix} -5.050 \quad \text{(F-5)}$$

and for Group Resurfaced

$$D_1^2(X) = \begin{bmatrix} X_1 -1.143 \\ X_2 -1.429 \\ X_3 -0.643 \\ X_4 -0.677 \\ X_5 -1.446 \end{bmatrix}^T \begin{bmatrix} 3.208 & -1.320 & -0.254 & 0.166 & 0.029 \\ -1.320 & 2.305 & 0.500 & 0.077 & -0.139 \\ -0.254 & 0.500 & 2.017 & -0.344 & -0.135 \\ 0.166 & 0.077 & -0.344 & 1.185 & 0.010 \\ 0.029 & -0.139 & -0.135 & 0.010 & 0.781 \end{bmatrix} \begin{bmatrix} X_1 -1.143 \\ X_2 -1.429 \\ X_3 -0.643 \\ X_4 -0.679 \\ X_5 -1.446 \end{bmatrix} -0.472 \quad \text{(F-6)}$$

where X_1 - rutting severity
X_2 - rutting area
X_3 - longitudinal cracking area
X_4 - transverse cracking area
X_5 - patching area

APPENDIX G

PERFORMANCE EQUATIONS

Table G-1. Performance Equations for Asphalt Concrete Pavements.

Alligator Cracking Severity

$$\rho = -0.25 + 0.38\ SN - 0.044\ AVT - 0.10\ TK, \quad 0.45 \leq \rho \leq 0.78 \qquad (G-1)$$

$$\beta = 2.38 - 0.02\ TI + 1.27\ TK - 0.09\ PI, \quad 1.0 \leq \beta \leq 8.15 \qquad (G-2)$$

Longitudinal Cracking Severity

$$\rho = 0.27 + 0.13\ SN - 0.038\ AVT - 0.0037\ FTC + 0.16\ TK + 0.012\ PI, \quad 0.25 \leq \rho \leq 1.12 \qquad (G-3)$$

$$\beta = 4.58 + 0.84\ SN - 0.17\ PI - 0.35\ TK \quad 1.0 \leq \beta \leq 8.10 \qquad (G-4)$$

Longitudinal Cracking Area

$$\rho = 4.45 - 0.26\ AVT + 0.53\ TK - 0.033\ FTC, \quad 0.23 \leq \rho \leq 1.51 \qquad (G-5)$$

$$\beta = -3.67 + 0.13\ SN + 0.38\ AVT + 0.067\ FTC - 0.14\ PI, \quad 0.76 \leq \beta \leq 4.23 \qquad (G-6)$$

Transverse Cracking Severity

$$\rho = 1.4 - 0.094\ AVT + 0.17\ TK - 0.0088\ FTC + 0.01\ PI, \quad 0.20 \leq \rho \leq 1.06 \qquad (G-7)$$

$$\beta = 3.28 \qquad (G-8)$$

PSI

$$\rho = 3.51 + 0.0092\ SN - 0.0042\ TI + 0.014\ BA - 0.023\ FTC + 0.0026\ PI - 0.18\ AVT \quad 0.0063 \leq \rho \leq 0.98 \qquad (G-9)$$

$$\beta = 2.06 \qquad (G-10)$$

Table G-2. Performance Equations for Overlaid Pavements.

Serviceability Index

$$\rho = 0.065 + 0.084\ TH - 0.0041\ SLL \qquad 0.12 \leq \rho \leq 1.4 \qquad (G-11)$$

$$\beta = 1.00 \qquad (G-12)$$

Alligator Cracking Area

$$\rho = -10.93 + 3.26\ SN + 0.33\ AVT \qquad 0.12 \leq \rho \leq 1.70 \qquad (G-13)$$

$$\beta = 1.86 \qquad (G-14)$$

Longitudinal Cracking Severity

$$\rho = -3.1 + 0.47\ SN + 0.21\ AVT\ 50, \qquad 0.12 \leq \rho \leq 1.75 \qquad (G-15)$$

$$\beta = -0.19 + 0.54\ SN + 0.059\ TI - 0.092\ PI, \quad 0.61 \leq \beta \leq 3.19 \qquad (G-16)$$

Longitudinal Cracking Area

$$\rho = -2.78 + 0.39\ SN - 0.034\ TI + 0.35\ AVT, \quad 0.10 \leq \rho \leq 1.80 \qquad (G-17)$$

$$\beta = 0.41 + 0.22\ SN + 0.036\ TI -0.053\ PI, \quad 0.74 \leq \beta \leq 2.21 \qquad (G-18)$$

Table G-3. Performance Equations for Surface Treated Pavements.

Rutting Severity

$$\rho = -0.0678 + 0.0032\ AVT + 0.00566\ FL - 0.00031\ SLL + 0.00048\ FTC, \quad 0.0027 \leq \rho \leq 0.121 \quad (G\text{-}19)$$

$$\beta = 1.78 \quad (G\text{-}20)$$

Rutting Area

$$\rho = -0.1035 + 0.00549\ AVT + 0.0067\ FL - 0.0015\ SLL + 0.00162\ PI + 0.00077\ FTC \quad 0.0036 \leq \rho \leq 1.70 \quad (G\text{-}21)$$

$$\beta = 1.540 + 0.0169\ TI - 0.072\ FL \quad 0.615 \leq \beta \leq 6.27 \quad (G\text{-}22)$$

Longitudinal Cracking Area*

$$\rho = -63.1 + 4.52\ AVT + 0.541\ TI + 7.41\ FL + 1.1145\ FTC, \quad 30.0 \leq \rho \leq 172.0 \quad (G\text{-}23)$$

$$\beta = 1.15 \quad (G\text{-}24)$$

Transverse Cracking Area*

$$\rho = -66.4 + 2.156\ TI + 10.12\ FL + 0.718\ FTC, \quad 41.0 \leq \rho \leq 176.0 \quad (G\text{-}25)$$

$$\beta = 2.059 - 0.0734\ FL - 0.06\ SLL + 0.0607\ PI - 0.00375\ FTC, \quad 0.61 \leq \beta \leq 2.65 \quad (G\text{-}26)$$

Patching Area

$$\rho = 0.00799 + 0.00252\ AVT + 0.000218\ TI + 0.00166\ FC - 0.00125\ PI \quad .0036 \leq \rho \leq 0.104 \quad (G\text{-}27)$$

$$\beta = 1.75 \quad (G\text{-}28)$$

PSI

$$\rho = -0.173 + 0.00687\ AVT - 0.000632\ TI + 0.0133\ FL + 0.00075\ SLL + 0.00153\ FTC - 0.0214\ DMD, \quad 0.0009 \leq \rho \leq 0.511 \quad (G\text{-}29)$$

$$\beta = 1.0 \quad (G\text{-}30)$$

* ρ is stated in months

Table G-4. Variables Used in Performance Equations.

SN	=	AASHO structural number
AVT	=	average monthly temperature (°F) - 50°
TK	=	thickness of surface asphalt concrete layer (inch)
TI	=	Thornthwaite index + 50
PI	=	subgrade plasticity index
FTC	=	annual average freeze thaw cycles
BA	=	thickness of base (inch)
TH	=	thickness of old asphalt concrete plus overlay thickness (inch)
SLL	=	subgrade liquid limit
FL	=	thickness of flexible base (inch)
DMD	=	dynaflect maximum deflection (mils)

APPENDIX H

VEHICLE OPERATING COST TABLES

Table H-1. Constant Speed Fuel Consumption.[a]

(gal/1000 mi) 0% Grade

	Vehicle				
Speed (mph)	Car mid-sized	SU-2	SU-3	2-S2	2-S3
5	55.4	212.0	236.0	465.0	470.0
10	55.4	207.0	217.0	367.0	370.0
15	47.3	167.0	198.0	284.0	287.0
20	38.3	132.0	179.0	203.0	205.0
25	38.0	121.0	168.0	198.0	204.0
30	37.3	112.0	156.0	193.0	204.0
35	37.6	113.0	153.0	186.0	202.0
40	38.0	115.0	149.0	180.0	201.0
45	40.5	123.0	149.0	174.0	199.0
50	43.0	133.0	149.0	169.0	199.0
55	47.9	139.0	153.0	168.0	202.0

[a] Compiled form reference (22), Appendix B.

Table H-2. Constant Speed Fuel Consumption.[a]
(gal/1000 mi) 0% Grade

	Vehicle				
Speed (mph)	Car	SU-2	SU-3	2-S2	2-S3 mid-sized
5	3.8	6.5	9.6	9.6	19.6
10	2.4	4.1	6.2	6.2	12.7
15	1.8	3.4	4.9	4.9	10.1
20	1.6	3.0	4.4	4.4	9.0
25	1.5	2.8	4.1	4.1	8.3
30	1.4	2.7	3.8	3.8	7.7
35	1.4	2.5	3.6	3.6	7.2
40	1.4	2.3	3.4	3.4	6.5
45	1.4	2.1	3.1	3.1	5.7
50	1.3	2.0	3.0	3.0	5.0
55	1.2	2.1	3.2	3.2	5.2

[a] Compiled form reference (22), Appendix B.

Table H-3. Constant Speed Tire Wear.[a]
(% worn/1000 mi) 0% Grade

	Vehicle				
Speed (mph)	Car mid-sized	SU-2	SU-3	2-S2	2-S3
5	0.08	0.10	0.10	0.09	0.12
10	0.08	0.12	0.11	0.09	0.12
15	0.09	0.14	0.13	0.10	0.13
20	0.11	0.18	0.15	0.12	0.15
25	0.13	0.22	0.18	0.14	0.16
30	0.16	0.28	0.21	0.16	0.18
35	0.20	0.36	0.25	0.19	0.21
40	0.26	0.46	0.29	0.23	0.23
45	0.32	0.57	0.34	0.27	0.27
50	0.41	0.72	0.40	0.33	0.31
55	0.51	0.90	0.47	0.40	0.36

[a] Compiled form reference (22), Appendix B.

Table H-4. Constant Speed Vehicle Maintenance and Repair.[a]
(% avg cost/1000 mi) 0% Grade

	Vehicle				
Speed (mph)	Car mid-sized	SU-2	SU-3	2-S2	2-S3
5	46.9	45.7	46.1	44.6	45.9
10	47.8	44.7	47.1	45.6	45.5
15	49.4	45.5	48.2	46.8	46.4
20	51.6	47.6	49.7	48.2	48.4
25	54.4	50.6	51.4	50.0	51.4
30	57.4	54.3	53.4	52.3	55.1
35	60.6	58.7	55.7	55.0	59.6
40	64.0	63.7	58.5	58.3	64.5
45	67.6	69.1	61.7	62.3	69.8
50	71.3	74.7	65.4	67.0	75.4
55	75.2	80.5	69.7	72.5	81.2

[a] Compiled form reference (22), Appendix B.

