ENHANCED PAVEMENT DETERIORATION MODELING THROUGH MAINTENANCE PARAMETERS

PB2000-103226

West Virginia Department of Transportation
Division of Highways

and

The Mid-Atlantic Universities Transportation Center

Final Report

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March 1998

Sponsored by the U.S. Department of Transportation Federal Highway Administration and the West Virginia Division of Highways.

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Technical Report Documentation Page

1. Report No. PB2000-103226	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Enhanced Pavement Deterioration Modeling Through Maintenance Parameters		5. Report Date March 1998 6. Performing Organization Code
7. Author(s) David R. Martinelli, Samir N. Shoukry, Jennifer A.Reigle		8. Performing Organization Report No.
9. Performing Organization Name and Address West Virginia University Dept. of Civil and Environmental Engineering P.O. Box 6103 Morgantown, WV 26506-6103		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address West Virginia Department of Transportation US Department of Transportation, Federal Highway Administration		13. Type of Report and Period Covered **Final** August 1995 - March 1998 14. Sponsoring Agency Code

15. Supplementary Notes

Sponsored by a grant from U.S. Department of Transportation, Federal Highway Administration and West Virginia Division of Highways

16. Abstract

The availability of a reliable index that is capable of reflecting the actual condition of distress on a pavement section is essential for decision making in pavement management. The objective of this study is to develop a universal measure of the distress condition on any pavement section. In this work, fuzzy sets are used to establish a unique index for describing the distress condition of a pavement section. The fuzzy-based model, which produces a fuzzy distress index (FDI), is capable of combining the quantitative as well as the qualitative nature of distress data into a global representation that requires no calibration, and independent of the pavement's location or use.

FDI values for different pavement sections are determined for the Nevada Department of Transportation (DOT) pavement condition data base. The behavior of the FDI over time is examined for a random sample of pavement sections, and compared to the corresponding Present Serviceability Index (PSI), calculated by the Nevada DOT. Results indicate that the PSI does not consistently reflect the information provided in the data base, while the FDI does represent this data both accurately and consistently.

17. Key Words	18. Distribution Statement
Pavement Management, distress condition evaluation, fuzzy sets application	

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

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The authors wish to extend thanks to the West Virginia Division of Highways and the Mid-Atlantic-Universities-Transportation-Center for sponsoring the work, and to WVDOH project monitor Mr. Rodney Welder. Acknowledgment is also extended to the Nevada State Department of Transportation, especially to Ms. Patricia Polish, for providing the pavement condition data base used in this study.

EXECUTIVE SUMMARY

The availability of a reliable index that is capable of reflecting the actual condition of distress on a pavement section is essential for pavement management, decision making, prioritization, planning, etc. The objective of this study is to develop a universal measure of the distress condition on any pavement section. This measure can be used in place of existing indices which vary from one state to the next. Also, conventional distress indices are often dependent on a set of regression constants that cannot be adjusted to reflect certain changes in maintenance policies without modification of the model.

Most of the data in a pavement management data base is dependent on the evaluation of pavement inspectors: thus the data becomes ambiguous as it is often recorded in linguistic measures. In this work, fuzzy sets are used to establish a unique index for describing the distress condition of a pavement section. The fuzzy-based model which produces such an index is capable of combining the quantitative as well as the qualitative nature of distress data into a global representation that requires no calibration, and is independent of the pavement's location or use. The development of this index is achieved by the fusion of a membership function describing the extent of distress of each parameter, with a membership function describing the perception of each parameter's significance to the overall condition of the pavement. The average of the fusions for all parameters results in a final membership function describing the overall distress condition of the pavement section. A defuzzification approach is used to weight the generated membership function and describe its position within the universe of all possible pavement distress conditions. The result is a number termed the Fuzzy Distress Index, or FDI, which describes the extent of distress on a pavement section.

For the development of an optimal condition assessment model, the study examined several factors which may affect the behavior of the FDI. These factors include (1) the number of membership functions used to define each parameter, (2) maximum verse varied weightings used to describe the perception of the significance of each parameter, (3) the shape of membership functions used to describe each parameter and its corresponding significance weighting, and (4) the

different methods used for defuzzification of the final membership function describing the overall distress condition of a particular pavement section.

FDI values for different pavement sections are determined for the Nevada Department of Transportation (DOT) pavement condition data base. The behavior of the FDI over time is examined for a random sample of pavement sections, and compared to the corresponding Present Serviceability Index (PSI), calculated by the Nevada DOT. Results indicate that the PSI does not consistently reflect the information provided in the data base, while the FDI does represent this data both accurately and consistently. The PSI is based on regression and considers only a limited number of distress parameters for determining the overall condition of a pavement section. However, the FDI is based on fuzzy set theory, and includes in its calculation a total of fourteen parameters, in addition to the perception of the significance of each individual parameter. Thus, the FDI is an extremely flexible measure of the overall pavement distress condition. The set of generated membership functions describing the different extent of every distress type are standardized over the 50 states, allowing the model to be implemented on any pavement in any location. Also, the parameter weights used in the assessment may be easily adjusted to reflect changes in maintenance policies or budget at the local, state, or national decision-making level.

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ABSTRACT

The availability of a reliable index that is capable of reflecting the actual condition of distress on a pavement section is essential for pavement management, decision making, prioritization, planning, etc. The objective of this study is to develop a universal measure of the distress condition on any pavement section. In this work, fuzzy sets are used to establish a unique index for describing the distress condition of a pavement section. The fuzzy-based model which produces such an index is capable of combining the quantitative as well as the qualitative nature of distress data into a global representation that requires no calibration, and is independent of the pavement's location or use. The development of this index is achieved by the fusion of a membership function describing the extent of distress of each parameter, with a membership function describing the perception of each parameter's significance to the overall condition of the pavement. The result is a number termed the Fuzzy Distress Index, or FDI, which describes the extent of distress on a pavement section

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CHAPTER 1

INTRODUCTION

1.1 Pavement Management Systems

The first task for transportation agencies is to maintain the assets that already exist. If roads are not kept in sound condition, they cannot support the level of service they are designed to handle. This means that the performance of the system declines: safe operating speeds drop, ride quality declines, travel times rise, and accidents increase adding further delays. The longer an action is deferred, the higher the eventual cost of restoration will be. Over the long term, essential transportation facilities must be maintained on a continuing, timely basis (US Department of Transportation, 1990). Pavement management systems include a methodology for synthesizing activities which maximize pavement life and benefits (Haas, et al., 1994).

A pavement management system (PMS) is a set of tools or methods that assist decision-makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a period of time (Grambling, 1994). This system consists of planning, design, monitoring, maintenance, reconstruction, budgeting, programming, construction, research, and rehabilitation.

One of the elements of a pavement management system is a model for pavement condition assessment. There are several fundamental reasons for developing such models, some of which include: to use in the prediction of future pavement conditions for specific pavements; to estimate the type and timing of maintenance and/or rehabilitation for specific pavements; to optimize pavement condition for a complete highway network; to use as a "feedback" loop to the pavement design process; to aid in estimating the cost and most effective maintenance strategy; and to use in pavement life-cycle cost analysis (Haas, et al., 1994).

To accomplish the goal of predicting future pavement conditions, historical data must be collected, including information on each pavement section's type and design, usage, pavement distress, traffic loading, environmental conditions, and maintenance history. This data is used to develop relationships for predicting future pavement conditions, which can ultimately be used to evaluate future rehabilitation needs for the highway system.

1.2 Pavement Evaluation Modeling

Pavement evaluation modeling plays an important role in pavement management systems. For decision making and initiating actions, it is necessary to know the extent of deterioration on a pavement section compared to other sections in the transportation network. Given the complexity of the national transportation network, it is essential to identify all significant factors which effect pavement deterioration, such as pavement design, type, and use, distress, ride quality, traffic loading, environmental conditions, and maintenance history. These factors are fundamental and can be input into an overall assessment model directly from the data base. Among these factors, however, the distress factor is more complicated: it is comprised of a number of parameters in the data base such as alligator cracking, linear cracking, sealing, patching, rut depth, raveling/flushing, shoulder condition, etc. Therefore, it is necessary to develop a unique scale for measuring the extent of distress on a particular pavement section.

