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# TEXAS PAVEMENT MANAGEMENT SYSTEM: SUMMARY REPORT

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and Jian-Neng Wang

RESEARCH REPORT 1908-5F

Project 7-1908

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16. Abstract

This report, the final for Project 1908, describes the performance models for jointed concrete pavements (JCPs) this project developed for incorporation in the TxDOT Pavement Management Information System (PMIS). As indicated in the report, these models appear to be reasonable indicators of general trends within the pavement population. In addition, the report explores the possibility of developing performance models based on stiffness loss estimated with deflection basin parameters obtained from falling weight deflectometer (FWD) measurements. We found the radius of curvature to be the most sensitive parameter for slab and base stiffnesses, though not sufficiently sensitive to determine subgrade modulus. Finally, this report presents the overall findings of Project 1908, along with conclusions and recommendations for future research.

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# SUMMARY REPORT

by

Terrence Dossey
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Virgil Anderson
Jian-Neng Wang

**Research Report 1908-5F**

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**

November 1995

## IMPLEMENTATION STATEMENT

This report presents information that can assist the Texas Department of Transportation (TxDOT) in the implementation of its Pavement Management Information System (PMIS) for rigid pavements in Texas. Accordingly, we recommend that the results of Project 1908 be incorporated into the various PMIS activities being undertaken by TxDOT. Indeed, this has already been accomplished, since some of the models have been incorporated in the PMIS programs, and since various findings related to planning and data collection have been incorporated in other projects, such as Project 1342, "Long-Term Data Collection for Pavements."

We also recommend that a follow-up project be undertaken over the next two years (1996-1998) to investigate the possibility of predicting pavement performance based on deterioration of the various pavement layers in service, as determined by network-level deflection measurements, particularly backcalculation of deflection basins. We also recommend that when data for composite pavements become available, a follow-up project be carried out to develop appropriate models for distress predictions of various types for composite pavements.

Finally, additional data collection on all classes of rigid pavement is being carried out over a 1995-97 time frame. As soon as these data become available, a follow-up project should be initiated to update the models presented in the various reports. Such new models should be significantly more effective than the current models, given that an additional round of data will increase the total data available for model building by 40-50 percent.

## ACKNOWLEDGMENTS

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As with any report, the contributions are too numerous to list everyone as authors. In this case, significant contributions have been made not only by Mr. Arif Beg and Mr. Arslan Razmi, but also by all the authors of the previous 1908 reports. Thanks are due to the CTR editorial staff headed by Mr. Ray Donley, whose contributions to these reports are always significant.

Prepared in cooperation with the Texas Department of Transportation.

# DISCLAIMERS

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

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# SUMMARY

This report, the final for Project 1908, describes the performance models for jointed concrete pavements (JCPs) this project developed for incorporation in the TxDOT Pavement Management Information System (PMIS). As indicated in the report, these models appear to be reasonable indicators of general trends within the pavement population. In addition, the report explores the possibility of developing performance models based on stiffness loss estimated with deflection basin parameters obtained from falling weight deflectometer (FWD) measurements. We found the radius of curvature to be the most sensitive parameter for slab and base stiffnesses, though not sufficiently sensitive to determine subgrade modulus. Finally, this report presents the overall findings of Project 1908, along with conclusions and recommendations for future research.

# CHAPTER 1. INTRODUCTION

## 1.1 BACKGROUND

### *1.1.1 Pavement Management Systems*

The U.S. highway industry spends billions of dollars each year on the maintenance and rehabilitation of pavements. Texas alone spends nearly $2 billion annually on improvements. This kind of investment requires a rationally planned, pragmatically designed, and carefully executed set of management activities. Such management is best ensured through a pavement management *system* (PMS), one that consists of a comprehensive and coordinated set of activities associated with the planning, design, construction, maintenance, evaluation, and research of pavements (Ref 1).

The importance of a comprehensive PMS is underscored by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). This Act requires that each state have a working PMS by October 1, 1995, on the National Highway System (NHS), and by October 1, 1997, on the non-NHS federal-aid highways (Ref 2).

### *1.1.2 TxDOT's Pavement Management Information System*

The Texas Department of Transportation (TxDOT) is currently in the final stages of developing a Pavement Management Information System (PMIS). The PMIS will be implemented in two stages. Stage I, addressing the statewide system, was completed and implemented in 1993. Stage II, a more detailed system addressing district-level implementation, was scheduled to be implemented during 1995-96. The PMIS contains approximately 180,000 sections which, when combined, make up the entire network of state-maintained highways (Ref 3), including both rigid and flexible pavements.

### *1.1.3 Overview of Project 1908*

One of the primary objectives of a PMS is to collect, store, and use data gathered from surveys to evaluate the present condition of pavement sections. Other objectives are to predict the future maintenance and rehabilitation needs of these pavement sections, and to prioritize present and future projects based on various considerations (economic, financial, technical, etc.).

To help achieve these objectives, and in order to develop a comprehensive Pavement Management Information System for rigid pavements, the Center for Transportation Research (CTR), in collaboration with TxDOT, undertook Project 1908 in September 1992. The objectives of this project were:

1. to develop appropriate models to predict pavement performance, preventive maintenance, rehabilitation, and heavy rehabilitation and reconstruction treatments for rigid pavements for use in the Texas PMIS;

2. to study the feasibility of expanding the Long-Term Pavement Performance (LTPP) database currently being maintained in Texas to include additional pavement test sections, to make the resulting database self-contained in Texas for better modeling of future efforts;
3. to evaluate and analyze the structural data, including the falling weight deflectometer (FWD) measurements currently available in the Texas Pavement Evaluation System (PES) database, to produce structural performance models for rigid pavements for use in the Texas PMIS;
4. to evaluate FWD data collected on rigid pavements added to the database in 1994-95;
5. to develop information related to environmental and weather factors (including their impact on rigid pavement performance in Texas);
6. to revise and improve recommendations for FWD data collection based on field studies performed under TxDOT Project 1342;
7. to make final recommendations to TxDOT as to what data should be included in the proposed PMIS database, based on structural, environmental, and traffic factors identified as significantly influencing pavement performance (and to prioritize the data items to be collected, dividing them into essential and optional);
8. to suggest modifications to decision trees for rigid pavement rehabilitation included in the PMIS;
9. to develop and evaluate FWD collection procedures and data for composite pavements and AC overlay of rigid pavements; and
10. to develop performance models for composite pavements to be used in the PMIS prediction equations.

Five major research reports were delivered under Project 1908. Report 1908-1, *Preliminary Distress and Performance Prediction Models for Concrete Pavements in Texas,* presents the results of a study to develop and test distress and performance prediction models for rigid pavements in Texas. Report 1908-2, *Design Specifications and Implementation Requirements for a Texas Long-Term Pavement Performance Program,* summarizes the requirements for developing a long-term pavement performance (LTPP) program for the state of Texas. It also describes an experiment design that keeps in view the existing LTPP and CTR experiment designs, as well as the type of data that should be collected. Finally, it also evaluates the human and financial resources required to establish, maintain, and monitor the database.

Report 1908-3, *Network Level Deflection Data Collection for Rigid Pavements,* evaluates the existing rigid pavement deflection data contained in the PES database and finds them to be inadequate for any network-level study of the structural behavior of rigid pavements. Recommendations are provided for future FWD data collection for rigid pavements at the network level. The optimum sample size, the testing procedures, and a cost estimate for the data collection plan are given. Report 1908-4, *Revised and Improved Distress Prediction Models for Rigid Pavements in Texas,* describes the development of updated prediction models for the Texas PMIS, focusing on prediction models for several types of rigid pavement distress. This final report, Report 1908-5F, summarizes the findings of the entire project and presents some conclusions and recommendations.

## 1.2 OBJECTIVES OF THIS REPORT

The main objectives of this report, the final report for Project 1908, are:

- to present a concise overview of Project 1908;
- to present performance models for jointed concrete pavements (JCPs) according to the PMIS Distress Manifestations;
- to explore development-of-stiffness-loss models based on deflection basin parameters obtained from FWD measurements; and
- to make recommendations for successful implementation of the project findings.

## 1.3 ORGANIZATION OF THIS REPORT

This report presents information that can assist TxDOT in the implementation of the PMIS for rigid pavements in Texas. Chapter 1 presents an overview of Project 1908 and states the scope and objectives of this report. Chapter 2 compares the distress classifications for jointed concrete pavements (JCPs) in the Center for Transportation Research (CTR) database and the TxDOT Pavement Evaluation Systems (PES) database. Additional models for JCPs are also presented. Chapter 3 discusses the possibility of using deflection basin parameters to evaluate stiffness loss in pavement layers. Also discussed are a sensitivity analysis of various parameters, and the possible development of stiffness loss models based on these parameters. Chapter 4 reviews the accomplishments of this project and compares them with the initial objectives. Conclusions are drawn and recommendations are made on the basis of work performed under this project.

