TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
"Stochastic Study of Design Parameters and Lack-of-Fit of Performance Model in the Texas Flexible Pavement Design System"	April 1974
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Malvin Holsen and W. Ronald Hudson	Research Report 123-23
9. Performing Organization Name and Address	10. Work Unit No.
Center for Highway Research The University of Texas at Austin Austin, Texas 78712	11. Contract or Grant No. Research Study 1-8-69-123
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Highway Department Planning & Research Division P. O. Box 5051 Austin, Texas 78763	14. Sponsoring Agency Code

15. Supplementary Notes

Work done in cooperation with the Federal Highway Administration, Department of Transportation.
Research Study Title: "A System Analysis of Pavement Design and Research Implementation"

16. Abstract

The need for developing a method to account for variations and uncertainties of factors in pavement design was recognized by the FHWA-HRB Advisory Committee of the "Workshop on the Structural Design of Asphalt-Concrete Pavement Systems" in 1970 as one of the most pressing problems facing pavement engineers. A first step in the solution of the problem was taken when stochastic design concepts were applied to the Texas Flexible Pavement Design System (FPS). The probabilistic approach makes it possible to design for a desired level of reliability through consideration of the variabilities and uncertainties associated with pavement input variables. In order to utilize this added feature of FPS, estimates of the variations associated with the various input parameters, and the lack-of-fit error of the empirical models used in the system have to be determined.

A study of the initial serviceability index of flexible pavements was performed to obtain better estimates of expected average values and variations associated with this input parameter. Twenty-one pavement projects were evaluated in the study, including ten hot-mix asphalt-concrete pavement and 11 with surface treatment. The study showed a significant difference in initial serviceability of the two types. A method for determining the variation in the performance equation caused by lack-of-fit is outlined herein, and recommendations for the types of data necessary for a quantitative evaluation are presented.

17. Key Words	18. Distribution Statement
initial serviceability index, flexible pavements, probability, stochastic, lack-of-fit, reliability, variability	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Form DOT F 1700.7 (8-69)

STOCHASTIC STUDY OF DESIGN PARAMETERS AND LACK-OF-FIT OF PERFORMANCE MODEL IN THE TEXAS FLEXIBLE PAVEMENT DESIGN SYSTEM

by

Malvin Holsen
W. Ronald Hudson

Research Report Number 123-23

A System Analysis of Pavement Design and Research Implementation

Research Project 1-8-69-123

conducted for

The Texas Highway Department

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Highway Design Division
Texas Highway Department

Texas Transportation Institute
Texas A&M University

Center for Highway Research
The University of Texas at Austin

April 1974

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

This report documents the work performed from 1973 to 1974 on quantifying variation of design inputs to the structural submodel in the Texas Flexible Pavement design system. This work has resulted in a method for quantifying the variation introduced into the performance model by lack-of-fit error. A study was performed on the initial serviceability index of flexible pavements, and the results are reported herein.

This is the twenty-third in a series of reports that describes the work accomplished in the project entitled "A System Analysis of Pavement Design and Research Implementation." The project is a long-range comprehensive research program to develop a system analysis of pavement design and management. The project is conducted in cooperation with the Federal Highway Administration, Department of Transportation.

Special thanks and appreciation are extended to Mr. James L. Brown and Dr. Michael I. Darter for their assistance and helpful suggestions to the study. Appreciation is expressed to Dr. B. Frank McCullough and Dr. Thomas W. Kennedy for a critical review of the report; to Mr. Noel Wolf, and Mr. Harold H. Dalrymple for their assistance on the project; to Mrs. Marie Fisher for typing and other help with the report; and to Mr. Arthur Frakes for editing the manuscript.

Malvin Holsen
W. Ronald Hudson

April 1974

LIST OF REPORTS

Report No. 123-1, "A Systems Approach Applied to Pavement Design and Research," by W. Ronald Hudson, B. Frank McCullough, F. H. Scrivner, and James L. Brown, describes a long-range comprehensive research program to develop a pavement systems analysis and presents a working systems model for the design of flexible pavements. March 1970

Report No. 123-2, "A Recommended Texas Highway Department Pavement Design System Users Manual," by James L. Brown, Larry J. Buttler, and Hugo E. Orellana, is a manual of instructions to Texas Highway Department personnel for obtaining and processing data for flexible pavement design system. March 1970

Report No. 123-3, "Characterization of the Swelling Clay Parameter Used in the Pavement Design System," by Arthur W. Witt, III, and B. Frank McCullough, describes the results of a study of the swelling clays parameter used in pavement design system. August 1970

Report No. 123-4, "Developing A Pavement Feedback Data System," by R. C. G. Haas, describes the initial planning and development of a pavement feedback data system. February 1971

Report No. 123-5, "A Systems Analysis of Rigid Pavement Design," by Ramesh K. Kher, W. R. Hudson, and B. F. McCullough, describes the development of a working systems model for the design of rigid pavements. November 1970

Report No. 123-6, "Calculation of the Elastic Moduli of a Two Layer Pavement System from Measured Surface Deflections," by F. H. Scrivner, C. H. Michalak, and William M. Moore, describes a computer program which will serve as a subsystem of a future Flexible Pavement System founded on linear elastic theory. March 1971

Report No. 123-6A, "Calculation of the Elastic Moduli of a Two Layer Pavement System from Measured Surface Deflections, Part II," by Frank H. Scrivner, Chester H. Michalak, and William M. Moore, is a supplement to Report No. 123-6 and describes the effect of a change in the specified location of one of the deflection points. December 1971

Report No. 123-7, "Annual Report on Important 1970-71 Pavement Research Needs," by B. Frank McCullough, James L. Brown, W. Ronald Hudson, and F. H. Scrivner, describes a list of priority research items based on findings from use of the pavement design system. April 1971

Report No. 123-8, "A Sensitivity Analysis of Flexible Pavement System FPS2," by Ramesh K. Kher, B. Frank McCullough, and W. Ronald Hudson, describes the overall importance of this system, the relative importance of the variables of the system and recommendations for efficient use of the computer program. August 1971

Report No. 123-9, "Skid Resistance Considerations in the Flexible Pavement Design System," by David C. Steitle and B. Frank McCullough, describes skid resistance consideration in the Flexible Pavement System based on the testing of aggregates in the laboratory to predict field performance and presents a nomograph for the field engineer to use to eliminate aggregates which would not provide adequate skid resistance performance, April 1972.

Report No. 123-10, "Flexible Pavement System - Second Generation, Incorporating Fatigue and Stochastic Concepts," by Surendra Prakash Jain, B. Frank McCullough and W. Ronald Hudson, describes the development of new structural design models for the design of flexible pavement which will replace the empirical relationship used at present in flexible pavement systems to simulate the transformation between the input variables and performance of a pavement, January 1972.

Report 123-11, "Flexible Pavement System Computer Program Documentation," by Dale L. Schafer, provides documentation and an easily updated documentation system for the computer program FPS-9. April 1972

Report No. 123-12, "A Pavement Feedback Data System," by Oren G. Strom, W. Ronald Hudson, and James L. Brown, defines a data system to acquire, store, and analyze performance feedback data from in-service flexible pavements, May 1972.

Report No. 123-13, "Benefit Analysis for Pavement Design System," by Frank McFarland, presents a method for relating motorist's costs to the pavement serviceability index and a discussion of several different methods of economic analysis.

Report No. 123-14, "Prediction of Low-Temperature and Thermal-Fatigue Cracking in Flexible Pavements," by Mohamed Y. Shahin and B. Frank McCullough, describes a design system for predicting temperature cracking in asphalt concrete surfaces, August 1972.

Report No. 123-15, "FPS-11 Flexible Pavement System Computer Program Documentation," by Hugo E. Orellana, gives the documentation of the computer program FPS-11, October 1972. April 1972

Report No. 123-16, "Fatigue and Stress Analysis Concepts for Modifying the Rigid Pavement Design System," by Piti Yimprasett and B. Frank McCullough, describes the fatigue of concrete and stress analyses of rigid pavement, October 1972.

Report No. 123-17, "The Optimization of a Flexible Pavement System Using Linear Elasticity," by Danny Y. Lu, Chia Shun Shih, and Frank H. Scrivner describes the integration of the current Flexible Pavement System computer program and Shell Oil Company's program BISTRO, for elastic layered systems, with special emphasis on economy of computation and evaluation of structural feasibility of materials, March 1973.

Report No. 123-18, "Probabilistic Design Concepts Applied to Flexible Pavement System Design," by Michael I. Darter and W. Ronald Hudson, describes the development and implementation of the probabilistic design approach and its incorporation into the Texas flexible pavement design system for new construction and asphalt concrete overlay, May 1973.

Report No. 123-19, "The Use of Condition Surveys, Profile Studies, and Maintenance Studies in Relating Pavement Distress to Pavement Performance," by Robert P. Smith and B. Frank McCullough, introduces the area of relating pavement distress to pavement performance, presents work accomplished in this area, and gives recommendations for future research, August 1973.

Report No. 123-20, "Implementation of a Complex Research Development of Flexible Pavement Design System into Texas Highway Department Design Operations," by Larry Butler and Hugo Orellana, describes the step-by-step process used in incorporating the implementation research into the actual working operation.

Report No. 123-21, "Rigid Pavement Design System, Input Guide for Program RPS2 In Use by the Texas Highway Department," by R. Frank Carmichael and B. Frank McCullough, describes the input variables necessary to use the Texas rigid pavement design system program RPS2, January 1974 (subject to approval).

Report No. 123-22, "An Integrated Pavement Design Processor," by Danny Y. Lu, Chia Shun Shih, Frank H. Scrivner, and Robert L. Lytton, provides a comprehensive decision framework with a capacity to drive different pavement design programs at the user's command through interactive queries between the computer and the design engineer.

Report No. 123-23, "Stochastic Study of Design Parameters and Lack-of-Fit of Performance Model in the Texas Flexible Pavement Design System," by Malvin Holsen and W. Ronald Hudson, describes a study of initial serviceability index of flexible pavements and a method for quantifying lack-of-fit of the performance equation.

ABSTRACT

The need for developing a method to account for variations and uncertainties of factors in pavement design was recognized by the FHWA-HRB Advisory Committee of the "Workshop on the Structural Design of Asphalt-Concrete Pavement Systems" in 1970 as one of the most pressing problems facing pavement engineers. A first step in the solution of the problem was taken when stochastic design concepts were applied to the Texas Flexible Pavement Design System (FPS) (Ref 2). The probabilistic approach makes it possible to design for a desired level of reliability through consideration of the variabilities and uncertainties associated with pavement input variables. In order to utilize this added feature of FPS, estimates of the variations associated with the various input parameters, and the lack-of-fit error of the empirical models used in the system have to be determined.

A study of the initial serviceability index of flexible pavements was performed to obtain better estimates of expected average values and variations associated with this input parameter. Twenty-one pavement projects were evaluated in the study, including ten hot-mix asphalt-concrete pavement and 11 with surface treatment. The study showed a significant difference in initial serviceability of the two types. A method for determining the variation in the performance equation caused by lack-of-fit is outlined herein, and recommendations for the types of data necessary for a quantitative evaluation are presented.

KEY WORDS: initial serviceability index, flexible pavements, probability, stochastic, lack-of-fit, reliability, variability.

SUMMARY

The need to be able to design for a specific level of reliability and account for the inherent variations in the different design factors has been recognized in many areas of design. Basic stochastic design theory was applied to the structural subsystem of the Texas Flexible Pavement Design System by Darter and Hudson (Ref 2), allowing the designer to determine the reliability of a specific design and design for a specific level of reliability. In order to utilize this added feature of FPS, estimates of the variations associated with the different design factors are needed. A study was made to quantify the variations associated with the initial serviceability index of flexible pavements. The study was designed to obtain both better estimates of expected average values and the variations of this design factor. A total of 21 newly constructed pavements were measured using the Surface Dynamics Profilometer. Eleven of the projects were surface-treated pavements while the remaining ten were hot-mix asphalt-concrete pavements. An equation for predicting the initial serviceability index on hot-mix apshalt-concrete pavements was derived, given pavement design parameters such as number of layers, type of materials and layer thicknesses. The equation is presented in Appendix 2.

Most of the models used in FPS are empirical equations based upon data collected on test sections and in-service pavements. There is a certain lack-of-fit associated with the equations, and in order to determine the variance of a design, the lack-of-fit has to be estimated. The lack-of-fit associated with the performance equation used in FPS is believed to be quite large due to wide variations in traffic, environmental conditions and materials in the State of Texas. A method for determining the lack-of-fit of the performance equation was developed, and a study for obtaining the data for quantifying the lack-of-fit was outlined.

