Common Characteristics of Good and Poorly Performing AC Pavements

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LTPP

FOREWORD

The request was simple: "Tell us what works." This report documents Long Term Pavement Performance (LTPP) analysis conducted to answer that question for asphalt concrete (AC) pavements. Performance measures considered included rutting, fatigue cracking, transverse cracking, and roughness.

The findings drawn from this analysis were limited. As a consequence, this report will not be formally published. It is being submitted to NTIS as a public record of the work performed.

T. Paul Teng, P.E.
Director
Office of Infrastructure
Research and Development

NOTICE

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16. Abstract

This report documents the analysis and findings of a study to identify the site conditions and design/construction features of flexible pavements that lead to good performance and those that lead to poor performance. Data from the Long Term Pavement Performance (LTPP) test sections were used along with findings from previous and ongoing analyses of LTPP data. As there were no known criteria for identifying performance expectations over time as good, normal, or poor, a group of experts was convened to establish criteria. Separate criteria were developed for performance in roughness (IRI), rutting, transverse cracking, and fatigue cracking.

This work attempted to identify the pavement characteristics that have a significant impact on the occurrence of these four distress types. In many cases, definitive conclusions could not be drawn, because the effects of the different characteristics are interactive. More in-depth analysis is needed to sort out these interactive effects.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
NOTE: Volumes greater than 1000 l shall be shown in m³.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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CHAPTER 1. INTRODUCTION

One of the objectives of the Long-Term Pavement Performance (LTPP) Program is to develop improved procedures for predicting the development of pavement distresses. These procedures are expected to be broad in their consideration of such key design features as layer thickness, material properties, and other design features such as drainage. A limited number of studies were conducted as part of the research by the Strategic Highway Research Program (SHRP), using the limited data available, with various objectives. One study's objectives were to evaluate the potential for model building and to provide guidance from this experience with the database for future modeling (Ref. 1). These studies were expected to be indicative, but not to provide final results. Currently, there are several initiatives underway to develop distress prediction procedures, and the results from the studies described herein will contribute to those efforts. Another objective of the LTPP Program is to determine which of the many individual parameters are significant to the occurrence of pavement distresses and their relative significance. These studies also require development of distress prediction procedures.

Because the development of comprehensive distress models may not occur in the near term, there is a near-term need to identify critical pavement design and construction features that could be readily implemented by highway agencies. It is expected that such implementation, if done correctly, can save agencies millions of dollars by extending the performance of new and rehabilitated pavements and by minimizing/eliminating costly premature failures.

RESEARCH OBJECTIVE

The objective of the research reported was to identify on an expedited basis the common design features of pavements that lead to good performance and those that lead to poor (substandard) performance, using data from LTPP test sections. Research results from other analyses of LTPP data were also to be included in these studies. Based on the design features identified as being critical to pavement performance reported herein, guidelines could then be developed for the design and construction of long-lived asphalt concrete (AC) and portland cement concrete (PCC) pavements.

RESEARCH APPROACH

The LTPP Program includes more than 490 General Pavement Studies (GPS) AC test sections, for which data have been collected since 1989. Many of these sections are exhibiting very little distress. However, lack of distress is not necessarily an indicator of good performance since lack of distress may possibly be due to young age, mild climate, an over-designed pavement section, and/or low traffic. As a simple example, a rut depth of 10 mm might indicate poor performance for a pavement 2 years of age, while 12 mm or more might be considered good for a pavement 20 years of age. Therefore, it was necessary to establish appropriate criteria to identify if certain pavement sections are exhibiting exceptionally good performance. Similarly, it was necessary to establish appropriate criteria to identify if certain pavement sections are exhibiting poor performance.

As such criteria did not exist, the approach adopted was to convene a panel of selected experts to decide what expectations should apply for two functional classes of pavements (interstate and non-interstate) and overlaid pavements over a period of 20 years, e.g., what should be considered good, normal, and poor performance for specific distress types, functional classes, and overlaid pavements. This approach and the resulting criteria are discussed in Chapter 2.

Once the criteria were established for each type of pavement and distress type (rut depth, fatigue cracking, transverse cracking, and roughness), the test sections were divided into data sets containing either good or poor performers for each pavement and distress type. As an example, there were good and poorly performing pavement data sets for each of four distress types for each of three pavement types. This amounted to 24 data sets available for the analyses. It should be noted that observations for a test section might fall in one data set at one point in time and in another at some other point in time. Similarly, observations for a test section could fall in one performance class for one distress and in another for a different distress. All of the observations collected at various times were included in the analysis.

The types of analyses conducted to identify the common characteristics of good and poorly performing pavements are described in Chapter 3 and the results are described in Chapters 4 through 7 by distress type.

In summary, the current research effort reported consisted of the following tasks:

- Task 1 - Establish Criteria
- Task 2 - Identify Test Sections
- Task 3 - Perform Analysis
- Task 4 - Report

Specific characteristics leading to good (above normal) and poor (below normal) performance of pavements are discussed in Chapter 8. A summary of the analytical results and recommendations for continued study appear in Chapter 9.

CHAPTER 2. PERFORMANCE CLASSIFICATION CRITERIA

The asphalt concrete pavement test sections in the LTPP General Pavement Studies vary widely in age since construction and in traffic experienced. The classification of these test sections as good, normal, or poor performers required criteria for establishing expectations for different distress types as a function of time and type of pavement. As mentioned in Chapter 1, the approach for developing these criteria or boundaries was to convene a panel of experts and to arrive at consensus decisions. This expert panel was convened December 16-17, 1996, and consisted of four experts from State Highway Agencies (SHAs), four Federal Highway Administration (FHWA) experts, and one consultant who had retired from the Virginia Department of Transportation (VDOT). Participants from the research staff included the three Co-Principal Investigators and a Senior Statistician.

APPROACH FOR DEVELOPING PERFORMANCE CLASSIFICATION CRITERIA

A proposed procedure for development of the criteria had been developed and was furnished to the group of experts for their consideration. This approach centered around a graphical approach involving plotting the boundaries between the three levels of performance for each distress type versus age since construction. Age since construction was selected because most engineers appear to think in terms of performance across a design life, as opposed to thinking of performance at some level of cumulative equivalent single-axle loads (ESALs).

Blank graphs were provided on paper and on transparencies for the use of the panel in their deliberations. Each page or transparency included blank plots for three levels of structural number, but the panel elected instead to think in terms of interstate, non-interstate, and overlaid pavements. Other plots were furnished for the three levels of structural number and for each distress type that included the actual data available. These plots provided some guidance as to the ranges of distress apparent in the LTPP test sections.

After considerable discussion on an individual distress type and the form of a graph of distress versus time, each individual drew in the two boundaries for the three types of pavements. These boundaries were then plotted on a transparency, projected, and discussed in detail. The panel then reached a consensus on the specific boundaries for each of the three types of pavements for an individual distress. There appeared to be reasonable agreement, with no seriously divergent opinions.

PERFORMANCE CLASSIFICATION CRITERIA

The results for these four distress types and the three types of pavements appear in Figures 1 through 4. Figures 5 through 8 include both the boundaries and plots of the LTPP data applicable to each category or combination. It should be noted that the data points represent individual observations rather than overall performance of individual test sections. Stated differently, time-sequence information is included such that a single test section can have several observations over a period of time. This appeared to the research team to be, by far, the most logical way in which to include the time-sequence information.

It should be noted that the expectations of the panel for interstate pavements involved less distress than for the non-interstate pavements, which is considered to be quite logical and consistent with highway practice. It should also be noted that the expectation from the panel for overlaid pavements was limited to 10 years of age. The dashed lines are extensions to the resulting boundary curves, so that overlaid pavements exceeding 10 years of age could be included.

The primary input by the panel (their choice) were magnitudes of distress at 20 years for the interstate and non-interstate pavements and at 10 years for the overlaid pavements, except they also selected the initial roughness levels. The shapes of the curves were discussed, but the panel elected to leave the connection of the selected points to the experience of the research team.

Observations of Figures 5 through 8 offer some useful information by themselves. In summary, very few of the test sections were found to have poor performance characteristics. Some specific comments from these observations follow:

1. As found from another study (Ref. 2), the rut depths for the majority of the pavements are well within the normal and good zones established by the panel. For the non-interstate pavements, the rutting performance appeared to essentially satisfy the panel's expectations as to satisfactory performance in rutting.

2. Relatively few of the test sections were experiencing what the panel would consider to be poor performance in roughness.

3. While the majority of the pavements had experienced transverse cracks at spacings less than 20 meters, most had not experienced cracks with average spacing less than the boundary between normal and poor performance, which was established at an average crack spacing of 4 meters.

4. Conversely, there were quite a few pavements that had experienced more fatigue than the panel would consider normal or satisfactory.

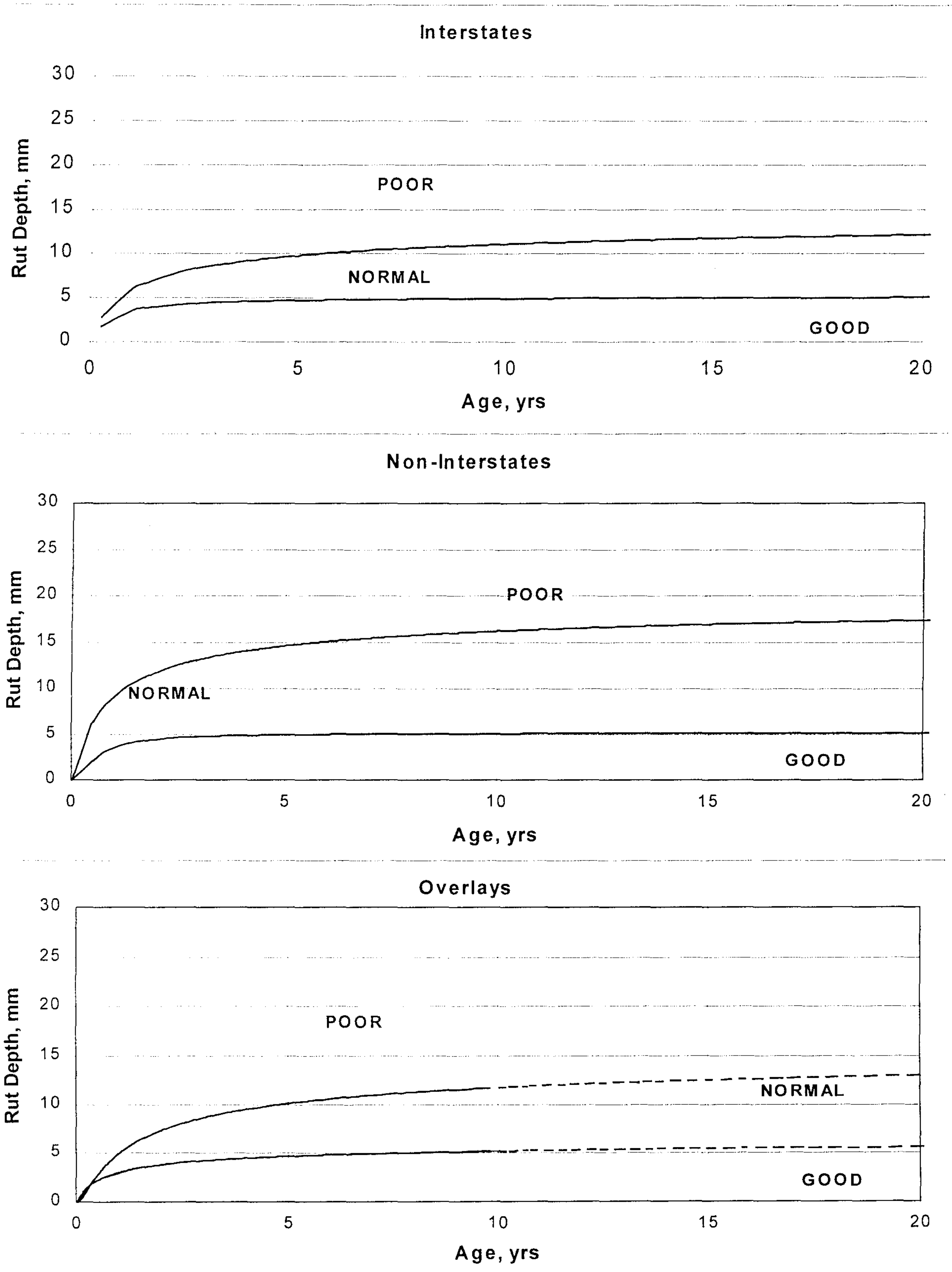


Figure 1. Boundaries for Good and Poorly Performing Pavements for Rutting.

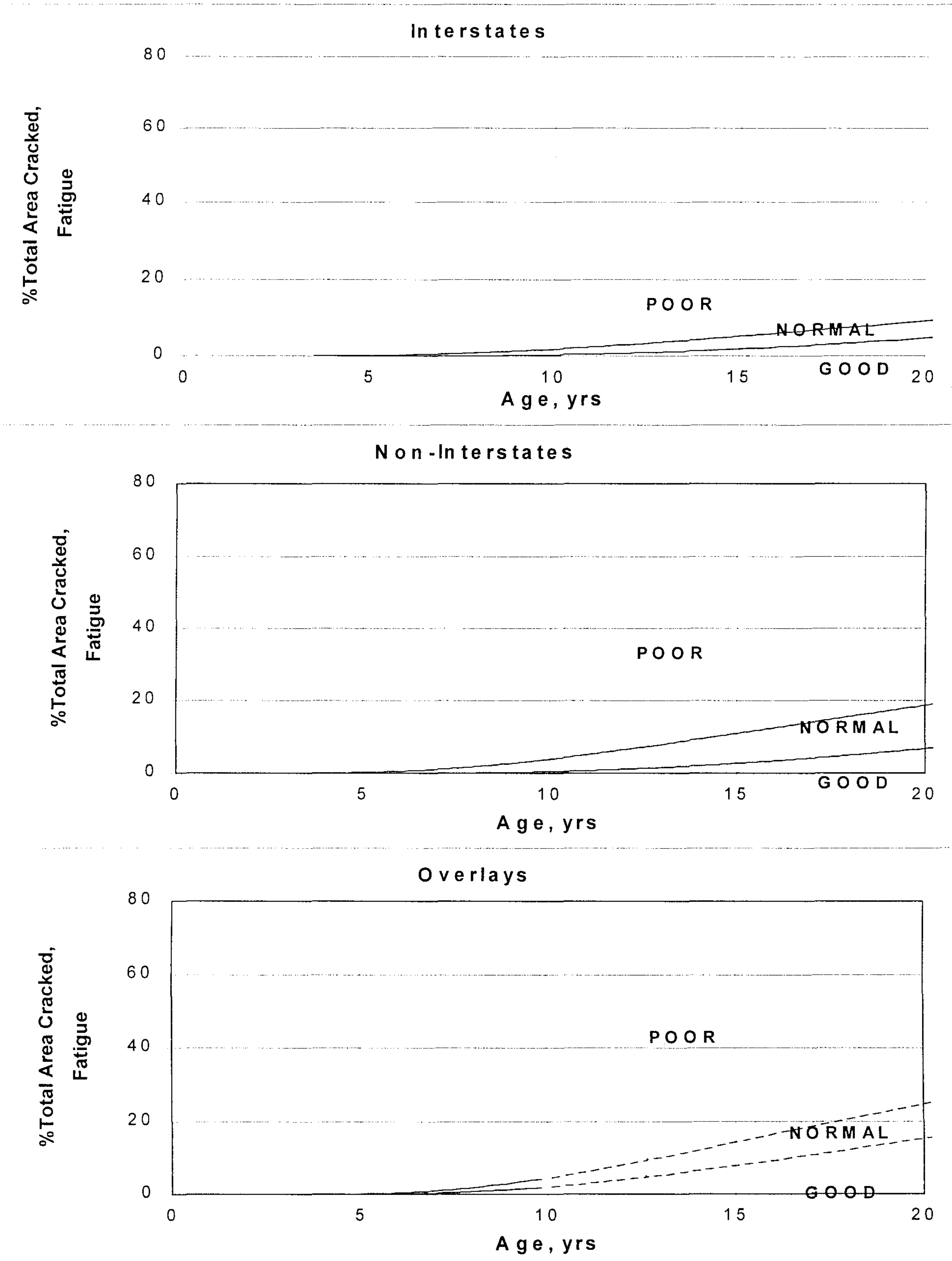


Figure 2. Boundaries for Good and Poorly Performing Pavements for Fatigue Cracking.

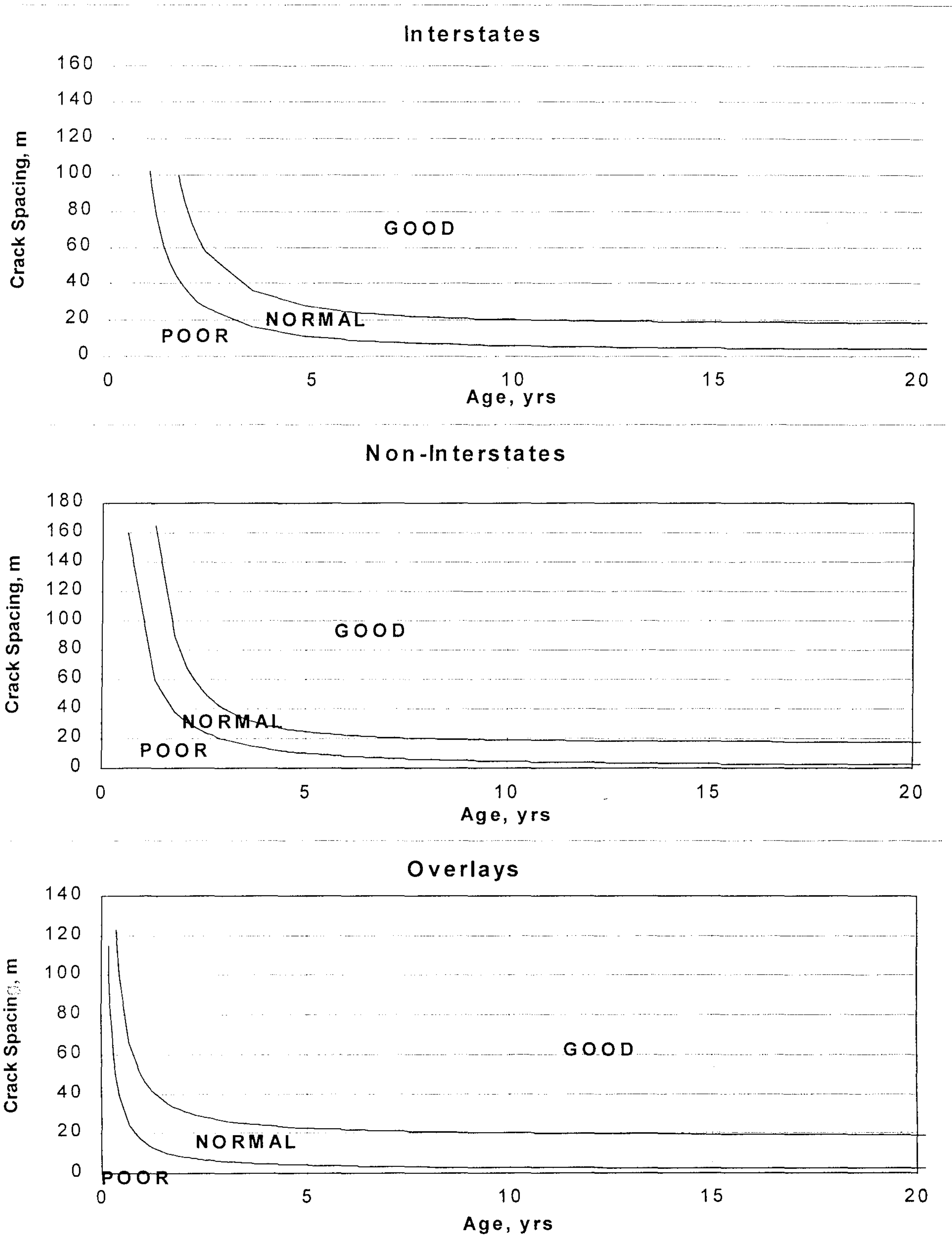


Figure 3. Boundaries for Good and Poorly Performing Pavements for Transverse Cracking.

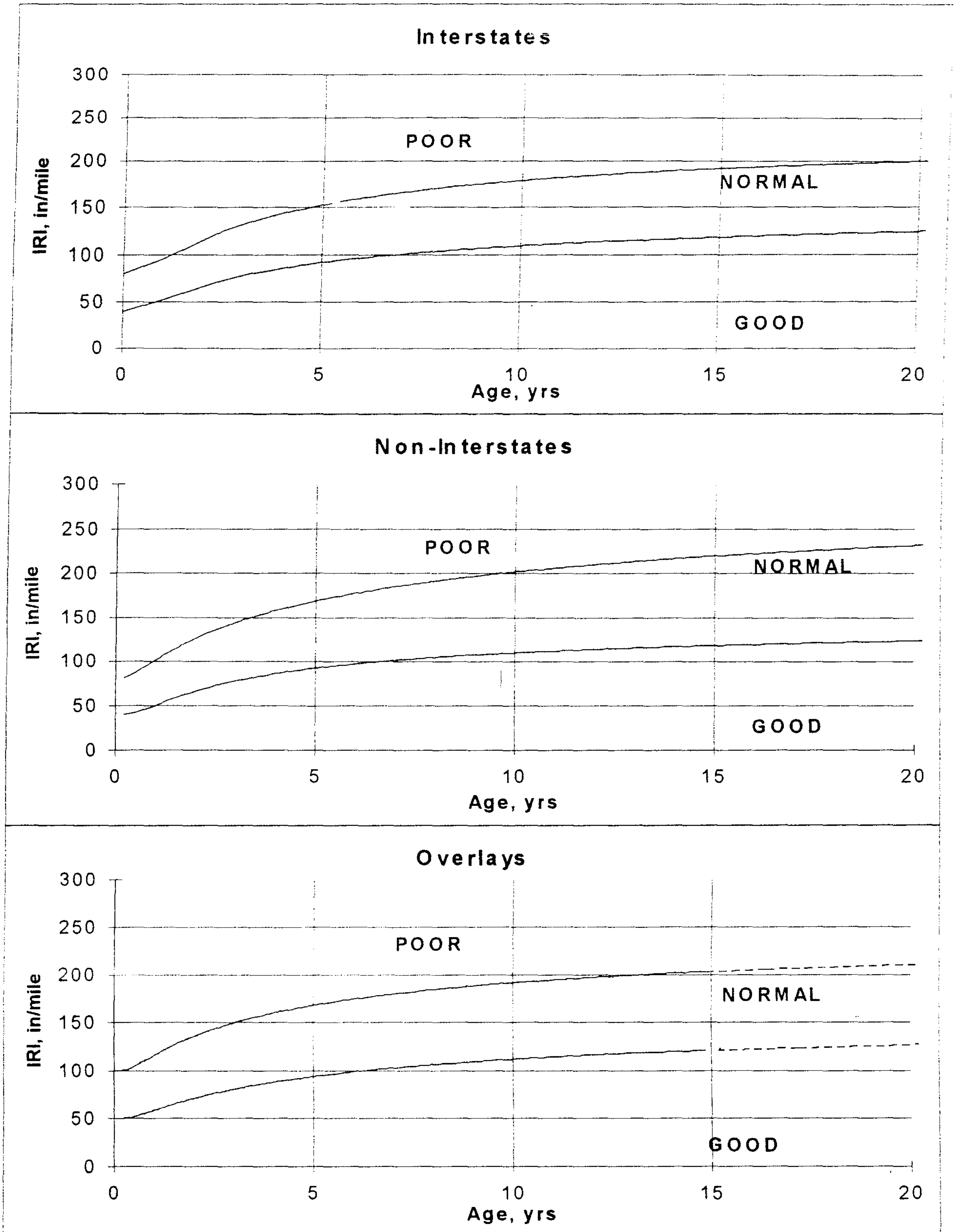


Figure 4. Boundaries for Good and Poorly Performing Pavements for Roughness (1 in/mile = 0.0159 m/km).

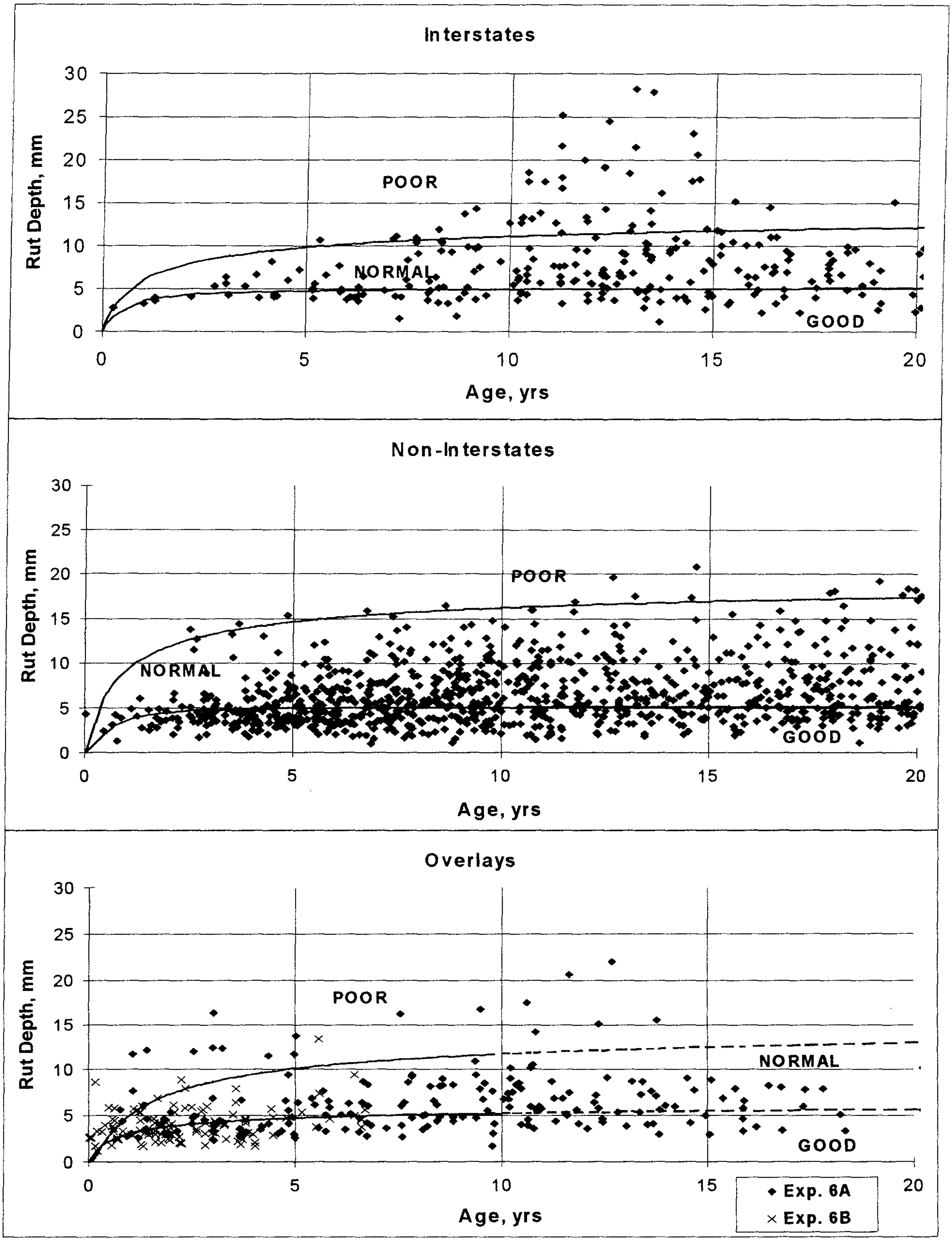


Figure 5. Boundaries for Good and Poorly Performing Pavements for Rutting With Observed Data.