# CHAPTER 2. DISTRESS PREDICTION MODELS FOR JOINTED CONCRETE PAVEMENTS

## 2.1 BACKGROUND

TxDOT maintains a rigid pavement database containing certain distress manifestations. The JCP models presented in Report 1908-4 provided two models as required in the PMIS: (1) failed joints and cracks per mile, and (2) number of slabs with longitudinal cracks per mile. In this report, the following additional models are reported as needed by TxDOT for PMIS applications: (1) failures (punchouts plus patches) per mile, (2) portland cement concrete patches per mile, (3) and apparent joint spacing. No model was developed for shattered slabs because the data available are not adequate for model development. Table 2.1 lists the distress models developed for JCP, along with their shape parameters $\alpha$, $\beta$, and $\rho$ and goodness-of-fit measure.

In addition, because of the scarcity of data, no modifying coefficient factors for structural, environmental, or traffic loading variables ($\sigma$, $\varepsilon$, and $\chi$ ) could be developed for these models. These variables can significantly influence behavior (and thus performance), and may also account for some scatter among the observed data.

*Table 2.1. Coefficients for JCP distress prediction models*

| | **Model Coefficients** | | | |
|---|---|---|---|---|
| **Distress Type** | $\alpha$ | $\beta$ | $\rho$ | **$R^2$** |
| Failed Joints and cracks | 37.02 | 5.21 | 7.95 | 0.53 |
| Longitudinal Cracks | 34.47 | 0.52 | 240.75 | 0.33 |
| Failures | 318 | 1.16 | 52.5 | 0.81 |
| PCC Patches | 9.08 | 9.24 | 18.6 | 0.52 |
| Apparent Joint Spacing | 41 | 0.0013 | 3.7 | * |
| | | | | |

*No value was obtained from analysis due to infinite possible solutions.

## 2.2 SUMMARY OF MODELS DEVELOPED IN RESEARCH REPORT 1908-4

### *2.2.1 Data Set Used in Calibrating the Models*

The data collected in 1982 and 1994 for the CTR database was used for calibrating the JCP models presented in Report 1908-4. A 1994 distress data collection effort, conducted under Project 1342, selected sections for survey that established a factorial experiment design for the PMIS. Since the pavement sections selected for survey in 1994 formed a well-balanced sample from the population of Texas pavements, we decided to use distress data collected from sections surveyed in 1982 and again in 1994 as the data set for the models' calibration.

### *2.2.2 Calibration of Distress Models*

The models presented make no distinction between reinforced and plain jointed pavement sections. A division of the data used for analysis showed that JPCP sections fell into fewer than five yearly age categories and do not, consequently, provide enough information for a cross-sectional analysis of JPCP sections. Therefore, both categories were combined for model calibration.

Because of the non-linear nature of the models, the NLIN (non-linear regression) procedure in the Statistical Analysis System (SAS) software package was used for the calibration. The $\alpha$, $\beta$, and $\rho$ shape coefficients are calibrated. Future distress surveys of Texas pavements should help to more clearly define distress trends, and, in addition, should provide enough information to allow for the calibration of separate models for JCP and JRCP.

### *2.2.3 Models Presented in Report 1908-4*

Figures 2.1 and 2.2 show a plot of the PMIS equation for two distress types. The models for failed joints and cracks per mile and number of slabs with longitudinal cracks were developed in study 1908-4. The data points shown represent averages for each age group (rather than individual observations), and were weighted for the regression according to frequency of observations in each age group.

### *2.2.4 Failed (Spalled) Joints and Cracks per Mile*

Figure 2.1 shows the trend of the data for spalled joints and cracks with age. These data also exhibit considerable scatter at ages greater than nine years. This seems to indicate that spalling does not generally occur early in pavement life, but rather begins to occur after 8 to 10 years. Even after 10 years of age, the observable data in Figure 2.1 do not show the same increasing trend with age as do the other distress types.

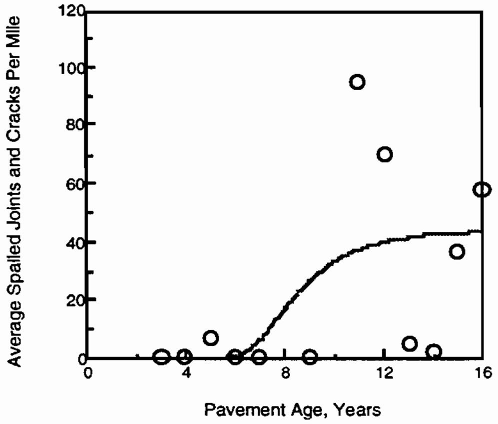


*Figure 2.1. Distress prediction model for spalled joints and cracks per mile (1 mile=1.61 km)*

### *2.2.5 Number of Slabs with Longitudinal Cracks per Mile*

Longitudinal cracks are affected by a number of variables, including slab dimensions, traffic loading, structural support, and particularly the presence or absence of reinforcing steel. Figure 2.2 shows the trend of number of slabs with longitudinal cracks per mile.

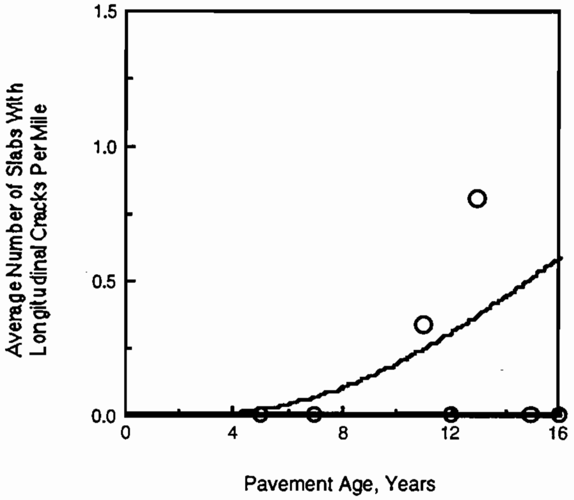


*Figure 2.2. Distress prediction model for slabs with longitudinal cracks per mile (1 mile=1.61 km)*

## 2.3 DEVELOPMENT OF ADDITIONAL JCP PERFORMANCE MODELS

In addition to the JCP performance models reported previously in Report 1908-4 (and summarized above), three additional performance models were needed to complete the list of jointed pavement distress types required by the TxDOT PMIS. These three distresses are failures (punchouts plus patches) per mile, portland cement concrete patches per mile, and apparent joint spacing.

### *2.3.1 Inference Space for the Models*

As explained previously, the available CTR jointed pavement database is not nearly as comprehensive as the CTR CRCP database. Comprehensive condition and inventory data for jointed pavements corresponding to PMIS needs were collected for the first time in 1994 as a joint effort between TxDOT projects 1908 and 1342. While some additional historical data are available (collected in 1982 and 1984), they do not correspond exactly to PMIS distress type definitions. In particular, punchout data were not collected at all in 1982 and only sparsely in 1984. For this reason, only 1994 jointed condition survey data were used in the following analysis.

In 1994, a condition survey was performed on both jointed plain concrete (JCP) and reinforced jointed pavement (JRCP). Table 2.2 shows the approximately equal survey of JCP and JRCP.

*Table 2.2 JCP distribution by type (Ref 8)*

| Pavement Type | Projects | Cumulative % | Test Sections | Cumulative % |
|---|---|---|---|---|
| JCP | 32 | 47 | 73 | 50 |
| JRCP | 36 | 100 | 72 | 100 |

Figure 2.3 shows the distribution of projects over a total of 14 districts. It can be clearly seen that the majority of surveys were performed in the districts of Houston, Dallas, and Beaumont, with 18, 15, and 11 construction projects, respectively. The location of the test sections according to climatic regions is shown in Figure 2.4.

*Figure 2.3. JCP project distribution by district*

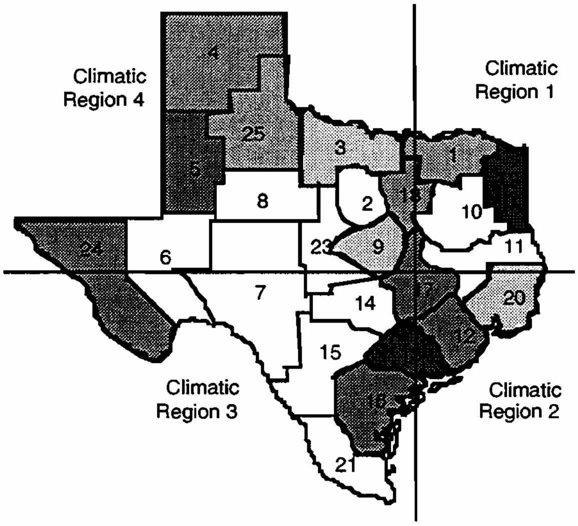


*Figure 2.4. Location of JCP projects surveyed*

Figure 2.5 summarizes the highway functional classification distribution of test sections surveyed. It can be observed that the condition survey was mostly performed on test sections for Interstate, U.S., and state highways, since jointed pavement is primarily used on heavy-traffic pavements.