Table H-5. Use Related Depreciation Expense.[a]
(% depreciable value/1000 mi) 0% Grade

Speed (mph)	Vehicle Car mid-sized	SU-2	SU-3	2-S2	2-S3
5	1.22	0.74	0.74	0.23	0.25
10	1.03	0.59	0.59	0.18	0.19
15	0.93	0.50	0.50	0.15	0.16
20	0.85	0.44	0.44	0.13	0.14
25	0.79	0.40	0.40	0.12	0.12
30	0.73	0.37	0.37	0.11	0.11
35	0.66	0.34	0.34	0.10	0.10
40	0.63	0.33	0.33	0.10	0.10
45	0.61	0.31	0.31	0.09	0.09
50	0.59	0.30	0.30	0.09	0.09
55	0.59	0.29	0.29	0.09	0.09

[a] Compiled form reference (22), Appendix B.

APPENDIX I

FORMULAS FOR COSTING REHABILITATION STRATEGIES

Rehabilitation Strategy	Formula
1" overlay + local digout	L (NL + 1)(F2 CT) + L(NL)(.06 CE)
5" overlay	L (NL + 1)(6.0 CJ)
1" overlay + level-up	L (NL + 1)(1.56 CT)
Fill cracks	L (NL) CP
Chip Seal (reflection cracking analysis)	L (NL)(1.2 CK)
Seal Coat	L (NL)(1.2 CL)
Double Seal Coat	L (NL)(2.04 CL)
Sectional Reconstruction	L (NL)(4.8 CL)

In the above table, the following notation is used:

L = project length

NL = number of lanes

CJ = cost of 1" overlay/lane mile ($10,000)

CE = cost of base and repair patching/lane mile ($140,000)

CP = cost of filling cracks/lane mile ($1,000)

CK = cost of ship seal/lane mile ($10,000)

CL = cost of seal coat/lane mile ($3,000)

1 = 0.67 for a 2-lane highway

1 = 1.33 for a multilane highway

1 = 2.33 for a freeway

APPENDIX J

COMPUTER PROGRAM: LISTING, SAMPLE DATA AND OUTPUT, DECK PREPARATION.

