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16. Abstract

This document presents the results of a study to develop and test distress and performance prediction models for rigid pavements (continuously reinforced concrete, jointed reinforced concrete, and jointed plain concrete pavements) in Texas. These models were developed for the Texas Department of Transportation (TxDOT) for possible incorporation into their Texas Pavement Management Information System (PMIS). Data for testing the models were obtained from databases maintained by TxDOT and the Center for Transportation Research (CTR) at The University of Texas at Austin. The database maintained by TxDOT is part of the Department's Pavement Evaluation System (PES). Additional maintenance and rehabilitation (M&R) data were obtained from TxDOT district offices.

The modeling process consisted of first identifying the prevalent distress manifestations for rigid pavements in Texas. The available data sources were then studied to determine whether data were available to test models for the prevalent distress manifestations identified. A survey was conducted to collect M&R data from TxDOT district offices. These M&R data were merged with the PES condition evaluation data in order to separate the condition data into M&R categories. Four M&R categories were defined: preventive, light, moderate, and heavy. A study was also performed to determine the compatibility between the PES and CTR databases.

Condition data from the PES and CTR databases were analyzed using the statistical analysis software, SAS. Scatter charts of distress levels versus pavement age were plotted to identify any trends in distress level with pavement age. Distress data from the CTR database for non-overlaid CRCP sections displayed little variance and a reasonable trend with pavement age. Hence the prediction models developed using these data are reliable and robust. The data available for asphalt-overlaid CRCP and JCP sections, and for non-overlaid JCP sections from the CTR and PES databases, were sparse and less detailed. Except for the non-overlaid JCP data, the remaining data showed no definite correlation between distress level and pavement age. Therefore, the models developed for overlaid CRCP and JCP sections, and for non-overlaid JCP sections, are less reliable.

Although the models presented in this study make only a small contribution to network-level pavement management, they do serve as a starting point for further development by helping to identify data requirements for developing future statistically significant models.

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by

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Research Report 1908-1

Research Project 7-1908

Texas Pavement Management Information System

conducted for the

Texas Department of Transportation

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

August 1993

IMPLEMENTATION STATEMENT

The preliminary prediction models developed in this research study can be used on an interim basis in the Texas Pavement Management Information System (PMIS). However, because they are conceptual models, they should be reviewed and updated as soon as adequate data become available to develop more robust models.

Prepared in cooperation with the Texas Department of Transportation

DISCLAIMERS

W. R. Hudson, P.E. (Texas No. 16821)
Research Supervisor

PREFACE

This is the first report which discusses the development of preliminary distress and performance prediction models for the Texas Pavement Management Information System (PMIS). This report focuses on prediction models for rigid pavements in Texas. Data collection, analysis procedures, and possible conclusions and recommendations are discussed in detail.

This first report deals mainly with the analysis of pavement condition data currently available in databases maintained by the Texas Department of Transportation (TxDOT) and the Center for Transportation Research (CTR) at The University of Texas at Austin. The TxDOT database is part of the Department's Pavement Evaluation System (PES).

The authors would like to extend their appreciation to all those who helped in this study. The assistance of Dr. Virgil L. Anderson, in the form of his expert advice throughout the project, is gratefully acknowledged. Special thanks also go to Athar Saeed and Joseph Leidy, graduate research assistants, for their help with data processing. Thanks are extended to TxDOT personnel at the district offices for their cooperation in furnishing historical maintenance data, and to Patricia Andrews of the TxDOT Maintenance and Operations Division.

ABSTRACT

This document presents the results of a study to develop and test distress and performance prediction models for rigid pavements (continuously reinforced concrete, jointed reinforced concrete, and jointed plain concrete pavements) in Texas. These models were developed for the Texas Department of Transportation (TxDOT) for possible incorporation into their Texas Pavement Management Information System (PMIS). Data for testing the models were obtained from databases maintained by TxDOT and the Center for Transportation Research (CTR) at The University of Texas at Austin. The database maintained by TxDOT is part of the Department's Pavement Evaluation System (PES). Additional maintenance and rehabilitation (M&R) data were obtained from TxDOT district offices.

The modeling process consisted of first identifying the prevalent distress manifestations for rigid pavements in Texas. The available data sources were then studied to determine whether data were available to test models for the prevalent distress manifestations identified. A survey was conducted to collect M&R data from TxDOT district offices. These M&R data were merged with the PES condition evaluation data in order to separate the condition data into M&R categories. Four M&R categories were defined: preventive, light, moderate, and heavy. A study was also performed to determine the compatibility between the PES and CTR databases.

Condition data from the PES and CTR databases were analyzed using the statistical analysis software, SAS. Scatter charts of distress levels versus pavement age were plotted to identify any trends in distress level with pavement age. Distress data from the CTR database for non-overlaid CRCP sections displayed little variance and a reasonable trend with pavement age. Hence the prediction models developed using those data are reliable and robust. The data available for asphalt-overlaid CRCP and JCP sections, and for non-overlaid JCP sections from the CTR and PES databases, were sparse and less detailed. Except for the non-overlaid JCP data, the remaining data showed no definite correlation between distress level and pavement age. Therefore, the models developed for overlaid CRCP and JCP sections, and for non-overlaid JCP sections, are less reliable.

Although the models presented in this study make only a small contribution to network-level pavement management, they do serve as a starting point for further development by helping to identify data requirements for developing future statistically significant models.

Key words: rigid pavements, distress models, performance models, distress manifestations, maintenance and rehabilitation (M&R) activities, data requirements, Pavement Management Information System (PMIS), Pavement Evaluation System (PES)

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SUMMARY

This research effort and this resulting report serve to present preliminary distress and performance prediction curves for interim use in the Texas Pavement Management Information System (PMIS). These are conceptual models developed using pavement condition data stored in the PES and CTR databases.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The most challenging and pressing issue currently confronting highway engineers in the U.S. is the preservation of the nation's highway infrastructure.

In December 1991, the President signed the Intermodal Surface Transportation Efficiency Act of 1991, providing authorizations for highways, highway safety, and mass transportation for the next six years (Ref 1). Total funding of about $155 billion will be available in fiscal years 1992-1997.

The Interstate System will retain its separate identity and will receive separate funding as follows:

- Complete funding for Interstate construction ($7.2 billion).
- Interstate substitute highways projects ($960 million).
- An Interstate maintenance program, at a total of $17 billion, which finances projects to rehabilitate, restore, and resurface the Interstate System.

The act requires that each State receiving Federal aid develop, establish, and implement six management systems. One of these systems is a highway pavement management system. Non-implementation of the management system by fiscal year 1996 will result in a 10 percent penalty of apportioned highway funds.

In the State of Texas, the Texas Department of Transportation (TxDOT) maintains 76,509 centerline miles (123,179 centerline km) of highway pavements. Of this total, 74,315 miles (119,647 km) are asphalt concrete (ACC), 1,326 miles (2,135 km) are continuously reinforced portland cement concrete (CRCP), and 868 miles (1,397 km) are jointed portland cement (JCP) concrete pavements. For the fiscal years 1987 until 1992, $2.461 billion has been spent on maintaining this highway network (Ref 2).

It is clear that both the Federal and State governments invest enormous resources in maintaining the highway network. To obtain the optimum benefit from this investment, there should be an organized and systematic manner of allocating these resources. This—together with the issues of rising costs, reduced resources, increased utilization of the pavement network, and budget needs that far exceed revenues—can be addressed with the help of a well-planned and well-implemented pavement management system (PMS).

The Federal Highway Administration (FHWA) defines a PMS as "a set of tools or methods that (can) assist the decision makers in finding cost-effective strategies for providing, evaluating, and maintaining pavements in serviceable condition" (Ref 3). A simplistic description of a PMS is that it is a method which will help make cost-effective decisions relative to "what, where, and when": *What* treatment is most cost-effective, *where* treatments are needed, and *when* is the best time to program a treatment.

The selection of the most appropriate rehabilitation strategy for a given section of pavement should be made in an organized and systematic manner, taking into account all relevant parameters and their respective impacts. The decision maker must assess the effectiveness of each treatment in terms of the project conditions and costs involved. He, or she, must also know the life expectancy of the repair and understand the effects on pavement performance if the repair is not done. However, for the engineer addressing this issue, many unanswered questions remain about the effectiveness of the rehabilitation techniques and strategies (Ref 4).

Thus the most challenging aspect of selecting a rehabilitation strategy is trying to predict how the pavement will perform with and without maintenance and rehabilitation (M&R). Rehabilitation performance prediction is much more difficult than new-pavement performance prediction. This is due largely to the shortage of long-term performance data on rehabilitation projects.

Selecting a successful rehabilitation strategy therefore depends on being able to determine the present condition of the existing pavement, its performance without M&R, and its performance with M&R.

TxDOT manages its pavements with a methodology known as the Pavement Management Information System (PMIS), as discussed in *Managing Texas Pavements*, an introduction to TxDOT's Pavement Management System and Concepts, a report published by the Texas Department of Transportation, Division of Highway Design, Pavement Management Section (D-8PM), January, 1993.

1.2 OBJECTIVES

The objective of this study is to develop distress and performance models for rigid pavements in Texas. In the process of developing these models, data stored in the current PES and CTR databases were evaluated to determine whether they could be used to develop and test reasonable prediction models. The model development process also involved identifying the data requirements needed to produce robust prediction models.

1.3 SCOPE AND ORGANIZATION OF THE STUDY

Chapters 2 and 3 discuss the role of distress and performance prediction models in a pavement management system and the specific application of the models developed in this study. The variables in the models and the data required to develop the models are also presented. Chapter 4 identifies sources of data that may be used for the analyses. Chapter 5 discusses the process of obtaining and processing maintenance and rehabilitation data required for the model development but not already available in the sources identified in Chapter 4. Chapter 6 and Chapter 7 present the analysis procedures and results prior to ACC overlay. Chapters 8 and 9 present the results after the application of ACC overlay. In Chapter 10, conclusions of the work and recommendations for future research are presented.

1.4 RESEARCH APPROACH

To develop the distress and performance prediction models, statistical analyses were performed on pavement condition and maintenance data. Models were developed for performance and distress manifestations prevalent in Texas.

The analysis procedure consisted of six stages: (1) model specification, (2) identification of distress manifestations prevalent in Texas, (3) identifying sources of data which may be used to construct and test the models, (4) collecting and processing maintenance and rehabilitation (M&R) data, (5) model development using statistical data analysis, and (6) presenting the results.

Data for the analysis were obtained from databases maintained by the Texas Department of Transportation (TxDOT) and the Center for Transportation Research (CTR) at The University of Texas at Austin. Maintenance and rehabilitation information was obtained from TxDOT's district offices. These datasets were placed on the University's IBM mainframe computer system for further analysis. Several computer programs were written to process and analyze the data. For this purpose the statistical analysis package SAS was used (Ref 5). Due to the non-linear nature of the models, the non-linear regression procedure in SAS, NLIN, was used to quantify values for the various coefficients chosen for incorporation into the prediction models.

CHAPTER 2. PAVEMENT DISTRESS AND PERFORMANCE ELEMENTS USED IN THE TEXAS PMIS

As outlined in Chapter 1, the primary objective of this study is to model distress development, and thus pavement performance, for rigid pavements. The amounts of distress and roughness a pavement presents are measures commonly used to evaluate the performance of pavements. Manifestations of distress include the loss in ride quality, a wide variety of surface cracking and damage, and safety as measured by the skid resistance. The combined and cumulative influences of traffic, pavement structure and materials, subgrade support, and climatic factors are known to contribute to the deterioration and distress of pavements.

This chapter describes briefly modeling elements such as utility curves, pavement performance curves, and decision trees used in the analytical modules of the Pavement Management Information System (PMIS) of TxDOT. The next chapter describes briefly the analytical capabilities of the Texas PMIS and discusses how these elements are used in the Texas PMIS.

2.1 DISTRESS AND PERFORMANCE CURVES

A new pavement exhibits little or no surface distress. As the pavement ages and is subjected to the cumulative effects of traffic and climatic loads, distresses begin to develop. The rate of distress development is a function of pavement age, loading rate, and material characteristics. For example, rutting of asphalt concrete pavements can develop early in pavement life, whereas—after initial temperature cracking of portland cement concrete pavements—additional load cracking develops at a slow rate which then increases with age. To capture the different rates of distress development in a generalized model, a sigmoidal model form was selected by TxDOT for the modeling of distress development in the Texas PMIS. The mathematical form of this model and description of the factors are presented below. The relationship between distress development and time for the general model is shown in Figure 2.1 (Ref 6). This is the first step in the PMIS modeling procedure.

$$D = \alpha\, e^{-\left(\frac{\rho}{N}\right)^{\beta}} \qquad (2.1)$$

where

D = predicted level of a given distress,
N = age of the pavement,
α, β, and ρ are shape parameters estimated by non-linear regression, and
e = base of the natural logarithm.

2.2 UTILITY CURVES

In the Texas Pavement Evaluation System (PES), a set of utility values is used to determine the value of the pavement to the pavement engineer at different condition levels. Utility can be considered the value of the service provided by the pavement as a function of a given damage level. Utility values vary from 1.0, the maximum value, to 0, when the pavement is considered to have no value to the riding public. Since it is still possible to drive over a pavement that has 100 percent cracking, the utility curve will not necessarily go all the way to a zero value.

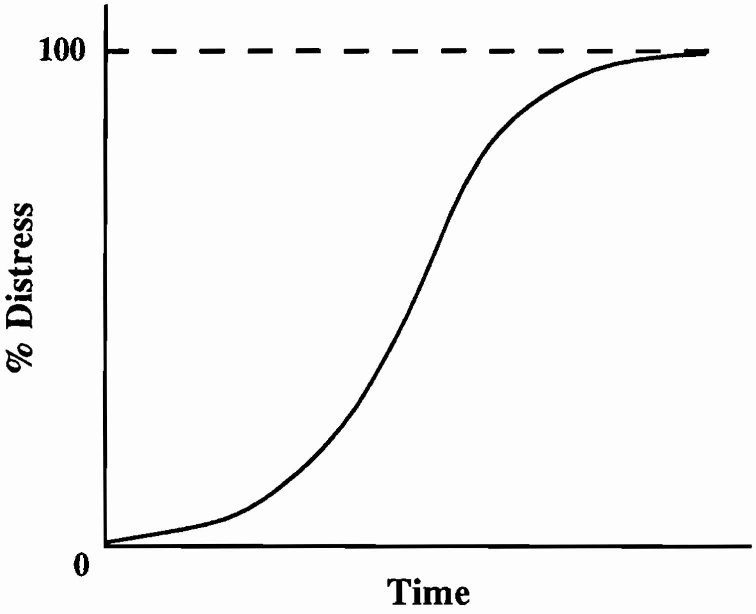


Figure 2.1. Distress Curve

The utility curve is also sigmoidal in shape (Figure 2.2) and can be represented in the following general mathematical and graphical form (Ref 6):

$$U = 1 - \alpha e^{-\left\{\frac{\rho}{N}\right\}^{\beta}} \qquad (2.2)$$

where

U = utility value,
e = base of the natural logarithm,
α = asymptote controlling the maximum utility loss,
ρ = coefficient which controls the life of the curve,
β = coefficient which controls the shape of the curve, and
N = pavement age.

Using these two curves, there is a direct relationship between the amount of distress observed in a pavement section and the utility value assigned to that pavement section. As the percentage of distress increases, the utility of the pavement decreases. In the Texas approach to distress analysis, a relationship was established between the individual distress levels and utility values (Ref 6). This relationship is used in the Texas PMIS to relate the distress and performance curves with the utility curves.

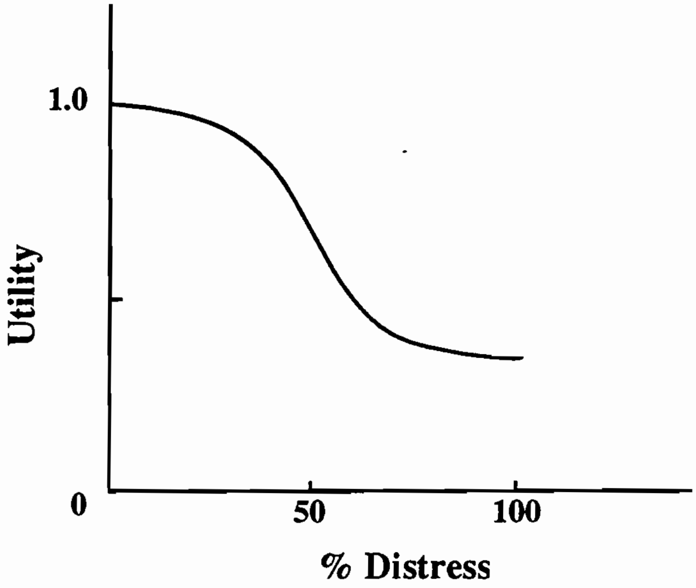


Figure 2.2. Utility Curve

The Texas PMIS considers several pavement types, including asphalt concrete (ACP), continuously reinforced concrete (CRCP), jointed concrete (JCP), and composite. Each of these pavement types has different and/or unique distress manifestations. It is therefore difficult or impossible to compare alligator cracking on ACP sections with punchouts on CRCP sections. However, since the utility values represent the value of the service provided by the pavement at a certain damage level, a common utility value for any pavement type may be used to make comparisons among the various pavement types.

2.3 SURVIVOR CURVES

A survivor curve is a curve which represents the number of units or percentage of a particular item which will remain in service at any given age. In pavement management, the item can be defined as the highway network and the item units are the pavement sections that comprise the network. The probable life of surviving pavement sections can be calculated at any age by dividing the remaining area under the curve by the number of sections surviving at that age (Ref 6). These survivor curves are not used in the current version of the Texas PMIS, but may be included in the future.

Several methods can be used to develop survivor curves. All of them use retirement or replacement as the end of the life of the item. A pavement is retired when it is resurfaced, reconstructed, or abandoned. In the Texas PMIS the trigger values for retirement will be the levels of service below which each condition is considered unacceptable.

The amount of distress present determines when a pavement is reconstructed, overlaid, or retired. Retirement is also a function of the policy used to define when a pavement needs to be overlaid, reconstructed, or abandoned. There can therefore be a survivor curve for each policy used to define retirement. The left-most survivor curve in Figure 2.3 represents a retirement policy which has a low acceptable distress level. Each curve to the right of this represents policies which have progressively higher acceptable distress levels before retirement.

Survivor curves can be modeled with the following general equation (Ref 6):

$$PS = 1 - e^{-\left\{\frac{\rho}{N}\right\}^{\beta}} \tag{2.3}$$

where

PS = probability of surviving,
e = base of the natural logarithm,
ρ = coefficient which controls the life of the curve,
β = coefficient which controls the shape of the curve, and
N = pavement age.

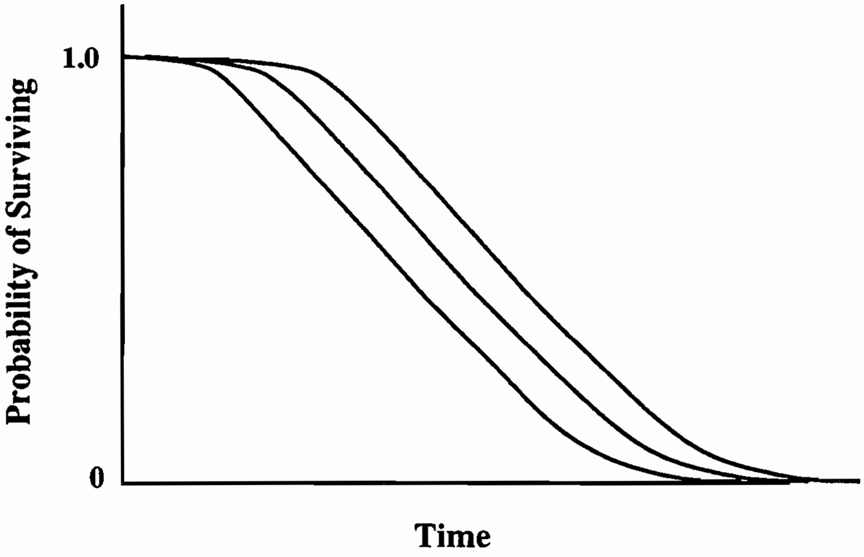


Figure 2.3. Survivor Curve

2.4 OTHER VARIABLES IN THE DISTRESS MODELS

As pointed out in Section 2.1, the pavement as it ages is subjected to the cumulative effects of traffic and climatic-induced loading, not just age. The various types of distress have different patterns of development. Some distresses develop rapidly early in the pavement life and the rate of development then decreases, e.g., faulting (Ref 7).

The extent of each distress manifestation is not related solely to time, but also to traffic, climatic factors, and subgrade support, as well as to an interaction of time with the other three variables. For example, a relationship of distress level with time and traffic can be developed for each distress manifestation. To understand the use of the curves in PMIS, it should be remembered that discrete curves must be developed for each distress type and each type of pavement with respect to traffic, structural adequacy, and climatic-induced loading. Seven distress types plus ride quality are needed to describe the behavior of flexible pavements in time according to PMIS specifications, combined with four possible options of corrective measures (preventive maintenance, light rehabilitation, medium rehabilitation, and heavy rehabilitation), adding up to 32 performance curves for flexible pavements required by the Texas PMIS.

Five distress types plus ride quality are included in the PMIS specifications for continuously reinforced concrete pavements (CRCP), and again, combined with four possible corrective measures, this adds up to 24 performance curves for CRCP pavements. For jointed concrete pavements (JCP) there are six pavement distresses required by the Texas PMIS specifications, which, combined with the four possible treatment types, adds up to 24 performance curves to be established for JCP pavements. These 48 performance curves for CRCP and JCP pavements are the main research focus of this report.

In order to express pavement life in terms of a single variable, pavement age, the sigmoidal equation form (Eq 2.1) may be modified to include the effects of traffic, structural adequacy, and climatic loading. This can be accomplished by multiplying the rho value with factors for traffic, structural adequacy, and climatic-induced loading. The resulting equation form can then be transformed to:

$$D = \alpha e^{-\left(\frac{\chi \varepsilon \sigma \rho}{N}\right)^{\beta}} \qquad (2.4)$$

where

D = level of distress,
e = base of the natural logarithm,
N = age of the pavement,
α = an asymptote controlling the maximum level of distress,
ρ = coefficient which controls the position of the first inflection point on the curve along the age axis,
β = coefficient which controls the shape of the curve (convex or concave),
χ = coefficient which modifies rho for effects of traffic loading,
ε = coefficient which modifies rho for effects of climatic loading, and
σ = coefficient which modifies rho for effects of subgrade support.

Factors included in Equation 2.4 have their significance verified using an ANOVA in the following chapters. The influence of the traffic, climatic factors, and subgrade support on the distress level will not be investigated in this study.

2.5 DECISION TREES

For determining repair treatments for the different types of pavements and distress, the Texas PMIS includes use of decision trees. These are based on ADT/Lane characteristics of the specific pavement section and level of distress and several other factors. Table 2.1 lists the ADT/Lane classifications for CRCP pavements included in the PMIS specifications.

TABLE 2.1. ADT/LANE CLASSIFICATIONS FOR CRCP PAVEMENTS (TxDOT INTERNAL MEMORANDUM, MAY 1993)

Functional Class	LOW ADT/Lane	HIGH ADT/Lane
1	1 - 7,499	7,500 +
2	1 - 7,499	7,500 +
3	1 - 7,499	7,500 +
4	1 - 2,999	3,000 +
5	1 - 1,999	2,000 +
6	1 - 1,999	2,000 +
7	1 - 1,999	2,000 +

A description of the decision tree specifications for CRCP pavements follows:

For a pavement section to be classified as in need of a **Heavy Rehabilitation or Reconstruction**:

For ADT/Lane = HIGH:

Punchouts + Asphalt Patches + Concrete Patches > 8 per mile (5 per km), or
Average Crack Spacing < 2 feet (0.6 m), or
Average Crack Spacing < 4 feet (1.2 m) and Average County Rainfall > 40 inches (101.6 cm) per year, or
Ride Score < 3.5 and Average Crack Spacing < 6 feet (1.8 m).

For ADT/Lane = LOW:

Punchouts + Asphalt Patches + Concrete Patches > 10 per mile (6 per km), or
Average Crack Spacing < 2 feet (0.6 m), or
Average Crack Spacing < 4 feet (1.2 m) and Average County Rainfall > 40 inches (101.6 cm) per year.

For a pavement section to be classified as in need of a **Medium Rehabilitation**:

For ADT/Lane = HIGH:

Spalled Cracks > 20%, or
Ride Score < 3.5.

For ADT/Lane = LOW:

Spalled Cracks > 33%, or
Ride Score < 3.0.

For a pavement section to be classified as in need of a **Light Rehabilitation**:

Punchouts > 0 per mile (0 per km).

For a pavement section to be classified as in need of **Preventive Maintenance:**

None.

CHAPTER 3. PAVEMENT PERFORMANCE MODELS, AND THEIR USE IN THE TEXAS PMIS

This chapter gives a brief description of the capabilities of the Texas PMIS and how the elements defined in the previous chapter are used in the analytical and reporting modules of the Texas PMIS.

3.1 FUNCTIONS OF THE TEXAS PMIS

Pavement management is a decision-making support tool which should incorporate the managerial objectives of a transportation agency. TxDOT's Pavement Management Information System (PMIS) is intended to provide appropriate support for decisions involved in the pavement management process.

The first series of steps in the PMIS involve data collection, entry, and verification. Following the data collection stage, computer programs perform specific analysis routines to estimate maintenance and rehabilitation (M&R) needs and determine the impacts of various funding scenarios. The major computer analysis modules already included or to be included in the Texas PMIS are:

- Estimate Maintenance and Rehabilitation Needs;
- Single-Year Analysis with Constrained Funds;
- Multiple-Year Analysis with Constrained Funds;
- Single-Year Analysis with District Selected Sections;
- Determine Impact of Allocation;
- Develop Recommended Budget;
- Calibration of PMIS Deterioration Models.

Before any analysis can be performed by these modules, the condition of all pavement sections in the network must be projected to a common time. The Texas PMIS uses two main elements to represent condition and performance information over time: (1) distress and performance curves, which are the projection of a specific type of distress or ride quality over a period of time; and (2) utility curves, which are directly related to the condition of the pavement. The PMIS may in the future use survivor curves, which are a probabilistic method of projecting the expected life of a section of pavement. In this report, the primary focus is on the development of performance and distress curves, although reference will be made to utility and survivor curves as necessary.

3.2 SELECTING M&R TREATMENTS: NEEDS ESTIMATE

The selection of the best M&R treatment is a project-level decision and is made in the normal engineering design and analysis process of a PMS once the section has been identified as a candidate project. The Texas PMIS is a network-level PMS aimed at identifying candidate sections and determining the funding needs. Thus, general funding categories which give approximate fund requirements are adequate.

Four maintenance and rehabilitation funding categories have been identified for the Texas PMIS: (1) preventive maintenance, (2) light rehabilitation, (3) medium rehabilitation, and (4) heavy rehabilitation/reconstruction. In addition, a do-nothing option is provided. A treatment is assigned based on trigger values. Trigger values are minimum acceptable levels of distress. The decision tree for CRCP pavements used by the Texas PMIS presented at the end of the previous chapter is a good example of the application of these concepts.

With the use of the decision trees and an appropriate set of unit costs, it is possible to estimate total pavement needs for the Texas pavement network and separate the required budget into the four funding categories identified above.

Using the distress curves, the level of distress at any time in the pavement's life can be estimated and the corresponding required M&R treatment assigned. This procedure is used in the multiple-year analysis module of the Texas PMIS.

3.3 PROJECTING PAVEMENT CONDITION OVER TIME

Projected future condition can be expressed in terms of distress or utility. As stated previously, this report is focused on the development of distress and performance curves; therefore, condition projection will be discussed with respect to distress curves.

It is assumed that the projection starts with an observed or measured condition identified as D_{obs} at given time YR_{obs} (see Figure 3.1). The distress curve corresponding to this observation is numbered 1 in Figure 3.1. A base year is determined, $YR_{Base\ 0}$. The base year is calculated from the general equation for the sigmoidal distress curve, Equation 3.1. The form of the base year formula is as follows:

$$T_{theo} = \frac{\chi \varepsilon \sigma \rho}{\left[\ln\left(\frac{\alpha}{D}\right)\right]^{\left(\frac{1}{\beta}\right)}} \tag{3.1}$$

where

T_{theo} = theoretical age,
χ = coefficient which modifies rho for effects of traffic loading,
ε = coefficient which modifies rho for effects of climatic loading,
σ = coefficient which modifies rho for effects of subgrade support,
ρ = coefficient which controls the life of the curve,
ln = natural logarithm,
α = an asymptote controlling the maximum level of distress,
β = coefficient which controls the shape of the curve (convex or concave), and
D = level of distress.

A treatment is programmed for some future time $YR_{tmt\ 1}$. At that time the distress is decreased by an amount based on the impact of the treatment from D_{bt1} to D_{at1}. Again a base year, YR_{Base1}, is determined using Equation 3.1, and the condition projected forward using a new curve 2.

To use this procedure, an expected level of reduction in distress must be established for each treatment. Also, the distress curve after the treatment must be a function of the treatment.

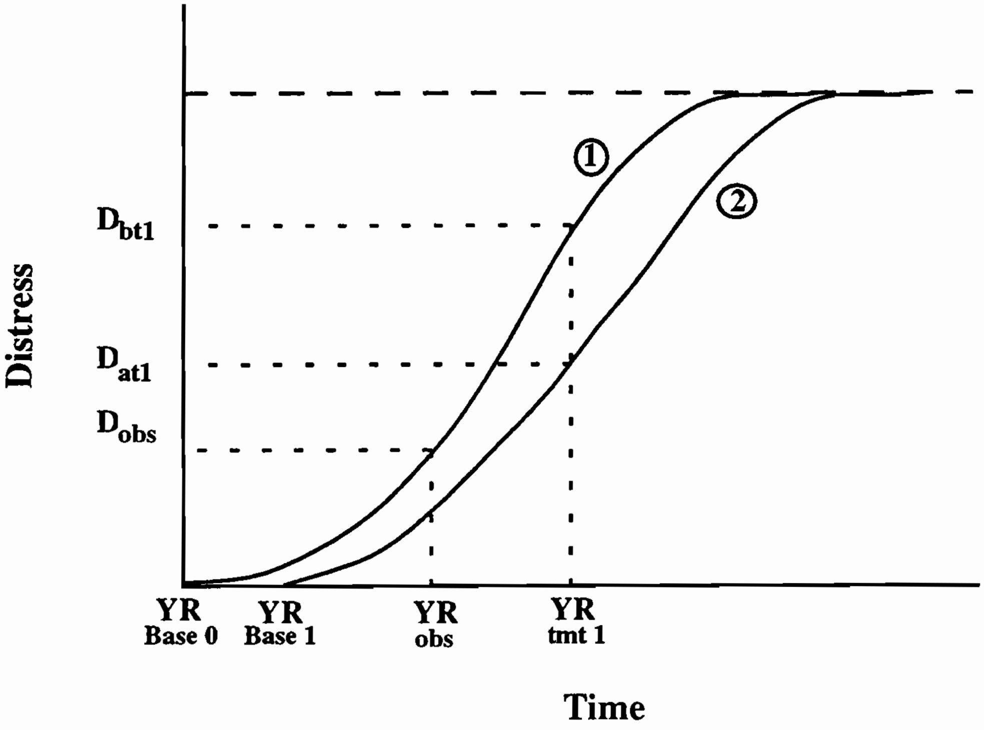


Figure 3.1. Condition Projection

3.4 CALCULATING THE EFFECTIVENESS OF A M&R TREATMENT: OPTIMIZATION

A major goal of the Texas PMIS is to assist decision makers in selecting sections of roadway for M&R when the total available funds are limited and are less than what is actually required. Economic, or cost-benefit, analysis helps determine whether the investment of funds in one project is more beneficial than investment of funds in another. Cost-benefit analysis, however, does not lend itself to certain engineering problems because of the difficulty in quantifying the impact or benefits of decisions in monetary terms (Ref 6). In such cases cost-effectiveness analysis can be used.