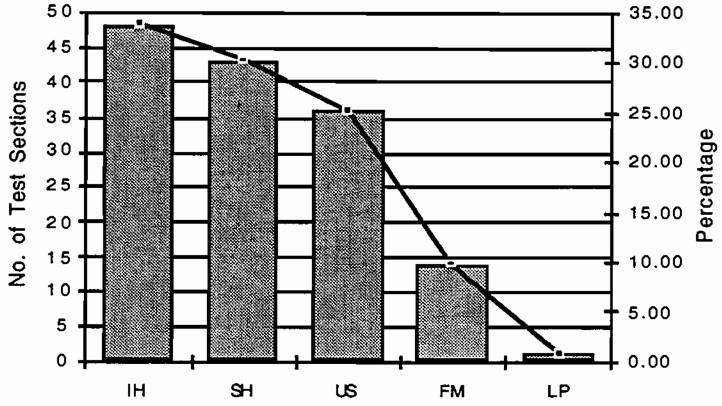


*Figure 2.5. JCP highway functional classification distribution*

Figure 2.6 shows the age distribution of the test sections. Two main conclusions can be derived from this chart. The projects surveyed are on average 25-27 years old, and around 17 percent of the projects are less than 15 years old. This indicates that, since the midpoint value for the factorial is 15 years, the JCP database is currently unbalanced in terms of age, a problem that is under study and that will be corrected by the current database study, TxDOT Project 2952.

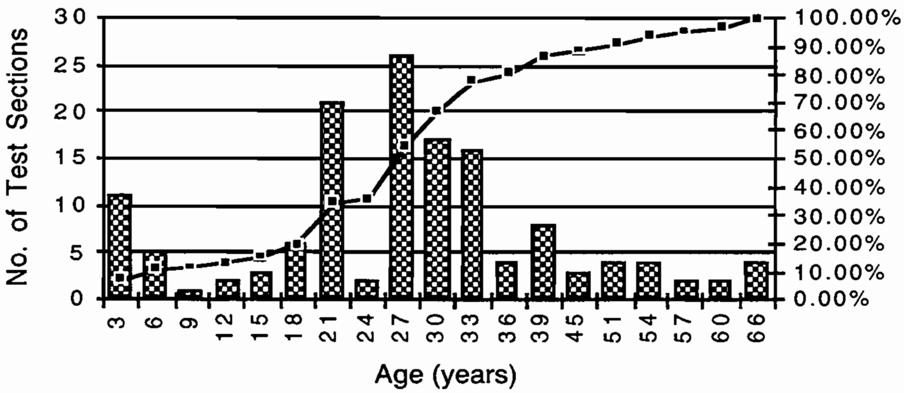


*Figure 2.6. Age distribution of test sections surveyed*

The number of overlaid vs. non-overlaid test sections is presented in Table 2.3. Despite the age of the pavement projects, 55 percent of the sections were still non-overlaid at the time of the survey.

*Table 2.3. Overlaid vs. non-overlaid JCP test sections*

| Status | Frequency | Percent |
|---|---|---|
| NON-OVERLAID | 81 | 55.9 |
| OVERLAID | 64 | 44.1 |

Finally, Table 2.4 shows the coarse aggregate type (CAT) distribution, while Figure 2.7 shows the thickness distribution of the test sections surveyed. Based on the CAT distribution, one-third of the test sections were built with limestone, and almost two-thirds were built with siliceous river gravel aggregates. The thickness of test sections ranged from 15.2 to 33 cm, with a significant number of pavements having a thickness of 25.4 cm.

*Table 2.4. JCP coarse aggregate type distribution*

| CAT | Frequency | Percent |
|---|---|---|
| LIMESTONE | 48 | 33.8 |
| SILICEOUS | 88 | 62.0 |
| OTHER | 6 | 4.2 |

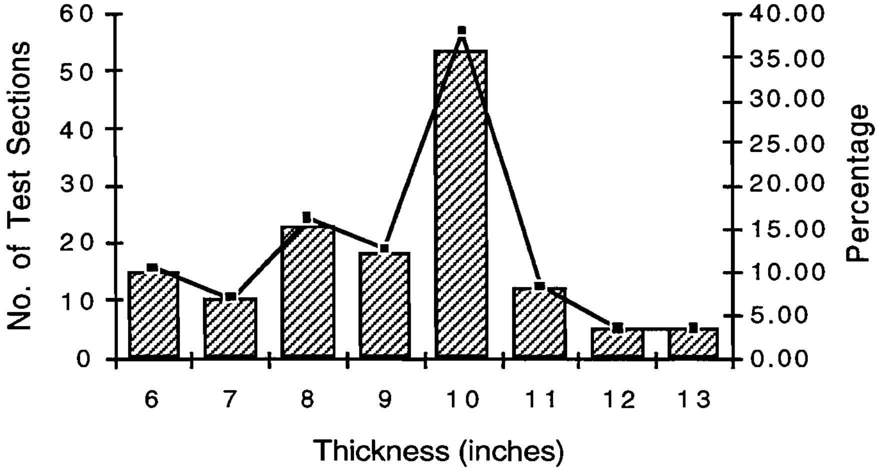


*Figure 2.7. JCP slab thickness distribution (1 inch=2.54 cm).*

### *2.3.2 Failure Prediction Model*

This prediction model was developed for non-overlaid jointed pavement. Failures were defined as punchouts plus patches, adjusting for the length of the test section to give a result in terms of failures per mile. Initially, separate models were planned for JCP and JRCP; however, the preliminary analysis of variance (ANOVA) found only pavement age and joint spacing to be significant at the alpha=.05 level, so a single combined model was developed for both pavement types. Figure 2.8 shows how the model fits the observed data points, which are averages for all the test sections of approximately the same age.

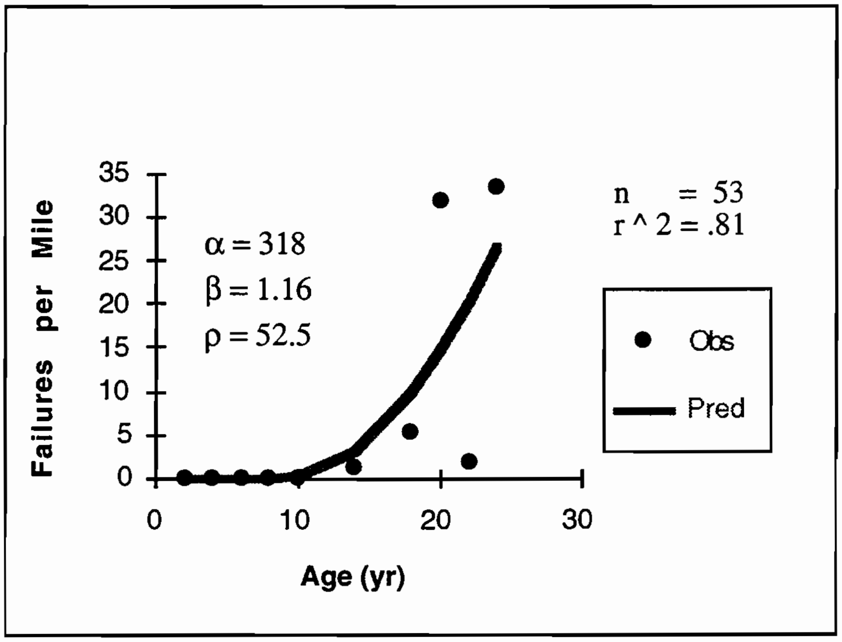


*Figure 2.8. Model for failures per mile (1 mile=1.61 km)*

Obviously, there is considerable scatter owing to the small number of sections used in the analysis. However, the model is reasonable (giving 15 failures per mile at 20 years) and can be updated in the future using the additional jointed pavement performance data being collected under TxDOT Project 2952.

### *2.3.3 Portland Cement Concrete Patches per Mile*

Using similar techniques, we developed a model to predict portland cement concrete (PCC) patches per mile. First, an ANOVA gave similar results to the failure model: only pavement age and joint spacing were found to be significant. Accordingly, a single model was used for both types of jointed pavement. It should be pointed out here that the researchers were aware that JCPs (non-reinforced) were invariably 4.5 m long, while JRCPs were typically 18.2 m long. In statistical terms, the type of pavement was therefore strongly correlated with the slab length. However, slab length was found to be the stronger variable, and separate analysis of the two pavement types did not yield results that were practically different in terms of failures or PCC patches per mile; thus, the single model was chosen.

Figure 2.9 shows the model for PCC patches per mile. This model also shows a significant amount of scatter, but it must be remembered that each point (observation) is an average from several pavement sections. Accordingly, a weighted fit was used to give the points having fewer sections less priority. Again, the model gives results that are quite reasonable (based on comparison to the CRCP models and on engineering judgment), showing an average of about 5 PCC patches per mile after 20 years.

