

DEVELOPING STOCHASTIC FLEXIBLE PAVEMENT DISTRESS  
AND SERVICEABILITY EQUATIONS

by

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Prepared for presentation at  
the Sixty-Fourth Annual  
Transportation Research Board Meeting  
to be held in  
Washington, D.C., January 1985

August 1984

## ABSTRACT

This paper summarizes the development of a method for predicting pavement performance in terms of present serviceability index and four primary distress types (area and severity) and application of the method to the design of flexible pavements. The method is based upon an S-shaped performance curve, the curve fit parameters for which can be determined using the methodology developed by Garcia-Diaz and Riggins. These parameters have been found for 164 pavement test sections throughout the State of Texas. The pavement test sections were categorized in three main types: asphaltic concrete pavements on unbound base course, asphaltic concrete pavements on bituminous base course, and asphaltic concrete overlays. The pavement structure including the elastic modulus of each layer, the environment, and the traffic data for these pavements were used to develop regression models for the curve fit parameters. A sensitivity analysis was made of these models to determine the effects of climate in four highway districts in Texas and the results proved to be satisfactory performance curves. The regression models along with the proposed performance equations and the stochastic form of these equations have been incorporated into the Texas Flexible Pavement Systems (FPS) design computer program. The modified version of FPS provides a listing of the optimal pavement designs selected on the basis of least total cost including material and user costs, overlay costs, and salvage values. This version of FPS lists all of the costs, the

performance periods, the thickness of overlays that were placed, and the ultimate pavement failure mode for each period. Typical results of these analyses are given.

## INTRODUCTION

This paper summarizes recent developments and actual applications of a pavement performance equation that predicts the loss of serviceability index and the deterioration of flexible pavements due to various types of distress. The performance model is an "S-shaped" curve which recognizes that the rate of deterioration of a pavement changes during its service life and that this deterioration process obeys boundary conditions at the beginning and end of its life. The methodology used to evaluate the curve fit parameters was developed by Garcia-Diaz and Riggins (1) and has been applied to field measurements of pavement performance obtained from the Texas data base for flexible pavements which is maintained at the Texas Transportation Institute. The pavement performance is evaluated in terms of the present serviceability index (PSI) and of the following types of distress (both area and severity):

- a) Rutting
- b) Alligator Cracking
- c) Longitudinal Cracking
- d) Transverse Cracking

The first two types of distress are regarded as load-related and the latter two as non-load related. The primary load-related independent variable is the number of 18-kip equivalent axle loads (ESALs) and the primary non-load related independent variable is the number of months since construction or major rehabilitation.

The curve fit parameters for each type of performance have been used in a regression analysis to develop models which allow the parameters to be determined in terms of pavement structure, environment, and traffic variables. The equation of the S-shaped curve is expressed in stochastic form to allow the designer to design a pavement to withstand the expected number of 18-kip ESALs or months of exposure to the environmental influences at a selected level of reliability before reaching a critical level of serviceability or distress, based upon a knowledge of the pavement structure, environment, and traffic. The proposed performance models are readily adaptable to computer applications and have been incorporated into the Texas Flexible Pavement System (FPS) design program. Examples of calculated results are given.

The first part of this paper presents background information pertaining to performance equations and the characteristics of the S-shaped curve. The following section deals with the regression models which are used to determine the curve fit parameters. The third concerns the methodology for predicting the number of 18-kip ESALs or the time required to reach a specified level of serviceability or distress. The final section deals with the application of the method to predicting the performance of Texas pavements, its incorporation into the FPS computer program, and its use in flexible pavement design in Texas.

## FORMS OF THE PERFORMANCE EQUATION

## AASHO Performance Curve

The performance of flexible pavements is evaluated in terms of functional and structural performance. The former is a measure of the riding quality of the pavement and can be quantified in terms of the Present Serviceability Index (PSI). The latter represents a measure of pavement deterioration as determined by the appearance of various forms of distress, e.g. rutting, cracking, patching, etc. The distress types can be quantified in terms of the affected area or the degree of severity of the distress. The two types of performance are related in that the same variables, i.e. pavement structure, environment, and traffic, affect the overall performance and the equation used to predict performance can be of the same form for both functional and structural performance.

The form of the performance equation as developed from the AASHO Road Test is as follows:

$$g = \left(\frac{N}{\rho}\right)^{\beta} \quad (1)$$

where

- g = damage function ranging from 0 to 1,
- N = the applied load, i.e. the accumulated 18-kip  
equivalent single axle loads or total elapsed time,
- $\rho$  = a curve fit parameter which represents the applied load

when  $g$  reaches a value of 1, and thus, gives the "scale" of the curve, and

$\beta$  = a curve fit parameter which defines the degree of curvature or the rate at which damage increases.

The damage function for functional performance is defined in terms of the serviceability index as,

$$g = \frac{P_o - P}{P_o - P_t} \quad (2)$$

where

$P$  = present serviceability index, i.e. serviceability index at a specific value of applied load,

$P_o$  = initial serviceability index, a value of 5 representing a perfectly smooth pavement, and

$P_t$  = terminal serviceability index, a value of 1.5 representing an extremely rough pavement.

The damage function for structural performance is defined in terms of critical values ( $g_c$ ) for distress area and severity. The shape of the functional and structural performance curves obtained from Equation 1 (along with Equation 2 for the functional performance) are shown in Figure 1.

#### The S-Shaped Performance Curve

The primary concern in the use of Equation (1) arises from the following imposed boundary conditions:

- a) The functional (structural) performance curve must have a maximum (minimum) value, at the traffic level or time equal to zero, and must be strictly decreasing (increasing) as the traffic level or time increases.
- b) The performance curve cannot predict negative values of serviceability index nor can it predict a distressed area greater than 100 percent of the total area for large values of traffic level or time.
- c) The performance curve should asymptotically approach the limiting values, as it is physically unrealistic to predict complete pavement failure, i.e. PSI=0 or distressed area=100 percent, at a specific traffic level or point in time.

Although the AASHO equation satisfies the first condition, it is found to be deficient in terms of the last two conditions. In order to overcome these limitations, Texas Transportation Institute researchers (4,5) have adopted the S-shaped performance curve. The equation for the pavement damage,  $g$ , is

$$g = e^{-\left(\frac{P}{N}\right)^{\beta}} \quad (3)$$

In the case of serviceability index, the definition of damage is

$$g = \frac{P_o - P}{P_o - P_f} \quad (4)$$



where

$P_f$  = the asymptotic value of serviceability index

The functional and structural performance curves obtained from this equation are shown in Figure 2. It is observed from this figure that all of the above boundary conditions are satisfied by Equation (3).