Basically, the cost-effectiveness analysis involves calculating the effect of each M&R treatment selected by the needs estimate procedure in terms of gain in utility or user benefit. Those treatments which give the greatest effectiveness for the available funds are selected as candidate sections for M&R. When multiple M&R alternatives are considered and the total effectiveness is maximized for a fixed funding level, it is referred to as a fixed-cost approach.

The effectiveness concept is based on the belief that higher condition levels for longer periods of time provide the best service to the road user. This can be thought of in terms of user benefit. One measure of this user benefit is the area between the utility versus time curves for the projection of pavement condition with and without M&R until the failure criteria is reached. This is illustrated in Figure 3.2. Curve 1 represents the "do-nothing" option and Curve 2 is the curve if a treatment is applied at time t.

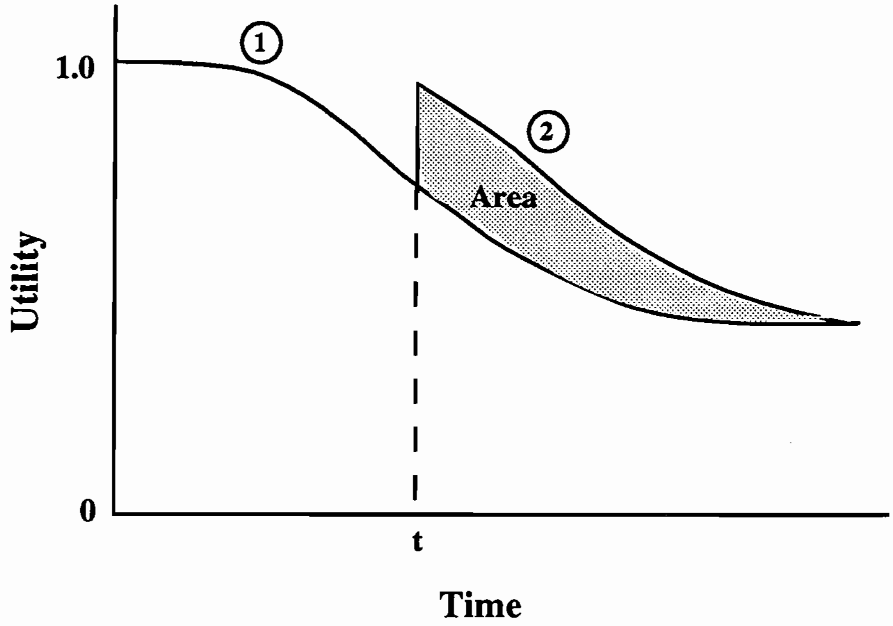


Figure 3.2. Effectiveness Area

To calculate the effectiveness area illustrated in Figure 3.2, the Texas PMIS uses a trapezoidal integration method. For each potential M&R treatment, the effectiveness area is calculated for each evaluation measure—e.g., ride quality, the various types of distress, structural capacity, etc.—and summed. The total effectiveness area is divided by the number of evaluation measures. This will give an average effective area per evaluation measure, which is a measure of the effectiveness of the M&R treatment.

$$EFF = \sum_{i=1}^{n} \frac{(AREA)_i}{n} \tag{3.2}$$

where

EFF = effectiveness of the M&R treatment,

n = number of evaluation measures, and

$AREA_i$ = effectiveness area calculated for each evaluation measure.

3.5 DATA REQUIREMENTS FOR PMIS MODEL DEVELOPMENT

The Texas Pavement Management Information System (PMIS) is primarily a network-level PMS. One of its functions is to select the most cost-effective M&R strategy for each pavement section. To determine the best M&R alternative it is necessary to quantify the improvement in pavement condition after M&R. For this purpose it is necessary to obtain data on both the M&R history of each section and the cost of each M&R strategy.

Chou (Ref 8) found that the coarse aggregate type in pavement slab construction affects pavement behavior and hence distress development over time. Two major types of aggregate were identified, siliceous river gravel (SRG) and limestone.

Rainfall and temperature constitute the climatic factors that are expected to influence pavement performance. The interaction of temperature and rainfall, temperature and coarse aggregate type, and rainfall and soil type may play a role in the formation and progression of certain distress manifestations.

Because the models developed in this study are for use at the network level, it is not feasible to consider specific M&R activities when selecting possible rehabilitation strategies. It is more practical to deal with groups of specific activities that are categorized to represent an overall strategy. For this study four such categories were defined: preventive maintenance, light rehabilitation, medium rehabilitation, and heavy rehabilitation. The study team decided to conduct an opinion survey of the TxDOT districts in order to categorize various M&R activities. The details of this survey are presented in Chapter 5.

Based on the model specifications presented in Chapter 2 and on the above discussion, the following data are required to adequately model pavement performance:

- pavement age,
- extent of pavement distress,
- coarse aggregate type (CAT),
- ride quality,
- traffic loading,
- subgrade support,
- climatic-induced loading, and
- maintenance and rehabilitation history.

Specific distress manifestations that are considered to be indicators of pavement performance are identified in Chapter 4.

CHAPTER 4. DATA SOURCES

As discussed in the previous chapters, historical data on the different types of distress are needed to develop distress and performance prediction curves. Some of these data may be obtained from existing national and local research databases. By defining a factorial arrangement of the significant factors that are thought to affect pavement performance in Texas, a sample of pavement sections can be selected from a research database such as COPES (Ref 5).

However, in Texas, data are already available from the annual pavement condition surveys performed by the Texas Department of Transportation (TxDOT) and the Center for Transportation Research (CTR) at The University of Texas at Austin. The TxDOT database is a part of the Pavement Evaluation System (PES) (Ref 12). CTR has two databases, one for JCP sections and the other for CRCP sections (Ref 16).

4.1 CTR CRCP DATABASE

The CRCP network in Texas is represented in the CTR database by 312 observation sections. Sections range in length from 0.1 to 1.7 miles (0.16 to 2.74 km) and have approximately the same design characteristics. They are identified by a 5-digit CFTR (Center For Transportation Research) number. The first two digits of this number represent the TxDOT district in which the section is located. The remaining three digits identify the pavement section in the district.

In the CRCP information system, provision is made for capturing routine condition survey information as well as data on climate, traffic, and materials. Reference 18 details the location of these data items in the various databases comprising the system.

Condition surveys for CRCP sections were performed in 1974, 1978, 1980, 1982, 1984, and 1987. Table 4.1 summarizes the specific distress types and the frequency with which they were surveyed during these years. Detailed definitions of the distress types are presented in Appendix A.

In 1988, a survey was conducted to collect data for structural evaluation, instead of distress data. As documented in Reference 18, the data collected in this survey consisted of

- deflections, measured with the Falling Weight Deflectometer (FWD);
- crack width, measured with a microscope;
- pavement temperature; and
- rut depth.

4.2 CTR JCP DATABASE

The CTR 1982 jointed concrete pavement database contains 4,019 pavement test sections. Each section is approximately 0.2 miles (0.32 km) in length. As in the case of the CRCP sections, JCP sections are also identified by a unique CFTR number.

TABLE 4.1. SUMMARY OF CONDITION SURVEY DATA IN THE CTR CRCP DATABASE

DISTRESS TYPE	TYPE	INTENSITY	SURVEY YEAR					
			74	78	80	82	84	87
Cracking	Transverse	Minor	●	●				●
		Severe	●	●				●
	Longitudinal		●					
	Localized	Minor	●					
		Severe	●					
Spalling		Minor	●	●	●	●		
		Severe	●	●	●	●	●	●
Pumping		Minor	●	●	●	●		
		Severe	●	●	●	●		
Punchouts		Minor	●	●	●	●		●
		Severe	●	●	●	●	●	●
Patch	AC		●	●	●	●	●	●
	PCC		●	●	●	●	●	●
Crack spacing	Transverse							●
Reflected cracks								●
Overlay bond failure								●

In this JCP database, provision is made to store routine condition survey data only. No provision has been made for collecting data on climate, traffic, materials, pavement design characteristics, or maintenance and rehabilitation histories. Appendix B contains detailed definitions of the distress types considered in the visual condition survey.

The specific distress types surveyed in 1982 and included in the JCP database are

- transverse cracks,
- spalled joints and cracks,
- faulted joints and cracks,
- bad joint sealants,
- corner breaks,

- minor longitudinal cracks (number per slab),
- severe longitudinal cracks (number per slab),
- patches (ACC and PCC),
- condition of edge joints, and
- pumping.

4.3 PES DATABASE

The PES database contains visual condition survey data for both flexible and rigid pavement sections. For this study, only the rigid pavement sections were considered. PES includes three concrete pavement types: jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP). In total, PES stores data for 1,413 rigid pavement sections, of which 876 are CRCP, 430 are JRCP, and 107 are JPCP.

PES pavement sections range in length from 0.1 to 3.0 miles (0.16 to 4.8 km), with the majority of sections being 2.0 miles (3.2 km) in length. Individual pavement sections are identified by start and end reference markers. TxDOT's Pavement Evaluation System Rater's Manual (Ref 14) details the procedure for establishing and interpreting reference markers. Basically, the reference marker locates a particular pavement section with respect to a grid imposed on the map of Texas. The grid axes are set on extreme western and northern points, where numbering begins with ten. The first number of the reference number for a route matches the approximate grid location. Subsequent reference marker numbers increase by two because each section is approximately 2 miles (3.2 km) in length.

Annual PES survey data for the period 1983 to 1990 are available for analysis. The following information is collected for PES:

- routine condition survey data,
- traffic data,
- ride quality data,
- skid resistance data, and
- pavement structural capacity.

The particular distress manifestations surveyed for CRCP and JCP sections during the routine condition surveys are presented in Table 4.2. Detailed definitions of the distress manifestations surveyed are included in Appendix C.

TABLE 4.2. DISTRESS MANIFESTATIONS FOR CRCP AND JCP SECTIONS SURVEYED ANNUALLY IN PES

DISTRESS MANIFESTATION	PAVEMENT TYPE		
	CRCP	JPCP	JRCP
CRACKING:			
Slabs with longitudinal cracks		●	●
Failed cracks		●	●
Crack spalling	●		
JOINT DEFICIENCIES:			
Failed joints		●	●
OTHER:			
Punchouts	●		
Asphalt patches	●		
Concrete patches	●	●	●
Shattered slabs		●	●
Average transverse crack spacing	●		
Apparent joint spacing		●	●
Failures		●	●

PES uses the survey data to calculate a condition score for each pavement section. This score indicates the section's overall condition at a particular point in time. Skid resistance data may be collected; however, they are not included in the current PES analysis procedures.

As is the case in the CTR databases, PES does not make provision for recording the maintenance and rehabilitation history of each pavement section. In addition, PES does not record the initial construction dates of the sections.

4.4 DATA AVAILABILITY AND COMPATIBILITY

In Chapter 2, the data items necessary to develop the performance and distress prediction models for this study were identified. Table 4.3 shows the data items currently available in the PES and CTR databases. Table 4.3 shows that neither of the databases contains information for all the data items.

The PES and CTR databases do not record maintenance and rehabilitation (M&R) histories for concrete pavement sections. A separate study was undertaken to obtain M&R history data. This study is discussed in detail in Chapter 5.

The data source for the Texas Pavement Management Information System (PMIS) will be PES. Therefore, any data used from the CTR database for model building nust be converted to the PES format.

The unit of measure of the extent of a distress has a direct effect on the coefficient estimates for the variables in the prediction model. For example, the extent of cracking can be recorded either as a percentage of the total pavement section area or as a percentage of the traveled area, i.e., area of the wheel paths. Thus models developed using the different methods of distress measurement will have different coefficient estimates unless they are converted to common units.

TABLE 4.3. DATA AVAILABILITY IN THE PES AND CTR DATABASES

DATA REQUIREMENTS	CTR		PES	
	CRCP	JCP	CRCP	JCP
Pavement age	●	●		
Distress level	●	●	●	●
Coarse aggregate type	●	●		
Ride quality			●	●
Traffic loading	●	●	●	●
Pavement structural adequacy	●	●	●	●
Climatic loading	●	●		
M&R history				

To determine the compatibility of the distress data in the two databases, a compatibility check was performed. The results of this check are discussed in the following sections.

4.4.1 COMPATIBILITY OF DEFINITIONS FOR CRCP DISTRESS TYPES IN PES AND CTR DATABASES

PES and CTR visual condition survey procedures consider basically the same distress manifestations for continuously reinforced concrete pavements. This can be seen in Tables 4.1 and 4.2. However, for CRCP sections, CTR has defined a minor and a severe intensity category for certain distress types. Two distress types having this categorization in the CTR database and also found in the PES database are crack spalling and punchouts. It is therefore necessary to compare the CTR definitions for these two distress types with those of the PES.

Minor crack spalling is defined by CTR (Ref 19) as a condition of cracking where the loss of material has formed a spall 1/2 inch (1.3 cm) wide. CTR defines severe crack spalling as cracks that have been widened to such an extent that the smoothness of ride is affected by the spall. PES does not differentiate between minor and severely spalled cracks. A spalled crack as defined by PES is a crack displaying spalling at least 1 inch (2.5 cm) wide (on either side of the crack) which covers more than 1 foot (0.3 m) of the crack's total length across the lane. From these definitions, it may be concluded that CTR's definition of a severely spalled crack is equivalent to the PES spalled crack definition.

A minor punchout is defined by CTR as a condition where longitudinal cracks have started to form but have not necessarily linked with transverse cracks. The CTR definition of a severe punchout is a condition where longitudinal cracks have linked with transverse cracks to form a block that moves under traffic. The PES definition of a punchout is a block formed when a longitudinal crack crosses two transverse cracks to form a block. Each of the boundaries of the block exhibits severe spalling or faulting, indicating movement under traffic.

From the definitions of punchouts it can be concluded that a severe punchout as defined by CTR is equivalent to the PES punchout definition. Definitions for ACC and PCC patches and average transverse crack spacing are the same in both the CTR and the PES databases.

4.4.2 COMPATIBILITY OF DEFINITIONS FOR JCP DISTRESS TYPES IN PES AND CTR DATABASES

The CTR condition survey of jointed concrete pavement does not define a minor and a severe intensity category for each distress type. The list of JCP distress types surveyed by CTR is presented in Table 4.1. PES distress types for JCP sections are presented in Table 4.2.

PES groups corner breaks, punchouts, ACC patches, failed concrete patches, and D-cracking into a single distress type called failures. Similarly, the measure of failed joints and cracks includes spalled transverse joints and spalled transverse cracks.

The CTR JCP database stores data for corner breaks and patches, but condition data for punchouts, failed concrete patches, and D-cracking are not recorded. Therefore, a measure of failures, as defined by PES, cannot be calculated using the CTR JCP condition data. However, a measure of failed joints and cracks, as defined by PES, can be calculated using the CTR JCP data.

PES condition surveys collected data on shattered slabs and apparent joint spacing. The CTR JCP condition survey does not survey these two distress types. The definitions for slabs with longitudinal cracks and concrete patches are the same in both databases.

4.4.3 COMPATIBILITY OF UNITS OF MEASUREMENT FOR DISTRESS MANIFESTATIONS IN PES AND CTR DATABASES

In the PES and CTR databases, the extent of a distress is measured as "the number occurring per pavement section." Average transverse cracking and apparent joint spacing are measured in feet (at the time of this writing, August 1993) in both databases.

The exception to this was the 1974 CTR CRCP condition survey. The unit of measurement for some distress types in the 1974 survey was an estimated percentage of the pavement area or length.

CHAPTER 5. MAINTENANCE DATA AND INFERENCE SPACE

The lack of maintenance and rehabilitation data led to the need for conducting a survey with the TxDOT district offices, the results of which are presented in the following sections. Another important consideration is the inference space of the data, which is discussed in detail for both the CTR and the PES databases.

5.1 MAINTENANCE AND REHABILITATION (M&R) DATA

Examination of TxDOT's PES database and the CTR rigid pavement database showed that neither database contains historical pavement maintenance and rehabilitation (M&R) data. M&R data are a key component in the development of the performance and distress prediction models being addressed in this study.

To obtain the required M&R data, 23 TxDOT district offices were requested to furnish the M&R history for a selection of pavement sections in their district. A survey questionnaire was sent to each office, on which district personnel reported the M&R histories.

5.1.1 SELECTION OF PAVEMENT SECTIONS

Pavement sections for which M&R data were requested were selected from the 1990 PES database. Of the eight annual PES datasets available, the 1990 data were used because the section reference markers for this year were the most recent. It was necessary to provide the districts with the most recent reference markers for each section because, if major rehabilitation or reconstruction was performed on a section, its beginning and/or end points might be relocated, resulting in a change in the reference markers. The PES database was chosen in lieu of the CTR database because (1) district offices are more familiar with the TxDOT reference marker system than with the CTR control, section, and job number referencing system, and (2) information could be extracted from the district office's records by cross-referencing with the PES section reference markers provided.

M&R histories were requested for 632 rigid pavement sections. The distribution of these sections by pavement type and district is presented in Table 5.1. The Austin district was not included in this survey because no rigid pavement sections were surveyed in this district in 1990. The statewide distribution of rigid pavement types is presented in Table 5.2.

TxDOT surveys only a portion of the State-maintained highway network each year. The sampling rates for visual condition survey and ride quality, for each functional class of road, are presented in Table 5.3.

TABLE 5.1. FREQUENCY DISTRIBUTION OF RIGID PAVEMENT SECTIONS BY TYPE AND DISTRICT (1990 PES DATABASE)

TxDOT DISTRICT		PAVEMENT TYPE		
NO.	**NAME**	**CRCP**	**JRCP**	**JPCP**
1	Paris	7	11	0
2	Fort Worth	110	3	0
3	Wichita Falls	33	0	7
4	Amarillo	28	1	0
5	Lubbock	43	1	0
6	Odessa	0	0	1
7	San Angelo	0	0	0
8	Abilene	0	3	0
9	Waco	2	2	0
10	Tyler	5	0	0
11	Lufkin	0	1	0
12	Houston	49	50	0
13	Yoakum	34	1	0
14	Austin	0	0	0
15	San Antonio	5	0	0
16	Corpus Christi	0	1	0
17	Bryan	9	0	0
18	Dallas	49	3	66
19	Atlanta	5	10	0
20	Beaumont	20	29	7
21	Pharr	0	0	0
23	Brownwood	0	0	0
24	El Paso	17	0	0
25	Childress	18	1	0
TOTAL		434	117	81
PERCENTAGE		68.67%	18.51%	12.82%

TABLE 5.2. STATEWIDE FREQUENCY DISTRIBUTION OF RIGID PAVEMENT SECTIONS BY TYPE AND DISTRICT

TxDOT DISTRICT		PAVEMENT TYPE		
NO.	**NAME**	**CRCP**	**JRCP**	**JPCP**
1	Paris	18	40	0
2	Fort Worth	243	12	0
3	Wichita Falls	64	3	15
4	Amarillo	31	2	2
5	Lubbock	58	2	0
6	Odessa	1	4	2
7	San Angelo	0	0	0
8	Abilene	0	10	0
9	Waco	10	8	0
10	Tyler	7	0	2
11	Lufkin	0	9	0
12	Houston	160	120	3
13	Yoakum	64	9	1
14	Austin	0	0	0
15	San Antonio	16	3	0
16	Corpus Christi	0	6	0
17	Bryan	13	1	0
18	Dallas	97	99	72
19	Atlanta	10	25	0
20	Beaumont	37	20	7
21	Pharr	0	4	3
23	Brownwood	0	0	0
24	El Paso	27	2	0
25	Childress	20	1	0
TOTAL		876	430	107
PERCENTAGE		62.00%	30.43%	7.57%

TABLE 5.3. TxDOT'S SAMPLING RATES FOR ANNUAL HIGHWAY CONDITION EVALUATION

HIGHWAY SYSTEM	ANNUAL EVALUATION FREQUENCY	
	VISUAL	RIDE QUALITY
Interstate Highways	100%	100%
U.S. Highways	50%	50%
State Highways	30%	50%
Farm-to-Market Roads	15%	20%

5.1.2 M&R INFORMATION REQUESTED

PES pavement evaluation data were available from 1983 through 1990, a period of eight years. M&R histories were therefore requested only for this eight-year period. M&R histories outside this eight-year period were not useful because the condition level prior to and after the maintenance activity could not be determined.

The specific information requested from the districts is listed below. Typical survey forms used to collect the data are included in Appendix D.

Specific information requested included:

- initial construction date of the pavement section,
- coarse aggregate type (CAT) used in the pavement's construction,
- categorization of M&R activities into one of four maintenance cost categories,
- date M&R was performed (month and year), and
- category of M&R performed.

The significance of collecting these data was discussed in Chapter 2. However, the importance of the last three items is discussed further below.

The report describing the Texas PMIS (Ref 6) contains a guide on categorizing M&R activities. However, this guide does not include all the M&R activities currently being performed by the TxDOT districts. It was therefore necessary to determine which M&R activities were being performed and to which M&R cost category they belong. To obtain this information, the districts were asked to complete FORM 1 (see Appendix D) of the survey. This form lists M&R activities and cost categories for CRCP and JCP sections. The districts were instructed to categorize only the activities they perform. Categorization of the activities was done by check-marking the appropriate box on FORM 1.

Once the M&R activities on FORM 1 were categorized, the specific M&R performed was reported by cost category on FORM 2 (see Appendix D). For example, if the M&R activity "crack sealing" was classified as preventive maintenance on FORM 1, and if crack sealing was performed on a section of pavement, then the preventive maintenance box on FORM 2 was checked and the date the M&R activity was performed was entered in the date column.

5.1.3 SURVEY RESPONSE

Twenty-three TxDOT districts were surveyed. Responses were received from 18 districts. Table 5.4 summarizes the response. Six of the 18 districts reported that they had no rigid pavement sections or that the sections present were not of substantial length (approaches to bridges and underpasses). Four districts made no response.

Of the 632 pavement sections for which M&R histories were requested, responses were obtained for 215 sections. The frequency distribution of these sections by district and pavement type is presented in Table 5.5.

TABLE 5.4. DISTRICT RESPONSE TO THE M&R HISTORY SURVEY

TxDOT DISTRICT		RESPONSE	RIGID SECTIONS
NO.	NAME	RECEIVED	PRESENT
1	Paris	●	●
2	Fort Worth		
3	Wichita Falls	●	●
4	Amarillo	●	●
5	Lubbock	●	●
6	Odessa	●	
7	San Angelo	●	
8	Abilene	●	●
9	Waco	●	●
10	Tyler		
11	Lufkin	●	
12	Houston	●	●
13	Yoakum		
14	Austin	----	---
15	San Antonio	●	●
16	Corpus Christi	●	
17	Bryan		
18	Dallas	●	●
19	Atlanta	●	●
20	Beaumont	●	
21	Pharr	●	
23	Brownwood	●	
24	El Paso	●	●
25	Childress	●	●
TOTAL		18	12
PERCENTAGE OF DISTRICTS		75.00%	50.00%

TABLE 5.5. SURVEY RESPONSE: FREQUENCY DISTRIBUTION OF RIGID PAVEMENT SECTIONS BY TYPE AND DISTRICT

TxDOT DISTRICT		PAVEMENT TYPE		
NO.	NAME	CRCP	JRCP	JPCP
1	Paris	7	5	0
2	Fort Worth			
3	Wichita Falls	22	0	7
4	Amarillo	11	0	0
5	Lubbock	32	1	0
6	Odessa	0	0	0
7	San Angelo	0	0	0
8	Abilene	0	0	0
9	Waco	0	0	0
10	Tyler			
11	Lufkin	0	0	0
12	Houston	21	12	0
13	Yoakum			
14	Austin			
15	San Antonio	0	0	0
16	Corpus Christi	0	0	0
17	Bryan			
18	Dallas	38	2	25
19	Atlanta	3	0	0
20	Beaumont			
21	Pharr	0	0	0
23	Brownwood	0	0	0
24	El Paso	12	0	0
25	Childress	16	1	0
TOTAL		162	21	32
PERCENTAGE OF TOTAL		75.35%	9.77%	14.88%

5.1.4 SURVEY RESPONSE PROBLEMS

The most common problems experienced with the data obtained from the M&R history survey are listed below:

1. reference marker values entered on survey FORM 2 do not match exactly with the reference markers for the same pavement section in the 1990 PES database;
2. the reported M&R dates did not include the month; and
3. coarse aggregate type was not reported for the majority of the pavement sections.

Survey responses with pavement sections having reference markers not matching those of the 1990 PES database were excluded from the study. When dates not having a month value were encountered, it was assumed that the construction, or M&R corresponding to the date, was performed in the middle of the year reported.

5.1.5 M&R DATA PROCESSING

The data obtained from the M&R history survey can be divided into two groups, (1) M&R activity categorization and (2) pavement section M&R history. The former group of data was used to categorize the M&R activities into one of the four M&R cost categories. The M&R history data were used to identify pavement sections before and after M&R. Condition data for the identified sections were analyzed to obtain pavement distress and performance prediction curves before and after M&R.

The procedures for analyzing and processing the survey data are discussed in the following sections.

5.1.6 M&R ACTIVITY CATEGORIZATION

The district offices were requested to report M&R history by category (preventive, light, moderate, heavy) and not in terms of specific M&R activities. To verify that the districts' definitions of the categories were similar to that proposed for the PMIS in Reference 6, the districts were required to categorize selected M&R activities.

The frequency and percentage of each M&R activity's classification were tabulated (see Tables 5.6 and 5.7). Each M&R activity was assigned to the M&R category having the highest percentage. Table 5.8 presents the M&R activity classification as determined from the survey of district offices.

It was found that, on average, most M&R activities were classified according to the Texas PMIS guidelines. However, a definite classification could not be obtained from the survey data for PCC overlay and micro surfacing of CRCP sections, or for joint reconstruction on JCP sections. In accordance with PMIS guidelines, PCC overlay of CRCP sections was classified as heavy maintenance. Micro surfacing of PCC sections was categorized as moderate maintenance.

TABLE 5.6. CLASSIFICATION OF M&R ACTIVITIES: FREQUENCY

M&R ACTIVITIES	M&R CATEGORIES (FREQUENCY)							
	CRCP				JCP			
	P	L	M	H	P	L	M	H
Drainage maintenance	8	2	2		7	1		
Clean/reshape ditches	7	3	1		5	1		
Clean and seal joints	5	2		2	7		1	
Seal severe cracks	5	3			7	1	1	
AC patching	1	5			3	6		
PCC patching	3	5	4	1	3	3	1	1
Seal all cracks	5	2			6	2	1	
Slab jacking & grouting	2	1	3		1	1	3	1
Repair joints	3	4	1	1	4	3	1	1
Joint reconstruction	1	2	3	2	1	2	2	2
Slab replacement		1	2	5		2	1	3
AC overlay	1	2	6	3	1	1	5	2
PCC overlay			2	2			1	2
Reconstruct				5		1		4
Micro surfacing	1		1		1		2	
Seal coat	2	1			2	1		
Plant mix seal			1					

P = PREVENTIVE
L = LIGHT
M = MODERATE
H = HEAVY

TABLE 5.7. CLASSIFICATION OF M&R ACTIVITIES: PERCENTAGE

M&R ACTIVITIES	M&R CATEGORIES (PERCENTAGE)							
	CRCP				JCP			
	P	L	M	H	P	L	M	H
Drainage maintenance	67	17	17	0	88	13	0	0
Clean/reshape ditches	64	27	9	0	83	17	0	0
Clean and seal joints	56	22	0	22	88	0	13	0
Seal severe cracks	63	38	0	0	78	11	11	0
AC patching	17	83	0	0	33	67	0	0
PCC patching	23	38	31	8	38	38	13	13
Seal all cracks	71	29	0	0	67	22	11	0
Slab jacking & grouting	33	17	50	0	17	17	50	17
Repair joints	33	44	11	11	44	33	11	11
Joint reconstruction	13	25	38	25	14	29	29	29
Slab replacement	0	13	25	63	0	33	17	50
AC overlay	8	17	50	25	11	11	56	22
PCC overlay	0	0	50	50	0	0	33	67
Reconstruct	0	0	0	100	0	20	0	80
Micro surfacing	50	0	50	0	33	0	67	0
Seal coat	67	33	0	0	67	33	0	0
Plant mix seal	0	0	100	0				

P = PREVENTIVE
L = LIGHT
M = MODERATE
H = HEAVY

TABLE 5.8. CLASSIFICATION OF M&R ACTIVITIES

M&R ACTIVITIES	M&R CATEGORIES							
	CRCP				JCP			
	P	L	M	H	P	L	M	H
Drainage maintenance	●				●			
Clean/reshape ditches	●				●			
Clean and seal joints	●				●			
Seal severe cracks	●				●			
AC patching		●				●		
PCC patching		●				●		
Seal all cracks	●				●			
Slab jacking & grouting			●				●	
Repair joints		●			●			
Joint reconstruction			●					●
Slab replacement				●				●
AC overlay			●				●	
PCC overlay				●				●
Reconstruct				●				●
Micro surfacing			●				●	
Seal coat	●				●			
Plant mix seal			●					

P = PREVENTIVE
L = LIGHT
M = MODERATE
H = HEAVY

5.1.7 PAVEMENT SECTION M&R HISTORY

The M&R history data obtained were entered onto a spreadsheet. Fields were created for the section identification, district, county, initial construction date, coarse aggregate type (CAT), date the M&R was performed, and category of M&R performed. From the M&R history survey, it was found that, from 1983 until 1990, maintenance was done—at most—three times on any particular section. Each M&R cost category (preventive, light, moderate, heavy) was assigned the numeric values 1, 2, 3, and 4, respectively.

The initial construction date and M&R dates were entered as decimal values rather than as date values (MONTH and YEAR). This format made date comparisons simpler later in the analysis process. A date was converted to a decimal value using the following expression:

DECIMAL DATE VALUE = YEAR + (MONTH - 1) / 12

In some of the survey responses, only the year in which construction or M&R was performed was reported. In these cases it was assumed that the construction or M&R was performed in the middle of the year reported on the survey form. For this assumption to be reflected in the date value, 0.5 was added to the year.

The data on the spreadsheet were converted to a text format and transferred to the University's IBM mainframe computer. This text file was converted into a SAS dataset to facilitate further analysis and processing using SAS.

5.1.8 DISTRESS AND PERFORMANCE PREDICTION MODELS AFTER M&R

Figure 5.1 outlines the procedure used to process and analyze data for producing pavement distress and performance prediction curves after M&R has been performed.

Each PES database was individually merged with the M&R history survey data. The resulting datasets were then appended together. Using the combined dataset, all PES condition data collected between consecutive M&R operations were selected as "after" M&R data. For example, if preventive M&R was performed in 1984 and moderate M&R in 1988, all condition survey data collected within that period were considered "after" M&R data relative to the preventive M&R operation performed in 1984.