IMPLEMENTATION STATEMENT

Results from the study of the initial serviceability index on flexible pavements can be implemented immediately into the operational flexible pavement design system. Average initial serviceability index was determined for hot-mix asphalt-concrete pavements and surface-treated pavements, and the obtained values can be used in the FPS-11 computer program presently used in the Texas Highway Department. Another program, FPS-13 (CFHR), requires the standard deviation of the initial serviceability index as an input, and the obtained values reported herein can be used when designing with this program.

The FPS-13 (CFHR) program also requires the lack-of-fit error of the performance equation as an input. A method for determining the lack-of-fit error associated with the performance equation is presented herein. Before this error can be quantified data have to be collected on in-serive pavements in Texas, and this work is one of the recommendations of this study.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

Consideration of "pavement design as a stochastic process" was stated to be one of the most important research needs in the field of pavement research by the FHWA-HRB Advisory Committee of the Workshop on the Structural Design of Asphalt-Concrete Pavement Systems in 1970.

> " ... so that designers can better evaluate the reliability of a particular design, it is necessary to develop a procedure that will predict variations in the pavement system response due to statistical variations in the input variables, such as load, environment, pavement geometry, and material properties including the effects of construction and testing variables. As part of this research, it will be necessary to include a significance study to determine the relative effect on the system response of variations in the different input variables (Ref 1)."

The latest development in the area of applying stochastic design concepts to pavement design systems was done by Darter and Hudson at the Center for Highway Research at The University of Texas at Austin (Ref 2). In this work, stochastic design concepts were applied to the structural submodel of the Texas Flexible Pavement Design System (FPS).

Purpose

The general purpose of this research effort is to quantify the variation associated with the performance equation in FPS. In order to quantify the total variation of the performance equation, the variance associated with each of the several different design inputs and also the lack-of-fit for the equation has to be determined. The initial serviceability index was probably the least known factor. A study was done to obtain information about expected average values and the variance associated with this design factor. The lack-of-fit associated with the performance equation is believed to be quite high due to large variations in traffic, environmental conditions, and materials within the State of Texas, and a method was developed for determining the lack-of-fit of the performance equation. A large-scale study is required for quantifying the variation introduced in the performance equation by the lack-of-fit, and a plan for obtaining the necessary data is outlined herein.

Background

Darter and Hudson state the purpose of applying stochastic concepts to pavement design as follows: "The underlying reason for formulating a probability-based design procedure is to make the design process responsive to the actual existing variabilities and uncertainties associated with the design, construction, and performance of flexible pavement" (Ref 2). To be able to evaluate the reliability of a design, or to design for a certain reliability level, it is necessary to predict the variations of the design outputs due to the variations in the design inputs.

The Texas Flexible Pavement Design System is a computerized working system containing several submodels. Stochastic design theory has been applied to one of these submodels, the structural subsystem. Basically, the structural subsystem consists of three models, the performance model, the deflection model and the traffic model, which combined, predict the performance or serviceability loss with time of a pavement design. Darter and Hudson applied basic stochastic design theory to the structural submodel enabling the designer to evaluate the reliability of his design (Ref 2). Part of this work includes a method to predict the variation of the model output as a function of the variation of the different input factors. There are several methods for determining the variance of a factor which is a function of several random variables. The method selected for use is called the partial derivative method, and it was adopted because of its relative ease and accuracy in application.

Approach

In order to be able to utilize the stochastic features of the FPS design system, estimates of the variations associated with the various design inputs were needed. In early versions, some of the estimates were crude because of limited data. The initial serviceability index was probably the least known input factor, and a study was done to obtain better estimates of expected average values and variations associated with this input parameter.

Part of the variation of the design outputs in FPS is caused by lack-of-fit error in the empirical design equations used in the program. A method for quantifying the lack-of-fit error in the performance equation is presented in this report. The findings of this study are presented in the following sequence:

A discussion of the reliability of a pavement design, the FPS working system, the performance model in FPS, and the stochastic design inputs to the performance model is given in Chapter 2.

In Chapter 3 a description of the lack-of-fit of the performance equation, the method developed for determining lack-of-fit, and the data needed for quantifying it is given.

A summary and conclusion from the study of initial serviceability index on flexible pavements is given in Chapter 4.

The results from the study and recommendations for future work in the area of stochastic pavement design are given in Chapter 5.

CHAPTER 2. STATE-OF-THE-ART

In this chapter, the work which has been done in applying stochastic design concepts to the performance model in the Texas Flexible Pavement Design System is summarized. The chapter is divided into five parts as follows:

(1) a general description of the reliability of pavement design,

(2) a short description of the now operational FPS design system,

(3) the performance model, which is a submodel in FPS is described in more detail,

(4) the various stochastic design parameters in the performance model, and

(5) the model for determining the total variance of the performance equation.

Reliability of Pavement Design

Darter and Hudson defined the reliability R of a pavement design as the probability that the allowable load applications of the pavement/subgrade system N will exceed the traffic loads to be applied n (Ref 2). This is compatible with the statement that reliability is the probability that the serviceability level of pavement will not fall below the minimum acceptable level before the performance period is over.

$$R = P(N > n) \tag{2.1}$$

Both allowable applications N and traffic loads to be applied n are dependent upon many factors. Allowable load applications N is dependent upon such factors as (1) pavement thickness T, (2) material properties P, and (3) environment E.

$$N = f(T, P, E, \ldots) \tag{2.2}$$

The estimate of the number of traffic loads which will be applied to a pavement during a certain time period is dependent upon such factors as (1) average daily traffic A , (2) percent trucks T , (3) axle load distribution L , and (4) equivalency factors F .

$$n = f(A, T, L, F, \ldots)$$

Results from the AASHO Road Test indicate both N and n to be approximately log normally distributed (Ref 25). Assuming this to be true and applying statistical theory, the following relationship between log N and log n was derived (Ref 2).

$$\overline{\log N} = \overline{\log n} + Z_R \sqrt{S^2_{\log N} + S^2_{\log n}} \tag{2.4}$$

where

$\overline{\log N}$ = average of the log of the number of 18-kip single-axle load applications to be used for design at level of reliability R ,

$\overline{\log n}$ = average traffic forecast of the log of the number of 18-kip single-axle load applications,

Z_R = standardized normal deviate from normal distribution tables with a mean of zero and a variance of one for given level of reliability,

$S_{\log N}$ = standard deviation of log N, and

$S_{\log n}$ = standard deviation of log n.

This reliability function can be used either to design a pavement for a specific reliability level or to analyze the reliability of a given pavement design.

Reliability was defined as the probability that N exceeds n ,

$$R = P[(\log N - \log n) > 0] \tag{2.5}$$

or

$$R = P[D > 0] \tag{2.6}$$

where

$$D = \log N - \log n$$

The function $f(D)$ is called the difference density function of log N and log n, and since log N and log n are both normally distributed, D will be normally distributed also. Function D is shown in Fig 2.1. Using bars above the expressions to represent their mean value, the mean value of the difference density function can be written as

$$\overline{D} = \overline{\log N} - \overline{\log n}$$

The variance of the difference between two uncorrelated functions is given as the sum of the variances of the two functions. Hence the standard deviation of D , S_D , can be computed by the following equation:

$$S_D = \sqrt{S^2_{\log N} + S^2_{\log n}} \tag{2.7}$$

where

$S^2_{\log N}$ = variance of log N ,
$S^2_{\log n}$ = variance of log n.

As shown in Fig 2.1, the reliability is given by the area to the right of zero.

$$R = P[D > 0] = \int_0^\infty f(D)dD \tag{2.8}$$

or

$$R = P[0 < (\log N - \log n) < \infty] = P[0 < D < \infty] \tag{2.9}$$

The relationship between D and the standardized normal variable Z is given by:

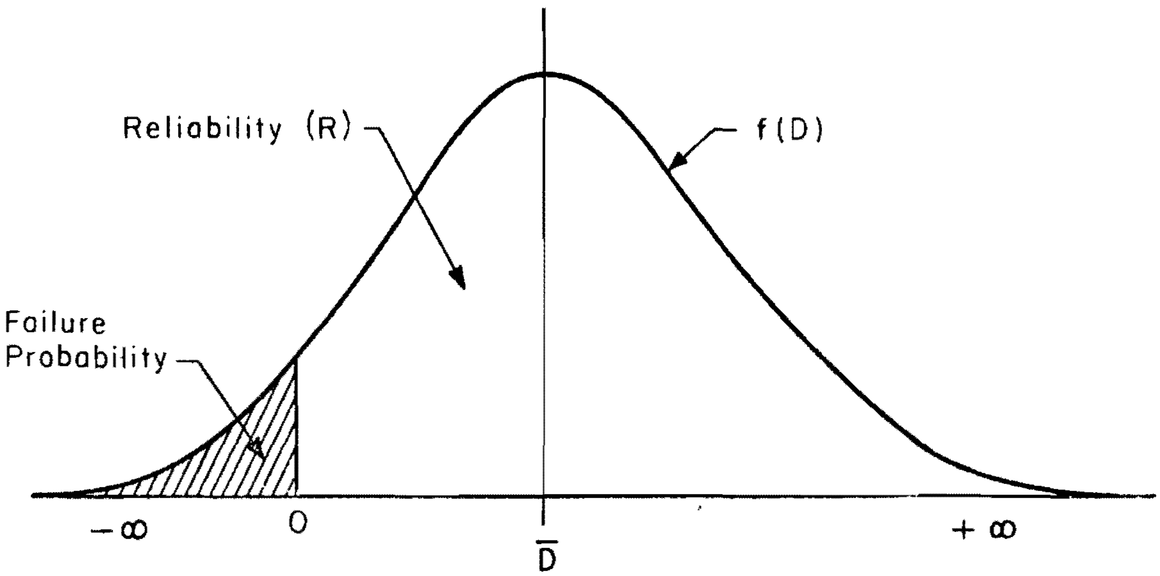


Fig 1. Difference density function [D = log N - log n] (Ref 2).

$$Z = \frac{D - \bar{D}}{S_D} \tag{2.10}$$

for

$$D = 0 , Z = Z_0 = -\frac{\bar{D}}{S_D} = -\frac{\overline{\log N} - \overline{\log n}}{\sqrt{S^2_{\log N} + S^2_{\log n}}} \tag{2.11}$$

for

$$D = \infty , Z = Z_\infty = \infty \tag{2.12}$$

By evaluating Z for the limits of D , Eq 2.9 can now be written as

$$R = P[Z_0 < Z < Z_\infty] \tag{2.13}$$

and the reliability can be easily determined by means of the normal distribution table.

In order to be able to design for a specific level of reliability, estimates of the average values and the variance associated with log N and log n must be determined. Since both N and n are dependent upon several factors, the total variances of each depend upon the variance of each of these various factors. This study was aimed toward developing a technique to determine the variation in log N caused by the lack-of-fit of the performance equation and to collect field data to determine average values and the variance of the initial serviceability index which is one of the inputs to the equation for predicting log N.

FPS - System

The Texas Flexible Design System (FPS) is a flexible highway pavement design system developed for the Texas Highway Department. The FPS system resulted from seven years work to apply AASHO Road Test results to the Texas design system (Ref 3). The FPS design system has been computerized to provide an output of feasible pavement designs sorted by increasing total cost. The primary purpose of FPS is to provide the designer with a means of investigating a large variety of pavement design options in a systematic and efficient manner (Ref 4).

The FPS design system consists of several "submodels":

(1) the structural subsystem consists of a traffic, a deflection (or a material-pavement characterization), and a performance model,

(2) the safety subsystem is restricted to the skid resistance of the pavement surface,

(3) the user-delay model calculates the cost to the user in case of overlay,

(4) the economic subsystem calculates the total cost of the project throughout its design life, accounting for initial cost, overlay cost, routine maintenance cost, user cost, and salvage value, and finally

(5) the overlay design model calculates the necessary overlays for rehabilitation of the pavement (Ref 5).

Stochastic design theory has been applied to the structural subsystem of the FPS design system only. This report deals also with that part of the structural subsystem which includes the performance model and the variance associated with the different design inputs to the model.

Performance Model

The performance equation is based upon the present serviceability concept developed at the AASHO Road Test (Ref 2), and it predicts the loss in serviceability depending upon deflection of the pavement structure, the number of load applications, temperature, and foundation movements due to swelling clay. The effect of swelling clay is not considered in this study. The performance equation for the Texas Flexible Pavement Design System is as follows:

$$\log N = \log Q + \log \alpha - 2 \log SCI - \log B + 6.0 \qquad (2.14)$$

where

N	=	number of predicted equivalent 18-kip single-axle load applications the pavement can take for one performance period,
Q	=	$\sqrt{5 - P2} - \sqrt{5 - P1}$, function of serviceability loss,
P1	=	estimated initial serviceability index for the type pavement considered,
P2	=	minimum acceptable serviceability level,
α	=	temperature parameter, estimated from previous weather data,
SCI	=	surface curvature index, calculated by the deflection equation using estimated strength coefficients and thicknesses for the different layers, and
B	=	regression coefficient.