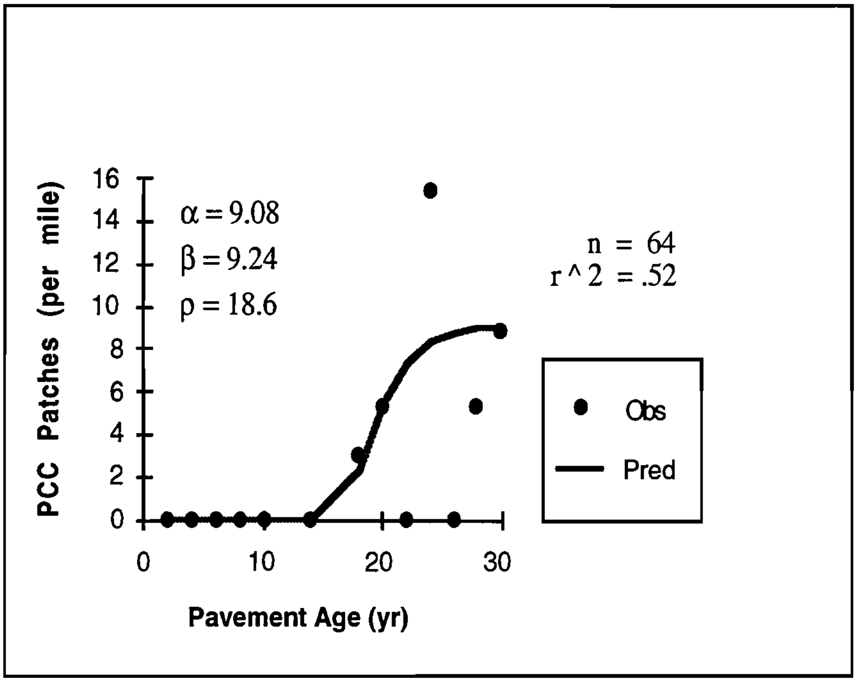


*Figure 2.9. Model for portland cement patches per mile (1 mile=1.61 km)*

### *2.3.4 Apparent Joint Spacing*

The last of the three additional models developed predicts apparent joint spacing (AJS). Apparent joint spacing is defined as the distance between discontinuities in jointed pavement, including both the as-constructed joints and significant transverse cracks that have developed since construction. In practice (1994 survey), the raters used a measuring wheel to locate joints and cracks in terms of distance from the beginning of the test section. Joints and cracks were differentiated (when possible) by circling the value on the collection form. In the computer database, no differentiation is made and both are essentially treated as cracks. For the purpose of this analysis, the apparent joint spacing was calculated by dividing the survey section length (usually 304 m) by the number of cracks plus one. Thus, a 304-m section with 99 cracks would have an apparent joint spacing of 3 m (304 / (99+1)).

The ANOVA results for AJS were initially surprising. Joint spacing, rather than pavement age, was found to be significant. However, a closer look at the data reveals few early age data points for AJS. Apparently, from the late age data, regardless of whether the pavement starts its life as a 4.5-m non-reinforced section or as a 18.2-m reinforced section, it generally cracks down to 4.5-m AJS sections. Since the initial joint spacing of each surveyed section is known, a model was developed using assumed initial joint spacings at age zero, which were weighted by the number of sections used to develop the average. Separate models were developed for 4.5-m slab length sections (Fig 2.10) and 18.2-m slab length sections (Fig 2.11), but if one model is needed for all pavements the model for 4.5 m sections is sufficient since there is little difference between the AJS after the first two years.

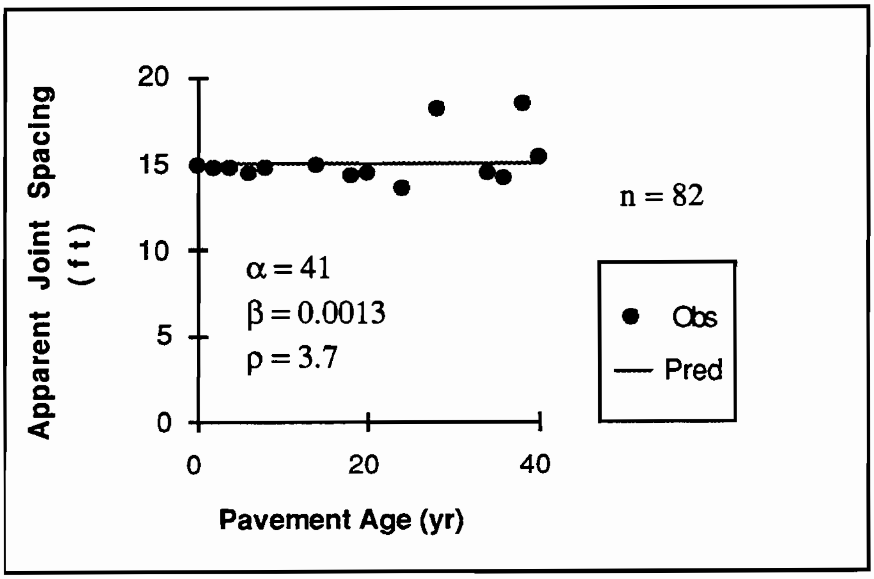


*Figure 2.10. Apparent joint spacing model for 15-ft sections (1 foot=0.304 m)*

In Figure 2.11, the response variable for AJS has been transformed by dividing the AJS into 4.5 m, the apparent final spacing. Thus, for an apparent joint spacing of 4.5 m the modeled variable would have the value 1.0, and for an AJS of 18.2 m (initial condition) the modeled variable would have the value 0.25.

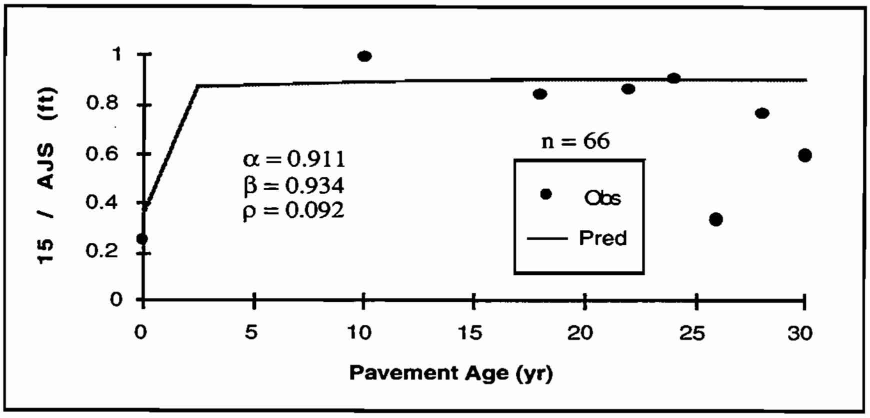


*Figure 2.11. Apparent joint spacing model for 60-ft sections (1 foot=0.304 m)*

## 2.4 DISCUSSION

It is evident from the figures that considerable unexplained scatter remains in each model. This is probably due to the use of only one year's condition survey data in developing the model. Also, because of the limited number of observations, no attempt was made to explain the variance with climatic, structural, or traffic variables. This further analysis must await the collection of additional condition survey data over 1995-1996. As a starting point for the PMIS models, these curves are quite reasonable and useful as indicators of general trends in the pavement population.

# CHAPTER 3. UTILITY OF FWD DATA FOR NETWORK-LEVEL RIGID PAVEMENT ANALYSIS

## 3.1 INTRODUCTION

This chapter introduces a methodology to help evaluate the network-level condition and performance of rigid pavements. The methodology is intended to assist engineers in knowing the current strength of pavements, scheduling the best time to perform overlay, and/or in optimizing the overlay design structures. The decrease in stiffness of individual or overall layers of pavement due to various factors is defined as stiffness loss. For pavements, stiffness loss can be treated as an "invisible distress," which can be used to evaluate the structural capacity of the pavements. This study focuses on stiffness loss calculated through FWD deflection data.

Traditionally, in order to find moduli of pavements, the modulus backcalculation method based on FWD measurements has been used. This method was derived from inversely calculating deflections by the application of elastic layer theory. Modulus backcalculation methods assume the seed values of elastic moduli of the pavement layers, calculate the theoretical deflection basin, and then compare the results with field deflection measurements to determine whether it is necessary to make adjustments based on the accuracy of results. For flexible pavements, ELSYM5, BISAR, and KENLAYER are widely used by engineers. On the network level, modulus backcalculation methods are not always convenient, since they take a great deal of time to calculate layer moduli.

However, determining stiffness loss by calculating deflection basin parameters, which in turn can be calculated directly from the deflection measurements, may be another feasible and less cumbersome way to evaluate the performance and condition of pavements, especially in network-level Pavement Management Information System (PMIS). For example, based on the stiffness loss, distress curves can be developed with pavement age and amount of traffic; these curves can then be used in the development of remaining life models for evaluating network-level pavement performance in Texas.

## 3.2 RESEARCH METHODOLOGY AND APPROACH

### *3.2.1 Literature Review*

Previously, the Center for Transportation Research (CTR) developed a failure prediction model using punchouts as the major failure criterion to estimate remaining pavement life (Ref 9). The developed model can estimate transverse crack spacing distributions for various designs and environmental conditions. This methodology was applied to computer program CRCP-5, which estimated the number of punchouts for various numbers of wheel load applications during a pavement's life.

The calibration of the CRCP failure prediction model was developed by Suh et al. (Ref 10) in CTR research report 1244-3. In this study, long-term distress curves that had various reliabilities were developed for continuously reinforced concrete (CRC) pavements in terms of the number of failures per mile using the rigid pavement database available at CTR. Calibration of the failure prediction model in the computer program CRCP-7 was performed based on these distress curves. The distress curves were classified based on coarse aggregate type, soil swelling condition, and different reliabilities.

In 1994, Dossey et al. (Ref 11) combined the above models and then developed the PAVLIF computer program and used it with actual field data. The PAVLIF program estimates the remaining life of pavements based on early age crack spacing, swelling condition, and aggregate type. For calibrating the failure models, the rigid pavement database was used to develop traffic regression models for CRC pavements (Ref 12). In order to apply the above results, the PAVLIF computer program, a convenient and subjective tool for pavement managers, was developed for IBM PC compatibles.