Condition-survey-age after M&R was calculated by subtracting the M&R date from the condition survey date. The mean value for each distress type was computed per age group for each pavement type and M&R cost category. The mean values were weighted by the frequency at each age. To obtain coefficient estimates for the relationship between weighted mean distress level and age after M&R, SAS's non-linear regression technique, NLIN (Ref 5), was applied.

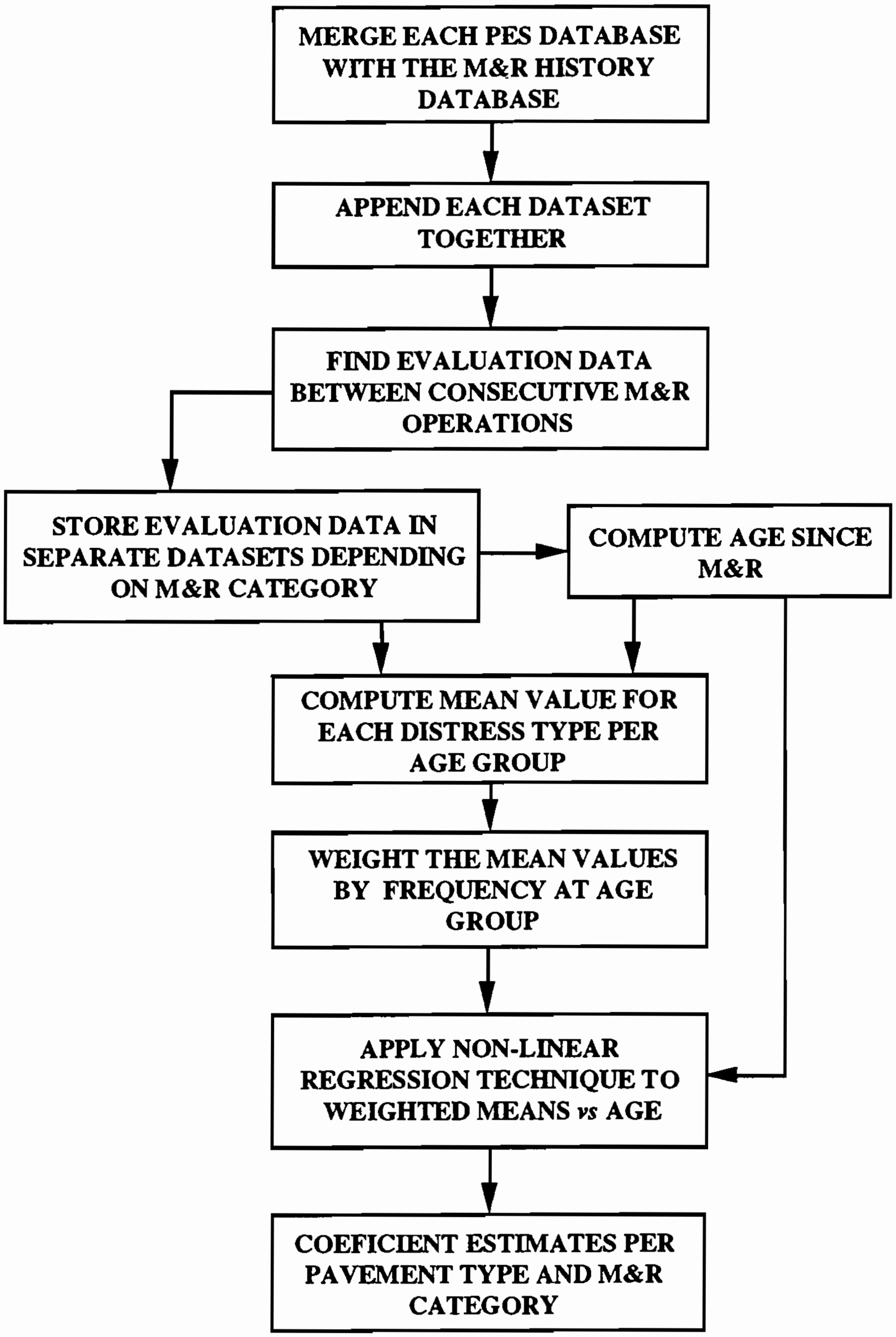


Figure 5.1. Procedure Used to Develop Distress and Performance Prediction Models After M&R

5.2 INFERENCE SPACE FOR PREDICTION MODELS

The first step was to examine the inference space in the database used for developing the models (Ref 20). This inference space determines the applicability of any model derived from the data. Since the desired models all predict distress as a function of age, several frequency distributions relating to pavement age were examined.

5.2.1 CTR CRCP DATABASE

Figure 5.2 shows the basic age distribution of the condition survey data. Every observation in the database from 1974 to 1987 (the last year a survey was performed) is considered as a separate observation. Thus, a section built in 1964 and surveyed in 1974 and 1984 would produce two observations and be counted in the 10-year and 20-year age groups on the graph. As can be seen from the figure, many observations are available over a wide range of pavement ages.

Figure 5.3 shows the current age of the pavement projects in the database, as of 1992. Most pavements in the database are now older than 15 years. Several recently constructed CRCP sections have been added to the database file, but no condition survey has been performed on them as yet.

In addition, by using the first overlay field (OV1) in the database, a rough indication of CRCP performance can be plotted. Figure 5.4 shows the distribution of pavement life, as indicated by years to first overlay. The mean time to first overlay was 16.7 years; 65 percent of the pavements were overlaid after 20 years.

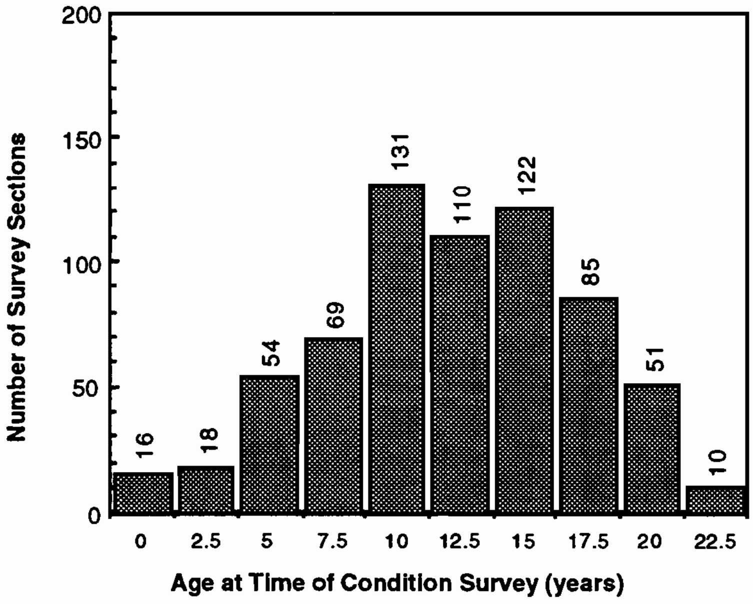


Figure 5.2. Age Distribution of Sections in the Model Inference Space

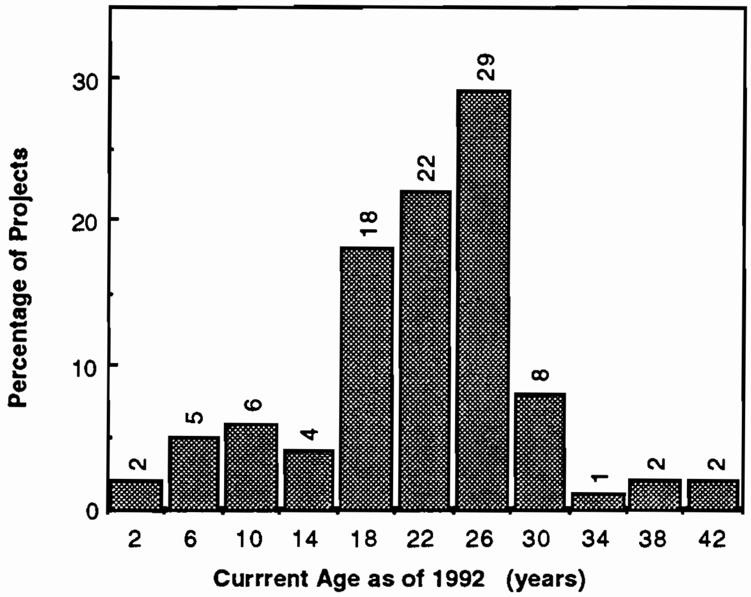


Figure 5.3. Current Age Distribution of Projects in the Database

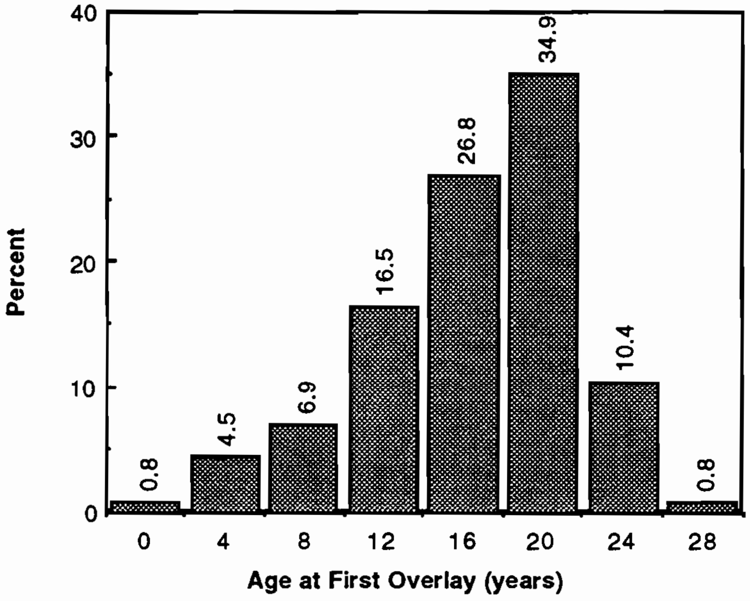


Figure 5.4. Pavement Age Distribution at First Overlay

Since environmental factors are expected to have an impact on the distress curves, a distribution of average annual minimum temperature (AAMT) was plotted. The AAMT is the yearly minimum temperature recorded at the weather station nearest the pavement segment, averaged over the years 1951-1980. This is a potentially important variable, because the interaction of temperature with rainfall (freeze-thaw cycling) and the interaction of temperature with coarse aggregate type (thermal expansion in the aggregate) may play an important role in the development of cracks and punchouts. As shown by Figure 5.5, low temperatures in Texas vary greatly, from a minimum of 7.5°F (–10.3°C) to approximately 60°F (15.6°C). A median low temperature of 30°F (–1.1°C) was selected as a separator level to differentiate "low" temperature conditions from "high" temperature conditions.

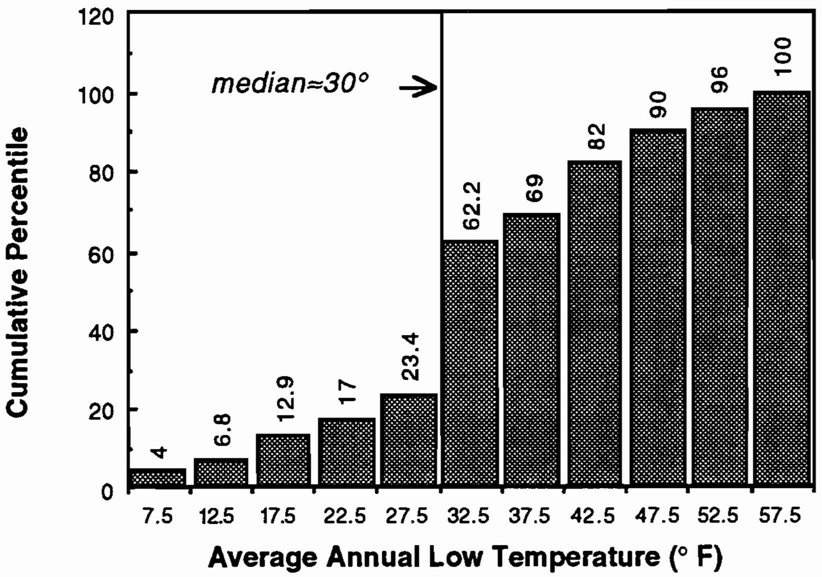


Figure 5.5. Cumulative Average Minimum Temperature Distribution

In a similar manner, the distribution of rainfall was examined (Figure 5.6). Previously a separator level of 30 inches/year (76.2 cm/year) was chosen to distinguish between "high" and "low" rainfall condition (Ref 24); the median rainfall amount of 33 inches/year (83.8 cm/year) found in this analysis agreed with the previous finding. Rainfall should also be investigated for its interaction with soil type (swelling content), which is available in the database. This investigation, however, is beyond the scope of this study.

It is expected that thicker pavements will exhibit distress later (in terms of time and loading) than thinner pavements. Unfortunately, the vast majority of survey sections in the database are 8-inch- (20.3-cm-) thick sections. Some thicker sections have been added recently and are currently being monitored. As of 1992, however, there are too few thick sections to contribute significantly to the analysis.

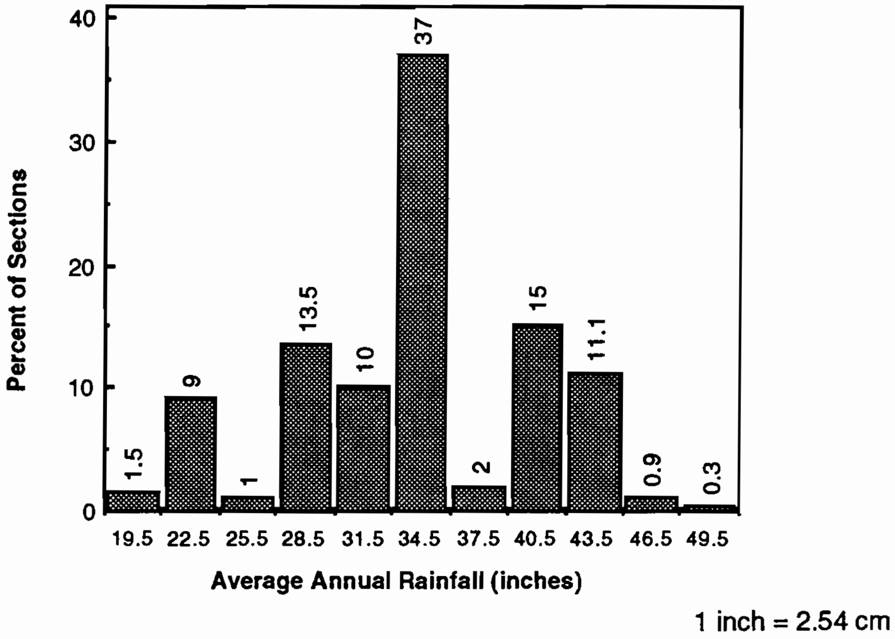


Figure 5.6. Distribution of Average Annual Rainfall

It was expected that traffic history will have a significant effect on pavement distress. For the purposes of this analysis, 18-kip equivalent single axle loads (ESAL) were used. In addition, traffic was not treated as a continuous variable but rather as a discrete variable that served as an adjustment factor to the age-distress curve, in terms of "high" or "low" traffic.

Because traffic loading has a cumulative effect on pavement performance, cumulative ESAL were calculated for each section from construction to the date the section was surveyed. The required detailed loading information was available for only 46 projects (approximately 138 sections). The available data were analyzed to determine a break point for ESAL per year which could be used to differentiate high traffic from low traffic. Figure 5.7 shows the average cumulative ESAL versus age for all the sections in the database with detailed traffic data. From this analysis, 1.4 million ESAL per year, the slope of the model in Figure 5.7, was chosen as the dividing line between high and low traffic.

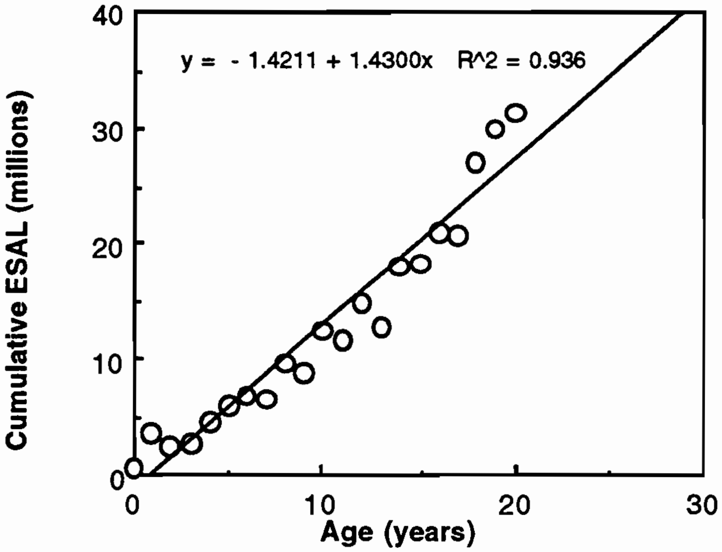


Figure 5.7. Average Cumulative ESAL for Database Sections

Cumulative ESAL data exist for relatively few sections in the database. In order to obtain enough degrees of freedom for a meaningful ANOVA, a traffic model was selected to estimate ESAL for sections which had only ADT and traffic growth rate data. Model 3 (Ref 18) produces an acceptable estimate for axle loads but should be used with caution for the urban districts in Texas, which sometimes have growth rates in excess of those represented in the model's inference space. Figure 5.8 compares the observed average two-way ESAL per year to the estimates given by Model 3.

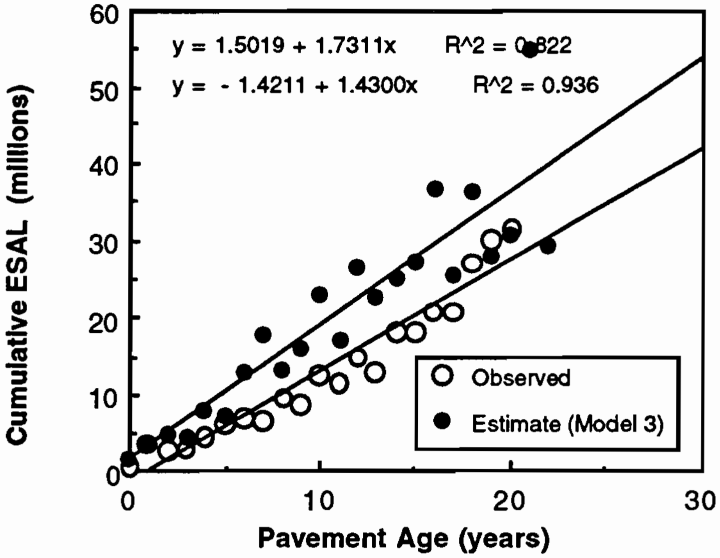


Figure 5.8. Comparison of Observed and Estimated ESAL

Model 3 estimates an average yearly ESAL of 1.7 million. This is higher than the average yearly ESAL computed from the observed data. The difference between the estimated and observed average yearly ESAL value may be due partly to the imprecision of the model, but also to the fact that, at the time the model was developed, observed ADT data were not available for many sections in the database which actually have high ADT values.

Model 3 was used to estimate ESAL values for sections in the database not having this information. These sections were then included in the analysis. Because the estimates from Model 3 are higher than the observed values for average yearly ESAL, the inclusion of these sections increased the average yearly ESAL value. It was therefore judged that this model was sufficiently accurate to determine whether ESAL/year were high or low, based on ADT. For the ANOVA, actual ESAL were used when available; otherwise the values estimated by the model were used.

Finally, it should be noted that the ESAL figures included in the database thus far are two-way ESAL across all lanes. Since only outside lanes were surveyed, a traffic distribution factor must be assumed. This, however, is outside the scope of this study and may be addressed when the traffic factor in Equation 2.4 is included in future analyses. Approximately 75 percent of the data are for pavements with two lanes in each direction.

5.2.2 INFERENCE SPACE OF PES DATA

The inference space of a dataset determines the applicability of any model derived from the data. Data items that can be used to describe the inference space of this dataset include pavement age, temperature, rainfall, and pavement thickness. None of these data items are recorded in the PES database. Initial construction dates were obtained from the TxDOT districts for a sample of PES pavement sections. Therefore, the inference space was described only with regard to pavement age. This description is presented below.

Figures 5.9, 5.10, and 5.11 present the age distribution at the time of condition survey for the PES sample sections used in this study. Every observation in the PES datasets from 1983 to 1990 is considered. Therefore, a section constructed in 1970 and surveyed in 1984 and again in 1990 would contribute to both the 14- and 20-year age groups on the graph.

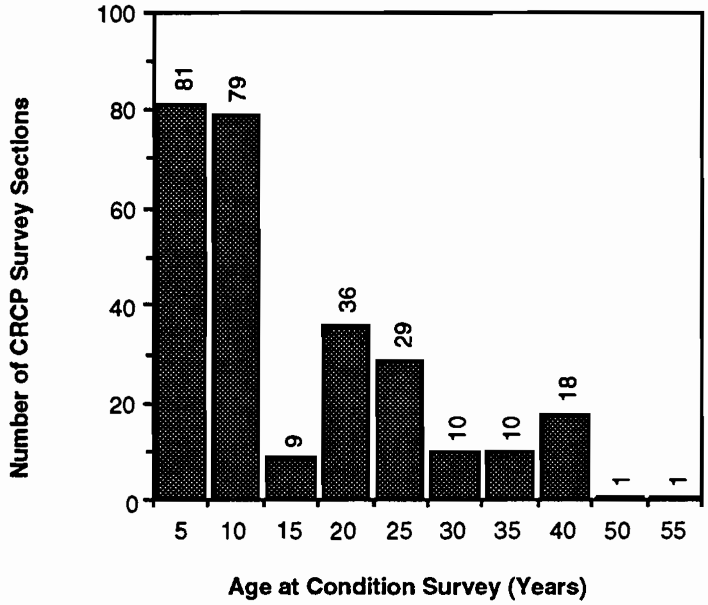


Figure 5.9. Age Distribution of PES CRCP Sections Included in the Analysis

Figure 5.10 shows that the majority of the sample JRCP sections are 20 to 45 years old. In Figure 5.11, the newest JPCP section in the sample was 20 years old. These figures indicate that the JCP network surveyed in 1990 was clearly aged.

Figures 5.9, 5.10, and 5.11 show the current age for each pavement type of the sample PES sections included in this analysis, as of the present date. Figure 5.9 shows that the majority of the sections are in the 5- to 20-year age groups as of 1990. A very small percentage was less than 5 years old.

Figures 5.10 and 5.11 show that the sections surveyed in 1990 and included in this study are relatively old.

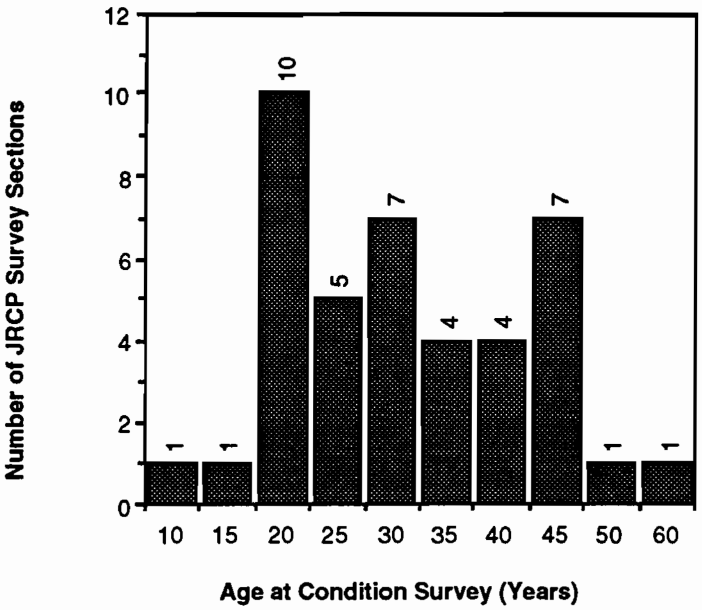


Figure 5.10. Age Distribution of PES JRCP Sections Included in the Analysis

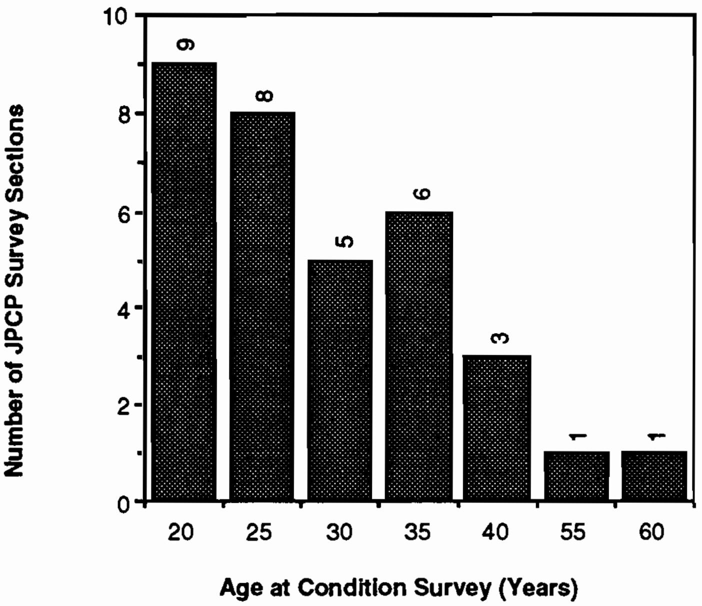


Figure 5.11. Age Distribution of PES JPCP Sections Included in the Analysis

CHAPTER 6. CRCP DISTRESS MODELS PRIOR TO ACC OVERLAY

A previous chapter of this document was devoted to describing the CTR and PES databases. This chapter concentrates on the CRCP distress models prior to any maintenance or rehabilitation activity.

6.1 ANALYSIS OF VARIANCE

An analysis of variance (ANOVA) was performed on the CTR CRCP data to determine which factors were significant predictors for each distress type (Ref 20). The factors age, cumulative ESAL since construction (CTRAF), average annual minimum temperature (TEMP), average yearly rainfall in inches (RAIN), coarse aggregate type (CAT), subbase treatment (SBT), swelling characteristics of soil (SOIL), highway type (HT), and their two-way interactions were examined. Because Interstate highways are maintained at a higher level of service, highway type (IH or US) is significant in terms of maintenance. Based on the ANOVA, the factors presented in Table 6.1 (in addition to age) were determined to be highly significant.

*TABLE 6.1. SIGNIFICANT FACTORS FROM THE ANOVA**

DISTRESS TYPE	SIGNIFICANT FACTORS
Minor Punchouts	AGE, SOIL, SOIL*CAT, TEMP*CAT, RAIN*SOIL
Severe Punchouts	CAT*AGE, AGE*TEMP, AGE, SOIL, TEMP*RAIN
PCC Patches	AGE, AGE*CAT, AGE*SBT, AGE*RAIN, AGE*HT
ACC Patches	AGE*TEMP, AGE*RAIN, AGE, AGE*HT
Cracks per 100 feet	TEMP*CAT, CTRAF*RAIN, AGE, RAIN, RAIN*AGE

*Factors connected with an asterisk are their two-way interactions

6.2 CRCP DISTRESS MODELS

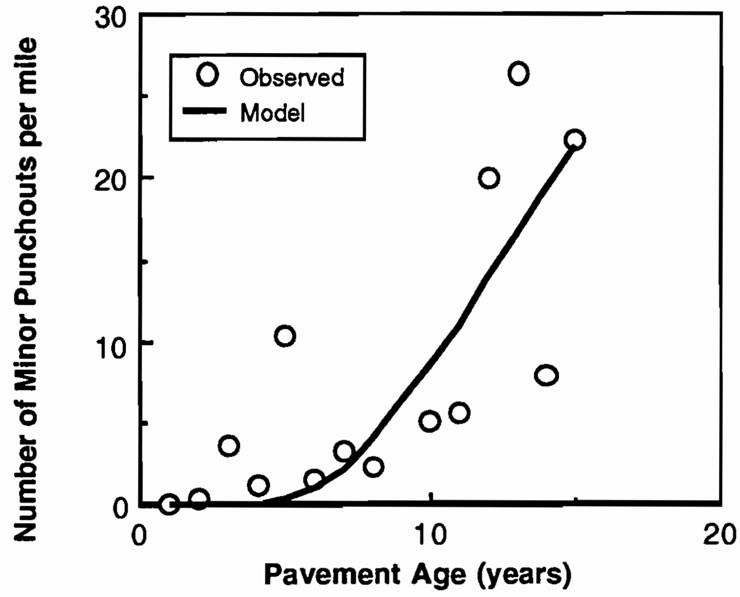
The ANOVA indicated that several factors are significant for each distress type. Pavement age was found to be one of these significant factors. The model specified by TxDOT for this study considers pavement age to be the primary predictor of distress level. However, it must be noted that, for certain distress types, the ANOVA identified other factors which were more significant predictors of distress than pavement age.

Pavement sections older than 15 years were not used in the analysis, since, after 15 years, more than half of the sections had been overlaid, and the remaining sections began to exhibit a "survivor effect." That is, any remaining data in the database are non-representative, since those 8-inch (20.3-cm) pavements which were weaker than average have already been overlaid.

The NLIN procedure from SAS, a non-linear least squares analysis, was used to find coefficient estimates for the generalized sigmoidal function (see Eq 2.4) defined in Chapter 2. The variables for modifying ρ for the effects of traffic (χ), subgrade condition (σ), and climate (ε) in Equation 2.4 were fixed at 1.0 for this study. To more clearly show the trend with time, average values weighted by frequency were used for all the analyses in this chapter.

6.2.1 MINOR PUNCHOUTS

Figure 6.1 shows the fit for minor punchouts. Considerable scatter is evident (presumably due to extrinsic climatic, structural, and loading factors), but a clear trend with age is visible. This model will give a reasonable estimate when age is the only available predictor.



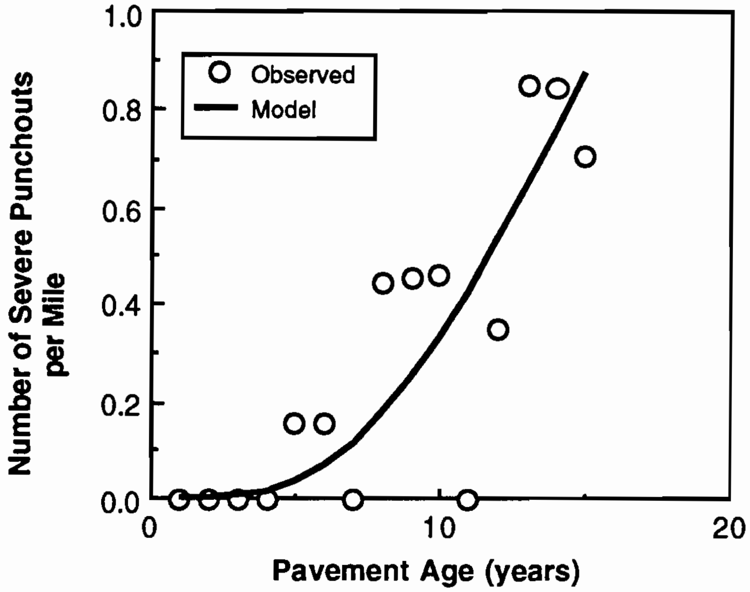
1 mile = 1.61 kilometers

$$\text{Number of Minor Punchouts per Mile} = 82.90\, e^{-\left(\frac{18.62}{AGE}\right)^{1.33}}$$

Figure 6.1. Prediction Curve for Minor Punchouts

6.2.2 SEVERE PUNCHOUTS

Figure 6.2 shows the fit for the severe punchout model. In contrast to minor punchouts, the data show that severe punchouts take longer to start developing, but that, once started, their rate of development increases rapidly.



