COMPUTERIZED METHOD OF PROJECTING REHABILITATION AND MAINTENANCE REQUIREMENTS DUE TO VEHICLE LOADINGS

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Research Report 298/312-1(Final)

Volume 5F

Computerized Methods of Projecting Rehabilitation and Maintenance Requirements Due to Vehicle Loadings

Research Projects 2-8-80-298 and 3-8-80-312

conducted for

The State Department of Highways and Public Transportation

by the

Texas Transportation Institute
The Texas A&M University System

Center for Transportation Research
The University of Texas at Austin

August 1981
ACKNOWLEDGMENT

This project was sponsored by the Texas State Department of Highways and Public Transportation through its Cooperative Research Program. Work concerning flexible pavements was developed at T.T.I. with Alberto Garcia-Diaz serving as principal investigator and Robert L. Lytton and Dock Burke as project staff members. Work concerning rigid pavements was developed at C.T.R. with Frank McCullough and C. Michael Walton as principal investigators. Mr. Robert L. Mikulin was the Contact Representative for the State Department of Highways and Public Transportation. The authors want to thank Mr. Robert L. Lewis, Mr. Byron Blaschke, Mr. Gerald Peck, and Mr. Robert L. Mikulin, all from SDHPT, for their outstanding cooperation and interest in this project. Proper acknowledgment is extended to Horacio Peña, Jack Allison, Daniel Orlich, Rafael Cal y Mayor, Jack Vathana, and Phung Lim for their excellent assistance.
DISCLAIMER

The views, interpretation, and conclusions expressed or implied in this report are those of the research group. They are not necessarily those of the Texas State Department of Highways and Public Transportation.
ABSTRACT

The goal of this research project is to revise and combine the REHAB and NULOAD computer models into a new approach to forecast pavement rehabilitation costs. The new approach is called RENU and it incorporates the following three main elements: (a) revised pavement performance equations, (b) design-oriented survivor curves, and (c) a procedure to predict the increment in axle loads when higher pay loads are allowed. The most relevant contribution of the new model in the area of flexible pavements is the development of a serviceability/distress approach to investigate the effect of vehicle loading on the life cycle of highways. This approach has the capability to predict if a pavement needs light to medium rehabilitation as a result of distress signs, when the riding conditions (PSI) has not yet reached a terminal value. The new approach is considered more reliable, for Texas flexible pavements, than the AASHTO methodology. In the area of rigid pavements the two most important improvements are the formulation of a modified AASHTO equation to include soil support values, regional factors, design characteristics, and traffic conditions typical of the Texas highway system, and the development of a failure prediction model to estimate maintenance needs.

The RENU approach was built using experimental values of material properties, climatic conditions, design factors, and traffic measurements obtained by the Texas Transportation Institute (TTI), and the Center for Transportation Research (CTR).

Briefly, the overall methodology can be summarized in four steps: (a) a load distribution procedure is incorporated to investigate the shift toward higher loads if a new legal axle load limit is considered,
(b) generation of a pavement performance functions based upon statistical criteria, (c) generation of survivor curves to predict the extent of road rehabilitation requirements in each of the periods of a planning horizon, and (d) determination of rehabilitation costs considering life cycles for both the current and new axle load legal limits.
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Chapter 1

INTRODUCTION

The purpose of this research study is to revise and combine the best elements of the REHAB and NULOAD computer models to develop a new model RENU to forecast pavement rehabilitation costs. The new model incorporates the following elements: (a) revised pavement performance equations, (b) design-oriented pavement survivor curves, and (c) a methodology to predict the increase in axle loads when higher payloads are allowed. The new model will be called RENU.

REHAB [24] is currently being used by the Texas State Department of Highways and Public Transportation (SDHPT) to estimate highway rehabilitation and maintenance funds needed to keep the state road system at an acceptable level of user serviceability. NULOAD [6] is a more recently developed computer model which uses the pavement performance equations formulated by the American Association of State Highway and Transportation Officials (AASHTO) to describe pavement behavior. The AASHTO equations [44] relate soil support values, regional factors, design characteristics, and traffic conditions to pavement serviceability.

As a result of continued preventive maintenance, the riding condition of a pavement may approach a terminal serviceability value in a very slow fashion, so that the need of rehabilitation will most likely be due to the appearance of pavement distress, at a time substantially shorter than that at which the pavement would reach terminal serviceability index. This behavior has been found to be quite common among Texas flexible pavements. The single most important contribution of the new model in the analysis of flexible pavements is the development of a serviceability/
distress approach to investigate the effect of vehicle loadings on the life cycle of highways. Serviceability and distress performance equations have been developed using available data on Texas flexible pavements. The parameters of the equations are estimated using experimental values of material properties, climatic conditions, design factors, and traffic measurements obtained by the Texas Transportation Institute by field observation.

The proposed model for flexible pavements predicts the life cycle for pavements of several types. In order to develop the model, the following types were considered: (a) asphaltic concrete (hot mix) on asphaltic stabilized base (black base), (b) thick asphaltic concrete, (c) asphaltic concrete pavements, (d) surface treated pavement, and (e) overlay. To identify the critical factor causing the need for rehabilitation for pavement sections of a given type, consideration was made of the serviceability condition (ride) and the following kinds of pavement distress: (a) alligator cracking, (b) longitudinal cracking, (c) transversal cracking (d) rutting, (e) flushing, (f) corrugation, (g) patching, (h) ravelling and (i) failures per lane mile.

An analysis of the conditions prevailing in Texas led to two significant considerations in the development of the RENU model. The first consideration is that asphaltic concrete on asphaltic stabilized base and thick asphaltic concrete pavements do not constitute a major part of the present highway mileage and, therefore, were included in the asphaltic concrete type, thus reducing the types of flexible pavements to three. The second consideration is that most pavements in Texas need rehabilitation as a result of critical levels of transverse cracking or alligator cracking, thus reducing the types of distress actually considered in the RENU program to two. If necessary, of course, the above five types of flexible pavements and nine types of distress signs can easily
be incorporated in the procedure. The corresponding equations are summarized elsewhere in this report.

Based on condition surveys of Texas rigid pavements, the structural design concept and the maintenance cost estimation procedure of the NULOAD program were revised to increase the accuracy of the predicted mileage to be rehabilitated. Revised survivor curves, modified AASHTO performance equations, and a failure prediction model to estimate maintenance costs are the major contributions in the area of rigid pavement analysis.

The revised performance equation for rigid pavements was developed from extensive Texas pavement data to allow the consideration of local material, especially subbase material. Additionally, in the development of the distress prediction model for rigid pavements, the following signs of distress were included: (a) spalling, (b) pumping, (c) punchouts, and (d) patches. Five types of data were utilized in this analysis: (a) environmental factors, (b) construction factors, (c) traffic, (d) age of pavement, and (e) distress factors.

A brief summary of the overall methodology follows. A load redistribution procedure is incorporated to investigate the shift toward higher loads if a new legal axle load limit is considered. For a given type of pavement, the mileage with critical values of serviceability index is assumed to be distributed according to a probability density function whose parameters are estimated using observed pavement data. Based on this density function, a survivor curve is generated to predict the extent of pavement rehabilitation requirements in each of the periods of a planning horizon. Life cycles are determined for both the current and the new axle load limits, and the corresponding pavement rehabilitation needs are finally translated into dollars.
Chapter 2
SYNTHESIS OF RELATED WORK

Past work on the development and improvement of computerized methods for estimating road rehabilitation requirements are summarized in the following three reports:

(a) "The McKinsey Report" [19], which relates to the original REHAB model.
(b) "The Updated Documentation Report" [28], which contains the input/output instructions for the present REHAB model.
(c) "Effects of Changes in Legal Load Limits on Pavement Cost" [2,3], which refer to the NULOAD model.

Due to the limitation that REHAB does not generate performance and survivor curves, it was felt that NULOAD represented a more effective potential planning procedure. However, NULOAD uses the AASHTO performance equations, which have been found to be unreliable for a large number of Texas pavement sections; additionally, NULOAD actually assumes survivor curves instead of generating them on the basis of obtained data. For this reason, it was decided that the most appropriate option would be the development of a new procedure, RENU, which would be similar to NULOAD but with Texas data-based performance and survivor curves.

The overall development of the new computerized procedure (RENU) was undertaken in two phases. The objective of the first phase of the study was to perform a comparison between REHAB and NULOAD and propose an improved methodology which would take into consideration SDHPT requirements concerning pavement classification, data availability, and district organization of the overall highway system. The results of the first phase of the study are summarized in three volumes. Volume 1 [31] contains the evaluation
procedure. This procedure was subdivided into three basic tasks:
(a) analysis of initial assumptions of REHAB and NULOAD, (b) evaluation of
data needs and data availability, and (c) documentation of findings and
recommendations. This third task contains an updated user manual for REHAB.
Volume 2 \[32\] is composed of a detailed flowchart of the program, a FORTRAN
list of the computerized procedure, a sample of the program output, and a
section with the description of all variables used in the model. Volume 3
\[33\] contains the NULOAD FORTRAN program and a sample output of this model.
The first phase of the study was developed in the period between June 1 and
August 31, 1980.

The objective of the second phase of the study was to actually develop
the new computerized procedure RENU. This objective was accomplished in
the period between September 1 and August 31, 1981. The results of this
phase are summarized in two additional volumes. Volume 4 contains a
user manual, a FORTRAN listing, and a sample output of RENU. Volume 5,
the final report of the study, presents the development, analysis, and dis-
cussion of the new procedure, as well as a summary of the results concerning
the Texas highway network. The basic topics included in the final report
can be listed as follows:

(a) Flexible Pavement Methodology (Chapter 3)
(b) Rigid Pavement Methodology (Chapter 4)
(c) Cost Methodology (Chapter 5)
(d) Load Shifting Procedure (Chapter 6)
(e) Applications of the Model (Chapter 7)
(f) Discussion of Results (Chapter 8)
(g) Conclusions and Recommendations (Chapter 9)
Chapter 3

FLEXIBLE PAVEMENT METHODOLOGY

The performance of a pavement during a specific period can be estimated by the reduction of user serviceability with increasing levels of traffic loads. When this reduction process is represented by a mathematical relationship with known shape and location parameters, it is possible to predict the load traffic required to lower a serviceability index to a specific critical level. Usually the performance of the road is measured in terms of the "Present Serviceability Index" (PSI), which is defined as a measurement of the pavement roughness at any instant of time and based upon a rating scale between 0 and 5.

A critical problem in the analysis of pavement performance is that most of the pavement data available correspond to relatively high levels of PSI. This limitation makes it difficult to predict the performance of older pavements, such as those exhibiting PSI values of 2.5 or less. A traditional approach to pavement rehabilitation is that of upgrading the pavement when the PSI reaches a critical value. By the time the pavement approaches this level, it may have already received a substantial amount of routine maintenance, which may reduce the deterioration rate of the pavement as traffic loading continues to increase.

The purpose of this chapter is to propose and discuss a rehabilitation approach which takes into consideration the effect of routine maintenance upon flexible pavement performance. Briefly, the approach consists of modeling the performance of pavement according to an S-shaped curve which may or may not reach a specified terminal PSI value, as seen in Figures 3-1(a) and 3-1(b). When the curve reaches the terminal PSI,
as in Figure 3-1(a), the riding conditions are considered unacceptable and
the pavement should be overlaid. When the curve does not reach the critical
PSI level, as in Figure 3-1(b), the need for rehabilitation is caused not
by a significant loss in riding quality, but rather by the presence of one
or more types of distress, such as: rutting, cracking, flushing, and
others. In this case the pavement should receive a light type of rehabili-
tation, perhaps a thin overlay (1 to 2 inches).

This chapter has been divided into four sections. Section 3-1 sum-
marizes the AASHO performance equations, which are currently used in
NULOAD. Section 3 develops the proposed serviceability/distress approach,
considered more reliable for the analysis of Texas flexible pavements.
Section 3.3 discusses the development of the survivor curves used to esti-
mate the percent of surviving miles of a given type of pavement section.
Section 3.4 presents the computerized procedure that results from the
implementation of the Texas Performance Equations (TPE) and the new sur-
vivor curves in the program NULOAD.
3.1 AASHTO Performance Equations

The procedure developed by the American Association of State Highway and Transportation Officials (AASHTO) to predict pavement performance is based upon an extensive road test conducted in Ottawa, Illinois, in the late 1950's and early 1960's. The results were published in 1961 as an Interim Design guide which was later revised in 1972.

In order to support a brief description of the AASHTO equation the following terms must be defined:

(a) Equivalent Single Axle Load Application
(b) Regional Factor
(c) Structural Number
(d) Soil Support Value

**Equivalent Single Axle Load Applications**

It is a measurement of traffic expressed as an equivalent number of single and tandem axle applications, and obtained as a function of the structural number and critical PSI. Using this factor, traffic can be equated to the number of equivalent 18,000 lb. load applications.

**Regional Factor**

This factor is used to adapt the AASHTO equations to conditions different from those that existed during the original road test. The values of the regional factor (R) are summarized in Table 3-1 as indicated in the AASHTO Interim Guide [1].
TABLE 3-1. REGIONAL FACTOR

<table>
<thead>
<tr>
<th>Condition</th>
<th>R Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road-bed material frozen to depth of 5 in. or more</td>
<td>0.2-1.0</td>
</tr>
<tr>
<td>Road-bed materials, dry summer and fall</td>
<td>0.3-1.5</td>
</tr>
<tr>
<td>Road-bed materials, wet spring thaw</td>
<td>4.0-5.0</td>
</tr>
</tbody>
</table>

**Structural Number**

It is an index number derived from an analysis of traffic, road-bed soil conditions, and regional factor that may be converted to thickness of various flexible pavement layers through the use of suitable layers coefficients related to the type of material being used in each of the pavement structures [43].

**Soil Support**

Also known as subgrade support value, it is an index of subgrade stiffness which is used in combination with the 18-kip ESALs for a given period of time to compute the design thickness required by the road.

The performance equations developed at the AASHTO Road Test express a pavement damage function in terms of vehicle loading. The damage function is defined as a relative loss in serviceability, and the traffic loading is measured in 18-kip equivalent single-axle load applications. In the formulation of the performance equations, the following notation will be used:

- \( t \) is years after construction or major rehabilitation
- \( P_t \) is the serviceability index at year \( t \)
- \( P_i \) is the initial value of serviceability index
- \( P_c \) is the critical serviceability index
is the number of 18-kip ESALs that have passed over a pavement

is a power which differs between rigid and flexible pavements and which depends upon the layer thickness, AASHTO layer coefficient of each layer, and the configuration of wheel loading applied. This function influences the shape of the serviceability curve

is the total number of 18-kip ESALs that will cause the amount of damage corresponding to a value of serviceability equal to 1.5. Additionally, the quantity \( p \) depends upon layer thicknesses, layer coefficients, and wheel configuration

is the regional factor

The damage function is defined as the ratio of the loss in serviceability at a given time to the total loss allowed. That is,

\[
g = \frac{P_i - P_t}{P_i - P_c} \tag{3-1}
\]

Usually \( P_i \) is 4.2 and \( P_c \) is 1.5, then Eq. (3-1)

\[
g = \frac{4.2 - P_t}{2.7} \tag{3-2}
\]

As can be seen from Eq. (3-2), the damage function is equal to 0.0 when the pavement is new and becomes 1.0 when the pavement reaches its critical serviceability index. This behavior can be observed in Figure 3-2.

The AASHTO performance equation can be written as:

\[
g = (R W i_p)^B \tag{3-3}
\]
Let \( g_t \) be the relative loss in serviceability after \( t \) periods since last rehabilitation, and let \( W_t \) be the corresponding number of 18-kip ESALs. Therefore, from Eq. (3-3),

\[
\ln(g_t) = \beta(\ln(R) + \ln(W_t) - \ln(\rho))
\]

(3-4)

The parameters \( \beta \) and \( \rho \) can be computed in terms of structural design and loading variables. As a result of the AASHTO Road Test, the following relationships were found for \( \beta \) and \( \rho \):

\[
\beta = 0.40 + \frac{0.081(L_1 + L_2) 
}{(SN + 1)^{5.19}}
\]

(3-5)

\[
\ln(\rho) = 5.93 \ln(SN + 1) - 4.79 \ln(L_1 + L_2) + 4.33 \ln(L_2)
\]

(3-6)

where:

\( L_1 \) = load on one single axle or on one tandem axle set
\( L_2 \) = axle code (\( L_2 = 1 \) for single axle and \( L_2 = 2 \) for tandem axle)

Eqs. (3-4), (3-5), and (3-6) can be combined to express \( W_t \), for \( L_1 = 18,000 \) pounds, \( L_2 = 1 \), \( P_f = 4.2 \), and \( P_c = 1.5 \), as:

\[
\ln(W_t) = 9.36(SN + 1) - 0.20 + \frac{\ln(\frac{4.2 - P_t}{2.7})}{0.40 + (1094/(SN + 1)^{5.19})}
\]

(3-7)
In general, the soil subgrade and climatic conditions differ from those encountered in the original experiment. If a soil support value $S_i$ and a regional factor $R$ are included in the analysis, Eq. (3-7) results in the final flexible pavement design equation given below:

$$\ln(W_t) = 9.36 \ln(SN + 1) - 0.20 + \frac{\ln(4.2 - P_t/2.7)}{0.40 + (1094/(SN + 1)^{5.19})}$$

$$+ \ln\left(\frac{1}{R}\right) + 0.372 (S_i - 3.0)$$

(3-8)

From Eq. (3-8), the terminal 18-kip ESALs required to reduce the serviceability index to $P_t$ is given by:

$$W_t = \frac{\rho g^{1/\beta}}{R}$$

(3-9)

For $g = 1$, Eq. (3-9) yields $W_o = \frac{\rho}{R}$.