The output of this unique distress scale may be included in an overall pavement condition assessment model for engineers and planners to develop maintenance plans that efficiently utilize resources and are within budget limitations. On a state level, planning engineers would consider the extent of distress among the other parameters to prioritize the execution of rehabilitation projects and allocation of maintenance funds. It can be seen that knowledge of the extent of distress is a common parameter at all levels of the decision making tree starting from the federal level down to the localities.

The concept of pavement serviceability-performance was introduced during the American Association of State Highway Officials (AASHO) Road Test, as documented by Carey and Irick (1960). Terms such as present serviceability, Present Serviceability Rating (PSR), and Present Serviceability Index (PSI) were given specific definitions. Present serviceability was defined as "the ability of a specific section of pavement to serve high-speed, high-volume, mixed (truck and automobile) traffic in its existing condition." The words "existing condition" refers to the current condition of the pavement, and not the past or predicted future condition. The Present Serviceability Rating (PSR) is a term used to describe the mean of the ratings of current pavement conditions assigned by actual individuals. The raters, usually consisting of a panel of Highway Research Board members, mark their opinion of the condition of a pavement section on a scale from zero (very poor) to five (very good) on a specific rating form. For highway pavements, the raters are also asked to indicate whether the pavement is acceptable or unacceptable as a primary highway. Finally, the Present Serviceability Index (PSI) is defined as a "mathematical combination of values obtained from certain physical measurements of a large number of pavements so formulated as to predict the PSR for those pavements within prescribed limits." Notice the difference: PSR refers to a rating assigned by a panel of individuals while PSI refers to the calculated value obtained from regression analysis.

The general mathematical form of the PSI was assumed to be (Carey and Irick, 1960):

$$PSI = C + (A_1R_1 + A_2R_2 + \ldots) + (B_1D_1 + B_2D_2 + \ldots) \tag{1.1}$$

where R_1, R_2, ... are functions of roughness and D_1, D_2, ... are functions of surface deterioration. The coefficients C, A_1, A_2, ... , B_1, B_2, ... are determined by a least squares regression analysis. The original PSI equation for flexible pavements, as developed in the AASHO Road Test is (Yoder and Witczak, 1975):

$$PSI = 5.03 - 1.9 \log(1+SV) - 0.01\sqrt{C+P} - 1.38\ RD^2 \tag{1.2}$$

where: SV = slope variance;

C = lineal feet of major cracking per 1000 ft^2 area;

P = bituminous patching in ft^2 per 1000 ft^2 area; and

RD = rut depth in inches (both wheel tracks) measured with a 4-foot straightedge.

Since the introduction of the concept of the prediction of pavement performance, a number of pavement condition indices have been developed: PSI is only one of the many performance indices in use today. Many of the indices are developed from pavement condition models based on regression. The basic shortcoming of current pavement assessment indices is their lack of uniqueness due to their dependancy on the type of data used to generate their formulas. Although current performance indices may function on a state level, they cannot be applied on a national or international scale. For many states, it is not even possible for the performance indices to function properly at the state level due to climatic, traffic, topographic, and other variations between states and within states. Subsequently, two very similar pavements in two different states or areas within a state may have different serviceability values, i.e. the ratings of their conditions may be significantly different.

Setting priorities for pavement maintenance and rehabilitation depends on the availability of a universal scale for assessing the overall condition of every element in the network. The PSR and PSI are examples of serviceability indices that were developed to tie the users' perspective of the quality of the pavement to measurable surface damage factors. It should also be noted, however, that the measure of satisfaction of the user should not be considered alone in maintenance decision-making. For example, small cracks do not affect the user, but a pavement with this characteristic should not be ignored: if the cracks are left without corrective maintenance, the condition of the pavement will become significantly worse. Therefore, an evaluation of the distress condition should be carried out first, and then the user factor can be combined with the index, along with any other significant parameters, for an assessment of the overall condition of the pavement.

1.3 Objective

The objective of this study is to develop a universal measure for assessing the overall condition of a pavement section within the universe of pavement conditions. This is accomplished through the development of a unique model based on the theory of fuzzy sets. Unlike previous models developed for pavement management systems, this model is capable of combining the quantitative as well as the qualitative nature of pavement condition data into a global representation that requires no calibration and is independent of the geographical location. The methodology for this study includes:

- a comprehensive literature search to carefully study the different modeling techniques used in the past and present, as well as the advantages and disadvantages of each theory;
- the collection of an organized pavement condition data base from the present dating back in time approximately fifteen years;
- the development of a universal model using the proper tools which allow for the inclusion of all significant parameters needed to generate a unique distress index; and
- a comparison between the new distress index and a corresponding index currently in use by a highway agency.

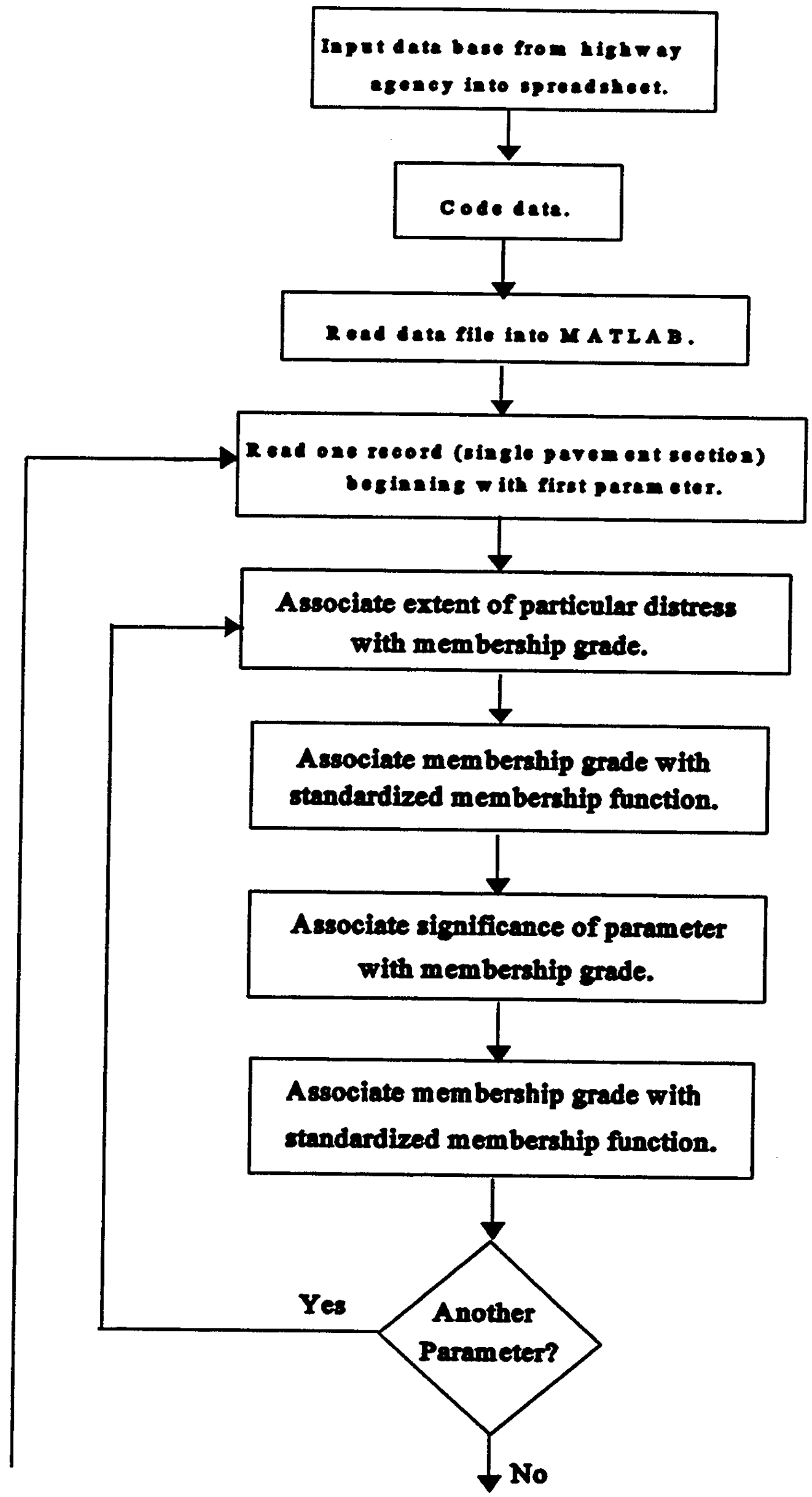
1.4 Structure of Data Base and Computer Programs