Program Listing

```
    //JACK JOB (W189,007A,S02,005,JA),'ALLISON'
    //*MAIN         USER=W189$JA
    //*TAMU         HOLDOUT
    //*PASSWORD**********************************************************
    //*XBM  WATFIV
    C
    C    MAIN PROGRAM
    C      THIS PROGRAM CALCULATES THE LIFE OF A PAVEMENT
    C      AND ASSESSES DELAYS IN REHABILITATION
    C
    C      THE MAIN PROGRAM IS THE DRIVER AND PERFORMS PRESENT
    C      WORTH AND BENEFIT-COST ANALYSES
    C
1           COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
           %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
2           COMMON /REM/ NM,RG,RMLIF,NMR,NR,LP
3           COMMON /CS/XIN,CJ,CK,CE,CL,CP,CC1,CC2,CC3,XLT,NL,IHT,ITF
4           DIMENSION Y(5),PSIJ(5),CST(5),PS(6),CSTT(6),CMC(30),PW(5),SI(5)
           1         ,SII(5),R(5),B(5),BC(6),BTT(6),BFF(6),BMM(6)
           2         ,PCCT(4),XTT(5),BO(6),BMR(6),BD(6),BTR(6),OILC(5)
           3         ,TIRC(5),DEP(5),REP(5)
5           DATA PCCT/.14,.04,.01,.81/
6           RHO(5)=0.0
7           BETA(5)=0.0
8           X(5)=0.0
9           READ(5,10)MN,NRO
10       10 FORMAT(2X,2I3)
11          READ(5,101)INTRA,CG,VT,CJ,CK,CE,CL,CP,CC1,CC2,CC3
12          READ(5,110)CQO,CTR1,CTR2,CTR3,CMR1,CMR2,CMR3,CMR4,CMR5
13          READ(5,110)VV1,VV2,VV3,VV4,VV5
14      110 FORMAT(10F7.0)
15      101 FORMAT(2X,I2,10F7.0)
16          WRITE(6,102)CJ,CC1,CK,CC3,CE,CC2,CL,CG
17      102 FORMAT('1',//////////,58X,'COST INFORMATION',//,23X,'OVERLAY',
           1 22X,'$',F8.0,'/IN/LANE MILE',4X,'PATCHING',17X,'$',F5.2,
           2 '/SQ YD',/,23X,'CHIP SEAL',21X,F8.0,
           3 '/LANE MILE',7X,'BASE AND SURFACE REPAIR',1X,F7.2,'/CU YD',
           4 /,23X,'BASE AND REPAIR PATCH',9X,F8.0,'/LANE MILE',7X,
           5 'CRACK SEALING',13X,F5.2,'/LINEAR FT',/,23X,'SEAL COAT',21X,
           6 F8.0,'/LANE MILE',7X,'GASOLINE',18X,F5.2,'/GAL')
18          WRITE(6,103)CP,CQO,VT,INTRA
19      103 FORMAT(23X,'FILL CRACKS',19X,F8.0,'/LANE MILE',7X,
           #        'OIL',23X,F5.2,'/QT',/,78X,
           1 'VALUE OF TIME',13X,F5.2,'/HR',//,23X,'INTEREST RATE',
           2        4X,I3,'%')
20          WRITE(6,130)
21      130 FORMAT(////,58X,'VEHICLE RELATED COSTS',///,23X,'ITEM',8X,
           1        'AUTO',8X,'SU-2',8X,'SU-3',8X,'2-S2',8X,'3-S2')
22          WRITE(6,131)CTR1,CTR2,CTR3,CTR3,CTR3
23      131 FORMAT(/,20X,'TIRES (EA)',5X,F5.0,4(7X,F5.0))
24          WRITE(6,132)CMR1,CMR2,CMR3,CMR4,CMR5
25      132 FORMAT(/,20X,'MAINTENANCE',4X,F5.2,4(7X,F5.0),/,20X,
           1        'AND REPAIRS (/1000 MI)')
26          WRITE(6,133)VV1,VV2,VV3,VV4,VV5
27      133 FORMAT(/,20X,'DEPRECIABLE',3X,F6.0,4(6X,F6.0),/,20X,'VALUE')
28          XIN=INTRA/100.0
29          DO 11 I=1,MN
30          READ(5,100)ICOM,IPVT,ADT,PCTTRK,PCTLNE,NM,RG,XLT,NL,IHT,ITF,SL
31      100 FORMAT(1X,I1,I1,F10.0,2F5.0,2X,I4,F5.2,F5.2,3I2,F5.2)
```

```
      WRITE(6,150)
  150 FORMAT('1',56X,'SECTION DESCRIPTION')
      IF(IPVT.EQ.1)WRITE(6,151)
      IF(IPVT.EQ.2)WRITE(6,152)
      IF(IPVT.EQ.3)WRITE(6,153)
  151 FORMAT(/,75X,'(OVERLAID PAVEMENT)')
  152 FORMAT(/,75X,'(SURFACE TREATED PAVEMENT)')
  153 FORMAT(/,75X,'(ASPHALT CONCRETE PAVEMENT)')
      WRITE(6,8)ADT,SL,PCTTRK,NL,PCTLNE,XLT
      WRITE(6,9)RG,IHT,NM,ITF
    8 FORMAT(//,35X,'AADT',15X,F7.0,3X,'SPEED LIMIT (MPH)',3X,
     1 F5.0,/,35X,'% TRUCKS',11X,F6.2,4X,'NUMBER OF LANES',
     2 7X,I2,/,35X,'% /LANE',12X,F6.2,4X,'SECTION LENGTH',7X,F6.2)
    9 FORMAT(35X,'% GROWTH /YR',7X,F6.2,4X,'HIGHWAY SYSTEM',8X,I2,
     1 /,35X,'SURFACE AGE (MON)',4X,I4,4X,'FACILITY TYPE',9X,I2)
      XTT(1)=ADT*(1-PCTTRK/100.)
      XTT(2)=ADT*PCCT(1)*PCTTRK/100.
      XTT(3)=ADT*PCCT(2)*PCTTRK/100.
      XTT(4)=ADT*PCCT(3)*PCTTRK/100.
      XTT(5)=ADT*PCCT(4)*PCTTRK/100.
      CALL MPG(SL,XTT,ADT,GC)
      CALL OILCON(SL,OILC)
      CALL TIRCON(SL,TIRC)
      CALL DEPCON(SL,DEP)
      CALL REPCON(SL,REP)
      RG=RG/1200.
      MM=0
      OV=0.0
      IF(IPVT.EQ.1)CALL OVLAY(MM,OV)
      IF(IPVT.EQ.2)CALL STREAT
      IF(IPVT.EQ.3)CALL HOTMX
      XN18=XN18*10.0**6
      XLIFE=XLIFE*10.0**6
      CALL REMLIF(MM)
      WRITE(6,201)
  201 FORMAT(//,58X,'LIFE PREDICTION',//,40X,
     1 'PREDICTED PAVEMENT CONDITION AT END OF SERVICE LIFE :')
      IF(IPVT.EQ.1)WRITE(6,1)
      IF(IPVT.EQ.2)WRITE(6,2)
      IF(IPVT.EQ.3)WRITE(6,3)
    1 FORMAT(/,52X,'PSI',4X,'ACA',4X,'LCS',4X,'LCA')
    2 FORMAT(/,51X,'RUTS',3X,'RUTA',3X,'LCA',4X,'TCA',4X,'PATA')
    3 FORMAT(/,52X,'ACS',4X,'LCS',4X,'LCA',4X,'TCS')
      WRITE(6,200)(X(J),J=1,N1)
      WRITE(6,300)XN18,SCOR,XLIFE,NR,RMLIF,NMR
  200 FORMAT(49X,5(3X,F4.2))
  300 FORMAT(/,28X,'N18/MONTH = ',E15.7,8X,'PROB OF CLASSIF =',E15.7
     1   ,/,28X,'EST. LIFE = ',E15.7,1X,'N18',3X,I5,' MON',/,28X,
     2 'REMAINING LIFE(N18) =' ,E15.7,4X,'REMAINING LIFE (MON) =',I5)
      WRITE(6,211)
  211 FORMAT(//,40X,'PREDICTED CONDITION PER YR (NO REHAB) AFTER SERVICE
     1 LIFE :')
      IF(IPVT.EQ.1)WRITE(6,1)
      IF(IPVT.EQ.2)WRITE(6,2)
      IF(IPVT.EQ.3)WRITE(6,3)
      CALL REHAB(X,IPVT,N1,COST,OV)
      COST1=COST
      DO 19 II=1,5
      R(II)=RHO(II)
      B(II)=BETA(II)
```

```
   19 Y(II)=X(II)
      XN18=XN18/10.0**6
       MM=1
      XLIFE=XLIFE/10.0**6
       NR1=NR/12+0.5
      NN=5
      IF(IPVT.EQ.2)CALL REMLIF(MM)
      IF(IPVT.EQ.2)GO TO 21
       IF(OV.EQ.0.0)GO TO 20
      IF(IPVT.EQ.1.OR.IPVT.EQ.3)CALL OVLAY(MM,OV)
      CALL REMLIF(MM)
      GO TO 21
   20 NR=NRO
   21 IF(NR.LT.5)NN=NR
      XX=XN18/(1.+NM*RG)*12.0
      NRR=NR1+NN
      NR11=NR1+1
      RG=RG*12.
      IJ=0
      DO 30 M=NR11,NRR
      AC=XX*(M+M*(M-1)/2.*RG)
      CALL DAMAGE(AC,N1,RHP,BETAP,R,B,IPVT,XN18,Y,PSI)
      CALL REHAB(Y,IPVT,N1,COST,O)
      IJ=IJ+1
      WRITE(6,210)IJ,(Y(K),K=1,N1)
  210 FORMAT(/,45X,I2,2X,5(3X,F4.2))
      PSIJ(IJ)=PSI
   30 CST(IJ)=COST
      CALL MAINT(CMC)
C
C     CALCULATE PW(0)
C
      S=0.0
      DO 31 M=1,NR
      XMC=CMC(M)/((1.+XIN)**M)
   31 S=S+XMC
      PWO=COST1+S
C
C    CALCULATE PW(1)-PW(NN)
C
      DO 32 M=1,NN
      J=NR11
      SI(M)=0.0
      DO 33 II=1,M
      XMC=CMC(J)/((1.+XIN)**II)
      J=J+1
   33 SI(M)=SI(M)+XMC
      J=1
      SII(M)=0.0
      IF(M.LT.NN)I3=M+1
      IF(M.EQ.NN)GO TO 40
      DO 34 II=I3,NR
      XMC=CMC(J)/((1.+XIN)**J)*(XIN*(1.+XIN)**NR/((1.+XIN)**NR-1))
      SII(M)=SII(M)+XMC
   34 J=J+1
   40 PW(M)=(CST(M)*XIN*(1.+XIN)**NR/((1.+XIN)**NR-1)+SII(M))
     1      *((((1.+XIN)**(NR-M)-1)/(XIN*(1.+XIN)**(NR-M)))/(1.+XIN)
     2      **M+SI(M)
   32 CONTINUE
      NNN=NN+1
```

```
      J=1
      DO 37 M=2,NNN
      CSTT(M)=CST(J)
      PS(M)=PSIJ(J)
   37 J=J+1
      CSTT(1)=COST1
      PS(1)=PSII
      DO 36 M=1,NNN
C
C    BENEFIT COST ANALYSIS
C
C    FUEL BENEFITS
C
      F2=.015
      F1=0.0001879*(4.7-PS(M))/(0.043771-0.0001879*4.7)
      BF=(F2*NR/2.-(F2-F1)/2.*(NR-NR*F1/F2))*CG/GC*365*ADT*XLT/NR
C
C   TIME BENEFITS
C
      IF(SL.GT.35.0)SB=SL*(0.8613*PS(M)**0.0928)
      IF(SL.LE.35.0.AND.SL.GE.15.0)SB=SL*(0.8613*PS(M)**0.0928
     1   +((1-0.8613*PS(M)**0.0928)*(35.0-SL)/20.0))
      IF(SL.LT.15.0)SB=SL
      BT=(XLT/SB-XLT/SL)*ADT*365*VT
      FAC=((1.+XIN)**NR-1.0)/(XIN*(1.0+XIN)**NR)
      BT=BT*FAC
      BF=BF*FAC
C
C       OIL SAVINGS
C
      DOC=(2.2847-0.3188*PS(M)-0.85)*XTT(1)*OILC(1)
     1   +(1.261-0.0561*PS(M)-1.05)*(XTT(2)*OILC(2)+XTT(3)*OILC(3)
     2   +XTT(4)*OILC(4)+XTT(5)*OILC(5))
      DOC=DOC*365*CQO*XLT*FAC
C
C      TIRE WEAR SAVINGS
C
      CALL TABLE(PS(M),TF,TF1,ZMRS,ZMRS1,ZMRS2,DP,DP1,DP2)
      DTC=TF*4*CTR1*TIRC(1)*XTT(1)+TF1*(6*TIRC(2)*CTR2*XTT(2)
     1   +10*TIRC(3)*CTR3*XTT(3)+14*TIRC(4)*CTR3*XTT(4)
     2   +18*TIRC(5)*CTR3*XTT(5))
      DTC=DTC*365*XLT*FAC
C
C     VEHICLE MAINTENANCE AND REPAIR SAVINGS
C
      DCM=CMR1*ZMRS*XTT(1)*REP(1)+ZMRS1*(CMR2*XTT(2)*REP(2)+
     1    CMR3*XTT(3)*REP(3))+ZMRS2*(CMR4*XTT(4)*REP(4)+
     2    CMR5*XTT(5)*REP(5))
      DCM=DCM*365*XLT*FAC
C
C      DEPRECIATION SAVINGS
C
      DDP=DP*DEP(1)*VV1*XTT(1)+DP1*(DEP(2)*VV2*XTT(2)
     1   +DEP(3)*VV3*XTT(3))+DP2*(DEP(4)*VV4*XTT(4)
     2   +DEP(5)*VV5*XTT(5))
      DDP=DDP*365*XLT*FAC
C
C  BENEFITS DUE TO REDUCED MAINTENANCE
C
      J=M+NR1-1
```

```
      BM=0.0
      DO 35 II=1,NR
      J=J+1
      IF(J.EQ.30)J=30
   35 BM=BM+(CMC(J)-CMC(II))/((1.0+XIN)**II)
      BTT(M)=BT
      BFF(M)=BF
      BMM(M)=BM
      BO(M)=DOC
      BTR(M)=DTC
      BMR(M)=DCM
      BD(M)=DDP
   36 BC(M)=(BF+BT+BM+DOC+DTC+DCM+DDP)/CSTT(M)
      MM=0
      WRITE(6,55)NR
   55 FORMAT(//,58X,'COST ANALYSIS',//,50X,'ANALYSIS PERIOD =',
     1 I4,' YRS',//,8X,'YR',4X,'PRESENT',5X,'REHAB',7X,'PSI',
     2 4X,'FUEL',6X,'OIL',7X,'TIRE',6X,'REPAIR',4X,'DEPR'
     3 ,6X,'TIME',6X,'MAINTENANCE',3X,'SAVINGS')
      WRITE(6,56)
   56 FORMAT(14X,'WORTH',7X,'COST',14X,'SAVINGS',3X,