The number of 18-kip ESALs that remains to be carried by the pavement, $W_r$ is equal to $W_o - W_t$, that is:

$$W_r = \frac{\rho}{R} \left(1 - g^{1/\beta}\right)$$

(3-10)

The equivalent annual number of 18-kip ESALs corresponding to $W_t$ can be computed as:

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

(3-11)

where $i$ is the annual growth rate of 18-kip ESALs.

3.2 Texas Pavement Performance Equations

The AASHTO model, represented in Figure 3-2, describes the performance
of a pavement as a riding surface in terms of variations in PSI. The per-
formance function of Figure 3-2 keeps the curvature constant along the
range of the traffic (or time) variable. A number of observed service-
ability values corresponding to Texas flexible pavements indicate that the
performance curve should show a reversal of curvature, as illustrated in
Figure 3-3. The asymptotic behavior of this curve is due to the reduction
of the deterioration rate because of routine maintenance. Once the PSI is
relatively stable, the road may need rehabilitation when one or more signs
of distress become important, as measured by the area affected and the
severity of the distress.

\[ g(W) = e^{-K/W^n} \]  

Figure 3-3. Performance Function (loss) for the Texas
Performance Approach

3.2.1 Basic Equations for Serviceability Analysis

After examining field data concerning flexible pavements performance,
the following function was postulated to represent the relative loss in
serviceability index for Texas highways:

where \( K \) and \( n \) are parameters, and \( W \) is the traffic load in 18-kip ESALs.
Figure 3-3 shows the behavior of the performance function for different
values of \( K \).
As can be verified in Figure 3-3, the performance function $g(w)$ has an inflection point, and an asymptote at $g(W) = 1.0$.

The damage function $g(W)$ can also be expressed as the ratio of the loss in serviceability after $W$ 18-kip ESALs to a specified maximum design loss.

Let $P_i$ be the initial PSI (at $W = 0$), $P_t$ be the PSI after $W_t$ 18-kip ESALs, and let $P_f$ be a lower bound on the PSI. Then the relative loss after $W_t$ ESALs can be expressed as:

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

(3-13)

Note that Eq. (3-13) is similar to Eq. (3-1) with the exception that the critical value $P_c$ has been substituted with the lower bound $P_f$.

From Eq. (3-13), it is possible to express $P_t$ as a function of $g_t$, as follows:

$$P_t = P_i - (P_i - P_f) g_t$$

(3-14a)

Eq. (3-14a) can be further rewritten after using Eq. (3-12). The final result is given by:

$$P_t = P_i - (P_i - P_f) e^{-K/W^n}$$

(3-14b)

Eq. (3-14b) is plotted in Figure 3-4 for different values of $K$, and in Figure 3-5 for different values of $P_f$. 

14
Figure 3-4. Serviceability vs \( W \), for Different \( K \)'s

Figure 3-5. Serviceability vs \( W \), for Different \( P_f \)'s
As illustrated in Figures 3-4 and 3-5, the serviceability value $P_f$ is actually an asymptote of the serviceability curve. The curve has an S-shape which indicates that beyond the inflection point the rate of loss in serviceability is reduced as pavement age increases. This behavior may be explained as a result of routine maintenance over the years. Because of the asymptotic behavior of the curve, a specific terminal value $P_t$, at which rehabilitation is considered necessary, must satisfy the condition $P_t > P_f$, as shown in Figure 3-4; otherwise, the terminal value $P_t$ is never reached and the pavement is assumed to fail as a result of one or more types of distress. The distress analysis will be presented in Section 3.2.2.

The complete determination of the postulated pavement performance function, Eq. (3-14b), requires the estimation of the parameters $K$, $n$, and $P_f$. The parameters can be estimated according to two different procedures. The first procedure, referred to as the statistical approach, uses past data on traffic loads between rehabilitations along with the theory of maximum likelihood estimators. The development of the statistical approach is shown in Appendices 4 and 6.

The second procedure, referred to as the mechanistic approach, computes the values of each parameter as a function of traffic, design, and climatic variables. For a specific pavement section, these variables are observed and each parameter is computed through regression analysis formulas. The independent variables used in the mechanistic approach are given in Table 3-2. Flexible pavements in the state of Texas can be generally classified into three groups: (a) Hot mix pavements, (b) Surface treated pavements, and (c) Overlays. Average values of the mechanistic properties are also given in Table 3-2. The formulation of the mechanistic approach is summarized in Appendix 6 (parts A and B).
### TABLE 3-2. AVERAGE VALUES OF THE MECHANISTIC AND CLIMATIC VARIABLES BY TYPE OF PAVEMENT

<table>
<thead>
<tr>
<th>Variable</th>
<th>Hot Mix Pavement</th>
<th>Surface Treated Pavement</th>
<th>Overlay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thornthwaite Index (TI)</td>
<td>3.6</td>
<td>6.2</td>
<td>7.5</td>
</tr>
<tr>
<td>Mean Precipitation (PR)</td>
<td>2.0</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Freeze-thaw cycle (FTC)</td>
<td>54.2</td>
<td>41.9</td>
<td>36.2</td>
</tr>
<tr>
<td>Wet-thaw cycle (WFTC)</td>
<td>4.3</td>
<td>3.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Mean Annual Temperature (TM)</td>
<td>62.6</td>
<td>64.0</td>
<td>65.1</td>
</tr>
<tr>
<td>18-kip ESALs (W)</td>
<td>368,300</td>
<td>94,700</td>
<td>1,089,100</td>
</tr>
<tr>
<td>Average daily traffic (ADT)</td>
<td>3,140</td>
<td>567</td>
<td>4,832</td>
</tr>
<tr>
<td>Dynaflect 1 (DMD)</td>
<td>1.17</td>
<td>1.54</td>
<td>1.10</td>
</tr>
<tr>
<td>Dynaflect 2 (VOL)</td>
<td>0.42</td>
<td>0.61</td>
<td>0.35</td>
</tr>
<tr>
<td>Composite Stiffness (AS)</td>
<td>0.57</td>
<td>0.69</td>
<td>0.76</td>
</tr>
<tr>
<td>Subgrade Stiffness (SCI)</td>
<td>0.24</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>Texas triaxial class (TTC)</td>
<td>4.4</td>
<td>5.1</td>
<td>5.2</td>
</tr>
<tr>
<td>Liquid Limit (SLL)</td>
<td>39.3</td>
<td>43.6</td>
<td>45.6</td>
</tr>
<tr>
<td>Plasticity Index (SPI)</td>
<td>21.1</td>
<td>25.3</td>
<td>27.1</td>
</tr>
<tr>
<td>Years since construction (T)</td>
<td>11.7</td>
<td>19.4</td>
<td>26.1</td>
</tr>
<tr>
<td>% Subgrade (SPP)</td>
<td>19.8</td>
<td>19.6</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Note: Every variable name has in parenthesis the name used in the regression equations contained in Appendix 1.
The performance relationship defined in Eq. (3-15) was used in NULOAD as a substitute for the AASHTO equation in the case of Texas flexible pavements. For each of the three most important types of flexible pavements, the parameters $K$ and $P_f$ were computed by the procedures of Appendices 8 and 9. The corresponding results, summarized in Table 3-3, were used in the new program (RENU). As can be seen, both the statistical and mechanistic approaches yield consistent results in $K$ values but are somewhat different in the $P_f$ values.

### Table 3-3. Parameters of Flexible Pavements Performance Equations (PSI)

<table>
<thead>
<tr>
<th>Type of Pavement</th>
<th>Mechanistic Approach</th>
<th>Statistical Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K$</td>
<td>$P_f$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot Mix Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural, Low traffic</td>
<td>41,250.</td>
<td>3.36</td>
</tr>
<tr>
<td>Hot Mix Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural, High traffic</td>
<td>412,500.</td>
<td>3.36</td>
</tr>
<tr>
<td>Hot Mix Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban, Low traffic</td>
<td>103,125.</td>
<td>3.36</td>
</tr>
<tr>
<td>Hot Mix Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban, High traffic</td>
<td>1,031,250.</td>
<td>3.36</td>
</tr>
<tr>
<td>Surface Treated Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>6,300.</td>
<td>3.24</td>
</tr>
<tr>
<td>Surface Treated Pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>13,125.</td>
<td>3.24</td>
</tr>
<tr>
<td>Overlay, Rural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low traffic</td>
<td>58,500.</td>
<td>3.26</td>
</tr>
<tr>
<td>Overlay, Rural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High traffic</td>
<td>585,500.</td>
<td>3.26</td>
</tr>
<tr>
<td>Overlay, Urban</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low traffic</td>
<td>155,250.</td>
<td>3.26</td>
</tr>
<tr>
<td>Overlay, Urban</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High traffic</td>
<td>1,552,500.</td>
<td>3.26</td>
</tr>
</tbody>
</table>

Note: The value of $n$ was assumed equal to 1 to simplify the analysis, see Appendices 6.
3.2.2 Basic Equations for Distress Analysis

The previous approach explained thus far bases the calculation of remaining pavement life upon serviceability index alone. However, it is well known that pavements may be seriously distressed and in need of major rehabilitation before the serviceability index drops to its terminal value. This is particularly true of pavements with severe alligator and transverse cracks. In cases when $P_f$ is higher than $P_t$ or when the remaining life calculated from the serviceability index equation is very long (say 30 to 40 years), the pavement will probably need major rehabilitation due to distress.

The analysis of pavement distress can be accomplished by examining the area of each of the following types of distress: alligator cracking, longitudinal cracking, transverse cracking, rutting, flushing, corrugation, patching, and ravelling. However, alligator and transverse cracking are the most important distress types in Texas. The degree or range to which a type of distress is extended can be expressed as the percent of the total pavement surface area in need of repair. The seriousness of the distress may be expressed as crack width, crack depth, relative displacement at a joint, etc. Usually, the severity of a given type of distress can be subjectively estimated by comparing the observed distress with photographs of different levels of severity, such as none, slight, moderate, or severe, and choosing numbers between zero and one (or 0 and 100%) to quantify the seriousness of surface failures. The Table 3-4 shows the rating values for area and severity used in this project.
TABLE 3-4. RANGES FOR AREA AND SEVERITY

<table>
<thead>
<tr>
<th>AREA</th>
<th>SEVERITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>Area Measurement</td>
</tr>
<tr>
<td>0</td>
<td>.0005</td>
</tr>
<tr>
<td>1</td>
<td>.080</td>
</tr>
<tr>
<td>2</td>
<td>.230</td>
</tr>
<tr>
<td>3</td>
<td>.500</td>
</tr>
</tbody>
</table>

The distress equations developed for Texas flexible pavement data are of the same form as the PSI equations,

\[
a = e^{-a_0/W^n}
\]

(3-15)

\[
s = s_f e^{-a_1-a_2/W^n}
\]

(3-16)

where

- \(a\) is percent of pavement surface area covered by distress
- \(s\) is severity of distress expressed in numerical form
- \(a_0\), \(a_1\), and \(a_2\) are deterioration rate constants
- \(W\) is traffic load in 18-kip ESALs.

Figure 3-6 illustrates the variation of distressed area for different values of the constant \(a_0\), as the traffic load is changed. The corresponding variation of the degree of distress severity is illustrated in Figure 3-7.
Figure 3-6. Variation of Area in a Distressed Pavement.

Figure 3-7. Variation of the Severity of the Distressed Pavement.
Appendix GA summarizes the development of a statistical procedure to compute the deterioration rate constants for the distress approach. Appendix 6B summarizes the development of a mechanistic procedure to estimate the same constants. Finally, Table 3-5 contains the results for Texas flexible pavements.

### TABLE 3-5. PARAMETERS FOR FLEXIBLE PAVEMENTS
PERFORMANCE EQUATIONS (DISTRESS)

<table>
<thead>
<tr>
<th>Type of Pavement</th>
<th>Mechanistic Approach</th>
<th>Statistical Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_0$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>Hot Mix, Rural Low traffic</td>
<td>2,000,000</td>
<td>0.40</td>
</tr>
<tr>
<td>Hot Mix, Rural High traffic</td>
<td>2,250,000</td>
<td>0.43</td>
</tr>
<tr>
<td>Hot Mix, Urban Low traffic</td>
<td>480,000</td>
<td>0.52</td>
</tr>
<tr>
<td>Hot Mix, Urban High traffic</td>
<td>5,000,000</td>
<td>0.45</td>
</tr>
<tr>
<td>Surface treated - Rural</td>
<td>12,500</td>
<td>0.25</td>
</tr>
<tr>
<td>Surface treated - Urban</td>
<td>35,300</td>
<td>0.45</td>
</tr>
<tr>
<td>Overlay, Rural Low traffic</td>
<td>170,000</td>
<td>0.28</td>
</tr>
<tr>
<td>Overlay, Rural High traffic</td>
<td>1,170,000</td>
<td>0.44</td>
</tr>
<tr>
<td>Overlay, Urban Low traffic</td>
<td>420,000</td>
<td>0.39</td>
</tr>
<tr>
<td>Overlay, Urban High traffic</td>
<td>4,100,000</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Note: In both approaches, the values of $a$, and $S_f$ have been assumed within a reasonable interval to satisfy the design life of each type of pavement.
3.3 Survivor Curves for Flexible Pavements

Survivor curves are empirical probability functions used to predict the percent of pavement mileage of a specific age which will not need rehabilitation in the short range future. This in turn can be used to estimate the percent of mileage which will need rehabilitation in the near future. This information complemented with data on existing mileage and rehabilitation cost can be used to estimate the funds needed in each period of a specified planning horizon.

Historical pavement data recorded by the Texas Highway Department and Texas Transportation Institute were considered as input to generate survivor curves for the most important types of Texas flexible pavements. However, lack of accurate and sufficient information for older pavements represents an important limitation in the complete determination of survivor functions. Some adjustments were made in order to obtain resulting equations that can be handled by conventional computer procedures.

Currently, the NULOAD program uses normal distribution with assumed mean and standard deviation to generate survivor curves. The new program RENU contains survivor curves generated on the basis of available data for each of the most important types of pavements in Texas.

The survivor functions developed for RENU can be generally written as:

\[ V = 1 - e^{-q/W^r} \]  

(3-17)

where

- \( V \) is the percent of surviving mileage,
- \( q \) is a constant affecting the survivor function,
- \( r \) is the exponent that affects the 18-kip ESALs,
- \( W \) is the number of 18-kip ESALs since construction or last rehabilitation.
The basic procedure of RENU to estimate the mileage of a given type of pavement which will (or will not) need rehabilitation is illustrated in Figure 3-8. Figure 3-8(a) represents the distribution of mileage by level of serviceability index. Figure 3-8(b) corresponds to the performance function and shows the traffic loads, $W^*$, at which a critical value of serviceability is reached. Figure 3-8(c) shows the probability density function for the mileage in need of rehabilitation. Figure 3-8(d) is the survivor curve. It gives the percent of pavement mileage with critical performance index which will not fail by the time the traffic load $W^*$ is reached.
Performance Index

Critical value

Notation
mileage with performance index equal to critical value
percent of mileage with critical performance value which needs rehabilitation

W* mean traffic load to failure for mileage with critical performance value

Figure 3-8. RENU Procedure to Generate Survivor Curves
The complete determination of the survivor curve defined by Eq. (3-17) requires the estimation of the parameters \( q \) and \( r \). This can be accomplished using the following procedures which are consistent with the methodology illustrated in Figure 3-8.

Step 1: Use the performance functions defined by Eqs. (3-12), (3-15), and (3-16) to generate values of \( W_t \) given critical values of the performance index \( (P_t, a_t, s_t) \). Define \( m \) as the number of values generated.

Step 2: Compute the coefficient of variation (See Appendix 5) and set it equal to \( \frac{\overline{W}}{S_w} \), where \( \overline{W} \) is the average traffic load corresponding to the \( m \) values generated in Step 1 and \( S_w \) is the standard deviation estimated from the same set of \( W \)'s.

Then from Appendix 5 it can be observed that

\[
\frac{\overline{W}}{S_w} = \left[ \frac{\Gamma(r - \frac{2}{r})}{\Gamma(r - 1)} - 1 \right]^{1/2}
\]  

(3-18)

where \( \Gamma(\cdot) \) is the Gamma function.

Step 3: Use a numerical method to solve the Eq. (3-18) for \( r \).

Step 4: Compute the value of \( q \) by either of the two following procedures.

Procedure 1. Set the value of \( q \) equal to:

\[
q = \left[ \frac{\overline{W}}{(r - 1)} \right]^{r}
\]  

(3-19)

where \( r \) is obtained in Step 3. Eq. (3-19) is developed in Appendix 5.
Procedure 2. Compute the value of $q$ by the following expression:

$$q = \frac{m}{\sum_{i=1}^{m} W_i^{-r}}$$

(3-20)

Eq. (3-20) is explained in Appendix 4.

The application of the procedure defined by Steps 1 through 4 using different levels for the critical index ($P_t$, $a_t$, or $s_t$) allows the generation of a family of functions

$$r = \begin{cases} 
F_1(P_t) \\
F_2(a_t) \\
F_3(s_t)
\end{cases}$$

(3-21)

where $F_1$ corresponds to the PSI option and $F_2$, $F_3$ to the distress option.