This equation was derived using data from the AASHO Road Test as explained in Ref 7. Log N is assumed to be normally distributed, and it has a certain variance associated with it at the design stage.

Stochastic Design Parameters in the Performance Model

In its present form there are four input variables in the performance equation, three of which are considered to be random. The three random variables are (1) the initial serviceability index, (2) the temperature parameter, (3) and the surface curvature index. The fourth input, the minimum acceptable serviceability level, is a design constant, and while it can be changed from one design to another, it cannot be considered a random variable.

Initial Serviceability Index. The initial serviceability index is a measure of the pavement's smoothness or riding quality immediately following construction. It might vary considerably from one project to another, and also within one given project. The serviceability index is usually measured on 1200-foot sections, and the value may change considerably from one section to another within the same project. There are quite a few factors that might cause this variability in the initial serviceability index. Type of flexible pavement is one of these factors. At the present time, designers distinguish between hot-mix asphalt-concrete pavements and surface-treated roads. In the study of the initial serviceability index reported in Chapter 4 this factor is considered, and the two pavement types are studied separately.

There are other factors which might cause variability in the initial smoothness of a pavement, such as (1) the contractor, (2) type of materials used, (3) number of layers in the structure, (4) type of construction equipment used, (5) change in topography, and (6) road alignment.

The initial serviceability index is only indirectly controlled in construction. Specification control for roughness usually includes criteria for a maximum of, say, one-eighth inch in ten feet. Often the pavement surface might meet these specifications, but still show significant roughness due to longer wavelengths which affect vehicles moving at high speeds.

In design, the initial serviceability index must be estimated. Generally a value of 4.2 has been used for hot-mix asphalt-concrete pavements, and 3.8 for surface-treated pavements. The 4.2 figure was the calculated average initial serviceability index of the flexible test sections at the AASHO Road Test. Very few serviceabillty measurements have been taken on newly constructed pavements to test whether or not the assumed serviceability levels were realistic. A study was undertaken to provide better estimates of average initial serviceability levels than those presently existing and also to obtain estimates of the variability associated with this design factor.

<u>Temperature Parameter</u>. The climatic parameter used in FPS is a temperature parameter α , which depends upon the maximum and minimum temperature in a given locality. Based upon ten years of temperature recording an average temperature parameter has been estimated for each Highway Department district headquarters in Texas (Ref 7). The temperature parameter α ranges from nine to 38. Since α was determined from data taken over a ten-year period, the estimates might be fairly good as far as long-time periods at a district headquarters are concerned, but it varies somewhat in a given district. Since all projects within a district are designed with the same temperature parameter, some variation will exist between design and actual values. Darter and Hudson (Ref 2) estimated the amount of variation by taking the difference in the temperature parameters between each district headquarters and the districts surrounding the district and calculating the mean square difference as follows:

$$S_{\alpha}^2 = \frac{\sum_{i=1}^{q} \sum_{j=1}^{b} D_{ij}^2}{h-2} \tag{2.15}$$

where

D_{ij} = difference between the α for district i and an abutting district j ,

q = 25 (number of districts in Texas)

b = number of districts abutting a given district i , and

h = total number of abutting districts.

The resulting variance was calculated to be $S_{\alpha}^{2} = 18.9$, and this estimate will be assumed to represent the uncertainty associated with the prediction of the temperature parameter for a specific project.

Surface Curvature Index. The surface curvature index is the material properties parameter in the performance equation used in FPS. The pavement/subgrade stiffness is characterized by the surface curvature index or SCI, which represents the numerical difference between sensors No. 1 and No. 2 of the Dynaflect*. The general layout of the Dynaflect (load wheels and sensors) is shown in Figs 2.2 and 2.3. The Dynaflect applies a dynamic cyclic load to the pavement and measures the response of the pavement. The resulting surface deflection basin can be used to calculate the in-situ sitffness coefficients, which vary from about 0.15 for a weak, wet clay to 1.00 for asphalt concrete (Ref 8). The stiffness coefficients are calculated by means of a computer program developed by Scrivner et al (Ref 9) entitled "Stiffness Coefficients." The stiffness coefficients computer program is part of the FPS (design) program. Given stiffness coefficients and layer thicknesses for the materials to be used in a proposed design, the stiffness coefficients computer program calculates the expected SCI for the pavement structure, and this calculated SCI is then used in the performance equation.

In order to obtain a reasonable estimate of the stiffness coefficients to be used in a particular design, the recommended Texas Highway Department procedure is to measure the deflections using the Dynaflect and the thickness by coring of similar pavement materials and similar subgrades in the area of the proposed project and then calculate the in-situ stiffness coefficients.

---

*Registered trade mark, Dresser-Atlas Company, Dallas, Texas (Ref 10)

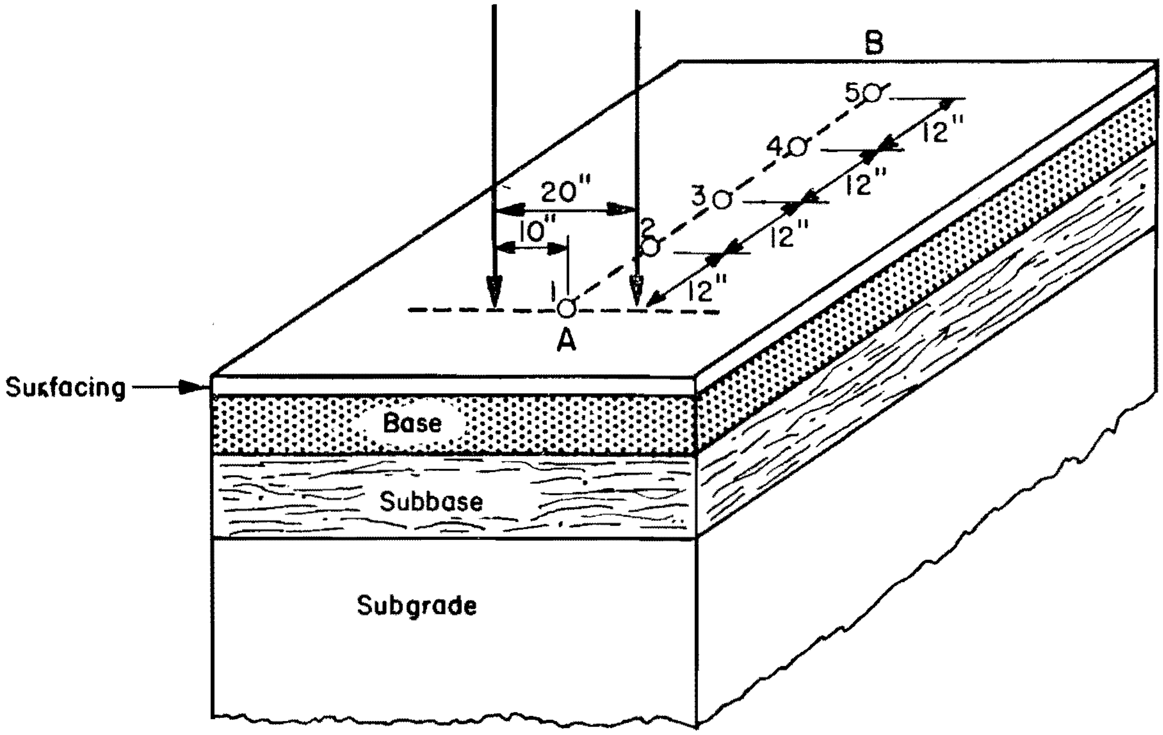


Fig 2.2. Position of Dynaflect sensors during test (Ref 16).

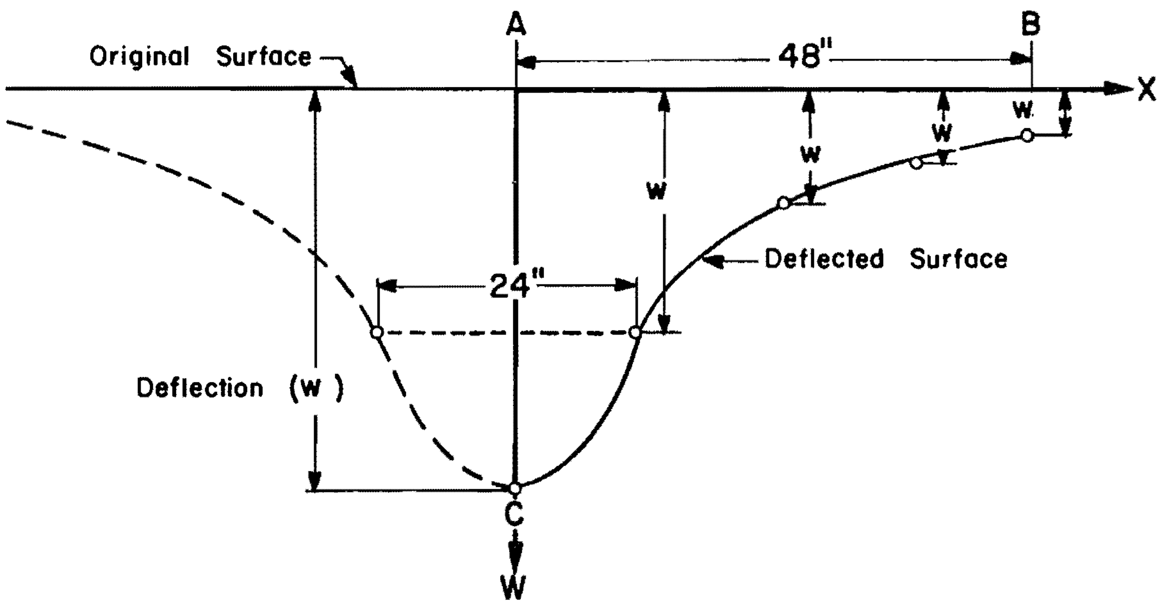


Fig 2.3. Typical deflection basin reconstructed from Dynaflect readings (Ref 16).

Many tests can be run in a short time period at relatively low cost and the stiffness coefficients to be used for design can be selected from these results.

There is a considerable variation associated with the surface curvature index. Studies in statistical quality control and in-situ measurements of pavement properties have pointed out the large variability which can be found in "as built" properties of pavement materials (Refs 11 through 15). The variation of the surface curvature index can be essentially grouped into two types:

(1) variation within a design project length, and

(2) variation due to the lack-of-fit of the deflection equation (used in the stiffness coefficients computer program).

The within project variation of SCI is caused by the variation in the pavement material stiffness coefficients and also the variation in the different layer thicknesses. Darter and Hudson found that the amount of variation changes depending upon materials used. Based upon limited source of data, they derived regression equations to predict the standard deviation of the stiffness coefficients from the mean, given a certain material (Ref 2).

Some variation is introduced into the design because the lack-of-fit of the deflection equation. No attempts have been made so far to determine the amount of this variation, and the quantification of this variation is one of the recommendations of this study.

Variance Model of the Performance Equation

Since log N is assumed to be normally distributed, the function is uniquely defined by its mean and standard deviation. There are different methods available for determining the variance of a variable which is a function of several random variables. The method adopted in FPS is called the "partial derivative method," and it was selected due to the complexity of the equation and its relative ease and accuracy in adaption. The random variables that are considered to influence the variance of log N are P1 , α , and SCI. There is also an associated lack-of-fit error in the performance model itself, which contributes to the variation of log N. Using the partial deviative method, the variance of log N is given as:

$$S^2_{\log N} = \left(\frac{\partial \log N}{\partial P1}\right)^2 S^2_{P1} + \left(\frac{\partial \log N}{\partial \alpha}\right)^2 S^2_{\alpha} + \left(\frac{\partial \log N}{\partial \text{ SCI}}\right)^2 S^2_{SCI} + S^2_{lof} \quad (2.17)$$

where

$S^2_{\log N}$ = total variance associated with log N,

S^2_{P1} = variance of the initial serviceability index,

S^2_{α} = variance of the temperature parameter α ,

S^2_{SCI} = variance of SCI of the pavement/subgrade system, and

S^2_{lof} = variance associated with the lack-of-fit of the performance equation.

Darter and Hudson presented approximate estimates of these variances, but some of the estimates were crude because of limited data. The input factor on which there had been the least amount of data gathered was the initial serviceability index. A study was performed in which one of the goals was to obtain a better estimate of the variance of this input factor. The results from the study are described in Chapter 4 of this report.

Part of the variation assoicated with the performance equation is caused by the so-called lack-of-fit of the equation. The conventional way to quantify lack-of-fit error is to analyze "repeat" measurements, or measurements taken on exact, similar "specimens." In evaluating the lack-of-fit error of the performance equation, this method constitutes a problem because of the inability of the pavement engineer to build exactly similar pavement sections. A different approach therefore had to be taken, and a method by which the lack-of-fit error of the performance equation can be evaluated is presented in the next chapter.