## REGRESSION MODELS FOR DESIGN CONSTANTS

The methodology for determining the design parameters in Equation (3) ( $\rho$ ,  $\beta$ , and  $P_f$ ) was developed by Garcia-Diaz and Riggins (1). The analysis of 164 test sections has been conducted on pavements classified as follows:

- a) Hot mix asphaltic concrete on a bituminous base (51 sections)
- b) Hot mix asphaltic concrete on an unbound flexible base (36 sections)
- c) Hot mix asphaltic concrete overlay placed on existing pavements (77 sections)

For each test section, the design parameters were evaluated for the following types of performance:

- a) Present serviceability index
- b) Rutting (area and severity)
- c) Alligator cracking (area and severity)
- d) Longitudinal cracking (area and severity)
- e) Transverse cracking (area and severity)

In addition to performance data, there is also an extensive set of pavement structure, environment, and traffic data available for each section. These data were studied to determine which variables could be considered as being independent, and to determine the effect of each variable on the design parameters,  $\rho$  and  $\beta$ . The variables found to be most significant, and thus used to develop regression models,

are given in Table 1. In this table the equivalent thickness ( $H'$ ) represents the transformed thickness of the pavement which is defined as,

$$H' = \sum_{i=1}^m (E_i/E_s)^n * t_i \quad (5)$$

where

- $M$  = number of layers under consideration,
- $E_i$  = elastic modulus for the  $i$ -th layer,
- $t_i$  = thickness of the  $i$ -th layer,
- $E_s$  = elastic modulus of the subgrade, and
- $n$  = Odemark's constant (0.33) or can be obtained from field data (7).

In order to obtain an indication of surface deflections, the  $H'$  term was transformed to,

$$HPR2 = \frac{E_s H'}{10^5} \quad (6)$$

The  $H'$  term is also used to define the surface curvature index as given by the expression,

$$HPR3 = \frac{10^{10}}{E_s (H')^3} \quad (7)$$

The decade multipliers in Equations (5) and (6) serve to scale the variables so that their magnitudes will be of the same order as the

remaining variables. The regression study consisted of determining the best arithmetic and logarithmic models which expressed the design parameters in terms of the variables given in Table 1, as well as HPR2 and HPR3. The arithmetic and logarithmic models for the present serviceability are given in Tables 2 and 3, respectively. The complete list of regression models for distress can be found in (2). Both model have been incorporated into the revised Texas FPS program but the logarithmic models are used only when the arithmetic models predict values of  $\rho$  or  $\beta$  that are out of range or physically unrealistic. In general, the logarithmic models do not give as good a fit to the data as do the arithmetic models.

## PREDICTION OF PAVEMENT PERFORMANCE

The prediction of pavement performance is concerned with determining the number of vehicles or time required to reach a minimum acceptable level of performance. In terms of functional performance, the prediction is made using the serviceability index damage function, Equation (2), with the S-shaped performance equation, Equation (3), viz.,

$$g = \frac{P_o - P}{P_o - P_f} = e^{-\left(\frac{P}{N}\right)^\beta} \quad (8)$$

This expression represents the loss in serviceability between the initial ( $P_o$ ) and final ( $P_f$ ) states. However, in making the performance predictions, the primary concern is not with the attainment of the final state, but with the performance to a selected terminal state. Therefore, Equation (8) must be "scaled down" to represent the performance loss between the initial level ( $P_o$ ) and the minimum acceptable or terminal level of performance ( $P_t$ ). This can be achieved by multiplying Equation (8) by a scaling factor, viz.,

$$g_t = \frac{P_o - P}{P_o - P_f} * \frac{P_o - P_f}{P_o - P_t} = \frac{P_o - P_f}{P_o - P_t} e^{-\left(\frac{P}{N}\right)^\beta} \quad (9)$$

or

$$g_t = c * e^{-\left(\frac{\rho}{N}\right)^\beta} \quad (10)$$

where

$$g_t = \frac{P_o - P}{P_o - P_t}$$

$$c = \frac{P_o - P_f}{P_o - P_t}$$

Taking the natural log of Equation (10) and solving for N gives,

$$N = \frac{\rho}{[-\ln(g_t/c)]^{1/\beta}} \quad (11)$$

This equation can be used to predict the number of vehicles or amount of time required to attain a minimum acceptable level of performance. For structural performance, Equation (11) can also be used by substituting the critical distress level ( $g_c$ ) for the term ( $g_t/c$ ).

The design parameters ( $\rho$ ,  $\beta$ , and  $P_f$ ) are determined from field data, and thus, the variability of the parameters must be taken into account. This can be achieved by finding the stochastic form of Equation (11). Taking the natural logarithm of this equation and expressing it in terms of the variance of  $\ln(N)$  gives,

$$\text{Var}[\ln(N)] = \text{Var}[\ln(\rho)] + \text{Var}\left[\frac{1}{\beta} * \ln(x)\right] \quad (12)$$

where

$$x = -\ln(g_t/c)$$

which can also be expressed as,

$$\text{Var}[\ln(N)] = \left(\frac{(\sigma_\rho)}{\hat{\rho}}\right)^2 + \left(\frac{1}{\hat{\beta}}\right)^2 * \text{Var}[\ln(x)] \quad (13)$$

where  $\hat{\rho}$  and  $\hat{\beta}$  represent the mean values of  $\rho$  and  $\beta$  as determined from the regression equations. The standard deviation of  $\rho$  (where  $(\sigma_\rho) = (\text{Var}(\rho))^{1/2}$ ) for the present serviceability index is shown in Figure 3.

The general form of the relation between  $(\sigma_\rho)$  and  $\hat{\rho}$  was found to be hyperbolic for serviceability index loss, rutting, and alligator cracking. The relation is

$$(\sigma_\rho) = \frac{\hat{\rho}}{a + b\hat{\rho}} \quad (14)$$

A linear relation was found for longitudinal and transverse cracking. The relation is

$$(\sigma_\rho) = a + b\hat{\rho} \quad (15)$$

Values of the constants  $a$  and  $b$  for serviceability index loss and the different types of distress are shown in Table 4. There was not a significant difference between the standard deviations of  $\rho$  for the different types of pavement or between area and severity of distress.

The variance of  $\ln(x)$  for the present serviceability index has been found to have a constant value of 0.125. This term is zero for

the distress equations since the variable ( $g_t/c$ ) is replaced by  $g_c$  or the critical distress level. Since this value is a constant, it can have no variance.

The design equation currently in use (3,6) is expressed in terms of the standard deviation of the common logarithm, therefore, for the sake of compatibility it becomes necessary to express Equation (13) in the following form:

$$\text{Var} [\log(N)] = 2.302 * \text{Var}[\ln(N)] \quad (16)$$

The expression for the variance of  $\log(N)$  is used to determine the number of 18-kip ESALs or the number of months for which a pavement must be designed in order to have a specified level of reliability. "Reliability" as it is used in the Texas FPS design program is defined as

$$\frac{R}{100} = \frac{1}{\sqrt{2\pi}} \int_{-\bar{z}}^{\infty} e^{-\frac{z^2}{2}} dz \quad (17)$$

where

$\bar{z}$  = the normal variable for a specified level of reliability in the performance of the pavement.