Eq. (3-22) applies to all categories of surface treated pavements. This equation was obtained by regression techniques. The corresponding correlation coefficient was equal to -0.594:

$$r = 13.53 - 3.85 \ln(P_t)$$

(3-22)

Eq. (3-23) applies to rural, hot mix pavements. The corresponding correlation coefficient was equal to -0.963:

$$r = 35.72 - 28.07 \ln(P_t)$$

(3-23)

Eq. (3-24) applies to urban, hot mix pavement. The correlation coefficient in this case was equal to -0.0976:

$$r = 44.22 - 37.30 \ln(P_t)$$

(3-24)
Eq. (3-25) applies to any type of overlaid pavement. The correlation coefficient was equal to -0.599:

$$ r = 11.85 - 0.34 P_t^3 $$  \hspace{1cm} (3-25)

Similar equations can be developed for the distress approach, but due to the lack of information, the values of $r$ and $q$ have been computed on the basis of $a_t = 0.5$ and $S_t = 0.5$.

Additionally, similar functions can be developed for the relationship between $q$ and $P_t$ in the PSI case. After investigating several types of algebraic expressions, the following function was found to exhibit the best goodness of fit:

$$ \ln(q) = A + B P_t $$ \hspace{1cm} (3-26)

The parameters $A$ and $B$ depend on the type of flexible pavement, as shown below:

(a) For hot mix pavement the relationships are:

$$ \ln(q) = 581.21 - 172.76 P_t $$  \hspace{1cm} (3-27)

and

$$ \ln(q) = 496.85 - 148.23 P_t $$  \hspace{1cm} (3-28)

Eq. (3-27) applies to high traffic and the corresponding correlation coefficient was equal to: -0.958. Eq. (3-28) applies to low traffic and the corresponding correlation coefficient was equal to -0.832.

For surface treated pavements the relationship is:

$$ \ln(q) = 111.35 - 5.65 P_t $$  \hspace{1cm} (3-29)

The correlation coefficient corresponding to Eq. (3-29) was -0.67.
(c) For overlaid pavements the relationships are:

\[ \ln(q) = 235.3 - 64.82 \, P_t \]  \hspace{1cm} (3-30)

\[ \ln(q) = 375.17 - 114.25 \, P_t \]  \hspace{1cm} (3-31)

Eq. (3-30) applies to low traffic and has a correlation coefficient of -0.602. Eq. (3-31) applies to high traffic and has a correlation coefficient of -0.603.

For the distress approach data on 18-kip ESALs and nature of the failure (area or severity) are not available to develop similar relationships.

Tables (3-6) and (3-7) contain the values of \( q \) and \( r \) obtained for the principal types of pavement in Texas. Table (3-6) has the values of the parameters for the PSI case, and Table (3-7) for the distress case.

**TABLE 3-6. SURVIVOR CURVE PARAMETERS, PSI CASE**

<table>
<thead>
<tr>
<th>Type of Pavement</th>
<th>( r )</th>
<th>( q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot mix pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural, Low traffic</td>
<td>10.0</td>
<td>7.028x10^{54}</td>
</tr>
<tr>
<td>Hot mix pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural, High traffic</td>
<td>10.0</td>
<td>7.03x10^{64}</td>
</tr>
<tr>
<td>Hot mix pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban, Low traffic</td>
<td>10.0</td>
<td>6.66x10^{58}</td>
</tr>
<tr>
<td>Hot mix pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban, High traffic</td>
<td>10.0</td>
<td>6.70x10^{58}</td>
</tr>
<tr>
<td>Surface treated pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rural</td>
<td>10.0</td>
<td>1.373x10^{44}</td>
</tr>
<tr>
<td>Surface treated pavement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>10.0</td>
<td>2.115x10^{48}</td>
</tr>
<tr>
<td>Overlay, Rural, Low traffic</td>
<td>10.0</td>
<td>2.10x10^{54}</td>
</tr>
<tr>
<td>Overlay, Rural, High traffic</td>
<td>10.0</td>
<td>2.10x10^{64}</td>
</tr>
<tr>
<td>Overlay, Urban, Low traffic</td>
<td>8.0</td>
<td>4.24x10^{46}</td>
</tr>
<tr>
<td>Overlay, Urban, High traffic</td>
<td>10.0</td>
<td>2.0x10^{68}</td>
</tr>
</tbody>
</table>
The numbers in Table 3-7 are average values computed with the same data used to develop Eqs. (3-22) through (3-25). Due to the limited data on distress types, the average values will be used in the RENU program instead of the equations.

**TABLE 3-7. SURVIVOR CURVE PARAMETERS, DISTRESS CASE**

<table>
<thead>
<tr>
<th>TYPE OF PAVEMENT</th>
<th>AREA</th>
<th>SEVERITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Mix Pavement, Rural</td>
<td>$R_2$</td>
<td>$q_2$</td>
</tr>
<tr>
<td>Hot Mix Pavement, Rural</td>
<td>3.0</td>
<td>$1.87 \times 10^{16}$</td>
</tr>
<tr>
<td>Hot Mix Pavement, Rural</td>
<td>2.5</td>
<td>$1.08 \times 10^{16}$</td>
</tr>
<tr>
<td>Hot Mix Pavement, Urban</td>
<td>3.0</td>
<td>$2.92 \times 10^{17}$</td>
</tr>
<tr>
<td>Hot Mix Pavement, Urban</td>
<td>3.2</td>
<td>$6.93 \times 10^{21}$</td>
</tr>
<tr>
<td>Surface Treated Pavement Urban</td>
<td>2.3</td>
<td>$4.45 \times 10^{10}$</td>
</tr>
<tr>
<td>Surface Treated Pavement Rural</td>
<td>2.25</td>
<td>$3.3 \times 10^{9}$</td>
</tr>
<tr>
<td>Overlay, Rural Low Traffic</td>
<td>3.0</td>
<td>$1.22 \times 10^{16}$</td>
</tr>
<tr>
<td>Overlay, Rural High Traffic</td>
<td>2.5</td>
<td>$7.56 \times 10^{15}$</td>
</tr>
<tr>
<td>Overlay, Urban Low Traffic</td>
<td>2.9</td>
<td>$4.99 \times 10^{16}$</td>
</tr>
<tr>
<td>Overlay, Urban High Traffic</td>
<td>3.1</td>
<td>$9.14 \times 10^{20}$</td>
</tr>
</tbody>
</table>

A graphical representation of the survivor curves for the principal types of Texas pavements is given in Appendix 3.
As it has been previously indicated throughout this report, the current version of the NULOAD procedure uses the AASHTO methodology to examine the service life cycle of highways. The fundamental procedure of the program is performed by the LYFCYC subroutine for which a simplified flow chart is given in Figure 3-9 to support further discussion of the RENU program. Figure 3-9 contains the basic methodology for the computation of the 18-kip ESALs and the design of the required pavement; in addition to the design, the program also estimates rehabilitation costs. Steps (1) and (2) of the flow-chart are accomplished through the AASHTO equations [Eq. (3-8)] in NULOAD. In the RENU program the computation of 18-Kip ESALs and PSI values is made through the Texas performance equations [Eqs. (3-12) and (3-15)]. Figure 3-10 shows a flow chart containing the methodology followed to compute 18-Kip ESALs through the Texas performance equations. Basically, the RENU program assigns a failure option (either PSI or distress) to each type of flexible pavements, depending on the values of $P_t$ and $P_f$. 
Figure 3-9. Basic Methodology of Subroutine LYFCYL, in RENU or NULOAD
Figure 3-10. Texas Performance Equations Procedure to Compute 18-Kip ESALs
4.1 Modification of AASHTO Equation for Rigid Pavement in Texas

The AASHTO performance equation provides relationships among traffic and pavement performance, structural design, and thickness. Although this equation represents the most comprehensive development of the relationships, the results are for general use. Further, the equation can be modified in order to improve the accuracy of prediction by utilizing local input data. For instance, Texas rigid pavements are normally 8 inches thick and have a K-value in the 60 to 200 pci range. Limestone and siliceous river gravel are two common subbase materials. Pavements reach a terminal level of service with approximately 6,000,000 applications of 18 kips ESAL. Information such as this has been monitored in Texas and has been very useful in updating the general AASHTO performance equation for the state's environment.

The revised AASHTO performance equation was developed to ease the use in the choice of local input data, especially types of subbase material. After modification, the sensitivity of the equation was checked to validate the prediction results as shown in Table 4.1 and Figure 4.1. The major change in the revised AASHTO performance equation is similar to the Strauss performance equation which was developed from extensive Texas rigid pavement data, as shown in Table 4.2.

The input data needed to develop a modified performance relationship for rigid pavements can be unified as follows:

- **E**: Modulus of elasticity of the concrete
- **K**: Modulus of support reaction
- **D**: Thickness of pavement
- **C**: Constant
The general form of the revised AASHTO performance relationship is given by Eq. (4-1):

\[
\log W_t = 7.37 \log (D+1) + 0.06 + \frac{-0.17609}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}}
+ 3.42 \log \left( \frac{C}{215.63} \right) \frac{D^{0.75} - 1.132}{D^{0.75} - \frac{18.42}{Z^{0.25}}}
\]

(4-1)

where \( Z = \frac{E}{K} \).

4.1.1 Siliceous-River-Gravel

Typical values for this subbase material are:

\[
\begin{align*}
K &= 150 \text{ pci} \\
E &= 6.5 \times 10^6 \\
D &= 8''
\end{align*}
\]

\[
Z = \frac{E}{K} = \frac{6.5 \times 10^6}{150} = 4.33 \times 10^4
\]

Assuming \( W = W_t \) 18-Kip ESALs, the modified performance relationship (4-1) can be used to obtain Eq. (4-2):

\[
\log W_t = 6.79885 + 3.42 \log \left( \frac{C}{215.63} \right) (1.04162)
= -1.12186 + 3.42 \log (C)
\]

(4-2)

From Eq. (4-2),

\[
\log C^{3.42} = \log W_t + 1.12186
\]
\[
C^{3.42} = W_t^{10.12186}
\]
\[
C = (13.239 W_t)^{0.29240}
\]

35
Assuming $W_t = 6.0 \times 10^6$ in Eq. (4-3), we can write

$$C = 204.157$$

4.1.2 Limestone

A similar procedure can be followed to compute the value of $C$ in the case of limestone subbases:

$$E = 4.4 \times 10^6$$

$$K = 150 \text{ pci}$$

$$Z = \frac{4.4 \times 10^6}{150} = 2.93 \times 10^4$$

$$D = 7.42"$$

$$\log W_t = 6.5992 + (3.42) \frac{C}{215.63} + \frac{3.364}{3.0883}$$

$$= -1.2550772 + 3.42 \log C \quad (4-4)$$

$$\log C^{3.42} = \log W_t + 1.2550772 \quad (4-5)$$

Again, assuming $W_t = 6.0 \times 10^6$ in Eq. (4-5), we finally obtain

$$C = 223.31$$

4.1.3 Summary of Modified Performance Equations

The final revised AASHTO performance equation for limestone in Texas is:

$$\log W_t = 7.37 \log (D+1) + 0.06 + \frac{-0.17609}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}}$$

$$+ 3.42 \log 1.04 \frac{D^{0.75} - 1.132}{D^{0.75} - 18.42/2^{0.25}} \quad (4-6)$$
The revised AASHTO performance equation for siliceous-river-gravel is as follows:

\[
\log W_t = 7.37 \log (D+1) + 0.06 + \frac{-0.17609}{1 + \frac{1.624 \times 10^7}{(D+1)^{8.46}}}
\]

\[
+ 3.42 \log 0.95 \left( \frac{D^{0.75} - 1.132}{D^{0.75} - 18.42/Z^{0.25}} \right)
\]

\[\text{(4-7)}\]
TABLE 4-1. SENSITIVITY STUDY OF THICKNESS OF PAVEMENT, K-VALUE, AND NUMBER OF APPLICATIONS

<table>
<thead>
<tr>
<th>D</th>
<th>K</th>
<th>Limestone</th>
<th>D</th>
<th>K</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.42</td>
<td>60</td>
<td>4.42 x 10^6</td>
<td>8.00</td>
<td>60</td>
<td>4.68 x 10^6</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>5.18 x 10^6</td>
<td>100</td>
<td></td>
<td>5.33 x 10^6</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>6.00 x 10^6</td>
<td>150</td>
<td></td>
<td>6.00 x 10^6</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>6.75 x 10^6</td>
<td>200</td>
<td></td>
<td>6.59 x 10^6</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>8.16 x 10^6</td>
<td>300</td>
<td></td>
<td>7.67 x 10^6</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td>1.22 x 10^7</td>
<td>600</td>
<td></td>
<td>1.05 x 10^7</td>
</tr>
<tr>
<td>8.00</td>
<td>60</td>
<td>7.01 x 10^6</td>
<td>8.72</td>
<td>60</td>
<td>8.14 x 10^6</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>8.12 x 10^6</td>
<td>100</td>
<td></td>
<td>9.16 x 10^6</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>9.30 x 10^6</td>
<td>150</td>
<td></td>
<td>1.02 x 10^7</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>1.04 x 10^7</td>
<td>200</td>
<td></td>
<td>1.11 x 10^7</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>1.23 x 10^7</td>
<td>300</td>
<td></td>
<td>1.27 x 10^7</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td>1.78 x 10^7</td>
<td>600</td>
<td></td>
<td>1.70 x 10^7</td>
</tr>
<tr>
<td>10.00</td>
<td>60</td>
<td>2.95 x 10^7</td>
<td>11.20</td>
<td>60</td>
<td>4.31 x 10^7</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>3.32 x 10^7</td>
<td>100</td>
<td></td>
<td>4.74 x 10^7</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>3.70 x 10^7</td>
<td>150</td>
<td></td>
<td>5.16 x 10^7</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>4.04 x 10^7</td>
<td>200</td>
<td></td>
<td>5.52 x 10^7</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>4.63 x 10^7</td>
<td>300</td>
<td></td>
<td>6.15 x 10^7</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td>6.16 x 10^7</td>
<td>600</td>
<td></td>
<td>7.66 x 10^7</td>
</tr>
<tr>
<td>12.00</td>
<td>60</td>
<td>1.00 x 10^8</td>
<td>13.32</td>
<td>60</td>
<td>1.41 x 10^8</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>1.11 x 10^8</td>
<td>100</td>
<td></td>
<td>1.53 x 10^8</td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>1.21 x 10^8</td>
<td>150</td>
<td></td>
<td>1.65 x 10^8</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>1.30 x 10^8</td>
<td>200</td>
<td></td>
<td>1.74 x 10^8</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>1.46 x 10^8</td>
<td>300</td>
<td></td>
<td>1.91 x 10^8</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td>1.85 x 10^8</td>
<td>600</td>
<td></td>
<td>2.29 x 10^8</td>
</tr>
</tbody>
</table>
For $K = 150$ PCI

Figure 4-1. Sensitivity of the Revised Equation
4.2 Texas Survivor Curve for Rigid Pavements

The use of survivor curves is a standard method of making management decisions relative to future estimates of time to retirement of physical properties. Physical properties are said to be retired from service when, for one reason or another, they are removed from productive service or altered and used in a second service life. Winfrey [42] developed many survivor curves that fit into three basic types: symmetrical, left-modal, and right-modal. The symmetrical type with the standard deviation of the survivor curve being defined by user input has been selected for use in NULOAD. The stochastic nature of survivor curves makes it very complicated for the user to select the proper standard deviation. For this reason, the revised NULOAD program makes use of the actual survivor curves from previous research [10]. The actual survivor curves, Figure 4.2, will not exactly represent the probability that a pavement of given age will require a timely overlay, but it will give the best approximation of Texas rigid pavement survivor probability. Velasco [10] verified that at present approximately 50 percent of rigid pavements in Texas will be overlaid by the time they are 15 years old. This is based on the assumption that the rigid pavement will have 15 failures per lane-miles per mile at 15 years of age. The field data shows that this assumption is likely to be realistic. Figure 4.2 shows the actual survivor curves for Texas rigid pavements.
Figure 4-2. Actual Texas Survivor Curve for Rigid Pavements
Chapter 5
ECONOMIC ANALYSIS

The purpose of this chapter is to summarize the basic steps of the methodology followed in RENU to achieve the following two objectives.

(a) Estimate the effects in terms of rehabilitation needs of changes in the legal axle load limits.
(b) Measure the impact of these changes in terms of budget needs for a specified planning horizon.

Although the economic analysis of RENU is similar to that performed by NULOAD, there are a few procedures in RENU which represent important analytical improvements. These procedures are:

(a) Incorporation of the Texas Highway Cost Index to account for future increases in material costs.
(b) Development of a mechanistic procedure to determine the thickness of flexible pavement overlays.
(c) Development of distress prediction models to estimate maintenance for rigid pavements.
5.1 Maintenance Costs

This section presents the analytical tools used to estimate maintenance costs for Texas flexible and rigid pavements. The methodology for flexible pavements is the same already existing in NULOAD: The EAROMAR equations [4] are used to predict maintenance costs for multi-lane freeways as functions of pavement age. For other types of pavements, the EAROMAR results are appropriately modified by multiplying by reduction coefficients reflecting past maintenance data for Texas. The methodology used in RENU for rigid pavements is considered to be more practical than the EAROMAR approach. The number of failures (punchouts and patches) per mile was chosen as the major criterion to predict maintenance needs and costs.

5.1.1 Flexible Pavement Maintenance Costs

RENU has the same maintenance cost options included in NULOAD. These are:

(a) use of the EAROMAR equations
(b) use of historical maintenance data
(c) no consideration of maintenance costs.

The cost models comprising the EAROMAR equations can be classified as follows:

Model 1: Model to estimate the number of square yards of bituminous skin patching per year and per lane mile.

Model 2: Model to estimate crack sealing in bituminous pavements per year and per lane mile.