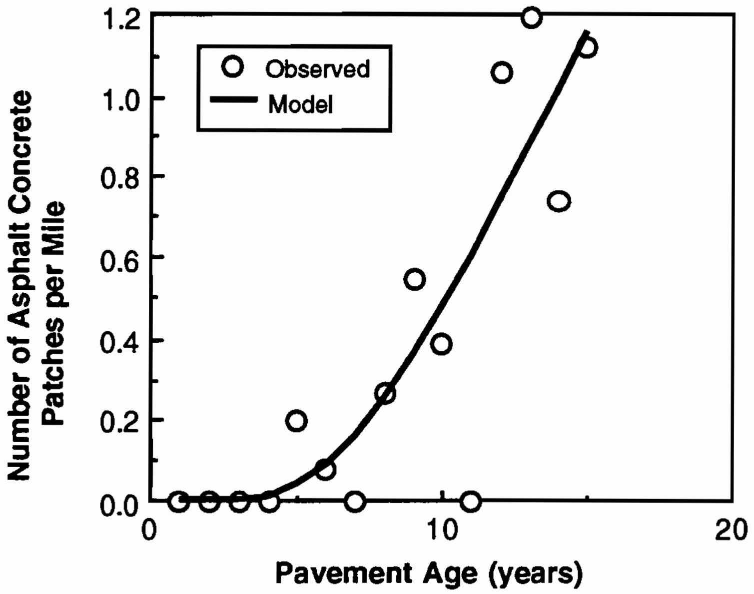
1 mile = 1.61 kilometers

$$\text{Number of Severe Punchouts per Mile} = 35.00\ e^{-\left(\frac{144.0}{AGE}\right)^{0.58}}$$

Figure 6.2. Prediction Curve for Severe Punchouts

6.2.3 ASPHALT CONCRETE PATCHES

Figure 6.3 shows the fit for the asphalt patch model. As for severe punchouts, the onset of patching is slow to begin, but, once started, it increases rapidly after 5 to 6 years.



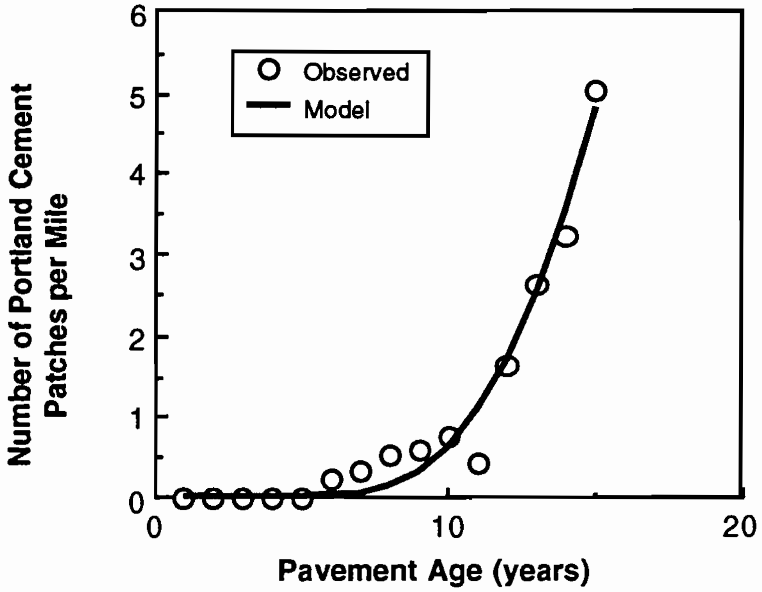
1 mile = 1.61 kilometers

$$\textbf{Number of ACC Patches per Mile} = 9.72\ e^{-\left(\frac{36.15}{AGE}\right)^{0.86}}$$

Figure 6.3. Prediction Curve for Asphalt Patching

6.2.4 PORTLAND CEMENT CONCRETE PATCHES

Figure 6.4 shows the prediction model for PCC patches. A clear trend with age is evident; no pavements in the sample were patched within the first 5 years, and an inflection point is present around 10 years, after which the rate of patching increases steeply.



1 mile = 1.61 kilometers

$$\text{Number of PCC Patches per Mile} = 146.0\ e^{-\left(\frac{40.32}{\text{AGE}}\right)^{1.23}}$$

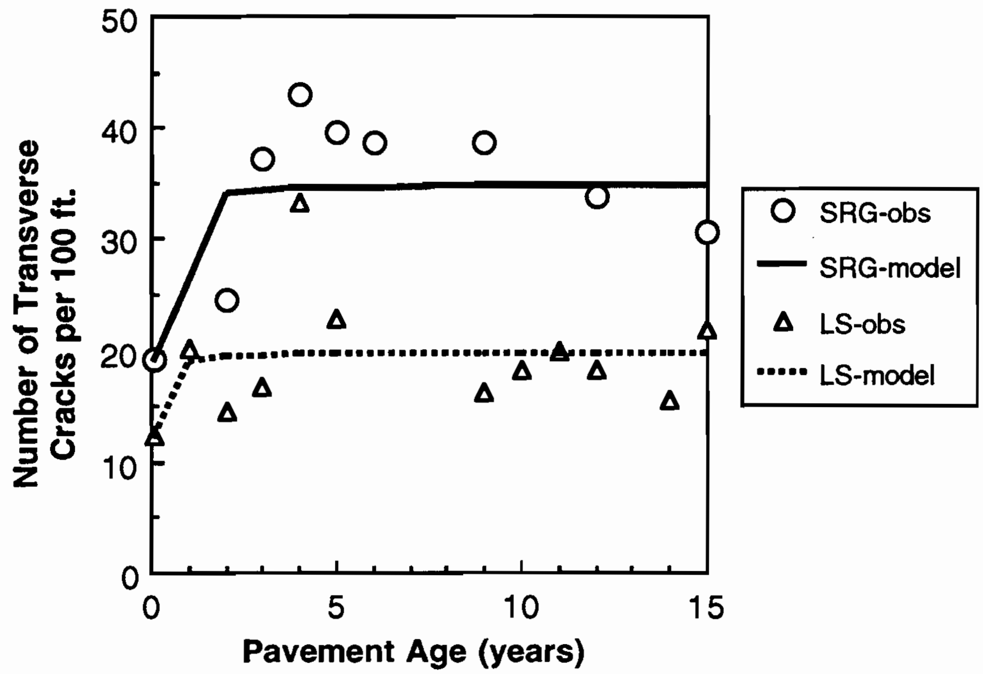
Figure 6.4. Prediction Curve for Portland Cement Concrete Patches

It must be noted that patching is not a distress per se, but rather a response to distress which is based on factors such as funding and district policy. It may be useful in the future to combine punchouts, asphalt patches, and portland cement patches into the general category "failures," as has been done in previous studies (e.g., 1244 and 472). However, these forms of distress are presented here in separate categories to maintain compatibility with the current specifications for distress models in the Texas PMIS.

6.2.5 TRANSVERSE CRACKS

Unlike the other distresses, crack spacing does not vary drastically with age (Ref 20). Typically, most early-age cracking occurs within days of slab placement, and nearly all cracking has taken place by the end of the first winter after placement. Several other factors have as much as or more influence than age, particularly coarse aggregate type. For this reason, two separate models were developed, one for limestone (LS) aggregate and another for siliceous river gravel (SRG) aggregate.

Figure 6.5 shows the fit of the model to the average crack spacing data from the CTR CRCP database. SRG is siliceous river gravel aggregate, and LS is limestone coarse aggregate.



100 feet = 30.5 meters

$$\text{Number of Transverse Cracks per 100ft. (SRG)} = 34.90\ e^{-\left(\frac{0.061}{\text{AGE}}\right)^{1.0}}$$

$$\text{Number of Transverse Cracks per 100ft. (LS)} = 19.79\ e^{-\left(\frac{0.051}{\text{AGE}}\right)^{1.06}}$$

Figure 6.5. Crack Spacing Performance Curves for Limestone and Siliceous River Gravel Aggregate Pavements

Figure 6.5 clearly shows that transverse crack development in limestone aggregate pavements tends to increase from around 12 to 20 cracks per 100 feet (per 30.5 m) in a fairly short period of time, and then to stay basically constant thereafter. Crack spacing on SRG pavements often increases with time to over 35 cracks per 100 feet (per 30.5 m). The slight decrease in the number of cracks in SRG pavements observed from 9 to 15 years is probably an early-age survivor effect, since many of these pavements are overlaid at an early age. Additional scatter in the plot may be explained by other extrinsic factors, such as temperature and season of placement (especially if the peak temperature coincided with peak heat of hydration). But again, due to the lack of data it was not possible to quantify these factors. Subbase friction, percent steel, and slab thickness may also play a role in increasing the scatter. Minimum temperature is included in the database, and its interaction with aggregate type was found to be significant. This is probably due to the large difference in thermal coefficients between the two aggregate types.

6.2.6 CRACK SPALLING

Data for spalling were extracted from archives of historical condition surveys, conducted by CTR in 1974, 1978, 1980, 1982, and 1984 (Ref 22). The 1974 data could not be used because only the percentage of spalled cracks was recorded, not the actual number of cracks. In subsequent years the data included both the percentage of spalled cracks and the total number of cracks. Spalling data were divided into two categories, minor and severe. Minor spalling was defined by CTR as "edge cracking where the loss of material has formed a spall 1/2 inch wide or less" (1.3 cm wide or less). If the spall is greater than 1/2 inch (1.3 cm) wide, it is classified as severe. Since the PES definition of spalling specifies spalling of "at least 1 inch wide" (2.5 cm wide), a decision was made to consider only the CTR severe spalling data in the analysis.

Figure 6.6 shows the distribution of the data relative to pavement age. Of the total of 18,554 sections, 85 percent were more than 5 years old at the time of the survey. The amount of data from all age groups was sufficient for modeling. Sections older than 15 years at the time of survey were not used in the analysis, since it has been shown in the analysis of the other distress types that a survivor effect tends to dominate after this period, as pavements are overlaid and removed from the sample population.

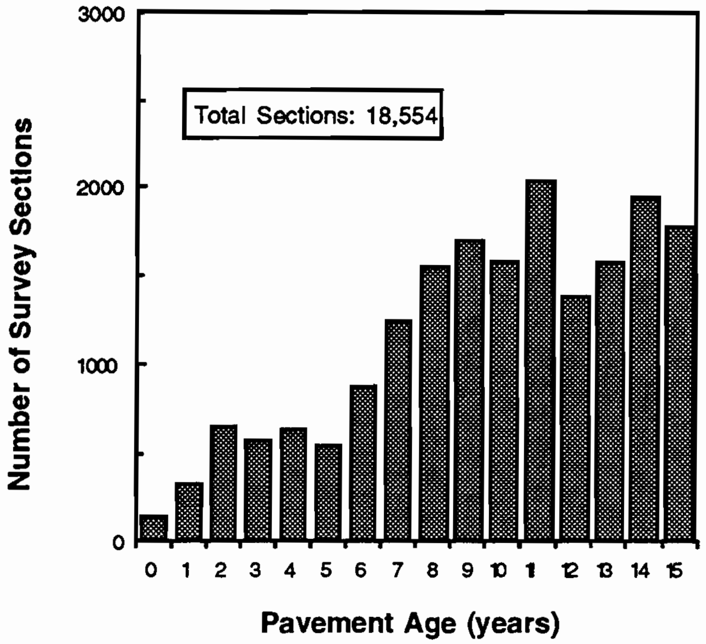
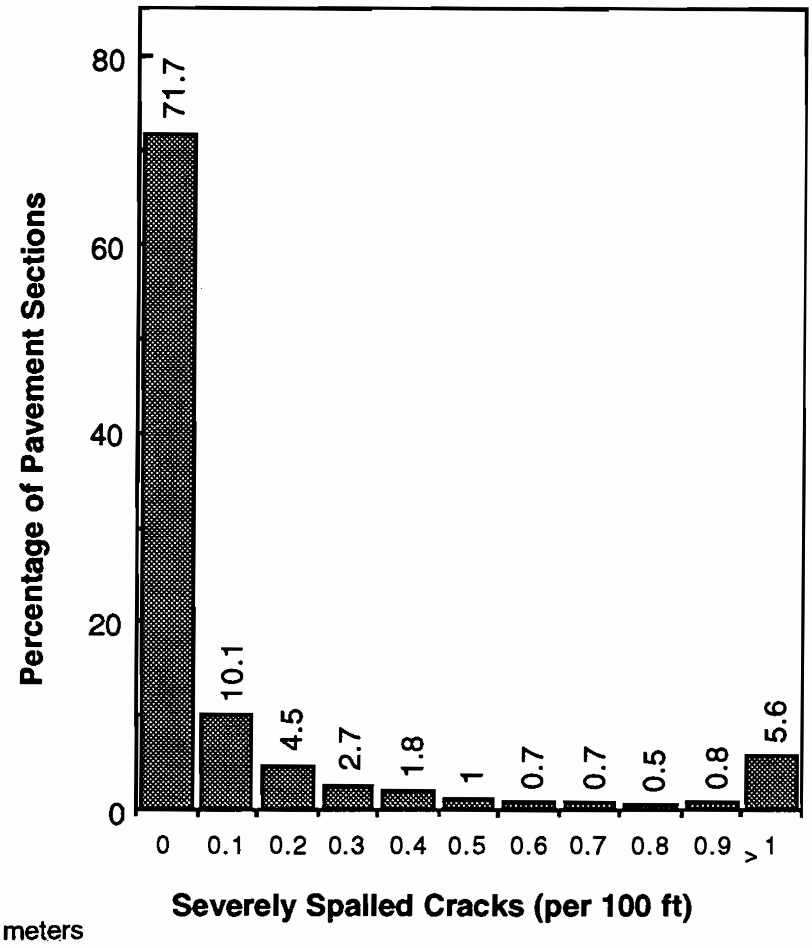


Figure 6.6. Age Distribution of Pavements at the Time of Survey

Figure 6.7 shows the distribution of the spalling data. The majority (72 percent) of survey sections displayed no spalling. This causes a severe skew in the data that makes them difficult to analyze. Further analysis was needed to identify factors which could explain why some sections suffer severe spalling while others do not.

An analysis of variance (ANOVA) was performed to determine which pavement, climate, and traffic factors had the most significant influence on the rate of spalling development. The factors considered were pavement age (AGE), pavement thickness (D), 1985 annual average daily traffic (ADT85), coarse aggregate type (CAT, river gravel or limestone), average annual rainfall (RAIN), mean annual low temperature (TEMP), subbase treatment (SBT), and highway type (HT). HT functions as a surrogate for other variables which have not been collected historically. Some possibilities for these "hidden variables" might be cross-section, layer thickness, steel reinforcement, or even policy issues such as maintenance intervals, distress thresholds, etc. The two-way interactions of age with the other predictors were also included in the analysis. Factors excluding age were not tested since the model specified in Chapter 2 requires that structural, climatic, and traffic factors be included only as modifiers to the age versus distress curves. Table 6.2 lists the factors found to be most significant.



100 feet = 30.5 meters

Figure 6.7. Distribution of Spalled Cracks

As shown in the table, the interaction of age with coarse aggregate type was the best predictor for crack spalling, followed by the cumulative rainfall on the section (Age*Rain), the age of the section, and the interaction of age with the type of subbase treatment.

TABLE 6.2. MOST SIGNIFICANT FACTORS FOR SEVERE SPALLING

FACTOR	F-SCORE	SIGNIFICANCE
Age*CAT	598.00	$p<0.0001$
Age*Rain	339.30	$p<0.0001$
Age	265.30	$p<0.0001$
Age*SBT	184.10	$p<0.0001$

Figure 6.8 shows the development of severe spalling with age for several commonly used coarse aggregates. From this figure, it seems that spalling develops with age, possibly at an exponential rate. Pavements constructed using SRG coarse aggregate exhibited an average rate of spalling more than ten times the rate of limestone pavements. The aggregate type "other" in Figure 6.8 consists of blended limestone and river gravel, or sometimes slag blended with limestone or gravel. These are grouped together because there are relatively few of them compared to LS and SRG pavements. Since they often include some SRG material, it is reasonable that their rate of spalling would lie somewhere in between "pure" LS and SRG aggregates.

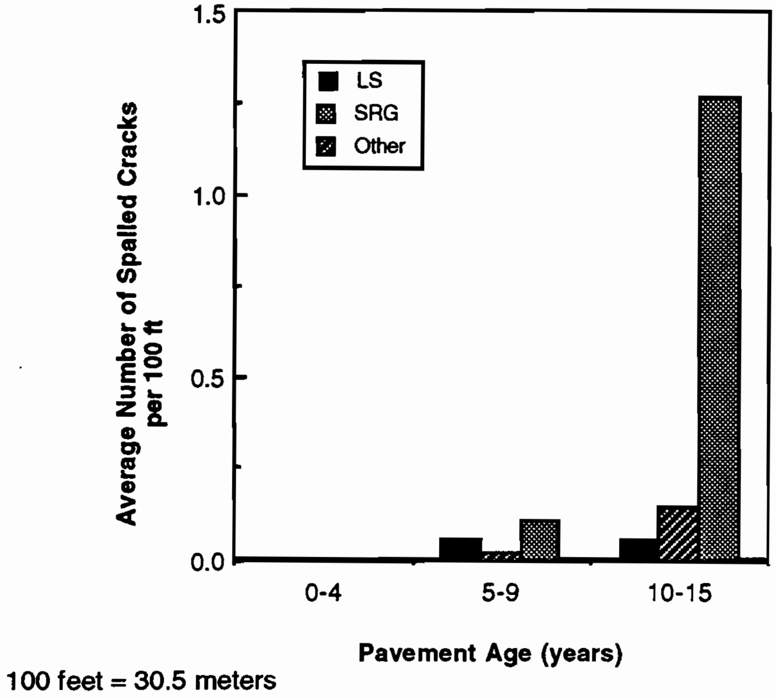
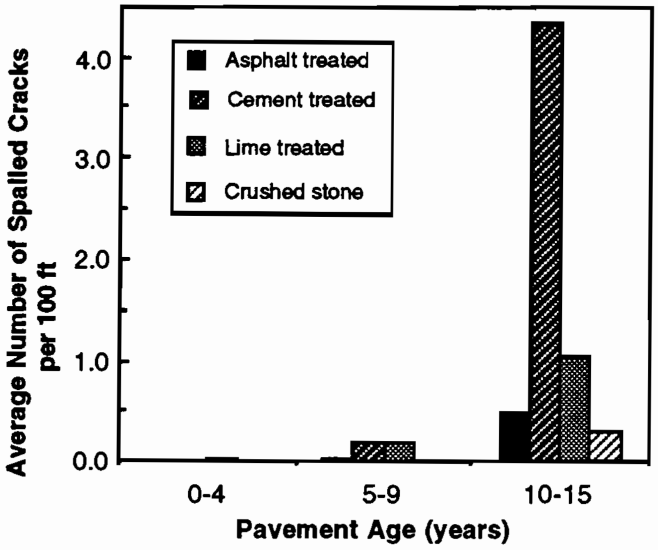


Figure 6.8. Spalled Cracks by Age and Coarse Aggregate Type

Figure 6.9 illustrates the relative effectiveness of the various subbase treatments, which were identified by the ANOVA as significant in predicting spalling rate. From the limited data available, crushed stone gave the best performance, followed by asphalt-treated subbase. The worst choice was cement-treated subbase.

These extrinsic factors, aggregate type, rainfall, age, and subbase treatment, explain (in part) why many pavements exhibit no crack spalling at all while others are severely spalled. Because of the extremely different performance of LS- and SRG-based pavements, at least two curves are needed to adequately model spalling.



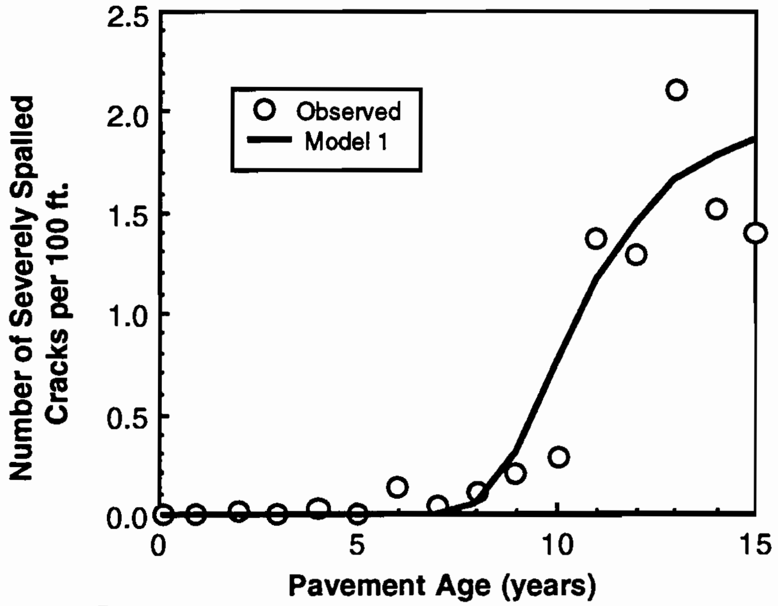
100 feet = 30.5 meters

Figure 6.9. Effect of Subbase Treatment on Spalling in Siliceous River Gravel Pavements

Spalling for CRCP was expressed as number of spalled cracks per 100 feet (per 30.5 m) of pavement. Figure 6.10 shows the fit to the SRG pavement data.

Pavements constructed of limestone coarse aggregate were much less prone to spalling. Figure 6.11 shows the fit to the limestone pavement spalling data.

Although the curves given accurately reflect the average values across Texas for severe spalling, it must be noted that a wide variance exists even within a given aggregate type that is not fully explained by the predictor variables in Table 6.3. Many sections from each aggregate type experienced no severe spalling.

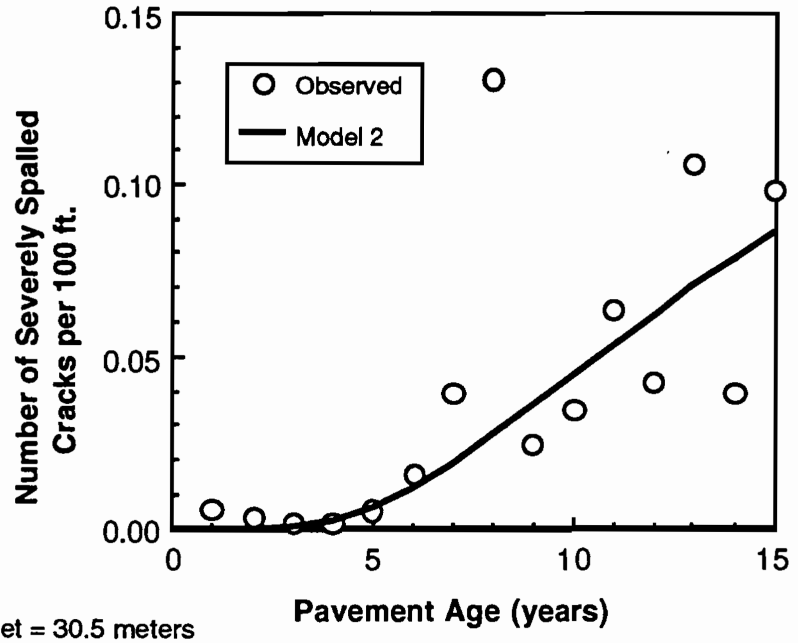


100 feet = 30.5 meters

1 mile = 1.61 kilometers

Number of Spalled Cracks per Mile (SRG) = $2.02\, e^{-\left(\frac{10.0}{AGE}\right)^{6.06}}$

Figure 6.10. Spalling Model (Siliceous River Gravel)



100 feet = 30.5 meters

1 mile = 1.61 kilometers

$$\text{Number of Spalled Cracks per Mile (LS)} = 0.33\, e^{-\left(\frac{20.0}{\text{AGE}}\right)^{1.00}}$$

Figure 6.11. Spalling Model (Limestone)

TABLE 6.3. COEFFICIENTS FOR CRCP DISTRESS MODELS BEFORE ANY M&R ACTIVITY (CTR DATABASE)

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
Minor Punchouts	82.90	1.33	18.62
Severe Punchouts*	35.00	0.58	144.00
PCC Patches	146.00	1.23	40.32
ACC Patches	9.72	0.86	36.15
Cracks/100 feet – LS	19.79	1.06	0.051
Cracks/100 feet – SRG	34.90	1.00	0.061
Crack Spalling – LS*	0.33	1.00	20.00
Crack Spalling – SRG*	2.02	6.06	10.00
Fractional PSI Loss	0.27	1.00	1.00

*Conforms to PES definition of distress

100 feet = 30.5 meters

6.2.7 *RIDE SCORE*

Data for ride score were extracted from archives of historical condition surveys. These surveys were conducted periodically by CTR in 1974, 1978, 1980, 1982, and 1984 (Ref 23). Approximately 300 projects were selected across Texas. A project consists of a continuous length of pavement with homogeneous properties such as pavement thickness, coarse aggregate type, traffic, etc. For most years, the condition surveys were carried out on every 0.2-mile (0.32-km) survey section within the overall project; in 1984, the survey section length was increased to 0.4 miles (0.64 km). Because so many subsections were surveyed for each project, a large amount of data was available for the analysis.

Figure 6.12 shows the distribution of the data relative to pavement age. Of the total of 8,878 sections surveyed, 45 percent were between 6 and 9 years old when surveyed. Although the distribution was skewed toward middle-aged pavements, a sufficient number of younger and older pavements were available to proceed with the analysis.

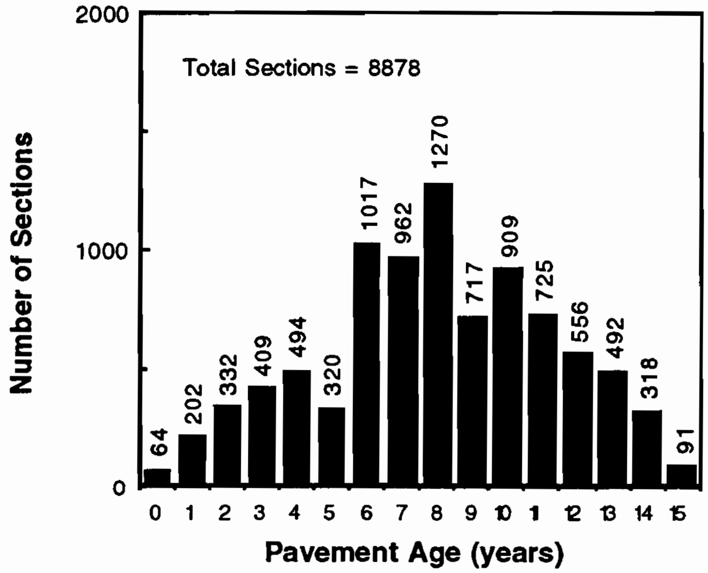


Figure 6.12. Age Distribution of Ride Scores at the Time of Survey

Figure 6.13 shows the distribution of the data relative to roughness, in SI units. Like the age distribution, it was non-uniform, with 84 percent of the pavement sections falling in the range from 3.0 to 4.0 (smooth). Although overlaid sections were excluded from the analysis, the overall good condition of the pavements probably reflects routine maintenance and light rehabilitation procedures, which are not documented in the database and thus could not be captured in the analysis. A plot of average PSI versus age (see Figure 6.14) shows a slight 2-year periodicity which is probably indicative of periodic maintenance.

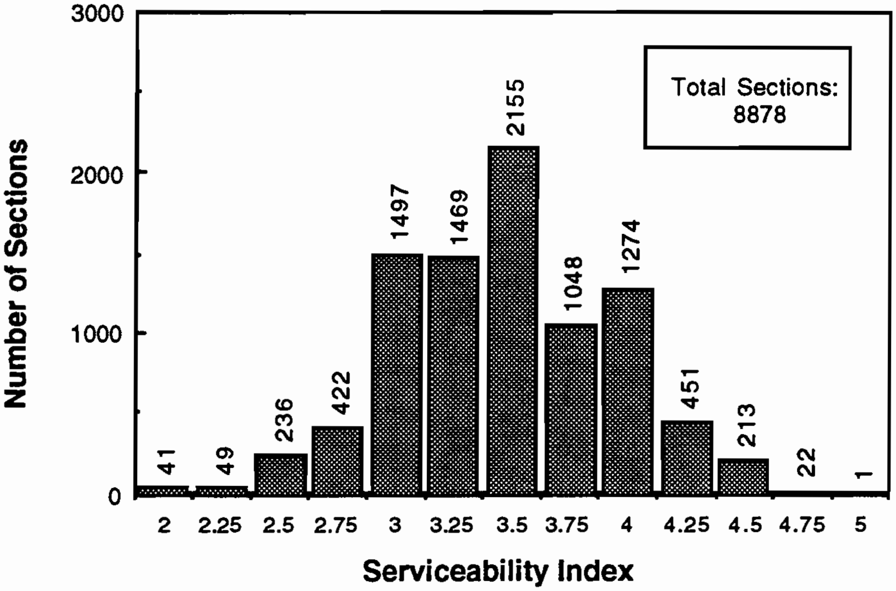
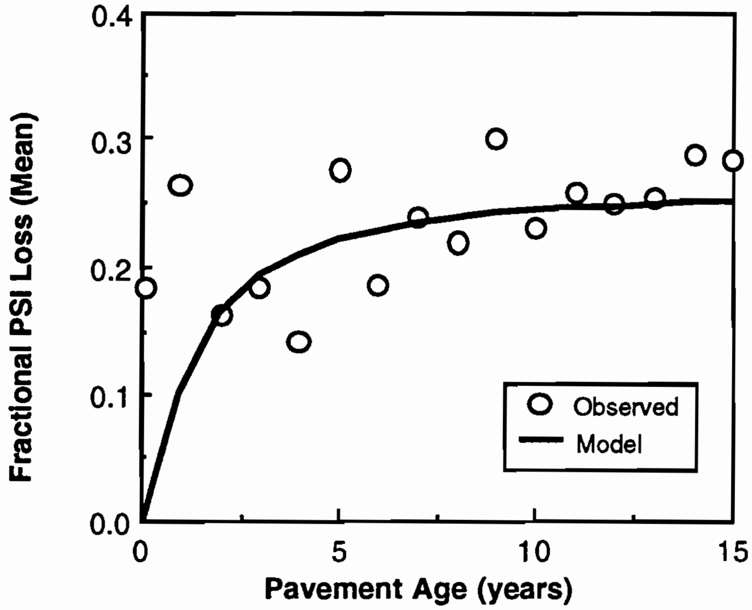


Figure 6.13. Distribution of Serviceability Index Data

Ride score for CRCP was modeled as fractional PSI loss versus age, normalized to a hypothetical initial SI of 4.5. The normalized SI loss (NSL) was calculated as follows:

NSL = (4.5 - PSI) / 4.5

NSL ranges from 0 (PSI ≥ 4.5) to 1 (PSI = 0). For example, if the present serviceability index (PSI) of a section is 3.5, then the section is assumed to have lost 1 SI unit of ride quality, giving an NSL of 0.22. This means the section has lost 22 percent of its initial smoothness. Figure 6.14 shows the best fit to the data.



$$\textbf{Fractional PSI Loss} = 0.27\ e^{-\left(\frac{1.0}{AGE}\right)^{1.0}}$$

Figure 6.14. Best Fit Model for Loss of Ride Score

When Figure 6.14 is examined, it should be remembered that the model was fit to the weighted average values of PSI; many more data points were available for medium age pavements than for 14- and 15-year old pavements. Thus the curve shown in Figure 6.14 passes through the 12- and 13-year points which are heavily weighted, but is pulled down from the 14- and 15-year points which have very few observations and thus less effect on the regression.