Typical values of  $\bar{z}$  corresponding to difference levels of confidence or degrees of reliability are given in Table 5.

The "difference distribution" is given by the distribution of differences between the logarithm of the number of 18-kip ESALs that



the pavement can withstand ( $\log(N)$ ) and the logarithm of the number of 18-kip ESALs that are actually applied to the pavement ( $\log n$ ). The mean difference  $D$ , is

$$\bar{D} = [\log(\bar{N}) - \log(\bar{n})] \quad (18)$$

and the variance of the difference distribution is

$$\text{Var}(D) = \text{Var}[\log(N)] + \text{Var}[\log(n)] \quad (19)$$

A good estimate of the  $\text{Var}[\log(n)]$  has been found by Darter, et al. (8) to be between 0.0229 and 0.0333. Setting the difference between  $\bar{D}$  and  $\bar{z}\sigma_D$  to equal zero gives

$$\log N = \log n + \bar{z} \{\text{Var}[\log(N)] + \text{Var}[\log(n)]\}^{1/2} \quad (20)$$

It is Equation (20) that is used to estimate  $N$ , the number of 18-kip ESALs or the number of months for which a pavement should be designed in order to achieve a level of reliability that is specified by the normal variable,  $\bar{z}$ .

## APPLICATIONS FOR PAVEMENT PERFORMANCE

### Sensitivity Analysis

The regression models described previously were subject to a sensitivity analysis to determine the effects of various combinations of climate on the performance curves. Four highway districts in Texas were chosen to represent extremes in climate for the state. The districts and regions in the state in which they are located, along with the climate associated with each area is as follows:

- a) District 1 (East) - Wet, some Freeze/thaw
- b) District 4 (North) - Dry, many Freeze/thaw
- c) District 17 (Central) - Wet, few Freeze/thaw
- d) District 21 (South) - Dry, no Freeze/thaw

The three types of pavement structure considered in this study are shown in Figure 4. The pavement climate, structure, and traffic variables were used with the equations given previously in Table 2, to determine the design parameters. The resulting performance curves, in terms of the present serviceability index, as a function of the number of 18-kip equivalent axle loads for each of the three pavement types is shown in Figures 5, 6, and 7. Referring to these figures, the following conclusions can be drawn concerning the functional performance of pavements in Texas:

- a) Asphaltic concrete pavements on bituminous bases are susceptible to freeze/thaw and to a lesser extent to the presence of excess moisture,

- b) Hot mix asphaltic concrete pavements on flexible base are susceptible to both freeze/thaw and excess moisture, and
- c) Overlaid pavements appear to be less dependent upon climate factors and depend to a greater extent upon the existing pavement structure.

The performance curves for the four distress types, in terms of both area and severity, for each highway district, have also been determined and can be found in (2).

#### Applications to Pavement Design

The regression equations which determine the shape of the performance curve and the probabilistic equations which determine the number of load applications for which the pavement should be designed (Equations 13, 14, 15, and 20) have been incorporated into the Texas Flexible Pavement System (FPS). Figure 8 shows a flow chart of subroutine "Time," which calculates the time required to attain a specified minimum level of performance. The calculation of pavement life for the present serviceability index, rutting, and alligator cracking cases involves an iterative procedure which calculates time as a function of N-18. This procedure is required, since these types of performance have been found to be load related (2). The iteration procedure consists of comparing the performance loss due to traffic (and expansive clay for the present serviceability index case) over a specified period of time to the minimum acceptable performance level. If the minimum performance level is not attained, the performance time is increased by a time increment that is calculated

using a Newton-Raphson convergence technique and the comparison is repeated. This process continues until the minimum performance level is attained, thus giving the time to failure. For the longitudinal and transverse cracking cases, this procedure is not required, as the distress types have been found to be time related (2). Therefore, the time required to reach a given level of distress can be calculated directly. After the first overlay has been placed, the program uses the overlay model for all subsequent performance periods.

The output of the FPS program provides a listing of the optimal pavement designs, as well as subsequent (if required) overlay strategies. The optimization scheme is based upon material costs (initial and future), highway user costs, and pavement performance. The revised version of FPS also provides a listing of the failure modes, i.e. performance loss due to serviceability or a specific distress (area or severity) type, and the time at which failure (the minimum performance level) will occur. This feature is provided for both initial construction and subsequent overlays. Figure 9 shows a typical page of output from the new FPS program. Note that the output gives the critical type of distress that caused the need for the overlay.

## CONCLUSIONS

The development of functional (PSI) structural (distress) performance equations for Texas and the incorporation of these equations into the Texas FPS computerized pavement design system makes it possible to develop optimal design strategies for flexible pavements in Texas. The equations are based upon observations on 164 pavement sections within the State, and predicted reasonable performance trends. The equations make use of the elastic modulus of each layer as determined non-destructively by a deflection survey (7) or as determined in the laboratory, which is a major change in the Texas flexible pavement structural subsystem. The probabilistic form of these equations has been incorporated into the new FPS, making it possible for the designer to select the level of reliability that he desires to have on the pavement. Because the program now checks several criteria including PSI, rutting, alligator cracking, longitudinal cracking, and transverse cracking to determine whether the useful service life has terminated, the rules for selecting a desired level of reliability which were developed for the old FPS using serviceability index alone do not appear to depend solely upon the level of traffic as it did formerly. For one reason, some form of distress usually appears to be the principal cause of rehabilitation and that makes the desired level of reliability depend not only upon the traffic level but upon the climate in which the pavement is to be built. Studies are continuing to develop new rules for selecting a

desirable level of reliability but in the meantime, even this result is encouraging for it indicates that the new FPS program, revised as described in this paper, is more realistic than the former version, more sensitive to the factors which cause pavement deterioration, and thus more useful in the design of flexible pavements.

## REFERENCES

1. Garcia-Diaz, A. and Riggins, M., "A Serviceability and Distress Methodology for Predicting Pavement Performance," presented at the 63rd Annual Meeting of the Transportation Research Board, Washington, D.C., January 1984.
2. Garcia-Diaz, A., Riggins, M., and Liu, S. J., "Development of Performance Equations and Survivor Curves for Flexible Pavements," Research Report No. 284-5, Texas Transportation Institute, Texas A&M University System, College Station, Texas, March 1984.
3. Holson, M. and Hudson, W. R., "Stochastic Study of Design Parameters and Lack-of-Fit of Performance Model in the Texas Flexible Pavement Design System," Research Report 123-23, Center for Highway Research, The University of Texas, Austin, Texas, April 1974.
4. Lytton, R. L. and Garcia-Diaz, A., "Evaluation of AASHO Road Test Satellite and Environmental Studies: Phase I," Research Report No. 20-7-17, Texas Transportation Institute, Texas A&M University System, College Station, Texas, January 1983.
5. Lytton, R. L. and Kohutek, G. L., "Evaluation of AASHO Road Test Satellite and Environmental Studies: Phase II," Research Report No. 20-7-17, Texas Transportation Institute, Texas A&M University System, College Station, Texas, June 1983.
6. Lytton, R. L., McFarland, W. F., and Schafer, D. L., "Flexible

Pavement Design and Management: Systems Approach Implementation," National Cooperative Highway Research Program Report 160, Transportation Research Board, National Research Council, Washington, D.C., 1975.