Model 3: Model to estimate the cost of bituminous base and surface repair per year and per lane mile.
The notation given below is used in the formulation of the flexible pavement maintenance models:

\[ C_1 = \text{cost per square yard of bituminous skin patching} \]
\[ C_2 = \text{cost per linear foot of crack sealing} \]
\[ C_3 = \text{cost per cubic yard of bituminous base and surface repair} \]
\[ T = \text{age of pavement in years} \]
\[ APC = \text{Annual patching cost per lane mile} \]
\[ ASC = \text{Annual sealing cost per lane mile} \]
\[ ABSC = \text{Annual base and surface repair cost} \]

Model 1:
\[
APC = \frac{1100 C_1}{1 + e^{-(T-10)/1.16}} \quad \text{($/lane-mile)} \quad (5-1)
\]

Model 2:
\[
ASC = \frac{1000 C_2}{1 + e^{-(T-10)/1.16}} \quad \text{($/lane-mile)} \quad (5-2)
\]

Model 3:
\[
ABSC = \frac{5 C_3}{1 + e^{-(T-10)/1.16}} \quad \text{($/lane-mile)} \quad (5-3)
\]

The input cost parameters \( C_1, C_2, C_3 \) can be obtained from sources such as the 1980 Heavy Construction Cost File [22].

To extend the use of the EAROMAR equations to roadway types other than freeways, samples of past maintenance costs for Interstate Highways, Farm to Market Roads, and U.S. and State Highways were studied to compute average costs per mile for each classification. The reduction factor for a type of pavement is computed as the ratio between the average cost per mile of the
given pavement and that for the freeway. Data needed for this analysis were
obtained from the SDHPT 1980 maintenance cost files for routine maintenance
of bituminous surfaces. The typical routine maintenance actions considered
are listed below:

(a) seal coat
(b) edge repair
(c) pot holes
(d) leveling or overlay
(e) correction of bleeding

Table 5.1 summarizes the results of the analysis. As an illustration of the
use of this table, the routine maintenance cost for Farm-to-Market roads can
be estimated as 38.2% of the cost per mile computed by the EAROMAR equations.

<table>
<thead>
<tr>
<th></th>
<th>OBS</th>
<th>MAINTENANCE AVE. EXPENDITURE/LN MILE</th>
<th>% OF INTERSTATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>4</td>
<td>$1,027.50</td>
<td>100%</td>
</tr>
<tr>
<td>Farm-to-Market</td>
<td>23</td>
<td>391.20</td>
<td>38.2%</td>
</tr>
<tr>
<td>State, U.S., other</td>
<td>62</td>
<td>325.10</td>
<td>31.6%</td>
</tr>
</tbody>
</table>

5.1.2 Rigid Pavements Maintenance Costs

Maintenance costs for rigid pavements are expressed as a function of
the number of failures per mile of pavement. In Research Project 3-8-75-177,
"Development & Implementation of the Design, Construction and Rehabilitation
of Rigid Pavements ".

The Center for Transportation Research at the University of Texas at
Austin has conducted state wide distress condition survey in 1974, 1978, and
1980. The distress manifestation recorded during these condition surveys
were spalling, pumping, punchouts, and patches. Data from condition survey in 1974 and 1978 were used to develop a distress prediction model for CRCP by Noble and McCullough in 1979. Five types of data were utilized for this development of the distress prediction models. Specifically these were data on:

(a) Environmental factors  
(b) Construction factors  
(c) Traffic  
(d) Age of pavement  
(e) Pavement distress factors

In accordance with SDHPT criteria, distress failures can be limited to punchouts and repaired patches on the pavement. The selection of the above factors were made on the basis of data availability and the results of an Analysis of Variance (ANOVA) performed prior to regression analysis. The following results were obtained:

\[
N = 0.381 - 0.4272x_1 + 0.018864x_2^2 + 0.5532x_3(x_2-x_1) + 0.0005928x_2x_4 + x_5
\]  

\(N\) = predicted number of failures per mile (punchouts and patches)  
\(x_1\) = pavement age at time of condition survey (years)  
\(x_2\) = pavement age at future time chosen for distress prediction  
\(x_3\) = number of failures per mile at time of condition survey  
\(x_4\) = Texas SDHPT temperature constant (Table 5-2)  
\(x_5\) = \(-5.840 + 1.1856x_2\) for pit run gravel subbase aggregate and for other subbase aggregates
<table>
<thead>
<tr>
<th>DISTRICT</th>
<th>$\bar{\alpha}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
</tr>
<tr>
<td>7</td>
<td>26</td>
</tr>
<tr>
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<td>25</td>
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<td>25</td>
<td>24</td>
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<td></td>
<td>19</td>
</tr>
</tbody>
</table>
Values of 0.672 and 2.436 for $R^2$ and the mean square error, respectively, show that the equation has an acceptable precision of prediction. The prediction relationship given in Eq. (5-4) requires the following input parameters:

(a) Condition survey data on the number of failures per mile
(b) Pavement age at the time of the survey (expressed in months)
(c) Pavement at time in the future for which the prediction is desired (months)
(d) District number needed to set the temperature constant for a particular district
(e) Subbase aggregate type 0 for limestone and 1 for silicious river

Figure 5-1. Cumulative Failures per Mile per Year

As shown in Figure 5-1, the cumulative number of failures is calculated for each year until this value approaches 15.0, at which time an overlay is needed. After the overlay, the number of failures drops to zero.
and starts accumulating again at a slower rate. This slower rate could be estimated to approximately 75 percent of the original rate \[15].

The number of failures per mile from Eq. \((5-4)\) was developed on the basis of two one-way traffic lanes. In order to estimate the number of failures per lane-mile per year, the lane distribution factor has to apply to the number of failures per mile. This factor ranges between 0.5 to 0.85. In the RENU program a lane distribution factor of 0.65 is used.

5.1.3 Highway Cost Index for Maintenance

The Texas Highway Cost Index has been incorporated into the projection of future maintenance costs. The Maintenance Material Cost Index from the current Forecasts of the Highway Cost Index \([35]\) is input by the user to the program as a constant rate by approximating the projected index to a straight line. Figure 5.2 illustrates a factor of 9% as obtained from the July 1980 report \([35]\).
Figure 5-2. Maintenance Materials Cost Index by Fiscal Years (1979 = 100)
5.2 Rehabilitation Costs

The rehabilitation activity considered in RENU consists of an overlay with asphalt concrete. The rehabilitation cost is a function of the thickness of the overlay, the cost of the materials used in the construction of the overlay, and the width of the shoulders. Two different methodologies are provided to determine the thickness of the overlay. In case of flexible pavements, use is made of elastic layer theory when heavy rehabilitation is needed due to the effect of traffic loadings. In case of rigid pavements, the thickness is determined using modified AASHTO equations.

5.2.1 Flexible Pavements

In the analysis of flexible pavements, RENU allows the consideration of two possibilities. If a pavement fails because of distress, a specified thickness of overlay is applied. The overlay thickness is a user input and can vary from one type of pavement to another. A thick overlay is recommended when the distress is of the type that causes a significant reduction in the structural strength of the pavement.

5.2.1.1 Pavements that Fail Because of Distress

Experience dictates that most pavements in Texas are rehabilitated when a significant amount of distress is present. The user must input the minimum overlay thickness that is recommended for each representative pavement section.

5.2.1.2 Pavements that Fail Because of Serviceability

Elastic layer theory employing the Russian Equations [34] will be utilized to determine the overlay thickness of pavements that fail because
of serviceability. The resulting overlay thickness is that which satisfies a maximum dynaflect deflection criterion when subjected to a specified load determined by the number of 18-kip ESALs to be applied during the design period.

Representative pavement sections have been coded into the program including the moduli of elasticity of the different layers. Table 5.3 shows the sections coded into RENU. The dynaflect maximum deflection allowed is based upon the design criteria shown in Table 5-4.

From the Texas performance equations for K, it is possible to express this value as a function of DMD. For the purpose of the present analysis, K will be described by the relationship

\[ K = (DMD)^{1/\beta} \]  

(5-5)

The value of \( \beta \) used in Eq. (5-5) can be obtained by solving this equation after \( K' \) is set to a specific value which can be found from Eq. (3-15) with \( n=1 \), that is,

\[ K = - W \ln \left( \frac{P_i - P_t}{P_i - P_f} \right) \]  

(5-6)

for given values of \( P_i, P_t, P_f, \) and \( W. \)

For a known value of \( \beta \), the variations in loading (ESALs) can be linked to changes in the dynaflect deflection (DMD) utilizing Eq. (5-7):

\[ DMD = - \left[ W \ln \left( \frac{P_i - P_t}{P_i - P_f} \right) \right]^\beta \]  

(5-7)
<table>
<thead>
<tr>
<th>Pavement</th>
<th>Layer Thickness (in.)</th>
<th>Modulus of Elasticity (0-overlay)</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4</td>
<td>0  1  2  3  4</td>
<td></td>
</tr>
<tr>
<td>Rural surface treated</td>
<td>.75 6.0</td>
<td>65,000 20,000 10,600</td>
<td>5,000</td>
</tr>
<tr>
<td>Rural Hot Mix (low traffic)</td>
<td>2.0 8.0</td>
<td>300,000 80,000 15,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Rural Overlaid (low traffic)</td>
<td>2.0 2.0 8.0</td>
<td>325,000 130,000 90,000 16,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Rural Hot Mix (high traffic)</td>
<td>4.0 12.0</td>
<td>305,000 100,000 16,500</td>
<td>6,000</td>
</tr>
<tr>
<td>Rural Overlaid (high traffic)</td>
<td>3.0 4.0 12.0</td>
<td>325,000 130,000 90,000 18,500</td>
<td>6,000</td>
</tr>
<tr>
<td>Urban surface treated</td>
<td>.75 8.0</td>
<td>65,000 20,000 12,800</td>
<td>6,100</td>
</tr>
<tr>
<td>Urban Hot Mix (low traffic)</td>
<td>2.0 8.0 6.0</td>
<td>300,000 85,000 22,000 16,400</td>
<td>6,000</td>
</tr>
<tr>
<td>Urban Overlaid (low traffic)</td>
<td>2.0 2.0 8.0 6.0</td>
<td>325,000 130,000 90,000 38,000 19,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Urban Hot Mix (high traffic)</td>
<td>4.0 10.0 6.0</td>
<td>325,000 95,000 35,000 18,500</td>
<td>6,000</td>
</tr>
<tr>
<td>Urban Overlaid (high traffic)</td>
<td>3.0 4.0 10.0 6.0</td>
<td>325,000 150,000 115,000 42,000 22,000</td>
<td>6,000</td>
</tr>
</tbody>
</table>
TABLE 5-4. DYNAFLECT MAXIMUM DEFLECTION CRITERIA FOR REPRESENTATIVE SECTIONS

<table>
<thead>
<tr>
<th>Pavement</th>
<th>DMD</th>
<th>Design Life 18-Kip ESALs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural Surface treated</td>
<td>1.2</td>
<td>20,000</td>
</tr>
<tr>
<td>Rural Hot Mix (low traffic)</td>
<td>.8</td>
<td>300,000</td>
</tr>
<tr>
<td>Rural Hot Mix (high traffic)</td>
<td>.7</td>
<td>3,000,000</td>
</tr>
<tr>
<td>Rural Overlaid Hot Mix (low traffic)</td>
<td>.7</td>
<td>260,000</td>
</tr>
<tr>
<td>Rural Overlaid Hot Mix (high traffic)</td>
<td>.6</td>
<td>2,600,000</td>
</tr>
<tr>
<td>Urban Surface treated</td>
<td>1.0</td>
<td>50,000</td>
</tr>
<tr>
<td>Urban Hot Mix (low traffic)</td>
<td>.7</td>
<td>750,000</td>
</tr>
<tr>
<td>Urban Hot Mix (high traffic)</td>
<td>.6</td>
<td>7,500,000</td>
</tr>
<tr>
<td>Urban Overlaid Hot Mix (low traffic)</td>
<td>.6</td>
<td>650,000</td>
</tr>
<tr>
<td>Urban Overlaid Hot Mix (high traffic)</td>
<td>.5</td>
<td>6,500,000</td>
</tr>
</tbody>
</table>
5.2.2 Rigid Pavements

The required overlay thickness for rigid pavements is determined using the modified AASHTO equations. Once this thickness is known, the cost of overlaying the traffic lanes and the shoulders can be determined. The methodology for determining the cost of the overlay and raising the shoulders up to the edge of the pavement is the same as that used in NULOAD [33].

5.2.3 Highway Cost Index for Rehabilitation

The Surfacing Cost Index from the current Forecasts of the Highway Cost Index [35] is input by the user as a constant rate by approximating the projected index to a straight line. This will account for future price increases in surfacing materials used in the placement of overlays. Figure 5-3 illustrates a factor of 11.8% as obtained from the July 1980 report [35].
Figure 5-3. Surfacing Cost Index by Fiscal Years (1979 = 100)
Chapter 6
THE SHIFTING PROCEDURE

6.1 The SDHPT Shifting Procedure

In order to evaluate the effect of legal load limit changes on future truck weight distributions, the cumulative percentage of gross vehicle weight (GVW) is shifted, according to tendencies observed in recent years. To accomplish this shifting procedure, the user should supply the appropriate load information for each of the truck types to be considered (basically, truck types 2D, 3A, 3-S2). Although the SDHPT procedure (SSP) currently considers the shifting of the distribution of gross vehicle weight (GVW), it is more useful when related data exist, to shift the distributions corresponding to single, tandem, tridem, steering axle loads, and empty vehicle weight.

The shifting procedure is a simple relationship according to which the existing GVW upper limit is multiplied by a factor that increases linearly from 1.0 to the ratio of practical maximum GVW at present (PMGVWP) to practical maximum GVW in the future. As the GVW increases from the lower limit of the first weight interval to the value of PMGVWP, the factor is linearly increased and at the limit becomes constant and equal to PMGVWF/PMGVWP. The result is the end point of a new interval.

Thus, the shifting is done by calculating a ratio, obtained from past experience, that will give the future vehicle weight distribution for a certain truck type. Afterwards, the relation between the future GVW and the axle weights is calculated manually for each truck type, and the future axle weight distribution is obtained. The empty weight for 1976
to date was estimated by assuming the same distribution prevailing in the years 1970-1974.

The ratio used for developing the SSP was based on a multiplying factor which is the result of an equation that implies all the different possibilities of a GVW increase for the 4 more common truck types (See Fig. 6-1 in which SGVW is smallest GVW).

The SSP was developed within the NCHRP report #141 and was incorporated into the RENU program to predict the effect of heavier trucks on pavements.

In an analysis of recent truck data, it was found that the weight constraints within the different vehicle types do not all experience a rightward shift, but that only a certain percentage shifts for each truck type. The reason being, that not all the trucks would experience an increment in weight, since some have demand constraints as well as volume constraints that make higher load capacities for them unnecessary.

In order to properly account for these constraints, the lower portion of the GVW cumulative frequency distribution will have to experience less of a shift to the right, or no shift at all. Only those vehicles operating in the upper GVW ranges would truly take advantage of the new allowable weight limits. Only those vehicles operating in the upper GVW distribution should then experience a substantial shift to the right.

Vehicles weighted empty were assumed to remain constant in both scenarios.
Multiplying Factor

$PMGVWF/PMGVWP$

1.0

$SGVW$

$PMGVWP$

Gross Vehicle Weight (Kips)

for $SGVW < GVW < PMGVWP$

$$\text{Multiplying Factor} = 1.0 + \frac{PMGVWF - 1.0}{PMGVWP - SGVW} \times (GVW - SGVW)$$

for $GVW > PMGVWP$

$$\text{Multiplying Factor} = \frac{PMGVWF}{PMGVWP}$$

Figure 6-1. Multiplying Factor Related to Gross Vehicle Weight for the NCHRP Procedure
6.2 The Modified SDHPT Shifting Procedure (MSP)

In order to modify the GVW distribution shifting procedure, it became necessary to modify only the multiplying factor to be used in the shifting procedure, using 1970-1974 data. Five different analyses were conducted, each using a constant payload, the equivalent to that hauled by 100 vehicles of a certain type operating on a particular highway class under present conditions. The procedure that best fitted the existing conditions was found to be the one that would consider only the shifting from the 50% cumulative, for truck types 2D and 3A and 33% cumulative, for truck types 3-s2 and 2-S1-2 (Fig. 6-2).

Recently, data from 1976 to 1979 was made available, making it possible to check the assumptions made previously. The following statistics were compared:

1. GVW accumulative frequency based on single year data or data combined for several years
2. GVW distribution histogram
3. Average GVW
4. % of overweight trucks
5. Axle weight accumulative frequency
6. Accumulative frequency vs. GVW for different years

The comparison was made using four common truck types and data for interstate rural highways and other main highways [45].

Some of the observations extracted from the comparison were:

1. A definite increase in GVW is observed from 1971-75 data to 1976-79 data.
2. The assumption that empty or lightly loaded vehicles will not experience the rightward shift due to demand and volume constraints is confirmed.
Figure 6-2. Multiplying Factor versus GVW Relationship for Modifying Data Generated under the Previous Law as Developed by Larkin, [14]
3. The axle weight data was also observed, showing change in axle weight and GVW according to the 1975 increase in limits, but no change in the distribution of steering axle weight.

4. The increase in GVW is mainly governed by the increase in axle weight [44].

As several tests have shown, it is not feasible to establish a definite percentage in which to begin the shifting for the four different truck types. As to the latest runs using 1979 data, truck types 2D and 3A experience a shifting in their GVW from 40% and 30% up to 100%, while truck types 3-S2 and 2-S1-2 experience shifting from 0% to 100% inclusive.

However, more data is needed in order to establish a definite percentage from which to begin the shifting so the user would rather input the percentage to use according to the most recent results available (Fig. 6-3).