Table 6.4 summarizes the coefficient values in Equation 2.4 for each CRCP distress type before any M&R activity.

6.3 PES CRCP DISTRESS MODELS

An examination of condition data from the PES database showed a poor correlation between distress level and pavement age for most distress and pavement types. The data from the CTR databases displayed a much better relationship between pavement age and distress level for most distress types. Therefore, all models for CRCP performance prior to overlay were developed using the CTR database.

TABLE 6.4. COEFFICIENTS FOR CRCP DISTRESS MODELS BEFORE ANY M&R ACTIVITY (PES DATABASE)

DISTRESS TYPE	**MODEL COEFFICIENTS**		
	α	β	ρ
Punchouts	No Data	No Data	No Data
PCC Patches	No Data	No Data	No Data
ACC Patches	No Data	No Data	No Data
Cracks/100 feet – LS	No Data	No Data	No Data
Cracks/100 feet – SRG	No Data	No Data	No Data
Crack Spalling – LS	No Data	No Data	No Data
Crack Spalling – SRG	No Data	No Data	No Data
Fractional PSI Loss	No Data	No Data	No Data

100 feet = 30.5 meters

CHAPTER 7. JCP DISTRESS MODELS PRIOR TO ACC OVERLAY

The CTR database does not differentiate between JRCP and JPCP sections. These two pavement types have different performance characteristics simply by the nature of their design. Ideally, separate distress prediction models should be developed for each of these pavement types. Therefore, some of the scatter observed in the distress data may be attributed to the combination of the data for the two different pavement types.

Figure 7.1 shows that the number of observations after 15 years decreases steadily due to the sections being overlaid with asphalt or being removed from the network. The remaining sections exhibit the "survivor effect"; that is, they are stronger than average and are therefore non-representative. Consequently, in order to develop representative models, pavement sections older than 15 years at the time of condition survey were excluded from this analysis.

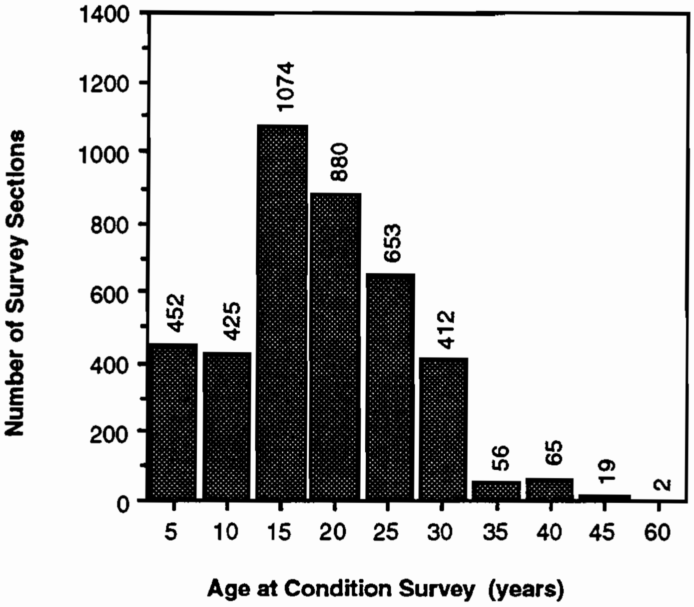


Figure 7.1. Age Distribution of CTR JCP Survey Sections

The NLIN procedure from SAS was used to find the best fit coefficients for the generalized sigmoidal function discussed in Chapter 2. The variables for modifying ρ for the effects of traffic (χ), subgrade condition (σ), and climate (ε) in Equation 2.4 were fixed at 1.0 for this study. To show more clearly the trend with age, average values weighted by frequency were used for the analysis.

Unlike in the CRCP distress modeling process, where distress level was regressed against pavement age group, the modeling for JCP sections regressed distress level against pavement age. Because of the poor trends in the data, scatter plots of the observations are included to assist in visualizing trends. These charts showed considerable scatter and no trend in the data with pavement age.

As stated previously, the objective of this study was to develop preliminary prediction models for the Texas PMIS with available data. Therefore, despite the poor relationship between pavement age and distress level, prediction curves were formulated with the available data, based on theoretical knowledge of distress mechanisms and development with time.

7.1 JCP DISTRESSES PRIOR TO M&R ACTIVITY

The following JCP distresses were found to be significant and are discussed below.

7.1.1 ACC AND PCC PATCHES

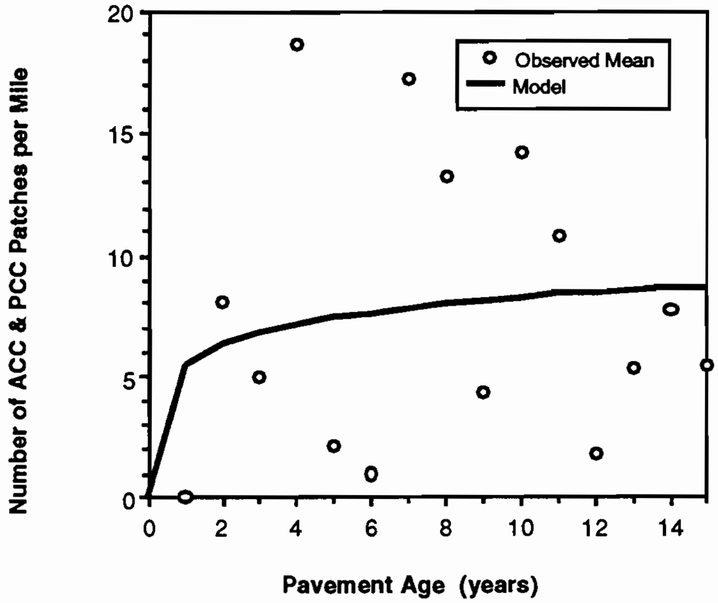
Data from the 1982 and 1984 CTR JCP databases were used in the development of the prediction model for ACC and PCC patches. The CTR data for patches include both ACC and PCC patches. The PES database records only the number of PCC patches. Therefore, if the model developed using the CTR data is used with current PES data, pavement age and maintenance effectiveness will be underestimated.

Figure 7.2 shows the scatter plot of observations for patches versus pavement age. The data show no precise trend with age. One of the factors that may explain this lack of trend is the inclusion of ACC and PCC patches for JRCP and JPCP into a single distress measure. However, it is expected that the number of patches per mile should increase with pavement age.

1 mile = 1.61 kilometers

Figure 7.2. Scatter Chart of Observations for Patches

Figure 7.3 presents the curve best fitted to the means of the observed data. This model indicates that patches develop at a steady rate after the first year of construction.



1 mile = 1.61 kilometers

$$\text{Number of Patches per Mile} = 22.25\ e^{-\left(\frac{10.0}{\text{AGE}}\right)^{0.15}}$$

Figure 7.3. Prediction Curve for Patches

7.1.2 CORNER BREAKS

Corner breaks are one of the five distress types that comprise failures as defined by PES. The other four distress types included in the measure of failures are punchouts, asphalt patches, concrete patches, and D-cracking. Table 4.2, which lists the prevalent distress types for JCP sections in Texas, does not include these four distress types. Therefore, the model for predicting the number of corner breaks per mile (per 1.61 km), developed using the CTR data, may be used as a substitute for predicting the number of failures per mile (per 1.61 km) in Texas.

Figure 7.4 shows the scatter plot of the observations for the number of corner breaks per mile (per 1.61 km). Corner breaks per mile (per 1.61 km) is a function of the slab length. Also, JRCP sections have longer slab length than JPCP sections. The smaller the slab length, the more slabs per mile (per 1.61 km), and therefore the greater the chances of more corner breaks per mile (per 1.61 km). The CTR database does not record the slab length; therefore, the model could not capture this factor, which may have explained some of the variance in the observed data.

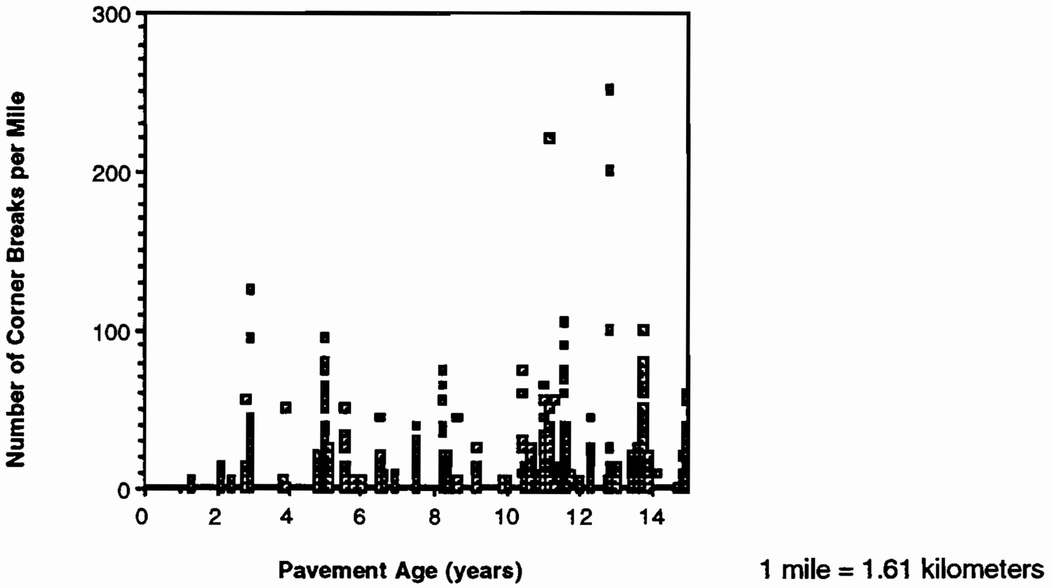
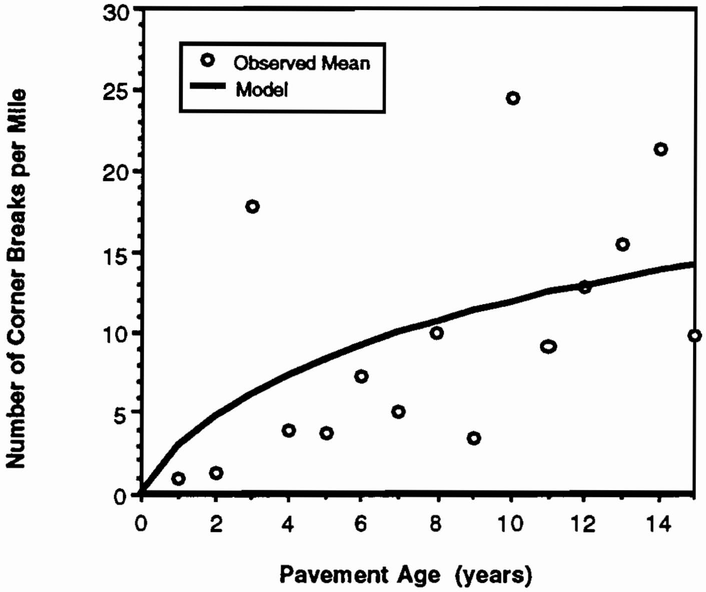


Figure 7.4. Scatter Chart of Observations for Corner Breaks

Figure 7.5 presents the model predicting the number of corner breaks per mile (per 1.61 km). The slight scatter in the observed means may be attributed to the data representing various slab lengths and pavement types.



1 mile = 1.61 kilometers

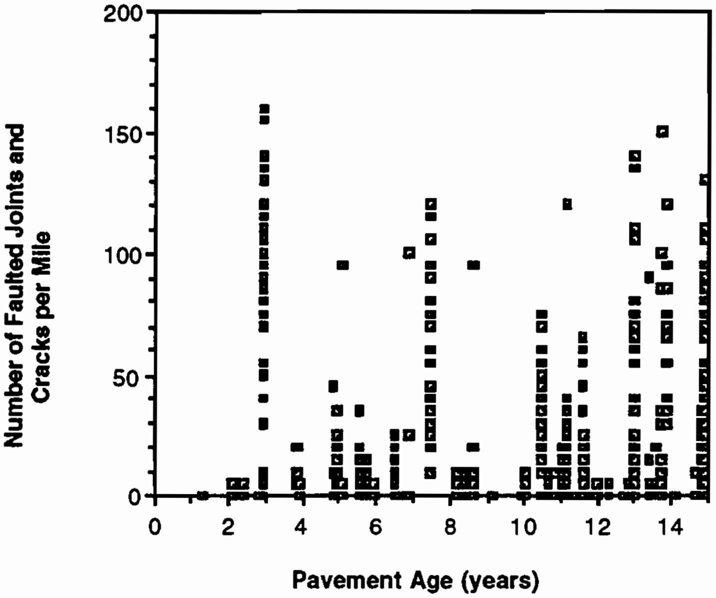
$$\text{Number of Corner Breaks per Mile} = 104.81\ e^{-\left(\frac{373.87}{\text{AGE}}\right)^{0.22}}$$

Figure 7.5. Prediction Curve for Corner Breaks

7.1.3 FAULTED JOINTS AND CRACKS

Data for developing the prediction model for faulted joints and cracks were obtained from the 1982 and 1984 CTR JCP databases. Figure 7.6 presents the scatter chart of the observed data for faulted joints and cracks. Considerable scatter and no clear trend with pavement age is evident. Engineering intuition suggests that faulting at joints and cracks should increase with pavement age. However, the degree of faulting is also dependent on the presence and condition of load transfer devices. Over time, load transfer devices deteriorate and may fail, resulting in faulting at the joint. Newly constructed pavements can also exhibit faulting if load transfer devices are absent or are incorrectly installed.

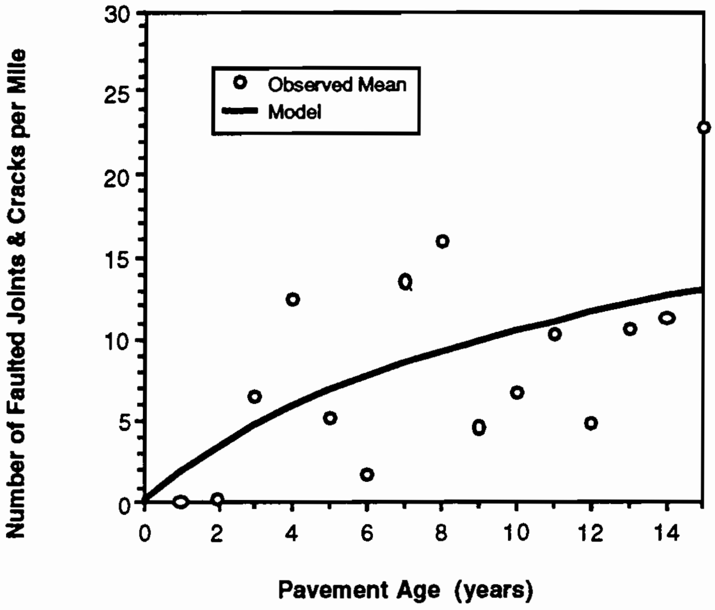
Faulting at cracks is due to loss of interlock between the aggregate on each side of the crack and voids beneath the slab at the crack. Reinforcing in the slab may help keep crack widths to a minimum, thereby ensuring aggregate interlock. Minimizing crack widths also prevents the ingress of water and thereby reduces the chances of pumping and the formation of voids.



1 mile = 1.61 kilometers

Figure 7.6. Scatter Chart of Observations for Faulted Joints and Cracks

The data available for modeling purposes in this study cannot be separated into pavements with and without load transfer devices or reinforced and non-reinforced pavements. These limitations of the data may explain some of the scatter in the observed data. Figure 7.7 shows the best fit curve through the observed means.



1 mile = 1.61 kilometers

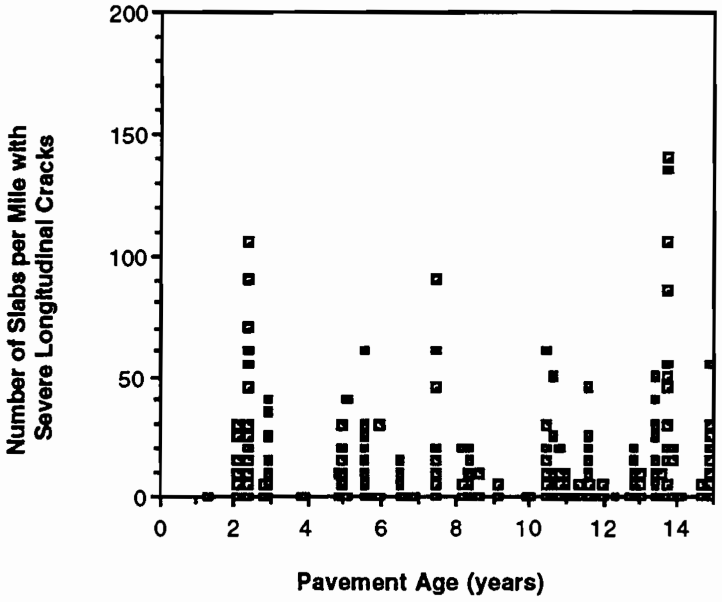
$$\text{Number of Faulted Joints \& Cracks per Mile} = 89.42\ e^{-\left(\frac{189.08}{\text{AGE}}\right)^{0.26}}$$

Figure 7.7. Prediction Curve for Faulted Joints and Cracks

7.1.4 SLABS WITH SEVERE LONGITUDINAL CRACKS

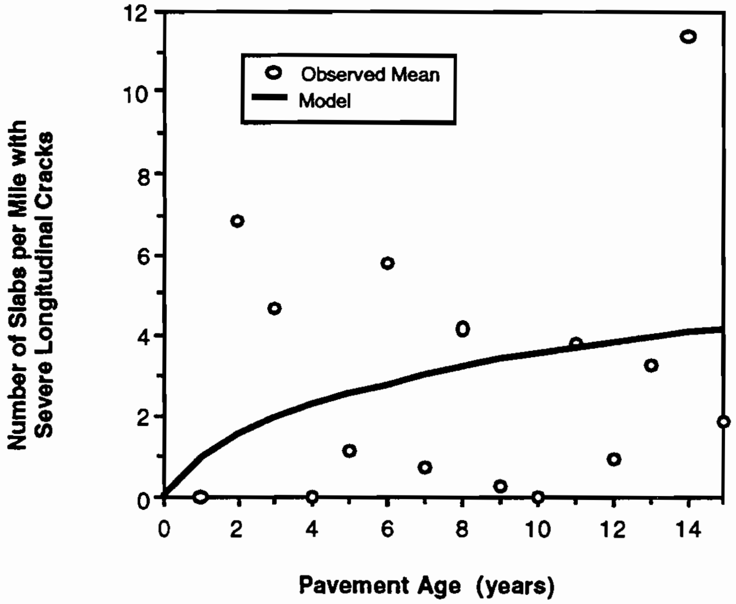
Longitudinal cracks are caused by one or by a combination of the following factors, viz., lateral contraction of the slab, curling, bending, lack of bearing support, failure of a fill, or paving practice. Pavement characteristics that can help quantify the above effects are slab dimensions, subgrade type, subgrade bearing capacity, and construction joint spacing. However, the data available for this analysis do not include these pavements characteristics. These aggregated data may explain some of the scatter observed in Figure 7.8.

Figure 7.9 shows the prediction curve for the number of slabs with severe longitudinal cracks.



1 mile = 1.61 kilometers

Figure 7.8. Scatter Chart of Observations for Slabs with Severe Longitudinal Cracks



1 mile = 1.61 kilometers

$$\text{Number of Slabs per Mile with Long. Cracks} = 29.68\, e^{-\left(\frac{410.29}{\text{AGE}}\right)^{0.21}}$$

Figure 7.9. Prediction Curve for Slabs with Severe Longitudinal Cracks

7.1.5 SPALLED JOINTS AND CRACKS

The scatter plot of the observations for spalled joints and cracks in Figure 7.10 shows no trend with pavement age. Spalling may be due to one, or to a combination, of the following factors: (1) movement of a crack or joint under load due to a void beneath the slab, or (2) incompressible material lodged in a crack or joint, preventing the slab from expanding as a result of a change in temperature. These factors develop over time, therefore implying that the development of spalling should also be related. To ensure that the model reflected this positive trend with age, the values for the β and ρ coefficients in Equation 2.6 were restricted to 1.0. The prediction model is presented in Figure 7.11.

Previously it was found that the type of coarse aggregate used to construct the pavement slab influenced the development of spalling. Two separate spalling models were developed to account for this phenomenon. Such an analysis, however, cannot be performed for the JCP spalling model, because the coarse aggregate type data are not recorded in the CTR JCP database.

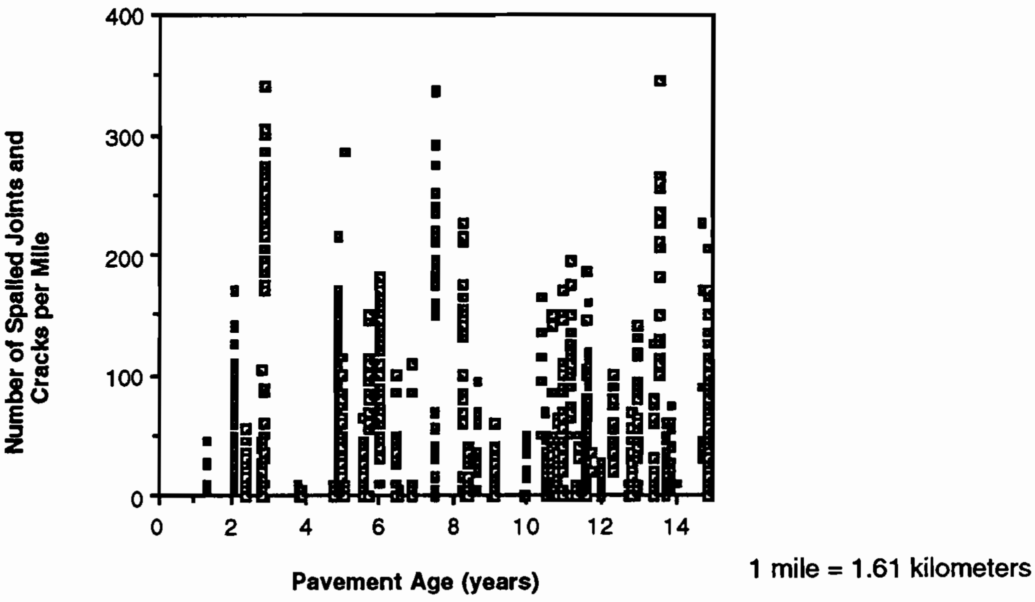
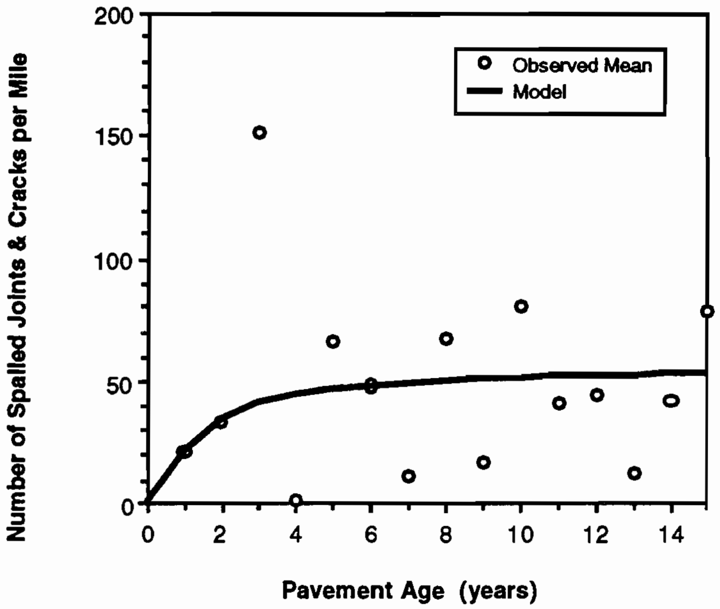


Figure 7.10. Scatter Chart of Observations for Spalled Joints and Cracks



1 mile = 1.61 kilometers

$$\textbf{Number of Spalled Joints \& Cracks per Mile} = 56.75\ e^{-\left(\frac{1.0}{AGE}\right)^{1.0}}$$

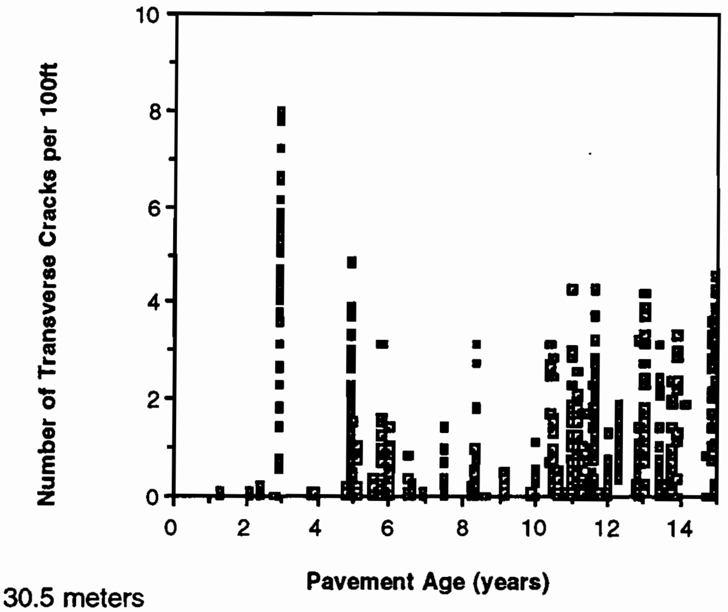
Figure 7.11. Prediction Curve for Spalled Joints and Cracks

7.1.6 TRANSVERSE CRACKS

The scatter chart in Figure 7.12 shows the observations for the number of transverse cracks per 100 feet (30.5 km) versus pavement age. There is no obvious trend with pavement age. In the analysis of the CTR CRCP data, it was found that most cracking occurs by the end of the first winter after construction. Thereafter the amount of cracking remains fairly constant.

Transverse cracking in JCP sections is dependent on slab length, width, and thickness and on the coarse aggregate type used in the slab construction. Unfortunately, none of these data are recorded in the CTR or PES databases.

Alternately, the effect of slab dimensions and aggregate type can be measured indirectly by recording the number of transverse discontinuities. Transverse discontinuities include both transverse cracks and joints. Transverse joints are spaced so as to minimize the number of uncontrolled transverse cracks. However, data on transverse discontinuities are also not available in the current CTR or PES databases and therefore could not be included as a factor in the model.

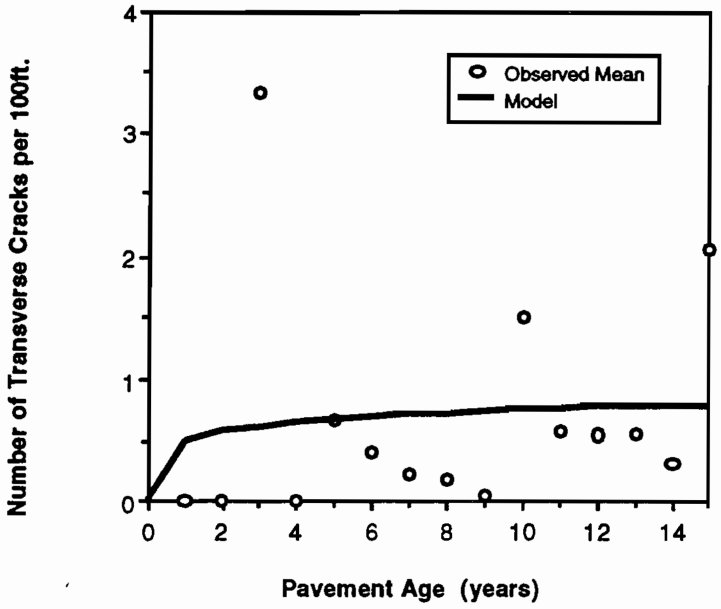


100 feet = 30.5 meters

Figure 7.12. Scatter Chart of Observations for Transverse Cracks

Figure 7.13 presents the model for predicting the number of transverse cracks per 100 feet (30.5 km). This curve shows that the greatest rate of crack development occurs within the first year after pavement construction. This is consistent with the findings in CRCP analysis, which is also applicable to JCP sections.

Because factors for coarse aggregate type and slab dimensions could not be included in this analysis due to the lack of data, the model presented in Figure 7.13 for transverse cracking has limited applicability and significance.



100 feet = 30.5 meters

$$\text{Number of Transverse Cracks per 100ft.} = 107.27\ e^{-\left(\frac{10.0}{AGE}\right)^{0.15}}$$

Figure 7.13. Prediction Curve for Transverse Cracks

7.2 JCP DISTRESS COEFFICIENTS

Table 7.1 summarizes the coefficient values for Equation 2.4 for each JCP distress type before ACC overlay from the CTR database.

TABLE 7.1. COEFFICIENTS FOR JCP DISTRESS MODELS: BEFORE ACC OVERLAY (CTR DATABASE)

DISTRESS TYPE	**MODEL COEFFICIENTS**		
	α	β	ρ
Patches	22.25	0.15	10.00
Corner Breaks	104.81	0.22	373.87
Faulted Joints & Cracks	89.42	0.26	189.08
Slabs with Long. Cracks	29.68	0.21	410.29
Spalled Joints & Cracks	56.75	1.00	1.00
Ride Score	No Data	No Data	No Data
Transverse Cracks/100 ft	107.23	0.15	10.00

100 feet
= 30.5 meters

7.3 JCP PREDICTION MODELS FROM PES DATABASE

Scatter plots of the PES data for each JCP distress type show very few observations per distress type and no definite trend with pavement age. Because of the inconclusive trend in the observed data and the small sample sizes, the 1982 and 1984 CTR JCP condition database was examined as an alternate data source. On examination, it was found that the CTR database contained significantly more observations per distress type than the PES database. However, the trends in the data were not any better than those found in the PES data. Because of the larger sample size, it was decided to use the CTR database for all possible modeling purposes. Models that could not be developed from the CTR data were constructed using the PES data.

TABLE 7.2. COEFFICIENTS FOR JCP DISTRESS MODELS: BEFORE ACC OVERLAY (PES DATABASE)

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
Patches	No Data	No Data	No Data
Corner Breaks	No Data	No Data	No Data
Faulted Joints & Cracks	No Data	No Data	No Data
Slabs with Long. Cracks	No Data	No Data	No Data
Spalled Joints & Cracks	No Data	No Data	No Data
Ride Score	No Data	No Data	No Data
Transverse Cracks/100 ft	No Data	No Data	No Data

100 feet = 30.5 meters

CHAPTER 8. CRCP DISTRESS MODELS AFTER AC OVERLAY

This chapter describes the development of CRCP distresses after AC overlay. Both the CTR and the PES databases are utilized for this purpose, as explained in the following sections.

8.1 CRCP DISTRESS MODELS AFTER ACC OVERLAY FROM CTR DATABASE

From engineering theory it is understood that traffic loading, environmental factors and construction materials affect the rate of distress development in pavements. After a rigid pavement has been overlaid with ACC, the rate of development of distress may be significantly different from that of the original pavement structure. For overlaid rigid pavements, overlay thickness, condition of the pavement before overlay, seating of the rigid pavement before overlay, and bond breaker layers between the PCC slab and ACC layer also play a role. These factors could not be captured in the modeling process because the PES and CTR databases do not store data for these factors.