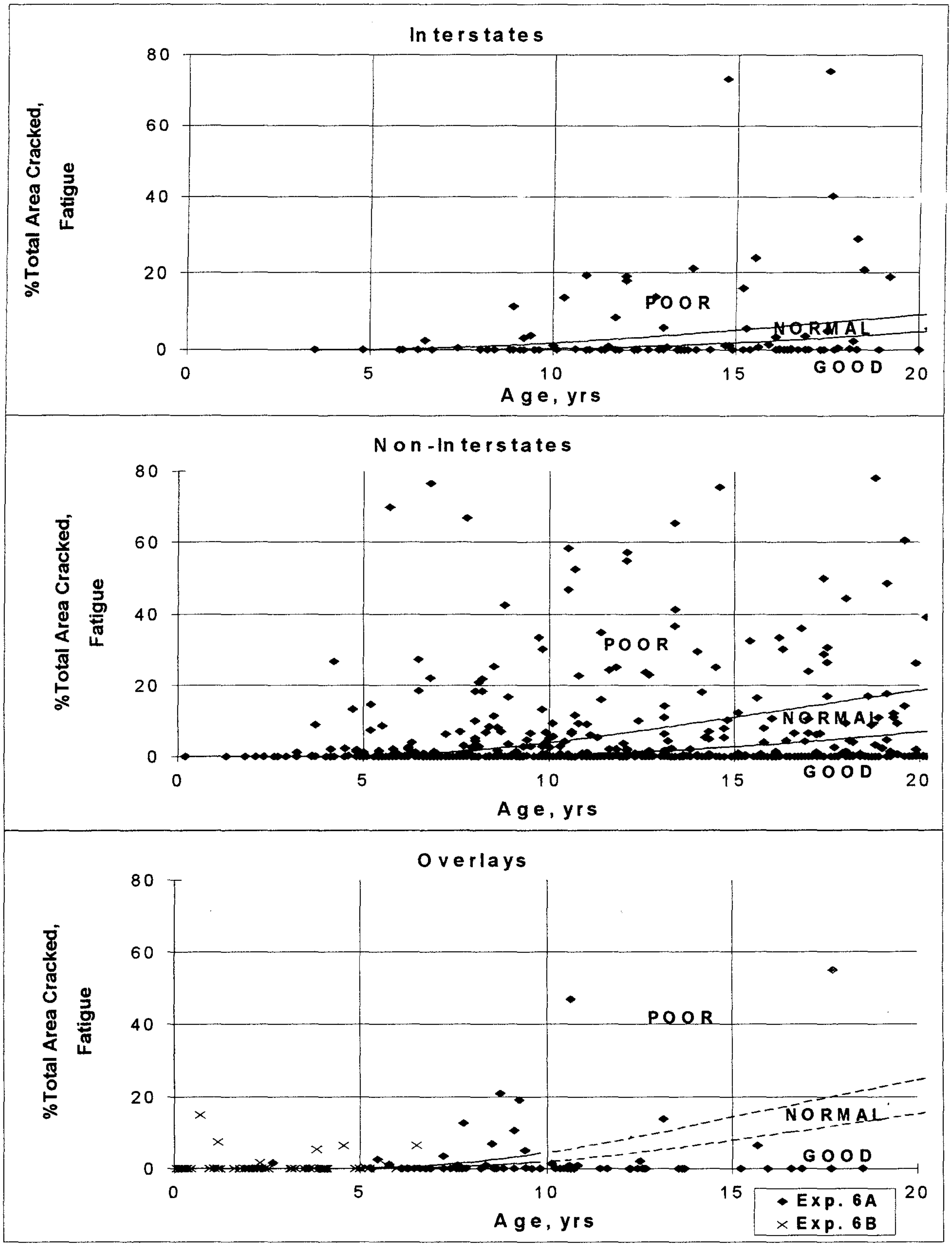


Figure 6. Boundaries for Good and Poorly Performing Pavements for Fatigue Cracking With Observed Data.

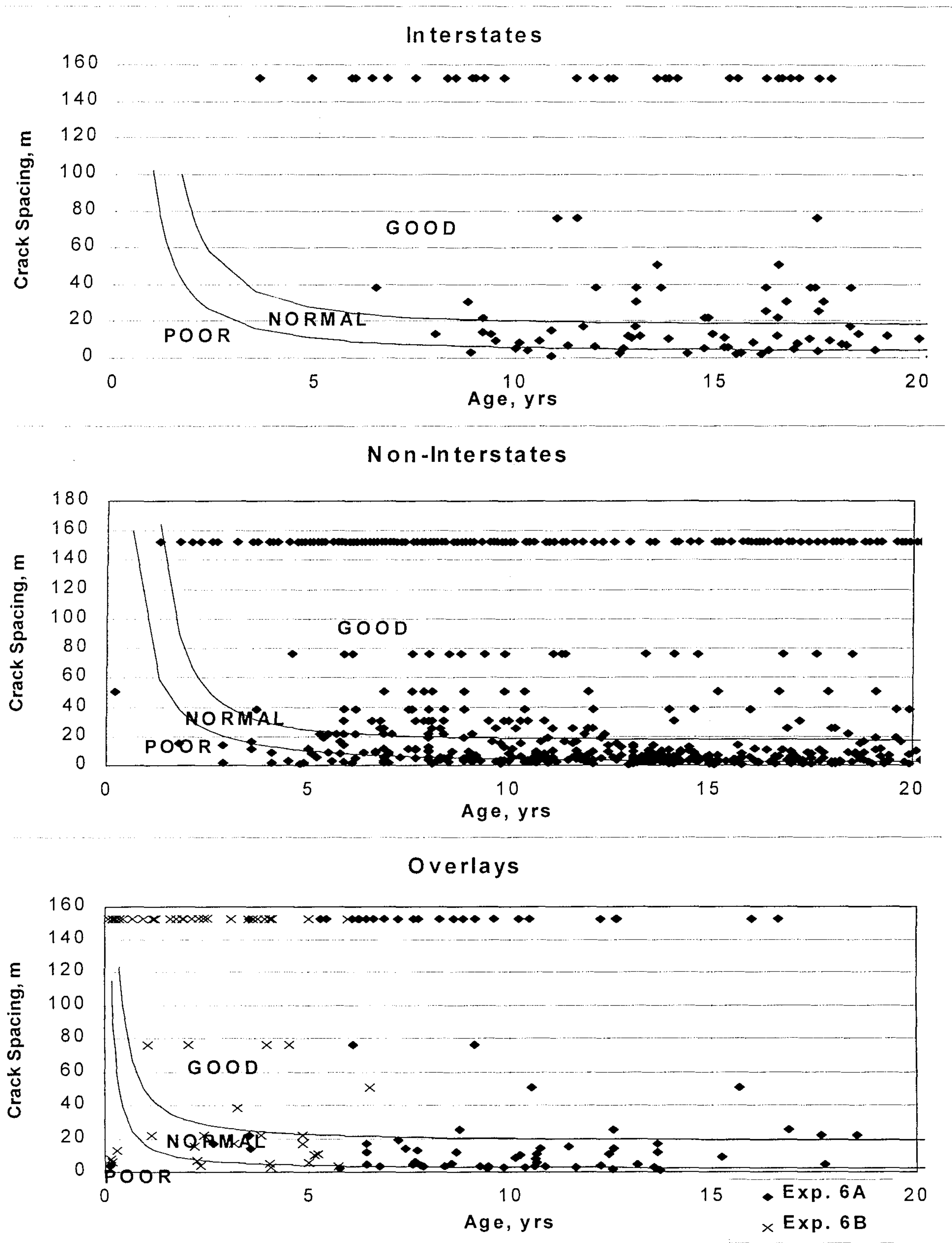


Figure 7. Boundaries for Good and Poorly Performing Pavements for Transverse Cracking With Observed Data.

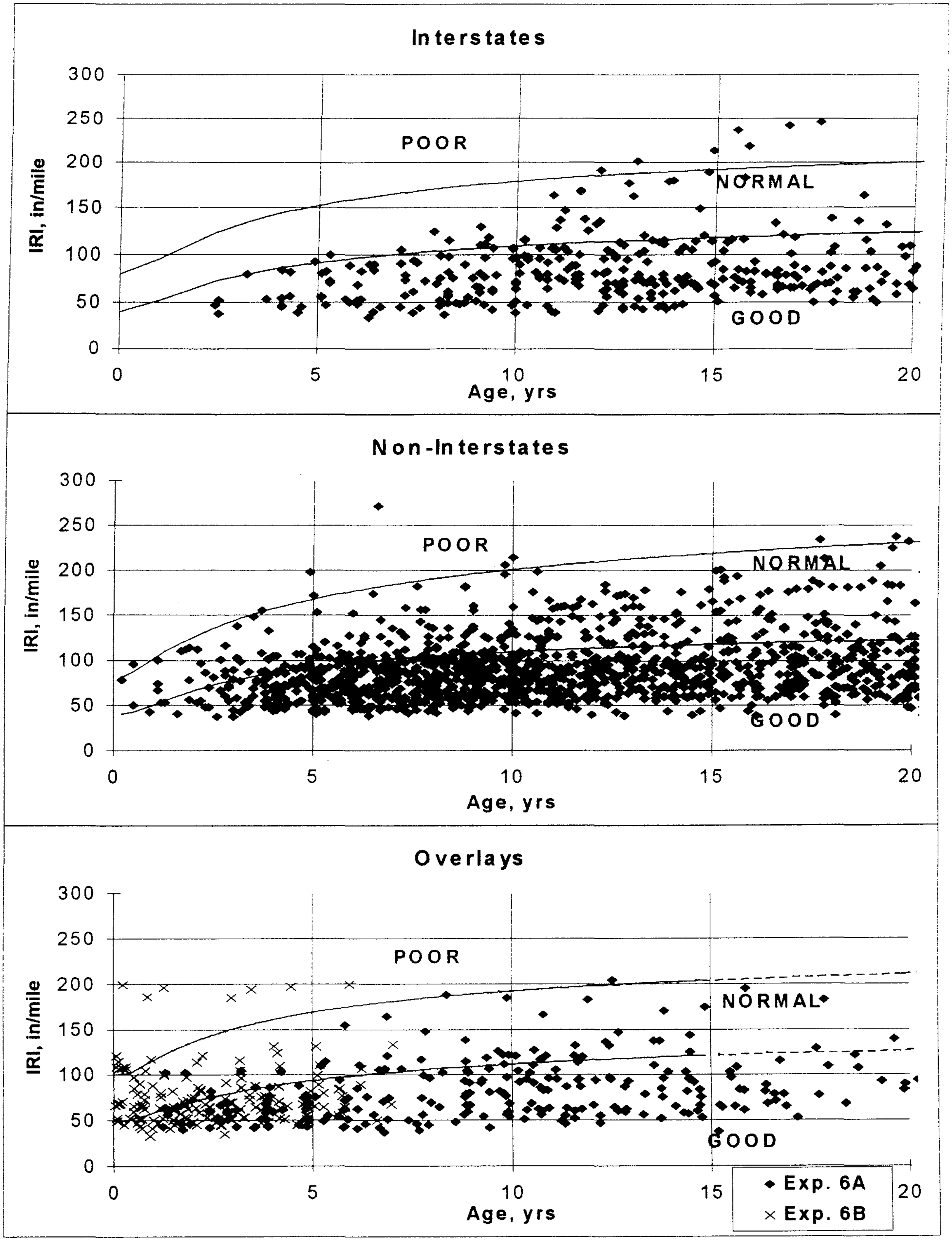


Figure 8. Boundaries for Good and Poorly Performing Pavements for Roughness With Observed Data (1 in/mile = 0.0159 m/km).

CHAPTER 3. SELECTION OF ANALYTICAL TECHNIQUES

Two approaches were considered to study the characteristics unique to well and poorly performing pavements. Two main approaches were examined. The first approach included methods that discriminate between performance types based on predictive equations or models. This approach can be described as discriminant analysis The second approach examined the characteristics of the available variables in the LTPP database individually. A description of both approaches and the selection of the method used in this study is presented in this chapter.

PERFORMANCE CLASSIFICATION OF OBSERVATION POINTS

Before the examination of the characteristics of the variables, each data point had to be classified according to its performance, e.g., good, poor, or normal performance. This was done with respect to the boundaries shown in Figures 1 through 4 in Chapter 2. A regression equation of distress versus age was developed to describe each boundary in those figures mathematically. The purpose of each equation was to calculate the good-normal and the poor-normal boundary values for each observation using the pavement age corresponding to the observations. Next, the observed distress value was compared with the corresponding calculated boundary values. If the value of the observed distress was between the two boundary values, then the point was classified as normal. Otherwise, the performance was considered either good or poor.

- In rutting, roughness, and fatigue cracking, the good-normal boundary is lower than the poor-normal boundary, as can be seen from Figures 1, 2, and 4 in Chapter 2. Therefore, a point was classified as good if its distress value was less than the corresponding calculated good-normal value. Conversely, the point was classified as poor if the value of its distress was higher than the corresponding calculated poor-normal value.

- For transverse cracking, the distress indicator is the crack spacing that decreases with time, so the good-normal boundary is higher than the poor-normal boundary as seen in Figure 3 in Chapter 2. Therefore, a point was considered good if its distress value was more than the corresponding calculated good-normal value and was considered poor if its distress value was less than the corresponding calculated poor-normal value.

As described in Chapter 2, the performance boundaries were defined according to the highway system. Therefore, for each distress type, a database was created for each highway system, e.g., for interstate, non-interstate, and overlaid pavements. The performance classification was carried out for each observation in each of the 12 databases, resulting in one data set representing pavements that performed well and another for pavements that performed poorly for each database.

SELECTION OF STATISTICAL METHODS

Following the performance classification of each observation point, the databases were examined to decide whether characteristics existed that differentiate good from poor performance. Since good and poor performances were the main interest of the study, the normal group was excluded from the analysis.

Discriminant Analysis

Discriminant analysis was considered first. In this method, the objective is to classify any observation into one of two or more classes using a set of variables or predictors. The purpose in the current study would be to classify an observation as either good or poor for performance purposes. Discriminant analysis can be performed using a regression equation. The response variable is related to the good and poor pavement classes and is formulated in a special way. If the response variable is y, the number of good sections is n_1, the number of poor sections is n_2, and the total number of observations (both good and poor) is n, then y would have two levels according to the following conditions:

> For **good** pavements, $y = -n_2/n$ (negative of the proportion of the **poor** pavements), and
> for **poor** pavements, $y = n_1/n$ (the proportion of the **good** pavements).

The response variable is then regressed over a set of predictor variables.

Another approach for conducting discriminant analysis is the traditional approach that is coded in many statistical packages (Ref. 3). In this approach, the response variable can assume its usual two levels, i.e., good and poor. The process then involves the following steps:

1. A set of variables is selected.
2. The discriminant analysis procedure uses this set to classify each observation into good or poor.
3. If the predicted classification is not accurate, the set of variables is adjusted and Steps 1 and 2 are repeated.
4. Steps 1 through 3 are repeated until acceptable classification is obtained.

Compared with the second approach, the first approach for conducting discriminant analysis has the advantage of being directly related to common regression diagnostics with which most researchers and engineers are familiar. This makes the approach easy to implement. In either of these two approaches however, development of predictive equations is imperative. Dr. Peter John, statistical consultant, and Brent Rauhut Engineering, Inc. (BRE) staff ran one trial of the discriminant analysis approach to determine its utility for this study; but it was readily apparent that it would be too time-consuming for this expedited study.

Other concerns about the use of discriminant analysis were:

- There was a serious imbalance between the number of test sections in the good versus the poor data sets for most of the distress/pavement combinations. For example, the database for rutting of non-interstate pavements had 217 observations, of which 200 were in the "good set" and only 17 were in the "poor set." Figures 5 through 8 illustrate this imbalance and disparity.

- There were many test sections for which one or more data elements were missing, such that the number of observations available would be further diminished for the multivariate regressions. For the example above, the selection of a set of 13 predictor variables reduced the 217 observations to 67 with all of the variables and reduced the poor set from 17 observations to just 4.

Student's t-Test

Because of the concerns noted above, the approach adopted in studying the characteristics of good and poor pavement performance was the Student's t-test approach that compared the mean of each variable in the good group with its mean in the poor group. In conducting this comparison, the test considered the number of points and the variation of the data available (Ref. 4).

The results of this test for the different highway systems (interstate, non-interstate, and overlaid pavements) are presented subsequently in tables for each type of distress considered important to define the pavement's performance. The results for each distress type are discussed separately and are included in different chapters of this report. In each of these tables, summary statistics (minimum, mean, maximum, and standard deviation) of the variables that are found to have significantly different means in the good and poor groups are presented. In addition to the summary statistics, the t- and p-values of the t-tests are also shown in these tables, as well as the number of points included in each data set and the overall degrees of freedom.

The hypothesis that the two means are not different will be rejected if the t-value is significantly large or the p-value is significantly small. The p-value is the probability of getting such a large value of t if there were really no difference between the populations. Therefore, small p-values (less than 0.05 for a 95% confidence level or greater) will lead to the conclusion that the means are actually different.

The individual variables that were found to have a significant difference between their means in the two data sets (good and poor performers) were considered as candidates for affecting pavement performance to be examined further. For example, if interstate pavements performing well with regard to fatigue cracking had a generally thicker AC layer than the poorly performing interstate pavements, then it would be concluded that interstate pavements with good performance with regard to fatigue cracking are probably characterized by thicker pavements.

Categorical Analysis: Chi-Square Statistical Tests

While most variables were described by continuous numerical values, some variables, such as the type of base treatment, the pavement type, and the environmental zones, had discrete descriptive values or levels. Categorical analyses were employed to decide whether trends existed in each of these variables that distinguished good performance from poor performance of pavements (Ref. 4). For each discrete variable, the number of good and poor performance observations was determined for each variable level. Chi-square statistical tests were then employed to compare these numbers with each other across all levels of the variable. If the comparison showed statistically significant differences, then the percentages of *good* performance observations for each variable level were calculated and compared across all the other levels of the variable. Good performance was associated with the variable level that had a higher percentage of good performance observations. For example, with regard to transverse cracking for non-interstate pavements, the wet-no freeze zone had a higher percentage of good performance observations than the wet-freeze zone. Then, it would be concluded that the wet-no freeze zone had more pavements performing well with regard to transverse cracking than the wet-freeze zone.

RESULTS FROM PREVIOUS STUDIES

It is to be noted, however, that the t-tests and the categorical analyses mentioned above do not take into account the interactions of the different variables and their effects on performance. It could be that the base properties *together* with thick AC layers were the cause of the good performance of interstate pavements. The t-tests will not isolate the effect of either of these variables on performance. On the other hand, the t-test results include the existing statistical values for each variable with respect to performance, and will identify variables to be considered further. Identification of possible interactions requires a more detailed statistical analysis, which was beyond the scope of this project. Selected parameters, however, were blocked and re-analyzed for those results that do not support and/or enhance historical experience or engineering reasonableness.

Given the above-mentioned shortcomings of the t-tests, it was not considered appropriate to identify recommendations to the highway community based on the t-tests alone. Therefore, the logical approach under these circumstances (the shortcomings of the t-tests on one hand and the time limitations on the other) was to bring all the results from study of the LTPP data to bear. If similar findings resulted from two or more studies conducted with differing statistical approaches, then recommendations can be made to the highway community with higher confidence. For this reason, the results from sensitivity analyses in the SHRP P-020 study (Ref. 1), rutting trend studies (Ref. 2), and the roughness study conducted by Soil and Materials Engineers (SME), Inc. (Ref. 5) have been included herein to augment the results from the t-tests.

There may be a perception, as data collection has continued for several years, that more confidence should be put in the current study compared with some of the previous studies, such as the P-020 study. However, the data used in the P-020 sensitivity analyses differed very little from the data available for the current study. There have been no new environmental data and virtually no change in the inventory and materials data for the GPS. The only new data are:

- More distress data.
- Some monitored traffic data (ESALs) to add to the historical data used in the P-020 analyses.
- Resilient modulus data for the Southern and North Atlantic Regions only.

In addition, close inspection of the variables that were found to be significant in the P-020 study (primarily materials and environmental data) shows that data for these variables remain unchanged, except for ESALs. The primary advantage to the now-augmented database is the additional time-sequence distress data. The current study, using t-tests, would be more conclusive only if more time were available to do a thorough analysis (such as that for the P-020 studies) using the additional time-sequence data.

SUMMARY

In summary, the statistical approach adopted was t-tests as described above; however, all available analytical results for the LTPP data were brought to bear on the conclusions. Brief descriptions of these previous studies are given subsequently to provide the reader (the highway community at large as well as highway researchers) with a convenient stand-alone document for future reference and use. The variables considered during these studies are identified in Table 1.

Table 1. List of Variables Used in Current Study.

Type of Variable	Variable
Environment or Climatic	Number of Days With Freezing Temperature
	Number of Days With Temperature > 32°C
	Annual Number of Days With Precipitation
	Annual Number of Days With High Precipitation
	Average Annual Number of Freeze-Thaw Cycles
	Freeze Index, Degree-Days
	Average Annual Precipitation, mm
	Environmental Zones
	Average Maximum Temperature, °C
	Average Minimum Temperature, °C
	Average Temperature Range, °C
Material, Asphalt Concrete	AC Grade
	AC Thickness, mm
	AC Backcalculated Resilient Modulus, MPa
	AC Indirect Tensile Strength After the M_R Test, kPa
	AC Indirect Tensile Strength Prior to the M_R Test, kPa
	AC Instantaneous Resilient Modulus at 5°C, 25°C, and 40°C, MPa
	AC Total Resilient Modulus at 5°C, 25°C, and 40°C, MPa
	Bulk Specific Gravity of AC Mix
	Water Absorption of AC Aggregate
	Maximum Specific Gravity of AC Mix
	Air Voids in AC Mix
	Asphalt Cement Content in AC Mix
	AC Aggregate Gradation Passing 38.1-mm Sieve
	AC Aggregate Gradation Passing 25.4-mm Sieve
	AC Aggregate Gradation Passing 19.0-mm Sieve
	AC Aggregate Gradation Passing 12.7-mm Sieve
	AC Aggregate Gradation Passing 9.5-mm Sieve
	AC Aggregate Gradation Passing 4.7-mm Sieve
	AC Aggregate Gradation Passing 2-mm Sieve
	AC Aggregate Gradation Passing 0.4-mm Sieve
	AC Aggregate Gradation Passing 0.2-mm Sieve
	AC Aggregate Gradation Passing 0.075-mm Sieve
	AC Viscosity at 60°C, poises

Table 1. List of Variables Used in Current Study (Continued).

Type of Variable	Variable
Material, Aggregate Base	Thickness of Base, mm
	Treated Base Material
	Granular Base Compaction Efficiency
	Base Backcalculated Resilient Modulus, MPa
	K1 From the Resilient Modulus Testing for the Granular Base
	K2 From the Resilient Modulus Testing for the Granular Base
	K5 From the Resilient Modulus Testing for the Granular Base
	Average Laboratory-Determined Granular Base Resilient Modulus at Different Confining and Deviatoric Pressures, MPa
	Percentage of Granular Base Aggregate Passing 76.2-mm Sieve
	Percentage of Granular Base Aggregate Passing 51-mm Sieve
	Percentage of Granular Base Aggregate Passing 38-mm Sieve
	Percentage of Granular Base Aggregate Passing 25.4-mm Sieve
	Percentage of Granular Base Aggregate Passing 19-mm Sieve
	Percentage of Granular Base Aggregate Passing 12.7-mm Sieve
	Percentage of Granular Base Aggregate Passing 9.5-mm Sieve
	Percentage of Granular Base Aggregate Passing 4.7-mm Sieve
	Percentage of Granular Base Aggregate Passing 2-mm Sieve
	Percentage of Granular Base Aggregate Passing 0.4-mm Sieve
	Percentage of Granular Base Aggregate Passing 0.2-mm Sieve
	Percentage of Granular Base Aggregate Passing 0.075-mm Sieve
	Liquid Limit of the Granular Base Material
	Plastic Limit of the Granular Base Material
	Plasticity Index of the Granular Base Material
	Maximum Density of the Granular Base Material, kg/m^3
	Optimum Moisture Content of the Granular Base Material, kg/m^3
	Laboratory-Measured Moisture Content of the Granular Base Material
	In Situ (Nuclear Gauge) Measured Dry Density of the Granular Base Material, kg/m^3
	In Situ (Nuclear Gauge) Measured Wet Density of the Granular Base Material, kg/m^3
	In Situ (Nuclear Gauge) Measured Moisture Content of the Granular Base Material, kg/m^3

Table 1. List of Variables Used in Current Study (Continued).

Type of Variable	Variable
Material, Subgrade Soils	Subgrade Soil Material Type
	Subgrade Compaction Efficiency
	Subgrade Backcalculated Resilient Modulus, MPa
	Average Laboratory-Determined Subgrade Modulus at Different Confining and Deviatoric Pressures, MPa
	K1 From the Resilient Modulus Testing for the Subgrade
	K2 From the Resilient Modulus Testing for the Subgrade
	K5 From the Resilient Modulus Testing for the Subgrade
	Subgrade Aggregate Passing 76.200-mm Sieve
	Percentage of Subgrade Soils Passing the 50.800-mm Sieve
	Percentage of Subgrade Soils Passing the 38.100-mm Sieve
	Percentage of Subgrade Soils Passing the 25.400-mm Sieve
	Percentage of Subgrade Soils Passing the 19.050-mm Sieve
	Percentage of Subgrade Soils Passing the 12.700-mm Sieve
	Percentage of Subgrade Soils Passing the 9.520-mm Sieve
	Percentage of Subgrade Soils Passing the 4.75-mm Sieve
	Percentage of Subgrade Soils Passing the 2.0-mm Sieve
	Percentage of Subgrade Soils Passing the 0.425-mm Sieve
	Percentage of Subgrade Soils Passing the 0.18-mm Sieve
	Percentage of Subgrade Soils Passing the 0.075-mm Sieve
	Percentage of Subgrade Soils Less Than 0.020-mm (Hydrometer Analysis)
	Percentage of Subgrade Soils Less Than 0.002-mm (Hydrometer Analysis)
	Percentage of Subgrade Soils Less Than 0.001-mm (Hydrometer Analysis)
	Percentage of Subgrade Soils Greater Than 2 mm
	Percentage of Coarse Sand in Subgrade Soil
	Percentage of Fine Sand in Subgrade Soil
	Percentage of Silt in Subgrade Soil
	Percentage of Clay in Subgrade Soil
	Percentage of Colloids in Subgrade Soil
	Liquid Limit of Subgrade Soil
	Plastic Limit of Subgrade Soil
	Plasticity Index of Subgrade Soil

Table 1. List of Variables Used in Current Study (Continued).