Nevertheless, the model used in the PAVLIF program was calibrated only for certain types of pavements; that is, it does not currently take stiffness loss of pavement layers into account. Therefore, no efforts have been made to study the effect of stiffness loss on pavement performance.

### *3.2.2 Mechanistic Analysis*

As mentioned in section 3.1, deflection basin parameters perhaps are good indicators to represent the moduli for individual layers or overall layers of rigid pavements. In order to select the best deflection basin parameter, one that is the most sensitive to pavement structures and material properties, mechanistic analysis is necessary, since current data do not provide adequate FWD data for different slab stiffnesses, base stiffnesses, and subgrade moduli. The procedure for mechanistic analysis consists of setting up the criteria, comparing models from different pavement software packages to actual data taken from FWD tests, and selecting the best model among them. The criteria is as follows:

(1) Ease of Use: For engineers, user-friendliness of a software is a major concern, since ease of use saves a great deal of time and money.

(2) Accuracy: In practice, the more accurate the results calculated from a software package, the higher priority engineers give to it.

(3) Accessibility: Pavement software packages will be chosen based on their availability on personal computers, so that most people are able to use them.

Once the mechanistic analysis has been completed, the best pavement model can be used to calculate the deflections of FWD testing.

## 3.3 EXAMINATION OF MODELS

### *3.3.1 Background of Selected Models*

Six models — ELSYM5, SLAB49, KENSLABS, KENLAYER, ABAQUS Dynamic Analysis, and ABAQUS Static Analysis — were considered These models, with the exception of the ABAQUS model, which is used in a workstation environment, can be used on an IBM PC and its compatibles. The results obtained from KENLAYER were almost the same as those obtained from ELSYM5, since they are based on the same linear elastic theory and use the same mathematical formulae to solve differential equations. In addition, KENSLABS did not perform well ( it did not always run the input files). Therefore, KENSLABS and KENLAYER were eliminated.

### *3.3.2 Description of tests of models*

Table 3.1 shows the pavement structures and material properties for three cases. The results comparing the four models to the actual FWD tests are shown in Figures 3.1 through 3.3, and the comparison based on the criteria previously mentioned is listed in Table 3.2. Although more cases need to be studied to ascertain which model is the best one, the trend shows that the ELSYM5 model is not effective in calculating FWD deflections, and that the ABAQUS dynamic model needs modification. Furthermore, the ABAQUS static model seems better than others in cases I and III , but the SLAB49 model is the best in Case II.

*Table 3.1 Pavement structures and material properties of three cases for mechanistic analysis*

| **Case I (IH 10)** | | | |
|---|---|---|---|
| *10000 lb Loading* | Thickness (inch) | Modulus (psi) | Poisson ratio |
| CRCP slab | 10 | 5,589,000 | 0.2 |
| ACP base | 6 | 431,000 | 0.27 |
| Subbase | 12 | 44,000 | 0.33 |
| Subgrade | 96 | 14,000 | 0.33 |
| **Case II (BRC)** | | | |
| *9270 lb Loading* | Thickness (inch) | Modulus (psi) | Poisson ratio |
| JRCP slab | 10 | 6,500,000 | 0.18 |
| AC base | 3 | 1,040,000 | 0.27 |
| Crush stone. subbase | 6 | 48,000 | 0.33 |
| Subgrade | 120 | 26,000 | 0.4 |
| **Case III (KTRB)** | | | |
| *12000 lb Loading* | Thickness (inch) | Modulus (psi) | Poisson ratio |
| Concrete slab | 6 | 4,000,000 | 0.15 |
| Crush Stone base | 4 | 10,000 | 0.3 |
| Compacted subgrade | 36 | 75,000 | 0.25 |
| Limestone subgrade | 500 | 35,000 | 0.33 |

1 inch-2.54 cm; 1 lb=0.453 kg; 1 psi=6.894 kPa

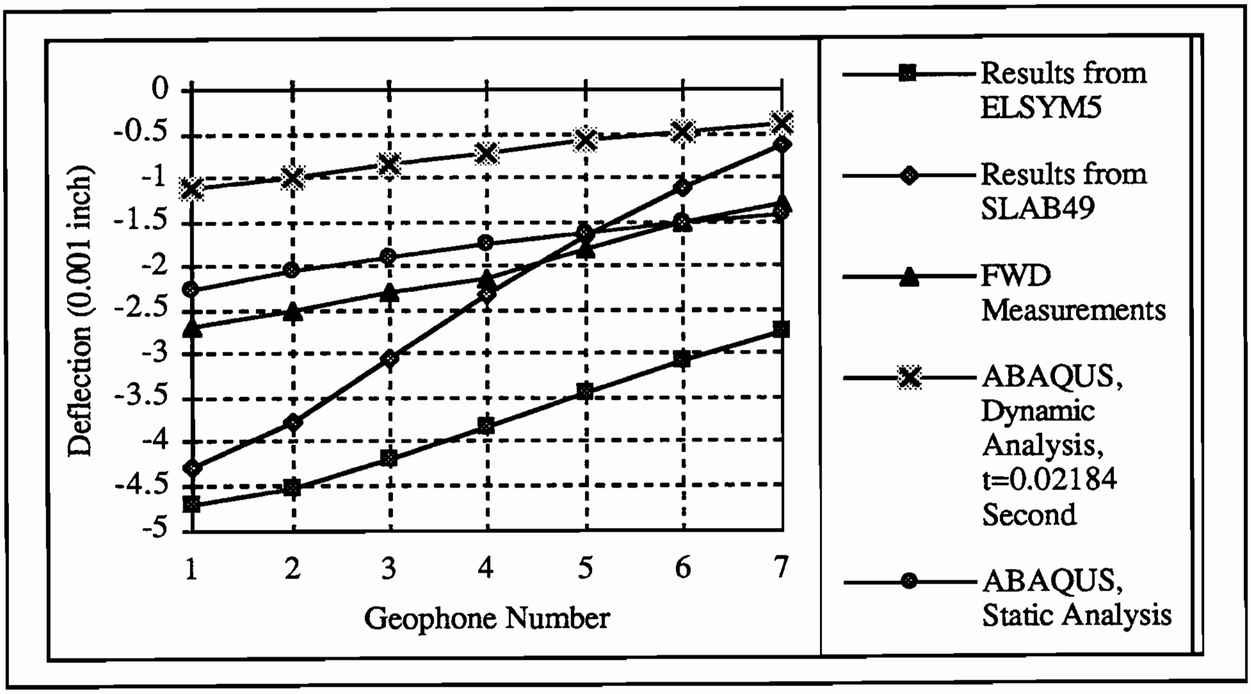


*Figure 3.1 IH 10 (close to El Paso) FWD measurements in comparison with results from pavement packages*

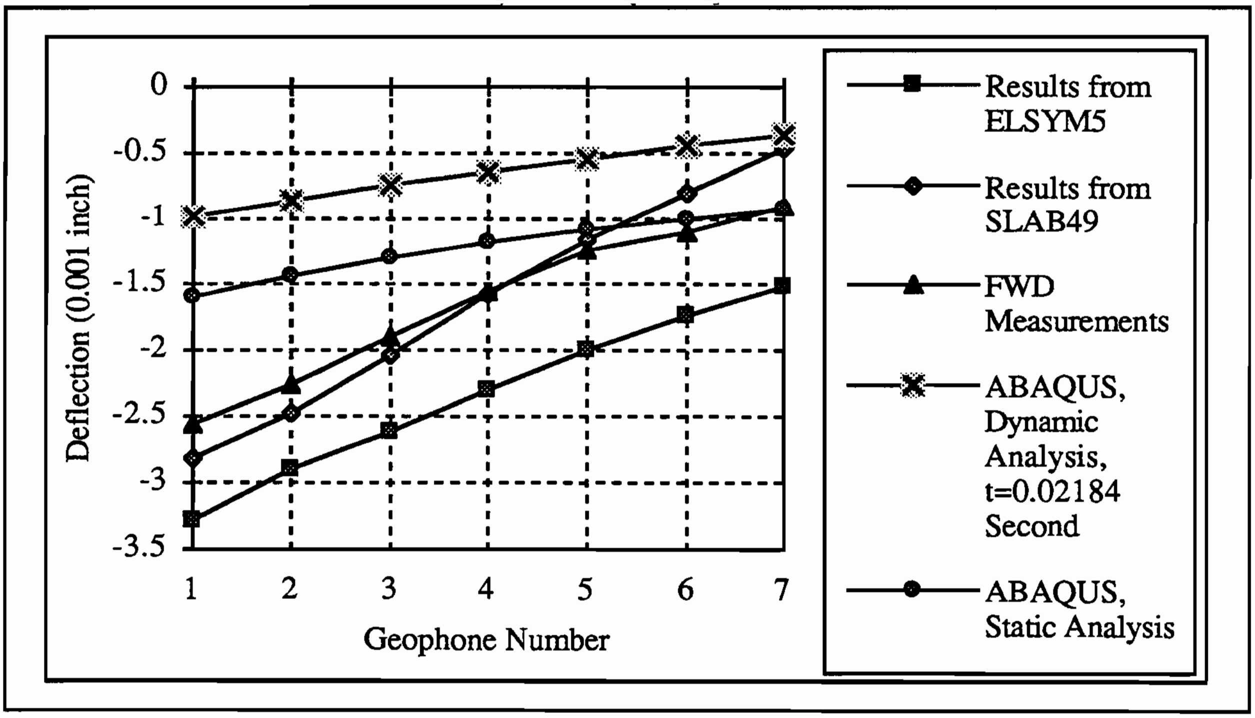


*Figure 3.2 BRC (UT JJP Research Center) FWD measurements in comparison with results from pavement packages*