7. Lytton, R. L. and Michalak, C. H., "Flexible Pavement Deflection Equation Using Elastic Moduli and Field Measurements," Research Report No. 207-7F, Texas Transportation Institute, Texas A&M University System, College Station, Texas, August 1979.
8. Darter, M. I. and Hudson, W. R., "Probabilistic Design Concepts Applied to Flexible Pavement System Design," Research Report 123-18, Center for Highway Research, University of Texas at Austin, May 1973.



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TABLE 1. Variables Used in the Regression Models

Environmental	Structural	Traffic
Thornthwaite Index (TI)	Plasticity Index (PI)	
Annual Freeze/Thaw Cycles (F/T)	Equivalent Thickness (H') <sup>1</sup>	N-18/month (N-18) <sup>6</sup>
Average Temperature (T <sub>AVG</sub> )	Percent Asphalt Binder (Binder) <sup>2</sup>	
	Overlay Thickness (OVTH) <sup>3</sup>	
	Total Asphalt Thickness (ASPH) <sup>4</sup>	
	Surfacing Thickness (HMAC) <sup>5</sup>	

1. Equivalent thickness is the transformed pavement thickness.
2. This term is for black base and hot mix asphalt concrete pavements.
3. This term is for overlay pavements.
4. This term is for black base pavements. It is the total asphalt thickness of black base + surfacing course.
5. This term is for Hot Mix pavements.
6. The N-18/month value represents the observed value during the first performance period.

TABLE 2. Arithmetic Regression Models for the Design Parameters (PSI)

HMAC Pavement on Bituminous Base	
$\rho$	$= -0.02182(F/T) - 0.00831(PI) + 0.04499(\text{Binder}) + 0.15019(\text{HPR2})$
$\beta$	$= 0.01201(TI) + 0.03166(F/T) + 0.13775(T_{\text{AVG}}) + 0.00114(PI)$ $- 0.31331(\text{Binder}) - 0.03234(\text{HPR2})$
$P_f$	$= -0.00637(F/T) - 0.01550(T_{\text{AVG}}) - 0.00658(PI)$ $+ 0.27714(\text{Binder}) + 0.05097(\text{HPR2})$
HMAC Pavement on Flexible Base	
$\rho$	$= -0.02000(TI) - 0.02481(F/T) - 0.03078(PI) + 0.60781(\text{Binder})$ $+ 0.06424(\text{HPR2})$
$\beta$	$= 0.04045(F/T) + 0.22931(T_{\text{AVG}}) - 0.53010(\text{Binder})$
$P_f$	$= -0.00665(F/T) - 0.07017(T_{\text{AVG}}) - 0.02472(PI)$ $+ 0.57235(\text{Binder}) + 0.00722(\text{HPR2})$
HMAC Overlays	
$\rho$	$= 0.26503(0VTH) + 0.07180(\text{HPR2})$
$\beta$	$= 0.00413(TI) + 0.01036(F/T) + 0.04769(T_{\text{AVG}}) + 0.01707(N-18)$ $- 0.09144(0VTH) - 0.01066(\text{HPR2})$
$P_f$	$= 0.33037(0VTH) + 0.07627(\text{HPR2})$

TABLE 3. Logarithmic Regression Models for the Design Parameters (PSI)

HMAC Pavement on Bituminous Base		
$\rho$	$= (F/T)^{-0.46679} * (T_{AVG})^{-0.86233} * (PI)^{-0.26711} * (HPR2)^{1.65694}$	
$\beta$	$= (F/T)^{0.60949} * (T_{AVG})^{0.93499} * (Binder)^{-1.37608} * (HPR2)^{-0.72725}$	
$P_f$	$= (F/T)^{-1.50634} * (T_{AVG})^{-2.69460} * (Binder)^{4.17755} * (HPR2)^{1.60919}$	
HMAC Pavement on Flexible Base		
$\rho$	$= (TI)^{-0.31419} * (F/T)^{-0.69942} * (T_{AVG})^{-0.96204} * (Binder)^{0.44492} * (HPR2)^{1.85110}$	
$\beta$	$= (F/T)^{0.40391} * (T_{AVG})^{0.44517} * (N-18)^{0.04576} * (Binder)^{-1.50340}$	
$P_f$	$= (F/T)^{-0.89516} * (T_{AVG})^{-3.14575} * (Binder)^{5.31210} * (HPR2)^{0.44486}$	
HMAC Overlays		
$\rho$	$= (F/T)^{-0.24351} * (Binder)^{0.71372} * (HPR2)^{0.18059}$	
$\beta$	$= (F/T)^{0.09767} * (N-18)^{0.17402} * (Binder)^{-0.30623} * (HPR2)^{-0.22623}$	
$P_f$	$= (F/T)^{-0.14525} * (T_{AVG})^{-0.25053} * (N-18)^{-0.24283} * (Binder)^{0.32304} * (HPR2)^{0.62508}$	

TABLE 4. Values of the Variance Parameters a and b

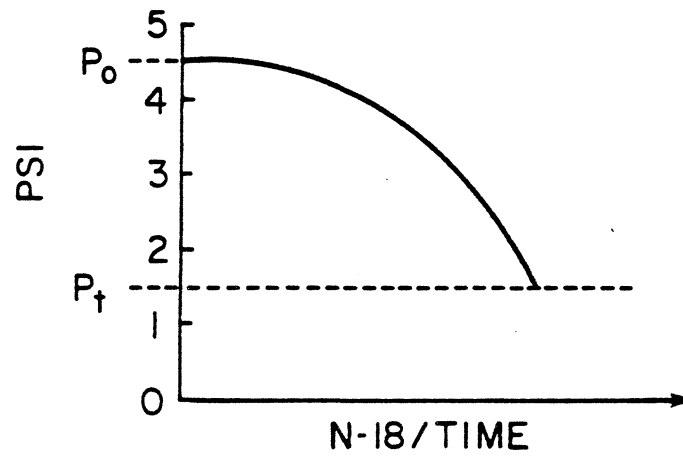
	<u>a</u>	<u>b</u>
Serviceability Index Loss	2.00	5.96
Rutting	3.90	4.91
Alligator Cracking	6.05	5.04
Longitudinal Cracking	0.00	0.0751
Transverse Cracking	0.00	0.0762

TABLE 5. Levels of Reliability Corresponding to Difference Levels of the Normal Variable.