     1 'SAVINGS',3X,'SAVINGS',3X,'SAVINGS',3X,'SAVINGS',3X,
     2 'SAVINGS',3X,'SAVINGS',7X,'COST RATIO',/,15X,'(R + M)')
      WRITE(6,50)MM,PWO,CSTT(1),PS(1),BFF(1),BO(1),BTR(1),BMR(1)
     1     ,BD(1),BTT(1),BMM(1),BC(1)
   50 FORMAT(8X,I2,3X,F8.0,4X,F8.0,4X,F5.2,2X,F8.0,2X,
     1        F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,2X,F8.0,4X,F7.2)
      IF(NNN.LT.2)GO TO 11
      DO 51 II=2,NNN
      N4=II-1
   51 WRITE(6,50)N4,PW(N4),CSTT(II),PS(II),BFF(II),BO(II),BTR(II),BMR(II
     1 ),BD(II),BTT(II),BMM(II),BC(II)
      COST=0.0
   11 CONTINUE
      STOP
      END
C
C

      SUBROUTINE OVLAY(MM,OV)
C
C        THIS SUBROUTINE CALCULATES RHO AND BETA FOR PERFORMANCE
C        EQUATIONS FOR OVERLAID PAVEMENTS
C
      COMMON /PROP/ FLEXL,PI,AVT50,TI50,YLL,FTC,SNB
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      DIMENSION XI1(25),XJ1(25),XM11(5),XM21(5)
      DATA XI1/ 5.63243,1.01758,.461747,-1.09697,1.017580,1.916100,
     % -.152991,-.251418,.461747,-.152991,3.63527,-4.00867,-1.09697,
     & -.251418,-4.00867,6.50071,9*0.0/
      DATA XJ1/ 4.11354,.845663,.887592,.0887682,.845663,1.12764,
     % -.760766,1.18094,.887592,-.760766,4.77476,-3.85191,.0887682,
     & 1.18094,-3.85191,4.53873,9*0.0/
      DATA XM11/ 3.77664,.5625,.921875,.671875,1*0.0/
      DATA XM21/ 3.25770,.9375,1.125,1.375,1*0.0/
      IF(MM.EQ.1)GO TO 5
      READ(5,100)FLEXL,PI,YLL,AVT50,TI50,FTC,OVT,SNB
  100 FORMAT(8F10.0)
      WRITE(6,250)
```

```
  250 FORMAT(//,56X,'SECTION PROPERTIES')
      WRITE(6,200)FLEXL,YLL,OVT,AVT50,SNB,TI50,PI,FTC
  200 FORMAT(/,17X,'THICKNESS OF ORIGINAL SURFACE + OVERLAY',1X,F7.2,
     1 4X,'SUBGRADE LIQUID LIMIT',19X,F7.2,/,17X,'OVERLAY THICKNESS',
     2 23X,F7.2,4X,'MEAN TEMPERATURE - 50',19X,F7.2,/,17X,
     3 'STRUCTURAL NUMBER',23X,F7.2,4X,'THORNTHWAITE INDEX + 50',17X,
     4 F7.2,/,17X,'SUBGRADE PLASTICITY INDEX',15X,F7.2,4X,
     5 'AVERAGE FREEZE THAW CYCLES',14X,F7.2)
      GO TO 6
    5 FLEXL=FLEXL+OV
      OVT=OV
CC
C     PSI
C
    6 BETA(1)=1.00
      RHO(1)=.084*FLEXL-.0041*YLL+.065
      IF(RHO(1).LT.0.120)RHO(1)=.120
      IF(RHO(1).GT.1.4)RHO(1)=1.4
C
C      ALLIGATOR CRACKING AREA
C
      RHO(2)=3.26*SNB+.33*AVT50-10.93
      BETA(2)=1.86
      IF(RHO(2).LT.0.12)RHO(2)=.12
      IF(RHO(2).GT.1.7000)RHO(2)=1.7000
C
C       LONGITUDINAL CRACKING SEVERITY
C
      RHO(3)=.47*SNB+.21*AVT50-3.1
      BETA(3)=.54*SNB+.059*TI50-.092*PI-.19
      IF(RHO(3).LT.0.12)RHO(3)=.12
      IF(RHO(3).GT.1.7500)RHO(3)=1.7500
      IF(BETA(3).LT.0.61)BETA(3)=.61
      IF(BETA(3).GT.3.1900)BETA(3)=3.1900
C
C      LONGITUDINAL CRACKING AREA
C
      RHO(4)=.39*SNB-.034*TI50+.35*AVT50-2.78
      BETA(4)=.22*SNB+.036*TI50-.053*PI+.41
      IF(RHO(4).LT.0.10)RHO(4)=.10
      IF(RHO(4).GT.1.8000)RHO(4)=1.8000
      IF(BETA(4).LT.0.74)BETA(4)=.74
      IF(BETA(4).GT.2.21)BETA(4)=2.21
C
      DO 1 I=1,4
      IF(ICOM.EQ.0)RHO(I)=.18275+0.787086*RHO(I)
      IF(ICOM.EQ.1)RHO(I)=.130989+0.372461*RHO(I)
    1 CONTINUE
      IF(MM.EQ.1)GO TO 111
      RHP=RHO(1)
      BETAP=BETA(1)
  111 N1=4
      N2=16
      CALL EQX(XI1,XJ1,XM11,XM21)
      CALL OVRL(MM)
      RETURN
      END
C
C
```

```
      SUBROUTINE STREAT
C
C       THIS SUBROUTINE CALCULATES RHO AND BETA FOR
C       SURFACE TREATED PAVEMENTS
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      DIMENSION XI2(25),XJ2(25),XM12(5),XM22(5)
      DATA XI2/ 11.0724,-1.65675,-.839039,.884178,-1.59906,-1.65675,
     1 3.13376,.248454,-.705718,.374911,-.839039,.248454,3.92245,
     2 -1.18322,-.0064125,.884178,-.705718,-1.18322,4.16391,
     3 -.249918,-1.59906,.374911,-.0064125,-.249918,1.2767/
      DATA XJ2/ 3.20761,-1.31988,-.254131,.16609,.0287696,-1.31988,
     1 2.30474,.499743,.0769393,-.138614,-.254131,.499743,2.01727,
     2 -.344275,-.134904,.16609,.0769393,-.344275,1.1852,.0103449,
     3 .0287696,-.138614,-.134904,.0103449,.780667/
      DATA XM12/ 1.01299,1.66234,.350649,.25974,.766234/
      DATA XM22/ 1.14286,1.42857,.642857,.678571,1.44643/
      N1=5
      N2=25
      READ(5,100)FLEXL,PI,YLL,AVT50,TI50,FTC,DMD
  100 FORMAT(7F10.0)
      WRITE(6,200)FLEXL,TI50,PI,FTC,YLL,DMD,AVT50
  200 FORMAT(//,56X,'SECTION PROPERTIES',//,28X,'THICKNESS OF FLEXIBLE
     1BASE',F7.2,4X,'THORNTHWAITE INDEX + 50',3X,F7.2,/,28X,'SUBGRADE PL
     2ASTICITY INDEX',2X,F7.2,4X,'AVERAGE FREEZE THAW CYCLES',F7.2,/,
     328X,'SUBGRADE LIQUID LIMIT',6X,F7.2,4X,'DYNAFLECT MAX DEFLECTION'
     4,2X,F7.2,/,28X,'MEAN TEMPERATURE - 50',6X,F7.2)
C
C     RUT SEV
      RHO(1) = -0.0678 + 0.0032*AVT50 + 0.00566*FLEXL - 0.00031*YLL
     & + 0.00048*FTC
      BETA(1) = 1.780
C
      IF( RHO(1) .GT. 0.121 ) RHO(1) = 0.121
      IF( RHO(1) .LT. 0.0027 ) RHO(1) = 0.0027
C
C     IF( BETA .GT. 5.94 ) BETA = 5.94
C     IF( BETA .LT. 0.527 ) BETA = 0.527
C
C
C     RUT AREA
      RHO(2) = -0.1035 + 0.00549*AVT50 + 0.0067*FLEXL - 0.0015*YLL
     & + 0.00162*PI + 0.00077*FTC
      BETA(2) = 1.540 + 0.0169*TI50 - 0.072*FLEXL
C
      IF( RHO(2) .GT. 0.117 ) RHO(2) = 0.117
      IF( RHO(2) .LT. 0.0036 ) RHO(2) = 0.0036
C
      IF( BETA(2) .GT. 6.27 ) BETA(2) = 6.27
      IF( BETA(2) .LT. 0.615 ) BETA(2) = 0.615
C
C
C     LONG AREA
C
      RHO(3) = -63.1 + 4.52*AVT50 + 0.541*TI50 + 7.41*FLEXL + 1.1145*FTC
      BETA(3) = 1.15
C
      IF( RHO(3) .GT. 172.0 ) RHO(3) = 172.0
      IF( RHO(3) .LT. 30.0 ) RHO(3) = 30.0
```

```
C
C       IF( BETA .GT. 2.65 ) BETA = 2.65
C       IF( BETA .LT. 0.68 ) BETA = 0.68
C
C
C       TRANS AREA
C
        RHO(4) = -66.4 + 2.156*TI50 + 10.12*FLEXL + 0.718*FTC
        BETA(4)= 2.059 + 0.0734*FLEXL - 0.06*YLL + 0.0607*PI - 0.00375*FTC
        IF( RHO(4) .GT. 176.0 ) RHO(4) = 176.0
        IF( RHO(4) .LT. 41.0 ) RHO(4) = 41.0
C
        IF( BETA(4) .GT. 2.65 ) BETA(4) = 2.65
        IF( BETA(4) .LT. 0.61 ) BETA(4) = 0.61
C
C
C       PATCHING
C
        RHO(5) = 0.00799 + 0.00252*AVT50 + 0.000218*TI50 + 0.00166*FLEXL
       1      - 0.00125*PI
        BETA(5) = 1.75
C
        IF( RHO(5) .GT. 0.104 ) RHO(5) = 0.104
        IF( RHO(5) .LT. 0.0036 ) RHO(5) = 0.0036
C
C       IF( BETA .GT. 5.36 ) BETA = 5.36
C       IF( BETA .LT. 0.63 ) BETA = 0.63
C
        CALL TRAFIC
        RHP=-0.173+0.00687*AVT50-0.000632*TI50+0.0133*FLEXL
       1    +0.00075*YLL+0.00153*FTC-0.0214*DMD
        IF(RHP.GT.0.511)RHP=0.511
        IF(RHP.LT.0.0009)RHP=0.0009
        BETAP=1.0
        CALL EQX(XI2,XJ2,XM12,XM22)
        CALL SURTR
        RETURN
        END
C
C

        SUBROUTINE HOTMX
C
C        THIS SUBROUTINE CALCULATES RHO AND BETA FOR
C        ASPHALT CONCRETE PAVEMENTS
C
        COMMON /PROP/ FLEXL,PI,AVT50,TI50,YLL,FTC,SNB
        COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
       %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
        DIMENSION XI3(25),XJ3(25),XM13(5),XM23(5)
        DATA XI3/ 1.46568,.427721,-.366242,-.662588,.427721,7.2861,
       1 -6.83016,-2.99698,-.366242,-6.83016,10.8184,.987962,-.662588,
       2 -2.99698,.987962,3.19869,9*0.0/
        DATA XJ3/ 1.08876,-1.32544,.307692,-.497041,-1.32544,15.5266,
       1 -10.4615,1.82249,.307692,-10.4615,8.0,-.923077,-.497041,
       2 1.82249,-.923077,1.18343,9*0.0/
        DATA XM13/ .631579,.843105,.539474,.828947,1*0.0/
        DATA XM23/ 2.2,1.0,1.2,1.8,1*0.0/
        N1=4
        N2=16
```

```
      READ(5,100)FLEXL,PI,AVT50,TI50,FTC,SNB,YLL,BASE
  100 FORMAT(8F10.0)
      WRITE (6,250)
  250 FORMAT(//,56X,'SECTION PROPERTIES')
      WRITE(6,200)FLEXL,YLL,BASE,AVT50,SNB,TI50,PI,FTC
  200 FORMAT(/,25X,'THICKNESS OF ASPHALT CONCRETE',F7.2,4X,'SUBGRADE LIQ
     1UID LIMIT',8X,F7.2,/,25X,'THICKNESS OF BASE',12X,F7.2,4X,'MEAN TEM
     2PERATURE - 50',8X,F7.2,/,25X,'STRUCTURAL NUMBER',12X,F7.2,4X,
     3'THORNTHWAITE INDEX + 50',6X,F7.2,/,25X,'SUBGRADE PLASTICITY INDEX
     4',4X,F7.2,4X,'AVERAGE FREEZE THAW CYCLES',3X,F7.2)
C
C      ALLIGATOR CRACKING SEVERITY
C
      RHO(1)=.38*SNB-.0044*AVT50-.1*FLEXL-.25
      BETA(1)=-.02*TI50+1.27*FLEXL-.09*PI+2.38
      IF(RHO(1).LT.0.45)RHO(1)=.45
      IF(RHO(1).GT.0.78)RHO(1)=.78
      IF(BETA(1).LT.1.00)BETA(1)=1.0
      IF(BETA(1).GT.8.1500)BETA(1)=8.1500
C
C      LONG SEV
C
      RHO(2)=.13*SNB-.038*AVT50-.0037*FTC+.16*FLEXL+.012*PI+.27
      BETA(2)=.84*SNB-.17*PI-.35*FLEXL+4.58
      IF(RHO(2).LT.0.25)RHO(2)=.25
      IF(RHO(2).GT.1.12)RHO(2)=1.12
      IF(BETA(2).LT.1.0)BETA(2)=1.0
      IF(BETA(2).GT.8.1000)BETA(2)=8.1000
C
C      LONG AREA
C
      RHO(3)=-.26*AVT50+.53*FLEXL-.033*FTC+4.45
      BETA(3)=.13*SNB+.38*AVT50+.067*FTC-.14*PI-3.67
      IF(RHO(3).LT.0.23)RHO(3)=.23
      IF(RHO(3).GT.1.51)RHO(3)=1.51
      IF(BETA(3).LT.0.76)BETA(3)=.76
      IF(BETA(3).GT.4.2300)BETA(3)=4.2300
C
C      TRANS SEV
C
      RHO(4)=-.094*AVT50+.17*FLEXL-.0088*FTC+.01*PI+1.4
      BETA(4)=3.2800