Once the shifted GVW is obtained, the axle weight distribution is obtained manually for each truck type, according to previous results and to the existing weight limits. First, the front axle (FA) or steering axle weight is obtained, with the following equations.

<table>
<thead>
<tr>
<th>Truck Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>FA = 2.0 + 0.27GVW</td>
</tr>
<tr>
<td>3A</td>
<td>FA = 2.9 + 0.2GVW</td>
</tr>
<tr>
<td>3-S-2</td>
<td>FA = 6.0 + 0.05GVW</td>
</tr>
<tr>
<td>2-S1-2</td>
<td>FA = 7.5 + 0.03GVW</td>
</tr>
</tbody>
</table>

Afterwards, subtracting the FA, as each truck type has either single axles or tandem axles, the remaining weight is distributed evenly among the loading axles (Fig. 6-4).
Figure 6-3. Modified SDHPT Shifting Procedure
(1) The user will decide on the %; the previous SSP computed the ratio for all trucks.
(2) The axle weight distribution is obtained manually for each type of truck.

Figure 6-4. Modified SDHPT Shifting Procedure
6.3 The Plotting Subroutine

As an auxiliary procedure that will enable the user to show the shifted results in a graphic form, the PLOTTING subroutine was added to the RENU Program. The plotting subroutine [46] permits comparison of two or more sets of data of which usually one is the unshifted cumulative frequency and the other is the shifted result. For the sake of clarity, it is advisable not to compare more than 4 sets of data, shifted and unshifted, at the same time.

The type of curve provided by the PLOTTING subroutine is of a simple form, with two coordinates, the X coordinate being the GVW (kips) or TAW (Tandem axle weight), providing up to 120 kips in the first case or 60 kips in the second case; the Y coordinate is the accumulated percent shifted. The usual graph is S-shaped, with an upper asymptote, as shown in Figure 6-5.
Figure 6-5. Shifting Procedure
Chapter 7
APPLICATIONS OF THE MODEL

7.1 Introduction

After developing RENU we have reached the stage at which we introduce a procedure designed to note specific strengths and general usefulness of the program. The purpose of this chapter is to identify a set of meaningful scenarios of the Texas highway system and produce rehabilitation and cost estimates by running RENU under conditions specified in each scenario.

The results from all the scenarios can be combined to assist decision making concerning the estimation of rehabilitation and maintenance funds needed in each period of a specified planning horizon. In Chapter 7 the results obtained for the scenarios will be used to assess the relative impact that factors such as the Highway Cost Index (HCI), change in the load limits and pavement performance have on funds needed.

Twelve scenarios were utilized to demonstrate RENU's response to changes in various input parameters. The flexible pavement network for Texas was the basis for the scenarios. The state was divided into two major geographical areas based upon main distress types prevailing in each area. Area 1 included District 1 and Districts 10 through 22, where pavements fail mainly because of alligator cracking. Area 2 includes Districts 2 through 9 and 23 through 25, where pavements fail mostly because of severe transversal cracking. Pavements were classified according to the following characteristics:

(a) Interstate, Farm to Market, U.S.-State
(b) rural or urban
(c) high or low traffic intensity
(d) hot mix, overlay or surface treated

The classification of Texas pavements was performed using the SDHPT Road Life and Road Inventory files.

The twelve scenarios were divided into two groups. The first group, consisting of eight scenarios, corresponds to different combinations of possible values for the HCI, load limits, and pavement performance. For each of these factors minimum and maximum levels were chosen to reflect realistic changes of interest. In these scenarios the rehabilitation needs are generated by the presence of several types of distress. In the second group, consisting of four additional scenarios, the rehabilitation needs are generated by significant worsening of riding conditions (PSI).

The following assumptions were made for the first eight scenarios:
(a) All pavements fail because of distress and thus receive a one inch overlay. Pavements in POTTS receive a 1½ inch overlay.
(b) The target value for pavements older than terminal service-ability (POTTS) is 10%.
(c) Maintenance and rehabilitation costs are the same statewide (based on costs obtained from District 17).
(d) The upper and lower values for the HCI are 12% and 2%.
(e) The upper and lower values for the legal load limits are:
Single axle : 26 - 22.4 kips
Tandem axle : 44 - 36 kips
Gross Weight : 120-80
The performance factor is defined as the time between the first and second overlays (except for the lanemiles in POTTS). The upper and lower values for this factor were set to 12 and 5 years, respectively. For a planning horizon of 18 years (through the year 2000), the minimum value of the performance factor corresponds to two overlays for all pavements not in POTTS. On the other hand, the maximum value (12 years) corresponds to only a fraction of the pavement receiving two overlays.

For the pavements in the second group, it is assumed that all pavements fail because of serviceability. The performance factor is defined as a terminal serviceability index \( P_t \) between 2.25 and 2.75, with an asymptotic serviceability value \( P_f \) of 2.0. The serviceability performance models for flexible pavements contained within RENU were developed using \( P_t = 2.5 \) and \( P_f = 2.0 \). Wide variations from these values should not be considered to avoid possibly illogical results.

7.2 Description of Texas Flexible Pavement Scenarios

The twelve scenarios for the application of the RENU program covering meaningful conditions concerning the HCI, load limits and performance factors are described in Tables 7.1 and 7.2. Table 7.1 specifies the values of each factor in each scenario. Table 7.2 summarizes some of the most important input parameters common to all scenarios.

7.3 Results

The output from RENU corresponding to each highway scenario can be classified as follows:
(a) Undiscounted Maintenance Costs for the Proposed Load Limits - Summarized in Table 7.3.

(b) Undiscounted Rehabilitation Costs for the Proposed Load Limits - Table 7.4.

(c) An Economic Analysis - Table 7.5.

(d) Increase in Costs per Lane Mile Due to Increased Load Limits - Table 7.6.
<table>
<thead>
<tr>
<th>Factor</th>
<th>Scenarios</th>
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<td>2</td>
<td>12</td>
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<td>12</td>
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<td>12</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Proposed Load Limits (kips)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>22.4</td>
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<td>26</td>
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<td>120</td>
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<td></td>
<td></td>
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<td>Time between first and second overlay **(years)</td>
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<td>12</td>
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<td>5</td>
<td>5</td>
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<td>5</td>
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<td>NA</td>
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<td>Terminal service-ability</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Maximum overlay thickness (inches)</td>
<td></td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>NA</td>
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<td>NA</td>
<td>6,4,5*</td>
<td>6,4,5*</td>
<td>6,4,5*</td>
<td>6,4,5*</td>
</tr>
</tbody>
</table>

(**) for all lane miles except those in POTTS

(*) 6" Interstate
4" FM
5" US & State
<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Analysis period</td>
<td>18 yrs</td>
</tr>
<tr>
<td>Annual Interest Rate</td>
<td>4% + PCI</td>
</tr>
<tr>
<td>Lane width</td>
<td></td>
</tr>
<tr>
<td>Interstate</td>
<td>12 ft</td>
</tr>
<tr>
<td>FM</td>
<td>11 ft</td>
</tr>
<tr>
<td>US - State</td>
<td>12 ft</td>
</tr>
<tr>
<td>Percent paved shoulders</td>
<td></td>
</tr>
<tr>
<td>Interstate</td>
<td>95%</td>
</tr>
<tr>
<td>FM</td>
<td>10%</td>
</tr>
<tr>
<td>US - State</td>
<td>10%</td>
</tr>
<tr>
<td>Cost of HMAC for overlay</td>
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</tr>
<tr>
<td>Cost of turf material for shoulder</td>
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<tr>
<td>Unit cost of bituminous patching</td>
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<td>Unit cost of bituminous crack sealing</td>
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<tr>
<td>Unit cost of bituminous base &amp; surface repair</td>
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<tr>
<td>Maintenance cost per yr per lane mile for Potts</td>
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</tr>
<tr>
<td>Interstate</td>
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<tr>
<td>FM</td>
<td>$750/lane mi/yr</td>
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<tr>
<td>US - State</td>
<td>$750/lane mi/yr</td>
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<tr>
<td>Present load limits (kips)</td>
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</tr>
<tr>
<td>Single axle</td>
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</tr>
<tr>
<td>Tandem axle</td>
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<tr>
<td>Gross weight</td>
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<td>Annual growth rate for ESALS</td>
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<td>Total lane miles</td>
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TABLE 7-3. UNDISCOUNTED MAINTENANCE COSTS FOR PROPOSED LOAD LIMITS (ALL COSTS IN MILLIONS OF DOLLARS)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Year 1</th>
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<th>3</th>
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<th>5</th>
<th>6</th>
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<td>84.002</td>
<td>111.210</td>
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<td>43.471</td>
<td>76.191</td>
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<td>142.244</td>
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<td>184.534</td>
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<td>202.311</td>
<td>50.394</td>
<td>225.043</td>
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TABLE 7-4. UNDISCOUNTED REHABILITATION COSTS FOR PROPOSED LOAD LIMITS (ALL COSTS IN MILLIONS OF DOLLAR)

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<th>7</th>
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<td>.379</td>
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### TABLE 7.5. ECONOMIC ANALYSIS (ALL COSTS IN MILLIONS OF DOLLARS)

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<td>Present Value</td>
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<td>Uniform Annual Equivalent</td>
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</table>

### TABLE 7.6. INCREASE IN COST/LANEMILE DUE TO CHANGE IN LOAD LIMITS (COST IN DOLLARS)

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<tr>
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8.1 Sensitivity Analysis for Flexible Pavements

The purpose of this chapter is to present a sensitivity analysis that was performed utilizing the first eight scenarios for flexible pavements. By employing a statistically designed experiment a number of factors can be studied to gain insight of their simultaneous effects on the response under investigation.

The factors studied in this analysis were the Highway Cost Index, the proposed load limits and the pavement performance to ascertain their effects or influence on the following six response variables:

(a) The change in the uniform annual maintenance, rehabilitation and total costs, of the present and proposed load limits for an 18 year analysis period.

(b) The change in the uniform annual maintenance, rehabilitation and total costs of the present and proposed load limits for a 9 year analysis period.

These costs do not include salvage value computations.

To explore such situations completely we cannot vary one factor at a time, we must rather consider all combinations of the factors. This plan is called a factorial design. This approach allows for the determination of main and interactive effects. A main effect may be defined as the change in response, say cost, produced by a change in the level of the factor. An interaction between two factors denotes that a change
in response between levels of one factor is not the same for all levels of the other factor.

For the three variables in this analysis, a $2^3$ design (the eight scenarios) covers all possible combinations of the testing conditions. Thus, six factorial designs were utilized, one for each of the response variables.

### TABLE 8-1. LEVELS FOR EACH FACTOR

<table>
<thead>
<tr>
<th>Variables</th>
<th>Low Level</th>
<th>High Level</th>
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</tr>
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<td>Proposed Load Limits</td>
<td>22.4-36-120 kips</td>
<td>26-44-120 kips</td>
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<tr>
<td>Performance</td>
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<td>5 years</td>
</tr>
</tbody>
</table>

A computerized package available for IBM computers, the Statistical Analysis System (SAS), was used to perform the calculations of the analysis.

### 8.2 Sensitivity Analysis

To estimate main effects and interactions effects, the following two formulas were utilized:

For main effects

$$E[X_i] = \frac{1}{2^{n-1}} \sum_k C_{ik} \gamma_k$$  \hspace{1cm} (8-1)

where

- $C_{ik} = +1$ or $-1$, and
- $\sum_k C_{ik} = 0$ for all $i$
For interactions:

\[
E[X_i X_j] = \frac{1}{2^{n-1}} \sum_{k} C_{ijk} Y_k
\]  \hspace{1cm} (8-2)

where

\[
C_{ijk} = +1 \text{ or } -1, \text{ and } \sum_{k} C_{ijk} = 0 \text{ for all } i, j
\]

Tables 8-3 through 8-8 produced by SAS show the significant factors and their corresponding effects for each of the response variables.

In these tables \(x_1, x_2, x_3\), are HCI, load limits and performance, respectively. Table 8-2 shows the values of the response variables \(y_1, y_2, y_3, y_4, y_5, y_6\) on page 78.

8.3 Discussion of Results

The effect of the load limits was the most predominant among all the response variables tested, proving significant in every test.

For the eighteen year planning horizon all of the factors proved significant including an interaction between \(x_1\) and \(x_2\) for the change in rehabilitation and total uniform annual costs. In the case of the shorter planning period 9 years only the proposed load limit proved significant.

Table 8-9 summarizes the significant factors for each response variable plus their effects.
8.4 Sensitivity Analysis for Rigid Pavements

A separate sensitivity study was made concerning the new rigid pavement features included in the RENU program. Three new variables were selected for this sensitivity analysis. They were:

(1) modulus of elasticity of concrete,  
(2) terminal level of PSI, and  
(3) number of failures per mile.

Two levels of each variable were chosen, and a $2^3$, or 8, observation factorial was performed. The dependent variable being considered was the Net Present Worth Delta Cost. This variable represents the change in the total overall cost produced when changing from the present to proposed axle load limits.

Table 8.10 indicates the values selected for the two levels of each variable, and the results calculated for Delta Cost by RENU. Figure 8.1 shows an illustration of how the Delta Cost changed as a function of the levels of the three independent variables. Increasing the concrete modulus, terminal PSI, and number of failures all had the effect of reducing the Delta Cost. The variable with the most sensitivity of these three was the failure per mile with the terminal PSI being somewhat less sensitive. Very little effect was noticed by the change in concrete modulus. Since the slopes of the lines in Figure 8.1 seem to remain constant, there is no indication of any change in Delta Costs caused by the interactive effects of any two variables.
<table>
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<th>X3</th>
<th>Y1</th>
<th>Y2</th>
<th>Y3</th>
<th>Y4</th>
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<td>-1</td>
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TABLE 8-3. RESULTS OF THE ANALYSIS OF VARIANCE FOR THE CHANGE IN THE UNIFORM ANNUAL MAINTENANCE COSTS OF PRESENT AND PROPOSED LOAD LIMITS FOR AN 18-YEAR ANALYSIS PERIOD.

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<th>PR &gt; F</th>
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Statistical Analysis System

General Linear Models Procedure

Dependent Variable: Y1
TABLE 8-4. RESULTS OF THE ANALYSIS OF VARIANCE FOR THE CHANGE IN THE UNIFORM ANNUAL REHABILITATION COSTS OF PRESENT AND PROPOSED LOAD LIMITS FOR AN 18-YEAR ANALYSIS PERIOD.

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<th>C.V.</th>
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<td>35.11639012</td>
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<th>PR &gt;</th>
<th>STD ERROR OF</th>
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### Table 8-5. Results of the Analysis of Variance for the Change in the Uniform Annual Total Costs of Present and Proposed Load Limits for an 18-Year Analysis Period.

**Statistical Analysis System**

**General Linear Models Procedure**

**Dependent Variable: Y3**

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<th>Source</th>
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<th>T</th>
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TABLE 8-6. RESULTS OF THE ANALYSIS OF VARIANCE FOR THE CHANGE IN THE UNIFORM ANNUAL MAINTENANCE COSTS OF PRESENT AND PROPOSED LOAD LIMITS FOR A 9-YEAR ANALYSIS PERIOD.

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### Table 8-7. Results of the Analysis of Variance for the Change in the Uniform Annual Rehabilitation Costs of the Present and Proposed Load Limits for a 9-Year Analysis Period.

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<td>x2*x3</td>
<td>-15.28437500</td>
<td>-4.85</td>
<td>0.1295</td>
<td>3.15262500</td>
</tr>
<tr>
<td>SOURCE</td>
<td>DF</td>
<td>SJM OF SQUARES</td>
<td>MEAN SQUARE</td>
<td>F VALUE</td>
</tr>
<tr>
<td>------------</td>
<td>----</td>
<td>----------------</td>
<td>-------------</td>
<td>---------</td>
</tr>
<tr>
<td>MODEL</td>
<td>6</td>
<td>37356.05824300</td>
<td>6226.00970717</td>
<td>91.48</td>
</tr>
<tr>
<td>ERROR</td>
<td>1</td>
<td>58.05944450</td>
<td>68.05944450</td>
<td></td>
</tr>
<tr>
<td>CORRECTED TOTAL</td>
<td>7</td>
<td>37424.11768750</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 8-8. Results of the Analysis of Variance for the Change in the Uniform Annual Total Costs of the Present and Proposed Load Limits for a 9-Year Analysis Period.**

**Statistical Analysis System**

**General Linear Models Procedure**

**Dependent Variable: Y6**

**Source**

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>DF</th>
<th>TYPE I SS</th>
<th>F VALUE</th>
<th>PR &gt; F</th>
<th>DF</th>
<th>TYPE IV SS</th>
<th>F VALUE</th>
<th>PR &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>1</td>
<td>484.314978050</td>
<td>71.16</td>
<td>0.0751</td>
<td>1</td>
<td>484.314978050</td>
<td>71.16</td>
<td>0.0751</td>
</tr>
<tr>
<td>X2</td>
<td>1</td>
<td>29607.1241250</td>
<td>420.33</td>
<td>0.0310</td>
<td>1</td>
<td>29607.1241250</td>
<td>420.33</td>
<td>0.0310</td>
</tr>
<tr>
<td>X3</td>
<td>1</td>
<td>823.14464050</td>
<td>12.10</td>
<td>0.1782</td>
<td>1</td>
<td>823.14464050</td>
<td>12.10</td>
<td>0.1782</td>
</tr>
<tr>
<td>X1*X2</td>
<td>1</td>
<td>1151.37668450</td>
<td>16.92</td>
<td>0.1518</td>
<td>1</td>
<td>1151.37668450</td>
<td>16.92</td>
<td>0.1518</td>
</tr>
<tr>
<td>X1*X3</td>
<td>1</td>
<td>53.15836050</td>
<td>0.78</td>
<td>0.5392</td>
<td>1</td>
<td>53.15836050</td>
<td>0.78</td>
<td>0.5392</td>
</tr>
<tr>
<td>X2*X3</td>
<td>1</td>
<td>1877.43536450</td>
<td>27.59</td>
<td>0.1198</td>
<td>1</td>
<td>1877.43536450</td>
<td>27.59</td>
<td>0.1198</td>
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</tbody>
</table>

**Parameter**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ESTIMATE</th>
<th>T FOR HO: PARAMETER = 0</th>
<th>PR &gt;</th>
<th>Std Error of Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTERCEPT</td>
<td>126.25225000</td>
<td>43.29</td>
<td>0.0147</td>
<td>2.91675000</td>
</tr>
<tr>
<td>X1</td>
<td>24.60475000</td>
<td>8.44</td>
<td>0.0751</td>
<td>2.91675000</td>
</tr>
<tr>
<td>X2</td>
<td>59.79875000</td>
<td>20.50</td>
<td>0.0210</td>
<td>2.91675000</td>
</tr>
<tr>
<td>X3</td>
<td>-10.14775000</td>
<td>-3.48</td>
<td>0.1782</td>
<td>2.91675000</td>
</tr>
<tr>
<td>X1*X2</td>
<td>11.99675000</td>
<td>4.11</td>
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<td>2.91675000</td>
</tr>
<tr>
<td>X1*X3</td>
<td>-2.57775000</td>
<td>-0.88</td>
<td>0.5392</td>
<td>2.91675000</td>
</tr>
<tr>
<td>X2*X3</td>
<td>-15.31925000</td>
<td>-5.25</td>
<td>0.1198</td>
<td>2.91675000</td>
</tr>
</tbody>
</table>
As an example of the interpretation of Table 8-9, for an 18 year analysis period the mean change or reduction in the maintenance annual uniform costs from the present to proposed load limits is 4.065 million dollars (response $y_1$). This can be rationalized by the effect of an increased overlay activity ($y_2$ or $y_5$) thus reducing the age of the existing pavements which signifies reduced maintenance costs.