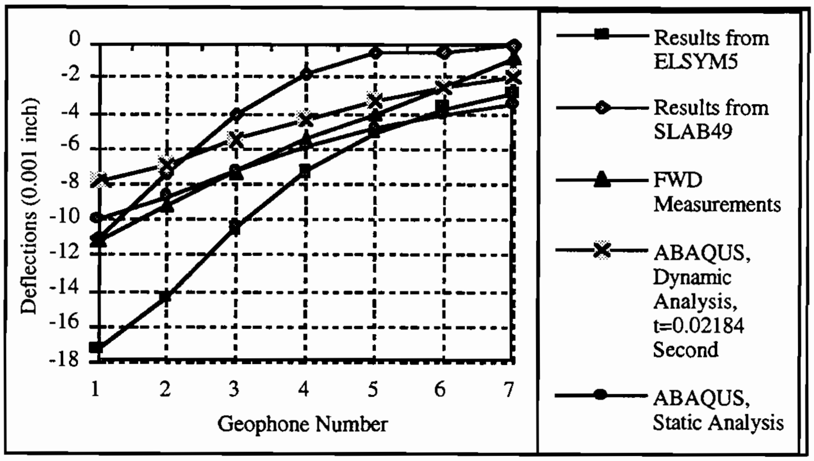


*Figure 3.3 KTRB ( Kentucky Transportation Research Building) FWD measurements in comparison with results from pavement packages*

*Table 3.2 Comparison among four models for FWD measurements*

| | SLAB49 | ELSYM5 | ABAQUS Dynamic Analysis | ABAQUS Static Analysis |
|---|---|---|---|---|
| Ease of Use | Fair | Good | Fair | Fair |
| Accuracy | Fair | Poor | Poor | Good |
| Accessibility | Good | Good | Fair | Fair |

### *3.3.3 Using Deflection Basin Parameters as Summary Variables*

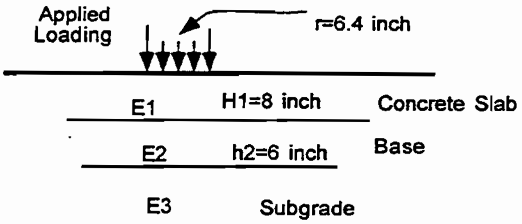
Two different pavements may have the same maximum deflection but different deflection basins, since the pavement structure and loading conditions vary. Therefore, in order to evaluate pavement structures, the Deflection Basin Parameters (DBP) can be used as indicators of the overall or individual pavement layer stiffness. In this study, thirteen deflection basin parameters were compared with respect to the stiffness of concrete slab, the stiffness of base, and the modulus of subgrade. These parameters are shown as follows:

(1) Maximum Deflection (MD),
(2) Surface Curvature Index (SCI),
(3) Base Curvature Index (BCI),
(4) Spreadability (SP),
(5) Basin Slope (BS),
(6) Slope Deflection (SD),
(7) Bending Index (BI),
(8) Radius of Curvature (RC),
(9) Tangent Slope (TS),
(10) Shape Factor (F1, F2),
(11) Sensor-7 Deflection (W7),
(12) Area (AREA),
(13) Area under the Deflection Curve (AUDC)

The definitions and references of DBP are listed in Table 3.3. The development of these parameters described in the following sections is based on the plate theory for rigid pavements. Based on criteria discussed in section 3.2.2, ELSYM5 was used as a tool for a sensitivity analysis of slab stiffness, base stiffness, and subgrade modulus. A sensitivity analysis was conducted to compare different pavement response parameters. The sensitivities of these response parameters were studied with respect to a three-layer pavement structure of concrete slab, base, and subgrade; the major variables were the stiffness of concrete slab, the stiffness of base, and subgrade modulus. Figure 3.4 shows pavement structures and several structural variables for sensitivity analyses.

According to Stocke et al. (Ref 13):

> In order to compare the individual parameters that have a range of dimensions and magnitudes, it was necessary to transform them into dimensionless parameters. This was accomplished by defining the parameter Sensitivity (S) as follows:
>
> $$S = [\, |P_1 - P_i\,| / P_m] \times 100$$
>
> where
>
> $P_1$ = the first value of the response parameter,
>
> $P_i$ = the ith value of the response parameter, and
>
> $P_m$ = the maximum value of the response parameter for the structural variable under consideration.
>
> This transformation ensures that the parameter sensitivity is always an increasing curve and that no value of S exceeds 100 percent and permits a comparison of its magnitude.



| Structure | Variables | | |
|---|---|---|---|
| | E1 (psi) | E2 (psi) | E3 (psi) |
| 1 | X | 3.0 E5 | 1600 |
| 2 | 4.5 E6 | Y | 16000 |
| 3 | 4.5 E6 | 3.0 E5 | Z |

X: E1 varied: 1.5 E6, 3.0 E6, 4.5 E6, 6.0 E6, 7.5 E6 psi
Y: E2 varied: 1.0 E5, 2.0 E5, 3.0 E5, 3.0 E5, 5.0 E5, 8.0 E5 psi
Z: E3 varied: 4000, 8000, 16000, 24000, 80000 psi

*Figure 3.4 Pavement structures used in study of sensitivity of some variables*

| Parameter | Definition [1] |
|---|---|
| Maximum Deflection | $MD = W_1$ |
| Surface Curvature Index | $SCI = W_1 - W_2$ |
| Base Curvature Index | $BCI = W_6 - W_7$ |
| Spreadability | $SP = (\Sigma W_i)/7 * W_1$ |
| Basin Slope | $BS = W_1 - W_7$ |
| Radius of Curvature | $RC = r^2/[2W_m(W_m/W_r - 1)]$ |
| Slope Deflection | $SD = Tan^{-1}[(W_m - W_b)/b]$ |
| Bending Index | $BI = W_m/a$ |
| Tangent Slope | $TS = (W_m - W_x)/x$ |
| Shape Factor F1, F2 | $F1 = (W_1 - W_3)/W_2$,<br>$F2 = W_2 - W_4)/W_3$ |
| Sensor-7 Deflection | $W_7$ |
| Area | $AREA = 6(1+2W_2/W_1+2W_3/W_1+$<br>$2W_4/W_1+2W_5/W_1+$<br>$2W6/W_1+W_7/W_1)$ |
| Area under the Deflection Curve | AUDC = Integrating the deflection curve over the interval from sensor 1 to sensor 7 |

[1] W = deflection;
subscript 1,2....7 : sensor locations,
subscript 0 : center of load,
subscript r : radius for $W_r = 5$ inches,
subscript m : maximum deflection,
subscript a : one-fourth length of deflection basin
subscript b : radius for $W_b = 24$ inches
subscript x : distance of tangent point from the point of maximum deflection

### *3.3.4. Description of Deflection Basin Parameters*

The literature shows a number of deflection basin parameters that have been used to define the effects of deflection testing. These parameters are listed in Table 3.3. Basically, Maximum Deflection, which is usually the deflection under the load wheel of the FWD, is often used as a rough estimation of pavement strength, under the general assumption that pavements with large deflections tend to fail more quickly than those with small deflections.

Surface Curvature Index (SCI) is a parameter that takes into account the fact that the strain in a pavement layer, particularly the surface layer, is associated with its curvature, and that the first two deflection readings, W-1 and W-2, are an indicator of this curvature.

Base Curvature Index was developed as an estimation of the strength of the base in a flexible pavement, while spreadability is a parameter that has been used by some authors to estimate the quality with which the load is spread to various layers.

Basin Slope, which is the average unit deflection between the central deflection reading and the outermost deflection, or W-7, is a general indicator of the rate at which pavement deflection propagates through the slab. It is not widely used, but is shown for reference.

Radius of Curvature, again, is estimated from various deflection measurements as a method of determining curvature and the strain generated in the pavement surface.

Bending Index is another parameter used to define the curvature — and thus the strain — in the pavement as a result of deflection testing.

Tangent Slope is a simplified approach to estimating curvature.

Shape Factor is proposed as a parameter related to the shape of the deflection basin which, again, would correlate with pavement performance; it is believed to be indicative of the stress induced in the surface layer.

Sensor 7 Deflection is the deflection under the outermost sensor of the falling weight deflectometer; it is believed by many to be indicative of the strength of the subgrade.

Area is calculated as shown in the second column of Table 3.3.

Area Under the Deflection Curve, described in column 2 of Table 3.3, has been hypothesized as a way of defining the flexibility or stiffness of the total pavement structure. Obviously, a pavement that deflects a great deal over its width will have a larger area under the deflection curve or between the original surface and the deflection curve than a pavement that does not deflect very much. On the other hand, a pavement that deflects a great deal over all the sensors will also have a large area. The parameter is not widely used but is one that has been examined.