      IF(RHO(4).LT.0.20)RHO(4)=.20
      IF(RHO(4).GT.1.0627)RHO(4)=1.0627
      DO 1 I=1,4
    1 RHO(I)=0.2016+1.487457*RHO(I)
      RHP=3.51+0.0092*SNB-0.0042*TI50+0.014*BASE-0.023*FTC
     1      +0.0026*PI-0.18*AVT50
      IF(RHP.GT.0.98)RHP=0.98
      IF(RHP.LT.0.0063)RHP=0.0063
      BETAP=2.06
      CALL EQX(XI3,XJ3,XM13,XM23)
      CALL HOTM
      RETURN
      END
C
C

      SUBROUTINE OVRL(MM)
C
```

```
C        THIS SUBROUTINE CALCULATES N18'S FOR G(W) VALUES OF
C        0.165 ,0.33 ,0.50 FOR OVERLAID PAVEMENTS , ORDERS THEM
C        AND FORM CONDITION DATA FOR EVALUATIONS WITH THE
C        DISCRIMINANT FUNCTION . RETURNS SERVICE LIFE (XLIFE).
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      COMMON /REM/ NM,RG,RMLIF,NMR,NR,LP
      XQ=0.0
      XP=0.0
      P1=4.5
      PF=2.7
      M=1
      IF(MM.EQ.0)CALL TRAFIC
      DO 1 J=1,3
      XQ=XQ+0.165
      XP=XP+0.28
C
C         PSI
C
      XN(M,1)=RHO(1)/(-1.*ALOG(XP))**(1./BETA(1))
C
C        ACA
C
      XN(M+1,1)=RHO(2)/(-1.*ALOG(XQ))**(1./BETA(2))
C
C        LCS
C
      XN(M+2,1)=RHO(3)/(-1.*ALOG(XQ))**(1./BETA(3))
C
C        LCA
C
      XN(M+3,1)=RHO(4)/(-1.*ALOG(XQ))**(1./BETA(4))
    1 M=M+4
      DO 6 I=1,12
    6 XN(I,2)=0.0
      CALL ORDER
      DO 2 I=1,12
      X(1)=P1-(P1-PF)*EXP(-1.*((RHO(1)/XN(I,1))**BETA(1)))
      DO 7 KK=2,4
    7 X(KK)=EXP(-1.*((RHO(KK)/XN(I,1))**BETA(KK)))
      DO 3 J=2,4
      IF(X(J).LE.0.1649)GO TO 101
      IF(X(J).LE.0.329)GO TO 102
      IF(X(J).LE.0.499)GO TO 103
      X(J)=3.0
      GO TO 3
  101 X(J)=0.0
      GO TO 3
  102 X(J)=1.0
      GO TO 3
  103 X(J)=2.0
    3 CONTINUE
      II=I
      S=0.0
      DO 8 J=2,4
      S=S+X(J)
    8 CONTINUE
      ISS=0
      IF(X(1).LT.3.0)ISS=1
```

```
      DO 9 J=2,4
      IS=0
      IF(X(J).EQ.3.0)IS=1
      ISS=ISS+IS
    9 CONTINUE
      CALL SCORE
      IF(SCOR.GE.0.700.AND.S.GE.3.0)GO TO 5
      IF(ISS.GE.2)GO TO 5
    2 CONTINUE
    5 XLIFE=XN(II,1)
      IF(MM.EQ.0)PSII=X(1)
      RETURN
      END
C
C
      SUBROUTINE SURTR
C
C       EQUIVALENT TO OVRL BUT FOR SURFACE TREATED PAVEMENTS
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      COMMON /REM/ NM,RG,RMLIF,NMR,NR,LP
      XQ=0.0
      M=1
      DO 1 J=1,3
      XQ=XQ+.165
C
C
C      RUTS
C
      XN(M,1)=RHO(1)/(-1.*ALOG(XQ))**(1./BETA(1))
      XN(M,2)=XN(M,1)/XN18
C
C      RUTA
C
      XN(M+1,1)=RHO(2)/(-1.*ALOG(XQ))**(1./BETA(2))
      XN(M+1,2)=XN(M+1,1)/XN18
C
C      LCA
C
      XN(M+2,2)=RHO(3)/(-1.*ALOG(XQ))**(1./BETA(3))
      XN(M+2,1)=XN(M+2,2)*XN18
C
C      TCA
C
      XN(M+3,2)=RHO(4)/(-1.*ALOG(XQ))**(1./BETA(4))
      XN(M+3,1)=XN(M+3,2)*XN18
C
C      PATA
C
      XN(M+4,1)=RHO(5)/(-1.*ALOG(XQ))**(1./BETA(5))
      XN(M+4,2)=XN(M+4,1)/XN18
    1 M=M+5
      CALL ORDER
      DO 2 I=1,15
      X(1)=EXP(-1.*((RHO(1)/XN(I,1))**BETA(1)))
      X(2)=EXP(-1.*((RHO(2)/XN(I,1))**BETA(2)))
      X(3)=EXP(-1.*((RHO(3)/XN(I,2))**BETA(3)))
      X(4)=EXP(-1.*((RHO(4)/XN(I,2))**BETA(4)))
```

```
      X(5)=EXP(-1.*((RHO(5)/XN(I,1))**BETA(5)))
      DO 3 J=1,5
      IF(X(J).LE.0.1649)GO TO 101
      IF(X(J).LE.0.329)GO TO 102
      IF(X(J).LE.0.499)GO TO 103
      X(J)=3.0
      GO TO 3
  101 X(J)=0.0
      GO TO 3
  102 X(J)=1.0
      GO TO 3
  103 X(J)=2.0
    3 CONTINUE
      II=I
      S=0.0
      DO 8 J=1,5
    8 S=S+X(J)
      ISS=0
      DO 9 J=1,5
      IS=0
      IF(X(J).EQ.3.0)IS=1
      ISS=ISS+IS
    9 CONTINUE
      CALL SCORE
      IF(SCOR.GE.0.800.AND.S.GE.3.0)GO TO 5
      IF(ISS.GE.2)GO TO 5
    2 CONTINUE
    5 XLIFE=XN(II,1)
      PSII=4.2-(4.2-0.83)*EXP(-1.*((RHP/XLIFE)**BETAP))
      RETURN
      END
C
C

      SUBROUTINE HOTM
C
C      EQUIVALENT TO OVRL BUT FOR ASPHALT CONCRETE PAVEMENTS
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      COMMON /REM/ NM,RG,RMLIF,NMR,NR,LP
      XQ=0.0
      M=1
      CALL TRAFIC
      DO 1 J=1,3
      XQ=XQ+.165
C
C       ACS
C
      XN(M,1)=RHO(1)/(-1.*ALOG(XQ))**(1./BETA(1))
C
C       LCS
C
      XN(M+1,1)=RHO(2)/(-1.*ALOG(XQ))**(1./BETA(2))
C
C      LCA
C
      XN(M+2,1)=RHO(3)/(-1.*ALOG(XQ))**(1./BETA(3))
C
C       TCS
```

```
C
      XN(M+3,1)=RHO(4)/(-1.*ALOG(XQ))**(1./BETA(4))
    1 M=M+4
      DO 6 I=1,12
    6 XN(I,2)=0.0
      CALL ORDER
      DO 2 I=1,12
      DO 7 KK=1,4
    7 X(KK)=EXP(-1.*((RHO(KK)/XN(I,1))**BETA(KK)))
      DO 3 J=1,4
      IF(X(J).LE.0.1649)GO TO 101
      IF(X(J).LE.0.329)GO TO 102
      IF(X(J).LE.0.499)GO TO 103
      X(J)=3.0
      GO TO 3
  101 X(J)=0.0
      GO TO 3
  102 X(J)=1.0
      GO TO 3
  103 X(J)=2.0
    3 CONTINUE
      II=I
      S=0.0
      DO 8 J=1,4
    8 S=S+X(J)
      ISS=0
      DO 9 J=1,4
      IS=0
      IF(X(J).EQ.3.0)IS=1
      ISS=ISS+IS
    9 CONTINUE
      CALL SCORE
      IF(SCOR.GE.0.700.AND.S.GE.3.0)GO TO 5
      IF(ISS.GE.2)GO TO 5
    2 CONTINUE
    5 XLIFE=XN(II,1)
      PSII=4.7-(4.7-2.06)*EXP(-1.*((RHP/XLIFE)**BETAP))
      RETURN
      END

      SUBROUTINE ORDER
C       THIS SUBROUTINE ORDERS A SEQUENCE OF N18 VALUES
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      DIMENSION XL(2)
      N=N1+3
      DO 8 I=1,N
      CALL XMAX(N-I+1,J,XL)
      DO 8 K=1,2
      XN(J,K)=XN(N-I+1,K)
    8 XN(N-I+1,K)=XL(K)
      RETURN
      END
C
C

      SUBROUTINE XMAX(N,J,XL)
C
C          THIS ROUTINE FINDS A MAXIMUM VALUE
```

```
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      DIMENSION XL(2)
      XL(1)=XN(1,1)
      J=1
      IF(N.EQ.1)GO TO 7
      DO 6 I=2,N
      IF(XN(I,1).LE.XL(1))GO TO 6
      XL(1)=XN(I,1)
      XL(2)=XN(I,2)
      J=I
    6 CONTINUE
    7 RETURN
      END
C
C

      SUBROUTINE SCORE
C
C      THIS ROUTINE PERFORMS DISCRIMINANT FUNCTION EVALUATION
C      D(X)=(X-XBAR)'Y(X-XBAR)+LN(DET Y)-2LN(PRIOR)
C      P(X/J)=EXP(-.5D(J))/SUM(K) EXP(-.5D(K))
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      DIMENSION Y(5),CONST(3),CONST1(3),X1(5),X2(5)
      CONST(1)=-3.77687
      CONST1(1)=0.47005
      CONST(2)=-5.04973
      CONST1(2)=-0.47177
      CONST(3)=-3.76657
      CONST1(3)=3.34623
      DO 2 J=1,N1
      Y(J)=X(J)
      X(J)=X(J)-XM1(J)
    2 Y(J)=Y(J)-XM2(J)
      J1=1
      DO 3 J=1,N1
      X1(J)=0.0
      X2(J)=0.0
      DO 4 K=1,N1
      X1(J)=X(K)*XI(J1)+X1(J)
      X2(J)=Y(K)*XJ(J1)+X2(J)
    4 J1=J1+1
    3 CONTINUE
      XK=0.0
      XL=0.0
      DO 5 J=1,N1
      XK=XK+X1(J)*X(J)
    5 XL=XL+X2(J)*Y(J)
      XK=XK+CONST(IPVT)
      XL=XL+CONST1(IPVT)
      SCOR=EXP(-.5*XL)/(EXP(-.5*XL)+EXP(-.5*XK))
      DO 10 I=1,N1
      X(I)=X(I)+XM1(I)
   10 CONTINUE
      RETURN
      END
C
```

```
C
      SUBROUTINE TRAFIC
C
C       THIS ROUTINE CALCULATES MONTHLY N18'S USING TRUCK
C       DISTRIBUTION INFORMATION FROM W-4 AND W-5 TABLES
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
C
      REAL NSING, NTAND, NSINGL, NTANDM,N18SIN, N18TAN, NTRUKS
C
      DIMENSION DISTSN(10,13), DISTAN(10,16), ESING(13), ETAND(16),
     + NSING(13), NTAND(16), NSINGL(10), NTANDM(10), PERCNT(10),
     * SINGLE(10), TANDEM(10), TTYPE(10)
C
      DATA DISTSN / 6.0,9*0.0,64.0,20.0,13.0,9.0,2.0,8.0,0.0,3*22.0,
     + 9.0,6.0,10.0,8.0,7.0,5.0,0.0,3*22.0,11.0,61.0,36.0,46.0,88.0,
     * 31.0,44.0,3*34.0,4.0,12.0,23.0,14.0,3.0,25.0,34.0,3*22.0,3.0,
     & 1.0,12.0,8.0,0.0,12.0,16.0,3*0.0,1.0,2*0.0,2.0,0.0,3.0,4*0.0,
     ) 1.0,0.0,2.0,6.0,0.0,8.0,6.0,3*0.0,1.0,0.0,2.0,3.0,0.0,5.0,4*0.0,
     ( 2*0.0,2.0,4.0,0.0,2.0,4*0.0,5*0.0,1.0,4*0.0,10*0.0,10*0.0 /
C
C
      DATA DISTAN / 10*0.0,0.0,18.0,0.0,16.0,12.0,0.0,25.0,3*0.0,0.0,
     + 21.0,0.0,35.0,16.0,0.0,50.0,0.0,33.0,33.0,0.0,15.0,0.0,30.0,
     = 13.,0.,25.,3*0.,0.,12.,0.,13.,19.,0.,0.,0.,67.,67.,0.,5.,0.,
     * 1.,10.,5*0.,0.,3.,0.,1.,3.,5*0.,0.,1.,0.,3.,7.,5*0.,0.,10.,
     & 0.,0.,9.,5*0.,0.,5.,0.,0.,5.,5*0.,0.,3.,0.,0.,3.,5*0.,0.,2.,
     ) 0.,1.,2.,5*0.,0.,2.,0.,0.,1.,5*0.,0.,2.,8*0.,0.,1.,8*0.,10*0./
C
C
      DATA ESING / 0.0,0.005,0.025,0.07,0.32,0.795,1.0,1.285,1.98,
     + 2.67,3.71,6.085,0.0 /
C
      DATA ETAND / 0.0,0.003,0.03,0.11,0.36,0.67,0.76,0.87,1.14,1.47,
     + 1.875,2.435,3.12,3.86,5.13,0.0 /
C
      DATA SINGLE / 2.0,1.0,3.0,2.0,1.0,5.0,2.0,3.0,2.0,1.0 /
      DATA TANDEM /0.0,1.0,0.0,1.0,2.0,0.0,2.0,0.0,1.0,2.0 /
C
      DATA PERCNT / 14.0,4.0,1.0,5.0,68.0,2.0,0.0,3*2.0 /
C
C
      NTYP = 10
C
C
C
      ADT = ADT * (PCTLNE/100.0)
      NTRUKS = ADT * 365.0 * (PCTTRK/100.0)
C
      DO 10 I = 1, NTYP
      TTYPE(I) = PERCNT(I) * NTRUKS * 0.01
      NSINGL(I) = TTYPE(I) * SINGLE(I)
      NTANDM(I) = TTYPE(I) * TANDEM(I)
   10 CONTINUE
C
C
      DO 14 J = 1, 13
   14 NSING(J) = 0.0
```

```
C
      DO 15 J = 1, 16
   15 NTAND(J) = 0.0
C
C
      DO 30 K = 1, 10
      DO 20 J = 1, 13
   20 NSING(J) = NSING(J) + NSINGL(K)*DISTSN(K,J)/100.0
   30 CONTINUE
C
C
      DO 50 K = 1, 10
      DO 40 J = 1, 16
   40 NTAND(J) = NTAND(J) + NTANDM(K)*DISTAN(K,J)/100.0