Type of Variable	Variable
Material, Subgrade Soils	Maximum Density of Subgrade Soil, kg/m^3
	Optimum Moisture Content of Subgrade Soil
	Laboratory-Measured Moisture Content of Subgrade Soil
	In Situ (Nuclear Gauge) Measured Dry Density of the Subgrade Soil, kg/m^3
	In Situ (Nuclear Gauge) Measured Wet Density of the Subgrade Soil, kg/m^3
	In Situ (Nuclear Gauge) Measured Moisture Content of the Subgrade Soil
	Depth to Refusal, m
Traffic/Age	Cumulative Annual Traffic in KESALs
	Average Annual Traffic in KESALs
	Age, Years
FWD*	FWD Sensor 1 Deflection, μ
	FWD Sensor 2 Deflection, μ
	FWD Sensor 3 Deflection, μ
	FWD Sensor 4 Deflection, μ
	FWD Sensor 5 Deflection, μ
	FWD Sensor 6 Deflection, μ
	FWD Sensor 7 Deflection, μ
	Surface Curvature Index, μ
	Base Curvature Index, μ
Overall Pavement Structure	Structural Number

* FWD = Falling-Weight Deflectometer

Notes:
1. The moisture contents used in the analysis are for only the time that the section was tested in the sampling/testing areas of the test sections, not within the test section.
2. The FWD deflection data are for the initial round of testing during the sampling and testing at each test section, but not at each time the distress data were collected.
3. The FWD data were not corrected for temperature, but were adjusted to a normalized load level.

CHAPTER 4. PERFORMANCE OF AC PAVEMENTS WITH REGARD TO RUTTING

Rutting is an important performance characteristic and deterioration mechanism of asphalt concrete pavements because of the detrimental effect on safety through potential hydroplaning. Rutting does have an effect on ride quality, but it is less of an issue than safety. The rutting data used in this study were derived from the transverse profile measurements using a 1.8-m (6-ft) straight edge.

Rutting, as measured on the pavement surface, is caused by the permanent deformation and/or lateral flow of material from traffic loads applied at the pavement's surface. In asphalt concrete layers, it is generally classified into two categories or types. These are densification and the lateral movement or plastic flow of materials. Rutting occurring in unbound base and subbase layers and/or subgrade is also caused by additional densification or consolidation of these unbound materials below the pavement surface. This type of rutting is usually referred to as mechanical deformation and is normally accompanied by cracking at the surface when the mix is too rigid or stiff relative to the underlying layers.

The objective of this analysis and the comparison of different data sets with different rutting behavior was to examine, in a practical way, the LTPP database and to identify the site conditions and design/construction features of the pavements that significantly affect rutting. Rutting of asphalt concrete-surfaced pavements has been investigated through numerous studies. From these studies, it has been found that rutting on asphalt concrete-surfaced pavements depends greatly on characteristics of the materials in the structural layers and subgrade, thicknesses of layers, climate, and the axle loads experienced by a pavement. There have been three research studies conducted using LTPP data to learn more about the causes of rutting. The results from each of these studies appear below.

RESULTS FROM THE t-TESTS

The objective of this study was to discriminate between characteristics of pavements that performed better and poorer than normal in rutting, i.e., what works and what does not work. The many characteristics existing in the good and poor data sets were compared for each type of pavement, using Student's t-test procedures as explained in Chapter 3. The objective was to learn which characteristics were statistically different between the good and poor performers.

Unlike the sensitivity analyses performed in the early analyses (Ref. 1), direct identification of significant characteristics and their relative significance did not occur; however, identification of variables that are significantly different between the good and poor data sets resulted in sets of candidate variables for comparison with those found to be significant to performance from other studies of LTPP data. If increases in a variable identified as significant in the P-020 sensitivity analyses were found to decrease rutting, and the magnitude of its mean value for the good data set is larger than for the poor set, the research team felt confident in recommending that designers seek to increase the magnitude in practice. If an increase in the variable was found in the P-020 studies to increase rutting, and the mean magnitude for the poor set was greatest, the recommendation would be to decrease the magnitude in practice. (This same approach was used for the other distress types or measures of pavement performance.)

The characteristics for which differences were statistically significant are listed in Tables 2, 5, and 7 for interstate, non-interstate, and overlaid pavements, respectively. In each table, basic statistical measures of each of the significant variables are presented. These measures included the minimum, mean, maximum, and standard deviation. Each of these measures is given once for the good group and once for the poor group. In addition to these measures, the t- and p-values of the t-test are given, as well as the number of points for each group and the overall degrees of freedom.

In addition to continuous variables, a categorical analysis was conducted on the type of base treatment, environmental zones, and type of pavement (full-depth vs. hot-mix asphalt concrete (HMAC) over granular base). The latter did not show significant results.

Interstate Pavements
The variables that were found to be statistically different between the good and poor groups for the interstate pavements are identified in Table 2. Some interesting points to note based on the results of these comparisons are given below. These points are then followed by specific results from the analysis (Table 2).

- Viscosity of the asphalt cement and a measure of the high-temperature condition were not found to be significant between the two groups of data. This could suggest that the type of asphalt (viscosity) was properly selected for the climatic area, such that there is no effect between these two parameters based on rutting. In other words, asphalt cements with higher viscosities should be used in those climatic areas with higher annual summer temperatures (i.e., warmer climates).

- A significantly higher freezing index and lower average annual minimum temperature (colder environments) were found for the poor group compared with the good group data set. This observation suggests that the larger amounts of rutting may be attributable to the granular base layer rather than the asphalt concrete surface. The test sections with the higher freezing indices generally have more freeze-thaw cycles and longer durations of spring thaw, which may be reducing the strength of the aggregate base and resulting in more permanent deformation in the aggregate base under heavier traffic levels.

  This observation is also supported by comparison of the mean asphalt concrete thicknesses for the two groups. The mean surface thickness for the good group is significantly greater than for those test sections in the poor group. If the rutting was occurring primarily in the surface layer, more rutting would be expected in the sections with the thicker asphalt concrete surface layers. In all probability, the thicker asphalt concrete layers are reducing the stresses and strains in the aggregate base, resulting in less permanent deformation than for those with thinner asphalt concrete surfaces. In addition, the moisture content of the granular base layer was found to be significantly higher for those test sections in the poor group, which would support the above hypothesis regarding the granular bases.

Table 2. Results of t-Tests for Performance of Interstate Pavements for Rutting.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Rut Depth, mm	1.5	3.6	5.1	0.9	48	2.8	13.7	20.7	3.8	21	-10.1	-17.232	<0.0001	67
Average Annual Min. Temp., °C	-2	7	19	6	48	-1	4	15	5	21	3	2.145	0.0356	67
Freeze Index, °C-days	0	264	1673	343	48	2	554	1226	583	21	-290	-2.589	0.0118	67
AC Thickness, mm	101	246	450	97	48	124	191	322	61	21	56	2.479	0.0157	67
Air Voids in AC, %	1.5	4.5	6.6	1.8	38	1.8	3.2	11.1	2.2	21	1.3	2.388	0.0203	57
AC Aggregate Gradation, % Passing 9.52-mm Sieve	54	74	89	11	38	54	69	80	8	21	5	2.204	0.0316	57
AC Aggregate Gradation, % Passing 0.180-mm Sieve	7	12	16	3	38	7	10	28	4	21	2	2.246	0.0286	57
AC Aggregate Gradation, % Passing 0.075-mm Sieve	3	7	13	3	38	4	5	9	1	21	2	2.806	0.0068	57
Granular Base Laboratory-Measured Moisture Content, %	2	5	13	3	38	4	7	17	3	20	-2	-2.023	0.0478	56
Subgrade Gradation, % Passing 76.2-mm Sieve	98	100	100	0.4	37	94	99	100	2	21	1	3.320	0.0016	56
Subgrade Gradation, % Passing 50.8-mm Sieve	94	99	100	1.4	37	89	96	100	4	21	3	4.025	0.0002	56
Subgrade Gradation, % Passing 38.1-mm Sieve	89	99	100	3	37	86	94	100	6	21	5	3.974	0.0002	56
Subgrade Gradation, % Passing 25.4-mm Sieve	79	97	100	5	37	80	92	100	8	21	5	2.812	0.0068	56
Subgrade Gradation, % Passing 19.0-mm Sieve	72	96	100	7	37	76	90	100	10	21	6	2.515	0.0148	56
Subgrade, % Passing 0.02 mm (Hydrometer Analysis)	1	29	52	17	32	4	18	57	12	18	11	2.357	0.0225	48

(Continued)

Table 2. Results of t-Tests for Performance of Interstate Pavements for Rutting.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Plastic Limit of Subgrade, %	0	5.9	17.0	7.2	37	0	10.6	25	7.8	21	-4.7	-2.332	0.0233	56
Rutting Rate (Rut Depth, μ/Cumul. KESALs)	0.3	2	5	2	32	2	25	88	31	16	-23	-4.243	0.0001	46
Total AC Resilient Modulus at 40°C, MPa	986	1827	2848	469	37	1310	1331	1400	38	5	496	2.354	0.0235	40
Normalized Sensor 7 Deflections (FWD Testing), μ	16	33	75	33	48	17	41	69	15	20	-8	-2.047	0.0446	66
Subgrade M_R at 2,6‡, MPa	35	57	78	12	28	67	70	71	2	4	-12	-2.048	0.0494	30

‡Numbers separated by a comma are the confining and deviatoric stresses in psi, respectively (1 psi = 6.895×10^{-3} MPa).

*Legend:

Diff. Means	=	Mean of good group minus mean of poor group.
t-value	=	Student's t statistic.
p-value	=	Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, α = 0.05).

To take a closer look at the freeze index, the database for interstate pavements was blocked into two groups using cumulative KESALs. The results of this blocking experiment are summarized in Table 3. As shown, the mean value for the good group has a significantly lower freeze index than that for the poor group for the higher traffic levels. For the lower traffic levels, no statistically significant difference was found between the two data sets, which concurs with previous experience.

- As the freeze index was found to be significantly different between the two data sets, but no significant difference was found for viscosity, the freeze index was blocked by two levels of viscosity and the data were re-analyzed. Results from this analysis are also shown in Table 3 and indicate that there is no significant difference in freeze index between the two groups of data when blocked by viscosity. This suggests that the asphalt cement was properly selected for the particular climatic area, such that there is no significant difference between the two data sets, and still supports the observation (or hypothesis) that most of the rutting for these interstate pavements may be occurring primarily in the granular base layer.

- The resilient modulus of the asphalt concrete layer was found to be higher for the good group than for the poor group, as expected. The higher resilient moduli for the good group would tend to decrease the stresses and strains occurring in the granular base layers, thereby reducing the potential rutting in those layers. This would still support the observation that the higher amounts of rutting (or higher percentages of the total measured rut depths) in this group of pavements may be assigned to the granular base layer.

- An apparent discrepancy between results of this evaluation and previous studies relates to the subgrade resilient modulus measured in the laboratory. As shown in Table 2, the laboratory-measured resilient moduli for the poor group are significantly greater than that for the good group. As this does not coincide with previous experience, the subgrade laboratory resilient modulus data were blocked by two levels using the normalized Sensor 7 deflection. Results from this analysis are shown in Table 3. As shown, there is no statistically significant difference between the two data sets when blocked by the normalized Sensor 7 deflections. This result would also support the observation that most of the rutting for the interstate pavements is related to the granular base layers.

Climatic Features. The environmental variables showing statistical differences were the average annual minimum temperature and the freeze index. The results showed that for the good group, the average annual minimum temperature was higher and the freeze index was lower, compared with the corresponding mean values for the poor group. This is an indication that the good group was associated with generally warmer climates than those for the poor group. (Note: The annual average minimum temperature is the average of the minimum monthly temperatures during the year.) This could suggest that the rutting is occurring in the granular base layer, as stated above.

Table 3. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Interstate Pavements, as Defined by Rutting.

Variable	Blocked by	Blocking Level	Results With Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Subgrade Lab. M_R, MPa	Normalized FWD Sensor 7, microns	≤30	*No observations fell in the poor group*													
		>30	No statistically significant difference													
Subgrade Moisture Content/PL	Normalized FWD Sensor 7, microns	≤30	No statistically significant difference													
		>30	No statistically significant difference													
Freeze Index (C°-Days)	Cumulative KESALs	≤320	No statistically significant difference													
		>320	0	116	396	1094	18	146	1144	5143	143	6	-1028	-4	0	22
Freeze Index (C°-Days)	Viscosity, poises	≤1616	No statistically significant difference													
		>1616	No statistically significant difference													

AC Features. For the AC layer variables, the study showed that significant differences existed for the AC thickness, the percentage of aggregate passing the 9.52-mm, 0.18-mm, and 0.075-mm sieve sizes, the air voids, and the layer stiffness. The results revealed that the good group had, on average, a thicker AC layer than did the poor group. In addition, there were higher percentages of aggregate passing the three sieve sizes identified above. This is an indication of the presence of more fine aggregates in the good group compared with the poor group. The presence of more fine aggregate in the good group appears to be the opposite of what was noted from the rutting trend studies (Ref. 2) discussed in the latter part of this chapter. However, this could be due to the influence of other variables, such as the AC resilient modulus at 40°C (i.e., the good group had higher resilient moduli).

The good group had more air voids in the asphalt mix than did the poor group. (It should be noted that the air voids were measured from cores taken well after initial consolidation under traffic was completed.) The resilient modulus of the AC layer was found to be higher for the good group than for the poor group. In general, it has been shown from previous studies that higher air voids allow more asphalt aging, resulting in higher resilient moduli, especially within the top 50 mm of the AC surface.

Granular Base Features. The moisture content of the granular base measured in the laboratory was higher for the poor group (7%) than for the good group (5%). However, the p-value was 0.0478 and is very close to the α-value (0.05), which makes it borderline significantly different.

Subgrade Soil Features. A study of subgrade variables showed that the mean percentage of subgrade material less than 0.02 mm was higher for the good group than for the poor group, and the plastic limit for the subgrade of the good group was lower than that of the poor group.

Structural Response Features. The deflections measured by the seventh sensor of the falling-weight deflectometer (FWD) was lower for the good group. This is an indication of a stiffer subgrade for the good group than for the poor group. However, the resilient modulus measured at a confining stress of 0.014 MPa and a deviatoric stress of 0.041 MPa was found to be lower for the good group (57 MPa) than for the poor group (70 MPa).

One explanation for this apparent discrepancy between the resilient modulus and the indication related to the seventh sensor is that the confining and deviatoric stresses may not correlate to the actual field conditions as the FWD data do. In addition, the inconsistency between laboratory and field subgrade moduli is a well-known problem that is under investigation by several researchers. More importantly, there are only four data points in the poor group, while there are 28 in the good group. The p-value for this variable also indicates that the difference is barely statistically significant, which gives little weight to conclusions drawn from this comparison.

Type of Base. Table 4 compares the numbers and percentages of interstate test sections in the good and poor groups with portland cement-treated base and with unbound granular base, indicating that the pavements with cement-treated base appear to experience less rutting. Table 4 also supports the observation that the unbound base may be contributing more heavily to the poorer performance.

Type of Environment. Table 5 shows the number of observations and the percentages of observations of good and poor performance for individual environmental zones. The observations for test sections in the dry-freeze and wet-no freeze zones are predominantly in the good performance group, those in the dry-no freeze zone are predominantly in the poor performance group, and they were approximately equally divided in the wet-freeze zone.

A comparison of the cumulative distributions of the amount of rutting in the different environmental zones is shown in Figure 10. The comparison shows that the pavements in the wet-no freeze zone generally experienced less rutting than those in the other environmental zones, while those in the dry no-freeze zone experienced the most rutting.

Table 4. Comparison of Rutting Performance of Interstate Pavements for Cement-Treated and Unbound Bases.

Performance	Cement-Treated		Unbound	
	Number of Sections	Percentage in Treatment Group	Number of Sections	Percentage in Treatment Group
Good	12	100	52	59
Poor	0	0	36	41
Total	12	100	88	100

Table 5. Comparison of Rutting Performance of Interstate Pavements for Different Environmental Zones.

Performance	Dry-Freeze		Dry-No Freeze		Wet-Freeze		Wet-No Freeze	
	Number of Observations in Zone	Percentage in Zone	Number of Observations in Zone	Percentage in Zone	Number of Observations in Zone	Percentage in Zone	Number of Observations in Zone	Percentage in Zone
Good	14	78	4	21	18	53	16	94
Poor	4	22	15	79	16	47	1	6
Total	18	100	19	100	34	100	17	100

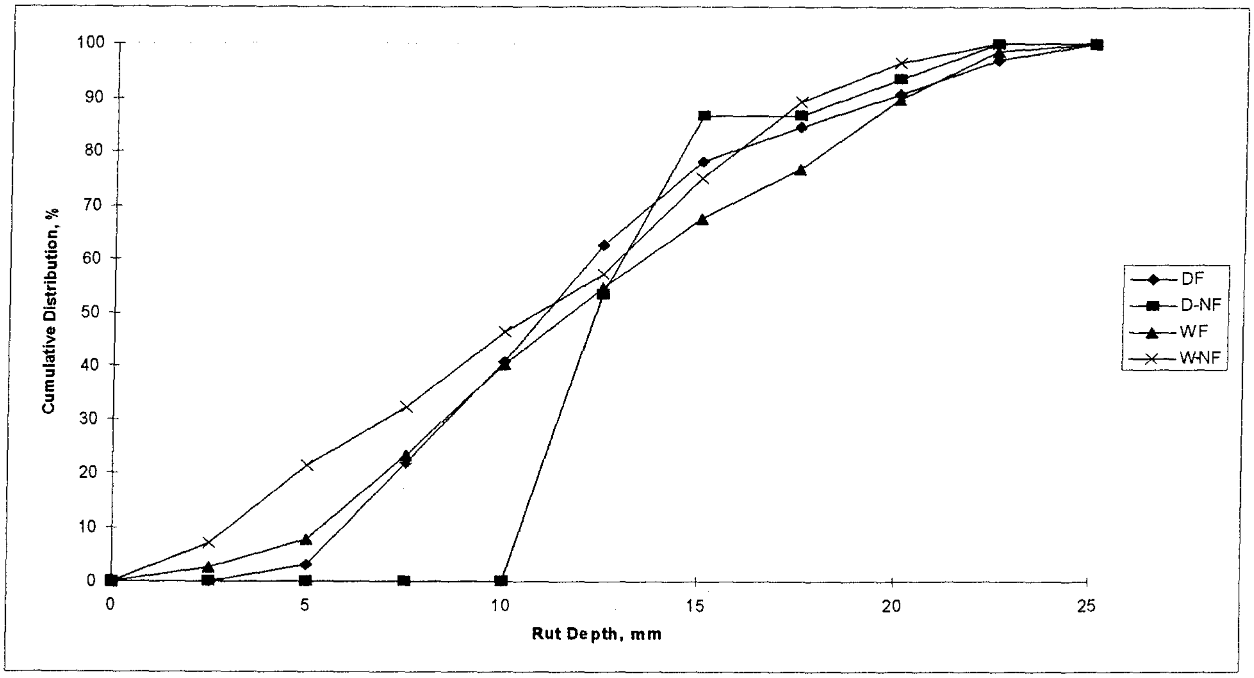


Figure 10. Cumulative Distribution of Rut Depths Comparing Pavements in Different Environmental Zones.

Non-Interstate Pavements

The variables that were found to be statistically different between the good and poor groups are identified in Table 6. The following provides a summary of a few observations made from the analyses of the non-interstate pavements. These observations are then followed by specific results from the analysis (Table 6).

- For the interstate pavements, the good group was found to have significantly thicker asphalt concrete layers than those in the poor group. However, the asphalt concrete resilient moduli were found to be significantly higher for the poor group. If the rutting was primarily occurring in the asphalt concrete layer, one would expect more rutting with the thicker asphalt concrete layers and/or a lower resilient modulus for those layers, or just the opposite of the results presented in Table 6. More importantly, differences in the viscosity data and some measure of the high temperature were found to be insignificant between both groups. This suggests that the asphalt cement may have been properly selected for the specific climatic regions at each test section (on average) and that the majority of the rutting is occurring in the subsurface layers, rather than in the surface layers.

- Reviewing Table 6, it is obvious that the cumulative KESALs are significantly greater for the test sections in the poor group. In fact, traffic appears to be the key parameter in dividing the poor and good groups, as one would expect.

- An apparent difference between these results and historical experience is in the resilient moduli of the aggregate base materials. As shown in Table 6, the mean

Table 6. Results of t-Tests for Performance of Non-Interstate Pavements for Rutting.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Rut Depth, mm	1	4	5	0.9	200	4	17	23	4	17	-13	-38.040	<0.0001	215
Average Min. Temp., °C	-4	7	18	6	198	3	11	17	28	16	-4	-2.476	0.0141	212
Annual Wet Days	24	116	202	42	198	87	152	192	41	16	-36	-3.411	0.0008	212
AC Thickness, mm	30	144	493	76	195	30	97	206	69	17	48	2.547	0.0116	210
Bulk Specific Gravity of AC	2.004	2.316	2.463	0.082	152	2.247	2.380	2.436	0.073	10	-0.064	-2.401	0.0175	160
Water Absorption, %	0.0	0.4	1.2	0.4	152	0.0	0.0	0.1	0.0	10	0.4	3.045	0.0027	160
Air Voids in AC, %	1.1	4.9	16.6	2.4	148	2.0	2.9	4.6	1.2	10	2.0	2.538	0.0121	156
Cumulative KESALs	4	776	10,529	1285	157	1249	2583	3818	1057	8	-1,807	-3.907	0.0001	163
Subgrade Gradation, % Passing 0.075-mm Sieve	6	76	98	26	159	12	64	92	28	17	12	2.410	0.0170	174
Annual Traffic, KESALs	1	79	565	100	157	106	153	194	39	8	-74	-2.070	0.0400	163
AC Backcalculated Modulus, MPa	222	1021	2974	572	165	560	3447	6941	2637	13	-2426	-9.540	0.0000	176
Granular Base M_R at 3, 3[‡], MPa	36	82	177	23	85	89	102	134	12	10	-20	-2.659	0.0092	93
Granular Base M_R at 3, 6, MPa	45	87	152	21	85	99	114	142	12	10	-27	-3.684	0.0002	93
Granular Base M_R at 3, 9, MPa	55	96	156	22	85	107	125	156	14	10	-29	-4.059	0.0001	93
Granular Base M_R at 5, 5, MPa	60	109	182	26	85	121	149	169	16	10	-40	-4.706	0.0000	93
Granular Base M_R at 5, 10, MPa	72	121	194	28	85	142	163	194	17	10	-42	-4.574	0.0000	93
Granular Base M_R at 5, 15, MPa	81	129	197	29	80	147	169	197	16	10	-40	-4.205	0.0001	88
Granular Base M_R at 10, 10, MPa	110	169	250	39	80	191	230	247	23	10	-60	-4.792	0.0000	88
Granular Base M_R at 10, 20, MPa	109	183	266	42	80	210	242	263	22	10	-59	-4.367	0.0000	88
Granular Base M_R at 10, 30, MPa	112	192	275	42	80	215	247	265	22	10	-55	-4.062	0.0001	88
Granular Base M_R at 15, 10, MPa	135	202	299	40	80	217	263	283	24	10	-61	-4.737	0.0000	88
Granular Base M_R at 15, 15[‡], MPa	137	213	304	44	80	237	276	294	22	10	-63	-4.430	0.0000	88

(Continued)

Table 6. Results of t-Tests for Performance of Non-Interstate Pavements for Rutting.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Granular Base M_R at 15, 30, MPa	134	239	345	52	80	268	306	335	24	10	-67	-4.033	0.0001	88
Granular Base M_R at 20, 15, MPa	160	250	361	53	80	271	324	346	28	10	-75	-4.358	0.0000	88
Granular Base M_R at 20, 30, MPa	155	264	383	57	80	292	337	369	26	10	-74	-3.987	0.0001	88
Granular Base M_R at 20, 40, MPa	157	287	424	66	80	316	361	403	32	10	-74	-3.474	0.0008	88
Width of Paved Shoulder, m	0	2	5	1	195	0	1	3	1	17	1	2.252	0.0254	210

‡Numbers separated by a comma are the confining and deviatoric stresses in psi, respectively (1 psi = 6.895×10^{-3} MPa).

*Legend:

Diff. Means	=	Mean of good group minus mean of poor group.
t-value	=	Student's t statistic.
p-value	=	Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, α = 0.05).

resilient modulus for the aggregate base is significantly greater in the poor group than for similar materials in the good group. As this was unexpected, the granular base resilient modulus was blocked by two levels of cumulative KESALs and the data were re-analyzed. These results are summarized in Table 7. As shown, there is no statistically significant difference between both data sets when the resilient moduli of the aggregate base materials are blocked into two levels of traffic.

- Similarly, the asphalt concrete resilient moduli were also blocked using two levels of cumulative KESALs. These results are also included in Table 7. As shown, there is no statistically significant difference between the mean asphalt concrete resilient moduli for both data sets.

- There is a significant difference between both groups for the annual number of wet days at each test site (Table 6). The poor group has a significantly greater number of annual wet days, which concurs with previous experience. More rainfall at each of the test sites in the poor group could suggest stripping and/or moisture damage in the asphalt concrete, or higher moisture contents in the aggregate base. However, moisture contents in the aggregate base were found to be insignificant between both data sets, and higher air voids in the asphalt concrete were found for the good group. Higher air voids suggest more permeability and a greater probability of moisture infiltration into the pavement structure than for lower air voids. Thus, this observation may be solely related to greater amounts of rutting associated with higher traffic levels (i.e., more traffic in the wetter climates).

- The significantly lower mean air voids in the poor group (2.9 percent) do support previous experience relative to the design air voids typically used for asphalt concrete mixture design (4 percent). For the good group, the mean AC air voids were 4.9 percent.

Climatic Features. The average annual minimum temperature for the good group was slightly lower and the annual number of wet days was less for the good group than for the poor group. This indicates that pavements in the good group, on average, were from a colder environment; however, one experienced less frequent precipitation. No significant difference was found between the different types of environment based on the categorical analyses.

AC Features. The average AC layer of the good group was thicker and the air voids in the mix were higher than for the poor group. The water absorption of the aggregate used in the mix showed a higher mean for the good group than for the poor group. The AC layer of the good group was found to have a lower backcalculated modulus than that of the poor group.

Traffic Features. The average annual and cumulative KESALs for the good group were less than one-third of those for the poor group; however, the rate of rutting was not found to be statistically insignificant between the two groups. It is expected that planned plots of rutting versus cumulative KESALs in future studies will help explain this, but it suggests that with time

Table 7. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Non-Interstate Pavements, as Defined by Rutting.

Variable	Blocked by	Blocking Level	Results With Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
AC Bulk Specific Gravity	Cumulative, KESALs	≤53	No statistically significant difference													
		>53	2.082	2.306	2.431	0.073	60	2.389	2.413	2.436	0.024	8	0	-4.09	0.000	66
AC Back-calculated Modulus, MPa	Cumulative, KESALs	≤53	No statistically significant difference													
		>53	No statistically significant difference													
Granular Base M_R, kPa	Cumulative, KESALs	≤53	*No observations fell in the poor group*													
		>53	No statistically significant difference													
Subgrade Moisture Content/PL	FWD Normalized Sensor 7, μ	≤35	*No observations fell in the poor group*													
		>35	No statistically significant difference													

(higher cumulative KESALs), some of those data points now in the good group could move to the poor group.