## 3.4 BASE STIFFNESS AND SUBGRADE MODULUS

This section illustrates the results of the sensitivity analyses based on the ELSYM5 model. There are three structural variables stated as follows:

### *Stiffness of Concrete Slab*

The sensitivity of various parameters was plotted in Figure 3.5 as a function of the concrete slab stiffness. The rate of change of sensitivity of all parameters decreased as the stiffness of concrete slab increased. Radius of Curvature was the most sensitive DBP, and Shape Factor F2 and Base Curvature Index were also good, whereas Surface Curvature Index, Spreadability, and Bending Index were less sensitive with respect to various moduli of concrete slab.

### *Base Stiffness*

Figure 3.6 shows the sensitivity as a function of the stiffness of the base layer. The Radius of Curvature exhibited the most sensitivity among the 13 parameters. Base Curvature Index and Shape Factor F2 were the other more sensitive parameters, but Surface Curvature Index, Spreadability, and Bending Index hardly changed with respect to the increase of base stiffness.

***Subgrade Modulus***

Sensor-7 Deflection ($W_7$) and Area Under the Deflection Curve (AUDC) were highly sensitive, while Surface Curvature Index, Spreadability, and Bending Index were less sensitive with respect to various subgrade moduli.

## 3.5 DISCUSSION OF RESULTS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Section 3.4 illustrates the sensitivity analyses based on results of the ELSYM5 model only. This model was used as an illustration because of ease-of use, although, as mentioned earlier, it may not be accurate enough for final use. From Figure 3.5 and Figure 3.6 we can see that the Radius of Curvature was the most sensitive parameter for slab and base stiffnesses, but not sensitive enough for subgrade modulus. Therefore, there are two alternatives: a single parameter for each pavement layer or a composite parameter for overall pavement layers.

After selecting the best model to calculate FWD deflections and obtaining the best parameter for deflection basin of rigid pavements, the future study based on this methodology and approach could be carried out as follows:

1) Classify the FWD deflection data into several groups based on different pavement material and climatic zones.
2) Calculate the deflection basins and determine the parameters.
3) Use parameters as stiffness loss indices to develop distress curves on various levels based on the rigid pavement database at CTR..
4) Verify and modify (if necessary) distress curves with historical condition data for use in the development of prediction models.
5) Incorporate the developed prediction models into existing PMIS.

## 3.6 AN APPRAISAL OF OTHER AREAS FOR POSSIBLE FUTURE APPLICATION

This study focuses on the condition and performance of rigid pavements. If found feasible for rigid pavements, this method can be applied to other kinds of pavements, including flexible and composite pavements, to ensure the reliability of methodology and approach.