In the cases of $y_2$, $y_3$ an interacting effect appears to exist between the HCI and the proposed load limit. A graphical illustration of interaction effects is given in Figures 8-1 and 8-2. Parallel or nearly parallel lines denote that there is not interaction present, while lines sloping away from each other signify a significant interaction effect, as seen for the interaction of $X_1$ and $y_2$ in the first set of graphs.

<table>
<thead>
<tr>
<th>Response Factor</th>
<th>$y_1$</th>
<th>$y_2$</th>
<th>$y_3$</th>
<th>$y_4$</th>
<th>$y_5$</th>
<th>$y_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td></td>
<td>27.59275</td>
<td>27.85025</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_2$</td>
<td>-4.065</td>
<td>32.53625</td>
<td>28.47125</td>
<td>-10.233</td>
<td>129.82925</td>
<td>119.5975</td>
</tr>
<tr>
<td>$X_3$</td>
<td></td>
<td>-13.33525</td>
<td>-11.35275</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_1X_2$</td>
<td></td>
<td>8.84625</td>
<td>7.69275</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Interaction $x_1, x_2$ on $y_1$

Interaction $x_1, x_3$ on $y_1$

Interaction $x_2, x_3$ on $y_1$

Interaction $x_1, x_2$ on $y_2$

Interaction $x_1, x_3$ on $y_2$

Interaction $x_1, x_3$ on $y_2$

Interaction $x_1, x_2$, on $y_3$

Interaction $x_1, x_2$ on $y_3$

Interaction $x_1, x_2$ on $y_3$

Figure 8-1. Two Factor Interaction in a Factorial Experiment for Responses $y_1, y_2,$ and $y_3$
Figure 8-1. Two Factor Interaction in a Factorial Experiment for Responses $y_1$, $y_2$, and $y_3$
TABLE 8.10. VALUES ARE NEW VARIABLES AND RESULTS.

<table>
<thead>
<tr>
<th>Case</th>
<th>Concrete Modulus (PSI)</th>
<th>Terminal PSI</th>
<th>Number of Failures</th>
<th>NPW Delta Cost (Millions of Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$4.5 \times 10^6$</td>
<td>3.0</td>
<td>2.0</td>
<td>23.42</td>
</tr>
<tr>
<td>2</td>
<td>$4.5 \times 10^6$</td>
<td>3.0</td>
<td>8.0</td>
<td>18.37</td>
</tr>
<tr>
<td>3</td>
<td>$4.5 \times 10^6$</td>
<td>2.5</td>
<td>2.0</td>
<td>26.00</td>
</tr>
<tr>
<td>4</td>
<td>$4.5 \times 10^6$</td>
<td>2.5</td>
<td>8.0</td>
<td>20.96</td>
</tr>
<tr>
<td>5</td>
<td>$6.0 \times 10^6$</td>
<td>3.0</td>
<td>2.0</td>
<td>23.07</td>
</tr>
<tr>
<td>6</td>
<td>$6.0 \times 10^6$</td>
<td>3.0</td>
<td>8.0</td>
<td>18.04</td>
</tr>
<tr>
<td>7</td>
<td>$6.0 \times 10^6$</td>
<td>2.5</td>
<td>2.0</td>
<td>25.60</td>
</tr>
<tr>
<td>8</td>
<td>$6.0 \times 10^6$</td>
<td>2.5</td>
<td>8.0</td>
<td>20.57</td>
</tr>
</tbody>
</table>
Figure 8.2: NPW delta cost as function of new variables.
Chapter 9

SUMMARY AND RECOMMENDATION

Briefly, the overall methodology can be synthetized presenting the basic changes made to the NULOAD program in order to obtain RENU: (a) a load distribution procedure has been modified to investigate the shift toward higher loads if new legal axle load limit is considered, (b) the Texas performance equations has been incorporated as an alternative to the AASHTO equations, (c) survivor curves has been generated and integrated to RENU, and (d) the capabilities of the model has been improved in the sense that the rehabilitation costs can be determined considering life cycles for both the current and new axle load legal limits.

The final recommendations of this research can be summarized as follows:

(a) Implementation of RENU in the SDHPT to forecast maintenance and rehabilitation costs considering appropriate levels of significant factors affecting the performance of Texas pavements.

(b) As future activities in other TTI projects such as studies 284 ("Flexible Pavement Data Base and Design") and 325 ("Estimating Remaining Service Life of Flexible Pavements"), research should be conducted to improve the equations to forecast pavement remaining service life and survivor mileage of pavements of a specific age, RENU should be properly modified to reflect such improvement. The current version can be modified to reflect such improvement. The current version of RENU will allow these
modifications without major difficulties.

(c) Emphasis is placed on the importance of maintaining an updated data base which recognizes differences among districts as a result of changes in climate, soil, traffic, and other conditions. In this way, RENU will produce reliable results for each of the 25 districts of the Texas highway system.
REFERENCES


37. Texas Highway Department, "Texas SDHPT Temperature Constant," Research Report No. 32.


45. Yu, Mark and Ng Paul, "Truck Use on Texas Highways," Master's Thesis currently being developed. Center for Transportation Research, The University of Texas at Austin, 1981.
APPENDIX 1

REGRESSION ANALYSIS

The purpose of this appendix is to summarize the results concerning the performance of Texas flexible pavements. The appendix is divided into two parts. Part A corresponds to the serviceability methodology and Part B to the distress methodology. The following notation is used in the presentation of results:

TI = Thornthwaite Index  
PR = Mean Precipitation  
FTC = Freeze-thaw cycle  
WFTC = Wet-thaw cycle  
TM = Mean Annual Temperature  
W = 18-Kip ESALs  
ADT = Average Daily Traffic  
DMD = Dynaflect  
AS = Composite Stiffness  
SCI = Subgrade Stiffness  
TTC = Texas Triaxial Class  
SLL = Liquid Limit  
SPI = Plasticity Index  
T = Years since reconstruction  
SPP = % Subgrade Soil Passing Sieve 200
PART A SERVICEABILITY

1. **Hot Mix Pavement, Rural, Low Traffic** \( (P_i = 4.70) \)

\[
K = 35,000 + 235 \times (SLL)^{-0.2} \times (FTC)^{-0.12} \times (TI)^{-0.22}
\]

\[
PF = 2.10 + 1236 \times (SLL)^{-0.8} \times (TM)^{-0.3} \times (FTC)^{-0.12} \times (WFC)^{-0.21} \times (TI)^{-0.22} \times (AS)^{2.5}
\]

2. **Hot Mix Pavement, Rural, High Traffic** \( (P_i = 4.70) \)

\[
K = 420,000 + 12,000 \times (T)^{0.39} \times (AS)^{2.83} \times (TFC)^{0.12} \times (SCI)^{0.85}
\]

For PF use Eq.\((A1-2)\).

3. **Hot Mix Pavement, Urban, Low Traffic** \( (P_i = 4.73) \)

\[
K = 120,000 - 213 \times 10^{-12} \times (SLL)^{1.64} \times (DMD)^{-0.46} \times (ALF)^{7.97} \times (AS)^{-1.43} \times (PR)^{-3.38} \times (W)^{-0.25} \times (T)^{1.03}
\]

\[
PF = 2.21 + 11.72 \times (SLL)^{-0.08} \times (SCI)^{-0.034} \times (ALF)^{-0.167} \times (WFC)^{-0.08} \times (AS)^{-0.48} \times (T)^{-0.059}
\]

4. **Hot Mix Pavement, Urban, High Traffic** \( (P_i = 4.73) \)

\[
K = 1,330,000 - 2.33 \times 10^{-12} \times (SLL)^{1.64} \times (DMD)^{-0.46} \times (ALF)^{-1.43} \times (AS)^{-1.43} \times (PR)^{-3.38} \times (W)^{-0.25} \times (T)^{1.03}
\]

For PF use Eq.\((A1-5)\).
5. **Surface Treated Pavement, Rural** \((P_i = 4.41)\)

\[
K = 8,250 - 0.684 (DMO)^{0.23} (TI)^{0.38} \times (WFTC)^{0.18} \tag{A1-7}
\]

\[
PF = 2.01 + 14.17 (SPI)^{0.018} (ALF)^{-0.55} (FTC)^{-0.24} (TTC)^{-0.17} (T)^{-0.085} (W)^{-0.55} \tag{A1-8}
\]

6. **Surface Treated Pavement, Urban** \((P_i = 4.41)\)

\[
K = 12,500 + 578 (DMO)^{0.13} (TI)^{0.33} (WFTC)^{0.18} (W)^{0.16} (T)^{1.48} \tag{A1-9}
\]

For PF use Eq. (A-8)

7. **Overlay, Rural, Low Traffic** \((P_i = 4.81)\)

\[
K = 58,300 + 1,253 \times (SCI)^{-0.32} \times (DMD)^{1.4} \times (TI)^{-0.89} (T)^{25} (TTC)^{-1.74} \tag{A1-10}
\]

\[
PF = 3.5 - 0.036 \times (SCI)^{-0.32} (DMD)^{1.4} (TI)^{0.89} (T)^{25} (TTC)^{25} \tag{A1-11}
\]

8. **Overlay, Rural, High Traffic** \((P_i = 4.81)\)

\[
K = 620,000 - 12,320 \times (SCI)^{-0.53} \times (DMD)^{1.5} (TI)^{0.89} (T)^{75} (TTC)^{-1.74} \tag{A1-12}
\]

PF is calculated by Eq. (A1-11)
9. **Overlay, Urban, Low Traffic** ($Pi = 4.81$)

\[
K = 183,000 - 231.6 \ (T)^{1.76} \ (SPP)^{0.8} \ (W)^{-0.47} \quad (A1-13)
\]

\[
PF = 2.00 + 1.31 \ (SCI)^{-0.15} \ (T)^{-0.021} \ (PR)^{-0.137} \quad (A1-14)
\]

10. **Overlay, Urban, High Traffic** ($Pi = 4.81$)

\[
K = 1,833,000 = 2234 \ (T)^{1.8} \ (SPP)^{0.6} \ (W)^{-0.27} \quad (A1-15)
\]

PF is calculated by Eq. (A1-14)
PART B: DISTRESS

1. TYPE OF PAVEMENT: HOT MIX

Rutting Severity

\[ A_1 = 10^{1.98} (SPI)^{-0.82} (ALF)^{0.47} (DMD)^{0.54} (W)^{-0.31} \]  \hspace{1cm} \text{(A1-16)}

\[ A_2 = 10^{6.3} \] \hspace{1.5cm} \text{(A1-17)}

\[ SF = 10^{9.42} (DMD)^{3.45} (W)^{-1.91} (SPI)^{-5.82} (ALF)^{2.80} \] \hspace{1cm} \text{(A1-17)}

Ravelling Severity

\[ A_1 = 10^{0.21} (ALF)^{-2.99} (DMD)^{0.80} (VOL)^{-0.88} (T)^{-1.17} \]
\[ \hspace{3.5cm} (18-KIP)^{-0.33} (FTC)^{-0.89} \] \hspace{2cm} \text{(A1-18)}

\[ A_2 = 10^{6.961} \] \hspace{2cm} \text{(A1-19)}

\[ SF = 10^{2.4} \] \hspace{2cm} \text{(A1-20)}

Flushing Severity

\[ A_1 = 10^{1.441} \] \hspace{2cm} \text{(A1-21)}

\[ A_2 = 10^{5.34} (AS)^{4.89} (ALF)^{-5.24} (SPI)^{-5.70} (WFTC)^{-1.72} (SLL)^{10.98} \] \hspace{1cm} \text{(A1-22)}

\[ SF = 10^{0.27} \] \hspace{2cm} \text{(A1-23)}
Corrugations Severity

\[ A_1 = 10^{-1.77} \text{ (ALF)}^{1.18} \text{ (FTC)}^{0.51} \text{ (TTC)}^{0.67} \text{ (T)}^{0.91} \quad (A1-24) \]
\[
A_2 = 0.00 \quad (A1-25)
\]
\[ SF = 10^{-5.96} \text{ (ALF)}^{2.37} \text{ (FTC)}^{1.03} \text{ (TTC)}^{1.37} \text{ (T)}^{1.91} \quad (A1-26) \]
\[
\text{ (ADT)}^{-0.86} \quad \text{ (18-KIP)}^{0.90}
\]

Alligator Cracking Severity

\[ A_1 = 10^{-0.03} \quad (A1-27) \]
\[ A_2 = 10^6.570 \quad (A1-28) \]
\[ SF = 10^{-5.5} \quad \text{ (T)}^{-5.84} \text{ (TTC)}^{17.30} \text{ (SPI)}^{0.82} \text{ (ADT)}^{6.78} \quad (A1-29) \]
\[
\text{ (18-KIP)}^{-9.07}
\]

Longitudinal Cracking Severity

\[ A_1 = 10^{-0.04} \quad (A1-30) \]
\[ A_2 = 10^6.34 \quad (A1-31) \]
\[ SF = 10^{-44.85} \text{ (TTC)}^{14.61} \text{ (AS)}^{-12.75} \text{ (TI)}^{8.46} \text{ (FTC)}^{1.71} \text{ (SLL)}^{24.62} \quad (A1-32) \]
\[
\text{ (SPI)}^{-22.61}
\]
Transverse Cracking Severity

\[ A_1 = 10^{1.132} \]  \hspace{1cm} (A1-33)

\[ A_2 = 10^{-14.64} \cdot (AS)^{5.74} \cdot (VOL)^{1.34} \cdot (SPP)^{17.44} \cdot (FTC)^{-0.25} \cdot (TIME-YRS)^{-2.35} \]  \hspace{1cm} (A1-34)

\[ SF = 10^{-0.754} \]  \hspace{1cm} (A1-35)

Patching Severity

\[ A_1 = 10^{1.077} \]  \hspace{1cm} (A1-36)

\[ A_2 = 10^{6.165} \]  \hspace{1cm} (A1-37)

\[ SF = 10^{-7.90} \cdot (ADT)^{-0.62} \cdot (SCI)^{1.0} \cdot (PR)^{2.21} \cdot (SLL)^{-8.97} \cdot (SPI)^{6.34} \]  \hspace{1cm} (A1-38)

Failures/Mile Severity

\[ A_1 = 10^{-1.37} \cdot (FTC)^{0.59} \cdot (TTC)^{2.13} \cdot (ALF)^{2.03} \cdot (ADT)^{-0.59} \cdot (SLL)^{-1.35} \]  \hspace{1cm} (A1-39)

\[ (18-KIP)^{0.60} \]

\[ A_2 = 0.00 \]  \hspace{1cm} (A1-40)

\[ SF = 10^{-1.281} \]  \hspace{1cm} (A1-41)
Rutting Area

\[ A_0 = 10^6.56 \]  

(A1-42)

Ravelling Area

\[ A_0 = 10^6.96 \]  

(A1-43)

Flushing Area

\[ A_0 = 10^6.82 \]  

(A1-44)

Corrugations Area

\[ A_0 = 0.000 \]  

(A1-45)

Alligator Cracking Area

\[ A_0 = 10^6.81 \]  

(A1-46)
Longitudinal Cracking Area

\[ A_0 = 10^{5.5} \]  

(A1-47)

Transverse Cracking Area

\[ A_0 = 10^{5.49} \]  

(A1-48)

Patching Area

\[ A_0 = 10^{6.351} \]  