The data base used in this study was provided by the Nevada Department of Transportation. It contains information for over 10,000 pavement sections in areas such as pavement condition, roughness, friction, ride quality, traffic loading, environmental conditions, and maintenance activities. Parameters from the data base included in the development of the Fuzzy Distress Index are: alligator cracking type, severity, and extent, linear cracking type, severity, and extent, sealing, rut-depth, patching, appearance, flushing/raveling, shoulder condition, roughness, and skid. Each parameter is described in detail in Appendix A.

The computer programs used for the development of the FDI were coded in the Matlab language. A flowchart representing the overall architecture of the computer programs is shown in

Figure 1.1. A copy of the commented program is found in Appendix B. Following the program is a sample of input data for a single pavement section and the resulting output, including the final membership function and the associated FDI value for that particular pavement section. The measures for alligator cracking type, linear cracking type, and sealing exist in the data base as linguistic terms, and therefore were manually coded before being input into the program. The codes used for each parameter can be found along with the parameter descriptions in Appendix A. Future work should include the writing of an additional program which accepts the input directly from the data base into the Matlab program.

Matlab is a technical computing environment for high-performance numeric computation and visualization. Matlab integrates numerical analysis, matrix computation, signal processing, and graphics in an easy-to-use environment where problems and solutions are expressed just as they are written mathematically -- without traditional programming. The name Matlab stands for matrix laboratory. It was written to provide easy access to matrix software. Matlab is an interactive system whose basic element is a matrix that does not require dimensioning. This allows you to solve many numerical problems in a fraction of the time it would take to write a program in a language such as Fortran, Basic, or C.


Input data base from highway agency into spreadsheet.
Code data.
Read data file into MATLAB.
Read one record (single pavement section) beginning with first parameter.
Associate extent of particular distress with membership grade.
Associate membership grade with standardized membership function.
Associate significance of parameter with membership grade.
Associate membership grade with standardized membership function.
Another Parameter?
Yes
No

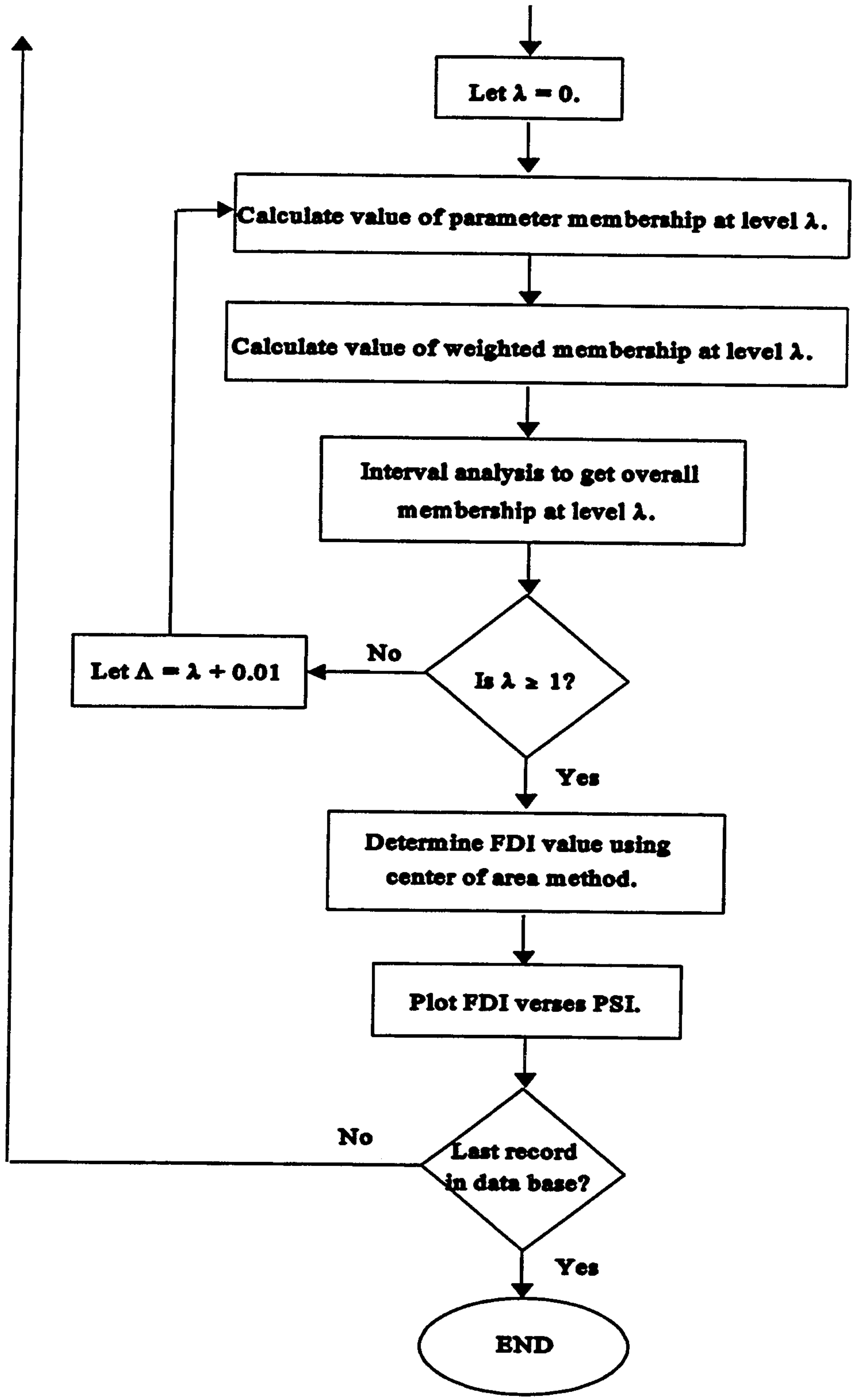


Figure 1.1 Flowchart of Architecture of Computer Programs.

1.5 Organization of Report

The findings from the literature review are summarized in Chapter 2. The development of the model and tools necessary to implement the system are discussed, followed by a numerical example in Chapter 3 which assesses the condition of a single pavement section selected from the Nevada data base. Chapter 4 is a sensitivity analysis of the proposed condition index (termed the Fuzzy Distress Index, or FDI), including a comparison of the FDI versus the Present Serviceability Index (PSI) currently being used by the Nevada Department of Transportation. A study of the FDI and PSI over time is presented in Chapter 5, followed by the conclusions in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Models yield important insight to several areas of pavement management systems including: the prediction of future pavement conditions for specific highway segments; the estimation of type and timing of maintenance and/or rehabilitation for specific highway segments; feedback to the pavement design process; and life-cycle economic analysis (Haas, et al., 1994). Highway pavement maintenance and rehabilitation activities make up a pavement management process that aims to preserve pavement conditions, strengthen pavement structures, and extend the service life of pavements.

The development of reliable pavement models involve four basic measures, as noted by Darter (1980). These measures include: an adequate database built from in-service pavements; the inclusion of all parameters that have a significant effect on pavement performance; an adequate functional form of the model; and a model that meets the proper statistical criteria for precision and accuracy (such as a small prediction error).