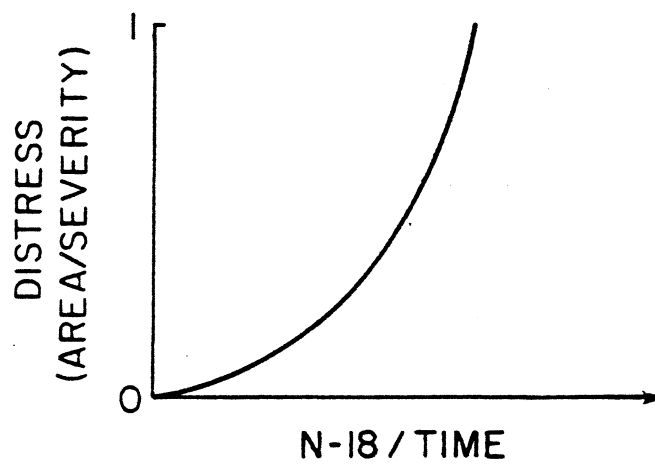
Reliability, <u>R</u>	Normal Variable, <u><math>\bar{z}</math></u>
50%	0.00
80%	0.84
90%	1.28
95%	1.65
99%	2.33

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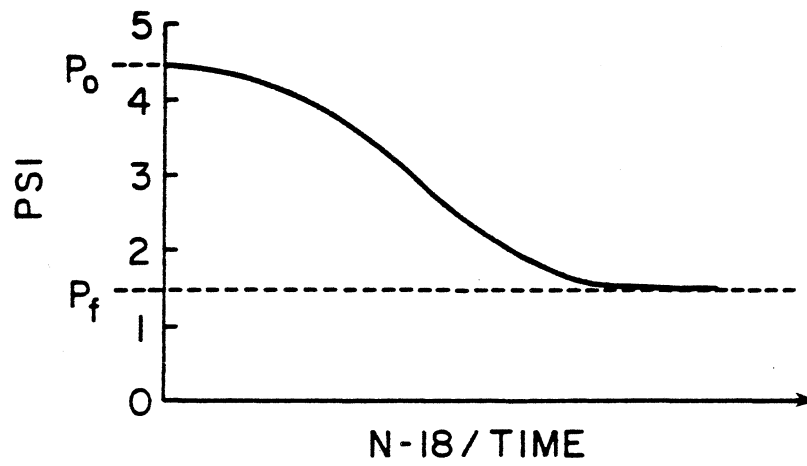
a) Functional Performance



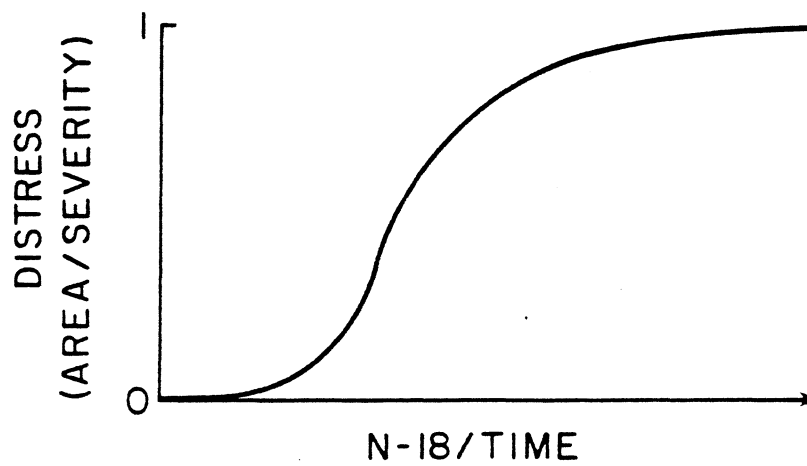
b) Structural Performance

Figure 1. Illustration of Typical AASHO Road Test Functional and Structural Performance Curves





a) Functional Performance



b) Structural Performance

Figure 2. Illustration of the S-shaped Functional and Structural Performance Curves

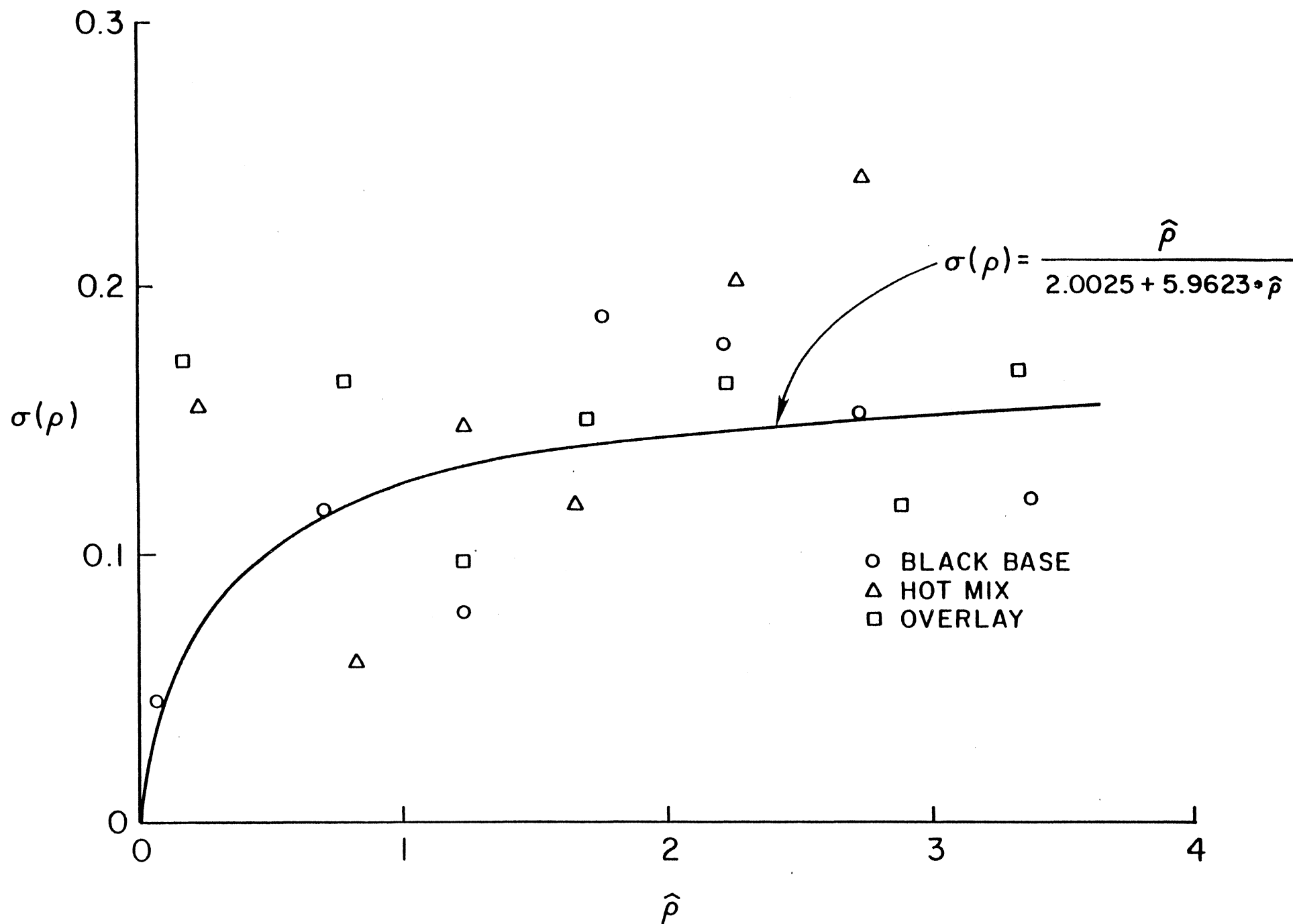


Figure 3. Relation Between the Standard Deviation and the Expected Value of  $\rho$  for Serviceability Index Loss