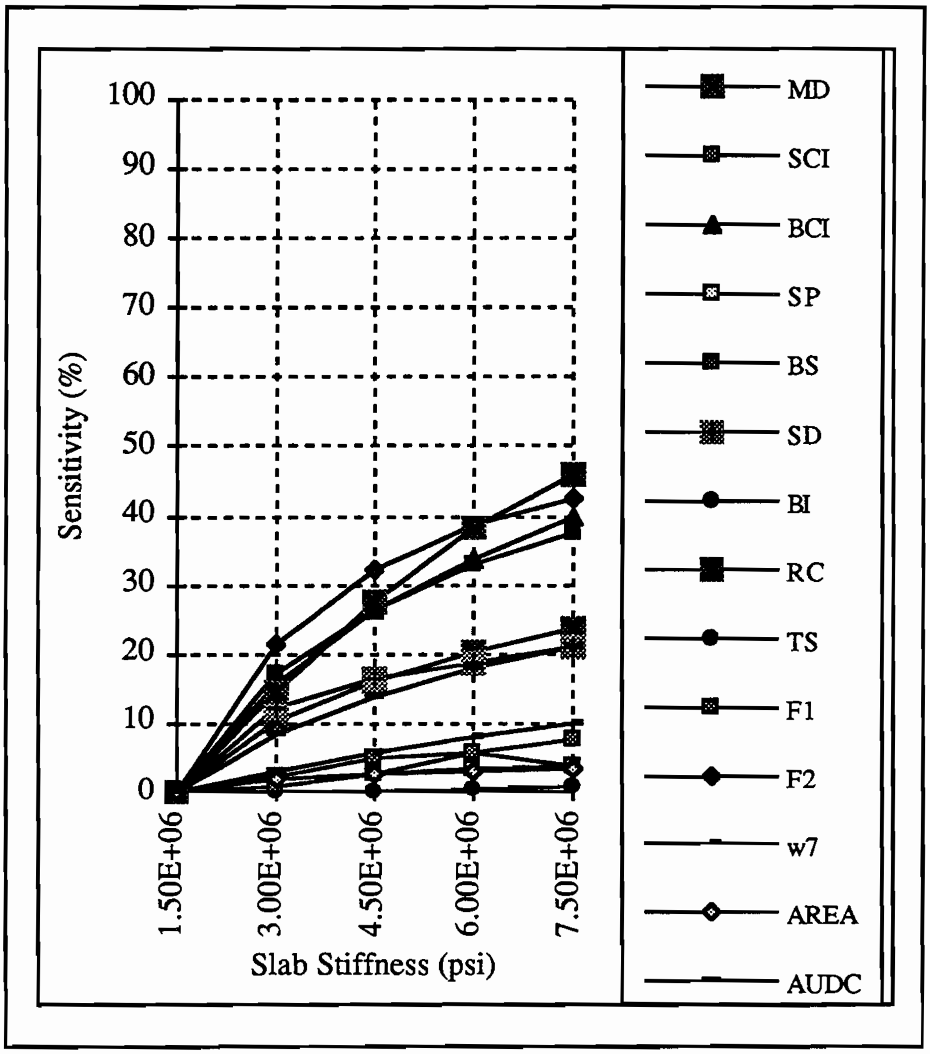


*Figure 3.5 Sensitivity as a function of concrete slab stiffness*

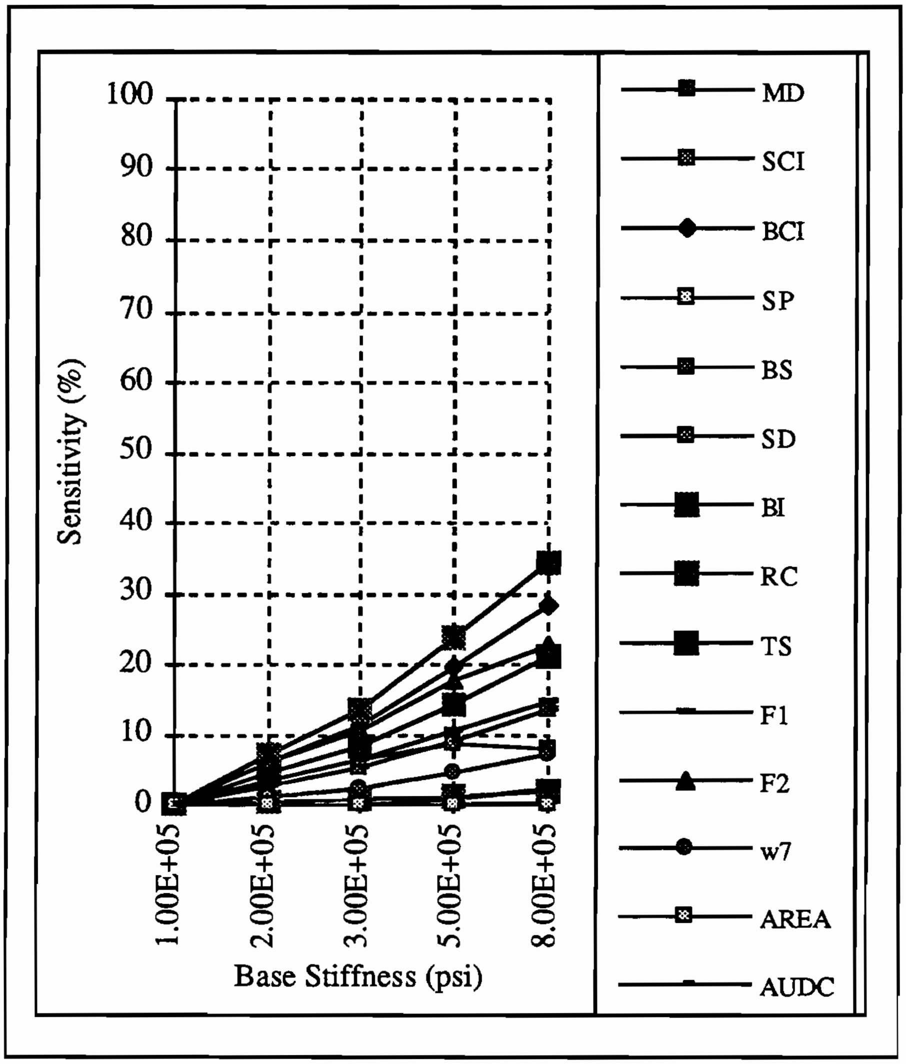


*Figure 3.6 Sensitivity as a function of base stiffness*

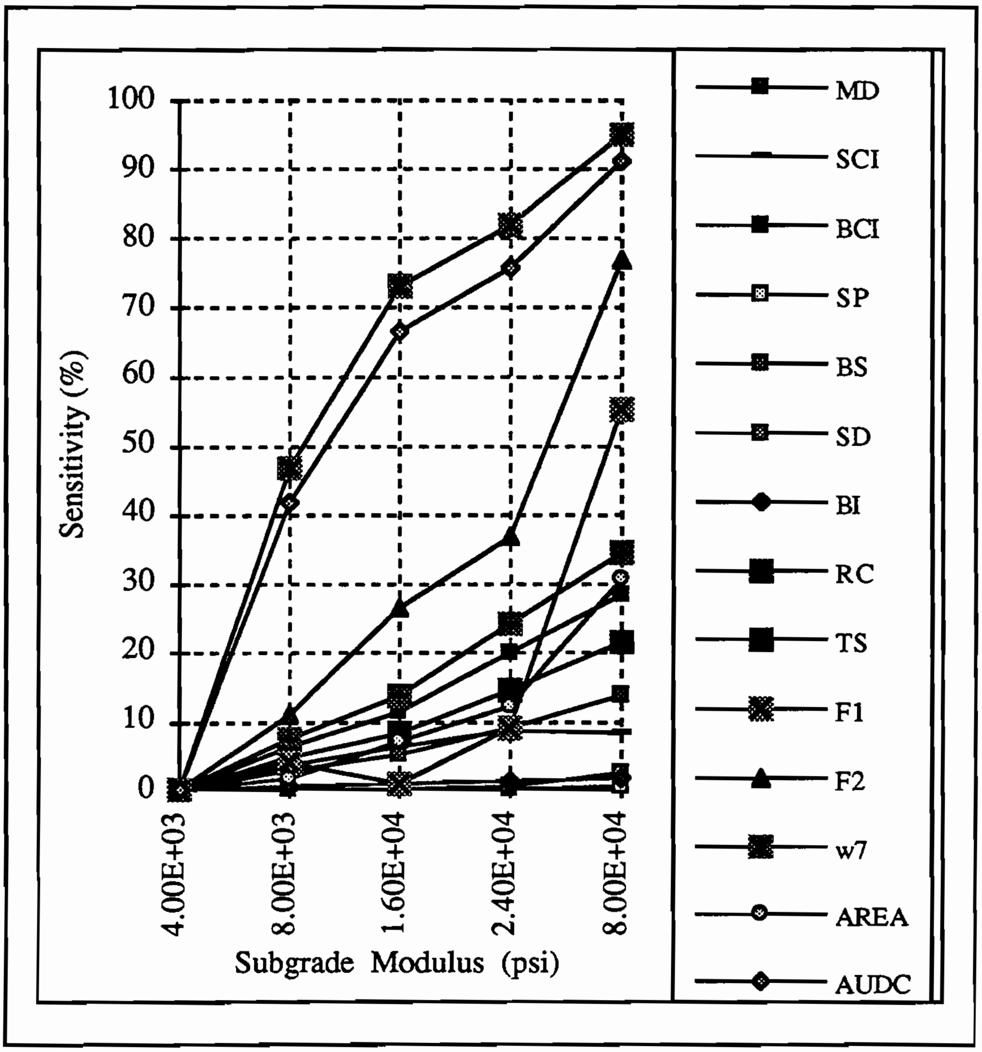


*Figure 3.7 Sensitivity as a function of subgrade stiffness*

# CHAPTER 4. SUMMARY AND EVALUATION OF PROJECT 1908

## 4.1 ACCOMPLISHMENTS

The major objectives identified in the original work plan of Project 1908 were achieved and delivered in the form of five project reports. Report 1908-1, published in August 1993, presented the results of a study to develop and test preliminary distress and performance prediction models for rigid pavements (CRPs, JRCPs, and JCPs) in Texas for incorporation into the PMIS. The modeling process consisted of first identifying the prevailing 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 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 conducted to determine the compatibility between the CTR and PES 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.

Report 1908-2, published in August 1993, identified the requirements for developing a Long-Term Pavement Performance (LTPP) program for the state of Texas. Test sections were identified for which distress data can be collected to develop the required models. An experimental design that retained the existing LTPP and CTR experiment designs was described. The recommended experiment designs met the current pavement design standards, latest research criteria, and climatic and geographical needs of Texas. The type of data that should be collected was discussed. The data items to be collected were divided into two categories: (1) inventory data items, and (2) monitoring data items. The human and financial resources required to establish the database and maintain and monitor it periodically were also evaluated. Technical memoranda originating from study 1908-2 staff had significant influence on the factorial design carried out in study 1342.

Report 1908-3, published in July 1994, evaluated the rigid pavement deflection data contained in the PES database and found it to be inadequate for any network-level study of the structural behavior of rigid pavements. The PES data were evaluated by comparing them with data contained in the CTR rigid pavement database. For network-level evaluation of the structural behavior of rigid pavements, recommendations were provided for future FWD data collection. The optimum sample size, the testing procedures, and a cost estimate for the data collection plan were given. The results were passed to study 1342 in the form of technical memoranda for prompt implementation in study 1342 data collection procedures.

Report 1908-4 described the development of updated distress prediction models for the TxDOT PMIS, focusing in particular on rigid pavements. Modifying factors to the general model equation were used, including the influence of structural effects, environmental loading, and traffic loading on the various distress types. These models greatly improved the preliminary ones, which were developed as a result of study 1908. These improvements were made possible primarily by data collection efforts undertaken during Project 1342. This report analyzed the data collected, which included a condition survey conducted by CTR and a survey of Texas districts to determine coarse aggregate use in construction of rigid pavements in the state. The models presented quantitatively predicted the following distress types:

| Pavement | Distress Type |
|---|---|
| JCP | Patches, corner breaks, faulted joints and cracks, spalled joints and cracks, transverse crack spacing, and slabs with longitudinal cracks |
| CRCP | Punchouts, patches, serviceability loss as measured by ride score, transverse crack spacing, crack spalling. |

It is worth mentioning that the interaction between Projects 1908 and 1342 proved to be beneficial to both. In the case of Project 1908, the fresh data made available by Project 1342 resulted in improved and updated prediction models for rigid pavements, while in the case of Project 1342, technical memoranda emerging from study 1908 had significant influence on the factorial design developed for data collection. The accomplishments of Project 1342 can also therefore be partially attributed to Project 1908.

This report, 1908-5F, is the final report of the project. It summarizes the project findings and discusses the possibility of using stiffness loss to predict the remaining life of rigid pavements. Updated and revised models for jointed concrete pavements, as well as recommendations for future research, are also presented in this report.

## 4.2 ADDITIONAL TASKS AND MODIFICATIONS

Project 1908, which got underway in 1992, represents a significant research effort, one characterized by close interaction between the TxDOT project director and the CTR project staff. Some of the tasks originally planned for the project were modified at the request of TxDOT, while others were deleted for various reasons (e.g., lack of available data or changes in program direction).

We originally planned to carry out a "Bayesian study" of environmental factors. However, in the second year of the project, the project director decided that this task was no longer pertinent; consequently, the work effort shifted to model development.

Significant work was performed in evaluating FWD testing at the network level. However, it was not possible to complete the subtask in Task 6, which involved the adequacy of backcalculation routines for performance predictions. There was inadequate data in the database for this purpose, though the results carried out are presented in Chapter 3 of this report.

The study originally envisioned a task (Task 8) to provide possible modifications for PMIS decision trees. This task was deleted by the TxDOT project director.

Task 9 involved performance models for composite pavements to be used in PMIS. Task 10 involved developing and evaluating FWD data collection procedures for composite pavements. Both of these tasks required interaction with Project 2952 for the collection of additional data; however, funding and programming delays prevented obtaining these data within the time frame of this project. While an extension to Project 1908 was considered, it was later dropped, with the TxDOT sponsors deciding that subsequent work on performance models for composite pavements would be carried out in a later project (after the necessary data are collected and edited).

An additional task, Task 12, added later in the project, involved the evaluation of network deflection data on rigid pavements from Project 1342. Again, the data could not be collected within the required time frame for completion of the project, and TxDOT deemed it preferable to drop this task in order to focus the effort on other segments of the project.

The major objectives of Project 1908 were fulfilled in a timely and effective fashion. The effort that was originally scheduled for the tasks discussed above was transferred to strengthen the modeling effort, and to produce effective results in the remainder of the study tasks. This was always done in conjunction with the sponsors and particularly with the project director's approval. No significant gaps remain in the work to be accomplished.

## 4.3 RECOMMENDATIONS

We recommend that the results of Project 1908 be incorporated into the various PMIS activities of TxDOT. Indeed, this has already been accomplished, since some of the models have been incorporated in the PMIS programs, and since various findings related to planning and data collection have been incorporated in other projects, such as Project 1342, "Long-Term Data Collection for Pavements."

We also recommend that a follow-up project be undertaken over the next two years (1996-1998) to investigate the possibility of predicting pavement performance based on deterioration of the various pavement layers in service, as determined by network-level deflection measurements, particularly backcalculation of deflection basins.

It is also recommended that when data for composite pavements become available, a follow-up project be carried out to develop appropriate models for distress predictions of various types for composite pavements.

Finally, additional data collection on all classes of rigid pavement is being carried out over a 1995-97 time frame. As soon as these data become available, a follow-up project should be initiated to update the models presented in the various reports. Such new models should be significantly more effective than the current models, given that an additional round of data will increase the total data available for model building by 40-50 percent.

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