Models are used within pavement management systems for the assessment of current pavement conditions as well as for the prediction of future pavement conditions. A review of existing literature reveals numerous techniques used for both assessing and predicting the condition of a pavement section. These techniques include Markov processes, regression, expert systems, neural networks, and fuzzy logic. Some of these methods are used for creating an index for condition evaluation, while other methods use this index for the prediction of future conditions. Therefore, it is necessary to create universal indices which can eventually be used for prediction in any type of model, irrespective of the pavement use or location.

2.2 Markov Modeling

Markov models use present pavement conditions to predict future conditions. The models are based on the assumption that the future condition state of a pavement section depends in a probabilistic manner only on the current condition state, while the history of past condition states provides no additional predictive value. The first step in developing a Markov model is to determine the one-step transition probabilities, $P_{ij}^{(1)}$. $P_{ij}^{(n)}$ represents the probability of transitioning from condition state I to condition state j in n time steps. The transition probabilities are usually shown in matrix form, where the rows of the matrix represent the current condition state and the columns represent the future condition state after n time steps. For pavement prediction modeling, one time step usually represents one year.

Butt, et al. (1987) developed a pavement performance prediction model based on the Pavement Condition Index (PCI) and age of the pavement. The results generated from the Markov prediction model above were then used (Butt, et al., 1994) in a probabilistic dynamic programming model for network level optimization. The objective function for the dynamic programming was based on the minimization of maintenance and rehabilitation costs for the network. Wang, et al. (1994) developed a Markov model for predicting the pavement condition state using the factors roughness level, crack level, crack change, and index to first crack. The model was validated by comparing the predicted value to the actual pavement behavior under routine maintenance. It was demonstrated that the fit of actual pavement behavior with Markovian prediction was satisfactory.

There are advantages to using Markov processes for predicting pavement distress. For example, future decisions for maintenance actions are not fixed, but instead depend on how the pavements actually perform. Also, actions to be taken at the present can be identified, and actions to be taken in the future can be determined with a high degree of probability. Finally, this model has the potential for significant cost savings by selecting less conservative rehabilitation actions that will still satisfy the prescribed performance standards.

There are also several drawbacks to Markov modeling. Transition probability matrices are developed based on time (usually a period of one year) and the factors affecting pavement condition. If a significant feature of the time period were to change (for example, if traffic loading increased from medium to heavy or if maintenance policies or methods changed over time), a different transition probability matrix would need to be defined to more accurately describe the future condition (Carnahan, et al., 1987). Another drawback of Markov models is that the models do not provide any guidance as to the physical factors which contribute to the change in pavement condition. In addition, the models are time independent, meaning that the probability of changing from one condition state to a lower condition state is not influenced by the age of the pavement. Finally, it is important to note that although the models are successful in predicting future pavement conditions, there must exist some form of measurement of the current condition upon which the model can build its prediction. The current models are built using parameters such as PSI or PCI, which are not standardized indices. Therefore, the models need universal parameters in order to build models which require no calibration and can be used independent of the state or locality where it is established.

2.3 Regression Based Modeling

Regression is a statistical tool used to relate two or more variables. For example, an independent variable X may be used to predict the value of a dependent variable Y. The best relationship to use to predict some Y from some X is one that minimizes the differences between the regression curve and the actual data. The term "least squares fit" comes from the minimization of the squared differences between the actual data points and their corresponding points on the fitted curve. Regression models are used for both assessing current pavement conditions as well as predicting future conditions.

Dossey and Hudson (1994) developed a model for predicting the level of distress on a pavement section, based on the age of the pavement and factors to adjust for the traffic, environment, and pavement structure. Similarly, Berger, et al. (1991) used past distress history of a highway network to predict future distress development. Shahin, et al. (1988) studied three curve fitting techniques for modeling pavement deterioration behavior. Two techniques, step-wise regression and B-spline approximation, do not guarantee that the resultant curve is always smooth or decreasing: PCI may increase with age. The third technique, constrained least-squares estimation has two constraints: first, the initial PCI value must take on a value of 100 (the best condition possible); and second, the first derivative, which represents the slope of the PCI, must be negative (not allowing PCI to increase over time). After determining the constrained least-squares as the best method for modeling PCI, they then use extrapolation to extend the curve beyond the available data for predicting future PCI values. A similar model was discussed in Shahin, et al. (1994), which fits a constrained polynomial curve to the data points. The predicted PCI values are used for the selection of maintenance and rehabilitation strategies. Lukanen and Han (1994) used a linear model to represent Present Serviceability Rating (PSR) versus age. They also fit a sigmoidal curve through the data points of each of the distresses for different groupings of pavement sections. The surface rating was calculated for each grouping to describe the deterioration of surface condition with time. The model was then used to estimate pavement life on the basis of condition. Fwa and Sinha (1985) derived a relationship between pavement performance and routine maintenance based on regression analysis using the Present Serviceability Index (PSI) developed by Trezos and Gulen (1983). Gopinth, et al. (1994) built a regression model to fit a curve to the PSI based on pavement age, structural number, equivalent standard axles, and cumulative precipitation. Similarly, George, et al. (1989) developed a best-fit model for assessing the Pavement Condition Ratings (PCR) for different types of pavements based on pavement age, equivalent standard axle load, and structural number.

There are several drawbacks to developing regression-based models for assessing and predicting pavement conditions. For example, a large number of data points is necessary in order for a regression model to be powerful, and it is important that there are significantly more data points than parameters. However, as the number of parameters incorporated into a regression model increases, the accuracy increases, although the complexity of the model also increases. Therefore, it is difficult to determine the ideal combination of data points and parameters to produce a most accurate model. Another drawback is that regression models require calibration. These models lack uniqueness due to their dependency on the type of data used to generate their formulas, and thus are valid only for identical geographic areas under similar conditions as the area used in the model development. Finally, regression models are difficult to update to reflect additional condition data as it is collected, and polynomial and sigmoidal prediction curves often yield the possibility for pavement condition to improve over time.

2.4 Empirical-Mechanistic Modeling

In the previous section, it is clear that regression models use field performance data. On the other hand, mechanistic models are based on pavement response parameters. Therefore, empirical-mechanistic models combine both field data and response parameters. This modeling technique is used for assessing the pavement condition. After creating a condition index from this assessment, curve fitting techniques are applied in some cases for the prediction of future conditions.

George, et al. (1988) developed Pavement Condition Rating (PCR) equations for both flexible and composite pavements. They then used serviceability trends to predict future pavement conditions at the project and network levels. Sood, et al. (1994) presented pavement performance models built with data collected from existing in-service road sections in India. Trends between different independent parameters were plotted to examine the behavior and interactions of different parameters. Time series analysis was used for predicting changes in different parameters.

Since empirical-mechanistic models are based on regression, the drawbacks to this modeling technique are similar to those mentioned previously. For example, the models require calibration, meaning that a model developed in one geographic area must be revised with new data in order for it to be useful in another area. Also, a large data base is needed to determine the regression coefficients, while on the other hand, the more data and parameters included in the model, the more complex the model becomes. In addition, the models are difficult to update to reflect new information that becomes available.

2.5 Expert Systems Modeling

Expert systems are another basis for the development of pavement performance and prediction models. These techniques utilize the opinions of pavement engineers and field supervisors in developing equations for pavement performance under different environments and traffic flows, thereby overcoming the difficult modeling problem of inadequate data. For example, expert systems are recommended techniques of pavement distress modeling for highway agencies that are just starting a pavement management system and therefore lack a sufficient amount of data. Expert systems differ from conventional programs in that they deal with knowledge manipulation, as opposed to conventional programs which are limited to fixed and precisely defined algorithms and data.

Kulkarni (1985) describes a method for developing a deterministic model where a pavement engineer sketches an expected performance curve for a given pavement under alternative rehabilitation actions. The development of a probabilistic model involves sketching expected performance curve as well as a band of uncertainty, which is often done in the absence of adequate field data. In both cases, a mathematical equation is then fitted to the sketched curve for pavement condition assessment or prediction. A final method for elicitation of a probabilistic model involves estimating probability distributions of the rate of pavement deterioration using an equation developed by Kulkarni (1985). Then, using regression analysis, it is possible to develop a prediction equation even when very little field data is available. Aougab, et al. (1989) studied pavement condition indicators which are used to develop and refine a sequence of decision trees for evaluating pavement performance, identifying pavement problems and their probable causes, and recommending appropriate corrective measures. PSI, PCI, and skid resistance are included in the decision system, along with other performance measures developed in this study, such as the damage level (DL), remaining life (RL), general performance indicator (GPI), and the deterioration cause indicator (DCI).