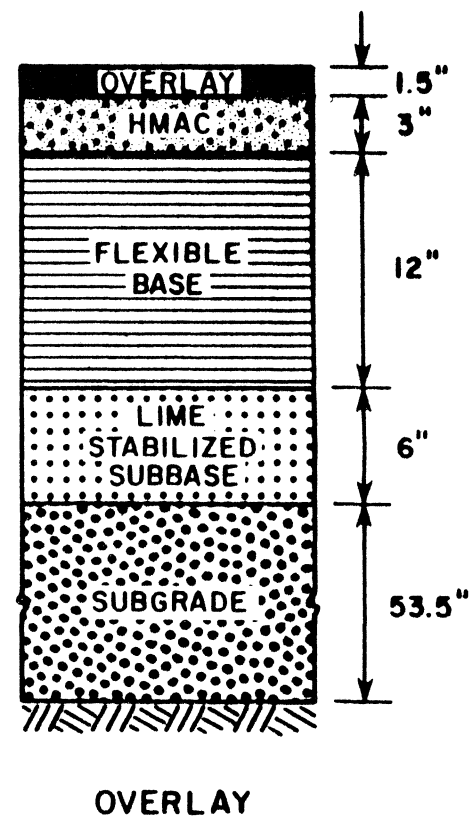
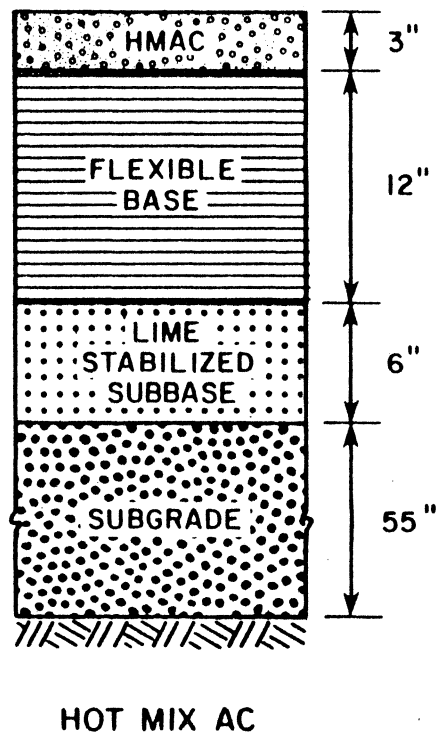
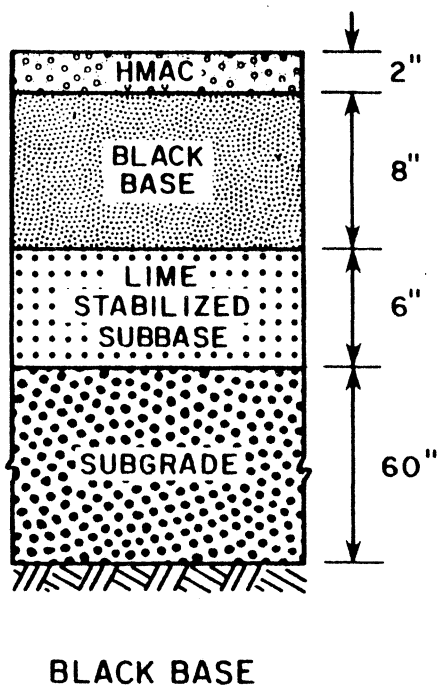