CHAPTER 3. LACK-OF-FIT OF THE PERFORMANCE EQUATION

The performance equation and a model for determining the variance associated with the performance equation were outlined in Chapter 2. The variance of log N is caused by variation in the initial serviceability index, the temperature parameter, the surface curvature index, and the variance caused by the lack-of-fit. This chapter discusses the lack-of-fit term, and outlines a procedure for quantifying it. The chapter is divided into three parts. The first part gives a discussion about lack-of-fit and some of the causes of it. The second part explains the mathematics involved for determining variance caused by the lack-of-fit, and the last part outlines a study for obtaining the data required for quantifying the lack-of-fit.

Lack-of-Fit

The performance equation used in the Texas Flexible Pavement Design System is an empirical equation based upon data collected from in-service pavements and test sections. Part of the variation in the performance equation is caused by lack-of-fit. The lack-of-fit represents the inability of the design model to predict exactly the results when actual average values of all the design parameters are known. The basic reasons for lack-of-fit are as follows:

(1) the model does not contain the proper design factors, and/or

(2) the design factors used are not in proper combination within the model.

From the AASHO Road Test data the mean square residual between predicted and actual applied 18-kip equivalent load applications was calculated to be 0.0812. This figure is believed to be much larger for pavements located in Texas because of widely varying environment, traffic, and materials. Darter and Hudson collected data on six flexible pavement projects in Texas and estimated the number of load applications carried since the pavements were opened to traffic using the performance equation, and then compared these figures with actual applied load applications. Two of these projects had untreated-base materials and the difference between predicted and actual applied loads was relatively small. The four other projects had treated-base materials such as lime, cement, or asphalt. For all these projects, the performance equation predicted a much higher number of load applications than was actually applied. The performance equation is very sensitive to the surface curvature index (SCI) of the pavement/subgrade system due to its exponent. Pavements with treated-base materials result in a stiff structure with low SCI values, causing log N to be large, and it appears, based upon the very limited amount of data, that the lack-of-fit associated with the performance equation is larger for pavements having treated-based materials than for those with untreated.

Model for Determining Lack-of-Fit

In order to quantify the lack-of-fit of the performance equation, several "representative" flexible pavement projects need to be selected throughout the State of Texas. The projects must be in their first performance period (must not have been overlayed) and the following data need to be collected, for separate 1200-foot or 0.2-mile sections:

(1) present serviceability index, measured with the Surface Dynamics Profilometer or Mays Road Meter,

(2) surface curvature index, measured with the Dynaflect, and

(3) number of 18-kip equivalent load applications that have passed over the section since construction.

For every project the initial serviceability index needs to be estimated. A special study of the initial serviceability index has been performed. The results are reported in Chapter 4 of this report, and the estimates should be based upon these results. The temperature parameter is also needed. The average temperature parameter has to be estimated for each Highway Department district headquarters in Texas, as described in Ref 7, and these estimates should be used.

Having the measured serviceability index and surface curvature index and the estimated initial serviceability and temperature coefficient, the total number of 18-kip single-axle load applications can be calculated using the following equation:

$$\log M = \log \left(\sqrt{5 - PSI} - \sqrt{5 - P1}\right) + \log \alpha - 2 \log SCI - \log B + 6.0 \qquad (3.1)$$

where

M	=	estimate of total number of 18-kip single-axle load applications that have passed over the section since it was opened to traffic,
PSI	=	measured present serviceability index,
P1	=	estimated initial serviceability index for that particular type of pavements,
SCI	=	surface curvature index measured by Dynaflect,
α	=	estimated temperature parameter, and
B	=	regression coefficient.

Log M should not be confused with log N, which is an estimate of the total number of 18-kip equivalent single-axle loads for a project at the <u>design stage</u> at which all the design inputs have been estimated.

There will be a certain variation associated with log M which is caused by:

(1) estimation error of P1 and α ,

(2) measurement error of PSI and SCI,

(3) within section variance of SCI, and

(4) error due to lack-of-fit of equation.

This can be written as:

$$\text{Var}\,[\log M] = \text{Var}\left[\log\left(\sqrt{5 - \text{measured PSI}} - \sqrt{5 - \text{P1}}\right)\right] + \text{Var}\,[\log \alpha] + \text{Var}\,[2 \log \text{SCI}] + \text{Var}\,[\text{LOF}] \quad (3.2)$$

Equation 3.1 is the same as the performance equation explained in Chapter 2, except that the inputs differ from those used at the design stage. Some of the inputs to Eq 3.1 are measured in the field, thus reducing some of the estimation (or pure) error introduced when all the parameters have to be estimated. The error introduced by lack-of-fit is the same in both cases, and by solving Eq 3.2 for the lack-of-fit term, the lack-of-fit of the performance equation at the design stage should be obtained.

The estimated load applications obtained from Eq 3.1 should then be compared with the actual applied 18-kip single-axle loads (m), which can be obtained from the Planning Survey Division, Texas Highway Department. Most likely there will be a difference between the two figures which herein is termed an error. Both log M and log m are assumed to be normally distributed, and the error will therefore be normally distributed and have a variation associated with it. The variance of the error is due to the variance of log M plus the variance of log m, and it can be written as:

$$\text{Var}\ [\log M - \log m] = \text{Var}\ [\log M] + \text{Var}\ [\log m] \tag{3.3}$$

or

$$\text{Var}\ [\log M] = \text{Var}\ [\log M - \log m] - \text{Var}\ [\log m]$$

There are now two equations for the variance of log M which are set to be equal, and the equation can be solved for the variance due to the lack-of-fit:

$$\begin{aligned}\text{Var}\ [\text{LOF}] = {} & \text{Var}\ [\log M - \log m] - \text{Var}\ [\log m] - \text{Var}\ [\log \alpha] \\ & - 2\ \text{Var}[\log \text{SCI}] - \text{Var}\left[\log \left(\sqrt{5 - \text{measured PSI}}\right.\right. \\ & \left.\left. - \sqrt{5 - \text{P1}}\right)\right]\end{aligned} \tag{3.4}$$

Data for Quantifying Lack-of-Fit

A considerable amount of data must be collected in order to quantify the lack-of-fit error associated with the performance equation in FPS. Part of this work has been done, in that a study of the initial serviceability index was performed. The results from this study are presented in Chapter 4 of this report and can be used in estimating the initial serviceability index of in-service pavements where such data are not available.

A study of in-service flexible pavements that are in their first performance period is now needed. This section discusses what type of data should be collected, factors to consider in the study, and how to obtain the necessary data.

As outlined in the previous section of this chapter, there are several types of data needed for quantifying lack-of-fit error of the performance equation:

(1) present serviceability index for every consecutive 1200-foot section (possibly each 0.2-mile) along two to three miles of every project,

(2) surface curvature index, measured with Dynaflect, taken for every 100 feet to get good estimates of mean SCI within each 1200-foot section,

(3) estimated initial serviceability index for each section for which such information is not available,

(4) total number of 18-kip equivalent single-axle load applications since construction (estimated by Planning Survey Division, Texas Highway Department), and

(5) temperature parameter for the district in which the project is located.

Since the objective of such a study is to quantify the lack-of-fit of the performance equation used in the Texas Flexible Pavement Design System, the study should inlcude all types of flexible pavements in the State of Texas. There is a variety of material and thickness combinations of in-service pavements in Texas, and it would be an enormous task to study all the combinations separately. The different types of designs will therefore have to be categorized into some form of grouping system.

Indications are that the performance equation seems to fit fairly well for pavements with untreated base materials, and not so well for projects built with treated base and subbase. Therefore, a distinction should be made between projects with treated and those with untreated base materials.

Type and thickness of the surface layer are also factors to consider. Basically, surface type and thickness can be divided into three groups:

(1) surface-treated and thin asphalt concrete (less than or equal to one and one-half inch),

(2) intermediate thickness, asphalt concrete (between one and one-half and four inches), and

(3) thick asphalt concrete (four inches or more).

Past experience indicates that there are reasons to believe that the State of Texas can be divided into "pavement performance regions," i.e., regions in which similar pavement structures have about equal performance from project to project. A pavement performance region can be better described as a region with approximately uniform environmental conditions and materials. Figure 3.1 gives a suggestion for dividing the State of Texas into seven regions. Before a study is undertaken, this factor should be studied thoroughly to define the

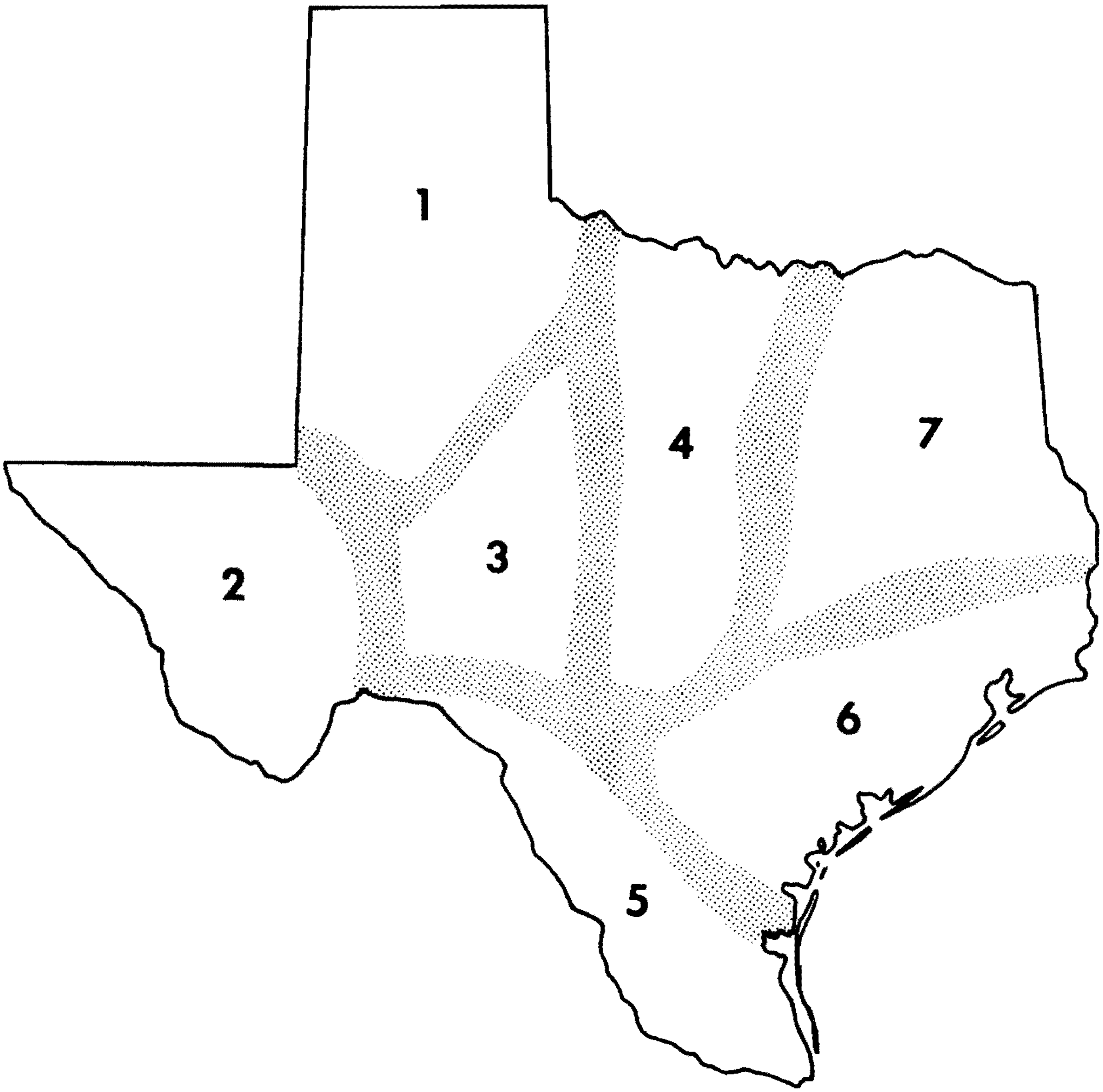


Fig 3.1. Regions of "Equal Pavement Performance."

boundaries of the regions more clearly. Some projects in each region should be included in the study, and they should be as close to the "center" of a region as possible to avoid interfering with conditions in a neighboring region.

The above paragraphs indicate some of the possible factors to consider in the data collection process. To control all the possible combinations of factors, an extensive and time-consuming study would be required. It is suggested that the data needed for quantifying the lack-of-fit error of the performance equation be collected through the Pavement Feedback Data System, a program currently being initiated for the State of Texas.