There are numerous drawbacks to using expert systems as a basis for pavement evaluation. For example, the models require calibration, meaning the models are not universal and are valid only in areas consisting of similar geographic locations and condition characteristics. Another drawback is that the models are based on engineering judgment and expertise. This requires training and significant experience in the field. Therefore, this method is more difficult and time consuming for younger, inexperienced personnel to comprehend.

2.6 Neural Networks Modeling

Neural networks are used for both pavement condition assessment and prediction modeling. A neural network problem is solved by the network adapting to the nature of the data received. Parameter values from a training-data set are fed into the network, and the output is based upon the weights assigned to each parameter link within the network. The output from the network is compared to the actual known value in the data base. The error is determined, and is propagated back through the network and the weights are adjusted accordingly. Next, the same input is fed through the network and the new error is computed. This technique is iterated until the error value of the final output is within some user-prescribed limits. The same method is followed for the next input in the training-data set until all data in the set is used. Finally, a checking-data set is used to verify how well the neural network can simulate the actual performance.

Ritchie, et al. (1991) developed an automated pavement evaluation model based on neural networks. They used digitized video image representations of a pavement surface to determine the type, severity , and extent of distresses. The distress parameters included were alligator, fatigue, or wheel path cracking, longitudinal cracking, transverse cracking, patching and potholes, and block cracking. Fwa and Chen (1993) used neural networks for priority assessment of highway pavement maintenance needs. The input parameters were highway functional class, skid resistance, crack width, crack length, Pavement Serviceability Index (PSI), and rut depth. The output was a priority rating which was determined for training the network by a linear equation, a nonlinear equation, and subjective assessment (a pavement engineer). The neural network produced results with an average absolute error of about 0.05 for both the linear and nonlinear priority rating functions. The error was significantly higher (0.092) for the subjective priority rating. Attoh-Okine (1995) used the variables equivalent axle loads, roughness, rutting in wheel path, fatigue cracking, and block cracking as input to a back propagation neural network algorithm for pavement prediction performance. The aim of the article, however, was to investigate the learning rate and momentum term for a specific architecture. Flintsch, et al. (1996) used neural networks for producing a list of candidate projects for consideration within a five year preservation program. The final decisions were made manually based on engineering judgment. The variables considered were pavement classification, region, structural number (SN), cracking, roughness, skid, rutting, patching, flushing, ADT, maintenance cost, and rate. Using current data for the prediction of future information, Randolph (1996) applied neural networks to two areas: pot-hole patching, for predicting the number of tons of material needed for repairs; and chip and seal operation, for predicting the miles of treated road and the daily cost of operation.

Models based on neural networks have several limitations. For example, this technique requires a large amount of data for training the model. Also, knowledge of the output is necessary for all data in both data sets in order to train the network. Since the model requires training, the architecture of the neural network is based on trial and error. In addition, as with the other techniques presented, neural networks are not capable of incorporating the qualitative nature of data into the model. Finally, it is important to note that if the input or the output of the model is a pavement condition assessment, it is necessary that the assessment index is a universal index so that the model can be implemented anywhere on the globe. For example, if a model is developed using a specific equation for PSI, the model is valid only for areas that use the same equation for calculating the index; otherwise the model requires calibration.

2.7 Fuzzy Sets Modeling

The concepts of fuzzy set theory were introduced by Lofti Zadeh in 1965 (Zadeh, 1965). This theory was developed as a tool with which meaningful solutions to complex problems with imprecise information can be found (Ross, 1995). Fuzzy logic is a means of incorporating both numerical (quantitative) and linguistic (qualitative) data into a model. Often a pavement condition data base includes linguistic rating terms such as "Alligator Cracking Type A" or "severely damaged." These terms may not be precise, but are meaningful classifications for assessing the condition of a particular pavement section. Usually, fuzzy logic is used in pavement management systems for determining an index for condition assessment. The development of this index is achieved by the fusion of a membership function describing the extent of distress of each parameter, with a membership function describing the perception of each parameter's relative. The average of the fusions for all parameters results in a final membership function describing the distress condition of the pavement section. The index can be derived based on the final membership. An introduction to the theory of fuzzy sets and membership functions is given in Appendix C.

Andonyadis, et al. (1985) used fuzzy sets for assessing pavement condition and assisting in priority ranking for maintenance decision making. The Average Daily Traffic (ADT) was obtained by traffic surveys, while performance data, including roughness, skid resistance, distress, and structural adequacy, were obtained by evaluation of each pavement section. Parameters were transformed using data provided by experts, and membership functions were determined by a computer program based on the above data base derived from expert opinion. The nonlinear membership functions represented acceptability ranges for different parameters. Although nonlinear, it is important to note that the membership functions contained specific minimum and maximum boundaries, which is a characteristic of triangular (linear) membership functions. A fuzzy PSI is the resultant output of the computer program. The PSI and friction number (FN) were then compared with acceptability and nonacceptability levels. Pavement Condition Rating (PCR) values and corresponding fuzzy sets are determined for pavement sections with unacceptable roughness.

Finally, through the use of a program based on expert systems, the pavement sections are ranked according to ADT, FN, and PCR, with respect to urgency for maintenance.

Elton and Juang (1988) compared pavement sections using a ranking index representing the overall condition based upon fuzzy logic. They suggested that the ranking index could be used as an absolute measure of the pavement condition, based on local criteria, thus "pavement evaluation procedures must be tailored to every locale." Triangular (linear) membership functions were derived for each parameter based on condition ratings assigned by individuals. Parameters included in the model were rutting, longitudinal cracking, transverse cracking, alligator cracking, and roughness. An importance weighting for each parameter was assigned arbitrarily and associated with a membership function describing the weighting. The calculation of the final membership function representing an overall pavement rating was determined from the weighted average equation using both the parameter membership functions and the weighting membership functions. The ranking index, called the Distress Index (DI), was calculated by an approximation of the center of area defuzzification technique, and ranges from 0 to 1. Defuzzification techniques are discussed in more detail in Chapter 4.

The final report by Tee, et al. (1989) documents the use of fuzzy sets in the development of a method for evaluating bridge inspection information which takes into account the imprecision and uncertainty in the inspection parameters. Since there are no established guidelines for the bridge inspector to follow, engineering judgment is a vital part of the bridge inspection process, thus the final condition assessment is based on imprecise information; individual intuition, experience, and human bias. Without the use of fuzzy sets, this information is impossible to quantify properly. Bridge inspection includes an evaluation of the extent of damage or deterioration of a section, as well as a numerical rating (based on linguistic terms such as "critically damaged" or "undamaged") describing the physical condition of the section. According to the proposed model, the rater also includes an importance weighting for each section, representing the significance of that section to the overall condition of the bridge. The importance factors are determined from the responses of an information survey and are defined by five membership functions. The fuzzy weighted average equation (discussed in Chapter 3) was applied to combine the individual ratings and weighting for each section, such that a unique number can be obtained for a particular section. This system can be used to assist bridge inspectors in assessing the rating of a particular bridge section, as well as to promote consistency in section evaluation among the inspectors.

Sun lijun and Zukang (1990) used fuzzy sets in performance evaluation and maintenance and rehabilitation decision making for asphalt pavements. A combination of linear and nonlinear membership functions (both defined by definite ranges for each grade) were developed based upon subjective ratings of various performance attributes by an expert panel. The parameters included in the pavement performance evaluation are deflection, roughness, Pavement Condition Index (PCI), and distress. The maintenance and repair strategy can then be selected based on the resultant pavement evaluation along with the accumulated traffic.