(A1-49)
2. **TYPE OF PAVEMENT: HOT MIX ON BLACK BASE**

**Rutting Severity**

\[
A_1 = 10^{0.360} \times (\text{TTC})^{-0.88} \times (\text{VOL})^{0.36} \times (\text{WFTC})^{0.23} \times (\text{ADT})^{0.38} \times (18-\text{KIP})^{-0.45} \quad (A1-50)
\]

\[
A_2 = 10^{-7.35} \times (\text{VOL})^{-1.34} \times (\text{WFTC})^{1.81} \times (\text{TTC})^{7.11} \times (\text{ADT})^{-0.58} \times (\text{ALF})^{11.23} \quad (A1-51)
\]

\[
\text{SF} = 10^{-1.13} \times (\text{VOL})^{2.44} \times (\text{WFTC})^{0.90} \times (\text{TTC})^{-5.25} \times (18-\text{KIP})^{-2.32} \times (\text{ADT})^{1.84} \quad (A1-52)
\]

**Ravelling Severity**

\[
A_1 = 10^{0.07} \quad (A1-53)
\]

\[
A_2 = 10^{3.74} \times (\text{AS})^{3.73} \times (\text{PR})^{-1.20} \times (\text{SPI})^{1.93} \times (18-\text{KIP})^{-1.41} \times (\text{ADT})^{1.11} \quad (A1-54)
\]

\[
\text{SF} = 10^{-0.06} \quad (A1-55)
\]

**Flushing Severity**

\[
A_1 = 10^{-9.57} \times (\text{WFTC})^{0.37} \times (\text{ADT})^{0.19} \times (\text{SPP})^{6.17} \times (\text{AS})^{4.56} \times (\text{SPI})^{-1.83} \quad (A1-56)
\]

\[
\text{SF} = 10^{-0.04} \quad (A1-58)
\]
Corrugations Severity

\[ A_1 = 10^{-0.04} \]  
\[ A_2 = 10^6.7 \]  
\[ SF = 10^{-2.2} \]

Alligator Cracking Severity

\[ A_1 = 10^{-0.03} (SCI)^{0.24} (ALF)^{-1.17} (TTC)^{1.25} (TI)^{-15.41} \]  
\[ (TIME-YRS)^{1.24} \]  
\[ A_2 = 10^6.88 \]  
\[ SF = 10^{-1.07} (SCI)^{1.05} (ALF)^{-4.64} (SPI)^{1.97} (TIME-YRS)^{5.22} \]

Longitudinal Cracking Severity

\[ A_1 = 10^{-0.02} (TI)^{-11.70} (TIME-YRS)^{0.54} (TTC)^{0.83} (SPI)^{-0.27} \]  
\[ (18-KIP)^{-0.17} \]  
\[ A_2 = 10^6.74 \]  
\[ SF = 10^{-2.26} (18-KIP)^{-1.35} (SPI)^{-1.29} (TIME-YRS)^{4.49} \]
Transverse Cracking Severity

\[ A_1 = 10^{-0.473} (FTC)^{-0.26} (PR)^{-1.21} (18-KIP)^{-0.41} (SCI)^{-0.26} (TIME-YRS)^{2.12} \]  
\[ A_2 = 10^{-1.70} (TIME-YRS)^{-0.70} (PR)^{1.57} (FTC)^{0.83} (AS)^{-4.03} \]  
\[ SF = 10^{11.79} (PR)^{-6.25} (18-KIP)^{-1.41} (FTC)^{-2.69} (TIME-YRS)^{7.20} (AS)^{12.76} \]

Patching Severity

\[ A_1 = 10^{-0.65} \]  
\[ A_2 = 10^{6.66} \]  
\[ SF = 10^{-2} \]

Failure/Mile Severity

\[ A_1 = 10^{0.10} \]  
\[ A_2 = 0.00 \]  
\[ SF = 10^{-0.3} \]
Rutting Area

\[ A_0 = 10^{6.97} \times (SCI)^{0.0054} \times (SPI)^{0.0033} \times (FTC)^{-0.0029} \times (18-KIP)^{-0.0098} \times (TIME-YRS)^{0.022} \times (ADT)^{-0.018} \]  
(A1-77)

Ravelling Area

\[ A_0 = 10^{5.20} \times (FTC)^{0.00076} \times (WFTC)^{-0.0011} \times (SPI)^{0.0012} \times (SPP)^{-0.010} \times (VOL)^{0.00040} \times (TIME-YRS)^{0.0017} \]  
(A1-78)

Flushing Area

\[ A_0 = 10^{4.98} \times (SPP)^{-0.013} \times (DMD)^{0.0034} \times (VOL)^{-0.0061} \times (18-KIP)^{-0.0012} \times (AS)^{-0.019} \]  
(A1-79)

Corrugations Area

\[ A_0 = 10^{6.2} \]  
(A1-80)

Alligator Cracking Area

\[ A_0 = 10^{7.01} \]  
(A1-81)
Longitudinal Cracking Area

\[ A_0 = 10^{6.84} \]

(A1-82)

Transverse Cracking Area

\[ A_0 = 10^{6.13} \]

(A1-83)

Patching Area

\[ A_0 = 10^{6.78} \]

(A1-84)
3. **TYPE OF PAVEMENT: SURFACE TREATED PAVEMENT**

**Rutting Severity**

\[ A_1 = 10^{6.01} \quad (A1-85) \]

\[ A_2 = 10^{7.32} (ADT)^{-0.15} (TIME-YRS)^{-0.25} (SPI)^{-0.97} (PR)^{0.55} \]
\[ (SLL)^{1.83} (TTC)^{-1.75} \quad (A1-86) \]

\[ SF = 10^{-0.2} \quad (A1-87) \]

**Ravelling Severity**

\[ A_1 = 10^{5.31} (VOL)^{-0.57} (AS)^{-2.42} (FTC)^{0.56} (PR)^{0.40} (WFTC)^{-0.39} \]
\[ (18-KIP)^{-0.064} \quad (A1-88) \]

\[ A_2 = 10^{6.05} (TI)^{0.67} (ALF)^{0.78} (VOL)^{0.23} (18-KIP)^{-0.24} (SPI)^{-1.46} \]
\[ (SLL)^{2.44} \quad (A1-89) \]

\[ SF = 10^{-0.01} \quad (A1-90) \]

**flushing Severity**

\[ A_1 = 10^{6.80} \quad (A1-91) \]

\[ A_2 = 10^{5.06} (WFTC)^{-0.15} (AS)^{-1.16} (SPI)^{0.38} (ADT)^{-0.30} (DMD)^{-0.36} \]
\[ SF = 10^{-9.2} (ALF)^{-9.33} (TTC)^{-14.63} (AS)^{-19.30} \quad (A1-93) \]
Corrugations Severity

\[ A1 = 10^{0.98} \quad (A1-94) \]
\[ A2 = 10^{6.18} \quad (A1-95) \]
\[ SF = 10^{-1.91} \quad (A1-96) \]

Alligator Cracking Severity

\[ A1 = 10^{1.49} \quad (A1-97) \]
\[ A2 = 10^{7.43} \quad (A1-98) \]
\[ SF = 10^{-0.25} \quad (A1-99) \]

Longitudinal Cracking Severity

\[ A1 = 10^{-0.36} (SLL)^{0.33} (TI)^{0.39} (VOL)^{-0.076} (PR)^{-0.49} (TTC)^{1.28} \quad (A1-100) \]
\[ A2 = 10^{6.0} \quad (A1-101) \]
\[ SF = 10^{-11.07} (T)^{2.11} (PR)^{-5.10} (ALF)^{-6.78} (SPI)^{7.18} (TTC)^{14.39} \quad (A1-102) \]
Transverse Cracking Severity

\[ A_1 = 10^{-0.46} \]  
\[ A_2 = 10^{6.81} \]  
\[ SF = 10^{-0.07} \]

(A1-103)  
(A1-104)  
(A1-105)

Patching Severity

\[ A_1 = 10^{-1.60} \]  
\[ A_2 = 10^{6.86} \]  
\[ SF = 10^{-0.31} \]

(A1-106)  
(A1-107)  
(A1-108)

Failures/Mile Severity

\[ A_1 = 10^{-1.58} \]  
\[ A_2 = 10^{6.24} \]  
\[ SF = 10^{-0.06} \]

(A1-109)  
(A1-110)  
(A1-111)
Rutting Area

\[ A_0 = 10^{7.05} \]  

(A1-112)

Ravelling Area

\[ A_0 = 10^{4.86} \times (PR)^{-0.31} \times 10^{-3} \times (TI)^{0.52} \times 10^{-3} \]  

(A1-113)

Flushing Area

\[ A_0 = 10^{4.96} \times (VOL)^{0.24} \times 10^{-3} \times (TI)^{0.40} \times 10^{-3} \times (W)^{-0.11} \times 10^{-3} \]  

(A1-114)

Corrugations Area

\[ A_0 = 10^{6.23} \]  

(A1-115)

Alligator Cracking Area

\[ A_0 = 10^{7.47} \times (TI)^{-0.16} \times 10^{-3} \times (DMD)^{-0.17} \times 10^{-3} \]  

(A1-116)

Longitudinal Cracking Area

\[ A_0 = 10^{5.05} \times (AS)^{-0.55} \times 10^{-3} \times (PR)^{0.26} \times 10^{-3} \]  

(A1-117)
Transverse Cracking Area

\[ A_0 = 10^{6.84} \]  

Patching Area

\[ A_0 = 10^{6.92} \left( \text{DMD} \right)^{0.14} \times 10^{-2} \left( \text{VOL} \right)^{-0.20} \times 10^{-2} \left( \text{TI} \right)^{-0.15} \times 10^{-2} \left( \text{SPP} \right)^{-0.17} \times 10^{-2} \]  

(A1-119)
4. **TYPE OF PAVEMENT:** OVERLAYS

**Rutting Severity**

\[
A_1 = 10^{-0.86} \ (TI)^{0.84} \ (PR)^{-0.69} \ (SPI)^{0.40} \ (ADT)^{0.25} \ (TIME-YRS)^{0.38} \ (A1-120)
\]

\[
A_2 = 10^{7.01}
\]

\[
SF = 10^{-12.95} \ (TI)^{3.55} \ (PR)^{-3.25} \ (SPI)^{1.85} \ (ADT)^{1.73} \ (TIME-YRS)^{-2.15} \ (A1-121)
\]

**Ravelling Severity**

\[
A_1 = 10^{-0.20} \quad (A1-122)
\]

\[
A_2 = 10^{5.13} \quad (A1-123)
\]

\[
SF = 10^{-0.25} \quad (A1-124)
\]

**Flushing Severity**

\[
A_1 = 10^{1.33} \quad (A1-125)
\]

\[
A_2 = 10^{5.03} \quad (A1-126)
\]

\[
SF = 10^{-0.71} \quad (A1-127)
\]
Corrugations Severity

\[ A_1 = 10^{-4.95} (FTC)^{-0.063} (PR)^{-0.22} (SPP)^{4.58} \]

\[ A_2 = 10^{6.191} \]

\[ SF = 10^{-17.11} (WFTC)^{-0.69} (W)^{0.11} (ALF)^{-0.98} (TTC)^{-2.34} (SPP)^{13.73} \]

Alligator Cracking Severity

\[ A_1 = 10^{-0.48} \]

\[ A_2 = 10^{6.74} \]

\[ SF = 10^{-0.03} \]

Longitudinal Cracking Severity

\[ A_1 = 10^{-4.41} \]

\[ A_2 = 10^{4.21} (FTC)^{-0.17} (SCI)^{0.16} (TTC)^{-0.86} (ADT)^{0.18} (TI)^{-1.23} \]

\[ SF = 10^{-15.37} (SLL)^{-3.79} (ADT)^{-0.70} (TI)^{7.00} (FTC)^{1.88} (TTC)^{16.74} (T)^{-2.00} \]
Transverse Cracking Severity

\[
\begin{align*}
A1 &= 10^{-43} \\
A2 &= 10^{5.53} \\
SF &= 10^{-0.04}
\end{align*}
\]

Patching Severity

\[
\begin{align*}
A1 &= 10^{-27} \\
A2 &= 10^{6.78} \\
SF &= 10^{-47}
\end{align*}
\]

Failure/Mile Severity

\[
\begin{align*}
A1 &= 10^{-30} \\
A2 &= 10^{0.11} \\
SF &= 10^{-50}
\end{align*}
\]
Rutting Area

\[ A_0 = 10^{7.17} \ (PR)^{0.011} \ (SPI)^{0.017} \ (SLL)^{-0.030} \]  

(A1-145)

Ravelling Area

\[ A_0 = 10^{5.246} \]  

(A1-146)

Flushing Area

\[ A_0 = 10^{5.14} \]  

(A1-147)

Corrugations Area

\[ A_0 = 10^{6.14} \]  

(A1-148)

Alligator Cracking Area

\[ A_0 = 10^{6.88} \]  

(A1-149)

Longitudinal Cracking Area

\[ A_0 = 10^{6.16} \]  

(A1-150)
Transverse Cracking Area

\[ A_0 = 10^{6.58} \]  \hspace{1cm} (A1-151)

Patching Area

\[ A_0 = 10^{6.88} \]  \hspace{1cm} (A1-152)
5. TYPE OF PAVEMENT: THICK HOT MIX

Rutting Severity
\[ A1 = 10^{-0.561} \]  
\[ A2 = 10^{5.619} \]  
\[ SF = 10^{-0.852} \]  

Ravelling Severity
\[ A1 = 10^{0.510} \]  
\[ A2 = 10^{6.430} \]  
\[ SF = 10^{-0.50} \]  

Flushing Severity
\[ A1 = 10^{-0.736} \]  
\[ A2 = 10^{6.23} \]  
\[ SF = 10^{-0.048} \]  

Corrugations Severity
None
Alligator Cracking Severity

\[ A_1 = 10^{-0.82} \] \hspace{1cm} (A1-162)

\[ A_2 = 10^{5.88} \] \hspace{1cm} (A1-163)

\[ SF = 10^{-3.52} \] \hspace{1cm} (A1-164)

Longitudinal Cracking Severity

\[ A_1 = 10^{-0.88} \] \hspace{1cm} (A1-165)

\[ A_2 = 10^{6.60} \] \hspace{1cm} (A1-166)

\[ SF = 10^{-1.06} \] \hspace{1cm} (A1-167)

Transverse Cracking Severity

\[ A_1 = 10^{0.728} \] \hspace{1cm} (A1-168)

\[ A_2 = 10^{5.887} \] \hspace{1cm} (A1-169)

\[ SF = 10^{-0.294} \] \hspace{1cm} (A1-170)
Patching Severity

\[
A_1 = 10^{-0.92}
\]

\[
A_2 = 10^{5.33}
\]

\[
SF = 10^{-0.89}
\]


Failures/Mile Severity

\[
A_1 = 10^{0.601}
\]

\[
A_2 = 10^6.7
\]

\[
SF = 10^{-0.891}
\]


Rutting Area

\[
A_0 = 10^{6.95}
\]

(A1-177)

Ravelling Area

\[
A_0 = 10^{4.58}
\]

(A1-178)
Flushing Area

\[ A_0 = 10^{4.408} \]

(A1-179)

Corrugations Area

\[ A_0 = 10^{5.3} \]

(A1-180)

Alligator Cracking Area

\[ A_0 = 10^{7.03} \]

(A1-181)

Longitudinal Cracking Area

\[ A_0 = 10^{6.00} \]

(A1-182)

Transverse Cracking Area

\[ A_0 = 10^{6.88} \]

(A1-183)

Patching Area

\[ A_0 = 10^{6.65} \]

(A1-184)
APPENDIX 2
SURVIVOR CURVES

This Appendix contains the survivor curves computer program which was used to generate the set of survivor functions, for flexible pavements, actually used in the RENU program. The computer routine to generate survivor curves has not been incorporated to the RENU program because of the increase in computer time implied by the parameters estimation process, on the other hand, the survivor curves generation is a process which does not need to be repeated more than one time if the initial data is not changed, which is actual situation.

This Appendix has been divided in two parts: the first one contains the flow chart of the survivor curves generation process and the second part is a print out of the computer program. The computer program has the following structure:

1. Subroutine GENERA which contains the procedure developed in Appendix 6 to generate a sample of values of 18-Kip ESALs corresponding with some critical value of the performance index.

2. Subroutine LIKEHO in which is solved the Gamma function and all the other statistical parameters needed are computed.

3. BLOCK DATA where the information corresponding to $P_f$'s and $K$'s values is supplied.
MAIN PROGRAM

Start

Choose given Type of Pavement

Read Observed Performance Constants

Call Genera

NP = 5

Stop
SUBROUTINE GENERA

Start

J = 1, 3

I = 1, M

Section Wear-out?