Present serviceability index can be obtained by either the Surface Dynamics Profilometer (Ref 18) or the Mays Road Meter (Ref 19). The Surface Dynamics Profilometer is the better instrument of the two. It is directly correlated to panel ratings on pavement sections, and since it is very stable against changes in vehicle characteristics, it is probably the instrument presently in use which introduces the least error in the data. The Mays Road Meter is quite sensitive to changes in physical characteristics of the automobile, such as wearout of shock-absorbers and changes in vehicle weight which produces a possible source of error in the measurements. The Mays Road Meter has not been correlated to panel ratings. It has been correlated to test sections measured by the Surface Dynamics Profilometer, which introduces another error into the data. The Surface Dynamics Profilometer is quite expensive, and at the present time, there is only one instrument in Texas, while there are seven of the relatively inexpensive Mays Road Meters. With the amount of data needed for a study to quantify the lack-of-fit of the performance equation, it would probably be advisable to use the Mays Road Meters for obtaining serviceability readings. The possible errors introduced should be recognized, and corrections should be made in the data analysis.

Probably the easiest and most economical way to obtain the necessary data would be to incorporate the data collection process into the Pavement Feedback Data System routine measurements being initiated in the State of Texas. The projects to be included in the study should be selected and each 0.2-mile section marked. When the districts are ready to make the serviceability measurements, a Dynaflect must be available and both measurements should be taken the same day.

The above discussion has centered around the type of data needed for quantifying lack-of-fit of the performance equation, factors to consider in the analysis, and how the necessary data can be obtained. Before the data collection process can start, an experimental design should be developed to determine the amount of data needed. The experimental design and selection of projects to be included in the study for quantifying lack-of-fit have not been done, and one of the recommendations of this study is that this work be done as soon as possible so that the data collection can begin.

CHAPTER 4. STUDY OF INITIAL SERVICEABILITY INDEX ON FLEXIBLE PAVEMENTS

The general concept of applying stochastic design theory to the structural submodel in the FPS Design System was developed by Darter and Hudson (Ref 2), and is outlined in Chapter 2 of this report. In order to utilize this added feature of FPS, estimates of the variation associated with the various design parameters need to be determined. Darter and Hudson started the work of quantifying variations, but for some of the factors, the estimates were crude because of the limited amount of data available. Very little information was available on the initial serviceability index of flexible pavements, which is one of the design parameters in FPS. This study was therefore initiated to obtain better estimates of expected average values and variances associated with this design factor.

Introduction and Objectives

The serviceability index of a pavement section is a function of the road profile; the smoother the road, the higher the serviceability index. Unfortunately, it is not possible to build a perfectly smooth pavement with the construction methods currently available, and the serviceability index is always below the ultimate level of 5.0.

Currently, the initial serviceability index is only indirectly controlled in construction. Specification control for roughness usually includes criteria of approximately one-eighth-inch in 10 feet. The pavement surface may often be within this specification criteria, but will have relatively low serviceability index due to longer wavelengths which affects vehicles moving at high speeds. Designers therefore, have to estimate an expected average value for initial serviceability index in design. The estimates presently being used are based upon a few measurements only, and one of the goals for this study was therefore to obtain better estimates of expected average serviceability index of newly constructed flexible pavements.

The initial serviceability index is a very important design parameter as it designates the "starting point" for the performance curve of a pavement design. If a pavement is built with a lower serviceability index than that assumed in design, the pavement might reach its terminal level before expected, and on the contrary, if it is built smoother than assumed, it might last longer than expected. This concept is schematically illustrated in Fig 4.1.

The serviceability index is measured over a specific length of pavement, usually 1200 feet. Serviceability might vary from section to section along a paving job, and also between different pavement projects. The serviceability index has previously been assumed to be a normally distributed variable, and one of the goals for this study was to test this assumption. Perhaps more important than the distribution is the magnitude of the variation associated with the various design parameters. Another goal for this study was therefore to quantify the variation associated with the serviceability index of newly constructed pavements.

In summation, the main goals set for the study were

(1) to obtain "reasonable" estimates of expected values of initial serviceability index for use in future design calculations,

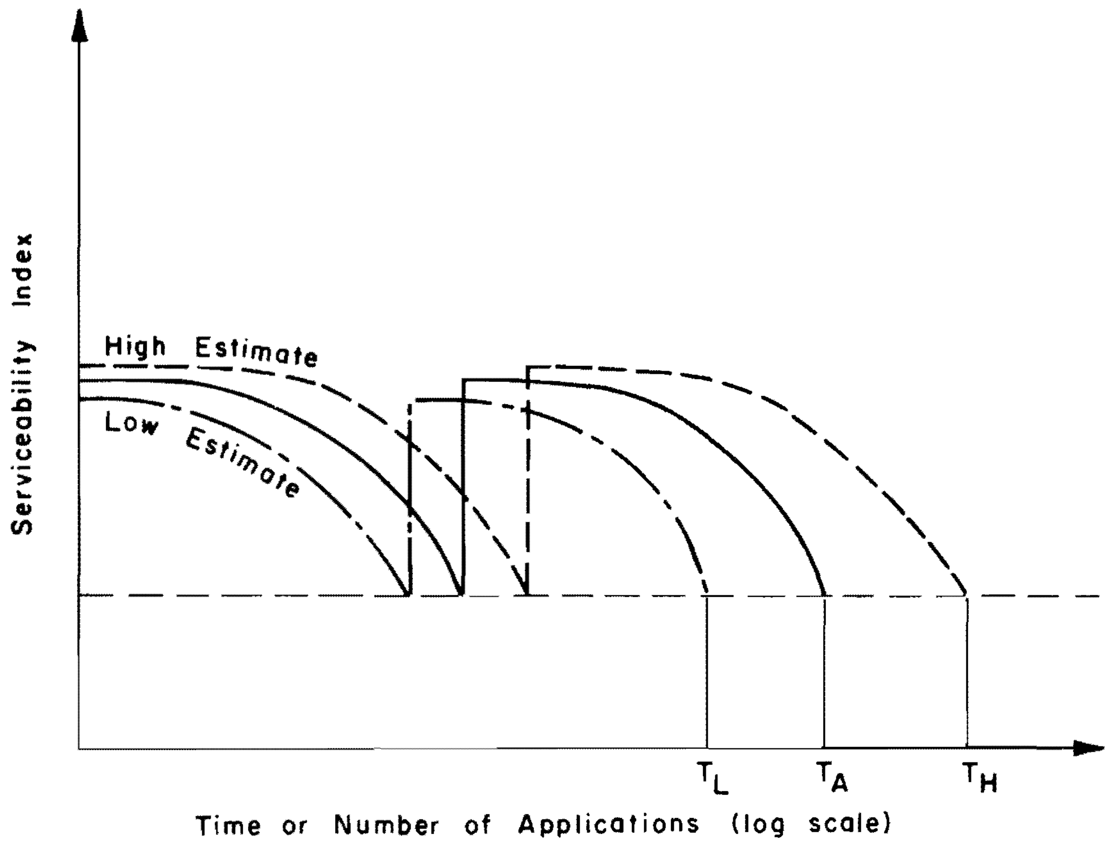
(2) test the assumption that the initial serviceability index is normally distributed, and

(3) to estimate the variance of initial serviceability index so the variation of this design factor can be accounted for in FPS.

In addition to these goals, factors influencing the initial smoothness of a pavement were to be studied to the extent such influence is explained by the obtained data.

Planning of the Study

Experimental Design. One of the first questions that arose when this study was initiated was: "How many data are required to give reasonable estimates of average values and the variance associated with the initial serviceability index?" Assuming the serviceability index is normally distributed, the number of projects required to obtain an acceptably accurate serviceability mean estimate can be calculated at a given confidence level, given an estimate of the variance associated with the serviceability index. To obtain a reasonable estimate of between-project variation of the initial



T_L = predicted service life for low estimate of initial serviceability index,

T_A = actual service life,

T_H = predicted service life for high estimate of initial serviceability index.

Fig 4.1. Influence of initial serviceability index on pavement performance. (Conceptual diagram, not to scale) serviceability index, similar studies conducted elsewhere in the United States were consulted.

In a study in Utah, the initial serviceability index was measured on 76 sections, each 0.2 mile long and each located on a different project (Ref 20). The standard deviation of the serviceability index as calculated to be 0.2. Because only one section was measured on each project, it was impossible to break the variation in the data into between-project and within-project variation, and the calculated variation therefore represents the total variation of the serviceability level on new flexible pavements in Utah.

In a similar study in Minnesota, the serviceability index was measured on 38 newly constructed flexible pavement sections, each 0.2 mile long and each located on a different project (Ref 21). The standard deviation of the serviceability level was calculated to be 0.28, and as in the Utah study, it represents the total variation of the serviceability index. Some of the difference in variation of the data collected in the two studies might be due to different types of measuring equipment used and greatly unequal sample sizes.

Too few measurements had been taken of the initial serviceability index on flexible pavements in Texas to obtain an estimate of the variation associated with this design parameter. Based upon the results from Utah and Minnesota, it was therefore thought that 0.2 (SI-units) might be a reasonable "first-hand" estimate of the standard deviation of the average initial serviceability index between projects for the State of Texas, and this value was used in the experiment design.

After conferring with Highway Department personnel, it was found that it would be desirable to obtain an estimate of mean initial serviceability index within the limits of ± 0.1 SI unit of the true mean with at least 90 percent confidence. By using the above information and the assumption that the initial serviceability index is normally distributed, the number of projects required to meet the specified constraints is specified by the following equation:

$$N = \frac{\sigma^2 Z^2}{L^2} = \frac{(0.2)^2 (1.645)^2}{(0.1)^2} = 10.8 \approx 11 \qquad (4.1)$$

where

N = number of projects required for estimating the mean initial serviceability index within ± 0.1 SI-unit of the true mean at 90 percent confidence,

σ = estimate of standard deviation of average initial serviceability index between projects (-0.2),

Z = the standardized normal variable (1.645 for $\frac{\alpha}{2}$ = 0.05, or 90 percent confidence), and

L = limit (0.1 SI-unit).

Because of the relatively large difference in design and construction methods between hot-mix asphalt-concrete pavements and surface-treated pavements, it would be better to analyze these two types separately. It was therefore concluded that data should be collected from at least 20 projects, ten hot-mix and ten surface-treated projects.

Limitations. The study was limited to flexible pavements only, including hot-mix asphalt-concrete pavements and surface-treated pavements. In order to minimize expenses, the study was limited to districts 13, 14, 15, and 17. Prudence should therefore be taken when utilizing the results for other areas where differenct construction methods might be used. Environmental conditions such as temperature and rainfall might also have an influence on the initial serviceability index, and caution should be shown when using the results in areas with differing climatic conditions.

Selection of Projects. In the selection process, the question arose as to what could be considered a newly constructed pavement. Past experience shows that very little serviceability loss can be found on pavements in the first year after construction. It was therefore reasoned that pavements one year old or less might be included in the study, but that the measurements should be taken as soon after construction as possible. The projects were then selected from the monthly construction reports from the Texas Highway Department (Ref 24).

Description of the Projects

Hot-Mix Asphalt-Concrete Pavements. A total of ten newly constructed hot-mix asphalt-concrete pavements were incorporated into the study. Eight of the projects are located in District 15, one in District 13, and one in

District 17. Some of the projects are located in typical swelling clay areas, which may account for a portion of the relatively large variation in the serviceability index between projects. On some of these projects, the measurements were taken approximately one year after construction, which would be time enough for the clay to start swelling and cause roughness on the surface. All the data that were collected were stored on magnetic tapes, and, by using spectral analysis programs, these data could be of help in future studies of the effect of swelling clay on the serviceability index.

The designs of the different projects varied considerably. This factor was analysed in the study, and the results are presented later in this chapter. The lengths of the projects varied from a low of 2.6 miles to a high of 15.3 miles, causing an unequal number of measured sections (each section is 1200 feet) within the different projects.

Surface-Treated Pavements. A total of 11 surface-treated pavement projects were measured and incorporated into the analysis. Five of the projects are located in District 14, while the remaining six are located in District 15. Eight of the projects are located in the limestone hill country west of IH 35, one project is located east of San Marcos in what might be a swelling clay area, and the remaining two are located southeast of San Antonio on the borderline between a swelling clay and a sandy area. Most of the projects had a two-layer surface treatment on top of emulsion asphalt-sprayed flexible base. Only two of the projects had a three-layer surface treatment. Both of these projects had an average initial serviceability index in the high range of the projects, which tends to support the theory that the more surface courses the smoother the surface. The surface-treated projects ranged in lengths from a low of 3.11 miles to a high of 7.16 miles.

Equipment and Measurements

The Surface Dynamic Profilometer (Ref 18) was used for measuring the surface profile. The data were first stored on analog tape. They were then processed on an analog-to-digital computer at the Texas Highway Department and stored on magnetic digital tapes (Ref 22). These tapes were then placed on the CDC 6600 computer at The University of Texas at Austin, and the "Serviceability Index Computer Program" was run on the data to obtain serviceability index readings for individual consecutive 1200-foot pavement sections. The

Surface Dynamics Profilometer is quite repeatable and stable against change in vehicle characteristics, but in this study to provide a means of error, all projects were run twice. Non-repeatability was found on only a few sections on two of the projects, and the cause was due to minor mechanical or electrical problems with the profilometer. When the deviation between two runs exceeded 0.4 SI-unit on any 1200-foot section, the section was excluded from the analysis. The Surface Dynamics Profilometer is quite sensitive to changes in road alignment and profile. During the data collection process, notes were taken about the roadway geometry, and sections having sharp curves and/or sharp changes in profile were excluded from the analysis also. Because of these limitations, the number of "useful" sections within different projects varied, and this is the reason the results from only a few sections on some projects could be used in the final analysis of the data.