Huihua and Henry (1990) introduce the use of fuzzy sets, in particular the concept of fuzzy clustering, for analyzing pavement skid resistance. The clustering technique uses a resemblance matrix as input and the output shows similarities among its objects. A standardized resemblance matrix is developed where the rows represent different parameters and the columns are all possible conditions for each parameter. The clustering is carried out on the basis of a certain level of lambda, between 0 and 1, determined by the user. If an entry in the matrix is above the threshold value, it is assigned a value of 1, and if the entry is below the threshold, it is assigned a value of 0. The clusters are then determined according to the relations existing between the elements at a particular lambda level. The higher the level of lambda, the greater the number of different classifications. Pavements are clustered according to design type and current conditions: thus pavements with similar characteristics can be classified together, aiding the user in maintenance decision-making.

Sinha, et al. (1990) document the use of fuzzy sets for rating bridge conditions. Bridge inspection practices lack guidelines for establishing relationships between the extent of deterioration and the associated rating assignment. Parameters in bridge inspection are not completely defined nor can they all be precisely measured: this results in subjectiveness which is not accounted for in the ratings. The fuzzy weighted average was used to determine a bridge component's resultant rating, where specific subcomponents were used as the parameters for each component. Importance weighting were imprecise measures where each weighting represented the degree of importance of a subcomponent relative to other subcomponents. This study concluded that fuzzy set theory was effective in minimizing subjectiveness and improving the overall accuracy of bridge condition assessment.

Using similar methods as Elton and Juang, Juang and Amirkhanian (1992) developed a Unified Pavement Distress Index (UPDI) for pavement distress evaluation. This index includes the distress parameters alligator cracking, rutting, potholes, patching, block cracking, and longitudinal cracking. Triangular (linear) membership functions were developed based upon guidelines determined through an extensive survey of opinions of highway personnel. The final membership representing the overall distress of a pavement section was calculated by the weighted average equation. The approximated center of area defuzzification method was then used to determine the

UPDI. This index is a value ranging from 0 to 1, and can be used to rank pavement sections according to their extent of distress.

Zhang, et al. (1993) developed an Overall Acceptability Index (OAI) which combines pavement roughness, distress, structural capacity, and safety, as well as their relative importance into a single index that gives a comprehensive evaluation of a pavement section. Data for formulating the model are collected from pavement engineers who completed a survey on the degree of acceptability, on a scale from 0 to 1, for all of the parameters. The degree of acceptability was plotted against a particular scale for each parameter. Using nonlinear regression analysis on the data from the survey, the best fit function (that with the greatest R^2 value) was chosen as the membership function for each parameter. To calculate the OAI, the weighted average equation is applied. This index represents the overall acceptability of a pavement section at a given overall condition (or particular measurement) for each parameter.

The few existing studies focusing on the use of fuzzy sets in pavement condition assessment show potential as successful evaluation techniques in pavement management, yet the studies possess several shortcomings. First, linear membership functions are implemented for simplification (Elton and Juang 1988, Juang and Amirkhanian 1992); however, pavement deterioration is not necessarily linear, as it depends on a large number of significant parameters. Each parameter is assigned a grade which indicates the degree of damage to a pavement section. If the grade is represented by a linear membership function, the distress condition range has a minimum and a maximum value: this concept does not necessarily allow all possible conditions to be represented. Nonlinear membership functions concentrate each grade assignment around a specific range of distress conditions with high degrees of membership, yet also allow for all other possible conditions to exist with small degrees of membership. This concept is illustrated in Figure 2.1.

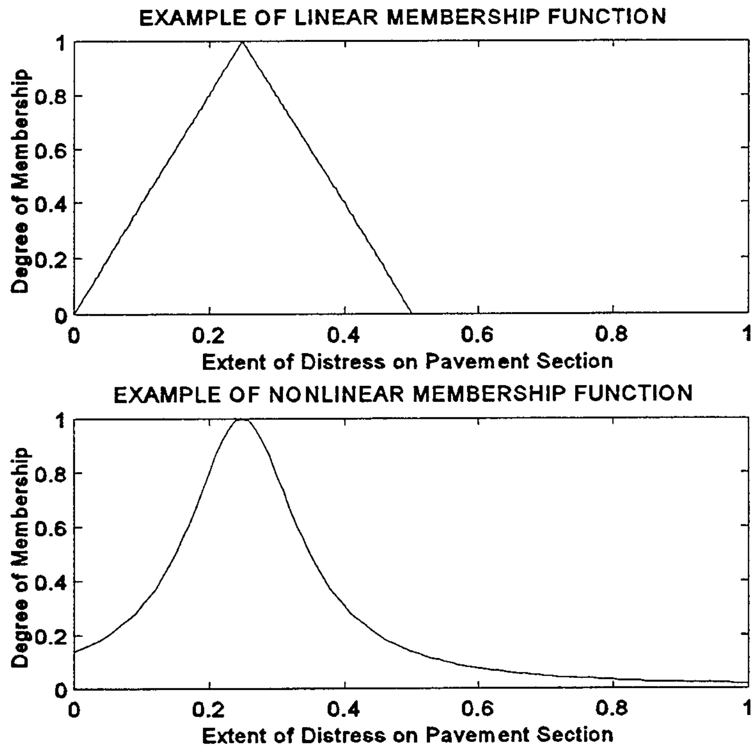


Figure 2.1 Linear (top) Verses Nonlinear (bottom) Membership Functions.

Second, the models focus on the characterization of few parameters rather than as many significant parameters as possible (Elton and Juang 1988, Juang and Amirkhanian 1992, Huihua and Henry 1990, Sun-Lijun and Yao-Zukang 1990). The overall distress condition of a pavement is not dependent upon cracking, roughness and pavement age alone. All of the parameters listed in Table 2.1 contribute to the overall pavement condition with varying degrees of significance. Many of the parameters included in this list were omitted in earlier models.

Third, the perception of parameter significance is used for establishing memberships. In the majority of past studies, questionnaires were sent to pavement engineers, and membership functions were generated according to expert opinions (Andonyadis, et al., 1985, Zhang, et al., 1993, Tee, et al., 1989). This statistical concept lacks the uniqueness which is characteristic of every membership function.

Table 2.1 Parameters Included in Distress Index Calculations

PARAMETERS INCLUDED IN DISTRESS INDEX CALCULATIONS
Alligator Cracking Type
Alligator Cracking Severity
Alligator Cracking Extent
Linear Cracking Type
Linear Cracking Severity
Linear Cracking Extent
Sealing
Average Rut Depth
Patching
Appearance
Flushing / Raveling
Shoulder Condition
Roughness
Skid Number

A fourth and very important shortcoming is the assumption that pavement evaluation procedures must be tailored to every locale (Elton and Juang 1988). Although previous models, including those based on Markov, regression, neural networks, and expert systems, in addition to fuzzy logic, are successful in assessing and/or predicting pavement conditions, they are not global.

If a model is developed for one area, it must be modified before being used in a different area. These models are not applicable in different regions because they require calibration for every change in location. They lack a universal index which would allow them to be implemented anywhere and on all levels of the decision making tree.

2.8 The Fuzzy Distress Index (FDI)

This study, consisting of different modeling techniques used for pavement evaluation and management, resulted in the awareness of the need for a universal model which produces a unique measure for the extent of distress on a pavement section. Careful consideration of the objectives, advantages, and disadvantages of each technique discussed in this chapter led to the conclusion that a basis using fuzzy logic yields the most potential for success in building such a model. Based on this theory, a unique distress index, termed the Fuzzy Distress Index (FDI), was developed.

The FDI represents a unique descriptor which focuses only on describing the distress condition of a pavement section, irrespective of the location, user's opinion, or previous history. It is developed directly from current distress conditions in the data base. The FDI is not a prediction based on certain relations between the current year (or previous years) and next year, such as the indices developed by Markov processes. Nor is it a rigid parameter established for a particular data base, such as regression-based indices. The FDI differs from an expert system index where a set of rules and conditions are built for a particular data base. It is not a result which is trained using specific parameters, as neural networks are trained. Instead, the FDI is developed from a fuzzy logic based computer program which can assess anything in a flexible manner. For example, the program can consider structural parameters only, resulting in a structural index, or surface parameters only, resulting in a surface index. Similarly, the program can consider a combination of parameters, resulting in an overall condition index. The use of a fuzzy logic based computer program also results in the standardization of membership functions for each parameter, thus eliminating the need for calibration.