Granular Base and Subgrade Soil Features. The mean of the granular base resilient modulus for the good group was lower than that for the poor. The gradation of the subgrade material showed that there was more material passing the 0.075-mm sieve size for the good group than for the poor group. As for the interstate pavements, there were more fines in the subgrade for the good group than for the poor group.

Surface Features. It was found that the mean width of the paved shoulder was greater for the good group than for the poor group, as expected.

Type of Base. Table 8 compares the numbers and percentages of non-interstate sections in the good and poor groups with cement-treated, lean concrete, and unbound bases. As can be seen, the cement-treated base (CTB) and the lean concrete bases performed very well, as did the untreated base.

Table 8. Comparison of Rutting Performance of Non-Interstate Pavements for Three Types of Base Materials.

Performance	CTB		Lean Concrete		Unbound	
	Number of Sections	Percentage in Treatment Group	Number of Sections	Percentage in Treatment Group	Number of Sections	Percentage in Treatment Group
Good	104	99	13	100	246	91
Poor	1	1	0	0	23	9
Total	105	100	13	100	269	100

Overlaid Pavements

The variables that were found to be statistically different between the good and poor groups are identified in Table 9. A summary of some of the observations from these results is provided below. These observations are then followed by specific results from the analysis.

- As shown in Table 9, the means for traffic (cumulative KESALs and annual traffic) are significantly different between the data groups. As expected, the poor group had significantly higher traffic levels. This may indicate that at equal traffic levels, there could be no difference in the various parameters and properties of the materials between both data sets.

Table 9. Results of t-Tests for Performance of Overlaid Pavements for Rutting.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Age of Overlay, years	0.5	6.3	21.8	5.0	135	0.02	3.4	13.8	4.2	41	2.9	3.331	0.0011	174
Rut Depths, mm	2	3.4	6.0	0.9	135	2.0	9.3	22.0	5.5	41	-5.9	-11.998	<0.0001	174
Annual Precipitation, mm	76	762	1666	447	135	76	993	3600	721	41	-234	-2.506	0.0131	174
Days With Freezing Temperature	3	116	244	65	135	5	80	192	80	41	36	3.187	0.0017	174
Freeze Index, °C-days	0	387	1861	471	135	0	194	1772	387	41	193	2.314	0.0218	174
Number of Freeze-Thaw Cycles	4	92	194	48	135	6	69	165	36	41	23	2.918	0.0040	174
Bulk Specific Gravity of AC	2.218	2.330	2.502	0.062	85	2.183	2.357	2.502	0.071	34	-0.026	-2.007	0.0471	117
Air Voids in AC, %	1.9	4.9	8.5	1.6	85	1.4	2.0	8.5	2.0	34	2.9	2.740	0.0071	117
AC Aggregate Gradation, % Passing 19.0-mm Sieve	84	98	100	4	85	85	96	100	4	34	2	2.446	0.0159	117
AC Aggregate Gradation, % Passing 12.7-mm Sieve	73	91	100	7	85	74	87	100	8	34	4	3.461	0.0008	117
AC Aggregate Gradation, % Passing 9.52-mm Sieve	65	82	100	8	85	65	77	96	9	34	5	2.897	0.0045	117
AC Aggregate Gradation, % Passing 4.75-mm Sieve	44	60	85	9	85	47	56	67	6	34	3	2.062	0.0414	117
Granular Base Thickness, mm	0	221	696	191	127	0	378	937	254	41	-157	-4.191	<0.0001	166
Subgrade Gradation, % Passing 76.2-mm Sieve	96	100	100	0	90	99	99	100	3	35	1	3.493	0.0007	123
Subgrade Gradation, % Passing 50.8-mm Sieve	90	99	100	2	90	92	97	100	3	35	2	2.022	0.0454	123
Subgrade In Situ Wet Density, kg/m^3	1650	2066	2339	160	79	1890	2147	2387	128	29	-80	-2.424	0.0170	106
Cumulative KESALs	5	866	6431	1177	114	3	2321	8710	3003	35	-1455	-4.244	0.0000	147
Annual Traffic, KESALs	2	147	889	156	114	44	513	1877	543	35	-366	-6.424	<0.0001	147
Rutting Rate (Rut Depth, μ/Cumul. KESALs)	0	34	620	94	114	1	86	876	192	35	-52	-2.173	0.0314	147

(Continued)

Table 9. Results of t-Tests for Performance of Overlaid Pavements for Rutting.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Age at Time of Overlay, years	1.8	12.2	32.6	6.2	123	3.2	14.9	35.1	7.9	40	-2.7	-2.224	0.0276	161
Sensor 1 Deflections (FWD Testing), μ	62	236	463	105	120	62	281	680	158	36	-45	-2.308	0.0223	154
Air Voids in Overlay, %	1	5	16	3	62	1	4	10	2	17	1	2.060	0.0427	77
Subgrade M_R at 2, 4[‡], MPa	36	61	92	18	29	48	82	125	26	6	-20	-2.316	0.0269	33
Subgrade M_R at 2, 6, MPa	32	59	92	18	29	48	81	125	27	6	-21	-2.400	0.0222	33
Subgrade M_R at 2, 8, MPa	31	59	94	19	29	47	80	123	28	6	-21	-2.269	0.0300	33
Subgrade M_R at 2, 10, MPa	32	60	97	20	29	48	80	121	29	6	-20	-2.112	0.0424	33
Subgrade M_R at 4, 6, MPa	41	72	106	21	29	51	95	143	33	6	-22	-2.152	0.0388	33
Subgrade M_R at 4, 8, MPa	39	71	107	22	29	51	94	140	33	6	-23	-2.129	0.0408	33
Width of Paved Shoulder, m	0	2	6	1	130	0	3	3	1	41	-1	-2.787	0.0059	169

[‡]Numbers separated by a comma are the confining and deviatoric stresses in psi, respectively (1 psi = 6.895×10^{-3} MPa).

*Legend:

Diff. Means = Mean of good group minus mean of poor group.

t-value = Student's t statistic.

p-value = Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, α = 0.05).

- As shown in Table 9, there are some apparent discrepancies when compared with previous experience. For example, the subgrade resilient modulus, the width of the paved shoulder, and the base thickness were all significantly higher for the poor group. Therefore, subgrade resilient modulus, base thickness, and width of paved shoulder, as well as AC aggregate gradation, and asphalt concrete bulk specific gravity were all blocked by cumulative KESALs and were re-analyzed. The results from this analysis of these different parameters blocked by traffic are shown in Table 10. As shown, all of these factors were found to be insignificant between both data sets once blocked by traffic, with the exception of the aggregate base thickness. This tends to support the initial observation that traffic may be the more important parameter between both data sets, which is significantly higher for the poor group. The poor group had significantly greater aggregate base thicknesses, which suggests a relationship between the aggregate base and poor rutting characteristics.

The ages of the pavements after overlay were higher for the good group than for the poor group. However, the mean ages of the pavements at the time of overlay were lower for the good group (12.2 versus 14.9 years) than for the poor group.

Climatic Features. There were more days with the temperature below freezing for the good group than for the poor group. The freeze index for the good group was also higher than that for the poor group. In addition, the number of freeze-thaw cycles was higher for the good group than for the poor group. The average annual precipitation for the good group was lower than that for the poor group. This indicates that the good group was, on average, from a colder climate, but one with less precipitation.

Traffic Features. The annual and cumulative KESALs were lower for the good group than for the poor group. The rutting rate for the good group was less than half that of the poor group. The other results should be reviewed with caution since the much higher traffic for the poor group could be influencing the results of the t-tests for other factors.

AC Features. The percentage of air voids in the old pavement and the overlay was higher for the good group than for the poor group. In addition, the mean bulk specific gravity of the AC mix used in the old pavement was lower for the good group than for the poor group. For the aggregate used in the AC mix of the old pavement, there was more material passing the 4.75-mm sieve size for the good group than for the poor group. Surprisingly, the granular base was shown to be less thick for the good group than for the poor group, while the differences in overlay thicknesses or total AC thicknesses were not found to be significant.

Subgrade Soil Features. The subgrade variables showed that there was more material passing the 76.2-mm sieve size. In addition, the laboratory-measured subgrade resilient modulus at different confining and deviatoric stresses was lower for the good group than for the poor group.

Table 10. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Overlaid Pavements, as Defined by Rutting.

Variable	Blocked by	Blocking Level	Results with Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
AC Bulk Specific Gravity	Average Annual Traffic, KESALs	≤150	No statistically significant difference													
		>150	No statistically significant difference													
AC Aggregate Gradation, 4.75 mm	Average Annual Traffic, KESALs	≤150	No statistically significant difference													
		>150	No statistically significant difference													
Width of Paved Shoulder	Average Annual Traffic, KESALs	≤150	No statistically significant difference													
		>150	No statistically significant difference													
Subgrade Moisture Content/PL	FWD Normalized Sensor 7, μ	≤35	No statistically significant difference													
		>35	No statistically significant difference													
Subgrade M_R MPa	Average Annual Traffic, KESALs	≤150	No statistically significant difference													
		>150	No statistically significant difference													
Granular Base Thickness, mm	Average Annual Traffic, KESALs	≤150	0	204	686	161	74	183	337	691	155	9	-133	-2.34	0.022	81
		>150	0	283	696	217	38	0	420	937	237	26	-137	-2.38	0.020	62

Surface Features. The average width of the paved shoulder was found to be greater for the poor group than for the good group.

Type of Environment. A comparison between environmental zones showed that there were more well-performing overlaid pavements in freeze zones than in non-freeze zones. This comparison is shown in Table 11.

Table 11. Comparison of Rutting Performance of Overlaid Pavements for Different Environmental Zones.

Performance	Dry Freeze		Dry-No Freeze		Wet-Freeze		Wet-No Freeze	
	Number of Observ-ations in Zone	Percent-age in Zone	Number of Observ-ations in Zone	Percent-age in Zone	Number of Observ-ations in Zone	Percent-age in Zone	Number of Observ-ations in Zone	Percent-age in Zone
Good	40	87	5	42	31	78	12	52
Poor	6	13	7	58	9	22	11	48
Total	46	100	12	100	40	100	23	100

Summary of Results of t-Tests

The objective of this study was to discriminate between characteristics of pavements that performed better and poorer than normal with regard to rutting, i.e., what works and what does not work.

The characteristics for which differences were most significant are listed in Table 12 by class of pavements. The letters P or G in a column indicates that there was a significant difference for that characteristic. The letter P indicates that the mean value of the characteristic was highest for the poor performance group, while the letter G indicates that the mean value was highest for the good performance group. The letter D means that increasing the characteristic value decreased rutting, while the letter I means that increasing the characteristic value increased rutting.

It should be noted that some of the variables shown in Table 12 are somewhat duplicative, because they approximately represent the same general characteristics. These are:

- Cumulative ESALs and average annual ESALs.
- Freeze index, annual number of days experiencing freeze-thaw cycles, and annual number of days with freezing air temperatures.
- Annual wet days and average annual precipitation (not exactly the same, but generally correlated closely).

Table 12. Summary of Results From t-Test Comparisons for Rutting.

Design Features and/or Site Conditions	Characteristic	Interstate	Non-Interstate	Overlay	Significant From Early Analyses
Traffic Features	Cumulative ESALs		P	P	I
	Average Annual ESALs		P	P	
Climatic Features	Freeze Index	P		G	I
	Days With Freezing Temp.			G	
	Number of Freeze-Thaw Cycles			G	
	Days With Temperature > 32°C				I
	Average Annual Minimum Temperature	G	P		D
	Annual Precipitation			P	I
	Annual Wet Days		P		
Subgrade Features	Subgrade < 76.2-mm Sieve	G		G	
	Subgrade < 0.075-mm Sieve		G		I
	Subgrade <0.02-mm	G			
	Plastic Limits of Subgrade	P			
	Subgrade Wet Density			P	
Load-Response Features	Sensor 7 Deflections	P			
	Sensor 1 Deflections			P	
Asphalt Concrete Features	AC Aggregate Gradation, <9.52 mm	G		G	
	AC Aggregate < 4.75-mm Sieve			G	D
	AC Aggregate >0.075-mm Sieve	G			
	AC Aggregate Water Absorption		G		

Table 12. Summary of Results From t-Test Comparisons for Rutting (Continued)

Design Features and/or Site Conditions	Characteristic	Interstate	Non-Interstate	Overlay	Significant From Early Analyses
Asphalt Concrete Features (Cont.)	AC Laboratory-Measured Resilient Modulus	G			
	AC Thickness	G	G		D
	Air Voids in AC	G	G	G	D
	Asphalt Viscosity				I
Granular Base Features	Moisture Content, %	P			
	Base Compaction				D
	Base Thickness			P	D
Surface Features	Rutting Rate	P			
	Age of Overlay			G	
	Width of Paved Shoulder		G		

- Subgrade passing the 0.075-mm sieve size and subgrade soil less than 0.02 mm (although particle sizes differ, both indicate the level of fine particles).

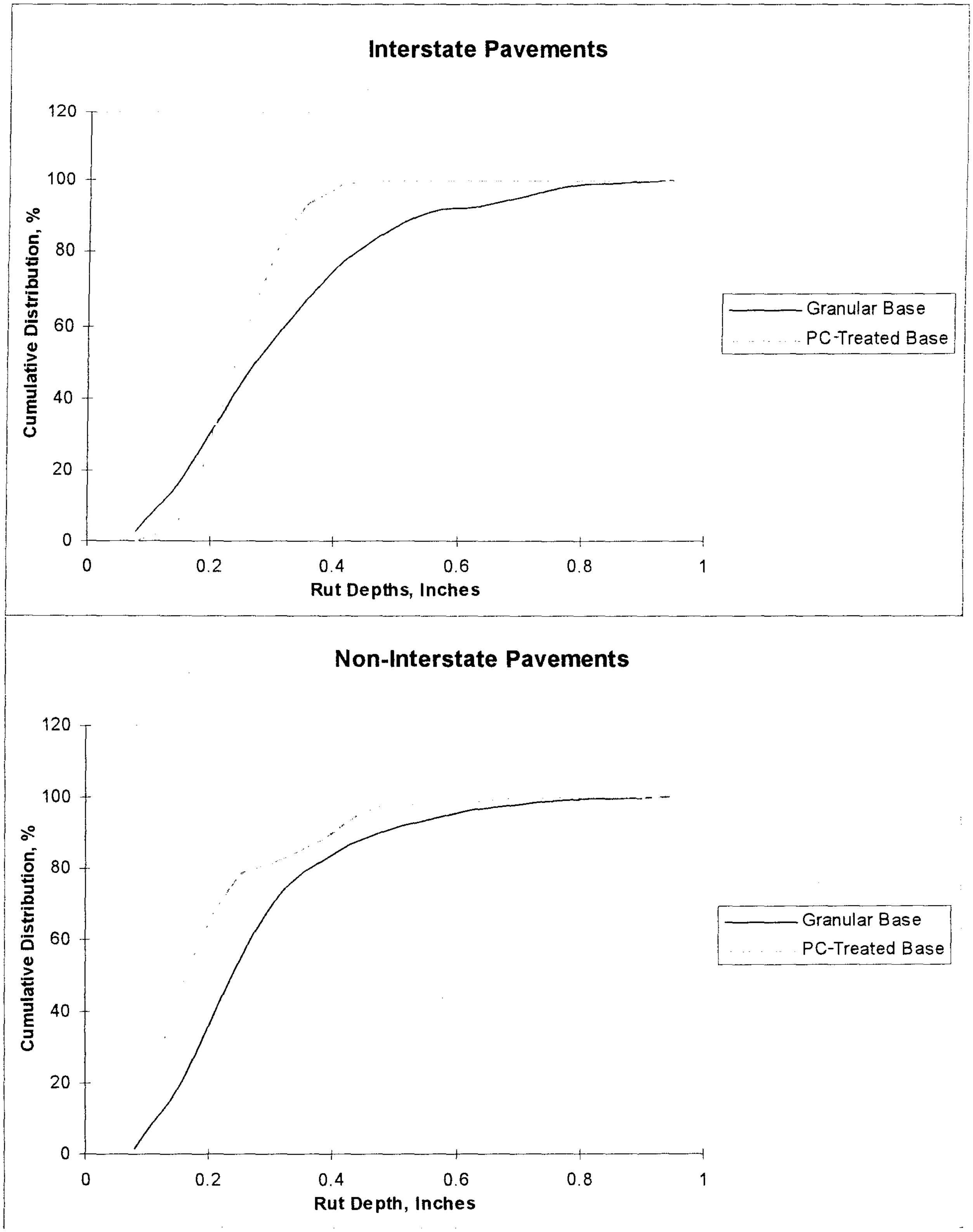
In addition to the t-test comparisons discussed above, some other means of comparing the rutting performance of the pavements were conducted and presented herein. Figure 11 provides cumulative distribution plots to illustrate differences in rutting performance for pavements with unbound granular and portland cement-treated bases. As can be seen, much greater percentages of the pavements with PC-treated bases had experienced lower rut depths than those with untreated bases.

Figure 12 compares the rutting performance of pavements with and without paved shoulders. As can be seen, rut depths were somewhat less for the pavements with paved shoulders.

Conclusions from the t-tests and related studies follow:

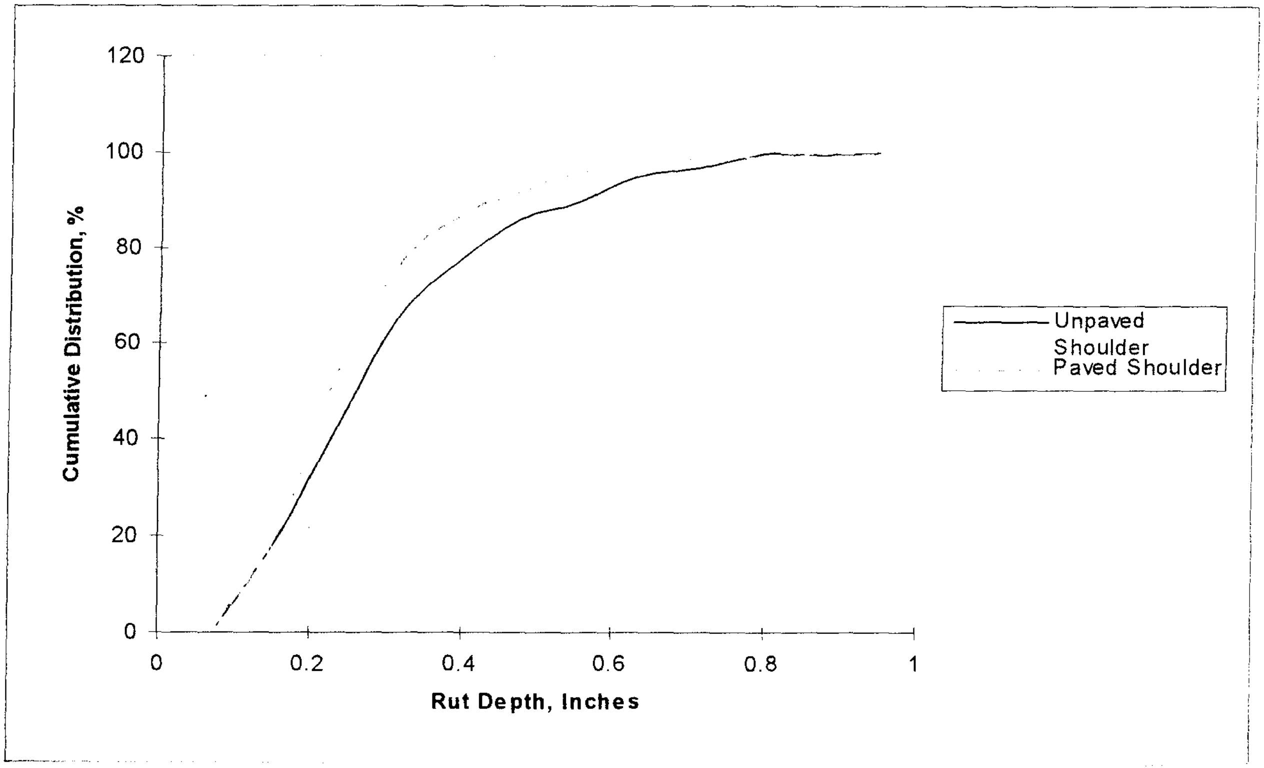
- Pavements with cement-treated bases generally had lower rut depths than those on unbound granular bases.

- While the interstate pavements in the good group experienced more cumulative KESALs than the poor group, the mean rutting rate (μ/KESAL) was approximately 12 times as high for the poor group as for the good group.



1 in = 25.4 mm

Figure 11. Cumulative Distribution of Rut Depths Comparing Pavements With Granular Base to Pavements With PC-Treated Base.



1 in = 25.4 mm

Figure 12. Cumulative Distribution of Rut Depths Comparing Pavements With Unpaved Shoulders to Pavements With Paved Shoulders.

- Mean AC thicknesses were approximately 50 mm greater for the good group than for the poor group (both interstate and non-interstate). Increasing the thicknesses of AC will reduce rutting, assuming that the materials are suitably selected and placed (properly compacted).

- The air voids in the AC (after substantial traffic) were much lower for the poor group than for the good group. The air voids studied were those after the pavements had experienced considerable traffic, which are controllable only through good mixture design and control of densities during construction. Unfortunately, the initial air voids of the material immediately after placement (prior to traffic) are unavailable for these test sections. While the mean values for the poor group were 1 percent to 2 percent lower than those for the good group, the ranges (difference between high and low values) were very similar, so the effects of air voids appear to be interactive with other variables. Control of air voids should be exercised during mixture design and initial placement.

- The overlaid pavements in the good group had, on average, been overlaid much longer than those in the poor group. As cumulative KESALs and the thicknesses of AC before or after overlay were not statistically different between the two groups, it appears that the performance differences in terms of rutting may be related primarily to differences in environment and material properties.

- The mean unbound granular base thicknesses were 221 and 378 mm for the good and poor groups of the overlaid pavements, respectively, whereas intuitively, the opposite would usually be expected. Although this cannot be claimed definitively, this could indicate that a substantial amount of the permanent deformation is occurring in the unbound granular base layers, or it could mean simply that thicker base layers were provided where thinner AC layers were used.

RESULTS FROM SENSITIVITY ANALYSES

These studies were conducted as part of SHRP Contract P-020, "Data Analysis." Reference 1 fully describes the "sensitivity analyses" conducted and their results. This study concerned the sensitivity of rutting in hot-mix asphalt concrete pavements to variations in layer thicknesses, traffic, material properties, or other variables significant to the occurrence of rutting. Such studies are generally conducted by first developing predictive equations for the distress, and then studying the effects of varying individual explanatory variables across reasonable ranges.

Models were developed and sensitivity analyses conducted for AC pavements with unbound granular base and portland cement-stabilized base, as well as for full-depth AC pavements. A total of 11 models were developed and sensitivity analyses were conducted. Numerical rankings for each model were developed in terms of relative sensitivity (1 for highest magnitude of change in rut depth when the parameter was varied over two standard deviations, 2 for the next highest magnitude, etc.).

From the sensitivity analyses, the 12 variables found to be most significant to rutting are listed below, in order of relative ranking, with the most significant variable at the top left and the least at the bottom right:

ESALs	Subgrade < 0.075-mm Sieve	Annual Precipitation
Air Voids in HMAC (-)	Days With Temp. > 32°C	Freeze Index
AC Thickness (-)	AC Agg. < 4.75 mm (#4) (-)	Base Compaction (-)
Base Thickness (-)	Asphalt Viscosity	Avg. Annual Min. Temp. (-)

Where a negative sign (-) appears after the parameter, this means that an increase in the magnitude of the variable was found to result in a decrease in rut depth for most models. No negative sign means that an increase in the variable was found to increase the rut depth. (Note again that the air voids were those measured <u>after experiencing traffic</u>, usually for some years.)

RESULTS FROM RUTTING TREND STUDIES

These studies (Ref. 2), conducted in late 1995 and early 1996, were relatively simplistic, involving only plotting rut depth versus age and observing the trends in the plots. However, the insight gained from these plots was considered to be so valuable that these types of studies are planned for all future analyses. The families of pavements studied separately were: (1) AC Over Granular Base, (2) Full-Depth AC, (3) AC Over Portland Cement-Treated Base, (4) AC Overlay of AC Pavements, and (5) AC Overlay of PCC Pavements.

The primary parameters studied were rate of rutting after initial consolidation under traffic and magnitude of rut depths measured. A rate of 1 mm or less per year was considered to be nominal, 1 to 2 mm was moderate, and greater than 2 mm per year was high. Numbers and percentages in each rutting rate category were identified and compared. The percentages in each category of rutting rate appear by pavement family below.

Rutting Rate	AC Over Granular Base	Full-Depth AC	AC Over Cement-Treated Base	AC Overlay of AC	AC Overlay of PCC
Nominal	57	75	53	49	54
Moderate	12	4	9	13	15
High	13	0	2	4	2
Decrease	8	15	13	16	4
Increase & Decrease	10	6	23	18	25

As summarized above, a substantial number of the test sections experienced decreasing rut depths with time and traffic. Others have noted this same phenomenon in their studies. Rut depths also were found to increase and decrease over time for some test sections.

Some of the results from review of these data indicate that the majority of the pavements were experiencing only a nominal rate of rutting and that very few were experiencing a high rate. It can also be seen that the full-depth AC pavements appeared to be experiencing much less rutting than the others.

The table below indicates low, high, and mean rut depths for families of pavements between 15 and 20 years of age (there were no test sections within this age group for AC Overlay of PCC).

Pavement Family	Sections	Rut Depths, mm		
		Low	High	Mean
AC Over Granular Base	41	2	18	7
Full-Depth AC	8	3	15	9
AC Over Cement-Treated Base	10	3	15	7
AC Overlay of AC	3	3	5	4

It can be seen that the mean rut depths after 15 to 20 years were quite low, and that even those experiencing the highest rut depths were just reaching a stage warranting consideration for overlay because of rutting. A separate study of AC mixture gradations indicated that pavements experiencing high rates of rutting were primarily those having more fine sand than the SUPERPAVE™ specifications will allow.

SUMMARY AND CONCLUSIONS ABOUT RUTTING PERFORMANCE

Comments on those characteristics found to be significant to the occurrence of rutting follow:

- Less than 10 percent of the test sections have poor performance characteristics based on rutting observations/measurements. The disparity in the number of data points within each group may be too large to adequately identify differences in the characteristics of good and poorly performing pavements. However, high traffic levels were found to be a very important feature or characteristic in terms of rutting.

- Another very important observation from these analyses is the exclusion of asphalt viscosity and some measure of the high temperature at each of the test sections. As stated previously, this may indicate that the asphalt viscosities or types of paving asphalts were properly selected for the high temperatures for these test sections. From previous studies conducted and previous experience, asphalt viscosity and high temperatures are two important parameters related to rutting. This observation may also suggest that the asphalt concrete mixture designs were adequate for the traffic and climatic conditions encountered at each site. It should be noted and understood, however, that the insignificance of a variable based on t-test results, such as the number of days with temperatures greater than 32°C or asphalt viscosity, does not necessarily indicate that rutting is not affected by those variables, but instead only indicates that the mean standard deviation between the two data sets differed very little.