Although the surface of the overlaid pavement is asphalt concrete, the pavement may still display certain typical rigid pavement distresses. This occurs because distresses occurring in the PCC slab are reflected through into the ACC layer. An ACC overlay on a PCC pavement changes the direct effect of traffic and modifies the temperature effect on the slab. This usually results in a slowing of distress development compared to that of a non-overlaid pavement of the same age. These lower rates of distress development should be reflected in the distress prediction curves when compared to the curves for the case prior to overlay.

Data for this analysis were obtained from the CTR CRCP database. Condition data were extracted for all pavement sections in the database after their first and before their second overlay. To visualize any trends in the observed data, scatter charts were plotted for each distress type. The plots showed that there were few observations per distress type, and the data indicated no conclusive trend with pavement age. This lack of trend may be attributed to pavement age not being the only significant predictor of distress. In particular, the condition of the pavement prior to overlay (which is known to be a significant factor in overlay performance) could not be considered in the analysis.

Despite the poor correlation between distress level and pavement age, preliminary prediction models had to be proposed for the interim needs of the Texas PMIS. Therefore, practical prediction curves, based on engineering theory and the understanding of distress development, were fitted to the observed data. These models may be used in the Texas PMIS on an interim basis.

The NLIN procedure from SAS (Ref 19) was used to find coefficient estimates for the variables in the generalized sigmoidal function defined in Chapter 2. The variables for modifying ρ for the effects of traffic (χ), subgrade condition (σ), and environment (ε) in Equation 2.4 were again fixed at 1.0 for this study due to the lack of data.

8.1.1 MINOR PUNCHOUTS

Figure 8.1 shows the scatter plot of the observations for minor punchouts per mile (per 1.61 km) on CRCP sections. The data display considerable scatter and no significant trend with age. Immediately after overlay there should be no punchouts visible in the ACC layer. However, as the pavement is subjected to stresses from traffic and environmentally induced loading during its service life, existing and new punchouts that develop in the underlying PCC slab are reflected into the ACC layer. Therefore, it is expected that the number of punchouts will increase with age.

Figure 8.2 shows the curve fitted to the observed mean values. In Figure 8.2, the observed mean at age-group zero has a value of approximately 30. However, from engineering experience, it is known that this level of distress is not common on newly overlaid pavements. On examining the individual observations contributing to this mean, it was found that all the observations were for one section of road. As this section of road does not represent the typical performance of overlaid CRCP sections in Texas, it was decided to disregard this mean observation.

The distress levels indicated by the prediction curve are much higher than those predicted by the corresponding before-ACC overlay, model presented in Section 6.1.3. As discussed earlier, one would expect the number of punchouts per mile (per 1.61 km) to be fewer after the section has been overlaid.

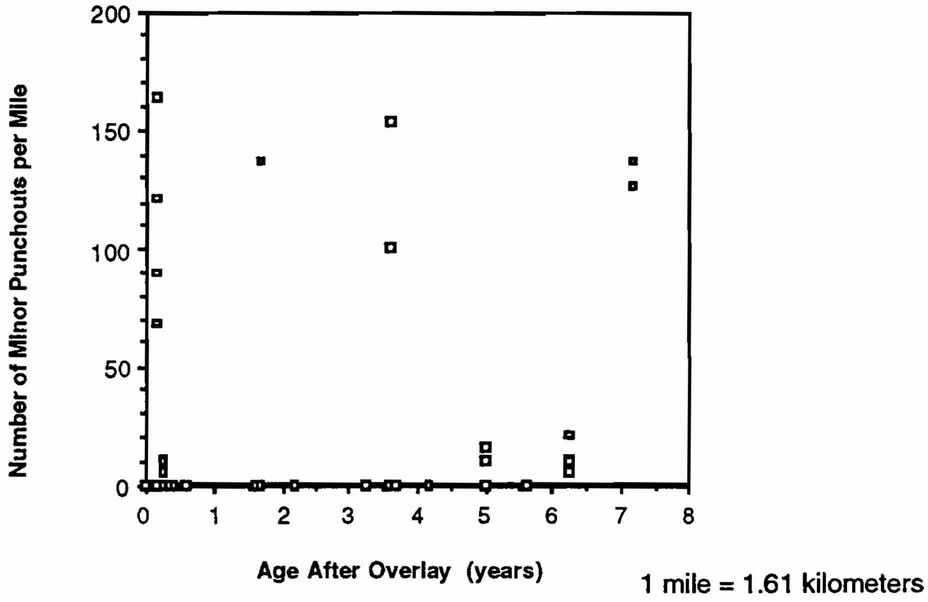
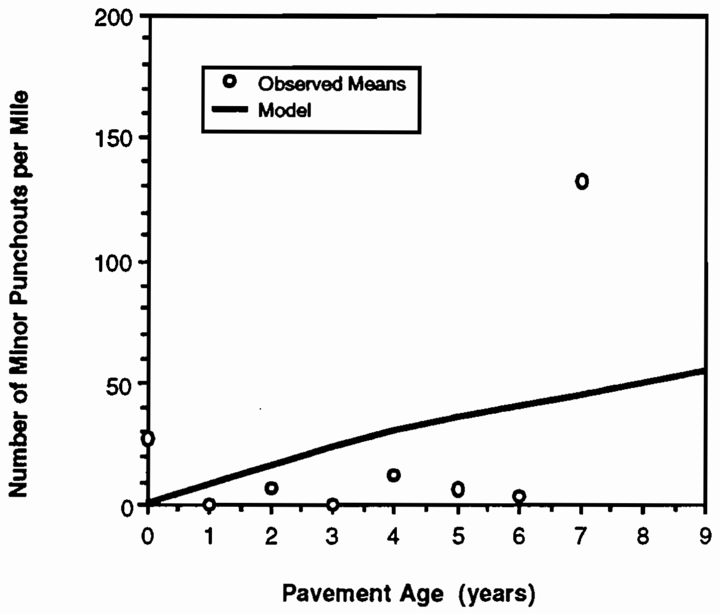


Figure 8.1. Scatter Chart of Observations for Minor Punchouts



1 mile = 1.61 kilometers

$$\text{Number of Minor Punchouts per Mile} = 1134.46\ e^{-\left(\frac{1282.71}{AGE}\right)^{0.23}}$$

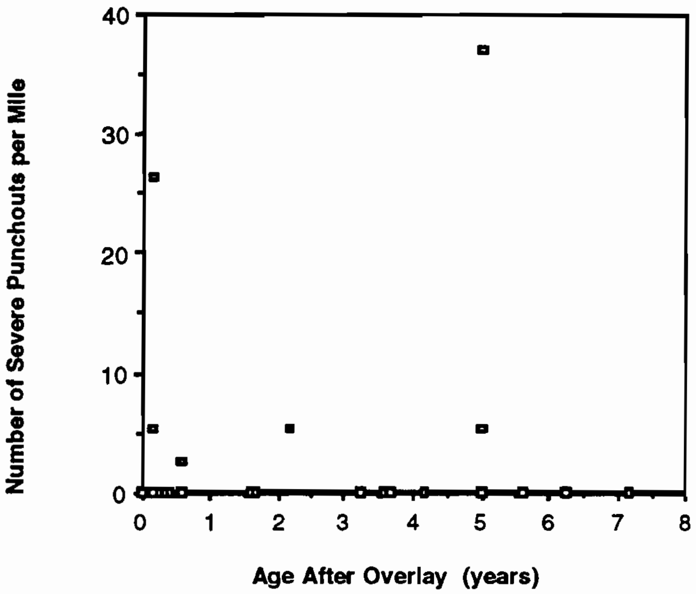
Figure 8.2. Prediction Curve for Minor Punchouts

8.1.2 SEVERE PUNCHOUTS

Figure 8.3 shows the scatter plot of the observations for severe punchouts. Most of the sections experience no severe punchouts. This is understandable, because the ACC overlay removes the direct effects of traffic and temperature from the slab, thereby decreasing the chances of severe distress development. The data show no trend with pavement age.

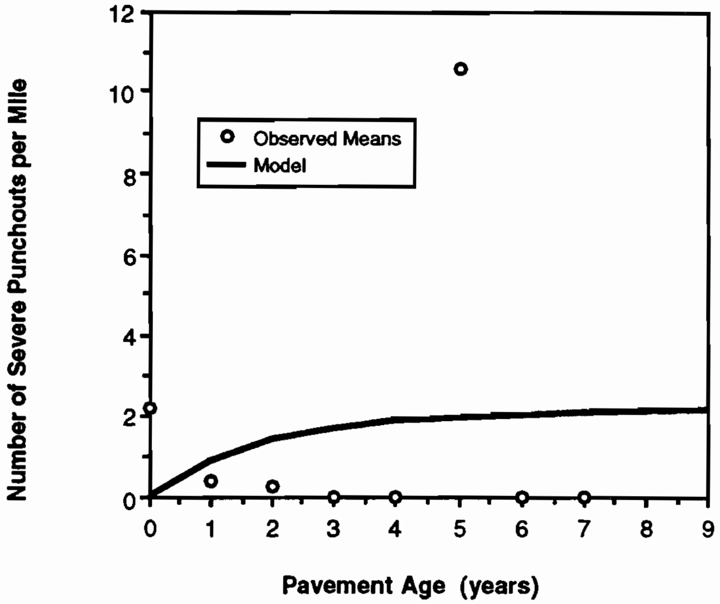
Because of the lack of any trend in the observed data, a practical curve was fitted to the data. The fitted curve is presented in Figure 8.4. A positive trend was imposed on the curve to reflect the theoretical understanding that the number of punchouts increases as the pavement ages.

The mean observation at pavement age zero was disregarded in the curve fitting process because only two observations from one section of road contributed to this mean value. These observations were considered outliers as they did not represent the general extent of severe punchouts on newly overlaid CRCP sections in Texas.



1 mile = 1.61 kilometers

Figure 8.3. Scatter Chart of Observations for Severe Punchouts



1 mile = 1.61 kilometers

$$\text{Number of Severe Punchouts per Mile} = 2.38\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 8.4. Prediction Curve for Severe Punchouts

8.1.3 ASPHALT PATCHES

Figure 8.5 presents the scatter plot of the observations for asphalt patches per mile (per 1.61 km). Again, no definite trend with pavement age is observed in the data. Figure 8.6 shows the prediction curve fitted to the observed data. Considerable scatter is evident in the plot of the means per age group in Figure 8.6.

The extent of ACC patching on overlaid CRCP sections is dependent on the condition of the pavement before overlay. If the pavement was not heavily distressed and was well-seated before being overlaid, fewer distresses would result after overlay that would require patching.

The model presented in Figure 8.6 is produced from a relatively small sample of pavements that may have had very different conditions prior to being overlaid. This may explain some of the scatter.

The mean observation at age-group zero was treated as an outlier. The individual observations contributing to the mean, displayed high levels of ACC patching. These levels of patching were considered atypical for newly overlaid CRCP sections. Therefore, the mean at age-group zero was not considered in the curve fitting process.

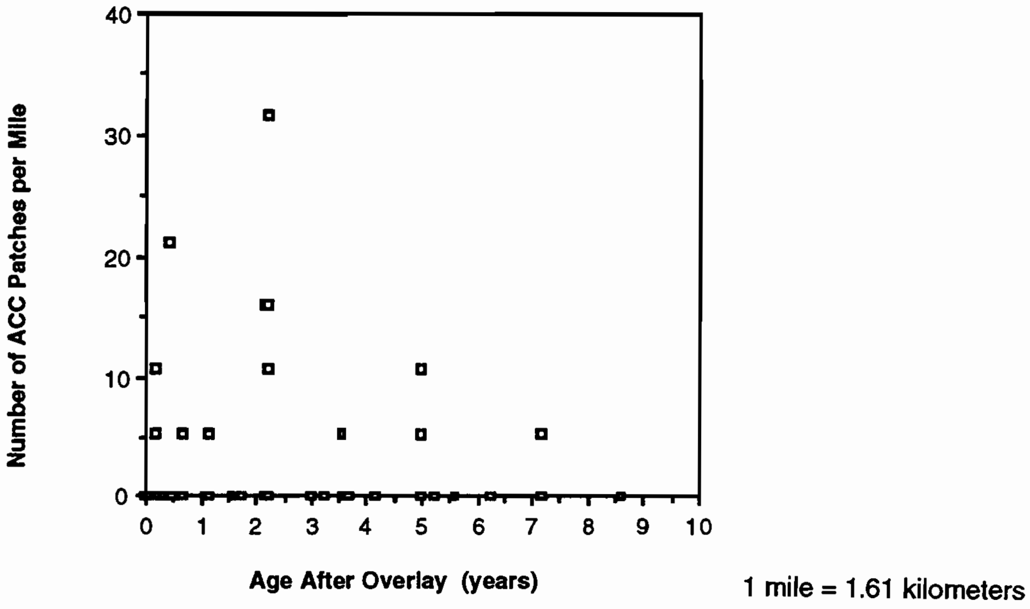
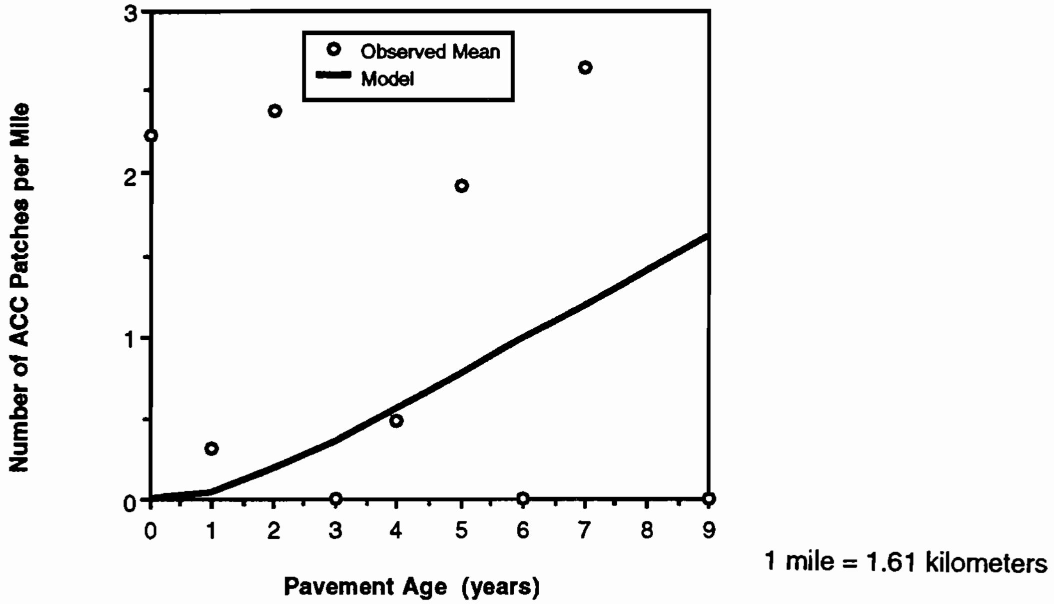


Figure 8.5. Scatter Chart of Observations for Asphalt Concrete Patching



$$\text{Number of ACC Patches per Mile} = 62.75\, e^{-\left(\frac{578.48}{\text{AGE}}\right)^{0.31}}$$

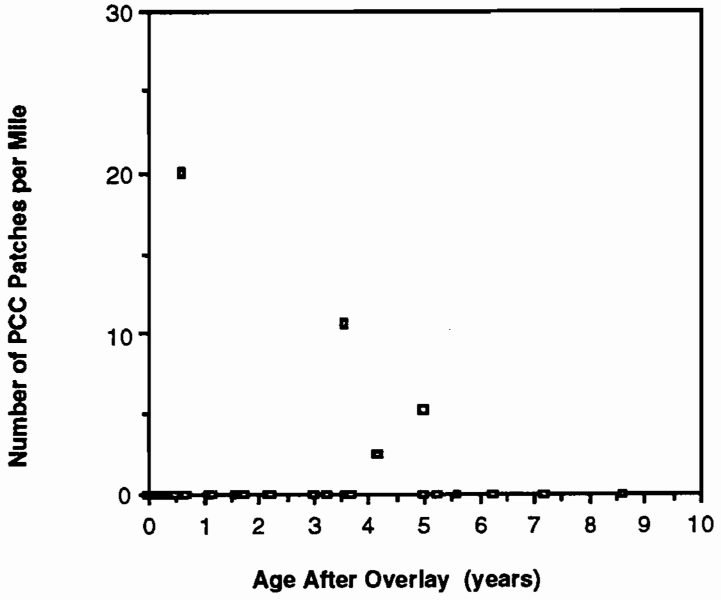
Figure 8.6. Prediction Curve for Asphalt Concrete Patching

8.1.4 PORTLAND CEMENT CONCRETE PATCHES

Figure 8.7 displays the scatter of observations for PCC patches per mile (per 1.61 km). The majority of the sections experience no PCC patches. Four sections, however, displayed a considerable amount of PCC patching.

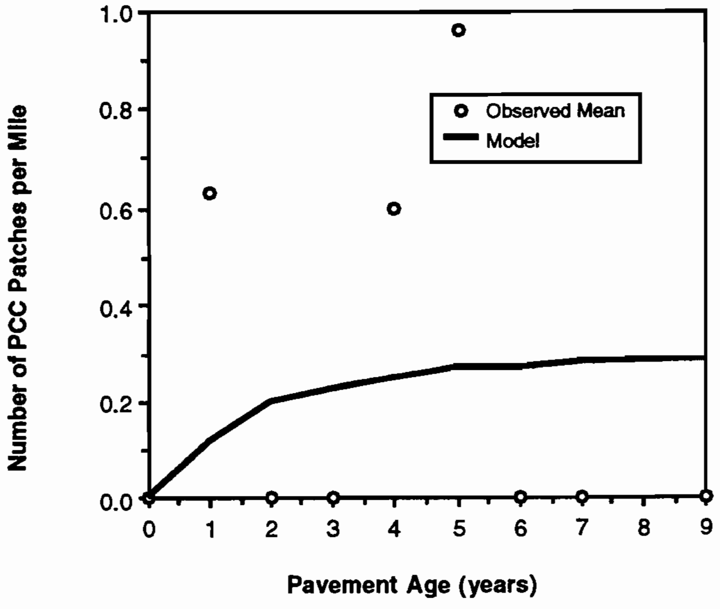
PCC patches on asphalt concrete surfaces are not as common as ACC patches. One of the reasons for this is to provide a smoother riding surface by patching with the same material as the pavement surface. If the pavement surface was asphalt concrete and a PCC patch was placed, the ACC surface would be compacted under traffic loading, while the PCC patch would not. This would result in bumps at the edges of the patch in the wheel path.

Figure 8.8 shows the curve fitted to the observed data. The values for β and ρ were restricted to 1.00 so that the model would show a positive trend with pavement age. The shape of the curve is strongly influenced by the four sections with high levels of PCC patching. This influence is compounded by the few observations in the dataset.



1 mile = 1.61 kilometers

Figure 8.7. Scatter Chart of Observations for Portland Cement Concrete Patches



1 mile = 1.61 kilometers

$$\text{Number of PCC Patches per Mile} = 0.32\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 8.8. Prediction Curve for Portland Cement Concrete Patches

8.1.5 TRANSVERSE CRACKS

Figures 8.9 and 8.10 show the observed data for transverse cracks per 100 feet (per 30.5 m) for CRCP sections constructed with siliceous river gravel (SRG) and limestone (LS), respectively. No trend is visible in either of the scatter plots. From these data it can be seen that most of the sections have between zero and ten transverse cracks per 100 feet (per 30.5 m). Four sections display very high levels of transverse cracking—130 to 190 cracks per 100 feet (426 to 623 cracks per 100 m). It must be noted that these data represent transverse cracks that have been reflected from the PCC slab through into the ACC overlay. Therefore, the number of reflected cracks observed on the ACC overlay surface will be influenced by the overlay thickness, the condition of the PCC slab before overlay, the presence of bond breaker layers, and the seating of the PCC slab before overlay. As stated before, data for these items are not recorded in either the CTR or PES databases. Therefore their impact on the model cannot be captured.

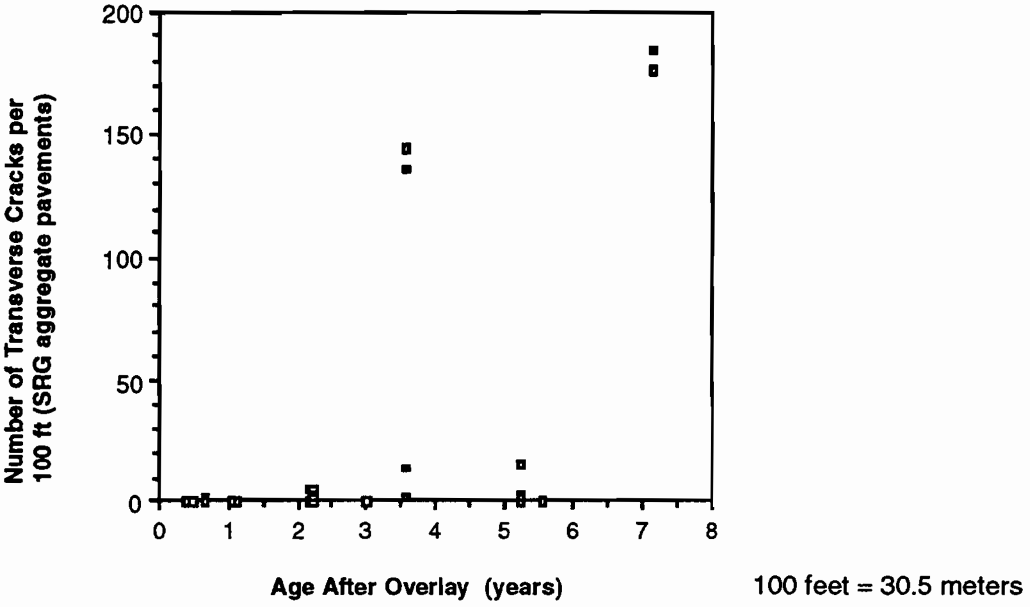
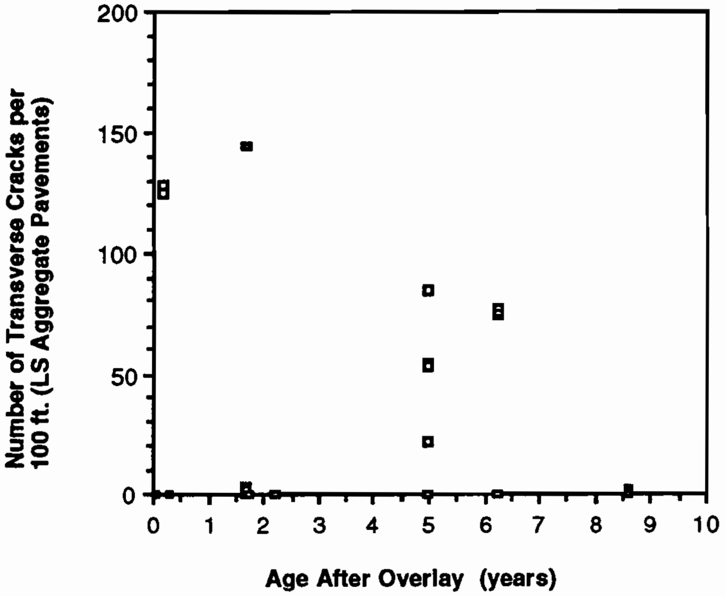


Figure 8.9. Scatter Chart of Observations for Transverse Cracks on SRG Aggregate Pavements

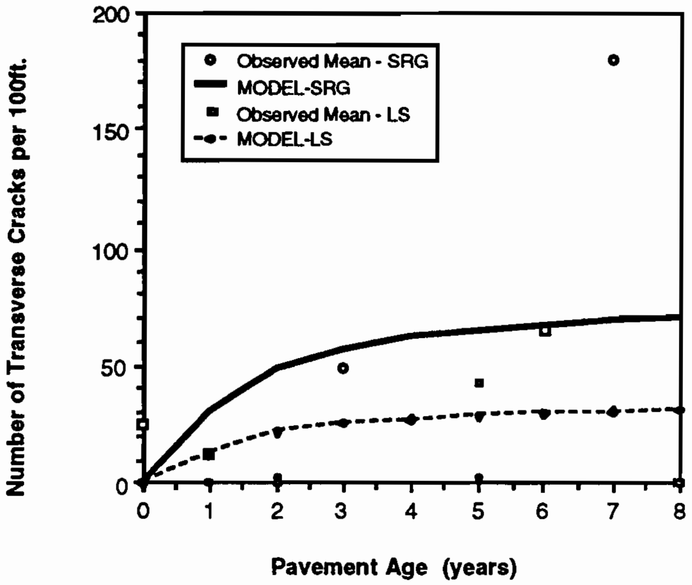


100 feet = 30.5 meters

Figure 8.10. Scatter Chart of Observations for Transverse Cracks on LS Aggregate Pavements

Because transverse cracking in overlaid PCC pavements is affected by factors other than coarse aggregate type, temperature, and subbase treatment, its development may be considerably different from that of the before-overlay case.

Figure 8.11 shows the prediction curves for transverse cracks per 100 feet (per 30.5 m). For the model to indicate an increase in distress level with age, β and ρ were restricted to 1.00. Two models are presented, one for CRCP pavements constructed with limestone (LS), and one for those constructed with siliceous river gravel (SRG). As discussed previously for non-overlaid CRCP sections, pavements constructed with siliceous river gravel (SRG) have a higher percentage of cracks per 100 feet (per 30.5 m), and these cracks develop at a faster rate than cracks in pavements constructed with limestone (LS) aggregate.



100 feet = 30.5 meters

$$\text{Number of Transverse Cracks per 100ft. (LS)} = 35.34\ e^{-\left(\frac{1.0}{AGE}\right)^{1.0}}$$

$$\text{Number of Transverse Cracks per 100ft. (SRG)} = 79.88\ e^{-\left(\frac{1.0}{AGE}\right)^{1.0}}$$

Figure 8.11. Prediction Curve for Transverse Cracks

Table 8.1 summarizes the coefficient values in Equation 2.6 for each CRCP distress type after ACC overlay using the CTR CRCP database.

TABLE 8.1. COEFFICIENTS FOR CRCP DISTRESS MODELS: AFTER ACC OVERLAY USING THE CTR DATABASE

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
Minor Punchouts	1133.46	0.23	1282.71
Severe Punchouts*	2.38	1.00	1.00
PCC Patches	0.32	1.00	1.00
ACC Patches	62.75	0.31	578.48
Cracks/100 ft — LS	35.42	1.00	1.00
Cracks/100 ft — SRG	79.88	1.00	1.00
Ride Score	No Data	No Data	No Data

*Conforms to PES definition of punchouts

100 feet = 30.5 meters

8.2 CRCP PREDICTION MODELS USING THE PES DATABASE

The scatter plots for CRCP showed that there are sufficient data for modeling purposes. However, the observed data showed no conclusive trend with pavement age. Because of the poor trend in the PES data, the CTR CRCP database was examined to serve as an alternate source of pavement condition data for developing the required prediction models.

As stated earlier, the CTR CRCP database does not store detailed M&R data. The only M&R data recorded in this database are the dates sections have been overlaid with ACC. It was therefore not possible to apply the M&R categories defined in Chapter 5 to condition data from the CTR database. However, two M&R categories were defined, the "before"-ACC overlay case, and the "after"-ACC overlay case.

It was found that the CTR CRCP database contained sufficient data which could be used to construct distress models for CRCP sections prior to ACC overlay. Because of the ample data in the CTR database and the fact that the data generally showed a positive correlation with pavement age, it was decided to use the CTR data to develop the distress models for CRCP sections prior to ACC overlay. This analysis was presented in Chapter 6.

Most of the distress and performance prediction models required for the Texas PMIS were therefore developed using data from the CTR database. However, the CTR database does not contain data to develop a prediction model for the fractional loss of ride score for CRCP sections after ACC overlay. It was therefore necessary to use the available PES data to develop this model.

Because the PES data displayed a poor relationship between age and distress, a practical curve was fitted to the observed data. It was necessary to specify boundary conditions for the curve based on theoretical understanding of distress mechanisms and development over time. The coefficients describing the curve might be used for the immediate needs for development of the Texas PMIS.

The NLIN procedure from SAS, a non-linear least squares analysis (Ref 5), was used to find the coefficient estimates for the variables in the generalized sigmoidal function defined in Chapter 2. The variables for modifying ρ for the effects of traffic (χ), subgrade condition (σ), and environment (ε) in Equation 2.4 were fixed at 1.0 for this study because there were insufficient data available to investigate the effects of these factors on the distress level.

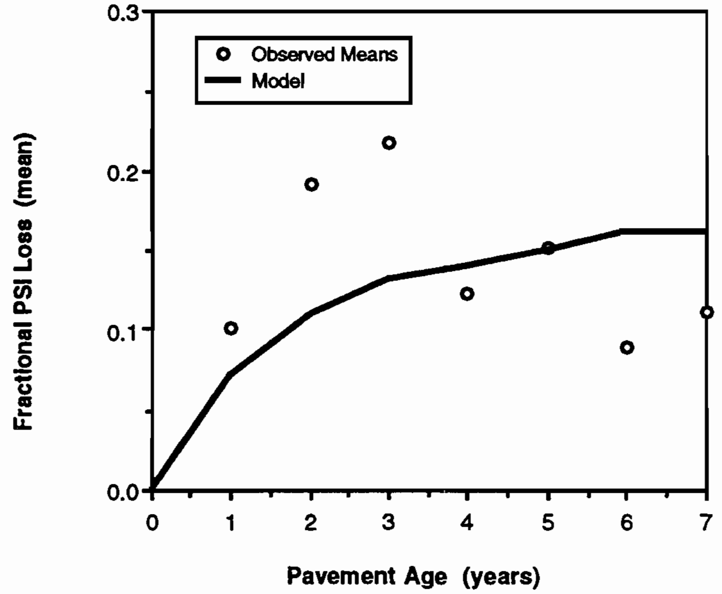
RIDE SCORE

As described earlier, ride score was modeled as fractional PSI loss versus age, normalized to a hypothetical initial SI of 4.5.

In Chapter 5, ACC overlay was categorized as a moderate M&R activity. Therefore, data from the combined moderate and heavy PES dataset were used to model the fractional loss of ride score after ACC overlay.

The PES data for loss of ride score displayed considerable scatter and no conclusive trend when plotted against pavement age. As the pavement is subjected to traffic and environmentally-induced loading, the loss of ride score will increase. The data are therefore expected to show a positive trend with age.

To obtain a model that reflected the expected theoretical trend in the loss of ride score, a curve having a positive trend with age was fitted to the means of the observed data. To ensure that the prediction curve showed a positive trend with age, the coefficient values for β and ρ in the model specification were restricted to 1.00. The resulting model is presented in Figure 8.12.



$$\text{Fractional PSI Loss} = 0.22\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 8.12. Prediction Curve for Fractional PSI Loss After Moderate or Heavy M&R

Table 8.2 summarizes the coefficient values for Equation 2.4 for each CRCP prediction model developed using the PES data for the "after"-moderate or heavy M&R case. Because of the lack of data, no coefficient values could be estimated.