The FDI represents the characterization of pavement distress. Similarly, additional pavement condition indices can be developed from other condition data, including structural parameters. These pavement condition indices can then be combined with pavement design and operating condition data, such as pavement design and use, age, traffic loading, and environmental conditions, to produce an overall evaluation of the pavement condition. The final performance model output and applications may include the determination of future pavement conditions, overall network quality, the remaining life of pavement sections, future maintenance or rehabilitation actions, or budget needs and allocation.

CHAPTER 3

THE OVERALL CONCEPT AND NUMERICAL EVALUATION OF THE FUZZY DISTRESS INDEX

3.1 Introduction

Chapter 3 is divided into two sections. The first section gives the concept upon which this study was built. This includes the significance of an overall assessment, the motivation behind the work, and the requirements for assessing the condition of a pavement section. The second section gives a simplified numerical example of the evaluation of the Fuzzy Distress Index (FDI) for a particular pavement section.

3.2 The Overall Concept

To characterize the overall condition of any structure, all elements related to this condition must be considered. Some elements may even be comprised of other elements. A pavement section is a structure, and the assessment of its overall condition for decision making purposes should not consider only the parameters of significance to the user. All parameters affecting its structural integrity should be included in its evaluation. The significance of each parameter from the point of view of the user or the concerned highway administration or both may be introduced as weights given to each parameter.

The overall assessment of a pavement section must include all elements affecting its condition, such as pavement design, type, and use, distress, traffic loading, environmental conditions, and maintenance history. The focus of this study is the evaluation of the element distress. Distress is comprised of a number of other elements, such as alligator cracking, linear cracking, sealing, rut depth, patching, raveling/flushing, shoulder condition, etc. The distress cannot be evaluated properly without considering all of these significant parameters.

The motivation behind this work is the development of a universal model capable of measuring the overall condition of any pavement section, irrespective of its location or use. Such a model can be usable to all fifty states without significant modification by eliminating the need for historical data to establish the model constraints. While this target would be nearly impossible using techniques such as regression or neural networks, it is realizable using fuzzy sets. In the fuzzy set concept, the universe of pavement conditions is comprised of all feasible conditions anywhere on the globe, irrespective of climate, region, soil type, design, etc.

The objective of this study is to develop a unique measure for defining the grading of the overall condition of a pavement section within the universe of pavement conditions. This requires the development of a membership function based on distress parameters and the perception of the significance of each parameter. A Fuzzy Distress Index (FDI) can then be developed to weight the generated membership function and describe its position within a universe of all possible pavement conditions. Every pavement condition assessment requires the following to be defined:

1). A description of every condition parameter by a membership function. A membership function is a unique relation between specific parameter values and their degree of "belongingness" to a set that describes all possible values for the parameter.

2). The perception of significance of each parameter. The significance of a parameter is difficult to quantify: it differs depending on the individual performing the rating. The perception of each parameter can be assigned as a weight to its membership. These weights may be composed of a combination of user (public) and state highway agency perceptions.

3). A sensitive measure of the position of the pavement condition membership function within the universe of all possible pavement conditions (defuzzification of the membership function).

Figure 3.1 is a flowchart of the concept of determining the Fuzzy Distress Index as described above.

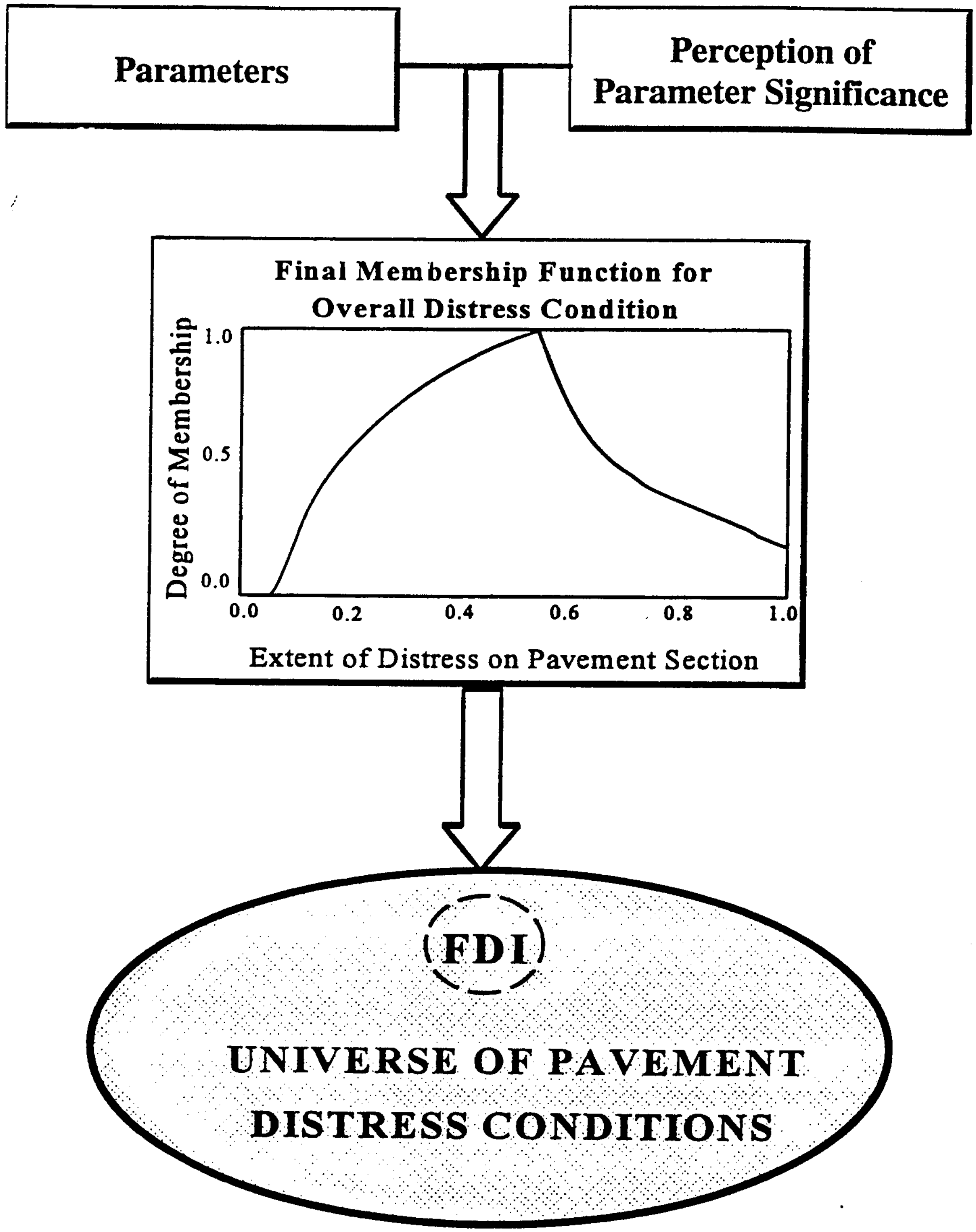


Figure 3.1 The process used in the calculation of the Fuzzy Distress Index.

3.3 A Numerical Example

3.3.1 Identification of Pavement Section and Parameter Measurements

The condition assessment requirements listed in the previous section are thoroughly explained throughout the following numerical example for calculating the Fuzzy Distress Index (FDI) of a single pavement section. The FDI is a sensitive measure of the extent of distress on a particular pavement. The pavement section under investigation is identified as ELFR428 00100E, and was extracted from year 1986 of the pavement condition data base provided by the Nevada Department of Transportation. The parameters and corresponding measurements for this pavement section are listed in Table 3.1. A complete listing of each parameter supplied in the data base, along with its corresponding description, method of measurement, and definition of membership functions are supplied in Appendix B.