- Asphalt concrete pavements built in the colder and wetter climates, on the average, were found to have a higher percentage of poorly performing pavements in terms of rutting. Based on the analyses conducted to date, it is suggested and appears that most of this rutting is related more to the granular base layer than the asphalt concrete surface layers. Thus, designers should pay much closer attention to this layer (selection of materials used during construction), and/or to the minimum asphalt concrete thickness placed above granular base layers, especially for interstate pavements. These analyses are inappropriate to identify the minimum AC thickness requirements for different traffic levels and pavement types. It should be noted, however, that trenches were not dug to clearly identify which layer or layers were the cause of rutting measured only at the surface.

- Proper attention to gradation of AC aggregates, especially avoiding excess fine sand in relation to the coarse aggregate, will reduce rutting.

While the t-test comparisons only indicate variables that are statistically different between two groups and do not indicate significance to the rutting performance directly, the identification of many of the same variables found to be significant during the early analyses appears to add credence to those findings.

CHAPTER 5. FATIGUE CRACKING

Fatigue cracking is an important deterioration mechanism of asphalt concrete-surfaced pavements, because of the detrimental effect these cracks have on the overall pavement strength and stiffness and because they provide a path for moisture to readily infiltrate the underlying layers and subgrade soils. Fatigue cracking is caused by repetitive wheel loadings over time. The pavement structure, mixture composition, and construction are major factors that affect both the initiation and propagation of fatigue cracks. In addition, the environment plays an influential role. The data available from the LTPP database were investigated to discriminate between the good and poorly performing pavements, as defined by fatigue cracking.

As discussed previously, the LTPP fatigue distress data were divided up into individual databases for interstate, non-interstate, and overlaid pavements. Each distress observation was evaluated as being either good, poor, or normal. This evaluation was based on the boundaries identified in Chapter 2. For each pavement group, basic statistical measures of each of the significant variables are presented. These measures include the minimum, mean, maximum, and standard deviation. Each of these measures is given once for the good group and once for the poor group. In addition to these measures, the t- and p-values of the t-test are given, as well as the number of points for each group and the overall degrees of freedom.

In addition to examining continuous variables, categorical variables were also examined. These categorical variables are the environmental zones, the pavement structure (full-depth vs. non-full-depth pavements), and base treatment. In comparing the categorical variables, a chi-square test was used. In fatigue cracking, the investigation of the base treatment did not provide significant results. Significant results from the categorical analysis were found for the non-interstate pavements only.

PREVIOUS STUDIES

There were no previous studies of fatigue cracking using LTPP data to augment this study because there were insufficient test sections that had experienced fatigue cracking at the time the early sensitivity analyses were conducted. However, there have been numerous studies on fatigue cracking of asphalt concrete pavements. The following summarizes the design features and site conditions that have been found to be important in terms of fatigue cracking.

Design Feature and/or Site Condition	Parameter/Property	Effect on Fatigue Cracking Given an Increase in Parameter
Traffic Features	• ESALs	Increases
Climatic/Environmental Features	• Annual Precipitation • Number of Freeze-Thaw Cycles • Mean Annual Pavement Temperature	Increases Increases Decreases

Design Feature and/or Site Condition	Parameter/Property	Effect on Fatigue Cracking Given an Increase in Parameter
Subgrade Features	• Resilient Modulus • Moisture Content/Optimum Moisture Content • Plasticity Index and/or Liquid Limit	Decreases Increases Increases
Design/Construction Features	• Asphalt Concrete Thickness • AC Modulus • AC Indirect Tensile Strength • Air Voids • Asphalt Viscosity • Base Modulus • Base Moisture Content/Optimum Moisture Content • Base Percent Passing No. 200 Sieve	Decreases Decreases Decreases Increases Increases Decreases Increases Increases

RESULTS FROM THE t-TESTS

Interstate Pavements

The variables that were found to be statistically different between the good and poor groups for the interstate pavements are identified in Table 13. Some of the more important observations from the analysis of this data are listed below, and are followed by specific results from this analysis.

- In general, analysis of these data sets supports the results from previous observations that softer asphalts (lower viscosities), higher temperatures, or a greater number of days with temperatures greater than 32°C, and thicker asphalt concrete layers perform better in terms of fatigue cracking. Conversely, traffic was found to be insignificant between both groups of data.

- Lower densities or lower subgrade percent compaction values generally result in more fatigue cracking than for pavements built on subgrades compacted well above 100 percent.

- Asphalt concrete pavements built in wet environments are more susceptible to fatigue cracking than those built in dryer environments.

- The base curvature index (FWD Sensor 3 deflection minus FWD Sensor 5 deflection), which is a measure of the granular base strength and modulus, was found to be significantly higher (indicating weaker base materials) in combination with significantly thicker granular base materials for the poor group. In other words, weaker base materials that are thicker will exhibit more fatigue cracking than those with thinner, but stronger, base materials.

Table 13. Results of t-Tests for Performance of Interstate Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Days With Temp. > 32°C	1	55	175	49	71	1	29	118	38	22	26	2.286	0.0246	91
Annual Number of Days With Precipitation	18	98	191	35	71	42	132	201	41	22	-34	-3.832	0.0002	91
Annual Number of Days With High Precipitation	1	13	43	11	71	6	23	36	9	22	-9	-3.552	0.0006	91
Annual Precipitation, mm	76	609	1600	381	71	279	965	1371	330	22	-356	-3.771	0.0003	91
Average Annual Temp. Range, °C	10	14	19	11	68	9	13	19	3	19	1	2.195	0.0309	85
AC Thickness, mm	76	254	457	101	71	127	203	304	51	22	51	2.019	0.0464	91
Bulk Specific Gravity of AC	1.904	2.323	2.502	0.116	59	2.302	2.406	2.539	0.071	18	-0.083	-2.879	0.0052	75
Max. Specific Gravity of AC	2.142	2.433	2.588	0.094	59	2.344	2.512	2.608	0.077	18	-0.079	-3.246	0.0017	75
AC Aggregate Gradation, % Passing 9.52-mm Sieve	51	71	95	11	59	52	65	86	9	18	7	2.256	0.0270	75
AC Aggregate Gradation, % Passing 4.75-mm Sieve	38	53	70	7	59	36	48	67	8	18	5	2.366	0.0206	75
AC Aggregate Gradation, % Passing 0.425-mm Sieve	15	21	38	5	59	11	17	31	5	18	4	2.741	0.0077	75
AC Aggregate Gradation, % Passing 0.180-mm Sieve	7	13	29	5	59	6	9	15	3	18	4	3.450	0.0009	75
AC Aggregate Gradation, % Passing 0.075-mm Sieve	4	7	13	3	59	3	5	8	2	18	2	3.562	0.0006	75
Viscosity of Asphalt at 60°C, poises	570	1298	2964	585	50	1350	1767	2063	232	11	-469	-2.598	0.0118	59
Granular Base Thickness, mm	101	305	1016	178	71	152	406	965	254	22	-101	-2.273	0.0254	91
Granular Base Gradation, % Passing 76.2-mm Sieve	97	100	100	0	59	85	99	100	4	18	1	2.839	0.0006	75
Granular Base Gradation, % Passing 50.8-mm Sieve	91	100	100	1	59	82	98	100	4	18	2	2.964	0.0041	75

(Continued)

Table 13. Results of t-Tests for Performance of Interstate Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Granular Base Gradation, % Passing 38.1-mm Sieve	89	99	100	2	59	81	96	100	5	18	3	4.558	<0.0001	75
Granular Base Gradation, % Passing 25.4-mm Sieve	82	95	100	5	59	79	90	100	7	18	5	3.121	0.0026	75
Granular Base Gradation, % Passing 0.180-mm Sieve	3	22	56	11	59	9	14	30	6	18	8	2.791	0.0067	75
Granular Base Gradation, % Passing 0.075-mm Sieve	0	14	37	9	59	5	8	17	3	18	5	2.489	0.015	75
Granular Base In Situ Moisture Content, %	3	6	18	4	50	2	4	6	1	12	3	2.123	0.0379	60
Subgrade Gradation, % Passing 0.075-mm Sieve	0	36	97	25	58	6	21	80	20	18	15	2.318	0.0232	74
Subgrade, % Passing 0.002 mm (Hydrometer Analysis)	0	13	36	10	55	0	7	25	8	18	6	2.113	0.0381	71
Subgrade Fine Sand, %	0	27	64	15	55	14	46	88	27	18	-19	-3.681	0.0004	71
Subgrade Silt, %	0	26	76	17	55	5	14	57	13	18	11	2.565	0.0124	71
Subgrade Clay, %	0	13	36	10	55	0	7	100	8	18	6	2.113	0.0381	71
Subgrade Optimum Moisture Content, %	8	13	25	4	58	8	11	15	2	18	2	2.325	0.0228	74
Subgrade Laboratory-Measured Moisture Content, %	3	12	27	7	58	3	8	20	4	18	4	2.399	0.0190	74
Subgrade In Situ Dry Density, kg/m^3	1634	1970	2323	128	50	1698	1858	2260	176	12	112	2.622	0.0111	60
Subgrade Compaction, %	91	104	116	7	49	89	98	112	6	12	6	2.553	0.0133	59
AC Backcalculated Modulus, MPa	1099	6298	13,969	2801	62	1586	4437	5766	1619	17	1861	2.614	0.0108	77

(Continued)

Table 13. Results of t-Tests for Performance of Interstate Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Granular Base Resilient Modulus at Confining Pressure of 0.02 MPa and a Deviatoric Stress of 0.02 MPa, MPa	35	61	87	12	21	82	82	82	0	4	-21	-3.592	0.0015	23
Area Cracked, %	0	0.3	4.1	0.8	71	3.0	26.0	93.0	24.0	22	-25.7	-9.172	<0.0001	91
Base Curvature Index, μ	10	44	178	33	69	11	61	137	61	22	-18	-2.148	0.0344	89
Rate of Cracking (% Area Cracked/KESAL)	0	2e-04	2e-03	5e-04	56	9e-04	8e-03	5e-02	1e-02	16	-8e-03	-5.528	<0.0001	70

*Legend:

Diff. Means = Mean of good group minus mean of poor group.

t-value = Student's t statistic.

p-value = Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, α = 0.05).

- The in situ granular base moisture content was significantly higher for the good group. As a result, the granular base moisture content was blocked by two levels of traffic and the data were re-analyzed. These results are shown in Table 14. As shown, the results for the higher traffic levels did not change, but they did change for the lower traffic level. For the lower traffic level, there is no significant difference between both groups of data.

  This blocking design was also completed for the asphalt viscosity and other parameters. These results are also shown in Table 14, but no significant changes from the initial results were found.

Climatic Features. The environmental variables showing statistical differences were the average annual temperature range, days with temperature greater than 30°C, average annual days with moisture, and average annual precipitation. The results showed that for the good group, the average annual temperature range and days per year with temperatures greater than 30°C were higher than for the poor group. The number of days per year with moisture and the average annual precipitation were lower for the good group than for the poor group. This appears to indicate that less fatigue cracking may be expected in warmer climates or in climates with limited precipitation. Alternatively, more fatigue "healing" in the AC during crack initiation and propagation may occur in the warmer climates.

AC Features. For the AC layer variables, the study showed that significant differences existed for the AC thickness, the percentage of aggregate passing the 9.52-mm, 4.75-mm, 0.425-mm, 0.180-mm, and 0.075-mm sieve sizes, bulk and maximum specific gravities, the layer stiffnesses, and the viscosity of the asphalt at 60°C. The results revealed that the good group had, on average, a thicker AC layer than did the poor group. In addition, there were higher percentages of aggregate passing the sieve sizes identified above. This is an indication of the presence of more fine aggregates in the good group as compared with the poor group.

The asphalt for the good group was, on average, less viscous than that for the poor group, but the mean backcalculated modulus for the mixtures was much higher for the good group. The mean modulus for both groups was relatively high, perhaps indicating that the AC mixtures placed on interstate pavements are generally relatively stiff. Also, as increasing asphalt viscosity in a mixture leads to increased brittleness, this additional brittleness may have contributed to the higher levels of fatigue cracking experienced by the poor group.

Granular Base Features. The poor group had, on average, thicker unbound base layers than the good group, while the good group had more material passing each of the six sieve sizes shown. While the base material in the good group is finer for all of the sieve sizes shown, only the differences in the 0.180-mm and 0.075-mm sieve sizes were substantial. The good group had more in situ moisture also, but the mean moisture contents were only 6 and 4 percent. The mean resilient modulus for the good group was substantially lower than that for the poor group.

Subgrade Soil Features. The mean percentages of subgrade material passing the 0.075-mm sieve and smaller than 0.002 mm (from hydrometer analysis), both the optimum and in situ

Table 14. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Interstate Pavements, as Defined by Fatigue Cracking.

Variable	Blocked by	Blocking Level	Results With Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Granular Base In Situ Moisture Content, %	Average Annual Traffic, KESALs	≤ 305	No statistically significant difference													
		>305	3	6	11	3	23	2	3	4	1	8	3	2.94	0.006	29
AC Viscosity (poises)	Average Annual Traffic, KESALs	≤ 305	570	845	1176	263	10	1817	1895	1975	86	6	-1050	-9.38	0.000	14
		>305	No statistically significant difference													
AC Bulk Specific Gravity	Average Annual Traffic, KESALs	≤ 305	2.273	2.325	2.382	0.033	20	2.374	2.448	2.539	0.078	8	-0.123	-5.88	0.000	26
		>305	No statistically significant difference													
Subgrade Moisture Content/PL	Average Annual Traffic, KESALs	≤ 305	No statistically significant difference													
		>305	No statistically significant difference													
Granular Base Thickness, mm	Average Annual Traffic, KESALs	≤305	137	314	1011	212	26	0	593	856	261	8	-279	-3.09	0.004	32
		>305	No statistically significant difference													

moisture contents, and the percent compaction and in situ dry density are substantially greater for the good group than for the poor group. The poor group had more fine sand while the good group had more silt. The good group also had more clay.

Structural Response Features. The Base Curvature Index (BCI) was much lower on average for the good group than for the poor group, indicating that the layers within 305 to 381 mm below the surface are much stiffer for the good group. (The BCI is the difference between the deflections measured by the third and fifth FWD sensors. The FWD sensor spacings used in the LTPP are 0 mm, 203 mm, 305 mm, 457 mm, 610 mm, 914 mm, and 1524 mm, which form the load drop location.) Conversely, the base resilient modulus measured in the laboratory was much higher for the poor group. However, there were only four data points in the poor group. The deflections measured by the FWD were not found to be significantly different and the difference between the mean sensor values in the two groups was small, apparently indicating that, on average, there was little difference in overall pavement stiffness between the groups.

Surface Features. It can be seen that the mean percentage of area cracked was less than 1 percent for the good group and more than 25 percent for the poor group. The maximum percentage of area cracked was 4 percent for the good group and 94 percent for the poor group. The mean rate of cracking was 40 times as high for the poor group compared with the good group. As the differences between the width of the paved shoulder and cumulative ESALs for the good and poor groups were not found to be significant, the causes for the much higher fatigue cracking rate for the poor group appear to result from differences in AC thickness, material properties, and environmental variables.

Non-Interstate Pavements

The variables that were found to be statistically different between the poor and good groups for the non-interstate pavements are shown in Table 15. In general, the results from these analyses support previous experience. However, asphalt concrete thickness (which is known to be an important pavement cross-section feature related to fatigue cracking) was found to be insignificant between the two groups of data. Another apparent discrepancy is that the asphalt concrete indirect tensile strength was found to be significantly higher for the poor group, which is just the opposite of previous experience. More importantly, traffic is also known to be a very important parameter related to fatigue cracking, but was found to be insignificant when comparing the two groups of data. As a result, various parameters or variables were blocked by traffic and those parameters were re-analyzed. These results are presented in Table 16.

Once blocked by traffic, the indirect tensile strength was found to be insignificant between both groups of data, which at least does not totally contradict previous experience. Asphalt concrete thickness was also blocked by traffic and was still found to be insignificant between both groups of data, so it was re-blocked using the modulus of the granular base material, because of the large difference between both groups of data. For very high modulus values of the base, no significant difference was found in asphalt concrete thickness between the two groups of data. However, for lower modulus values, the asphalt concrete thickness of the surface layer was found to be significantly thicker for the good group data set, which supports previous observations.

The mean age for the observations of good pavements was higher than that for the observations of the poor sections, which means that the good sections are, on average, older than the poor sections. Additional observations from Table 15 are noted below.

Table 15. Results of t-Tests for Performance of Non-Interstate Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Age, years	0.2	13.6	30.4	6.2	334	3.2	11.4	29.1	5.7	103	2.2	3.219	0.0014	435
Days With Freezing Temp.	0	92	236	69	325	0	72	182	58	102	20	2.673	0.0078	425
Days With Precipitation	39	116	225	41	325	38	132	204	34	102	-16	-3.464	0.0006	425
Days With High Precipitation	0	19	60	12	325	2	26	44	10	102	-8	-6.046	<0.0001	425
Average Annual Number of Freeze-Thaw Cycles	0	73	197	48	325	0	61	167	40	102	12	2.380	0.0178	425
Freeze Index, °C-days	0	338	4547	503	325	0	207	1517	337	102	236	2.461	0.0142	425
Average Annual Precipitation (mm)	178	838	2133	431	325	152	1092	1753	356	102	-254	-5.699	<0.0001	425
Average Min. Temp., °C	-12	7	21	7	321	-2	9	19	6	101	-2	-2.284	0.0229	420
Average Temp. Range, °C	8	13	18	2	321	9	12	18	1	101	1	2.364	0.0185	420
AC Aggregate Gradation, % Passing 9.52-mm Sieve	45	79	100	12	255	56	75	98	11	61	4	2.065	0.0397	314
Granular Base Gradation, % Passing 0.425-mm Sieve	1	31	77	14	289	4	38	99	22	83	-7	-3.337	0.0009	370
Granular Base Gradation, % Passing 0.180-mm Sieve	1	20	59	11	289	4	26	99	17	83	-6	-3.243	0.0013	370
Granular Base Gradation, % Passing 0.075-mm Sieve	0	13	37	7	289	3	17	98	15	83	-4	-3.359	0.0009	370
Granular Base In Situ Moisture Content, %	2	7	31	5	242	2	8	31	6	66	-1	-2.205	0.0232	306
Subgrade Gradation, % Passing 25.4-mm Sieve	15	94	100	12	281	80	97	100	4	81	-3	-2.027	0.0434	360
Subgrade Gradation, % Passing 19.0-mm Sieve	15	93	100	13	281	74	96	100	6	81	-3	-2.206	0.0280	360
Subgrade Gradation, % Passing 12.7-mm Sieve	15	90	100	15	281	65	94	100	8	81	-3	-2.266	0.0240	360
Subgrade Gradation, % Passing 9.52-mm Sieve	12	89	100	16	281	59	93	100	10	81	-4	-2.180	0.0299	360

(Continued)

Table 15. Results of t-Tests for Performance of Non-Interstate Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Subgrade Gradation, % Passing 4.750-mm Sieve	12	85	100	19	281	43	90	100	13	81	-4	-2.043	0.0418	360
Subgrade Plastic Limit, %	0	10	38	9	281	0	13	32	10	81	-2	-2.126	0.0341	360
Subgrade Laboratory- Measured Moisture Content, %	1	10	29	6	263	3	13	22	6	76	-3	-3.613	0.0003	337
Subgrade In Situ Moisture Content, %	1	13	34	7	235	4	15	31	8	65	-2	-2.362	0.0188	298
Gran. Base Backcalculated Modulus, MPa	30	609	6895	1382	265	24	279	934	215	84	330	2.179	0.0300	347
AC Indirect Tensile Strength Prior to the M_R test, kPa	514	1328	2742	400	180	668	1465	1935	279	53	-137	-2.336	0.0203	231
Subgrade M_R at 2, 4[‡], MPa	34	68	127	21	143	20	58	115	20	45	10	2.925	0.0039	186
Subgrade M_R at 2, 6, MPa	34	69	132	21	143	18	59	112	20	45	9	2.579	0.0107	186
Subgrade M_R at 2, 8, MPa	32	67	137	22	143	17	58	108	22	45	9	2.519	0.0126	186
Subgrade M_R at 2, 10, MPa	0	67	141	24	143	18	57	106	22	45	10	2.456	0.0150	186
Subgrade M_R at 4, 2, MPa	48	82	179	24	143	27	72	135	23	45	10	2.465	0.0146	186
Subgrade M_R at 4, 4, MPa	44	82	152	23	143	20	71	135	23	45	11	2.682	0.0080	186
Subgrade M_R at 4, 6, MPa	42	81	145	23	143	17	69	126	23	45	12	3.037	0.0027	186
Subgrade M_R at 4, 8, MPa	40	82	148	25	143	18	68	120	24	45	14	3.168	0.0018	186
Subgrade M_R at 4,10[†], MPa	38	82	153	26	143	19	68	125	24	45	14	3.139	0.0020	186
Subgrade M_R at 6, 2, MPa	21	90	193	31	143	34	78	149	27	45	12	2.213	0.0281	186
Subgrade M_R at 6, 4, MPa	51	92	160	27	143	25	77	138	24	45	14	3.251	0.0014	186
Subgrade M_R at 6, 6, MPa	47	89	157	26	143	21	73	130	27	45	16	3.[illegible]72	0.0005	186
Subgrade M_R at 6, 8, MPa	45	89	155	26	143	20	74	134	26	45	15	3.[illegible]09	0.0008	186
Subgrade M_R at 6, 10, MPa	42	89	156	27	143	20	74	139	26	45	15	3.280	0.0012	186

(Continued)

Table 15. Results of t-Tests for Performance of Non-Interstate Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Sensor 1 Deflection (FWD Testing), μ	59	279	979	161	332	71	396	1027	232	103	-117	-5.754	<0.0001	433
Sensor 2 Deflection (FWD Testing), μ	49	205	688	112	332	51	286	821	163	103	-81	-5.669	<0.0001	433
Sensor 3 Deflection (FWD Testing), μ	39	164	495	84	332	45	220	712	124	103	-56	-5.241	<0.0001	433
Sensor 4 Deflection (FWD Testing), μ	22	121	344	60	332	37	154	523	83	103	-32	-4.356	<0.0001	433
Sensor 5 Deflection (FWD Testing), μ	13	93	265	45	332	32	111	380	58	103	-18	-3.296	0.0011	433
Surface Curvature Index, μ	10	115	491	90	332	26	176	505	134	103	-61	-5.238	<0.0001	433
Base Curvature Index, μ	4	70	287	47	332	12	108	332	78	103	-38	-5.993	<0.0001	433
Area Cracked, %	0	0.2	8	0.8	334	0.3	26	84	24	103	-25.8	-19.648	<0.0001	435
Rate of Cracking (% area cracked/KESAL)	0	0.0003	0.0153	0.001	288	0.0008	0.076	0.92	0.18	77	-0.08	-7.160	<0.0001	363

‡Numbers separated by a comma are the confining and deviatoric stresses in psi, respectively (1 psi = 6.895×10^{-3} MPa).

*Legend:

Diff. Means = Mean of good group minus mean of poor group.

t-value = Student's t statistic.

p-value = Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, $\alpha = 0.05$).

Table 16. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Non-Interstate Pavements, as Defined by Fatigue Cracking.

Variable	Blocked by	Blocking Level	Results With Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Indirect Tensile Strength, kPa	Average Annual Traffic, KESALs	≤ 67	No statistically significant difference													
		>67	No statistically significant difference													
AC Thickness	Average Annual Traffic, KESALs	≤ 67	No statistically significant difference													
		>67	No statistically significant difference													
Subgrade Moisture Content/PL	Average Annual Traffic, KESALs	≤67	0.16	0.68	1.65	0.30	69	0.47	0.86	1.13	0.18	15	-0.18	-2.30	0.024	82
		>67	No statistically significant difference													
Cumulative Traffic	GB Backcalculated Modulus, kPa	≤241	No statistically significant difference													
		>241	No statistically significant difference													
AC Thickness, mm	GB Backcalculated Modulus, kPa	≤241	25	152	333	71	123	28	120	277	84	52	32	2.31	0.022	173
		>241	No statistically significant difference													
Granular Base Thickness, mm	GB Backcalculated Modulus, kPa	≤241	No statistically significant difference													
		>241	No statistically significant difference													

<u>Traffic Features</u>. The cumulative ESALs were <u>not</u> found to be significantly different between the groups. Also, the mean area cracked is less than 1 percent for the good group and the maximum is only 8 percent, while these values are 26 and 84 percent, respectively, for the poor group. As the differences in area cracked are major and the sections performing poorly are younger than those performing well, it is clear that variables other than age and ESALs are responsible for the great differences in performance.

The mean rate of cracking was nearly 300 times as high for the poor group as for the good group. However, when area cracked vs. cumulative ESALs were reviewed, it was concluded that the means are skewed by test sections with high levels of cracking and low traffic in the poor group and low levels of cracking and high traffic in the good group.

<u>Climatic Features</u>. The environmental variables found to be statistically different are average annual number of days with freezing temperatures, freeze index, average annual number of freeze-thaw cycles, average annual number of days with moisture and with high moisture, average annual total precipitation, and average annual minimum temperatures and temperature range. Review of the t-test results indicates that the good group was, on average, from a colder climate with less precipitation.

<u>AC Features</u>. The only statistical differences for the AC layers were for the percentage of the AC aggregate passing the 9.52-mm and 0.425-mm sieves. Although found to be statistically different between the two groups, the numerical differences are actually too small to have much effect on performance.

<u>Granular Base Features</u>. The good group had substantially more unbound base materials passing the 9.52-mm and 0.425-mm sieves than the poor group, but was substantially stiffer (higher backcalculated elastic moduli). The greater stiffness for the good group was also indicated by a lower Base Curvature Index (BCI) from the deflection testing.

<u>Subgrade Soil Features</u>. The subgrade materials of the good group showed on average less material passing the 25.4-mm, 19.0-mm, 12.7-mm, 9.52-mm, and the 4.75-mm sieves, but the finer sizes were not statistically different. The stiffness of the subgrade from resilient modulus testing was greater, which may have been partially due to less in situ moisture for the good group.

<u>Structural Response Features</u>. The average deflections measured by the first six sensors on the FWD were all smaller for the good group, indicating overall stiffer pavements. This was further corroborated by lower BCI and Surface Curvature Index (SCI) values for the good group. The SCI is calculated as the difference between the first and third FWD sensors. The lower the SCI, the stiffer the top 200 mm of the pavement.

<u>Type of Environment</u>. In addition, Table 17 shows a categorical comparison between the different environmental zones for the good and poor groups. It can be seen from Table 17 that the freeze environments have a higher percentage of good observations than the non-freeze environments, and that the dry environments have higher percentages of good observations than the wet environments.

Table 17. Comparison of Performance in Environmental Zones for Non-Interstate Pavements.

Performance	Dry-Freeze		Dry-No Freeze		Wet-Freeze		Wet-No Freeze	
	No. of Obser-vations in Zone	Percentage in Zone	No. of Obser-vations in Zone	Percentage in Zone	No. of Obser-vations in Zone	Percentage in Zone	No. of Obser-vations in Zone	Percentage in Zone
Good	79	94	19	87	97	72	136	70
Poor	5	6	2	13	37	28	58	30
Total	84	100	21	100	134	100	194	100

The results of this comparison are also illustrated in Figure 13. It can be seen that the pavements in the Dry-Freeze zone have experienced more cracking than those in the other zones, and that cracking for the two wet zones is similar. The Dry-No Freeze zone has much less cracked area than the Dry-Freeze zone.