Normality Assumptions

The normal distribution is a very convenient distribution to work with in stochastic design, and the initial serviceability index has previously been assumed to be normally distributed, without too much data to support the assumption. In order to test this assumption, the serviceability values from the ten hot-mix asphalt projects were put in one group, and the eleven surface-treated projects in another group. The total number of 1200-foot sections measured on the hot-mix projects was 113, ranging from three sections on Project No. 2, to 17 sections on Project No. 7. On the surface-treated pavements a total of 144 SI values were obtained, ranging from seven measured sections on Project No. 7 to 17 sections on Project No. 6. The data are shown in Appendix 1.

Figures 4.2 and 4.3 show the histograms of the serviceability index for the hot-mix projects and the surface-treated projects, respectively. A visual analysis of the distributions to test the hypothesis that the samples come from normally distributed propulations may be aided by three statistical tests available, (1) the chi-square goodness-of-fit test, which is used to judge the normality assumption, (2) the skewness test, used to test whether the data are significantly skew to one or the other sides, and (3) the kurtosis test to show whether or not the distribution is too peaked or too flat-topped (Ref 26).

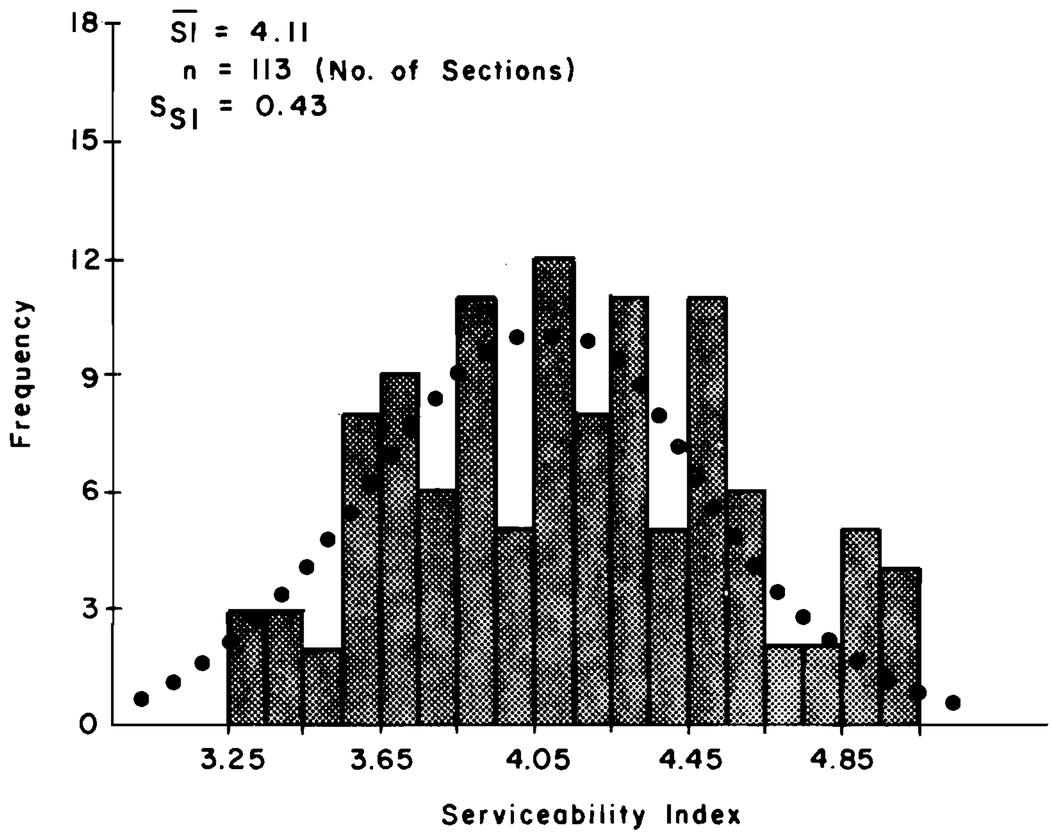


Fig 4.2. Histogram of initial serviceability index of hot-mix asphalt-concrete pavement sections.

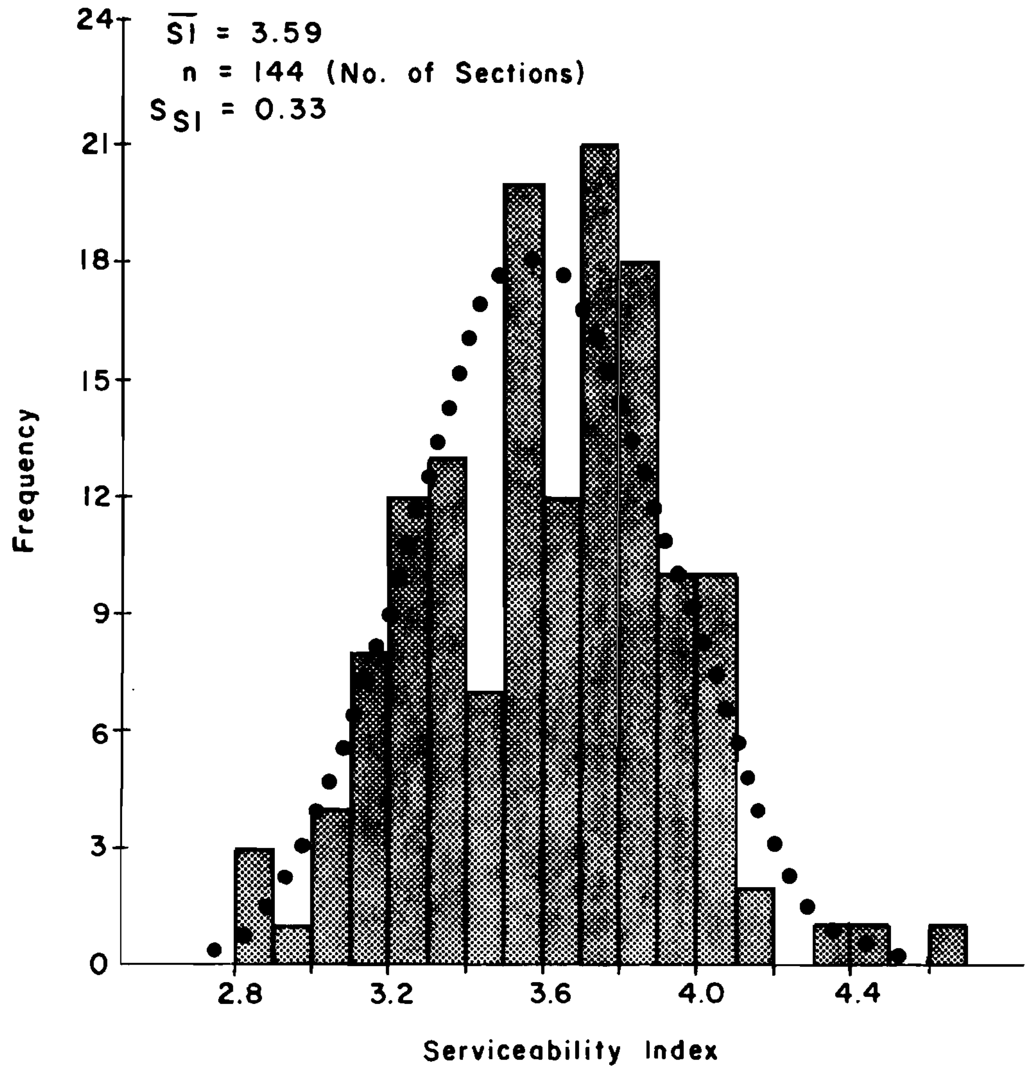


Fig 4.3. Histogram of initial serviceability index of surface-treated pavement sections.

Results from the three tests are summarized in Table 4.1. The distributions were tested at a five percent confidence level, and neither of the two distributions could be rejected for any of the tests except for the hot-mix distribution, which had to be rejected for the kurtosis test, indicating a too flat-topped distribution. However, the distribution was also tested at the one percent confidence level at which it could not be rejected for any of the three tests. As a result of these tests it can be concluded that the assumption that the initial serviceability index comes from a normally distributed population, seem to be valid based upon the data gathered in this study.

Hot-mix Asphalt-Concrete Projects

On the ten projects measured, 113 1200-foot sections were included in the analysis, but because of the different lengths of the projects and because some sections had to be omitted because of the abrupt roadway geometry or presence of bridges, the number of sections within each project varied. The average initial serviceability index of all the sections was calculated to be 4.11, while the project mean ranged from a low of 3.52 to a high of 4.54. The standard deviation of the project average was caluclated to be 0.3103, which is somewhat higher than was assumed. A summary for the ten projects is shown in Table 4.2. A one-way analysis of variance was run on the data, and the results are shown in Table 4.3. The between-project mean square was calculated to be 1.1979, and when tested with the F-test it showed to be significant variation between the projects at the one percent level. In order to explain the reason for the relatively large between-project mean square, attempts were made to analyze the various factors that might influence the initial serviceability index of hot-mix asphalt-concrete pavements. The results from this analysis are reported in the following paragraphs.

Pavement Designs. The plans for all the projects were obtained from the Texas Highway Department, and a summary of the designs is shown in Table 4.4. When studying the pavement designs, it was discovered that Project No. 9 is not a newly constructed pavement, but an overlay on an old structure. However, the project was included in the analysis because the overlay consists of four inches hot-mix asphalt-concrete to two courses, and the old pavement is considered as granular base material only.

TABLE 4.1. NORMALITY TESTS ON INITIAL SERVICEABILITY INDEX DISTRIBUTIONS

Pavement Type	Rejected at 5 Percent		
	Chi-Square	Skewness	Kurtosis
Hot-mix asphalt-concrete	No	No	Yes
Surface-treated	No	No	No

TABLE 4.2. SUMMARY OF INITIAL SERVICEABILITY INDEX ON TEN HOT-MIX ASPHALT-CONCRETE PAVEMENT PROJECTS

Project Number	Number of Sections	Project Mean	Standard Deviation	Coefficient of Variation
1	10	4.51	.34	7.61
2	3	4.15	.10	2.41
3	14	3.90	.26	6.78
4	12	3.52	.20	5.69
5	9	4.21	.50	11.80
6	14	3.92	.24	6.12
7	17	4.33	.31	7.26
8	9	4.15	.30	7.25
9	11	3.94	.33	8.31
10	14	4.54	.32	7.07

TABLE 4.3. ANALYSIS OF VARIANCE OF INITIAL SERVICEABILITY INDEX ON TEN HOT-MIX ASPHALT-CONCRETE PAVEMENT PROJECTS

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-ratio
Between projects	10.7812	9	1.1979	12.5032*
Within projects	9.8683	103	.0959	
Total	20.6494	112		

*Significant variation between projects

TABLE 4.4. HOT-MIX ASPHALT-CONCRETE PAVEMENT DESIGNS

Project Number	Average SI	Number of Surface Courses	Surface Thickness (inches)	Number of Asphalt-Treated Base Courses	Asphalt-Treated Base Thickness (inches)	Number of Granular Base Courses	Granular Base Thickness (inches)
1	4.51	1	1.0	3	7.0	1	11.0
2	4.15	1	1.5	2	6.5	1	12.0
3	3.90	2	1.5	4	13.5	2	9.0
4	3.52	1	1.5	0	0.0	2	9.5
5	4.21	1	1.5	0	0.0	3	18.0
6	3.92	2	3.0	0	0.0	3	18.0
7	4.33	2	1.5	4	12.5	0	0.0
8	4.15	2	1.5	4	12.5	0	0.0
9	3.94	2*	4.0	0	0.0	2	12.0
10	4.54	2	1.5	4	10.5	3	9.0

*Overlay on existing pavement structure

Because of the relatively large variation found on the hot-mix asphalt projects, an attempt was made to run an analysis of variance to observe what influence the different designs had on the initial serviceability index. The number of passes with a laydown machine and the total thickness of asphalt mix materials were thought to be important factors which would influence the initial serviceability index. Asphalt-treated base materials had been put down with laydown machine on all the projects where such materials were used, and the projects were therefore grouped into two groups depending upon the number of surface and asphalt-treated base courses, (1) projects with four or more asphalt material courses, and (2) projects with three or less asphalt-material courses. Next, the projects were divided into two more groups depending on total thickness of the surface courses, plus asphalt-treated base, (1) above or equal to ten inches, and (2) below ten inches. By grouping the projects as described above a factorial of four was derived, but because of many observations in two of the cells in the factorial and very few in the two others, the analysis is unreliable, and is therefore not presented.