   50 CONTINUE
C
C
      N18SIN = 0.0
C
      DO 60 J = 1, 13
   60 N18SIN = N18SIN + NSING(J) * ESING(J)
C
C
      N18TAN = 0.0
      DO 70 J = 1, 16
   70 N18TAN = N18TAN + NTAND(J) * ETAND(J)
C
      XN18 = N18SIN + N18TAN
C
      XN18=XN18/12.0/1000000.
      RETURN
      END

      SUBROUTINE EQX(YI,YJ,YM1,YM2)
C
C      THIS ROUTINE RENAMES VECTORS FOR DISCRIMINANT ANALYSIS
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      DIMENSION YI(25),YJ(25),YM1(5),YM2(5)
      DO 1 I=1,25
      XI(I)=YI(I)
    1 XJ(I)=YJ(I)
      DO 2 I=1,5
      XM1(I)=YM1(I)
    2 XM2(I)=YM2(I)
      RETURN
      END

      SUBROUTINE REHAB(X,IPVT,N1,COST,OV)
C
C      THIS ROUTINE SELECTS REHAB ALTERNATIVES BASED UPON
C      LEVELS OF SERVICEABILITY/DISTRESS
C
      COMMON /CS/XIN,CJ,CK,CE,CL,CP,CC1,CC2,CC3,XLT,NL,IHT,ITF
      DIMENSION X(5),C(5)
      DA=0.4166
      CA=1.2*CJ
      DO 20 I=1,5
   20 C(I)=0.0
```

```
      IF(ITF.EQ.1)XLN1=NL+0.67
      IF(ITF.EQ.2)XLN1=NL+1.33
      IF(ITF.EQ.3)XLN1=NL+2.33
      IF(IPVT.EQ.1)GO TO 1
      IF(IPVT.EQ.2)GO TO 2
      IF(IPVT.EQ.3)GO TO 3
    3 IF(X(1).LT.1.1)C(1)=CP*XLT*NL
      IF(X(1).GT.1.1.AND.X(1).LT.2.1)C(1)=XLT*XLN1*CJ*1.2+XLT*NL*.05*CE*
     1 1.2
      IF(X(1).GT.2.1)C(1)=XLT*XLN1*DA/0.10*CA*1.2
      IF(X(1).LT.0.9)C(1)=0.0
      DO 10 I=2,4
      IF(X(I).LT.1.1)C(I)=0.0
      IF(X(I).GT.1.1.AND.X(I).LT.2.1)C(I)=CP*XLT*NL
      IF(X(I).GT.2.1)C(I)=XLT*NL*CK*1.2
   10 CONTINUE
      OV=0.0
      IF(X(1).GT.1.1.AND.X(1).LT.2.1)OV=1.0
      IF(X(1).GT.2.1)OV=5.0
      GO TO 4
    1 IF(X(1).LE.2.9)C(1)=XLT*XLN1*1.3*CJ*1.20
      IF(X(1).GT.2.9)C(1)=0.0
      IF(X(2).GT.0.1.AND.X(2).LT.1.1)C(2)=CP*XLT*NL
      IF(X(2).GT.1.1.AND.X(2).LT.2.1)C(2)=XLT*XLN1*CJ*1.2+XLT*NL*.05*CE*
     1 1.2
      IF(X(2).GT.2.1)C(2)=XLT*XLN1*DA/0.1*CA*1.2
      IF(X(2).LT.0.1)C(2)=0.0
      DO 11 I=3,4
      IF(X(I).LT.1.1)C(I)=0.0
      IF(X(I).GT.1.1.AND.X(I).LT.2.1)C(I)=CP*XLT*NL
      IF(X(I).GT.2.1)C(I)=XLT*NL*CK*1.2
   11 CONTINUE
      OV=0.0
      IF(X(2).GT.1.1.AND.X(2).LT.2.1)OV=1.0
      IF(X(1).LE.2.9)OV=1.2
      IF(X(2).GT.2.1)OV=5.0
      GO TO 4
    2 DO 12 I=1,2
      IF(X(I).LT.0.9)C(I)=0.0
      IF(X(I).GT.0.1.AND.X(I).LT.1.1)C(I)=XLT*NL*CL*1.2
      IF(X(I).GT.1.1.AND.X(I).LT.2.1)C(I)=1.7*XLT*NL*CL*1.2
      IF(X(I).GT.2.1)C(I)=4.0*XLT*NL*CL*1.2
   12 CONTINUE
      DO 13 I=3,4
      IF(X(I).LT.2.0)C(I)=0.0
      IF(X(I).GE.2.0)C(I)=CP*XLT*NL*1.2
   13 CONTINUE
      IF(X(5).LT.2.0)C(5)=0.0
      IF(X(5).GT.1.1.AND.X(5).LT.2.1)C(5)=XLT*NL*CL*1.2
      IF(X(5).GT.2.1)C(5)=1.7*XLT*NL*CL*1.2
      OV=0.0
    4 COST=C(1)
      DO 8 I=2,N1
      IF(C(I).GT.COST)COST=C(I)
    8 CONTINUE
      RETURN
      END

      SUBROUTINE REMLIF(MM)
C
```

```
C
C       THIS ROUTINE TRANSLATES SERVICE LIFE AND REMAINING LIFE
C       TO MONTHS
C
      COMMON/ALL/ICOM,IPVT,RHO(5),BETA(5),XN(15,2),X(5),XI(25),XJ(25),PS
     %II,RHP,BETAP,XM1(5),XM2(5),SCOR,XLIFE,N1,N2,XN18,PCTTRK,PCTLNE,ADT
      COMMON /REM/ NM,RG,RMLIF,NMR,NR,LP
      IF(MM.EQ.1)GO TO 20
      X0=XN18/(1.+NM*RG)
      DO 3 I=1,360
      AC=X0*(I+(I*(I-1))/2.*RG)
      IF(AC.GE.XLIFE)GO TO 4
      GO TO 3
    4 NR=I
      GO TO 5
    3 CONTINUE
    5 CONTINUE
      ACCL=X0*(NM+(NM*(NM-1))/2.*RG)
      RMLIF=XLIFE-ACCL
      NMR=0
      IF(RMLIF.LE.0.0)RMLIF=0.0
      IF(RMLIF.EQ.0.0)GO TO 12
      DO 10 I=2,360
      AC=XN18*(I+(I*(I-1))/2.*RG)
      IF(AC.GE.RMLIF)GO TO 11
      GO TO 10
   11 NMR=I
      GO TO 12
   10 CONTINUE
      GO TO 12
   20 XX=XN18/(1.+NM*RG)*(1.+NR*RG)
      DO 21 I=1,360
      AC=XX*(I+(I*(I-1))/2.*RG/12.)
      IF(AC.GE.XLIFE)GO TO 22
      GO TO 21
   22 NR=I
      NR=NR/12.+.5
      RETURN
   21 CONTINUE
   12 RETURN
      END

      SUBROUTINE DAMAGE(AC,N1,RHP,BETAP,RHO,BETA,IPVT,XN18,Y,PSI)
C
C       THIS ROUTINE PREDICTS THE PAVEMENT CONDITION WHEN
C       REHABILITATION IS DELAYED
C
      DIMENSION RHO(5),BETA(5),Y(5),P1(3),PF(3)
      P1(1)=4.5
      P1(2)=4.2
      P1(3)=4.7
      PF(1)=2.7
      PF(2)=0.83
      PF(3)=2.06
      J=1
      IF(IPVT.EQ.1)J=2
      DO 1 I=J,N1
      A=AC
      IF(IPVT.EQ.2.AND.I.EQ.3)A=AC/XN18
      IF(IPVT.EQ.2.AND.I.EQ.4)A=AC/XN18
    1 Y(I)=EXP(-1.0*((RHO(I)/A)**BETA(I)))
```

```
      PSI=P1(IPVT)-(P1(IPVT)-PF(IPVT))*EXP(-1.0*((RHP/A)**BETAP))
      IF(IPVT.EQ.1)Y(1)=PSI
      DO 2 I=J,N1
      IF(Y(I).LE.0.1649)GO TO 101
      IF(Y(I).LE.0.329)GO TO 102
      IF(Y(I).LE.0.499)GO TO 103
      Y(I)=3.0
      GO TO 2
  101 Y(I)=0.0
      GO TO 2
  102 Y(I)=1.0
      GO TO 2
  103 Y(I)=2.0
    2 CONTINUE
      RETURN
      END

      SUBROUTINE MAINT(CMC)
C
C      THIS ROUTINE CALCULATES EAROMAR MAINTENANCE COSTS
C      FOR PAVEMENT AGES (1-30 YRS)
C
      COMMON /CS/XIN,CJ,CK,CE,CL,CP,CC1,CC2,CC3,XLT,NL,IHT,ITF
      DIMENSION CMC(30)
      IF(IHT.EQ.1)CC=1.0
      IF(IHT.EQ.2)CC=0.316
      IF(IHT.EQ.3)CC=.382
      DO 1 I=1,30
      CMC(I)=CC*((1100*CC1+1000*CC2+5*CC3)/(1.0+EXP(-1.0*(I-10)/1.16)))
    1 CMC(I)=CMC(I)*NL
      RETURN
      END
C

      SUBROUTINE OILCON(SL,OILC)
C
C      OIL CONSUMPTION FOR A GIVEN SPEED
C
      DIMENSION OILC(5),X51(44)
      DATA X51/3.8,6.5,9.6,19.6,2.4,4.1,6.2,12.7,1.8,3.4,4.9,10.1,
     1        1.6,3.0,4.4,9.0,1.5,2.8,4.1,8.3,1.4,2.7,3.8,7.7,
     2        1.4,2.5,3.6,7.2,1.4,2.3,3.4,6.5,1.4,2.1,3.1,5.7,
     3        1.3,2.0,3.0,5.0,1.2,2.1,3.2,5.2/
      ISL=SL/5*4-3
      OILC(1)=X51(ISL)/1000.0
      OILC(2)=X51(ISL+1)/1000.0
      OILC(3)=X51(ISL+2)/1000.0
      OILC(4)=OILC(3)
      OILC(5)=X51(ISL+3)/1000.0
      RETURN
      END
C

      SUBROUTINE TIRCON(S,T)
C
C      TIRE WEAR FOR A GIVEN SPEED
C
      DIMENSION T(5),X52(55)
      DATA X52/.08,.08,.09,.11,.13,.16,.20,.26,.32,.41,.51,
     1          .10,.12,.14,.18,.22,.28,.36,.46,.57,.72,.90,
```

```
     2          .10,.11,.13,.15,.18,.21,.25,.29,.34,.40,.47,
     3          .09,.09,.10,.12,.14,.16,.19,.23,.27,.33,.40,
     4          .12,.12,.13,.15,.16,.18,.21,.23,.27,.31,.36/
      I=S/5
      T(1)=X52(I)/100.0/1000.0
      T(2)=X52(I+11)/1000.0/100.0
      T(3)=X52(I+22)/100.0/1000.0
      T(4)=X52(I+33)/100.0/1000.0
      T(5)=X52(I+44)/100.0/1000.0
      RETURN
      END
C
      SUBROUTINE DEPCON(S,D)
C
C      DEPRECIATION CHARGE FOR GIVEN SPEED
C
      DIMENSION D(5),X53(44)
      DATA X53/1.22,1.03,.93,.85,.79,.73,.66,.63,.61,.59,.59,
     1          .74,.59,.50,.44,.40,.37,.34,.33,.31,.30,.29,
     2          .23,.18,.15,.13,.12,.11,.10,.10,.09,.09,.09,
     3          .25,.19,.16,.14,.12,.11,.10,.10,.09,.09,.09/
      I=S/5
      D(1)=X53(I)/100.0/1000.0
      D(2)=X53(I+11)/100.0/1000.0
      D(3)=X53(I+22)/100.0/1000.0
      D(4)=D(3)
      D(5)=X53(I+33)/100.0/1000.0
      RETURN
      END
C
      SUBROUTINE TABLE(PS,TF,TF1,ZMRS,ZMRS1,ZMRS2,DP,DP1,DP2)
C
C      CONTAINS FACTORS FOR TIRE WEAR , REPAIRS , DEPRECIATION FOR
C      DIFFERENT LEVELS OF SERVICEABILITY
C
      DIMENSION X54(8),X55(8),X56(8),X57(8),X58(8),X59(8),X60(8),X61(8)
      DATA X54/1.64,1.21,.88,.61,.40,.24,.10,0.0/
      DATA X55/.75,.52,.35,.24,.15,.08,.03,0.0/
      DATA X56/1.47,1.15,.88,.54,.32,.17,.07,0.0/
      DATA X57/.83,.58,.40,.27,.17,.10,.04,0.0/
      DATA X58/1.49,.96,.64,.41,.25,.14,.06,0.0/
      DATA X59/.16,.11,.08,.06,.04,.02,.01,0.0/
      DATA X60/.39,.29,.21,.15,.10,.06,.03,0.0/
      DATA X61/.38,.28,.20,.15,.10,.06,.03,0.0/
      XXJ=1.0
      DO 1 I=1,8
      IF(PS.LE.(XXJ+.25))GO TO 2
      GO TO 1
    2 K=I
      GO TO 3
    1 XXJ=XXJ+0.5
    3 TF=X54(K)
      TF1=X55(K)
      ZMRS=X56(K)
      ZMRS1=X57(K)
      ZMRS2=X58(K)
      DP=X59(K)
      DP1=X60(K)
```

```
      DP2=X61(K)
      RETURN
      END
C
      SUBROUTINE MPG(S,XTT,ADT,GC)
      DIMENSION XTT(5),X62(55)
      DATA X62/55.4,55.4,47.3,38.7,38.0,37.3,37.6,38.0,40.5,43.0,47.9,
     1 212.0,207.,167.,132.,121.,112.,113.,115.,123.,133.,139.,
     2 236.,217.,198.,179.,168.,156.,153.,149.,149.,149.,153.,
     3 465.,367.,284.,203.,198.,193.,186.,180.,174.,169.,168.,
     4 470.,370.,287.,205.,204.,204.,202.,201.,199.,199.,202./
      I=S/5
      GC=(XTT(1)/X62(I)+XTT(2)/X62(I+11)+XTT(3)/X62(I+22)+
     1    XTT(4)/X62(I+33)+XTT(5)/X62(I+44))*1000.0/ADT
      RETURN
      END
C
C
      SUBROUTINE REPCON(S,REP)
C
C      % AVE COST OF MAINT / REPAIRS FOR DIFFERENT SPEEDS
C
      DIMENSION REP(5),X70(55)
      DATA X70/46.9,47.8,49.4,51.6,54.4,57.4,60.6,64.0,67.6,71.3,75.2
     1        ,45.7,44.7,45.5,47.6,50.6,54.3,58.7,63.7,69.1,74.7,80.5
     2      ,46.1,47.1,48.2,49.7,51.4,53.4,55.7,58.5,61.7,65.4,69.7
     3      ,44.6,45.6,46.8,48.2,50.0,52.3,55.0,58.3,62.3,67.0,72.5
     4      ,45.9,45.5,46.4,48.4,51.4,55.1,59.6,64.5,69.8,75.4,81.2/
      I=S/5
      DO 1 J=1,5
      REP(J)=X70(I)/100.0/1000.0
    1 I=I+11
      RETURN
      END
//$DATA
```