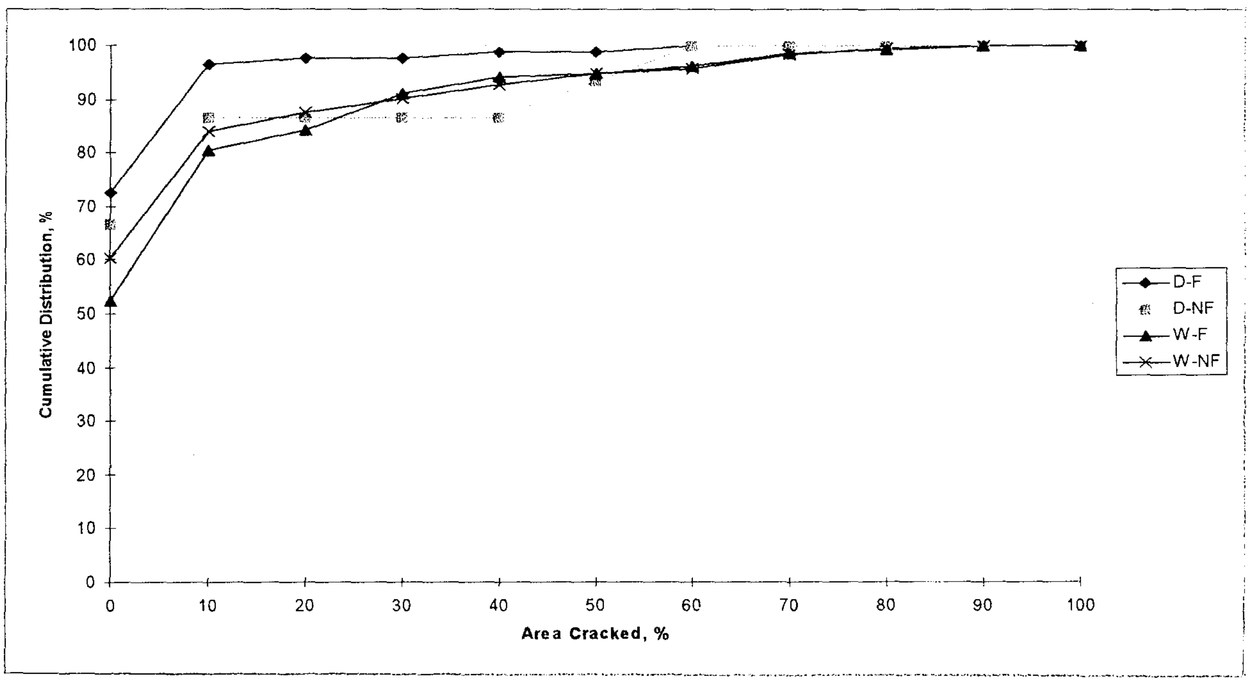


Figure 13. Cumulative Distribution of Area Cracked Comparing Pavements in Different Environmental Zones.

Type of Pavement. It was found from categorical data analysis that the full-depth pavements generally performed better than the pavements with unbound granular base courses. These results appear in Table 18. It can be seen from Table 18 that full-depth pavements had 92 percent of the good observations, while only 76 percent of the pavements with a base course had good observations. Conversely, it can be seen from the same table that there is a higher percentage of observations of poorly performing sections in the pavements with an unbound base course than there are in the full-depth pavements.

The comparison is also shown in Figure 14. The figure clearly shows that the full-depth AC pavements experienced less cracking than those with an unbound base course.

Table 18. Comparison of Performance of Full-Depth Pavements and Pavements With an Unbound Base Course for Non-Interstate Highways.

Performance	Full-Depth		AC Over Unbound Granular Base	
	No. of Observations	Percentage in Group	No. of Observations	Percentage in Group
Good	73	92	334	76
Poor	6	8	103	24
Total	79	100	437	100

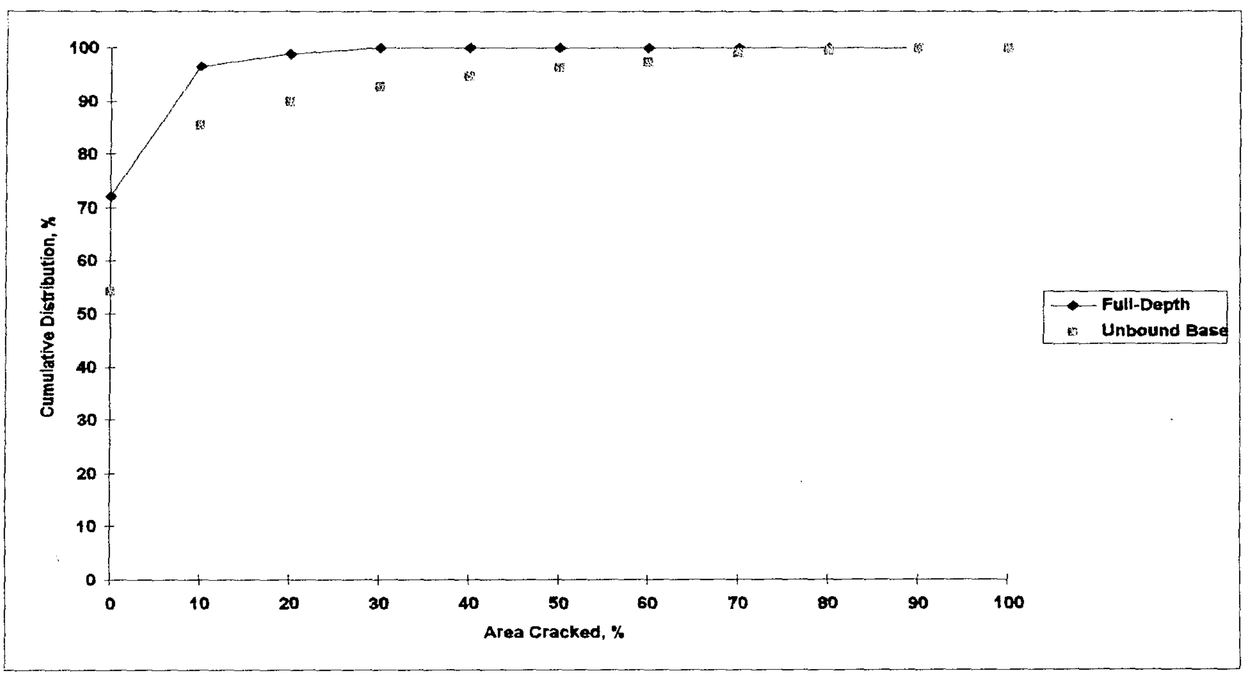


Figure 14. Cumulative Distribution of Area Cracked for Full-Depth AC Pavements and AC Pavements With Unbound Granular Base for Non-Interstate Highways.

Some comments about the above results follow:

- The AC thicknesses, on average, are around 127 mm, which is substantially less than that for the interstate pavements. The Base Curvature Indices also were substantially less for the interstate pavements, indicating that the interstate pavements were generally stiffer (as expected).

- All of the full-depth pavements (good and poor combined) had a mean of 1.0-percent cracked area, while the pavements with unbound base had a mean of 6.2-percent cracked area. In addition, a comparison of the full-depth AC pavements vs. AC pavements with an unbound base (Table 18) showed that the full-depth pavements had a higher percentage of good pavements than did the pavements with base courses. This appears to indicate that full-depth AC pavements may generally be expected to perform better for fatigue cracking than pavements designed with an unbound base.

Overlaid Pavements

The results of the t-tests for the overlays are shown in Table 19. As shown in Table 19, the granular base backcalculated modulus is significantly higher for the good group, which would be expected. Conversely, asphalt concrete/overlay thickness was found to be insignificant between both data groups, which is a discrepancy based on previous experience. Another apparent discrepancy is that the asphalt concrete indirect tensile strength was significantly higher for the poor group, and cumulative traffic was also found to be insignificant between both groups of data. As a result, various parameters were blocked into two levels using the backcalculated base modulus and cumulative traffic. These results for the re-analysis are shown in Table 20.

As shown, the asphalt concrete thickness, when blocked by the backcalculated base modulus, was found to be significantly higher in the good group for the lower values of the base modulus and insignificant for the higher base moduli, as one might expect. This is the same result that was found for the interstate pavements. Specifically, the asphalt concrete thickness was found to be significantly higher for the good group, which concurs with previous experience.

The asphalt concrete indirect tensile strength when blocked by the backcalculated base modulus was found to be insignificant between both data sets, and does not totally contradict previous experience.

It was found that, on average, the ages of the good pavements at the time of overlay were higher than those of the poor group. One possible explanation for this is that the older pavements had less fatigue cracking at the time of overlay. However, the distress prior to overlay is available only for GPS-6B test sections. Student t-tests were run on the GPS-6B observations to investigate whether the mean of fatigue cracking prior to overlay for the good group was different from that of the poor group. The results did not show any significant differences.

AC Features. The only AC variable found to be statistically different between the groups was indirect tensile strength. The mean value for the poor group was 2.8 times higher than that for the good group. However, there were only 4 data points in the poor group, as compared to 30 in the good group.

Table 19. Results of t-Tests for Overlaid Pavements for Fatigue Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Granular Base Liquid Limit, %	0	7	29	9	59	0	1	11	3	16	6	2.689	0.0089	73
Granular Base Plastic Limit, %	0	5	21	7	59	0	1	10	2	16	4	2.357	0.0211	73
Granular Base Plasticity Index, %	0	2	9	3	59	0	0	1	0	16	2	2.377	0.0201	73
Age of Old Pavement at Overlay, years	3	15	27	5	73	3	9	23	5	15	6	3.626	0.0005	86
Base Compaction, %	77	94	100	5	47	94	97	103	3	14	-3	-2.362	0.0215	59
Sensor 1 Deflection (FWD Testing), μ	89	224	681	120	73	115	314	463	114	18	-90	-2.865	0.0052	89
Sensor 2 Deflection (FWD Testing), μ	67	176	493	90	73	93	248	379	92	18	-72	-3.017	0.0033	89
Sensor 3 Deflection (FWD Testing), μ	61	148	378	71	73	81	207	324	75	18	-59	-3.120	0.0024	89
Sensor 4 Deflection (FWD Testing), μ	49	114	247	50	73	54	156	260	59	18	-42	-3.044	0.0031	89
Sensor 5 Deflection (FWD Testing), μ	38	90	167	38	73	46	119	207	46	18	-29	-2.695	0.0084	89
Surface Curvature Index, μ	18	76	303	57	73	35	107	169	45	18	-30	-2.157	0.0337	89
Base Curvature Index, μ	14	58	211	40	73	34	88	139	34	18	-30	-2.968	0.0039	89
Granular Base Backcalculated M_R, MPa	59	566	1863	493	62	27	130	258	65	14	436	3.287	0.0016	74
Indirect Tensile Strength Measured After Running the M_R Test, kPa	101	432	1785	620	30	101	1204	1746	776	4	-773	-2.282	0.0293	32
Rate of Cracking (% area cracked/KESAL)	0e+00	1e-04	3e-03	4e-04	68	1e-04	1e-02	7e-02	2e-02	16	-1e-02	-5.511	<0.0001	82

*Legend:

Diff. Means = Mean of good group minus mean of poor group.

t-value = Student's t statistic.

p-value = Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, $\alpha = 0.05$).

Table 20. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Overlaid Pavements, as Defined by Fatigue Cracking.

Variable	Blocked by	Blocking Level	Results with Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Cumulative Traffic, KESALs	Backcalculated Base Modulus, kPa	≤355	No statistically significant difference													
		>355	*No observations fell in the poor group*													
AC Thickness, mm	Backcalculated Base Modulus, kPa	≤355	127	247	432	81	20	137	189	300	50	12	58	2.21	0.035	30
		>355	*No observations fell in the poor group*													
Overlay Thickness, mm	Backcalculated Base Modulus, kPa	≤355	No statistically significant difference													
		>355	*No observations fell in the poor group*													
AC Indirect Tensile Strength, (kPa)	Backcalculated Base Modulus, kPa	≤355	No statistically significant difference													
		>355	*No observations fell in the poor group*													
AC Indirect Tensile Strength, kPa	Average Annual Traffic, KESALs	≤142	No statistically significant difference													
		>142	101	431	1785	683	15	1746	1746	1746	0	2	-1315	-2.65	0.018	15
AC Thickness, mm	Average Annual Traffic, KESALs	≤142	No statistically significant difference													
		>142	No statistically significant difference													
Overlay Thickness, mm	Average Annual Traffic, KESALs	≤142	No statistically significant difference													
		>142	No statistically significant difference													

Granular Base Features. The only characteristics of the granular base found to be significantly different were the backcalculated elastic moduli and the Atterberg limits of the fines, for which the plasticity index only varied from 0 to 9 percent. It is believed that the differences in Atterberg limits had little effect on the performance of overlays in fatigue cracking; however, the good group has a substantially higher granular base stiffness than the poor group.

Structural Response Features. The deflections for the first five FWD sensors and the SCI and BCI were all lower for the good group, indicating that the overall pavement stiffness is higher.

SUMMARY OF RESULTS

The variables showing the most significant differences between the good and poor groups appear in Table 21. The letters P or G in a column indicate that there was a significant difference for the characteristic. The letter P means that the poorly performing pavements had a significantly higher mean value for the characteristic than did the good performing pavements. The letter G means that the good performing pavements had a higher mean value than the poorly performing pavements.

All the pavement classes (non-interstate, interstate, and overlays) showed a significantly higher level of and rate of fatigue cracking for the poor group compared with the good group.

Only 6 of the 27 variables found to have statistically significant differences and entered into Table 19 can be directly controlled by the State highway agencies. These six are discussed below:

- Thicker AC layers should result in less fatigue cracking if the mixtures are properly designed and placed.
- Use of asphalt with lower viscosity may be expected to result in less fatigue cracking.
- Full-depth AC pavements appear to experience less fatigue cracking than pavements having AC over granular base, probably due to the stiffer overall structure.
- It appears that more fines in AC aggregate passing the 0.180-mm and 0.075-mm sieves may reduce fatigue cracking, but the fines should remain within SUPERPAVE™ specifications to avoid excessive rutting.
- The results for the amount of fines in the granular base differed between the interstate and non-interstate pavements. For the interstate pavements, the good group was associated with more fines, while the poor group was associated with more fines in the non-interstate pavements. Thus, no clear recommendation may be made for fines in granular base materials.

Table 21. Results From Comparison of Characteristics of Pavements Displaying Good or Poor Performance for Fatigue Cracking.

Characteristic Group	Characteristic	Overlay	Non-Interstate	Interstate
Climatic Features	No. of Days With High Moisture		P	P
	No. of Days With Moisture		P	P
	Annual Precipitation		P	P
	Freeze-Thaw Cycles		G	
	Freeze Index		G	
	No. of Days With Freezing Temperature		G	
	No. of Days With Temp. > 32°C		P	G
Asphalt Concrete Features	Thickness	G	G	G
	Backcalculated Modulus			G
	Viscosity at 60°C			P
	Aggregate Passing 0.180-mm (#80) and 0.075-mm (#200) Sieves			G
Granular Base Features	Thickness			P
	Backcalculated Modulus	G	G	
	Passing 0.180-mm (#80), and 0.075-mm (#200) Sieves		P	G
	Base Compaction	P		
	Plasticity Index	G		
	In Situ Moisture Content		P	G
Subgrade Soil Features	Laboratory Measured M_R		G	
	Passing 0.075-mm (#200) and Smaller Than 0.002 mm			G
	% Fine Sand			P
	% Silt			G

(Continued)

Table 21. Results From Comparison of Characteristics of Pavements Displaying Good or Poor Performance for Fatigue Cracking.

Characteristic Group	Characteristic	Overlay	Non-Interstate	Interstate
Subgrade Soil Features (Cont.)	% Clay			G
	Plastic Limit		P	
	In Situ Moisture Content		P	G
	Optimum Moisture Content			G
Structural Response Features (FWD)	Deflections, Sensors 1-4	P	P	
	Deflections, Sensors 5 and 6		P	
	BCI†	P	P	P
	SCI*	P	P	

* Surface Curvature Index = FWD Sensor 1 - FWD Sensor 3.

† Base Curvature Index = FWD Sensor 3 - FWD Sensor 5.

- For the interstate pavements, the mean thickness of the granular base was found to be less for the good group than for the poor group. This is probably a consequence of the AC layer being thicker for the good group, simply meaning that a higher overall stiffness of a pavement structure may be expected to reduce bending and consequent fatigue.

It is important to remember that the t-tests only compare mean values between two groups and do not evaluate relative significance of the variables, or interactions of two or more variables, to the occurrence of distress. The recommendations above are believed to be reasonable, but cannot be stated at high confidence levels until corroborated by more comprehensive statistical studies.

CHAPTER 6. TRANSVERSE CRACKING

Transverse cracking is thermally induced and can cause a reduction of the structural capacity of the AC layer, the infiltration of moisture in the base and subgrade leading to the overall deterioration of the pavement, and increased roughness and decreased ride quality. Pavement structure and material properties are major factors in resisting transverse cracking, while the environment is the major factor causing the formation of transverse cracks. It should be noted that transverse cracks are not always thermally induced. Thermal cracking, shrinkage cracking in cement-treated bases (CTB), and other high-strength base layers, and reflective cracking all contribute to the accumulation of transverse cracks. No distinction is made in the LTPP database as to their actual cause.

This chapter presents the results of two studies using LTPP data that were aimed at understanding pavement behavior in transverse cracking. The first study was the sensitivity analyses conducted under the SHRP P-20 project (Ref. 1). The second study is the current study to distinguish between the characteristics of good and poorly performing pavements.

RESULTS FROM THE t-TESTS

The objective of this study was to discriminate between characteristics of pavements that performed better and worse than normal in transverse cracking, i.e., what works and what does not work. The many characteristics existing in the good and poor data sets were compared for each type of pavement using Student's t-test procedures as explained in Chapter 3.

The characteristics for which differences were statistically significant are listed in Tables 17, 18, and 21 for interstate, non-interstate, and overlaid pavements, respectively. In each table, basic statistical measures of each of the variables with statistical significance are presented. These measures included the minimum, mean, maximum, and standard deviation. Each of these measures is given once for the good group and once for the poor group. In addition to these measures, the t- and p-values of the t-test are given, as well as the number of points for each group and the overall degrees of freedom.

Interstate Pavements

The results from the t-tests for interstate pavements are shown in Table 22. As shown in Table 22, none of those parameters previously found to be important to the formation of transverse cracks were found to be significant between both data groups. This could suggest that the transverse cracks observed and recorded on the interstate pavements may, in fact, not be temperature-related, but may be a result of other mechanisms.

Most of those parameters listed in Table 22 are related to the load-response characteristics of the pavement structure and subgrade gradation. As such, some of the variables that were found to be insignificant (for example, asphalt viscosity, asphalt concrete thickness, asphalt concrete resilient modulus and indirect tensile strength, asphalt concrete bulk specific gravity and cumulative traffic) were then blocked by the freeze index and re-analyzed. The results from this additional analysis by blocking certain parameters did not change the results. In other words, all of those parameters

Table 22. Results of t-Tests for Performance of Interstate Pavements for Transverse Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
AC Aggregate Gradation, % Passing 25.4-mm Sieve	80	97	100	6	37	100	100	100	0	11	-3	-2.020	0.0493	46
AC Aggregate Gradation, % Passing 19.0-mm Sieve	68	91	100	9	37	91	97	100	2	11	-6	-2.459	0.0178	46
Subgrade Gradation, % Passing 25.4-mm Sieve	82	97	100	4	36	79	93	100	8	11	4	2.425	0.0194	45
Subgrade Gradation, % Passing 19.0-mm Sieve	77	96	100	5	36	72	90	99	10	11	6	2.645	0.0112	45
Subgrade Gradation, % Passing 12.7-mm Sieve	72	93	100	7	36	64	86	98	12	11	7	2.509	0.0158	45
Subgrade Gradation, % Passing 9.52-mm Sieve	68	92	100	8	36	59	83	98	14	11	9	2.477	0.0171	45
Subgrade Gradation, % Passing 4.75-mm Sieve	61	87	99	11	36	50	76	98	18	11	11	2.525	0.0152	45
Sensor 1 Deflection (FWD Testing), μ	63	193	589	111	47	146	277	457	99	11	-84	-2.295	0.0255	56
Sensor 2 Deflection (FWD Testing), μ	52	153	479	86	47	118	224	361	80	11	-71	-2.487	0.0159	56
Sensor 3 Deflection (FWD Testing), μ	48	131	402	69	47	106	192	296	65	11	-61	-2.644	0.0106	56
Sensor 4 Deflection (FWD Testing), μ	32	106	305	52	47	89	152	242	49	11	-46	-2.723	0.0086	56
Sensor 5 Deflection (FWD Testing), μ	23	86	224	38	47	69	121	198	37	11	-35	-2.766	0.0077	56
Sensor 6 Deflection (FWD Testing), μ	13	58	130	25	47	42	78	134	24	11	-20	-2.401	0.0197	56
Rate of Cracking, cracks/KESAL	2.00e-05	5.50e-04	2.79e-03	6.20e-04	38	2.23e-03	3.38e-02	1.66e-01	5.42e-02	10	-3.32e-02	-3.897	0.0003	46
Base Curvature Index, μ	10	46	178	35	47	29	71	133	32	11	-25	-2.224	0.0300	56

*Legend:

Diff. Means	=	Mean of good group minus mean of poor group.
t-value	=	Student's t statistic.
p-value	=	Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, $\alpha = 0.05$).

found to be insignificant between the data groups considering individual parameters were also found to be insignificant between both data groups when blocked by the freeze index. Only the FWD data, gradations of coarse aggregates in the AC and in the subgrade, and rate of cracking per KESAL were found to be statistically different. The fact that the rate of transverse cracking per KESAL and FWD data (as well as the Base Curvature Index) were found to be significant suggests the possibility of a different mechanism resulting in these cracks, for example, the combination (or coupling) of thermal and wheel loads causing the formation of transverse cracks.

Unfortunately, the results from the t-tests were affected by a shortage of observations in both the poor and good groups. This resulted from the fact that a large number of the observations fell into the normal group (see Figure 7 in Chapter 2). There were 48 observations in the good group, but only 11 in the poor group.

Some other variables would also have been found to be significantly different on the basis of their mean values alone, but the t-test takes into account variability as well. If variability is very high for one group, the procedure could not confirm that the difference between the two groups is meaningful at the desired confidence level. As an example, the mean for the freeze index was 525 for the good group and 856 for the poor group, which is obviously a significant difference, but the standard deviations were 898 and 962, respectively. As can be seen, the standard deviations are larger than the mean values.

Surface Features. The standard deviations for the "rate of cracking" (cracks per KESAL) were also larger for the two data sets than the means, but the difference between the means approached two orders of magnitude so the rate of cracking was found to be significantly different. However, it is moot whether this represents one or a combination of physical characteristics that actually affected transverse cracking.

AC and Subgrade Soil Features. While the gradations of the coarse aggregate in the AC were found to be statistically different for the two data sets, as were coarse materials in the subgrade, it appears possible that these differences have no bearing on the formation of transverse cracks.

Structural Response Features. Deflections measured by the first six sensors were lower for the good group than for the poor group. This indicated an overall stiffer pavement for the good group. In addition, the value of the BCI was lower for the good group than for the poor group, indicating a stronger base for the good group.

Non-Interstate Pavements

The variables that showed significant differences between the good and poor groups for the non-interstate pavements are shown in Table 23. Conversely to the results obtained from the Interstate Pavement Group, almost all of the parameters and properties checked between both data sets were found to be significant, as shown in Table 23.

Most of the data sets in the poor group were found in the colder and drier environments. In other words, the freeze index was significantly greater and the annual precipitation was significantly less for the poor group. Conversely, the good group had significantly lower asphalt concrete thicknesses and significantly higher resilient moduli. This contradicts previous experience.

Table 23. Results of t-Tests for Performance of Non-Interstate Pavements for Transverse Cracking.

Characteristics Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Instantaneous Resilient Modulus at 5°C, MPa	3660	7167	14,147	2410	139	3660	5811	7025	832	17	1356	2.298	0.0229	154
Total Resilient Modulus at 5°C, MPa	3061	5714	11,380	1901	139	3352	4789	5398	663	17	925	1.986	0.0488	154
Instantaneous Resilient Modulus at 25°C, MPa	2146	4705	9728	1596	139	2856	3852	4722	556	18	852	2.243	0.0263	155
Total Resilient Modulus at 25°C, MPa	1753	3522	7771	1204	139	2170	2882	3373	388	18	640	2.235	0.0269	155
Instantaneous Resilient Modulus at 40°C, MPa	935	2237	4088	744	141	1283	1800	2364	268	17	437	2.397	0.0177	156
Total Resilient Modulus at 40°C, MPa	619	1659	2959	552	141	888	1277	1756	222	17	383	2.829	0.0053	156
Structure Number	1	4	7	1	267	2	5	9	2	57	-1	-5.820	<0.0001	322
Number of Days With Freezing Temperature	0	65	203	62	266	22	130	200	49	51	-66	-7.158	<0.0001	315
Number of Days With Temp. > 32°C	0	55	169	39	266	0	22	99	27	51	33	5.771	<0.0001	315
Number of Days With High Precipitation	1	23	44	11	266	1	18	40	10	51	5	3.057	0.0024	315
Number of Freeze-Thaw Cycles	0	55	170	44	266	20	93	167	28	51	-38	-5.940	<0.0001	315
Freeze Index, °C-days	0	175	1535	308	266	14	826	4547	1181	51	-651	-7.762	<0.0001	315
Annual Precipitation, mm	152	990	1778	381	266	102	838	1524	356	51	152	2.572	0.0106	315
Average Maximum Temperature, °C	7	23	31	6	263	4	15	26	6	50	8	8.642	<0.0001	311
Average Minimum Temperature, °C	-4	10	20	6	263	-12	2	14	6	50	8	8.361	<0.0001	311
AC Thickness, mm	25	127	406	76	267	51	178	280	51	57	-51	-3.700	0.0003	322
Bulk Specific Gravity in AC	1.938	2.312	2.538	0.104	200	2.219	2.349	2.463	0.060	45	-0.037	-2.290	0.0229	243
Water Absorption, %	0.0	0.6	2.8	0.5	200	0.0	0.4	1.3	0.4	45	0.2	2.339	0.0201	243
AC Aggregate Gradation, % Passing 0.425-mm Sieve	7	24	54	7	196	11	21	35	6	44	3	2.456	0.0148	238

(Continued)

Table 23. Results of t-Tests for Performance of Non-Interstate Pavements for Transverse Cracking.