TABLE 8.2. COEFFICIENTS FOR CRCP DISTRESS MODELS: AFTER MODERATE OR HEAVY M&R (USING PES DATABASE)

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
Fractional PSI Loss	0.22	1.00	1.00
Severe Punchouts	No Data	No Data	No Data
PCC Patches	No Data	No Data	No Data
ACC Patches	No Data	No Data	No Data
Cracks/100 ft — LS	No Data	No Data	No Data
Cracks/100 ft — SRG	No Data	No Data	No Data

100 feet = 30.5 meters

CHAPTER 9. JCP DISTRESS MODELS AFTER ACC OVERLAY

This chapter presents the distress models for jointed concrete pavements using both the CTR and the PES databases after the application of either a maintenance or a rehabilitation activity. The shortcomings and the advantages of both these databases are also discussed.

9.1 JCP DISTRESS MODELS AFTER ACC OVERLAY USING CTR DATABASE

As discussed earlier, the ACC overlay has an effect on the rate of distress development. The overlay changes the direct effect of traffic loading and the temperature effect on the PCC slab. This often results in lower rates of distress development. For overlaid sections, the condition of the pavement prior to overlay, the overlay thickness, the seating of the PCC slab before overlay, and the presence of bond breaker layers all affect the rate of distress development.

As in the case of overlaid CRCP sections, many of the observed typical rigid pavement distresses are reflected from the PCC slab through into the ACC overlay.

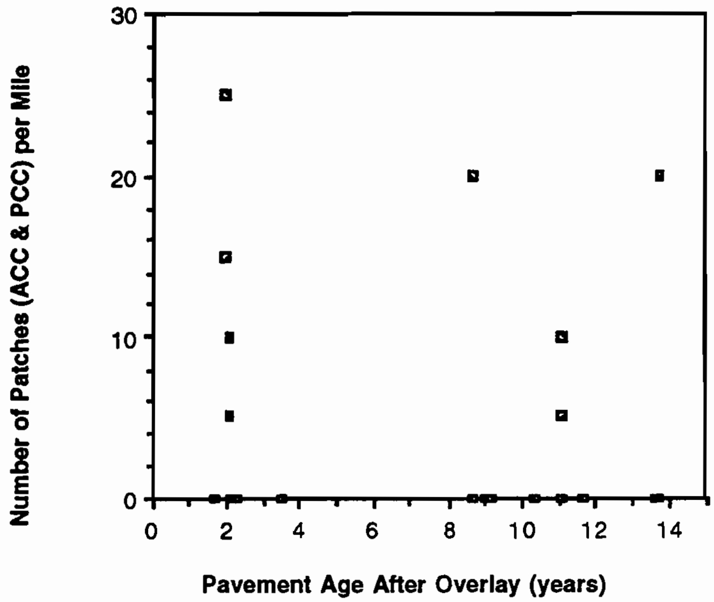
Pavement condition data for this analysis were obtained from the CTR JCP database. The CTR JCP database does not record the date an ACC overlay was placed. It was therefore necessary to obtain the overlay dates from TxDOT records. The overlay date closest to and prior to the 1982 condition survey date was selected as the overlay date.

The observations for each distress type were plotted against "pavement age after overlay." These scatter charts show a small sample size for each distress type. Also, considerable scatter is evident, and no trend with age is present. The absence of any trend in the observed data when plotted against pavement age shows that age may not be the best predictor of distress. Because of insufficient data to drive the model, and because the model does not address the effects of other distress predictors, the prediction curves fitted to this data represent a poor correlation between pavement age and distress level.

9.1.1 ACC AND PCC PATCHES

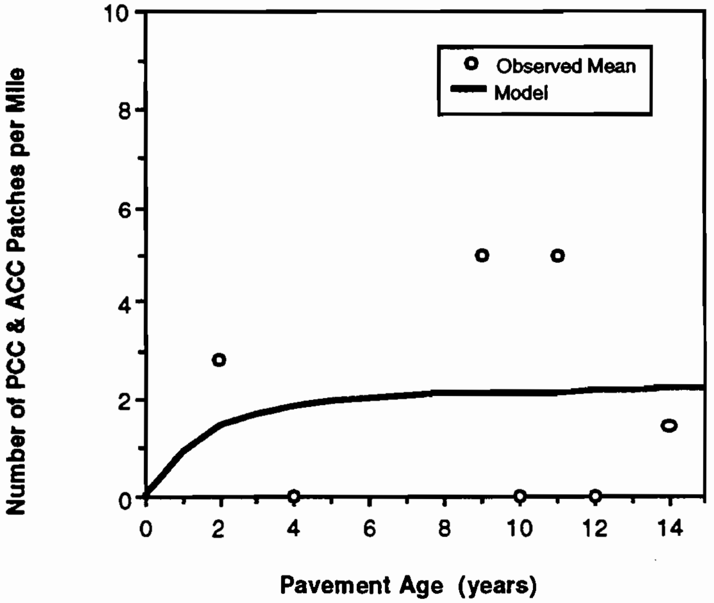
As discussed earlier for the prediction model for patches prior to ACC overlay, the CTR database combines condition survey data for PCC and ACC patches. The PES database, on the other hand, records only the condition of PCC patches for the corresponding distress type. Therefore, if the model based on the CTR data is used with the current PES data, pavement age and maintenance effectiveness will be underestimated.

Figure 9.1 shows the scatter plot of the observations for patches per mile (per 1.61 km). It is clear from the plot that there are few observations and that these display no trend with pavement age. Therefore it was necessary to fit a practical prediction curve to the observed mean values. For the curve to have a positive trend with age, and thereby to be consistent with a theoretical understanding of the development of patches, the values for the β and ρ coefficients in Equation 2.4 were restricted to 1.0. This restriction also forced the curve to pass through the origin. The resulting prediction model is presented in Figure 9.2. Because of the sparse data, this model has limited applicability and will be revised in later analyses.



1 mile = 1.61 kilometers

Figure 9.1. Scatter Chart of Observations for Patches



1 mile = 1.61 kilometers

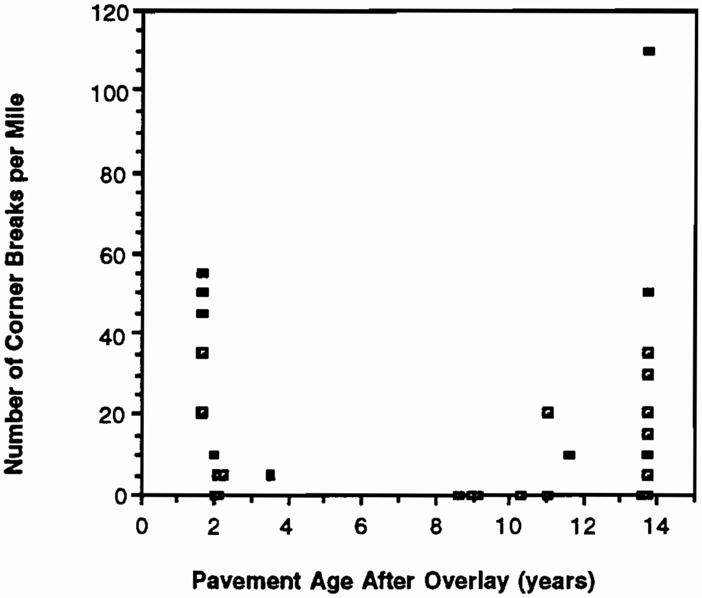
$$\text{Number of Patches per Mile} = 2.35\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.2. Prediction Curve for Patches

9.1.2 CORNER BREAKS

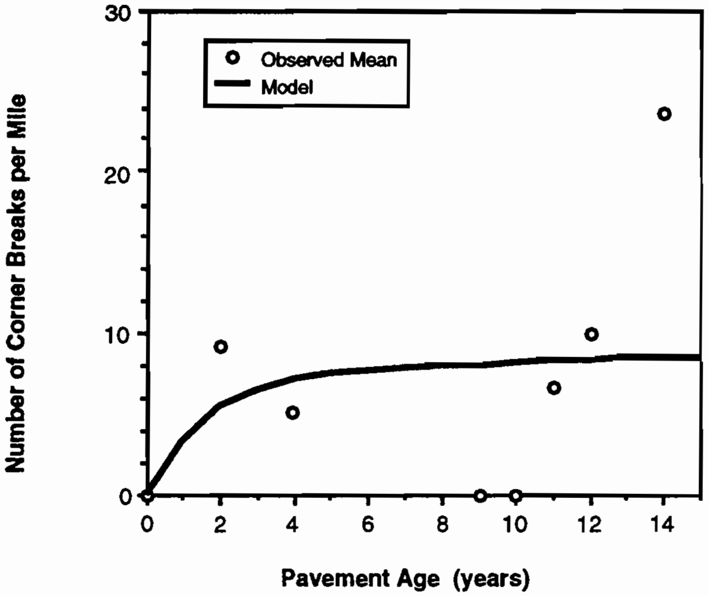
The discussion presented earlier for predicting corner breaks prior to ACC overlay of JCP sections also applies here. In essence, the model for predicting corner breaks may be used as a substitute for predicting failures per mile (per 1.61 km) as defined by PES. The model will, however, overestimate pavement age and maintenance effectiveness.

Again, the scatter plot of the observations for corner breaks shows very little data for modeling and no trend with pavement age. The best fitted curve to the observed mean values is presented in Figure 9.3. Because of the small sample used to produce this model, its prediction capabilities are limited.



1 mile = 1.61 kilometers

Figure 9.3. Scatter Chart of Observations for Corner Breaks



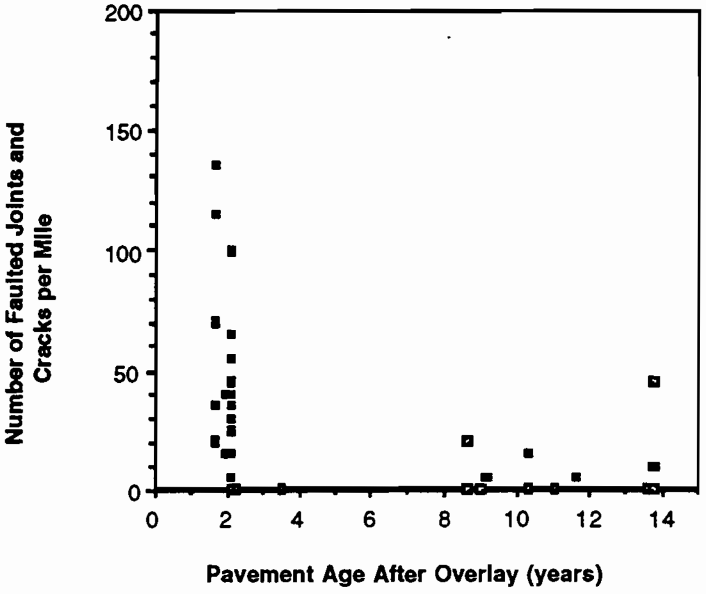
1 mile = 1.61 kilometers

$$\text{Number of Corner Breaks per Mile} = 9.06\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.4. Prediction Curve for Corner Breaks

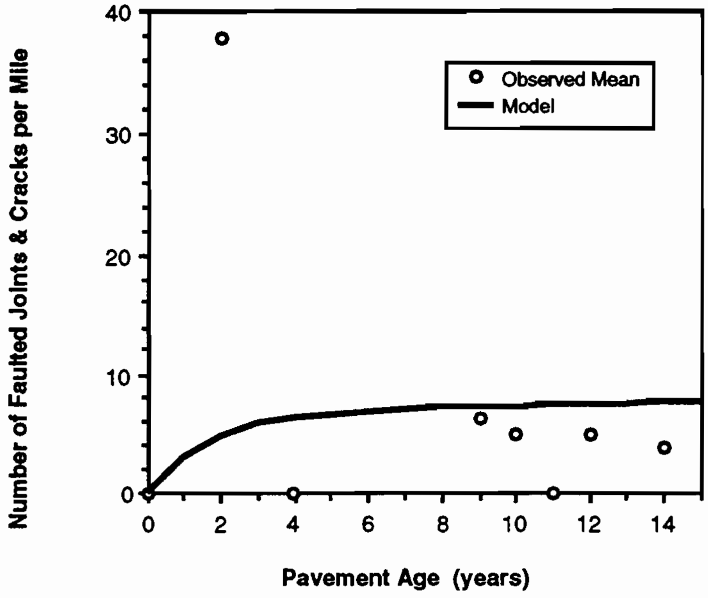
9.1.3 FAULTED JOINTS AND CRACKS

The scatter plot of the observations in Figure 9.5 shows very few data which could be used to develop a model that has a strong correlation with pavement age and distress level. The data also display no conclusive trend with pavement age. However, as discussed earlier, the faulting of joints and cracks is expected to increase with age and, therefore, a positive trend was imposed on the prediction model. For the practical prediction curve to show a positive trend with age, the values for the β and ρ coefficients in Equation 2.4 were restricted to 1.0.



1 mile = 1.61 kilometers

Figure 9.5. Scatter Chart of Observations for Faulted Joints and Cracks



1 mile = 1.61 kilometers

$$\text{Number of Faulted Joints \& Cracks per Mile} = 8.03\ e^{-\left(\frac{1.0}{AGE}\right)^{1.0}}$$

Figure 9.6. Prediction Curve for Faulted Joints and Cracks

9.1.4 TRANSVERSE CRACKS

The scatter chart of transverse cracks per 100 feet (per 30.5 m) (see Fig 9.7) shows that a small sample is available for modeling purposes. The data also display no trend with pavement age. It is expected that the number of transverse cracks should increase with pavement age. For the prediction curve to have a positive trend, Equation 2.4 was used, and the values for the β and ρ coefficients were restricted to 1.0. The resulting model is presented in Figure 9.8.

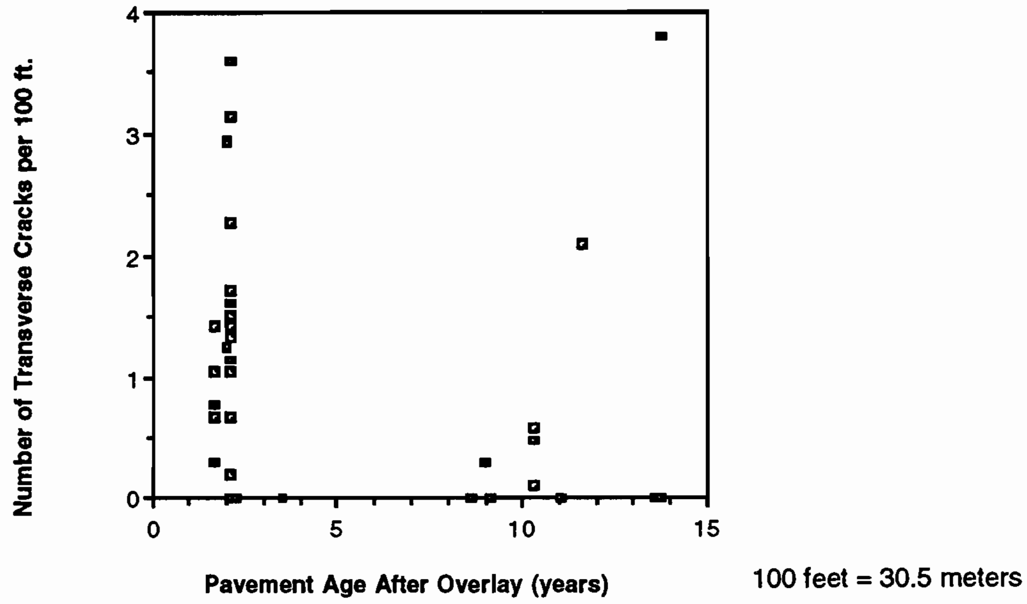
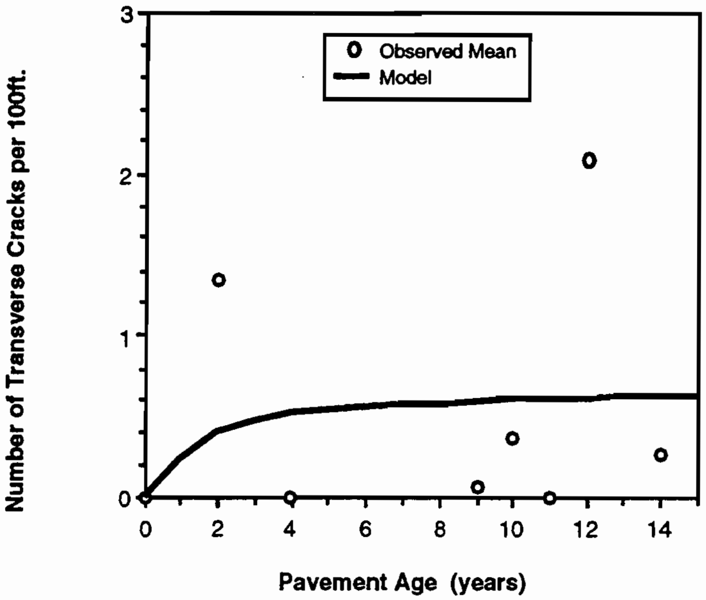


Figure 9.7. Scatter Chart of Observations for Transverse Cracks



100 feet = 30.5 meters

$$\text{Number of Transverse Cracks per 100ft.} = 34.80\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.8. Prediction Curve for Transverse Cracks per 100 Feet (per 30.5 Meters)

Table 9.1 summarizes the coefficient values appropriate in Equation 2.4 for each JCP distress type after ACC overlay using the CTR jointed pavement database.

TABLE 9.1. COEFFICIENTS FOR JCP DISTRESS MODELS USING THE CTR DATABASE: AFTER ACC OVERLAY

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
Patches	2.35	1.00	1.00
Corner Breaks	9.09	1.00	1.00
Fractional PSI Loss	No Data	No Data	No Data
No. of Shattered Slabs/mile	No Data	No Data	No Data
No. of Failures/mile	No Data	No Data	No Data
Faulted Joints & Cracks	8.03	1.00	1.00
Transverse Cracks/100 feet	34.80	1.00	1.00

100 feet = 30.5 meters

9.2 JCP PREDICTION MODELS USING THE PES DATABASE

Scatter plots of the PES data for each JCP distress type showed very few observations per distress type and no definite trend with pavement age. Because of the inconclusive trend in the observed data and the small sample sizes, the 1982 and 1984 CTR JCP condition database was examined as an alternate data source. On examination, it was found that the CTR database contained significantly more observations per distress type than the PES database. However, the trends in the data were not any better than those found in the PES data. Because of the larger sample size, it was decided to use the CTR database for all possible modeling purposes. Models that could not be developed from the CTR data were constructed using the PES data.

The CTR JCP database stores condition data for the before- and after-ACC overlay cases only and does not differentiate between the four M&R categories (preventive, light, moderate, heavy) defined in Chapter 5. Therefore models for predicting the number of slabs with severe longitudinal cracks, and the number of spalled joints and cracks, after moderate or heavy M&R, could not be developed using the CTR data. It was therefore necessary to use the PES JCP data to produce these models.

The Texas PMIS specification also required that prediction models be developed for the number of PCC patches per mile (per 1.61 km), the number of failures per mile (per 1.61 km), and the fractional loss of ride score. The CTR JCP database does not record data for failures and ride score. Also, the CTR data for patches are not separated into PCC and ACC patches; instead, this information is recorded as a single data item. Therefore the CTR data were not used to develop a prediction model for PCC patching because the single data item would have not matched the PMIS specification.

The PES data were used to develop prediction models for (1) the number of PCC patches per mile, (2) the number of failures per mile, and (3) fractional loss of ride score. Because of the few observations and no precise trend in the data, practical models were produced using the available data. As discussed earlier, boundary conditions were assumed based on theory. The resulting models are again intended to serve only the immediate needs for development of the Texas PMIS.

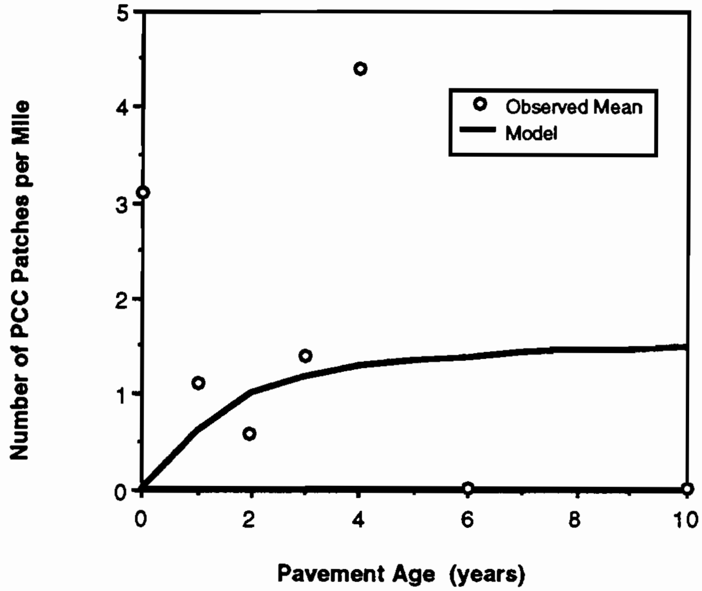
The NLIN procedure from SAS, a non-linear least squares analysis (Ref 5), was used to find the coefficient estimates for the variables in the generalized sigmoidal function defined in Chapter 2. The variables for modifying ρ for the effects of traffic (χ), subgrade condition (σ), and environment (ε) in Equation 2.4 were fixed at 1.0 for this study.

9.2.1 PCC PATCHES

Patches are repairs to other distresses. As a pavement ages, it is subjected to the loading effects of traffic and environment, which results in higher distress levels. These higher distress levels indirectly imply more patches. Therefore a positive trend of PCC patches with pavement age is expected. However, the observed means in Figure 9.9 show considerable scatter and no strong trend when plotted against pavement age.

To ensure that the prediction curve displayed a positive trend, the values for β and ρ in the model specification were restricted to 1.0. Figure 9.9 shows the fitted practical prediction curve for the number of PCC patches per mile after light or preventive M&R.

The observed mean at age-group zero has a value of approximately 3 PCC patches per mile. It is known from engineering experience that it is uncommon for a new pavement to sustain any load-related distresses requiring patching, although it is possible for defects during the pavement's construction to be patched. Examining the data at age-group zero identified a single observation having a value of 55 patches per mile. This single observation was considered an outlier. By eliminating this single outlier, the mean was approximately 0.4 patches per mile (0.6 patches per kilometer) at age-group zero. Therefore, the prediction curve in Figure 9.9 was fitted through the origin.



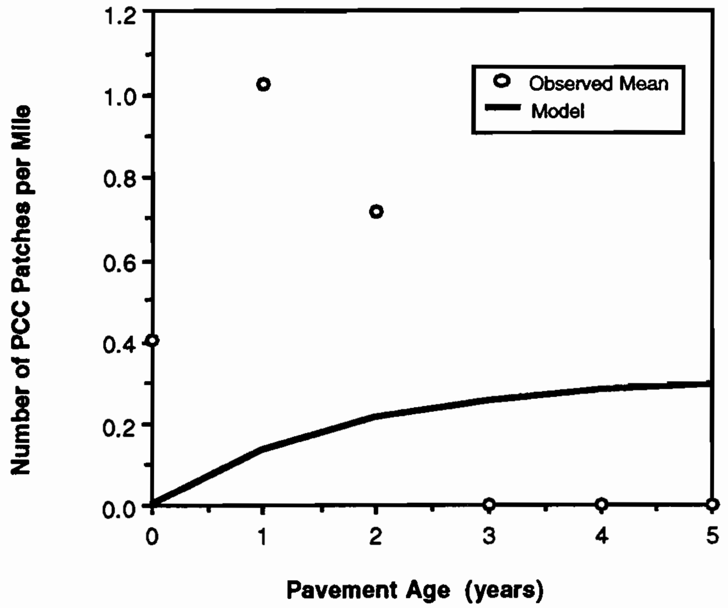
1 mile = 1.61 kilometers

$$\text{Number of PCC Patches per Mile} = 1.639\ e^{-\left(\frac{1.00}{\text{AGE}}\right)^{1.00}}$$

Figure 9.9. Prediction Curve for the Number of PCC Patches per Mile (per 1.61 Kilometers) After Preventive or Light M&R

Figure 9.10 shows the prediction model for the number of PCC patches per mile (per 1.61 km) after moderate or heavy M&R. For the model to display the expected positive trend with age, it was necessary to restrict the values for the β and ρ coefficients to 1.0.

As in the model for PCC patches per mile after light or preventive M&R, the observed mean at age-group zero is strongly influenced by outliers. This mean value was therefore not significant in determining the boundary condition and the shape of the practical prediction curve.



1 mile = 1.61 kilometers

$$\text{Number of PCC Patches per Mile} = 0.35\, e^{-\left(\frac{1.00}{\text{AGE}}\right)^{1.00}}$$

Figure 9.10. Prediction Curve for the Number of PCC Patches per Mile (per 1.61 Kilometers) After Moderate or Heavy M&R

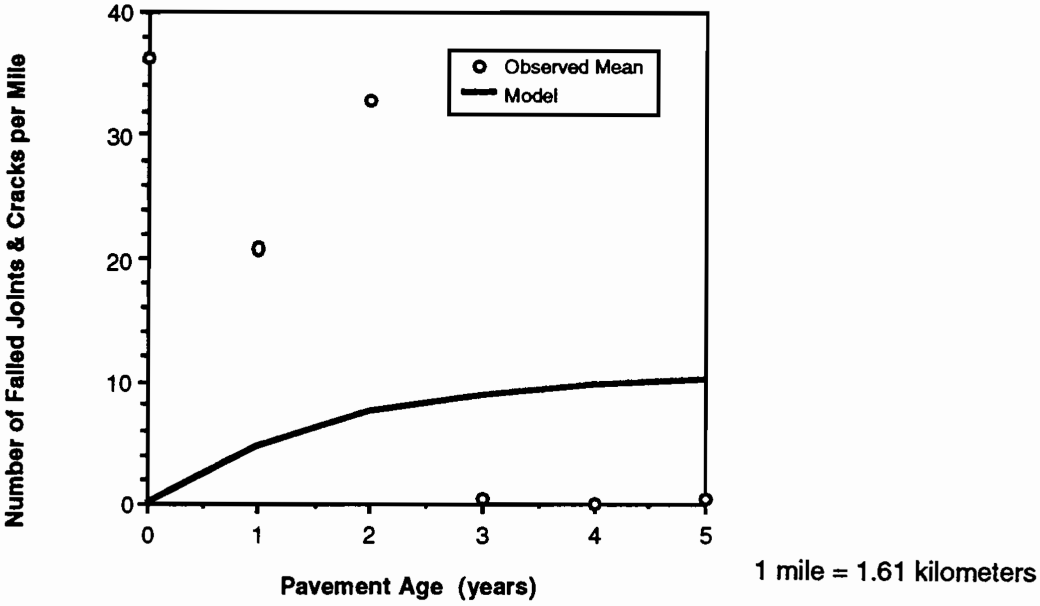
9.2.2 FAILED JOINTS AND CRACKS

The PES data were also used to develop a model for predicting failed joints and cracks after moderate or heavy M&R. The model for predicting the distress level after preventive or light M&R was produced using the CTR JCP data.

A very small sample was available for producing a prediction model for failed joints and cracks. The mean values of the observed data, shown in Figure 9.11, display no clear trend when plotted against pavement age. One would expect the number of failed joints and cracks to increase as the pavement ages and is subjected to the cumulative effects of traffic and environmentally induced loading.

Although the trend in the data was inconclusive, and although there was very few data for any significant statistical modeling, a practical prediction curve was fitted to the mean values of the observed data. The expected positive trend with age was imposed on the prediction curve. This was accomplished by restricting the values for β and ρ in the model specification to 1.0. The resulting model is presented in Figure 9.11.

The observed mean at zero was abnormally high. On examining the observations at age-group zero, it was found that one observation had a very high value, while the remaining observations indicated 0 to 25 failed joints and cracks per mile (per 1.61 km). All of these observations were from two pavement sections. As these sections do not reflect the generally understood trend of distress development, they were considered outliers and were not taken into account when fitting the prediction curve.



$$\text{Number of Failed Joints \& Cracks per Mile} = 19.59\ e^{-\left(\frac{1.00}{\text{AGE}}\right)^{1.00}}$$

Figure 9.11. Prediction Curve for the Number of Failed Joints and Cracks per Mile (per 1.61 Kilometers) After Preventive or Light M&R

9.2.3 SLABS WITH LONGITUDINAL CRACKS

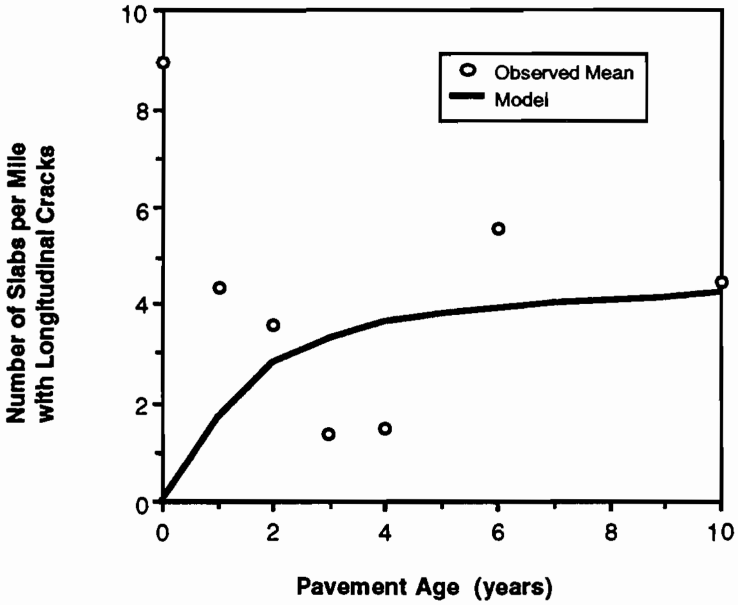
A model for predicting the number of slabs per mile (per 1.61 km) having longitudinal cracks after moderate or heavy M&R was developed using the PES data. The model for the "after"-preventive and light M&R case was developed using the CTR JCP data.

The scatter plot of the observations for slabs with longitudinal cracks is presented previously. This plot shows that the sample is relatively small to perform any significant statistical modeling. Also, the data display no particular trend when plotted against pavement age.

The maximum number of slabs per mile (per 1.61 km) having longitudinal cracks is dependent on the slab design. Data on the slab design characteristics are currently not recorded in the CTR or PES databases. It was therefore not possible to account for this factor in the modeling process. As with most distresses, the number of slabs per mile having longitudinal cracks should increase as the pavement ages. It was therefore expected that the model should display a positive trend with pavement age.

Because the observed data showed no specific trend with pavement age, it was necessary to ensure that the model represented the expected positive trend. To impose the trend on the fitted curve, the values for β and ρ in the model specification were restricted to 1.0. The resulting model is presented in Figure 9.12.

The mean distress level at age-group zero was considered to be abnormally high and counter to engineering knowledge. Examination of the individual observations at age-group zero identified two pavement sections having very high levels of distress. These two observations resulted in the abnormally high mean at age zero. If these two outliers were removed, the observed mean would be approximately 0.8 instead of 9.0. Therefore, the fitted practical curve was forced through the origin.



1 mile = 1.61 kilometers

$$\text{Number of Slabs per Mile with Long. Cracks} = 4.64\ e^{-\left(\frac{1.00}{\text{AGE}}\right)^{1.00}}$$

Figure 9.12. Prediction Curve for the Number of Slabs per Mile (per 1.61 Kilometers) with Longitudinal Cracks After Preventive or Light M&R

9.2.4 FAILURES

As defined in Appendix C, a failure is a combined measure of corner breaks, punchouts, AC patches, failed concrete patches, and D-cracking. The CTR JCP database does not store condition information for each of these specific distress types, except for corner breaks. Therefore the PES data were used to develop the model for predicting the number of failures per mile for the "after"-preventive or light M&R case and the "after"-moderate or heavy M&R case.