FIGURE 4. Pavement Types Used for Sensitivity Analysis

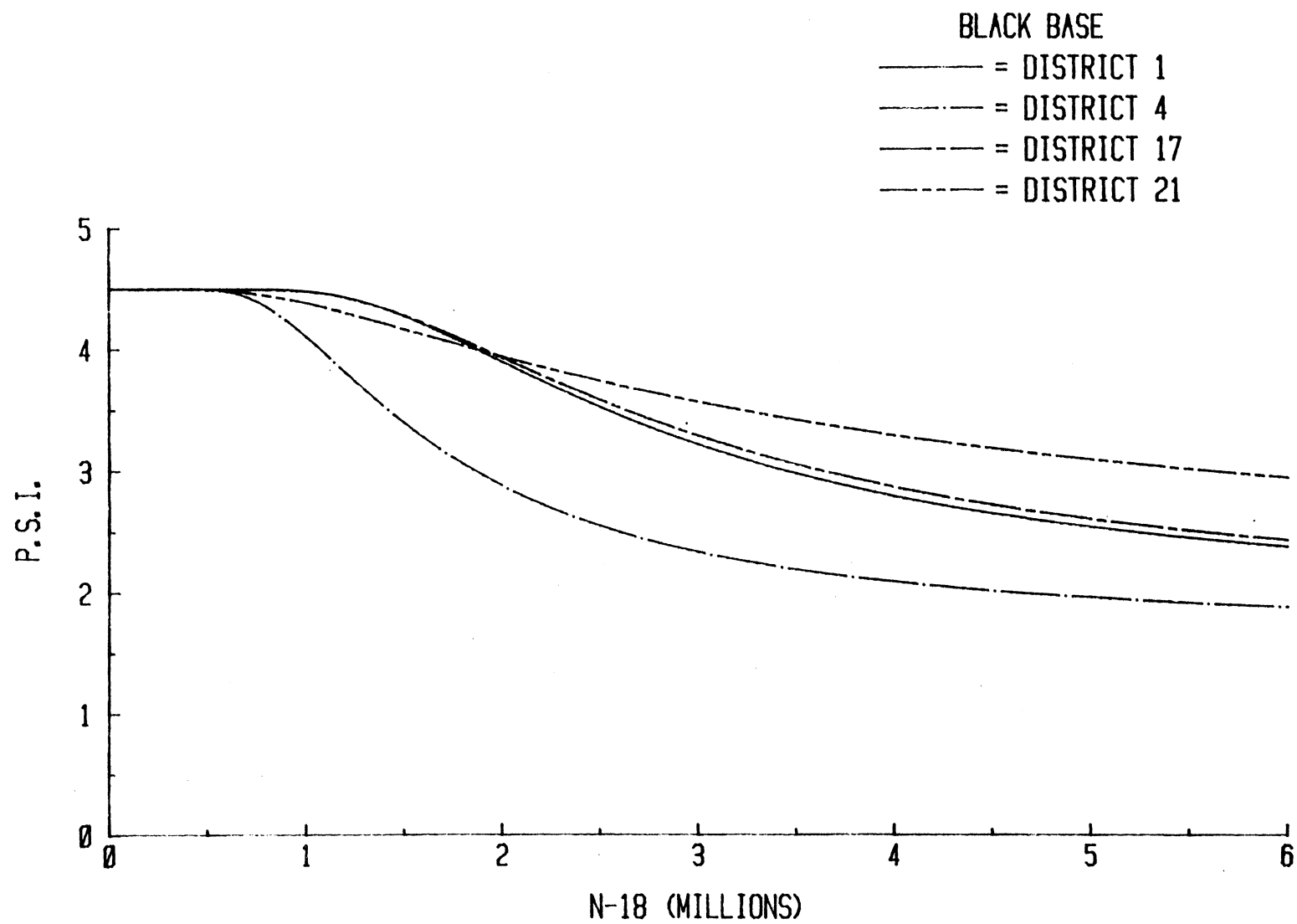


Figure 5. PSI Sensitivity Results for Pavements on Bituminous Base

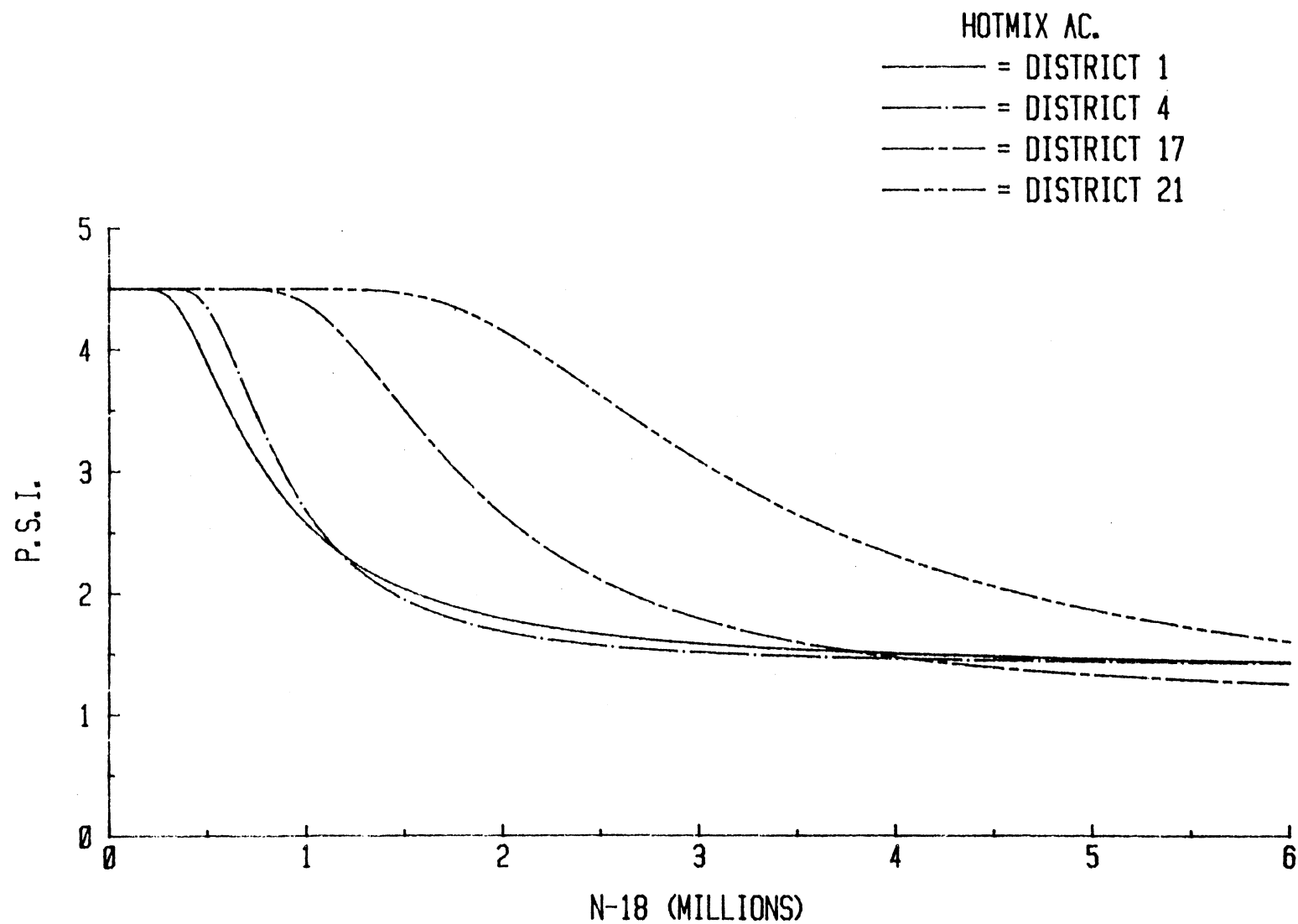


FIGURE 6. PSI Sensitivity Results for Hot Mix AC Pavements

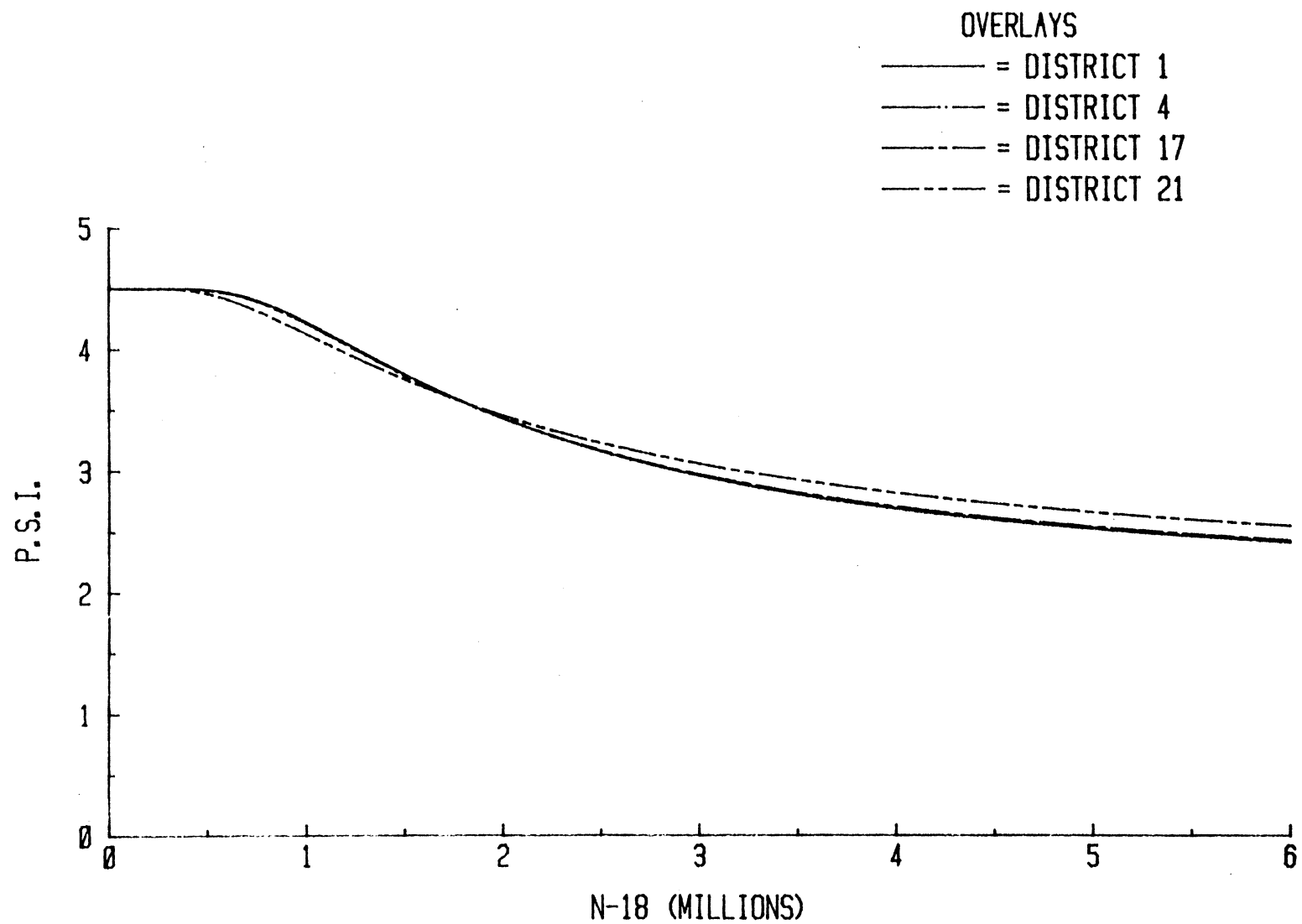


FIGURE 7. PSI Sensitivity Results for Overlay Pavements

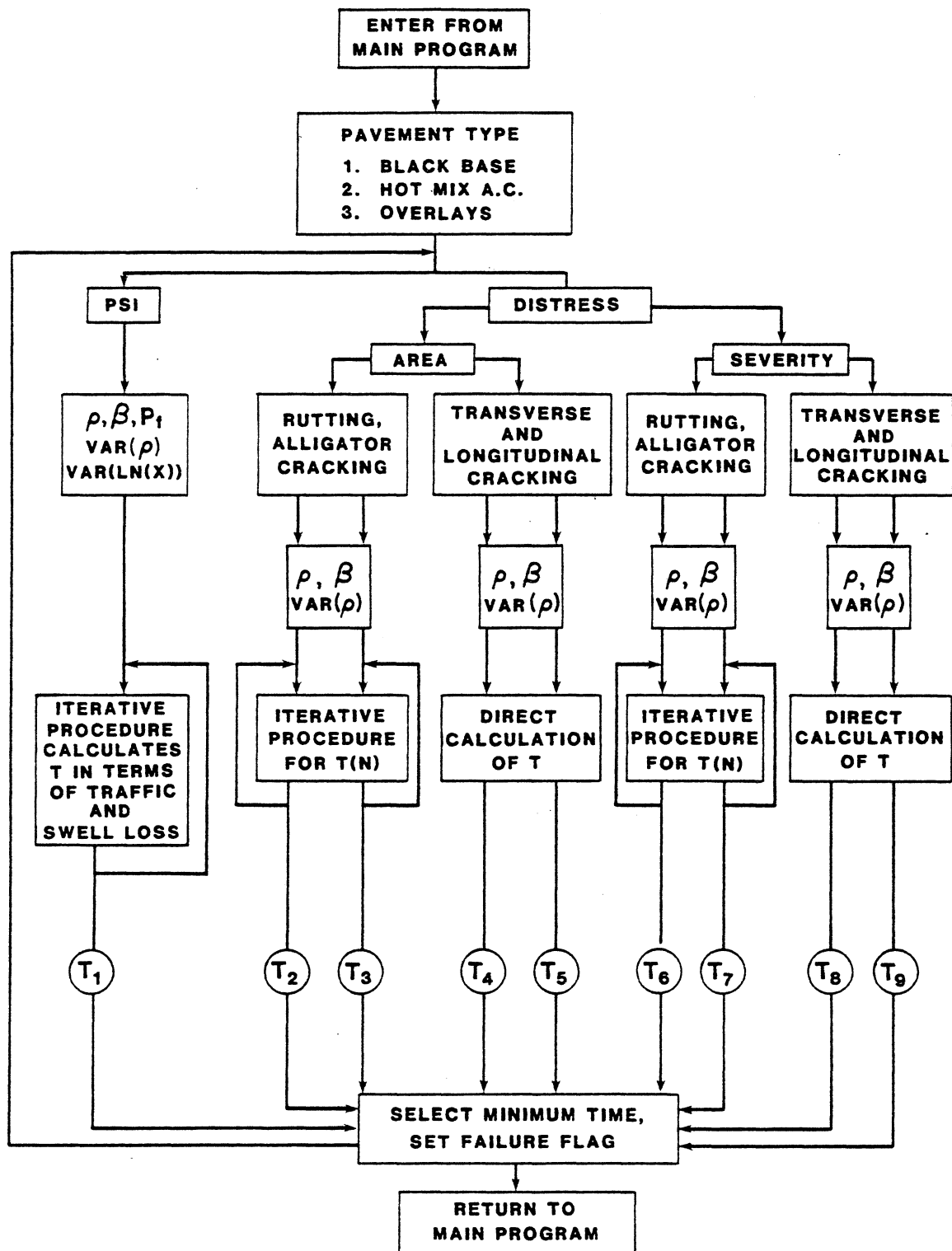


Figure 8. Flow Chart for Calculating the Time an Overlay is Required

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Figure 9. Typical Output of the New Texas FPS Elastic Layered Pavement Design Program

THE TOTAL NUMBER OF FEASIBLE DESIGNS CONSIDERED WAS

DISTRESS CODES ARE

RU-A	RUTTING AREA	RU-S	RUTTING SEVERITY
AC-A	ALLIGATOR CRACK AREA	AC-S	ALLIGATOR CRACK SEVERITY
LC-A	LONGITUDINAL CRACK AREA	LC-S	LONGITUDINAL CRACK SEVERITY
TC-A	TRANSVERSE CRACK AREA	TC-S	TRANSVERSE CRACK SEVERITY
PSI	PRESENT SERVICEABILITY INDEX		