Characteristics Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Granular Base Gradation, % Passing 0.425-mm Sieve	2	34	98	17	231	5	28	99	19	46	6	2.106	0.0361	275
Granular Base Liquid Limit, %	0	6	31	9	231	0	2	22	5	46	4	2.849	0.0047	275
Granular Base Plastic Limit, %	0	4	25	7	231	0	1	17	4	46	3	2.775	0.0059	275
Granular Base Plasticity Index, %	0	1	11	3	230	0	0	5	1	46	1	2.621	0.0093	274
Granular Base Maximum Density, %	106	131	149	10	229	111	134	149	8	46	-4	-2.286	0.0230	273
Granular Base Laboratory- Measured Moisture Content, %	2	7	20	4	229	2	5	17	3	43	2	3.099	0.0021	270
Granular Base In Situ Dry Density, kg/m^3	1250	2019	2435	240	181	1666	2115	2307	128	36	-96	-2.394	0.0175	215
Granular Base In Situ Moisture Content, %	3	8	31	6	181	2	5	19	3	36	3	2.976	0.0033	215
Subgrade Gradation, % Passing 76.2-mm Sieve, %	92	100	100	1	227	94	99	100	2	41	1	2.196	0.0289	266
Subgrade Gradation, % Passing 2.00-mm Sieve, %	12	83	100	20	227	28	76	99	23	41	7	2.233	0.0264	266
Subgrade Gradation, % Passing 0.425-mm Sieve, %	8	72	99	23	227	15	56	99	29	41	16	3.988	<0.0001	266
Subgrade Gradation, % Passing 0.180-mm Sieve, %	4	55	98	25	227	3	43	99	32	41	11	2.549	0.0144	266
Subgrade, % Passing 0.02 mm (Hydrometer Analysis)	1	31	91	22	205	1	22	80	22	41	9	2.356	0.0193	244
Subgrade, % Passing 0.002 mm (Hydrometer Analysis)	0	18	54	13	205	0	13	52	15	41	5	2.403	0.0170	244
Subgrade > 2 mm, %	0	17	78	19	205	1	25	72	23	41	-8	-2.260	0.0247	244

(Continued)

Table 23. Results of t-Tests for Performance of Non-Interstate Pavements for Transverse Cracking.

Characteristics Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Coarse Sand, %	0	12	31	8	205	0	19	49	15	41	-7	-4.445	<0.0001	244
Fine Sand, %	2	31	94	25	205	0	21	66	18	41	10	2.434	0.0157	244
Clay, %	0	18	54	13	205	0	13	52	15	41	5	2.381	0.0180	244
Subgrade Maximum Density, kg/m^3	1441	1810	2260	160	210	1570	1890	2227	192	36	-80	-2.833	0.0050	244
Subgrade Optimum Moisture Content, %	7	14	28	5	210	7	12	23	5	36	2	2.168	0.0311	244
Subgrade Laboratory-Measured Moisture Content, %	1	12	30	7	210	3	10	27	7	36	2	1.971	0.0499	244
Subgrade In Situ Dry Density, kg/m^3	1121	1810	2563	208	174	1442	1938	2563	224	34	-128	-3.244	0.0014	206
Subgrade In Situ Wet Density, kg/m^3	1442	1938	2691	208	174	1618	2018	2675	208	34	-80	-2.168	0.0313	206
Subgrade In Situ Moisture Content, %	2	15	34	8	174	3	12	33	8	34	3	2.114	0.0357	206
Annual KESALs	1	105	1432	142	211	10	169	1398	368	52	-64	-2.120	0.0349	261
Cumulative KESALs	7	1194	26,486	2259	209	59	2432	24,191	5778	50	-1238	-2.427	0.0159	257
Sensor 7 Deflection (FWD Testing), μ	4	32	91	17	266	13	38	80	15	57	-6	-2.304	0.0219	321

*Legend:

Diff. Means = Mean of good group minus mean of poor group.

t-value = Student's t statistic.

p-value = Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, $\alpha = 0.05$).

(Continued)

Table 24. Results of t-Tests When Blocked by Selected Parameters/Features for Performance of Non-Interstate Pavements, as Defined by Transverse Cracking.

Variable	Blocked by	Blocking Level	Results with Blocking													
			Good					Poor					Diff. in Means	t-value	p-value	Degrees of Freedom
			Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Asphalt Viscosity, poises	Freeze Index (C°-Days)	≤117	No statistically significant difference													
		>117	288	1415	3662	686	83	632	1788	3662	904	33	-373	-2.41	0.018	114
AC Thickness, mm	Freeze Index (C°-Days)	≤117	28	124	333	79	156	198	204	216	8	4	-80	-2.03	0.044	158
		>117	No statistically significant difference													
AC Total M_R @ 25°C, MPa	Freeze Index (C°-Days)	≤117	*No observations fell in the poor group*													
		>117	No statistically significant difference													
AC Bulk Specific Gravity	Freeze Index (C°-Days)	≤117	No statistically significant difference													
		>117	No statistically significant difference													
Cumulative Traffic, KESALs	Freeze Index (C°-Days)	≤117	No statistically significant difference													
		>117	9	676	4297	674	89	59	2663	24,191	6063	49	-1987	-3	0	132

As these results contradict previous experience, some of the parameters evaluated were blocked by freeze index and re-analyzed, similar to those for interstate pavements. Results of this analysis are included in Table 24.

When asphalt viscosity is blocked by freeze index, the good group has significantly lower viscosity values, which supports previous experience. However, the asphalt concrete thickness of the good group, when blocked by freeze index, is still significantly lower than that for the poor group. Similarly, the asphalt concrete resilient moduli when blocked by freeze index are insignificant between both data sets.

The other important item to note is that the cumulative traffic when blocked by freeze index is significantly less in the good group data set. From the previous analysis of rutting and fatigue cracking, the thicker asphalt concrete sections were associated with the heavier traffic levels. As a result, the asphalt concrete thickness analysis may be influenced by traffic, simply because there were significantly greater amounts of traffic in the poor group compared with the good group.

Climatic Features. The environmental variables that were found to be statistically different between the two groups are annual number of days with freezing temperature, annual freeze-thaw cycles, freeze index, annual number of days with temperature greater than 32°C, annual average maximum temperature, and annual average minimum temperature.

As would be expected, the good performers were, on average, from a warmer climate; however, it was one that experienced more precipitation. This is corroborated by Table 25, which shows that the no freeze zones have a higher percentage of observations of good pavements than the freeze zones. For the wet zones, wet-no freeze had many more good pavements than poor, but the wet-freeze zone did not.

Type of Environment. The comparison of transverse cracking performance in different environmental zones is illustrated in Figure 15. It can be seen from the figure that the freeze zones have a higher percentage of observations with less crack spacing (i.e., more transverse cracking) than those in the no-freeze zones.

Traffic Features. The average annual and cumulative KESALs were much higher for the poor group than for the good group. This is interesting as it may indicate that traffic may contribute to the occurrence of transverse cracking. This cannot be stated with confidence, however, as it is apparent that the pavements in the poor group are, on average, from a much colder climate. The following comments are made about these results:

- Within the environmental variables, the temperatures had higher relative significance than the moisture and precipitation variables. This is, of course, consistent with expectations.

- More traffic was associated with the poorly performing observations in transverse cracking. Although this was true for the population of pavements included in the study, it may or may not indicate that traffic makes a significant contribution to transverse cracking.

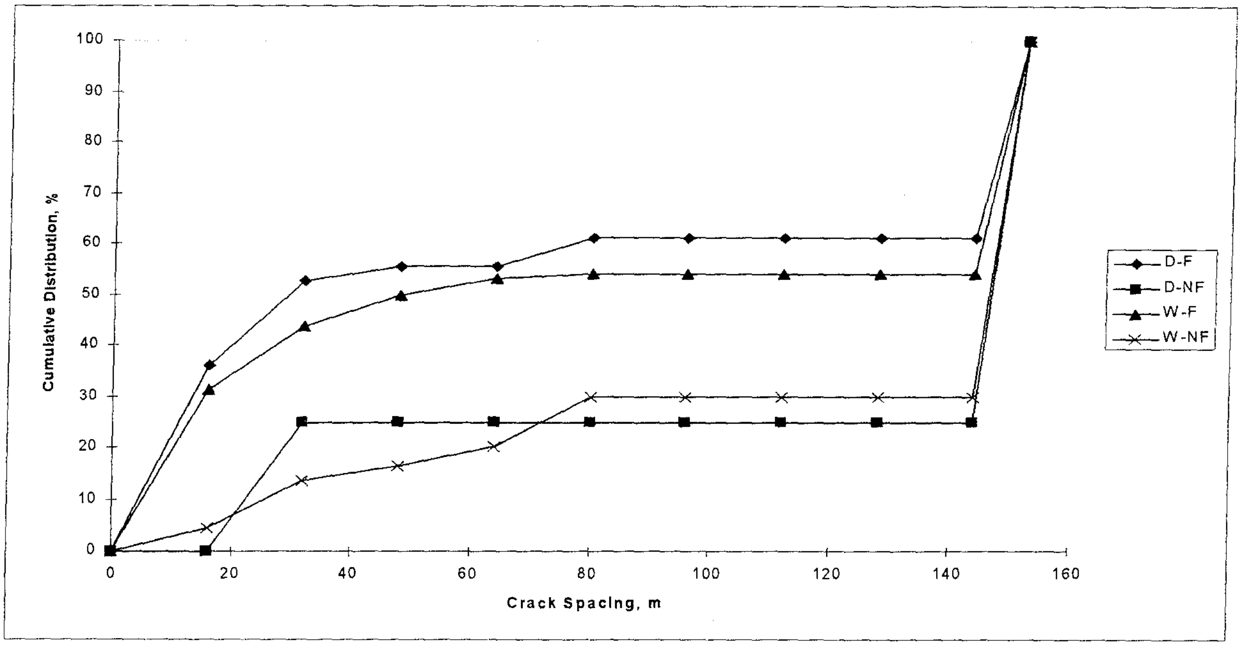


Figure 15. Cumulative Distribution of Crack Spacing Comparing Non-Interstate Pavements in Different Environmental Zones.

Table 25. Comparison of Transverse Cracking Performance of Non-Interstate Pavements for Different Environmental Zones.

Performance	Dry-Freeze		Dry-No Freeze		Wet-Freeze		Wet-No Freeze	
	No. of Obser-vations in Zone	Percentage in Zone	No. of Obser-vations in Zone	Percentage in Zone	No. of Obser-vations in Zone	Percentage in Zone	No. of Obser-vations in Zone	Percentage in Zone
Good	23	64	8	100	66	69	169	96
Poor	13	36	0	0	30	31	8	4
Total	36	100	8	100	96	100	177	100

- The group of pavements with unbound granular bases included a higher percentage of good performing sections than did the sections with cement-treated bases. The mean transverse crack spacing was 59 m for the pavements with cement-treated bases and 103 m for the ones without treated bases. The mean rate of deterioration was 4.5 cracks/year for the sections with cement-treated bases, and 1.2 cracks/year for the sections without treated bases.

__AC Features.__ The AC layer variables that showed significant differences were indirect tensile strength, instantaneous and total average resilient modulus, structural number, AC thickness, water absorption of aggregate in the mix, and percentage of aggregate passing the 0.425-mm sieve size. The results show that the AC layer for the good group had a higher tensile strength and resilient modulus than the AC layer for the poor group. In addition, the water absorption of the aggregate in the AC mix of the pavements in the good group was higher than that in the poor group. The percentage passing the 0.425-mm sieve size was higher for the good group.

Both the structural number for the pavement and the asphalt layer thickness were smaller for the good group than for the poor group. This is a surprising result as a greater AC thickness is usually expected to decrease transverse cracking. However, the very substantial difference in climate (mean freeze index of 1487 for the poor group vs. only 315 for good group) probably had a greater effect than the AC thickness. This probably also reflects the tendency to build thicker AC layers in colder climates.

Granular Base Features. The variables found to be significantly different for the granular base were the Atterberg limits, the moisture variables, and the percentage of granular base material passing the 0.425-mm sieve size. These variables showed that the good group had more moisture than the poor group. In addition, the Atterberg limits for the good group were higher than that for the poor group. However, the values of the Atterberg limits for both groups were low. This does not seem to indicate much difference between the good and poor groups for the granular base. In addition, the percentage passing the 0.425-mm sieve size was higher for the good group.

Table 26 compares the performances of pavements with unbound granular bases and pavements with cement-treated bases (CTB). The pavements with unbound granular bases appear to experience less transverse cracking. This comparison is shown graphically in Figure 16, and clearly shows that there is a higher percentage of observations with less crack spacing (i.e., more transverse cracking) in the CTB group than there is for the unbound base group.

Table 26. Comparison of Transverse Cracking Performance of Non-Interstate Pavements for Cement-Treated and Unbound Bases.

Performance	CTB		Unbound	
	No. of Sections	Percentage in Treatment Group	No. of Sections	Percentage in Treatment Group
Good	24	47	267	82
Poor	27	53	57	18
Total	51	100	324	100

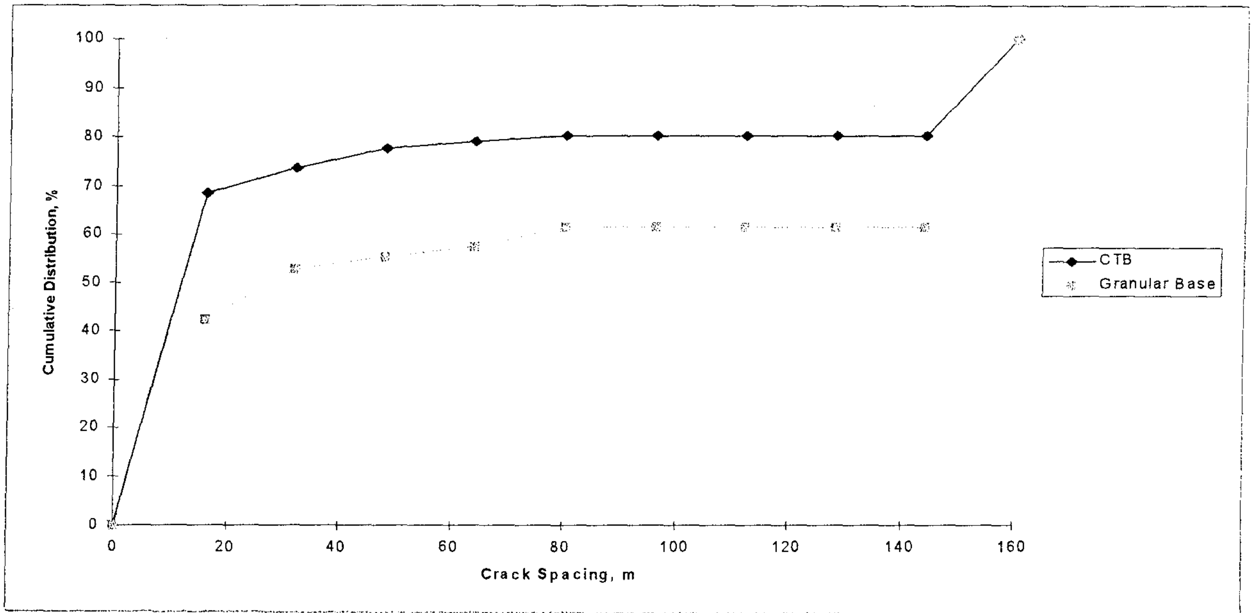


Figure 16. Cumulative Distribution of Crack Spacing Comparing Non-Interstate Pavements With CTB and Unbound Base.

Subgrade Soil Features. Subgrade material for the good group had more fines and more moisture. However, the value of the seventh sensor of the FWD data was less for the good group than for the poor group. This was an indication of a stronger subgrade as mentioned above. The presence of more moisture in the subgrade could be attributed to the presence of more fines in the soil.

Overlaid Pavements

The variables found to have significant differences for overlaid pavements appear in Table 27, and some of the climatic parameters are consistent with previous experience. However, almost none of the asphalt concrete parameters were found to be significant between both data sets for the overlaid pavements. As a result, asphalt viscosity, asphalt thickness, resilient modulus indirect tensile strength, asphalt concrete bulk specific gravity and cumulative traffic were blocked by freeze index to determine if different results would be obtained. Although all of the important material properties of the asphalt concrete were blocked by freeze index, no statistically significant difference was found between both data sets. Therefore, the additional analysis did not change any of the initial results.

Climatic Features. The environmental variables show that, in general, the good group has mean values that pertain to a warmer climate than the poor group.

Structural Response Features. The value of the base curvature index (BCI) was higher for the poor group than for the good group. This was an indication of a stiffer granular base for the good group. In addition, the values of the first three FWD sensors were lower for the good group than

Table 27. Results of t-Tests for Overlays for Transverse Cracking.

Characteristic Checked	Good Group					Poor Group					Diff. Means*	t-value*	p-value*	Degrees of Freedom
	Min.	Mean	Max.	Std. Dev.	N	Min.	Mean	Max.	Std. Dev.	N				
Average Max. Temperature, °C	8	23	31	6	21	6	14	20	6	4	9	2.928	0.0076	23
Average Min. Temperature, °C	-4	10	17	6	21	-2	3	6	4	4	7	2.260	0.0336	23
Average Temperature Range, °C	12	13	18	2	21	8	11	15	3	4	2	2.509	0.0196	23
Number of Days > 32°C	2	69	167	44	31	0	21	53	24	4	48	2.136	0.0402	33
Number of Freeze-Thaw Cycles	4	55	165	45	31	93	104	112	9	4	-49	-2.180	0.0365	33
AC Aggregate Gradation, % Passing 2.00-mm Sieve	31	39	46	5	34	37	46	71	12	7	-7	-3.208	0.0027	39
Coarse Sand in Subgrade, %	1	9	19	5	37	2	14	28	10	7	-5	-2.212	0.0324	42
Subgrade Maximum Density, kg/m^3	1562	1853	2243	139	35	1693	1981	2237	170	7	-128	-2.607	0.0128	40
Subgrade Optimum Moisture Content, %	6	13	22	3	35	6	10	17	4	7	3	2.549	0.0148	40
Sensor 1 Deflection (FWD Testing), μ	89	216	463	112	44	185	312	681	155	9	-96	-2.270	0.0274	51
Sensor 2 Deflection (FWD Testing), μ	67	169	368	87	44	155	246	493	112	9	-77	-2.393	0.0204	51
Sensor 3 Deflection (FWD Testing), μ	61	142	304	70	44	127	202	378	84	9	-60	-2.345	0.0230	51
Base Curvature Index, μ	6	26	68	20	44	16	43	115	30	9	-17	-2.596	0.0123	51

*Legend:

Diff. Means = Mean of good group minus mean of poor group.

t-value = Student's t statistic.

p-value = Probability that another random sample would provide evidence (as strong as the one reported) that the two means are different when the population means are actually not different (significance level, $\alpha = 0.05$).

for the poor group. This was an indication of an overall stiffer pavement for the good group. While the differences in thicknesses of the layers did not prove to be significant, the overall stiffer structures for the good group should result in less bending under wheel loads.

As reflective cracking through an overlay is believed to depend on both thermal and wheel-load stresses, the reduced bending is believed to have contributed to the occurrence of fewer transverse and reflection cracks for the good group.

Subgrade Soil Features. The most important difference noted for the subgrade was that there is significantly more coarse sand for the poor group. As a result, the optimum moisture content was lower for the poor group. The maximum dry density was also slightly higher for the poor group.

AC Features. The only variable found to be statistically different for the AC was aggregate passing the 2.00-mm sieve, for which the mean amount for the poor group was somewhat higher. There was no significant difference found for granular base variables.

Summary of Results of t-Tests

The variables with statistical differences are shown in Table 28 for the three pavement types. The letter P or G indicates a statistical difference for that variable. The letter P means that the poor group had the higher mean of the variable, while the letter G means that the good group had the higher mean of the variable.

Variables found to be significant for the early sensitivity analyses are also included in Table 28. An "I" indicates that the crack spacing increases as the magnitude of the variable increases. A "D" indicates a decrease in crack spacing as the variable increases.

Age would be expected to be important, considering that it was found to be the most significant variable during the sensitivity analyses. The reason that it was not found to be significant in this study was that the mean ages were almost identical (13.4 vs. 13.9 years for the interstate pavements and 11.7 vs. 11.9 years for the non-interstate pavements). Differences between mean asphalt viscosities were similarly not sufficient to be significant.

Subgrade material passing the 0.075-mm sieve was found to be significant for the sensitivity analyses, but the hydrometer analysis sizes were not included in those analyses. It can be seen that the differences between the mean subgrade material smaller than 0.02 mm and 0.002 mm were found to be significant.

As discussed previously in this chapter, mean freeze indices for the interstate pavements did vary substantially, but the variability was so great that the t-tests did not indicate them to be significant. For the non-interstate pavements, the differences in the mean number of annual freeze-thaw cycles were found to be significant, which also implies a colder climate for the poor group.

Table 28. Summary of Results From t-Test Comparisons for Transverse Cracking (Crack Spacing).

Design Feature and/or Site Condition	Characteristic	Interstate	Non-Interstate	Overlay	Significant From Early Analyses
Traffic Features	ESALs		P		I
Climatic Features	Annual Precipitation		G		I
	Freeze Index				I
	Days With Temp. >32°C		G		D
	Average Max. Temp.			G	
	Average Min. Temp.			G	
	Average Temp. Range			G	
	Number of Days > 32°C			G	
	Number of Freeze-Thaw Cycles			P	
	Annual Freeze-Thaw Cycles		P		I
	No. of Days With Freezing Temp.		P		
	Annual Average Min. Temp.		G		
Subgrade Features	Subgrade <0.075-mm Sieve				I
	Coarse Sand in Subgrade		P	P	
	Subgrade <0.02 and 0.002 mm		G		

Table 28. Summary of Results from t-Test Comparisons for Transverse Cracking (Crack Spacing) (Continued).

Design Feature and/or Site Condition	Characteristic	Interstate	Non-Interstate	Overlay	Significant From Early Analyses
Subgrade Features (Cont.)	Fine Sand in Subgrade		G		
Asphalt Concrete Features	AC Thickness	G	P		I
	Asphalt Viscosity		P		I
	AC Aggregate <4.75-mm Sieve				D
	AC Aggregate <0.425-mm Sieve		G		
	Water Absorption - AC Aggregate		G		
Granular Base Features	Base Thickness				D
	Base Compaction				I
	Atterberg Limits - Granular Base		G		
	Granular Base Aggregate <0.425-mm (#40)		G		
	Base Moisture Content		G		
Load-Response Features	Deflections (FWD)	P		P	
Surface Features	Age				D

It can be seen that other variables, for which values were greater for the good group of interstate pavements, indicate primarily that the subgrade and granular base had more fines.

RESULTS FROM SENSITIVITY ANALYSES

The procedures used for the sensitivity analyses for transverse cracking (Ref. 1) were essentially the same as described in Chapter 4 for rutting. However, there were not enough sections with transverse cracking available for some environmental zones to allow separate modeling. Therefore, the HMAC on granular base and the full-depth HMAC types of pavements were combined together in one database. The 12 variables found to be most significant for transverse cracking are listed below, in order of relative ranking, with the most significant variable at the top left and the least at the bottom right:

Age (-)	Asphalt Viscosity	Subgrade < 0.075-mm Sieve
Annual Precipitation	Base Compaction	ESALs
AC Thickness	Freeze Index	Annual Freeze-Thaw Cycles
Base Thickness (-)	Days With Temp. > 32°C (-)	HMAC Agg.< 4.75-mm Sieve (-)

Where a negative sign appears after the parameter, this means that an increase in the magnitude of the variable was generally found to result in a decrease in the transverse crack spacing, which means more transverse cracking. No negative sign indicates the opposite result from an increase in the magnitude of the variable. It should be noted that the finding that increases in freeze index or annual freeze-thaw cycles will increase crack spacing is very questionable, as is the finding that increases in the annual number of days with temperatures higher than 32°C will decrease crack spacing. The findings from the t-tests (described previously in this chapter) do not support these findings.

SUMMARY AND CONCLUSIONS ABOUT TRANSVERSE CRACKING

Since the t-tests do not draw directly on pavement performance, the conclusions from the t-tests need to be buttressed with results from other studies. Only 3 of the 12 characteristics found in the early analyses to be significant to the occurrence of transverse cracking are controllable by highway engineers. Comments on these three characteristics follow:

- Increasing AC thickness is believed to reduce transverse cracking, but neither the sensitivity analyses nor the t-test comparisons clearly confirms this. Out of five sensitivity analyses on models developed during the early analyses, three found that increasing AC thickness decreased transverse cracking and two found that it increased transverse cracking. For the t-tests, the AC thickness was greatest for the good group for interstate and overlaid pavements. The AC thickness for the non-interstate pavements was greatest for the poor group (175 mm vs. 134 mm).

- Increasing asphalt viscosity was found in the sensitivity analyses to increase transverse crack spacing, which may or may not be the case for individual pavements. This may depend on the relative effects of increasing tensile strength versus the increased brittleness.

- Increasing base compaction was found during the early analyses in one environmental region to decrease transverse cracking. The relative compaction levels for the t-tests were not sufficiently different to be considered very significant. For the interstate pavements, the base compaction was 98.6 percent for the good group and 96.6 percent for the poor group. For the non-interstate pavements, the base compaction was 98.1 percent for the poor group and 96.0 percent for the good group.

- Overall stiffness of the pavement structure appears for overlaid pavements to affect the occurrence of reflective cracking. A stiffer structure is believed to reduce bending under wheel loads, thus diminishing their contribution to the cracking.

While the t-test comparisons only indicate variables that are statistically different between the two groups and do not indicate significance in the occurrence of transverse cracking directly, the identification of many of the same variables to be significant during the early analyses tends to indicate that those variables are indeed significant.

CHAPTER 7. ROUGHNESS

Roughness is a measure of ride comfort and quality, expressed as the International Roughness Index (IRI), and is a very important performance measure, because user costs increase with an increase in the roughness of a pavement. Therefore, in order to reduce user costs and increase the return from the tax payers' money, as well as to offer good ride quality for the public, highway agencies are concerned with minimizing roughness on highway networks. Factors that cause roughness in pavements include pavement structure and construction, subgrade characteristics, the amount of traffic, environmental factors, and others.

This chapter presents the results of three studies using LTPP data that were aimed at understanding the occurrence of roughness in pavements. The first study was the sensitivity analyses conducted under the SHRP P-20 project (Ref. 1). The second study is the current t-test studies, which provided limited results. Table 29 shows the limited number of test sections with IRI values occurring in the poor group. As shown, there are so few test sections that no statements can be made regarding common characteristics between the good and poorly performing data sets based on roughness. The third study was recently completed by Soil and Materials Engineers, Inc. (SME) (Ref. 5).

RESULTS FROM SENSITIVITY ANALYSES

The procedures used for the sensitivity analyses of roughness (Ref. 1) were essentially the same as described in Chapter 4 for rutting. A total of six models were developed for change in roughness and the sensitivity analyses conducted. The 12 variables found to be most significant for roughness are listed below in order of relative ranking, with the most significant variable at the top left and the least at the bottom right:

KESALs	Base Thickness (-)	Base Compaction
Asphalt Viscosity	Freeze Index	Annual Precipitation
Days With Temp >37°C (-)	Subgrade <0.075 mm	Daily Temp. Range
AC Thickness (-)	Air Voids in AC	Annual No. of Freeze-Thaw Cycles

Where a negative sign appears after the parameter, this means that an increase in the magnitude of the variable was found to result in a decrease in the roughness. No negative sign indicates the opposite result from an increase in the magnitude of the variable.

RESULTS FROM MEAN COMPARISONS

There was such an imbalance between good performing pavements and poorly performing pavements that t-tests could not reasonably be conducted. Most of the observations reflected performance within the good or normal zones (see Figure 8), so there were too few observations with which to compare the poor group. Rather than attempting t-tests, the means of the variables found to be significant in the early sensitivity analyses (Ref. 1) for the two groups were simply compared. These results are discussed below.

Table 29. Test Sections With Poor Performance Characteristics, as Defined by Roughness for Interstate, Non-Interstate, and Overlaid Pavements.