Figure 9.13 presents the model for predicting the number of failures per mile (per 1.61 km) after preventive or light M&R. From the scatter chart it is noted that the observations are clustered in the zero- to four-year age group, and no absolute trend with pavement age is evident.

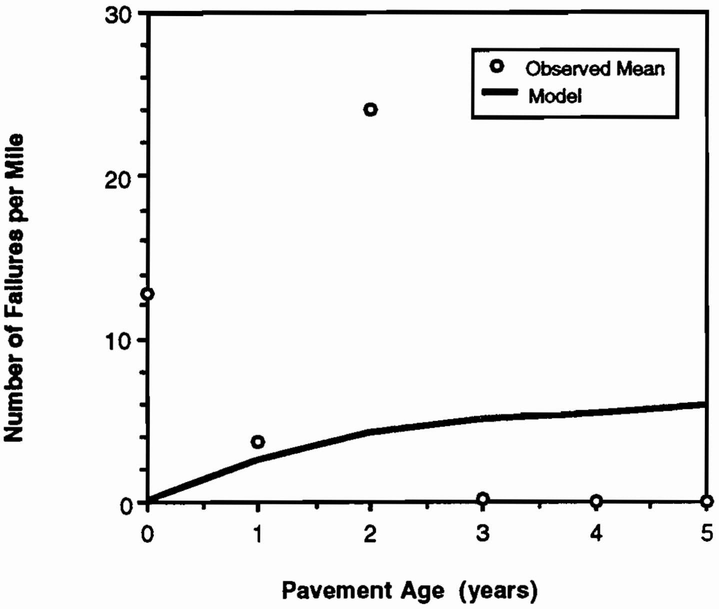
As a pavement is subjected to the cumulative loading effects of traffic and environment over its service life, the number of distresses and failures will increase. Therefore, it is expected that the prediction curve for the number of failures per mile (per 1.61 km) will increase with pavement age. The prediction curve fitted to the mean values of the observed data displays the expected positive trend with age.

Figure 9.14 presents the prediction model for the number of failures per mile (per 1.61 km) after moderate or heavy M&R. Because the observed data showed no trend with pavement age, it was necessary to impose a positive trend on the prediction curve to be consistent with a theoretical understanding of the development of failures. Therefore the values for β and ρ in the model specification were restricted to 1.0.

1 mile = 1.61 kilometers

$$\text{Number of Failures per Mile} = 33.12\ e^{-\left(\frac{10.0}{\text{AGE}}\right)^{0.082}}$$

Figure 9.13. Prediction Curve for the Number of Failures per Mile (per 1.61 Kilometers) After Preventive or Light M&R



1 mile = 1.61 kilometers

$$\text{Number of Failures per Mile} = 7.00\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.14. Prediction Curve for the Number of Failures per Mile (per 1.61 Kilometers) After Moderate or Heavy M&R

9.2.5 *SHATTERED SLABS*

It is expected that, immediately after construction, not many shattered slabs will be encountered. However, as the pavement ages and is subjected to traffic and environmentally induced loading, the number of shattered slabs should increase. Therefore, the prediction curve should have a positive trend with age. The observed data, however, do not indicate this expected trend.

For the model to show an increasing number of shattered slabs per mile (per 1.61 km) with age, β and ρ in the model specification were restricted to 1.0.

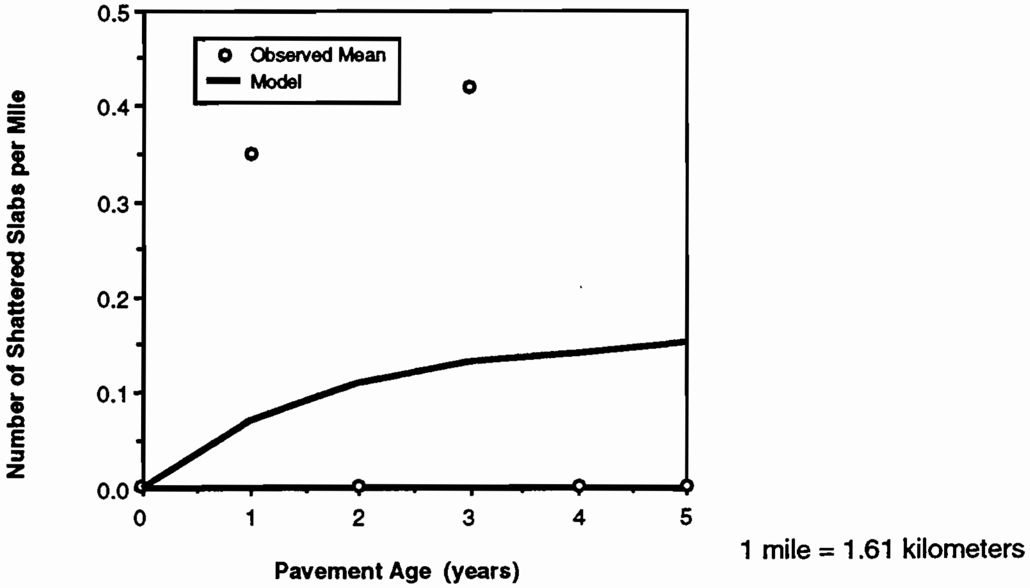
The prediction model for shattered slabs per mile (per 1.61 km) after preventive or light M&R is presented in Figure 9.15, and the model for the "after"-moderate or heavy M&R case is shown in Figure 9.16.

It must be noted that the prediction curves for these models have been fitted to a small sample which shows no distinguishable trend with age. Therefore, these models present a weak relationship between distress level and pavement age.

1 mile = 1.61 kilometers

$$\text{Number of Shattered Slabs per Mile} = 0.021\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.15. Prediction Curve for the Number of Shattered Slabs per Mile (per 1.61 Kilometers) After Preventive or Light M&R



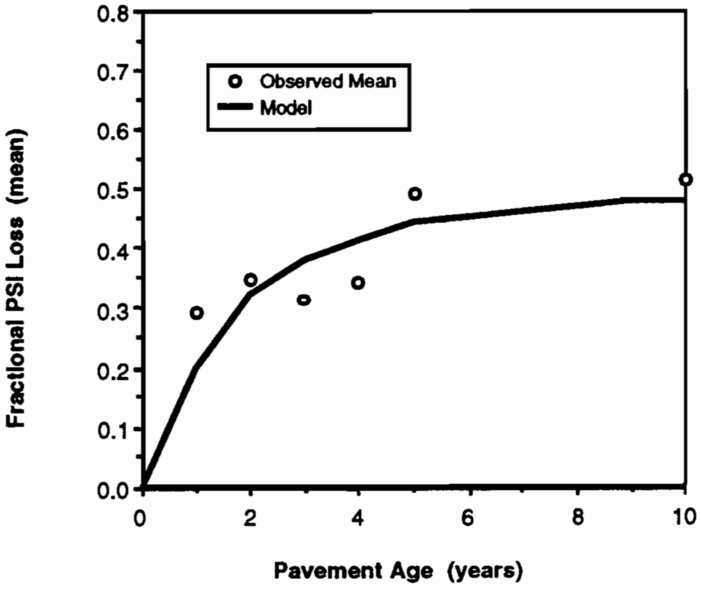
$$\text{Number of Shattered Slabs per Mile} = 0.19\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.16. Prediction Curve for the Number of Shattered Slabs per Mile (per 1.61 Kilometers) After Moderate or Heavy M&R

9.2.6 RIDE SCORE

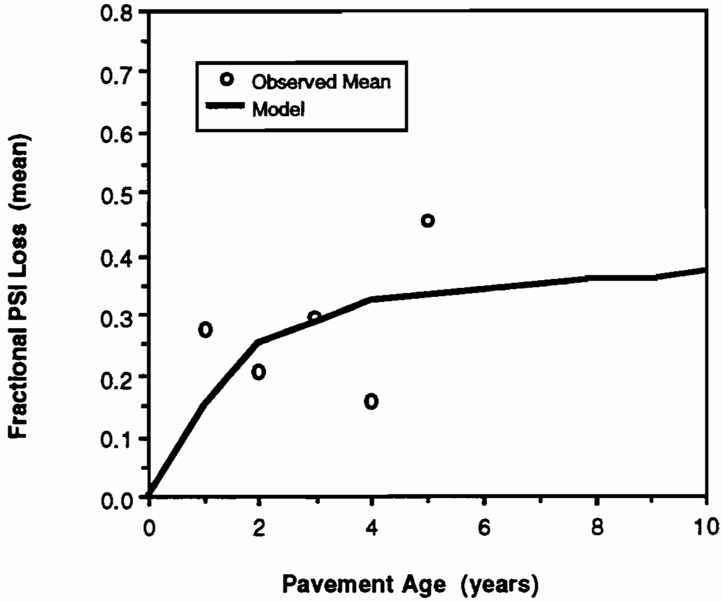
The data for loss of ride score showed no absolute trend with pavement age. As discussed earlier, theoretically, the fractional loss of ride score is expected to increase with pavement age. Therefore, in order to develop a model that complied with an engineering understanding of the fractional loss of ride score, it was necessary to impose a positive trend on the curve fitted to the observed data. The positive trend was obtained by restricting the values for β and ρ in the model specification to 1.0.

The prediction curve was fitted to the mean values of the observed data. The results of this modeling are presented in Figures 9.17 and 9.18 for the "after"-preventive or light M&R case, and the "after"-moderate or heavy M&R case, respectively.



$$\text{Fractional PSI Loss} = 0.53\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.17. Prediction Curve for Fractional PSI Loss After Preventive or Light M&R



$$\text{Fractional PSI Loss} = 0.41\ e^{-\left(\frac{1.0}{\text{AGE}}\right)^{1.0}}$$

Figure 9.18. Prediction Curve for Fractional PSI Loss After Moderate or Heavy M&R

Table 9.2 summarizes the coefficient values for Equation 2.6 for each JCP prediction model developed using the PES data for the "after"-preventive or light M&R case.

TABLE 9.2. COEFFICIENTS FOR JCP DISTRESS MODELS: AFTER PREVENTIVE OR LIGHT M&R USING THE PES DATABASE

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
PCC Patches	1.64	1.00	1.00
Failed Joints & Cracks	19.59	1.00	1.00
Slabs with Long. Cracks	4.64	1.00	1.00
Failures	33.12	0.082	10.0
Shattered Slabs	0.021	1.00	1.00
Fractional PSI Loss	0.53	1.00	1.00

Table 9.3 summarizes the coefficient values for Equation 2.6 for each JCP prediction model developed using the PES data for the after moderate or heavy M&R case.

TABLE 9.3. COEFFICIENTS FOR JCP DISTRESS MODELS: AFTER MODERATE OR HEAVY M&R USING THE PES DATABASE

DISTRESS TYPE	MODEL COEFFICIENTS		
	α	β	ρ
PCC Patches	0.35	1.00	1.00
Failures	7.00	1.00	1.00
Shattered Slabs	0.19	1.00	1.00
Fractional PSI Loss	0.41	1.00	1.00

CHAPTER 10. CONCLUSIONS AND RECOMMENDATIONS

In this study the researchers examined and used the pavement condition data stored in the CTR and PES databases to develop distress and performance prediction models for rigid pavements in Texas.

10.1 CONCLUSIONS

10.1.1 MODELS FOR NON-OVERLAID CRCP SECTIONS—CTR DATABASE

It was found that condition data for non-overlaid CRCP sections from the CTR database showed a reasonable relationship between distress level and pavement age. These data were used to develop distress prediction models. The results of these analyses were good; the models produced are reasonably robust, and they are valid for practical use.

10.1.2 MODELS FOR NON-OVERLAID JCP SECTIONS—CTR DATABASE

The 1982 and 1984 CTR JCP databases contained cross-sectional data. These two databases were combined for this study to obtain time-series distress data. However, only the data for patching and faulting contained in the 1984 database were relevant to this study. Thus the prediction models developed for these two distress types are based on time-series data which displayed an acceptable trend with pavement age. The results of these analyses are considered to be adequate.

The remaining distress prediction models were based on cross-sectional data. Therefore, they are statistically less significant and are suitable for interim use only.

10.1.3 MODELS FOR OVERLAID CRCP AND JCP SECTIONS—CTR AND PES DATABASES

Examination of the condition data for overlaid CRCP sections and overlaid and non-overlaid JCP sections in the CTR database showed considerable scatter and poor correlation between pavement age and distress level. Similar trends were found in the condition data from the PES database. This inconclusive trend in the data is attributed to a combination of

(1) incomplete data for prediction factors other than pavement age,
(2) data items describing key pavement characteristics are not included in the datasets, and
(3) inadequate amounts of data.

Reasonable models therefore could not be produced for these pavement types based only on the data. It was therefore necessary to fit practical prediction curves to the available data based on engineering theory, experience, and an understanding of distress development. These curves may be used in the Texas PMIS on an interim basis until more robust models are developed as suggested under recommendation number six.

Although the models presented in this study make only a small contribution to network-level pavement management, they do help to identify key data requirements for developing future statistically significant models. It was found that the current PES and CTR databases should be expanded to include sufficient data and more sections to be used for developing robust pavement performance prediction models in the future. This will be discussed under recommendation number one.

10.2 RECOMMENDATIONS

From the experience gained in this study, several recommendations are made which can help to develop future models which reliably predict distress and performance levels. These recommendations are presented below.

(1) Analysis of the CRCP (after ACC overlay) and JCP (before and after ACC overlay) condition data in both the PES and CTR databases identified serious deficiencies in the data available for modeling purposes. In order to produce robust prediction models for these pavement types in the future, it is recommended that the following data be collected:

	CRCP	JCP
• Cumulative traffic	•	•
• Initial construction date	•	•
• Pavement type	•	•
• Slab dimensions (length, width, thickness)	•	•
• Percent reinforcing	•	•
• Coarse aggregate type in the pavement slab	•	•
• Sub-base treatment	•	•
• Joint type	•	•
• Environmental data (rainfall, temperature)	•	•
• Overlay date(s)	•	•
• Overlay thickness	•	•

(2) The available distress data for the majority of distress types for overlaid CRCP sections and for all JCP sections showed considerable scatter and a poor correlation with pavement age. To reduce the variance in the observed data and to develop models that are robust predictors of distress level, the following recommendations are made:

- Collect data on the following factors and include them in future analyses: cumulative traffic, subgrade condition, environment, slab dimensions, percent reinforcing, and coarse aggregate type.
- Use cumulative traffic as the primary predictor of distress and performance development rather than pavement age.

(3) Due to insufficient M&R data, researchers were unsuccessful in developing prediction models for pavements that had undergone preventive, light, moderate, or heavy maintenance and rehabilitation. Instead models were developed for only the before and after ACC overlay cases. To develop models for each of the four M&R cases it is essential to have adequate M&R data. Therefore, it is recommended that the following M&R data be collected

per pavement section, and stored in a format, preferably electronic, that is readily accessible for reporting and analysis purposes:

- M&R activity performed,
- date the M&R activity was performed, and
- cost of the M&R activity performed.

(4) From the above recommendations, it is clear that a considerable amount of additional data is required to develop statistically significant prediction models. It is recommended that the required data be collected only for pavement test sections that have been selected as part of a factorial arrangement of the significant factors influencing pavement performance in Texas. Figure 10.1 outlines the recommended process for selecting test sections, collecting data, and updating the prediction models.

(5) It is recommended that when more data become available from an organized and systematic data collection program, as proposed in recommendation number four, further research be undertaken to develop more robust prediction models.

(6) It is recommended that the prediction curves developed in this study be used in the Texas PMIS on an interim basis until more robust models are developed.

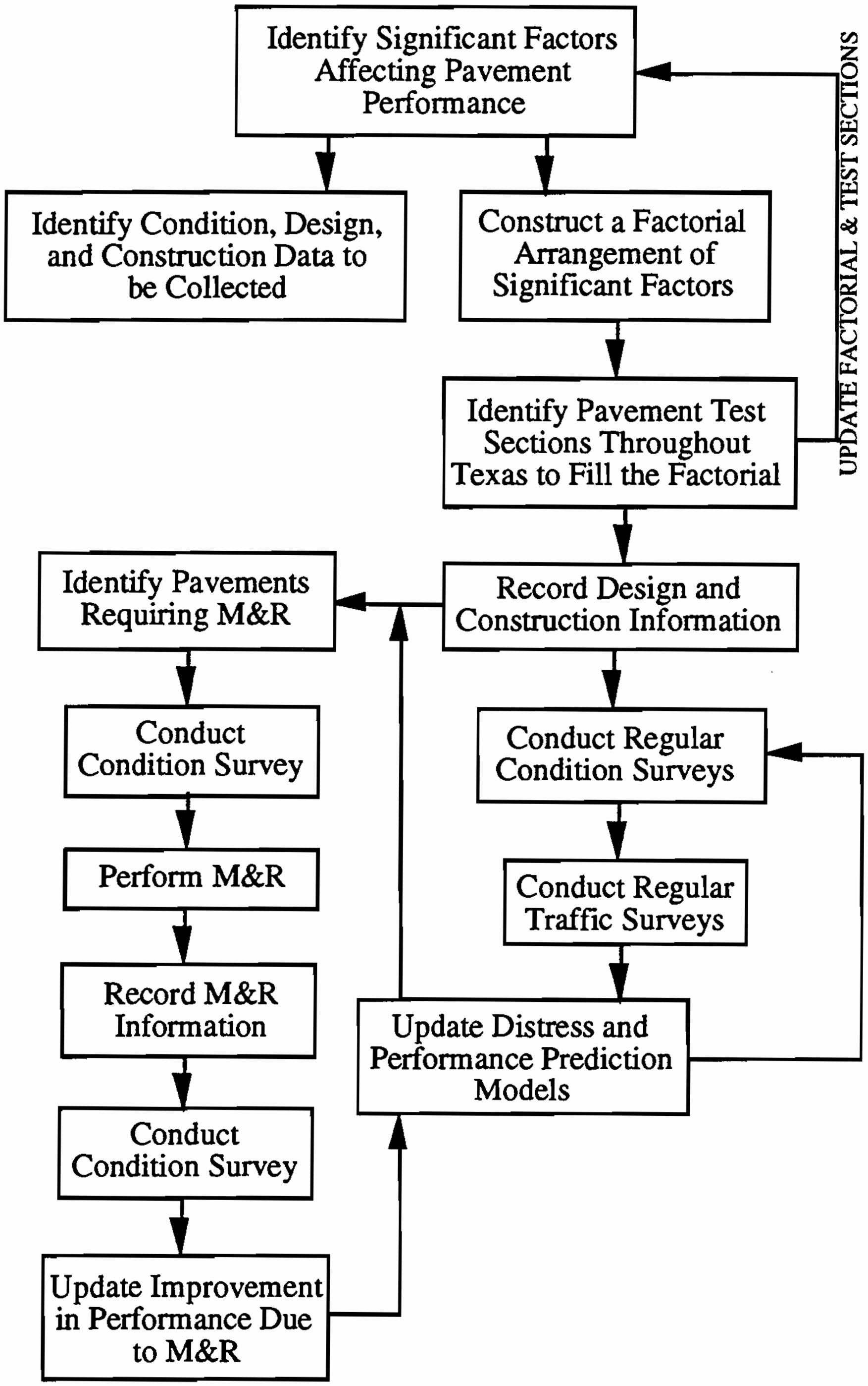


Figure 10.1. Recommended Process to Update Distress and Performance Prediction Models

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APPENDIX A

DEFINITIONS OF CTR CRCP DISTRESS TYPES

APPENDIX A. DEFINITIONS OF CTR CRCP DISTRESS TYPES

1. Spalled Cracks

Definition:

Cracks which exhibit secondary cracking or breaking of the crack edges. The depth of a spall is generally < 1 inch, but its width can be much greater. Minor and severelyspalled cracks are distinguished by the width of the spall. Minor spalled cracks have a width < 1/2 inch (1.3 cm); severely-spalled cracks have a width > 1/2 inch (1.3 cm).

How to Rate:

Only transverse cracks showing signs of spalling are counted. The whole crack is defined by the most severe condition of spalling that exists along its length.

Special Cases:

If a Y-type crack is encountered and both branches show spalling, and if the branches are longer than half the lane width, then two cracks are counted; otherwise, one.

2. Punchout

Definition

When closely spaced transverse cracks are linked by a longitudinal crack to form a block, the block is called a punchout. A minor punchout exists where a block has formed, but no movement under traffic is apparent and no spalling is present. A severe punchout exists where the block moves under traffic.

How to Rate:

The number of minor and severe punchouts per 0.2-mile (0.32-km) section is recorded.

Special Cases:

A long punchout can be recorded as several smaller punchouts if the longitudinal crack has distinct kinks in it.

3. Asphalt Patch

Definition:

A localized volume of asphalt concrete which has been placed to the full depth of the surrounding concrete slab as a temporary method of correcting surface or structural defects in the pavement structure.

How to Rate:

The condition and the size of the patch is not recorded. ACC patching of spalling and overlaying part of a concrete pavement is not classified as patching.

The number of ACC patches per 0.2-mile (0.32-km) pavement section is recorded.

4. Concrete Patch

Definition:

A localized area of portland cement concrete which has been placed to the full depth of the surrounding concrete slab, as a temporary method of correcting surface or structural defects.

How to Rate:

The condition and the size of the patch is not recorded. PCC patching of spalling and overlaying part of a concrete pavement are not classified as patching.

The number of PCC patches per 0.2-mile (0.32-km) pavement section is recorded.

APPENDIX B

DEFINITIONS OF CTR JCP DISTRESS TYPES

APPENDIX B. DEFINITIONS OF CTR JCP DISTRESS TYPES

1. Failed Joints and Cracks

Definition:

Joints and cracks which show signs of spalling are rated as failed. A spalled crack or joint shows signs of chipping or secondary cracking on either side, along all its length. If joint or crack spalling is wider than 1 inch (2.5 cm), it is counted as spalled.

How to Rate:

The number of failed joints and cracks per 0.2-mile (0.32-km) section is counted.

Only the transverse joints and cracks which show signs of spalling are counted. The whole crack or joint is defined by the most severe condition of spalling that exists along the crack.

2. Corner Breaks and Punchouts

Definition:

Corner breaks occur when a crack connects a joint with a longitudinal edge of the slab. Punchouts occur when a longitudinal crack intersects two closely spaced transverse cracks, causing a portion of the slab, approximately rectangular in shape, to be separated from the rest of the slab. Both of the above distress manifestations result in smaller slabs which may begin to deflect under load.

How to Rate:

These two distress manifestations are considered as one in the visual survey.

The number of corner breaks and punchouts is recorded per 0.2-mile (0.32-km) section.

3. Asphalt and Portland Cement Concrete Patches

Definition:

A localized volume of asphalt and portland cement concrete which has been placed to the full depth of the surrounding concrete slab as a temporary method of correcting surface or structural defects in the pavement structure.

How to Rate:

The number of ACC and PCC repair patches in the outside lane of the 0.2-mile (0.32-km) section is recorded. Portland cement concrete and asphaltic concrete patches are both included in this category.

The size of the patch is not recorded. If the patch exhibits the same characteristics as a corner break or a punchout, it is recorded as a corner break or a punchout.

4. Slabs with Severe Longitudinal Cracks

Definition:

Slabs with a crack or cracks in approximately the same direction as the flow of traffic are counted in this category. The longitudinal cracks may be short or may extend the entire length of the slab.

How to Rate

The number of slabs per 0.2-mile (0.32-km) section having severe longitudinal cracks is recorded.

APPENDIX C

DEFINITIONS OF PES DISTRESS TYPES

APPENDIX C. DEFINITIONS OF PES DISTRESS TYPES

A. CRCP SECTIONS

1. Spalled Crack

Definition:

A crack which shows signs of edge chipping on either side, along some or all of its length.

How to Rate:

Only spalled transverse cracks are counted.

Number of spalled cracks per pavement section length.

The crack must display spalling at least 1 inch (2.5 cm) wide, and covering more than 1 foot (0.3 m) of the crack's total length.

2. Punchout

Definition

A punchout is formed when a longitudinal crack intersects two closely spaced transverse cracks. The block, or slab, of pavement that is formed is usually rectangular in shape.

How to Rate:

The number of punchouts per pavement section is recorded.

Punchout boundaries exhibit either severe spalling or faulting one edge higher than the other by at least 1/4 inch (0.64 cm). If the punchout is longer than 10 feet (3 m), then rate 1 punchout for every 10 feet (3 m) of length.

3. Asphalt Patch

Definition:

A localized volume of asphalt concrete which has been placed to the full depth of the surrounding concrete slab as a temporary method of correcting surface or structural defects in the pavement structure.

How to Rate:

Number of patches per pavement section is recorded.

Asphalt concrete materials placed to repair surface or crack spalls, overlays, or level-ups are not to be counted as patches. An asphalt patch must be at least 8 inches (20. 3 cm) long [square or rectangular shape]. The width is not important. Long patches > 10 feet (3 m) must be rated as 1 patch per every 10 feet (3 m).

4. Concrete Patch

Definition:

A localized area of portland cement concrete which has been placed to the full depth of the surrounding concrete slab, as a temporary method of correcting surface or structural defects.

How to Rate:

Number of patches per pavement section is recorded.

Portland cement concrete materials placed to repair surface or crack spalls, overlays, or level-ups are not to be counted as patches. A concrete patch must be at least 8 inches (20.3 cm) long [square or rectangular shape]. The width is not important. Long patches > 10 feet (3 m) must be rated as 1 patch per every 10 feet (3 m).

5. Average Transverse Crack Spacing

Definition:

Average crack spacing is not a distress type. It is, however, a measure of whether or not the CRC slab is behaving as designed. A CRC section with a small average crack spacing has a greater probability of deteriorating into a series of small punchouts, when compared to a slab with a large average crack spacing. It is used as a method of obtaining the percentage of transverse cracks that are spalled.

How to Rate:

The total number of transverse cracks observed in three selected 200-foot-long (61-meter-long) sections are counted. The average crack spacing is calculated as follows:

Average Crack Spacing = 600 feet / (Total Number of Cracks)

= 182.9 meters / (Total Number of Cracks)

Acceptable rating values for PES data entry are crack spacings of 75 feet (22.9 m) or less. If the crack spacing is greater than 75 feet (22.9 m) , the program will enter 75 feet (22.9 m) as the average crack spacing.

B. JCP SECTIONS

1. Failed Joints and Cracks

Definition:

This distress type covers two items: spalled joints or transverse cracks, and asphalt patches of spalled joints or transverse cracks.

How to Rate:

A spalled joint or transverse crack must display signs of edge chipping or secondary cracking. The chipping must be at least 1 inch (2.5 cm) wide and covering more than 1 foot (0.3 m) of the crack's total length.

The number of failed joints and cracks per pavement section is recorded..

2. Failures

Definition:

Failures are localized areas where traffic loads do not appear to be transferred across load transfer devices. Failures are typically areas of surface deterioration and disintegration.

Corner Breaks:
A corner break occurs when a crack connects a joint with a longitudinal edge of the slab. To be rated as a failure, the crack must intersect between 1 foot (0.3 m) and halfway across each edge of the slab.

Punchout:

A punchout occurs when a longitudinal crack intersects two closely spaced transverse cracks, causing a portion of the slab, approximately rectangular in shape, to be separated from the rest of the slab. For long punchouts, record one punchout for every 10 feet (3 m).

Asphalt Patches:

The three types of AC patches are considered: full depth patches which must be more than 10 feet (3 m) long (the average depth of a JCP slab); shallow depth patches of a corner break or punchout; and patches > 10 feet (3 m) long, used to repair joints and/or longitudinal or transverse cracks.

Concrete Patches:

Portland cement concrete patches which are spalled or faulted around the edges should be rated as failures, in the punchout category.

D-Cracking:

D-cracking is a series of closely spaced crescent shaped, hairline cracks which tend to cluster together along joints, slab edges, and/or large transverse or longitudinal cracks.

How to Rate:

Total number of failures observed per pavement section is recorded.

3. Shattered Slabs

Definition:

A shattered slab is a slab so badly cracked that it warrants complete replacement.

How to Rate:

If five or more failures are found, or if one or more failures cover more than half of slab area, then the slab is considered to be shattered. The following items are considered failures: corner breaks, punchouts, asphalt patches, failed concrete patches, and D-cracking.

Number of shattered slabs per pavement section is recorded.

4. Slabs with Longitudinal Cracks

Definition:

A longitudinal crack is a crack which runs roughly parallel to the roadway centerline.

How to Rate:

If a severely spalled or faulted longitudinal crack travels from one transverse joint to the next, or from one transverse joint to an edge joint and is greater than half the slab's length, then the crack is rated as a longitudinal crack.

The total number of slabs with longitudinal cracks per pavement section is recorded.

5. Concrete Patches

Definition:

A portland cement concrete patch is a localized volume of newer concrete which is placed to full depth of an existing slab to correct surface or structural defects in the pavement structure.

How to Rate:

Full depth concrete patches are usually cut into the slab; thus the patch is cleanly shaped into either a square or a rectangle. Therefore, rate all cleanly shaped square or rectangular concrete patches. The patch should be at least 10 inches (25.4 cm) long. The width of the patch should not be considered.

The following should not be rated as PCC patches.

Level-ups and overlays.
Repaired spalls in good condition.
Patched corner breaks in good condition.

The number of patches per pavement section is recorded.

6. Apparent Joint Spacing

Definition:

Some transverse cracks may become so wide that they look and act like joints. These apparent joints are important because they serve to divide the original slab into smaller units.

How to Rate:

Apparent joint spacing should be measured for a longitudinal distance of 200 feet (61 m), three times for each section (beginning, middle, end), and then averaged.

PES will accept entries in the range of 15-75 feet (4.6-22.9 m). Entries less than 15 feet (< 4.6 m) will be recorded as 15 feet, and entries greater than 75 feet (> 22.9 m) will be recorded as 75 feet.

APPENDIX D

M&R HISTORY SURVEY FORMS

APPENDIX D. M&R HISTORY SURVEY FORMS

FORM 1 : CATEGORIZATION OF MANTENANCE ACTIVITIES

MAINTENANCE & REHABILITATION ACTIVITY	MAINTENANCE & REHABILITATION CATEGORIES							
	CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS				JOINTED CONCRETE PAVEMENTS (PLAIN & REINFORCED)			
	PREVENTIVE MAINTENANCE	LIGHT REHABILITATION	MEDIUM REHABILITATION	HEAVY REHABILITATION	PREVENTIVE MAINTENANCE	LIGHT REHABILITATION	MEDIUM REHABILITATION	HEAVY REHABILITATION
Drainage maintenance								
Clean/reshape ditches								
Clean & seal joints								
Seal severe cracks								
AC Patching								
PCC patching								
Seal all cracks								
Slab jacking & grouting								
Repair joints								
Joint reconstruction								
Slab replacement								
AC Overlay								
PCC Overlay								
Reconstruct								
Other:								

Check mark the appropriate box

FORM 2: MAINTENANCE AND REHABILITATION HISTORY

SECTION IDENTIFICATION:

District Name: .... District Number: .... County: ....

Highway Number: .... Maintenance Section Number: ....

Reference Marker: Begin: .... End: ....

INITIAL CONSTRUCTION DATE: Completion Date: ....

Coarse Aggregate Type: ....

M&R HISTORY: *

Date	Preventive Maintenance	Light Rehabilitation	Medium Rehabilitation	Heavy Rehabilitation

* From 1983 onwards only. Check mark the appropriate box.