Sample Data

```
   03  7
   4 1.20  6.00    10000. 10000. 140000.3000.  1000.  3.47   .25     450.
 1.00  68.0   194.0  465.0  41.6   99.0   140.0  145.0  145.0
 7501. 8673.  45350. 48687. 51630.
  3 3290.0    18.7 40.0 2  60 3.5 1.0   4 3 2 55.
  1.5      27.5      8.2        31.3      83.0      2.62      47.5       14.0
  1 16780.    13.9 50.  2  60 3.5 1.0   4 1 3 55.
 4.0      38.9      63.4       18.300    89.100    11.000    1.0        3.2800
  2 350.00000 5.00 50.  2  20 3.5 1.0   2 2 1 55.
 6.       23.1      41.63      17.4      52.1      35.52     1.55
/*END
```

Sample Output

COST INFORMATION

OVERLAY	$ 10000./IN/LANE MILE	PATCHING	$ 3.47/SQ YD
CHIP SEAL	10000./LANE MILE	BASE AND SURFACE REPAIR	450.00/CU YD
BASE AND REPAIR PATCH	140000./LANE MILE	CRACK SEALING	0.25/LINEAR FT
SEAL COAT	3000./LANE MILE	GASOLINE	1.20/GAL
FILL CRACKS	1000./LANE MILE	OIL	1.00/QT
		VALUE OF TIME	6.00/HR

INTEREST RATE 4%

VEHICLE RELATED COSTS

ITEM	AUTO	SU-2	SU-3	2-S2	3-S2
TIRES (EA)	68.	194.	465.	465.	465.
MAINTENANCE AND REPAIRS (/1000 MI)	41.60	99.	140.	145.	145.
DEPRECIABLE VALUE	7501.	8673.	45350.	48687.	51630.