The actual values of the six design parameters shown in Table 4.4 were then coded as independent variables and regressed on the initial serviceability index using a stepwise regression computer program (Ref 23). The equation for predicting the initial serviceability index, given the pavement design and summary tables from the regression is presented in Appendix 2. When allowing for squared and interaction terms of the independent variables, accounting could be made for about 50 percent of the variation in the data. This might seem very low, but when checking the residual between average measured serviceability values and predicted values, the equation seems to predict very well, However, caution should be taken when using the equation, especially when different designs from any of the ten shown in Table 4.4 are used. The number of asphalt-treated base courses was the next important factor, accounting for 17 percent of the variation. The coefficients in the regression equation were positive for both number of asphalt-treated base courses and asphalt-treated base thickneses, indicating an increase in initial serviceability index with increasing number of asphalt courses and thicker pavements.

Length of Projects. The total length of the pavement project was considered to be an important factor which would influence the initial serviceability index. The reasoning was that long projects would be smoother than shorter ones because the effect of initial equipment adjustments would be smaller on the longer projects. To test this assumption, the projects were divided into two groups, (1) less than or equal to five miles, and (2) above five miles. Some 38 sections were located in the "short projects" group with a mean serviceability index of 4.12 and a standard deviation of .53. There were 75 sections in the "above five miles" group with a mean of 4.11 and a standard deviation of 0.37. The two group means were tested against each other, and no significant difference was found. Coding the actual project lengths as an independent variable and regressing on the serviceability index also was tried. The variable accounted for only one percent of the variation in the data, and it was therefore concluded that based upon the available data, there was no reason to believe that longer projects will be smoother than the shorter projects.

Other Factors Influencing the Initial Serviceability Index. There is quite a variety of factors, or combination of factors, which can influence the smoothness of a new hot-mix asphalt-concrete pavement. Type of laydown machine, roller equipment, experience of equipment operators, and type of control are all such factors. None of these factors were studied separately in this study because of the limited amount of data. When studying the specifications for the different projects, all of them specified the same type of layout machine, and it was therefore impossible to compare them to some other type. To study all these factors, a more extensive study would be required.

Surface-Treated Pavement Projects

Table 4.5 is a summary for the 11 surface-treated projects measured. The table shows the number of sections, the mean, the standard deviation and the coefficient of variation of the initial serviceability index for each project. A total of 144 1200-foot sections was measured, and the mean serviceability index was calculated to be 3.59. The project means ranged from a low of 3.29 to a high of 3.83 with a standard deviation of the project means of 0.20. A one-way analysis of variance was run on the data, and the results from this analysis are shown in Table 4.6. The within-project mean square was calculated

TABLE 4.5. SUMMARY OF INITIAL SERVICEABILITY INDEX ON ELEVEN SURFACE-TREATED PAVEMENT PROJECTS

Project Number	Number of Sections	Project Mean	Standard Deviation	Variation of Coefficient
1	12	3.35	.28	8.49
2	17	3.65	.30	8.10
3	13	3.83	.22	5.77
4	14	3.50	.30	8.53
5	15	3.29	.27	8.09
6	17	3.79	.22	5.74
7	7	3.29	.32	9.69
8	12	3.79	.35	9.35
9	13	3.54	.38	10.62
10	10	3.64	.31	8.47
11	14	3.59	.21	5.93

TABLE 4.6. ANALYSIS OF VARIANCE OF INITIAL SERVICEABILITY INDEX ON ELEVEN SURFACE-TREATED PAVEMENT PROJECTS

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-ratio
Between projects	4.7439	10	.4744	5.7799*
Within projects	10.9161	133	.0821	
Total	15.6600	143		

*Significant variation between projects

to be 0.0821 and the between-project mean square to be 0.4744. Both the within and between-project mean square were considerably lower than for the hot-mix asphalt-concrete projects; indicating a more uniform surface smoothness for surface-treated roads. The F-test showed the variation between the projects to be significant at the one percent level, and it was decided to consider some of the factors which might affect the initial serviceability index.

Pavement Designs. In order to observe what effect the pavement design might have on the initial serviceability index, the plans for all the surface-treated projects were studied. A summary of the designs is shown in Tabe 4.7. Nine of the 11 projects measured had a two-course surface treatment, and the remaining two projects had a three-course surface treatment. A study was done to observe the effect of number of surface courses on the serviceability level, but because only two projects had three courses, the results were unreliable and are threfore not presented. However, both the three-course projects had an average serviceability index above the total mean, indicating a smoother surface on projects with more surface courses. Other factors in the design which were observed were rate of asphalt application, aggregate type and gradation, rate of aggregate, and base thickness. Only negligible correlation could be found between any of these factors and the initial serviceability index.

Length of Projects. The surface-treated projects were divided into two groups, below or equal to five miles, and above five miles total length. The mean serviceability index was calculated along with the standard deviation for each group. Only a minor difference in the mean could be found between the two groups, and, when tested, the difference was not significant.

Age of Projects. All the surface-treated pavements were one year old or less when the measurements were taken. Because of the relatively low structural capacity of surface-treated surfaces, it was thought that some of the projects already might have started to deteriorate. However, when attempting to correlate the number of months after construction with the serviceability index, only negligible correlation could be found.

TABLE 4.7. SURFACE-TREATED PAVEMENT DESIGNS

Project Number	Average SI	Number of Surface Courses	Flexible Thickness (inches)	Emulsion Asphalt on Flexible Base
1	3.35	2	6	Yes
2	3.65	3	12	No
3	3.84	2	6	Yes
4	3.50	2	6	Yes
5	3.29	2	8	No
6	3.79	2	6	Yes
7	3.28	2	6	Yes
8	3.79	2	6	No
9	3.54	3	6	Yes
10	3.63	2	6	Yes
11	3.59	2	10	Yes

CHAPTER 5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter summarizes the work which has been done in this study and gives recommendations as to future work needed in this area.

Summary

The need to be able to design for a specific level of reliability and account for the inherent variations in the different design factors has been recognized in many areas of design. Basic stochastic design theory was applied to the structural subsystem of the Texas Flexible Pavement Design System by Darter and Hudson (Ref 2), allowing the designer to determine the reliability of a specific design and design for a specific level of reliability. In order to utilize this added feature of FPS, estimates of the variations associated with the different design factors are needed. A study was made to quantify the variations associated with the initial serviceability index of flexible pavements. The study was designed to obtain better estimates of expected average values and the variations of this design factor. A total of 21 newly constructed pavements was measured using the Surface Dynamics Profilometer. Eleven of the projects were surface-treated pavements while the remaining ten were hot-mix asphalt-concrete pavements. An equation for predicting the initial serviceability index on hot-mix asphalt-concrete pavements was derived, given pavement design parameters such as number of layers, type of materials, and layer thicknesses. The equation is presented in Appendix 2.

Most of the models used in FPS are empirical equations based upon data collected on test sections and in-service pavements. There is a certain lack-of-fit associated with the equations, and in order to determine the variance of a design, the lack-of-fit has to be estimated. The lack-of-fit associated with the performance equation used in FPS is believed to be quite large due to wide variations in traffic, environmental conditions and materials in the State of Texas. A method for determining the lack-of-fit of the performance equation was developed, and a study for obtaining the data for quantifying the lack-of-fit was outlined.

Conclusions

Initial Serviceability Index. From the study of the initial serviceability index, the following brief conclusions were drawn:

(1) The initial serviceability index varies depending upon whether the pavement has a hot-mix asphalt-concrete surface or is surface-treated. Surface-treated pavements are generally rougher than hot-mix asphalt-concrete pavements.

(2) The analysis of variance showed that there is a significant variation in the initial serviceability index. The variation could be broken into between-project variation and within-porject variation. The within-project variation was about the same for both hot-mix and surface-treated pavements. The between-porject variance, however, was much larger for hot-mix asphalt-concrete pavements than for surface-treated, indicating that surface-treated pavements are more uniform. This can probably be credited to less variation in design parameters (number of layers and thicknesses) for the surface-treated projects.

(3) The analysis of variance indicates that the surface becomes smoother with an increasing number of passes with the laydown machine and increasing thickness of bituminous materials.

(4) With the amount of data collected, only negligible correlation could be found between the initial serviceability index and the total length of the projects and the number of months between construction and the time the measurements were taken.

(5) An equation for predicting the initial serviceability index on hot-mix asphalt-concrete pavements, given the pavement design parameters, was derived.

Lack-of Fit of the Performance Equation. The work of quantifying the lack-of-fit of the performance equation presently used in FPS was initiated in this study. A method by which the lack-of-fit can be determined, was developed (Eq 3.4), and a study for gathering the necessary data was outlined.

Recommendations

Based upon this study, the following recommendations are given for further development in applying probabilistic design methods to pavement design systems and quantifying variations associated with the various design parameters in the system:

(1) The study of the initial serviceability index covered only a few of the 25 Highway Department districts in Texas. In order to obtain better estimates covering the whole state, serviceability data need to be collected from new projects in other districts. Serviceability

measurements should be taken immediately following construction on every new pavement project. This work can probably be included as a routine in the Pavement Feedback Data System (PFDS) presently being developed and initiated in Texas.

(2) Serviceability readings collected on newly constructed pavements indicate a smoother surface with increasing number of passes with the laydown machine. It is therefore recommended that designers consider the tradeoff between increase in cost resulting from more passes with the laydown machine and the sacrifice in final smoothness of the surface with fewer passes.

(3) Influence on the initial serviceability index from factors such as type of laydown machine, roller equipment, experience of equipment operators, and type of control was not considered in the study of initial serviceability index. It is therefore recommended that information about these factors be collected in any future study so these possible effects can be evaluated.

(4) A method for quantifying the lack-of-fit of the performance equation in FPS was developed (Eq 3.4). There now exists a need for collecting the data necessary for determining this error. Immediate needs are (1) a detailed experimental design, and (2) selection of projects from which the data should be collected. Data should be collected from across the state, and the most convenient way to obtain these data would probably be through PFDS.

(5) Among the types of data needed for quantifying lack-of-fit error of the performance equation is deflection measurements. The surface curvature index needs to be quantified better for different types of pavement structures, and an experimental design needs to be performed so that the necessary data needed for quantification can be obtained from data gathered for the lack-of-fit study.

(6) Most types of data collected on pavements are stochastic in nature. To assure that adequate data are collected through the Pavement Feedback Data System presently being initiated in the State of Texas, experimental designs and sampling plans need to be set up.

REFERENCES

1. Advisory Committee of FHWA-HRB Workshop on Structural Design of Asphalt Concrete Pavement Systems, Special Report 126, Highway Research Board, 1971.

2. Darter, M. I. and W. R. Hudson, "Probabilistic Design Concepts Applied to Flexible Pavement Design Systems," Research Report No. 123-18, published jointly by the Texas Highway Department; Texas Transportation Institute, Texas A&M University; and the Center for Highway Research, The University of Texas at Austin, 1973.

3. Scrivner, F. H., W. M. Moore, W. F. McFarland, and G. R. Carey, "A System Approach to the Flexible Pavement Design Problem," Research Report No. 32-11, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1968.

4. Hudson, W. R., B. F. McCullcugh, F. H. Scrivner, and J. L. Brown, "A System Approach Applied to Pavement Design and Research," Research Report 123-1, published jointly by the Texas Highway Department; Texas Transportation Institute, Texas A&M University, and the Center for Highway Research, The University of Texas at Austin, 1970.

5. Brown, J. L., and H. E. Orellana, "An Asphaltic Concrete Overlay Design Subsystem, "Texas Highway Department, Research Report 101-F, 1970.

6. Carey, W. N., Jr., and P. E. Irick, "The Pavement Serviceability - Performance Concept," Bulletin 250, Highway Research Board, 1960.

7. Scrivner, F. H., and W. M. Moore, "Flexible Pavement Performance Related to Deflections, Axle Applications, Temperature, and Foundation Movements," Research Report 32-13, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1969.

8. Scrivner, F. H., C. H. Michalak, and W. M. Moore, "Calculation of the Elastic Moduli of a Two-layer Pavement System from Measured Surface Deflections," Research Report 123-6, published jointly by the Texas Highway Department, Texas Transportation Institute, Texas A&M University; and Center for Highway Research, The University of Texas at Austin,

9. "Flexible Pavement Designer's Manual - Part I, Texas Highway Department Pavement Design System," Highway Design Division, Texas Highway Department, 1972.

10. Scrivner, F. H., G. Swift, and W. M. Moore, "A New Research Tool for Measuring Pavement Deflections," Highway Research Record No. 129, Highway Research Board, 1966.