Yes

Compute \( W_i \) from \( g's \) Equation

Compute % of Sections that wear out

Call Likehoo

Print Results

Call Survive

Return

Ignore it

no
SUBROUTINE LIKEHO

Start

Compute
Sum of Ln ( W_i )

Compute n

Compute Gamma ( n-1/n )

Compute Average of W_i's

Compute K_2

Return
SUBROUTINE SURVIV

Start

For a given Type of Pavement

\[ n, K_2 \]

\[ W(1) \]

Compute Density Function Value

Compute Cumulative Function

Compute Survivor Function

Increase \[ W_i \]

Return
OPTIONS
    DIMENSION TUTEA(100),LL(100),XNXD(500),W(200),
    COMM  PFI(31),XI(31),PF2(48),XK2(48),PF3(48),XK3(48),PF4(48),
    XK4(48),PF5(48),XK5(48),F1(5),P(9),PF(48),XK(48)
    DO 1 M=1,5
  10 CONTINUE
    WRITE(0,11)
  11 FORMAT(5X,'TYPE OF PAVEMENT HCT MIX PAVEMENT LCW'/)
    M = 31
    DO 111 K1=1,M
        PF(K1)=PFI(K1)
        XK(K1)=XK1(K1) + 238.43
    111 CONTINUE
    CALL GENERA(M,NF)
    GO TO 1
  20 CONTINUE
    WRITE(0,21)
  21 FORMAT(5X,'TYPE OF PAVEMENT SURFACE TREATED '/)
    M = 48
    DO 112 K2=1,M
        PF(K2)=PF2(K2)
        XK(K2)=XK2(K2) + 2340.11
    112 CONTINUE
    CALL GENERA(M,NF)
    GO TO 1
  30 CONTINUE
    WRITE(0,31)
  31 FORMAT(5X,'TYPE OF PAVEMENT HOT MIX PAVEMENT LCW'/)
    M = 40
    DO 113 K3=1,M
        PF(K3)=PF3(K3)
        XK(K3)=XK3(K3) + 2340.11
    113 CONTINUE
    CALL GENERA(M,NF)
    GO TO 1
  40 CONTINUE
    WRITE(0,41)
  41 FORMAT(5X,'TYPE OF PAVEMENT OVERLAY LCW'/)
    M = 48
    DO 114 K4=1,M
        PF(K4)=PF4(K4)
        XK(K4)=XK4(K4) + 74.89
    114 CONTINUE
    CALL GENERA(M,NF)
    GO TO 1
  50 CONTINUE
    WRITE(0,51)
  51 FORMAT(5X,'TYPE OF PAVEMENT OVERLAY HIGH'/)
    M = 48
    DO 115 K5=1,M
        PF(K5)=PF5(K5)
        XK(K5)=XK5(K5) + 733.03
    115 CONTINUE
    CALL GENERA(M,NF)
  1 CONTINUE
STOP
END
SUBROUTINE GENERA(K,NP)
DIMENSION TUTEA(10C),LL(10C),XNINC(5000),W(200)
COMMON PF1(31),XI(31),PF2(48),XK(48),PF3(48),XK3(48),PF4(48),
* XK(48),PF5(48),XK5(48),P(5),P(9),PF(48),XK(48)
WRITE(0,71)
71 FORMAT(1X,'SERVE INDEX',10X,'% OF SECTS THAT WEAR OUT',5X,'LOG(K)
* ',10X,'N*/J/)   
DO 2 J=1,N
   L = 0
   DO 3 I=1,J
3 CONTINUE
   STR=2
   IF(NP=9) GO TO 63
   TOTLAL = (-XK(I)/ALOG((FI(NP) - PI(J))/PI(NP) - PF(I)))
   IF(NP=91) AND TOTLAL GT .550000) TOTLAL=375.000
   IF(NP=92) AND TOTLAL GT .550000) TOTLAL=325.000
   IF(NP=94) AND TOTLAL GT .450000) TOTLAL=325.000
   IF(NP=95) AND TOTLAL GT .400000) TOTLAL=325.000
   L = L + 1
   LL(L) = I
   TOTLAL(L) = TOTLAL
   GO TO 3
63 IF(I#L) GO TO 3
   IF(L#G) GO TO 777
   GO TO 62
62 AL = L
   WRITE(0,63) (TUTEA(I),I=1,L)
63 FORMAT(5A,3F15.6)
   XM = M
   PWEAR = XL/XM
   PWEAR = (XM-XL)/XM
   IF(L#L) GO TO 777
   CALL LIKEC(TUTEA,L,J,LL,XX,KP,NN)
   GO TO 680
777 CONTINUE
   PWEAR = 0
   PWEAR = 1
   XN = 22222.
   XK = 333333.
680 WRITE(0,682) P(J),PWEAR,KP,XN
682 FORMAT(13X,F4.2,21X,F5.3,14X,F12.1,7X,F8.3/)
2 CONTINUE
RETURN
END

SUBROUTINE LIKEC(TUTEA,L,J,LL,XX,KP,NN)
DIMENSION XAVE(1500)
DIMENSION TUTEA(10C),LL(10C),XNINC(5000),W(200)
COMMON PF1(31),XI(31),PF2(48),XK(48),PF3(48),XK3(48),PF4(48),
* XK(48),PF5(48),XK5(48),P(5),P(9),PF(48),XK(48)
S1 = J
   D = I=1,L
   Y = ALUG(TUTEA(I))
   S1 = S1 + Y
8 CONTINUE
   AL = L
   STUT = 0

132
DO 10 J1=1,L
STCT = STOT * TCTEA(J1)
10 CONTINUE
AVTCT = STOT / XL

COMPUTATION OF STANDARD DEVIATION AND COEFFICIENT OF VARIATION

S2 = 0.
DO 91 J3=1,L
91 S2 = S2 + (TCTEA(J3) - AVTCT)**2
XL = XL - 1.
SM = S2/XL
SIGMA = S2**0.5
CV = SIGMA / AVTCT

TRIAL AND ERROR PROCEDURE TO ESTIMATE N VALUES USING CV VALUE

XN = 2.5
DO 200 KK=1,10000
ANN1 = (XN - 1.) / XN
XNN0(1) = XNN1
DO 133 J3=1,10000
IF(XNN0(I) * LT * 400.) GO TO 214
K1 = I + 1
XNN0(K1) = XNN0(1) - 1.
IF(XNN0(I+1) * LT * 400.) GO TO 214
133 CONTINUE
214 IF(ISEQ(I)) GO TO 215
ARGAMM = XNN0(I+1)
GO TO 210
215 ARGAMM = XNN0(1)
GO TO 217
216 CONTINUE
PP1 = 1.
L2 = I+1
DO 134 J2=1,L2
PP1 = PP1 * XNN(J2)
134 CONTINUE
GO TO 218
217 CONTINUE
PP1 = 1.
218 GAMN0 = PP1 * GAMMA(ARGAMM)
ANN2 = (XN - 2.) / XN
XNN0(1) = XNN2
DO 314 JJ=1,10000
IF(XNN(JJ) * LT * 400.) GO TO 314
K2 = JJ + 1
XNN(J2) = XNN(JJ) - 1.
IF(XNN(JJ+1) * LT * 400.) GO TO 314
314 CONTINUE
314 IF(JJ*EQ*1) GO TO 315
ARGAMM = XNN(JJ+1)
GO TO 310
315 ARGAMM = XNN(1)
GO TO 317
316 CONTINUE
PP2 = 1.
L3 = JJ + 1
GO 137 J3=1,L3
PP2 = PP2 * XNN(J3)
APPENDIX 3

SURVIVOR CURVES FOR TEXAS PAVEMENTS

This appendix contains the graphical representation of the survivor functions corresponding to all the types of pavements considered for Texas.
Figure 3A-1. Survivor Curve for Rural-Overlaid-Low Traffic Pavement Using Serviceability Criteria
Figure 3A-2. Survivor Curve for Rural-Overlaid-Low Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-3. Survivor Curve for Rural-Overlaid-Low Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-4. Survivor Curve for Rural-Overlaid-High Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-5. Survivor Curve for Rural-Overlaid-High Traffic Pavement Using Serviceability Criteria
Figure 3A-6. Survivor Curve for Rural-Overlaid-High Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-7. Survivor Curve for Urban-Overlaid-Low Traffic Pavement Using Serviceability Criteria.
Figure 3A-8. Survivor Curve for Urban-Overlaid-Low Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-9. Survivor Curve for Urgan-Overlaid-Low Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-10. Survivor Curve for Urban-Overlaid-High Traffic Pavement Using Serviceability Criteria
Figure 3A-11. Survivor Curve for Urban-Overlaid-High Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-12. Survivor Curve for Urban-Overlaid-High Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-13. Survivor Curve for Rural-Hot Mix-Low Traffic Pavement Using Serviceability Criteria.
Figure 3A-14. Survivor Curve for Rural-Hot Mix-Low Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-15. Survivor Curve for Rural-Hot Mix-Low Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-16. Survivor Curve for Rural-Hot Mix-High Traffic Pavement Using Serviceability Criteria
Figure 3A-17. Survivor Curve for Rural-Hot Mix-High Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-18. Survivor Curve for Rural-Hot Mix-High Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-19. Survivor Curve for Urban-Hot Mix Low Traffic Pavement Using Serviceability Criteria
Figure 3A-20. Survivor Curve for Urban-Hot Mix-Low Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-21. Survivor Curve for Urban-Hot Mix Low Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-22. Survivor Curve for Urban-Hot Mix High Traffic Pavement Using Serviceability Criteria
Figure 3A-23. Survivor Curve for Urban-Hot Mix-High Traffic Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-24. Survivor Curve for Urgan-Hot Mix-High Traffic Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-25. Survivor curve for Rural-Surface Treated Pavement using Serviceability criteria
Figure 3A-26. Survivor curve for Rural-Surface Treated Pavement Having Alligator Cracking (Area) type of Distress
Figure 3A-27. Survivor Curve for Rural-Surface Treated Pavement Having Transversal Cracking (Severity) Type of Distress
Figure 3A-28. Survivor Curve for Urban-Surface Treated Pavement using Serviceability Criteria
Figure 3A-29. Survivor Curve for Urban-Surface Treated Pavement Having Alligator Cracking (Area) Type of Distress
Figure 3A-30. Survivor Curve for Urban-Surface Teated Pavement Having Transversal Cracking (Severity) Type of Distress
Definition of Likelihood Function. The likelihood function of m random variables \( W_1, W_2, \ldots, W_m \) is the joint density of the m random variables \( g(W_1, W_2, \ldots, W_m; t, z) \) which is considered to be a function of \( t \) and \( z \). In particular, if \( W_1, W_2, \ldots, W_m \) is a random sample, the joint density function is:

\[
g(W_1, \ldots, W_m; t, z) = f(W_1; t, z) \times \cdots \times f(W_m; t, z) \quad (A4-1)
\]

The likelihood \( g(W_1, \ldots, W_m; t, z) \) gives the relative likelihood that the random variables assume a particular value \( w_1, w_2, \ldots, w_m \).

A likelihood estimator can be defined as follows:

Let \( L(t, z) = g(W_1, W_2, \ldots, W_m; t, z) \) be the likelihood function for the random variables \( W_1, W_2, \ldots, W_m \). If \( \hat{t} \) and \( \hat{z} \) are the values of \( t \) and \( z \) in which maximizes \( L(t, z) \), then \( \hat{t} \) and \( \hat{z} \) are the maximum likelihood estimators of \( t \) and \( z \), respectively.

Many likelihood functions satisfy regularity conditions so that the maximum likelihood estimators are the solution of the simultaneous system of equations:

\[
\begin{align*}
\frac{\partial L(t, z)}{\partial t} &= 0 \quad (A4-2) \\
\frac{\partial L(t, z)}{\partial z} &= 0 \quad (A4-3)
\end{align*}
\]

Also \( L(t, z) \) and \( L_n \left[ L(t, z) \right] \) have their maximum at the same values of \( t \) and \( z \), and it is sometimes easier to find the maximum of the logarithm of the likelihood function.

Given the cumulative density function

\[
F(W; t, z) = e^{-z/W^t} \quad (A4-4)
\]
the corresponding density function of the random variable $W$ is

$$f(W; t, z) = \frac{t z}{W^{t+1}} e^{-z/W^t} \quad (A4-5)$$

Defining the likelihood function as indicated in Eq. (A4-1) and using Eq. (A4-5) as density function of the random variable $W$, the solution of the system of Eqs. (A4-2), (A4-3) gives the following results in terms of the maximum likelihood estimators of $t$ and $z$:

$$\sum_{i=1}^{m} \ln(W_i) - m = m \left( \sum_{i=1}^{m} W_i^{-t} \ln(W_i) \right) \quad (A4-6)$$

$$\hat{z} = \frac{m}{\sum_{i=1}^{m} W_i^{-t}} \quad (A4-7)$$

An approximate solution to the system of equations defined by Eqs. (A4-6) and (A4-7) can be obtained by using a numerical method.

The previous result can be used to estimate the parameters of both the performance function and the survivor curve corresponding to a given type of flexible pavement. In the case of the performance function

$$g(W) = e^{-K/W}$$

$t=1$ and $z=K$. Therefore,

$$\hat{K} = \frac{m}{\sum_{i=1}^{m} W_i^{-1}} \quad (A4-8)$$
APPENDIX 5

MEAN AND COEFFICIENT OF VARIATION OF LOAD APPLICATIONS

The expected value of the random variable \( W \) presented in Appendix 4 can be obtained as follows:

\[
E(W) = \int_0^\infty W f(W,t,z) dW 
\]  

(A5-1)

in particular

\[
E(W) = \int_0^\infty \frac{t}{Z} e^{-Z/W^t} dW 
\]  

(A5-2)

Integrating the above expression,

\[
E(W) = Z^{1/t} P\left(\frac{t-1}{t}\right) 
\]  

(A5-3)

where \( P(\cdot) \) is the Gamma function.

Using the average of \( W_i \)'s as estimator of \( E(W) \), Eq. (A5-3) can be written as:

\[
\bar{W} = Z^{1/t} P\left(\frac{t-1}{t}\right) 
\]  

(A5-4)

From Eq.(A5-4) the value of \( z \) can be derived as shown below

\[
z = \left[ \frac{\bar{W}}{r\left(\frac{t-1}{t}\right)} \right]^t 
\]  

(A5-5)

The variance of the random variable \( W \) can be obtained by the expression:
\[
\text{Var}(W) = \int_0^\infty W^2 \frac{t z}{W^{t+1}} e^{-zW^t} \, dW \quad (A5-6)
\]

Integrating, the resulting value for the variance is:

\[
\text{Var}(W) = z^{2/t} \left[ \frac{\Gamma(t-2)}{t} - \frac{\Gamma(t-1)}{t} \right] \quad (A5-7)
\]

Therefore, the standard deviation is equal to:

\[
\sigma(W) = z^{1/t} \left[ \frac{\Gamma(t-2)}{t} - \frac{\Gamma(t-1)}{t} \right]^{1/2} \quad (A5-8)
\]

The coefficient of variation is defined as:

\[
CV = \frac{E(W)}{\sigma(W)} \approx \frac{\bar{W}}{S_W} \quad (A5-9)
\]

Where \( \bar{W} \) and \( S_W \) are the average and standard deviation of a random sample of \( W \)'s. Using Eqs. (A5-3) and (A5-8), CV can be written as:

\[
CV = \left\{ \frac{\Gamma(t-2)}{t} - 1 \right\}^{1/2} \quad (A5-10)
\]

Eq. (A5-9) can be used to estimate the value of CV. Using this value, Eq. (A5-10) can be solved to obtain \( t \).

The methodology presented in this appendix can be used as an alternative to the methodology presented in Appendix 4. A combination of both methodologies is also possible. For instance Eq. (A5-5) can be used to estimate \( z \) after using Eq. (A4-6) to estimate \( t \).
APPENDIX 6
ESTIMATION OF FLEXIBLE PAVEMENT PARAMETERS

6A. PSI PERFORMANCE PARAMETERS

The estimation of the performance equations parameters can be accompanied by two methodologies:

(1) Statistical Approach: $P_f$ and $K$ can be obtained following the next steps:

Step 1. Fix $n$ equal 1. It can be observed by experience that the value of $n$ is around 1 in the case of performance equations.

Step 2. Observe a set of values of $W$ (18-Kip ESALs) from historical data and for different representative sections of pavements.

Step 3. Use Eq. (A4-7) from Appendix 4 to compute $K$.

Step 4. Having $K$ and a sample of values of $W_i$ compute $P_{fj}$'s values by the expression:

$$P_{fj} = P_i - \frac{P_i - P_f}{e^{-K/W_j}}$$  \hspace{1cm} (A6-1)

Eq. (A6-1) was obtained from Eq. (3-15).

Step 5. Compute the average of $P_{fj}$'s values.

Step 6. Set $P_f$ equal to $P_f$ and adopt the $K$ value from set (3).

(2) Mechanistic Approach: The technique presented through this approach is based upon a set of regression equations for $K$ and $P_f$ values, using as independent variables the mechanistic observations presented in Table 3-2. The methodology, which can be applied to any specific type of pavement, is as follows:

Step 1. Set $n$ equal 1.
Step 2. Using the regression equation from Appendix 1A and the mechanistic variables contained in Table 3-2, compute $R$ and $P_f$ for different representative sections of the pavement type under consideration.

Step 3. Adopt the values of $P_f$ equal to the $\bar{P}_f$, $K$ equal to the $\bar{K}$.

6B. DISTRESS PERFORMANCE PARAMETERS

Similarly, for the distress case a statistical methodology and a mechanistic approach can be used to estimate the parameters of the performance equations.

(1) Statistical Approach: Five basic steps should be followed:

Step 1. Fix $n$ equal 1, $a_2$ in a range between 0.20 and 0.30, and $s_f$ in a range between 0.9 and 1.0.

Step 2. Observe different values of $W$, (18-Kip ESALs) from historical data and for different representative sections of the type of pavement under consideration.

Step 3. Use Eq. (A4-7) from Appendix 4 to compute $a_0$ for the area equation.

Step 4. Use Eq. (A4-7) to compute $a_2$ for the severity equation using the values of $a_1$ and $s_f$ assumed in Step 1.

Step 5. Compute the average values for $a_0$ and $a_2$.

(2) Mechanistic Approach: Three basic steps must be followed in that case:

Step 1. Set $n$ equal 1.

Step 2. Using the regression equations contained in Appendix 1B, compute $a_0$, $a_1$, $a_2$, and $s_f$ values for different representative pavement sections of the type of pavement under consideration.
Step 3. Adopt the average values of $a_0$, $a_1$, $a_2$, and $s_f$ as representative magnitude for the constants.