SECTION DESCRIPTION (ASPHALT CONCRETE PAVEMENT)

AADT	3290.	SPEED LIMIT (MPH)	55.
% TRUCKS	18.70	NUMBER OF LANES	4
% /LANE	40.00	SECTION LENGTH	1.00
% GROWTH /YR	3.50	HIGHWAY SYSTEM	3
SURFACE AGE (MON)	60	FACILITY TYPE	2

SECTION PROPERTIES

THICKNESS OF ASPHALT CONCRETE	1.50	SUBGRADE LIQUID LIMIT	47.50
THICKNESS OF BASE	14.00	MEAN TEMPERATURE - 50	8.20
STRUCTURAL NUMBER	2.62	THORNTHWAITE INDEX + 50	31.30
SUBGRADE PLASTICITY INDEX	27.50	AVERAGE FREEZE THAW CYCLES	83.00

LIFE PREDICTION

PREDICTED PAVEMENT CONDITION AT END OF SERVICE LIFE :

ACS	LCS	LCA	TCS
1.00	1.00	2.00	1.00

N18/MONTH = 0.7411004E 04 PROB OF CLASSIF = 0.9554008E 00
EST. LIFE = 0.7148051E 06 N18 100 MON
REMAINING LIFE(N18) = 0.3038098E 06 REMAINING LIFE (MON) = 39

PREDICTED CONDITION PER YR (NO REHAB) AFTER SERVICE LIFE :

	ACS	LCS	LCA	TCS
1	1.00	1.00	2.00	1.00
2	1.00	1.00	2.00	2.00
3	2.00	2.00	3.00	3.00
4	2.00	2.00	3.00	3.00
5	2.00	2.00	3.00	3.00

COST ANALYSIS

ANALYSIS PERIOD = 7 YRS

YR	PRESENT WORTH (R + M)	REHAB COST	PSI	FUEL SAVINGS	OIL SAVINGS	TIRE SAVINGS	REPAIR SAVINGS	DEPR SAVINGS	TIME SAVINGS	MAINTENANCE SAVINGS	SAVINGS COST RATIO
0	4934.	4000.	2.43	1280.	5113.	13695.	157751.	24300.	21778.	41328.	66.3
1	6468.	4000.	2.37	1295.	5254.	13695.	157751.	24300.	22484.	47447.	68.0
2	10088.	4000.	2.31	1312.	5425.	13695.	157751.	24300.	23365.	51873.	69.4
3	65746.	97560.	2.26	1325.	5551.	13695.	157751.	24300.	24033.	54526.	2.8
4	58824.	97560.	2.22	1333.	5646.	19894.	252606.	32469.	24548.	55885.	4.0
5	52829.	97560.	2.20	1340.	5719.	19894.	252606.	32469.	24950.	56515.	4.0

SECTION DESCRIPTION

(OVERLAID PAVEMENT)

AADT	16780.	SPEED LIMIT (MPH)	55.
% TRUCKS	13.90	NUMBER OF LANES	4
% /LANE	50.00	SECTION LENGTH	1.00
% GROWTH /YR	3.50	HIGHWAY SYSTEM	1
SURFACE AGE (MON)	60	FACILITY TYPE	3

SECTION PROPERTIES

THICKNESS OF ORIGINAL SURFACE + OVERLAY	4.00	SUBGRADE LIQUID LIMIT	63.40
OVERLAY THICKNESS	1.00	MEAN TEMPERATURE - 50	18.30
STRUCTURAL NUMBER	3.28	THORNTHWAITE INDEX + 50	89.10
SUBGRADE PLASTICITY INDEX	38.90	AVERAGE FREEZE THAW CYCLES	11.00

LIFE PREDICTION

PREDICTED PAVEMENT CONDITION AT END OF SERVICE LIFE :

PSI	ACA	LCS	LCA
3.02	2.00	2.00	2.00

N18/MONTH = 0.3512024E 05 PROB OF CLASSIF = 0.8134362E 00
EST. LIFE = 0.1526561E 07 N18 48 MON
REMAINING LIFE(N18) = 0.0000000E 00 REMAINING LIFE (MON) = 0

PREDICTED CONDITION PER YR (NO REHAB) AFTER SERVICE LIFE :

	PSI	ACA	LCS	LCA
1	2.96	3.00	3.00	3.00
2	2.91	3.00	3.00	3.00
3	2.88	3.00	3.00	3.00
4	2.86	3.00	3.00	3.00

COST ANALYSIS

ANALYSIS PERIOD = 4 YRS

YR	PRESENT WORTH (R + M)	REHAB COST	PSI	FUEL SAVINGS	OIL SAVINGS	TIRE SAVINGS	REPAIR SAVINGS	DEPR SAVINGS	TIME SAVINGS	MAINTENANCE SAVINGS	SAVINGS COST RATIO
0	109769.	109560.	3.02	3966.	11479.	23141.	274023.	47244.	58223.	5674.	3.8
1	279534.	379739.	2.96	4059.	11964.	23141.	274023.	47244.	60579.	11988.	1.1
2	183483.	379739.	2.91	4125.	12315.	23141.	274023.	47244.	62319.	22497.	1.1
3	92042.	379739.	2.88	4171.	12571.	23141.	274023.	47244.	63606.	36822.	1.2
4	5884.	379739.	2.86	4206.	12766.	23141.	274023.	47244.	64594.	52809.	1.2

SECTION DESCRIPTION (SURFACE TREATED PAVEMENT)

AADT	350.	SPEED LIMIT (MPH)	55.
% TRUCKS	5.00	NUMBER OF LANES	2
% /LANE	50.00	SECTION LENGTH	1.00
% GROWTH /YR	3.50	HIGHWAY SYSTEM	2
SURFACE AGE (MON)	20	FACILITY TYPE	1

SECTION PROPERTIES

THICKNESS OF FLEXIBLE BASE	6.00	THORNTHWAITE INDEX + 50	52.10
SUBGRADE PLASTICITY INDEX	23.10	AVERAGE FREEZE THAW CYCLES	35.52
SUBGRADE LIQUID LIMIT	41.63	DYNAFLECT MAX DEFLECTION	1.55
MEAN TEMPERATURE - 50	17.40		

LIFE PREDICTION

PREDICTED PAVEMENT CONDITION AT END OF SERVICE LIFE :

RUTS	RUTA	LCA	TCA	PATA
1.00	0.00	1.00	1.00	0.00

N18/MONTH = 0.2635046E 03 PROB OF CLASSIF = 0.9171120E 00
EST. LIFE = 0.2190803E 05 N18 80 MON
REMAINING LIFE(N18) = 0.1679044E 05 REMAINING LIFE (MON) = 59

PREDICTED CONDITION PER YR (NO REHAB) AFTER SERVICE LIFE :

	RUTS	RUTA	LCA	TCA	PATA
1	1.00	0.00	1.00	1.00	0.00
2	2.00	1.00	1.00	1.00	0.00
3	2.00	1.00	1.00	1.00	0.00
4	3.00	2.00	2.00	2.00	1.00
5	3.00	2.00	2.00	2.00	1.00

COST ANALYSIS

ANALYSIS PERIOD = 6 YRS

YR	PRESENT WORTH (R + M)	REHAB COST	PSI	FUEL SAVINGS	OIL SAVINGS	TIRE SAVINGS	REPAIR SAVINGS	DEPR SAVINGS	TIME SAVINGS	MAINTENANCE SAVINGS	SAVINGS COST RATIO
0	7374.	7200.	3.78	70.	174.	115.	1607.	325.	956.	8399.	1.6
1	6211.	7200.	3.74	73.	186.	284.	3886.	650.	1000.	11396.	2.4
2	8685.	12240.	3.59	82.	223.	284.	3886.	650.	1140.	14313.	1.6
3	7648.	12240.	3.44	90.	260.	284.	3886.	650.	1284.	16820.	1.9
4	12447.	28800.	3.30	97.	295.	284.	3886.	650.	1430.	18641.	0.8
5	10237.	28800.	3.17	104.	329.	489.	7262.	1271.	1575.	19734.	1.0

Data Preparation for Use of Computer Program

Card 1

Cols.	Format	Variable Description
3-5	I3	Number of sections included in computer run
6-8	I3	Estimated life of seal a coat

Card 2 Cost Information

Cols.	Format	Variable Description
3-4	I2	Discount rate
5-11	F7.0	Cost of gasoline ($/gal)
12-18	F7.0	Value of time ($/hr)
19-25	F7.0	Cost of 1" overlay ($/lane mi)
26-32	F7.0	Cost of chip seal ($/lane mi)
33-39	F7.0	Cost of base and repair patching ($/lane mi)
40-46	F7.0	Cost of seal coat ($/lane mi)
47-53	F7.0	Cost of filling cracks ($/lane mi)
54-60	F7.0	Patching (Maint) ($/sq yd)
61-67	F7.0	Crack sealing (Maint) ($/lane ft)
68-73	F7.0	Base and surface repair (Maint) ($/cu yd)

Card 3 Cost Information

Cols.	Format	Variable Description
1-7	F7.0	Cost of qt of oil
8-14	F7.0	Cost of tire for automobile
15-21	F7.0	Cost of tire for single unit truck
22-28	F7.0	Cost of tire for semi-truck
29-35	F7.0	Cost of maintenance and repairs for automobile ($/1000 mi)
36-42	F7.0	Cost of maintenance and repairs for SU-2 ($/1000 mi)
43-49	F7.0	Cost of maintenance and repairs for SU-3 ($/1000 mi)
50-56	F7.0	Cost of maintenance and repairs for 2-S2 ($/1000 mi)
57-63	F7.0	Cost of maintenance and repairs for 3-S2 ($/1000 mi)

Card 4 Cost Information

Cols.	Format	Variable Description
1-7	F7.0	Depreciable value for automobiles
8-14	F7.0	Depreciable value for SU-2
15-21	F7.0	Depreciable value for SU-3
22-28	F7.0	Depreciable value for 2-S2
29-35	F7.0	Depreciable value for 3-S2

Card 5 Section Description

Cols.	Format	Variable Description
2	I1	Indicator for composite pavement
		0 not composite overlaid section
		1 composite overlaid section
3	I1	Pavement Type
		1 overlay
		2 surface treated
		3 asphalt concrete
4-13	F10.0	Average annual daily traffic
14-18	F5.0	Percent trucks
19-23	F5.0	Percent trucks per lane
26-29	I4	Age of surface in months
30-34	F5.2	Traffic growth rate (%)
35-39	F5.2	Project length (miles)
40-41	I2	Number of lanes
42-43	I2	Highway Type Indicator
		1 Interstate
		2 Farm to Market
		3 US/State
44-45	I2	Facility Type Indicator
		1 two lane
		2 multilane
		3 freeway
46-50	F5.2	Speed limit (mph) in multiples of 5

Card 6 Section Pavement Properties

(Asphalt Concrete)

Cols.	Format	Variable Description
1-10	F10.0	Thickness of asphalt concrete layer (in)
11-20	F10.0	Subgrade Plasticity Index
21-30	F10.0	Average Temperature - 50°F
31-40	F10.0	Thornthwaite Index + 50
41-50	F10.0	Annual average freeze thaw cycles
51-60	F10.0	Structural number (AASHO)
61-70	F10.0	Subgrade Liquid Limit
71-80	F10.0	Thickness of flexible base (in)

(Overlay)

1-10	F10.0	Thickness of original surface + overlay (in)
11-20	F10.0	Subgrade Plasticity Index
21-30	F10.0	Subgrade Liquid Limit
31-40	F10.0	Average Temperature - 50°F
41-50	F10.0	Thornthwaite Index + 50
51-60	F10.0	Annual average freeze thaw cycles
61-70	F10.0	Overlay thickness (in)
71-80	F10.0	Structural number* (AASHO)

*For composite pavements use 0.55 as rigid layer coefficient in place of 1.0.

(Surface Treated)

Cols.	Format	Variable Description
1-10	F10.0	Thickness of flexible base (in)
11-20	F10.0	Subgrade Plasticity Index
21-30	F10.0	Subgrade Liquid Limit
31-40	F10.0	Average temperature - 50°F
41-50	F10.0	Thornthwaite Index
51-60	F10.0	Annual average freeze thaw cycles
61-70	F10.0	Dynaflect maximum deflection (mils)

For more than one section, repeat cards 5, 6 for each section. Cards 1-4 contain information applicable to all sections being analyzed.