Section No.	Environmental Region	Structure
IRI - Interstate		
041002	D-NF	10.4" AC directly on silty gravel with sand SG
041003	D-NF	13.1" AC, 6" GB, clayey sand with gravel SG
891125	W-F	5.2" AC, 37.8" GB, well-graded sand with LT SG
891127	W-F	4.9" AC, 39.8" GB, silty sand with gravel SG
IRI - Non-Interstate		
341030	W-F	12.2" AC, 30.2" GB, poorly graded sand with silt and gravel SG
404088	W-F	12.2" AC, 6.1" Lime TB, sandy lean clay SG
481130	W-NF	2.7" AC, 17.9" GB, 8" lime TSB, fat clay with sand SG
481178	W-NF	8.5" AC, 10.8" GB, 4.5" Lime TSB, sandy lean clay SG
483679	W-NF	1.6" AC, 8.4" cement TB, sandy lean clay SG
483835		8.7" AC, 14" GB, 6" lime TSB, silty sand SG
811804	D-F	3.5" AC, 22.6" GB, lean clay SG
IRI - Overlays		
021004	W-F	5.4" AC, 27" GB, poorly graded gravel with silt sand SG
111400	W-F	16.7" AC, 12" GB, clayey gravel with sand SG
421618	W-F	7.9" AC, 9.6" GB, sandy lean clay with gravel
486079	D-F	10" AC, 5" GB, silty sand SG
511423	W-F	7.5" AC, 8.5" GB, 1" cement TSB, clayey sand with gravel SG
531007	D-F	6.4" AC, 13" GB, silt with sand SG
906410	D-F	6.6" AC, 9.4" GB, sandy silt SG
906412	D-F	8.4" AC, 9.8" GB, silty sand SG

1 in = 25.4 mm

- In examining these variables, only cursory examination of the means was conducted. As mentioned above, the unevenly large number of good observations compared with poor observations prevents the drawing of meaningful conclusions from rigorous statistical tests.

- For the interstate pavements, the good sections compared with the poor sections had the following characteristics:

  - A higher number of days with temperatures above 32°C.
  - A larger number of freeze-thaw cycles.
  - A lower freeze index.
  - A thinner base thickness.
  - More subgrade material passing the 0.075 mm sieve size.

  In addition to the above comparisons, Figure 17 shows the cumulative distribution of the IRI for the interstate pavements in different environmental zones. The figure shows that the wet-no freeze zone has the highest percentage of observations with lower IRI values than the other environmental zones for most of the range of IRI values. On the other hand, the wet-freeze zone has the highest IRI values for the same proportions of observations in the other zones.

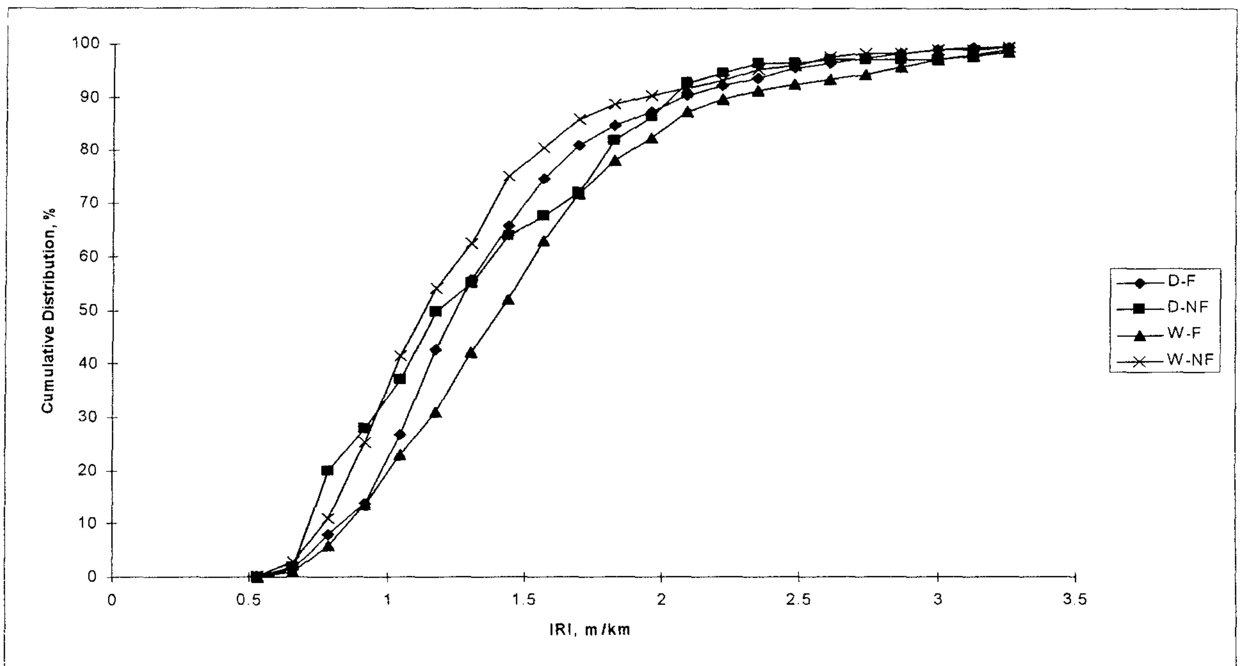


Figure 17. Cumulative Distribution of IRI Comparing Interstate Pavements in Different Environmental Zones.

- For the non-interstate pavements, the good sections compared with the poor sections had the following characteristics:

  - A thinner base thickness.
  - Less subgrade material passing the 0.075 mm sieve size.
  - Higher traffic levels.

- For the overlaid pavements, the good sections compared with the poor sections had the following characteristics:

  - More annual precipitation.
  - A higher number of days with temperatures above 32°C.
  - A larger number of freeze-thaw cycles.
  - A thinner AC layer.
  - A thicker base.

The values of different distresses (fatigue cracking, transverse cracking, and rutting) were also studied for the observations found to be poor with regard to IRI. These studies indicate that the poorly performing sections with regard to roughness had high levels of transverse cracking and low levels of fatigue cracking. There were not enough data to draw conclusions about rut depth.

RESULTS OF THE STUDY BY SOIL AND MATERIALS ENGINEERS, INC.

A study was conducted by Soil and Materials Engineers, Inc. (SME) (Ref. 5) to investigate the development of pavement roughness. One objective of this study was to develop roughness models using data from GPS test sections. The research conducted to achieve this objective and its results are summarized herein to provide insight into the performance of pavement sections in terms of roughness. For all the analyses described in this section, IRI refers to the average of the IRI of the left and right wheelpaths. For relevance to AC pavements, only the results of the study done on the sections in the GPS-1 and GPS-2 experiments are reported here for the non-overlaid pavements. For the overlaid pavements, only the results of the study on the sections in the GPS-6 experiments are reported.

General Trends in IRI Development

Changes in IRI over time were investigated first. In this investigation, IRI was plotted vs. age for individual test sections and the resulting trends were observed. It was noted that IRI increased or was stable over time for most test sections, but decreased over time for others. Linear regression was performed on the observed data to determine the sections that showed positive and negative IRI growth trends. This was done by observing the sign of the correlation coefficients and the slope of the linear fit.

Observing the performance trends for GPS-1 and GPS-2 test sections that showed an increase in IRI over time indicated an exponential IRI growth trend. The performance trend was then modeled using non-linear regression. For the overlaid pavements, linear regression was performed on the observed IRI vs. age of the pavement and the slope of the regression equations were related to the parameters that could affect the increase in IRI.

Modeling of IRI Over Time

From observing the performance trends, the exponential equation used for modeling IRI over time for GPS-1 and GPS-2 pavements was of the form:

$$IRI(t) = IRI_o e^{r(t)\,t} \tag{1}$$

where,

IRI_0	=	estimated initial IRI (after traffic loading)
	=	f(structural and subgrade properties)
$r(t)$	=	growth rate function
	=	f(climate, traffic, subgrade, pavement layer properties)
t	=	time in years

For GPS-1, the best models were obtained when the data were classified by environmental region and by the percentage of subgrade material passing the 0.075 mm sieve. For the dry zones, no subdivision by subgrade material was done. However, for the wet zones, the data were divided into three sub-data sets according to the percentage of the subgrade material passing the 0.075 mm sieve (greater than 50 percent, between 20 and 50 percent, and less than 20 percent). Therefore, eight data sets were developed (three for each of two wet zones and one for each of two dry zones) and a separate model was developed for each.

For GPS-2, the models were developed only for test sections having either bases of cement aggregate mixture, HMAC, asphalt-treated aggregate, soil cement, or lean concrete. No division of the data according to environmental zone was made.

The experiment that is concerned with AC overlays over AC pavements is GPS-6. Therefore, only the results from the SME report that concern this experiment are related herein. Linear regression of IRI values vs. age was performed on individual sections. From the linear regression, the rate of increase of IRI, which is the slope of the fitted line, was related to the factors that could affect roughness. Attempts were made to analyze the data of the GPS-6B experiment; however, there were limited data with which to analyze changes in roughness over time. Consequently, the data from GPS-6B were not included in the analysis.

In relating the slope of the fitted line to the factors affecting roughness, two data sets were used. In one data set, all slopes were included. In the other set, only slopes that were greater than 0.03 m/km/year were included. In the first case, the most significant factor was the minimum surface modulus. In the second case, the structural number was the most significant variable.

Summary and Conclusions From the SME Studies

Models were developed to predict the increase of IRI with age. Only the results from the sensitivity analyses for models developed from GPS-1, GPS-2, and GPS-6 data are reported here. For the GPS-1 and GPS-2 groups, two parameters were predicted. One was the initial IRI value and the other was the roughness growth rate. The models were exponential in form. The sensitivities of the models to some factors that affect the increase in roughness were studied. The following are conclusions made by the authors of the SME report:

For the GPS-1 test sections, in the no-freeze zones and in the wet-freeze zones and having pavements on coarse-grained soils with high percentages of the subgrade material passing the 0.075 mm sieve, the significant factors were found to be the structural number and the thickness of the AC layer. For pavements on fine-grained soils, the performance in roughness was found to be highly correlated with the percentage of subgrade material passing the 0.075 mm (#200) sieve and with the Atterberg limits of the subgrade soil. Roughness was found to be strongly related to the number of days with temperatures above 32°C in the hot climates, and to the freeze index and freeze-thaw cycles in the cold climates. Pavements with thick AC layers and very thin bases were found to be more sensitive to subgrade and climate conditions than pavements with thicker bases. For wet-freeze environments and frost-susceptible subgrade soils, high overburden pressure appeared to be critical since it reduced frost heave effects.

For the GPS-2 pavements, there were indications that for lean concrete and cement-treated aggregate bases, higher subgrade moisture resulted in less roughness over time. In addition, for these two types of base treatments, higher IRI values appeared to be associated with greater base thicknesses. The soil cement bases, on the other hand, showed a decreasing IRI with thicker bases. There was no significance associated with traffic levels in the correlation analysis for the GPS-2 pavements. The study of the GPS-1 pavements indicated that the effects of traffic were only noticeable for very thin pavements or pavements with small structural numbers. The fact that the GPS-2 test sections are characterized by pavements with high structural numbers may be the cause of the insignificance of the traffic effects.

For the GPS-6B data, the results of the study indicated little effect of the roughness prior to the overlay on the roughness after overlay. Analysis of the rate of increase of IRI values with factors that affect the development of roughness was conducted on GPS-6A test sections. The rate of increase was determined from the slope of a linear fit of a regression model between IRI values and age for individual test sections. Linear models were then developed between the slope and some factors, but the resulting models showed low coefficients of determination and high standard errors.

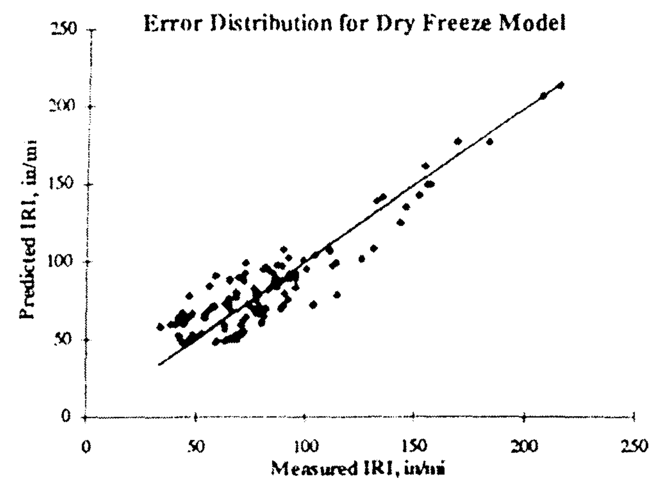
The above conclusions were made by the authors of the SME report. The following are comments made by the authors of this report on the SME study. The study provided roughness prediction models for GPS-1 and GPS-2 pavements, as well as models for the rate of increase of IRI values with some structural and environmental parameters. The plots presented in the SME report of the observed vs. predicted IRI values showed points clustering around the line of equality. Although no statistical measures were given as to the proximity of the points to the line of equality, visual inspection seems to indicate a close proximity (see Figure 18). If statistical verification of this proximity can be obtained, these models can be very useful tools for future sensitivity analyses and other purposes.

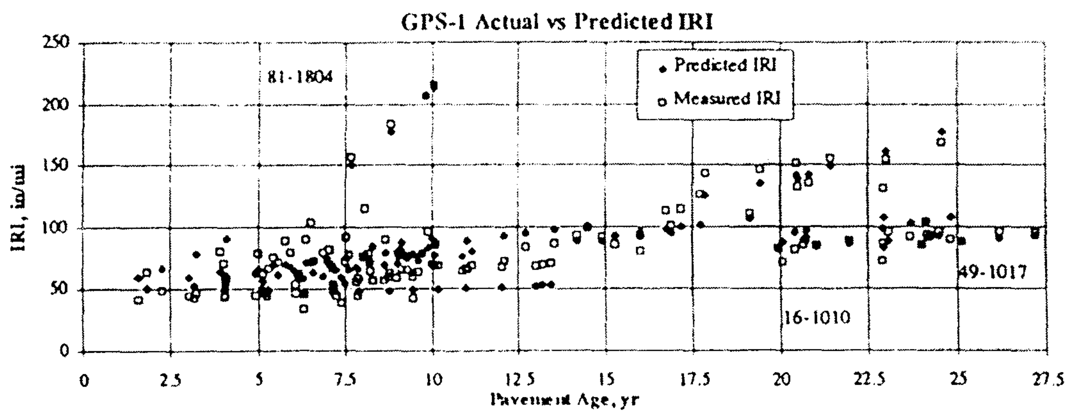
$$IRI(t) = IRI_0 e^{r_0 \frac{t^S}{T}}$$

$$IRI_0 = A(P200)^B + C(Po)^D + E(\%Sand)^F + G(\%ACinSN/_{100})^H$$

$$r_0 = \frac{I(KESAL/yr)^J}{K(SN)^L} + O(AnnPrecip)^P + Q(\frac{FZI * P200 * w\%}{Po})^R$$

A = 250.1471	F = 5.5503	K = 300	R = 1.5855
B = -0.0287	G = 203.8493	L = 4	S = 1.0952
C = -517.4179	H = 0.05983	O = 0.0006	T = 0.1879
D = -0.06407	I = 0.005	P = 0.6708	
E = -2.847E-10	J = 1.7	Q = 6.84E-09	





1 in/mi = 0.0158 m/km

Figure 18. IRI Model Developed for the GPS-1 Dry-Freeze Sections (from Ref. 5).

SUMMARY AND CONCLUSION

The variables found by the early sensitivity analyses to most significantly affect roughness appear in Table 30, along with the mean values for the poor and good groups for the three types of pavement. Of these variables, the ones that can be controlled by the SHAs are AC air voids, AC viscosity, AC thickness, and granular base thickness.

Table 30 also shows how changing the different variables affects roughness in different pavement structures and environmental zones. An "I" means that increasing the variable increases roughness. A "D" means that increasing the variable decreases roughness. It can be seen from Table 30 that the effects of a variable on roughness growth may vary for different climates and types of pavement.

For the study of good and poor pavements, the number of good observations was found to be much larger than the number of poor observations. Consequently, it was not possible to conduct this study using t-tests. However, observing such an enormous inclination of the data toward good performing test sections, it can be concluded that the expected level of roughness that defines poor performance is rarely exceeded (at least for the population of test sections in the LTPP). This can be seen by examining Figure 8, where the actual IRI data from the LTPP database were added to the curves delineating the boundaries between good, normal, and poorly performing pavement sections roughness. It can be seen that for all the pavement structure types, there are very few points with regard to the poor-normal boundary.

A summary of results from a research study conducted by SME was also included. The study was aimed at examining the behavior of roughness and modeling its initiation and development. Only the results concerning AC pavements were reported. The study examined the behavior of pavements in terms of roughness under different conditions of environment, traffic, and structural properties.

Table 31 lists the characteristics of AC pavement that were found from the early analyses (Ref. 1) and the SME studies (Ref. 5) to be significant to the "growth" of roughness. An I or a D in a column indicates that the characteristic (or variable) in that row is significant. An I in a column indicates that the analyses represented in that column found that increases in the variable will increase roughness. A D in the column indicates that increases in the variable will decrease roughness.

As can be seen from Table 31, there is no agreement on three of the variables, but much can be concluded from the findings that were in agreement and from others found to be significant by only one of the analyses. The following are the conclusions:

- Increasing traffic will generally result in additional roughness.
- Increasing AC thickness or the structural number may be expected to decrease the growth of roughness.

Table 30. Summary Results of Sensitivity Analyses and Study of Good and Poor Pavements for Roughness.

Variable	Results of Sensitivity Analyses (Ref. 1)						Mean Values of Variables in Good and Poor Groups					
	HMAC on ...						Interstate		Non-Interstate		Overlaid	
	Granular Base				CTB	Full Depth						
	W-NF	W-F	D-NF	D-F			GOOD	POOR	GOOD	POOR	GOOD	POOR
Avg. Temperature Range	I						24	20	24	22	24	21
No. of Days Temp. >32°C	I	D	D	I	I	D	36	29	38	29	33	22
Annual Freeze-Thaw Cycles	D						92	66	82	87	89	82
Air Voids, %	I	I		D	I		4.2	3.5	4.4	5.1	4.8	3.7
Base Compaction, %	D						99.0	99.3	95.0	98.0	94.8	97.2
Freezing Index		I		I	I	I	707	1796	705	83	1232	783
Subgrade <0.075 mm (#200), %			I		I	D	31	17	34	79	38	21
Total Precipitation, mm	I		I		D		785	967	891	1067	732	794
AC Viscosity at 60°C, poise	D	I	I	I			1548	Missing	1749	1564	1715	2062
AC Thickness, mm	D	I	D	D	D	D	222	164	146	163	208	308
Granular Base Thickness, mm	D	D	D	I	I		424	833	368	577	366	304
Annual KESALs	I	I	I	I	I	I	440	475	101	64	246	135
No. of Observations							221	6	735	12	209	14

Table 31. Summary of Variables Found To Be Significant to Roughness of AC Pavements.

Characteristic	SME Studies	Early Analyses
KESALs	I	I
Asphalt Viscosity		I
Days With Temp. >32°C	I	D
AC Thickness	D	D
Base Thickness	I	D
Freeze Index	I	I
Subgrade < 0.075 mm Sieve	I	I
Air Voids in AC		I
Base Compaction		I
Annual Precipitation	D	I
Daily Temp. Range		I
Annual No. of Freeze-Thaw Cycles	I	I
Atterberg Limits of Subgrade	I	
Structural No.	D	
High Overburden Pressure	D	

- Roughness growth will generally be greater in cold climates or where the subgrade is clay, e.g., in situations where differential volume change may be expected along the roadway.

CHAPTER 8. WHAT WORKS AND WHAT DOES NOT FOR AC PAVEMENTS

The research approach adopted aims at gleaning whatever is possible from analyses of LTPP data that have been conducted over the past 5 years. These results have been summarized at the end of each chapter for a specific distress. The approach in this chapter will be to further consolidate these results to reflect as well as possible which pavement characteristics will improve performance and which tend to decrease performance.

Table 32 concerns those variables that can be controlled by SHAs with regard to design and construction. As can be seen, only six of the apparently significant variables are controllable by SHA personnel. The "D" entries indicate a decrease in distress with an increase in the variable, and the "I" entries indicate an increase in distress. The question marks indicate that the effects are uncertain or variable. The following general comments are offered:

- Using thicker asphalt concrete layers or increasing the overall pavement structural stiffness may be expected to decrease rutting, fatigue cracking, and roughness, and would probably help decrease transverse cracking, assuming that the mixture design and construction are adequate.

- Increasing base thickness may be expected to decrease rutting, as long as the material properties and placement are appropriate. Effects on other distresses are unclear.

- Air voids must be controlled through mixture design and proper compaction. The message from the LTPP data is that the air voids after compaction by traffic are often too low, resulting in deeper ruts.

- There are indications from studies of fatigue cracking and transverse cracking that use of high-viscosity asphalt will increase these distresses. This deserves more study before acceptance for all four distress types. From the rutting analysis, viscosity was not found to be significant between both data groups. However, this may simply be a result of using softer asphalts in the colder climates.

- It has generally been believed from past experience that increasing compaction for granular base materials was generally good, as long as sufficient drainage was not precluded. It is not clear why increased compaction would result in increased roughness, or increases in any of the distresses. This also deserves more study before acceptance. The increased densities noted in Table 30 could be due to traffic densification prior to the collection of the initial data and may not be indicative of the as-constructed densities.

Table 33 concerns those variables that cannot be controlled by SHA personnel, but should be considered in design. The convention for entries is the same as for Table 31.

Table 32. Effects of Variables SHA Personnel Can Control.

Characteristic	Distress Type			
	Rutting	Fatigue Cracking	Transverse Cracking	Roughness
AC Thickness	D	D	D	D
Base Thickness	D	?	?	?
Air Voids in AC	*	*	*	*
Asphalt Viscosity	I	I	D	I
Base Compaction	?	?	?	I
Structural Number	D	D	?	D

* Only initial air voids are controllable and data available are for air voids after consolidation by traffic.

Table 33. Effects of Variables To Be Considered in Design.

Characteristic	Distress Type			
	Rutting	Fatigue Cracking	Transverse Cracking	Roughness
Expected ESALs	I	I	I	I
Annual No. of Days With Temp. > 32°C	I	D	D	?
Freeze Index	?	?	I	I
Annual No. of Freeze-Thaw Cycles	?	?	I	I
Annual Precipitation	I	I	I	?
Subgrade < 0.075 mm Sieve	?	?	?	I
Annual Days With Freezing Temp.	D	?	I	?
Age	?	?	I	?

The following are comments on uncontrollable factors to be considered in design:

- Increasing ESALs creates more distress, even for transverse and reflection cracking.
- High temperatures may be expected to encourage rutting, but cracking appears to be diminished in warm climates.

- Colder climates appear to experience more transverse cracking and appear to offer more potential for the growth of roughness.

- Wet climates appear to encourage rutting, fatigue cracking, transverse cracking, and perhaps roughness.

- The effects of clay subgrades are not clear (and may be variable) for rutting, fatigue cracking, and transverse cracking, but may be expected to increase the potential for roughness. Most of the pavements in the good groups for the t-tests had more fines in the subgrade than those in the poor groups. This is probably due to the fact that the cohesion from the clay fraction can offer substantial stiffness to the soil mass, unless it becomes wet.

- Age was found in the early sensitivity analyses to be the most significant factor for transverse cracking. This is certainly partially the result of the accumulation of freezes, thaws, and ESALs as age increases.

It must be recognized that analysis of the LTPP data will be an ongoing process for some years, and that the results will expand and become more specific as the process continues. While most of the results only tend to corroborate what the highway community already felt they knew from experience or other studies, this is valuable and to be expected. Other results from these studies are not so well known and identify new areas to be investigated.

The objective of this study was to document, on an expedited basis, what the LTPP data could tell us now and to report these results so that SHA design and construction personnel could put them into practice. The authors believe that these results will prove to be useful, but plan to continue to study the data to provide more specific knowledge based on more detailed analyses.

CHAPTER 9. SUMMARY AND RECOMMENDATIONS FOR CONTINUED RESEARCH

The analyses reported in this document were intended to study the LTPP data and report what could be gleaned on an expedited basis and reported to the highway community. This included previous studies. There are two very important observations made from this study. Both of these observations are listed below.

- Many of the parameters are interrelated and separating individual properties without considering the effects of other design features and parameters can lead to improper conclusions. This was clearly demonstrated for some of the apparent discrepancies noted in analyzing the two data groups. Once some of these parameters were blocked by specific features, then many of the results did concur with previous experience.

- More importantly, it should be pointed out and understood that only about 10 percent of the test sections have poor performance characteristics, as defined by rutting, fatigue cracking, and transverse cracking observations. For rutting, less than 2 percent of the test sections have poor performance characteristics. This disparity or imbalance in the number of points within each group may be too large to adequately identify differences in the characteristics of good and poor performing pavements. Thus, the results presented and reported in this document primarily should be used for checking the adequacy of the data without conducting additional detailed analyses of the data sets.

This study used all available LTPP data and results from other reports to focus on characteristics of pavements that have a significant impact on the occurrence of the four most common AC pavement distresses. The next logical step will be to establish the relative significance of these variables to the occurrence of distresses, so that designers can make informed decisions. The most obvious decisions would be the selection of materials and thicknesses for the AC and base layers; whether the base should be treated; and, if so, with what and how thick should it be?

These decisions will need to be made in terms of their impact on the various distress types, costs, and in consideration of the environment in which the pavement must function. Other questions to be answered are: What is the impact of the expected traffic? What impacts do the environmental characteristics have on the various distress types to be considered? How do these variables interact? These are questions that are usually answered by conducting sensitivity analyses.

Other studies of the data are expected to contribute to identification and understanding of the various mechanisms that lead to pavement deterioration. The mechanisms will include those leading to consolidation and permanent deformation, fracture mechanisms for both fatigue and transverse cracking, and a number of mechanisms that interact together to cause the growth of roughness.

After detailed studies of the data and the mechanisms involved in formation of distress, component models for individual distresses will need to be selected and/or developed. These component models can then be improved and revised through iterative testing against the measured data from LTPP.

The long-term objective will be the integration of the distress models into an integrated model to be used for distress predictions and design.

REFERENCES

1. Simpson, A.L.; Rauhut, J.B.; Jordahl, P.R.; Owusu-Antwi, E., Darter, M.I.; Riaz, A.; Pendleton, O.J.; Lee, Y.H., *Sensitivity Analyses for Selected Pavement Distress*, Report No. SHRP-P-393, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

2. Simpson, A.L. and Rauhut, J.B., *Rutting Trends in HMAC Pavements*, Unpublished Technical Report for the Federal Highway Administration, June 1996.

3. *JMP Statistics and Graphics Guide, Version 3.1*, SAS Institute, Inc., Cary, N.C., 1995.

4. Rosner, B., *Fundamentals of Biostatistics*, PWS-Kent Publishing Company, Boston, MA, 1990.

5. Perara, R.W., Byrum, C., and Kohn, S.D., *Study to Investigate the Development Pavement Roughness*, Draft Report, FHWA Contract No. DTFH61-95-C-00124, Soil and Materials Engineers, Inc., Plymouth, MI, 1997.