11. Granley, Edwin C., "Quality Assurance in Highway Construction, Part 4,- Variations of Bituminous Construction," Public Roads, Vol 35, No. 9, August 1969

12. Granley, Edwin C., "Quality Assurance in Highway Construction, Part 6 - Control Charts," Public Roads, Vol 35, No. 11, December 1969.

13. McMahon, Thurmul F., and Wesley M. Baker, "Quality Assurance in Highway Construction, Part 3 - Quality Assurance of Portland Cement Concrete," Public Roads, Vol 35, No. 8, June 1969.

14. McMahon, Thurmul F., and Woodrow F. Halstead, "Quality Assurance in Highway Contruction, Part 1 - Introduction and Concepts," Public Roads, Vol 35, No. 6, February 1969.

15. McMahon, Thurmul F., "Quality Assurance in Highway Construction, Part 2 - Quality Assurance of Enbankments and Base Cources," Public Roads, Vol 35, No. 7, April 1969.

16. Scrivner, F. H., and W. M. Moore, "An Empirical Equation for Predicting Pavement Deflections," Research Report No. 32-12, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1968.

17. Haugen, E. B., Probabilistic Approaches to Design, John Wiley and Sons, Inc., New York, 1968.

18. Walker, R. S., F. L. Roberts, and W. R. Hudson, "A Profile Measuring, Recording and Processing System," Research Report 73-2, Center for Highway Research, The University of Texas at Austin, April 1970.

19. Walker, R. S., and W. R. Hudson, "A Correlation Study of the Mays Road Meter with the Surface Dynamics Profilometer," Research Report 156-1, Center for Highway Research, The University of Texas at Austin, February 1973.

20. Liddle, W. J., "Evaluation of Pavement Serviceability on Utah Highways," Interim Report, Utah State Highway Department, 1969.

21. Kersten, M. S., and E. L. Skok, Jr., "Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota," Interim Report, University of Minnesota, 1968.

22. Walker, R. S., and W. R. Hudson, "Analog-to-Digital System," Research Report 73-4, Center for Highway Research, The University of Texas at Austin, 1970.

23. Dixon, W. J., "BMDO2R - Stepwise Regression Computer Program," University of California Publication in Automatic Computation No. 2, University of California Press, Berkeley, 1968 (Program is modified for CDC-6600 computer at The University of Texas at Austin).

24. Texas Highway Department, Construction Division, Construction Reports, July 1972, and January 1973.

25. "The AASHO Road Test, Report 5 - Pavement Research," Special Report 61 Highway Research Board, 1962.

26. Snedcor, G. W., and W. G. Cochram, "Statistical Methods," Iowa State University Press, Sixth Edition, 1967.

APPENDIX 1

MEASURED INITIAL SERVICEABILITY INDEX ON HOT-MIX ASPHALT-CONCRETE AND SURFACE-TREATED PAVEMENTS

TABLE A1.1. MEASURED INITIAL SERVICEABILITY INDEX ON HOT-MIX ASPHALT-CONCRETE PAVEMENT

Sections	Projects 1	2	3	4	5	6	7	8	9	10
1	4.00	4.15	4.15	3.60	3.70	4.00	4.65	4.50	3.35	4.60
2	5.00	4.25	3.85	3.25	4.00	3.60	4.30	3.90	3.95	4.45
3	4.85	4.05	4.20	3.55	3.65	3.80	4.45	4.50	4.35	4.50
4	4.45		4.10	3.60	3.80	4.15	4.50	4.30	4.15	4.70
5	4.60		3.95	3.85	4.60	4.25	4.95	3.70	3.65	4.85
6	5.00		3.90	3.80	4.80	4.10	4.05	3.85	4.10	4.50
7	4.30		3.65	3.55	4.90	3.55	4.20	4.10	4.10	4.30
8	4.40		4.05	3.55	3.90	3.90	4.25	4.45	3.60	4.45
9	4.25		3.75	3.25	4.55	3.50	4.35	4.05	4.20	5.00
10	4.10		3.65	3.50		3.80	3.90		3.40	3.70
11			3.70	3.65		4.15	4.75		4.25	4.45
12			3.85	3.30		3.90	3.80			4.85
13			3.40			4.05	4.25			4.40
14			4.40			4.10	4.20			4.85
15							3.90			
16							4.55			
17							4.55			
Mean	4.51	4.15	3.90	3.52	4.21	3.92	4.33	4.15	3.94	4.54

TABLE A1.2. MEASURED INITIAL SERVICEABILITY INDEX ON SURFACE-TREATED PAVEMENTS

	Projects										
Sections	1	2	3	4	5	6	7	8	9	10	11
1	3.05	3.70	4.05	3.80	3.55	3.75	3.45	3.75	3.25	3.70	3.80
2	3.30	3.55	4.00	2.85	4.00	3.65	3.25	3.40	3.50	3.15	3.85
3	3.35	3.85	3.95	3.50	3.20	3.80	3.10	3.30	2.80	3.55	3.50
4	3.95	3.50	3.85	3.40	3.35	3.80	3.25	3.70	3.30	3.55	3.55
5	3.10	4.00	3.75	3.25	3.00	4.40	3.70	3.90	3.80	3.70	3.65
6	3.15	3.80	3.80	3.45	3.20	3.60	3.15	4.05	3.30	3.70	3.35
7	3.20	3.90	3.75	3.50	3.50	3.65	3.50	3.65	3.85	4.00	3.75
8	3.75	4.10	3.55	3.70	2.80	3.55		4.15	4.00	3.95	3.25
9	3.30	3.55	3.45	3.00	3.25	3.85		3.80	3.70	3.90	3.30
10	3.05	3.70	3.85	3.60	3.35	3.55		3.55	3.15	3.10	3.70
11	3.50	3.40	4.30	3.75	3.30	4.05		3.60	3.90		3.65
12	3.55	3.55	3.90	3.60	3.15	3.65		4.60	3.45		3.35
13		3.80	3.65	3.70	3.20	4.05			4.05		3.90
14		3.70		3.90	3.25	3.65					3.70
15		2.90			3.30	3.70					
16		3.85				3.80					
17		3.20				3.85					
Mean	3.35	3.65	3.83	3.50	3.29	3.79	3.29	3.79	3.54	3.63	3.59

APPENDIX 2

PREDICTION EQUATION FOR INITIAL SERVICEABILITY INDEX, AND STATISTICS FROM REGRESSION

MODEL FOR PREDICTING INITIAL SERVICEABILITY INDEX, GIVEN PAVEMENT DESIGN

$$
\begin{aligned}
ISI = {} & 0.395(ABC) + 0.052(ABT) + 0.611(SC)^2 - 1.021(SC \times ST) \\
& + 0.366(SC \times ABT) - 0.010(ABC)^2 - 0.003(ABC \times ABT) \\
& + 0.003(FBC \times FBT.)
\end{aligned} \tag{A2.1}
$$

where

ISI = initial serviceability index,

ABC = number of asphalt-treated base courses,

ABT = total thickness of asphalt-treated base,

SC = number of surface courses,

ST = total thickness of surface courses,

FBC = number of flexible base courses,

FBT = total thickness of flexible base courses.

TABLE A2.1. SUMMARY STATISTICS FROM REGRESSION

Step No.	Variable Entered*	Multiple R^2	Increase R^2
1	ABC	.1890	.1890
2	ABT	.3618	.1728
3	FBC $\times$ FBT	.4022	.0404
4	ABC $\times$ ABT	.4427	.0405
5	ABC^2	.4497	.0069
6	SC $\times$ ABT	.4555	.0068
7	SC $\times$ ST	.4791	.0226
8	SC^2	.5000	.0210

*Abbreviations same as in prediction equation

TABLE A2.2. MEASURED PROJECT AVERAGE INITIAL SERVICEABILITY INDEX, PREDICTED SERVICEABILITY INDEX, AND RESIDUALS

Project Number	Measured Project Average SI	Predicted SI	Residuals
1	4.51	4.50	.01
2	4.15	4.15	.00
3	3.90	3.90	.00
4	3.52	3.54	-.02
5	4.21	4.21	.00
6	3.92	3.92	.00
7	4.33	4.27	.06
8	4.15	4.27	-.12
9	3.94	3.92	.02
10	3.54	3.54	.00

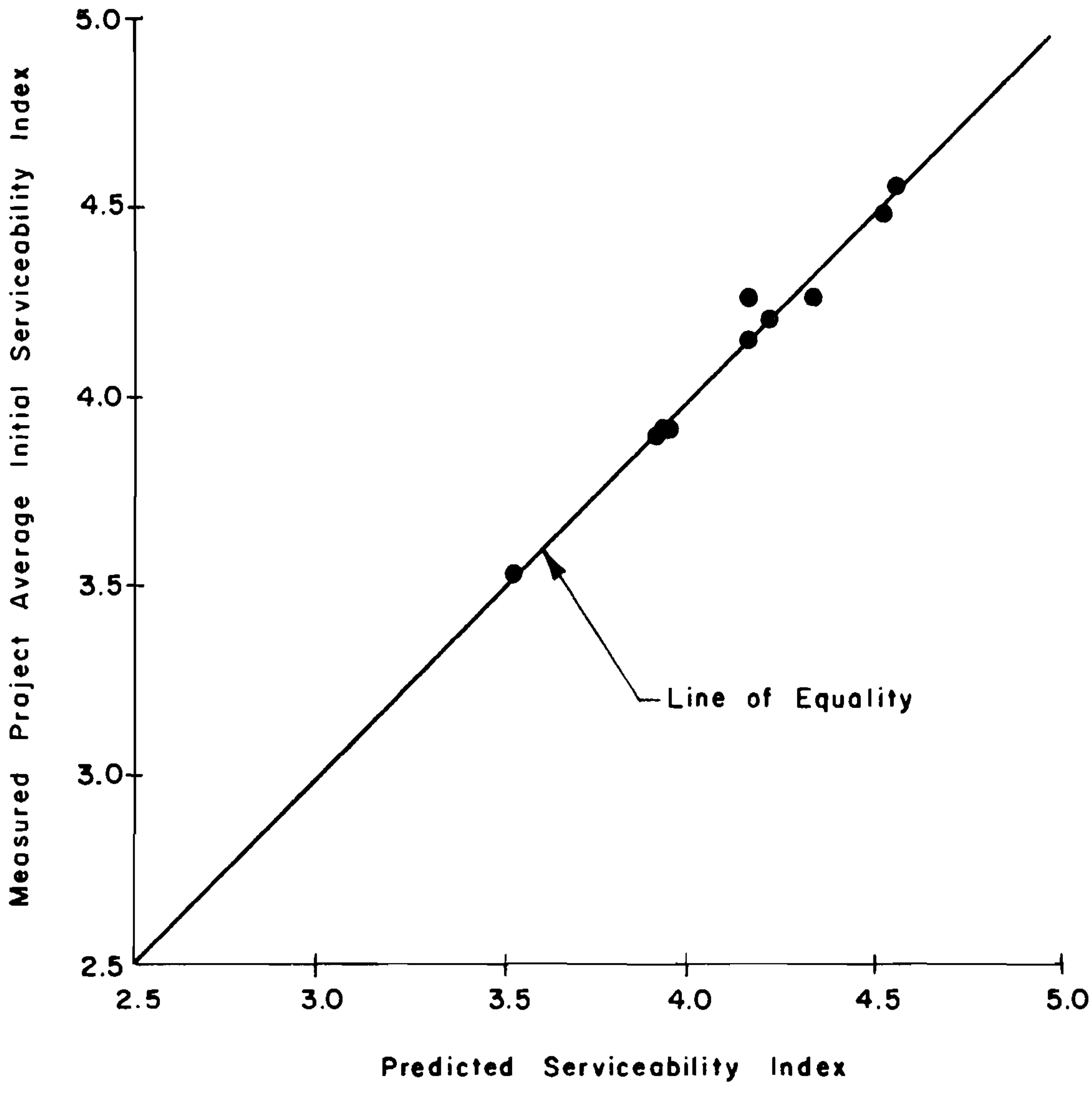


Fig A2.1. Measured project average initial serviceability index versus predicted.

THE AUTHORS

Malvin Holsen is a Research Engineer Assistant with the Center for Highway Research where his interest is in the design analysis of flexible pavements. He has had experience in traffic engineering with the Highway Department in Norway, and is a member of several professional societies.

W. Ronald Hudson is a Professor of Civil Engineering and Director of Research, Council for Advanced Transportation Studies at The University of Texas at Austin. He has had a wide variety of experience as a research engineer with the Texas Highway Department and the Center for Highway Research at The University of Texas at Austin and was Assistant Chief of the Rigid Pavement Research Branch of the AASHO Road Test. He is the author of numerous publications and was the recipient of the 1967 ASCE J. James R. Croes Medal. He is presently concerned with research in the areas of (1) analysis and design of pavement management systems, (2) measurement of pavement roughness performance, (3) slab analysis and design, and (4) tensile strength of stabilized subbase materials.