3.3.2 Membership Function Development for Parameter Measurement

The first step in calculating a pavement condition index is to determine the contribution of each individual parameter to the overall distress status of the section under consideration. To set an example for the method of assessing this contribution using fuzzy sets, consider the distress parameter "patching." A unique description of all possible conditions for this parameter can be set according to the guidelines shown in Table 3.2 (alternatively, the SHRP's *Distress Identification Manual for the Long-Term Pavement Performance Project* (1993) may be used).

Table 3.1 Parameters and Measurements for Pavement Section ELFR428 00100E

Pavement Section - ELFR428 00100E	
PARAMETER	**MEASUREMENT**
Alligator Cracking Type	C
Alligator Cracking Severity	0.25
Alligator Cracking Extent	850
Linear Cracking Type	C
Linear Cracking Severity	0.25
Linear Cracking Extent	65
Sealing	N
Average Rut-Depth	0.23
Patching	60
Appearance	10
Raveling / Flushing	19
Shoulder Condition	24
Roughness	292
Skid	0

The next step is to describe each grade in the "patching" universe by a membership function. For generalization, we will assume that within this universe, patching severity varies between 0 and 1. Now each grade can be described by a membership function that will be assumed to have a nonlinear generalized bell shape (Jang and Gulley 1995). The universe of patching severity can be described as shown in Figure 3.2. Therefore, from the table above, if patching on a 1000 ft^2 pavement section is measured at 60 ft^2 (Table 3.1), it has a "B" severity (Table 3.2) whose membership function is shown on the graph of the universe of severity (Figure 3.1) by a dark line.

Table 3.2 Guidelines for "Patching"

Parameter - PATCHING	
MEASUREMENT	GRADE
Patching <= 50	A
50 < Patching <= 100	B
100 < Patching <= 150	C
150 < Patching <= 200	D
200 < Patching <= 250	E
250 < Patching <= 300	F
300 < Patching <= 350	G
350 < Patching <= 400	H
400 < Patching <=450	M
450 < Patching <= 500	N
Patching > 500	P

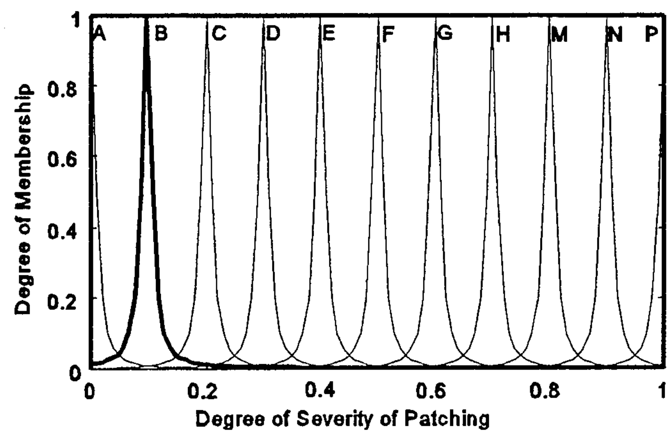


Figure 3.2 Membership Functions for Patching Grades.

3.3.3 Membership Function Development for Parameter Significance

The parameter "patching" is also given a weight which indicates its importance to the overall distress condition. The universe of significance of a particular distress parameter can range from insignificant to extremely significant. Thus, the actual significance of a parameter may fall anywhere within these limits. The assigned degrees of significance can be changed easily to fit any view of the concerned Department of Transportation or to reflect certain policies. For the present illustration, assume that the universe of any distress parameter significance (weighting) will be divided into eleven levels as shown in Figure 3.3. Note that a weighting of A represents minimal importance of the parameter to the overall condition of the pavement section, and a weighting of F represents extreme importance of the parameter to the overall condition of the pavement section.

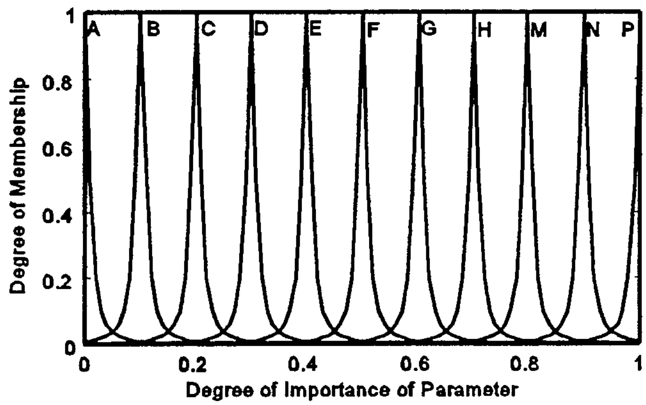


Figure 3.3 The Universe of Parameter Significance.

Assume that the weighting for "patching" is given an importance grade of P, or extremely important. In order to assess the contribution of a single parameter to the overall distress membership function of the pavement section, cuts are taken at different levels of membership starting from level zero. A cut at a particular level, λ, is referred to as a lambda-cut. The contribution of a particular parameter is determined by fuzzy multiplication of a lambda-cut for the parameter times the same level lambda-cut for the weighting function. This is done for all levels of lambda, from zero to one.

$$C_{i,\lambda} = P_{i,\lambda} * W_{i,\lambda} \tag{3.1}$$

where $C_{i,\lambda}$ = the contribution of parameter I to the overall distress membership function of a particular pavement section at lambda-cut level λ.

$P_{i,\lambda}$ = an interval representing the extent of distress of parameter I at lambda-cut level λ.

$W_{i,\lambda}$ = an interval representing the importance weighting (or significance) of parameter I at lambda-cut level λ.

For the patching example, a lambda-cut at $\lambda = 0.50$ results in the interval (0.09, 0.11), obtained from the parameter membership function. The corresponding lambda-cut from the weighting membership function results in the interval (0.99, 1.0). This is shown in Figure 3.4.

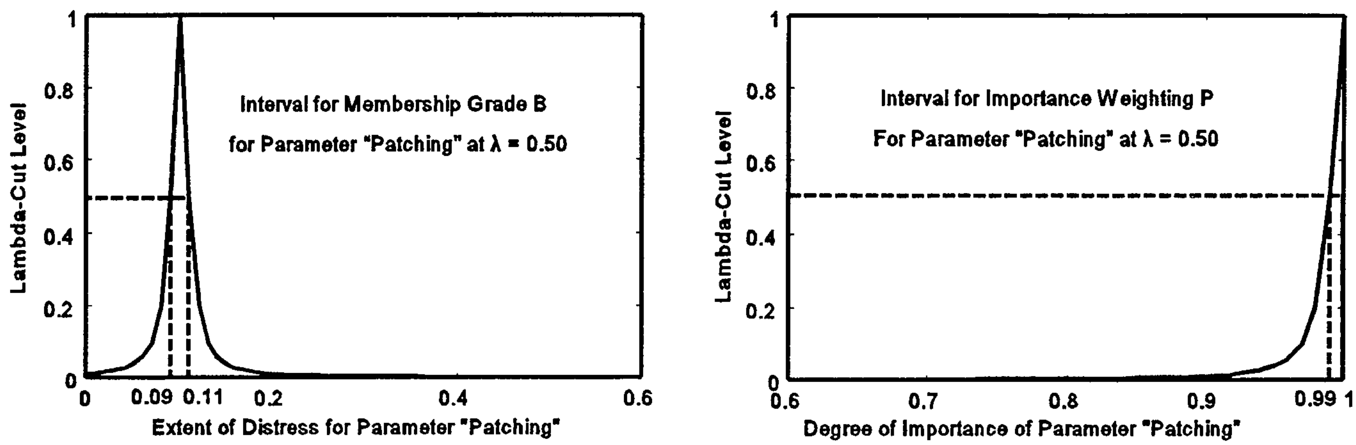


Figure 3.4 Definitions of $P_{(patching,\ \lambda = 0.50)}$ (on Left) and $W_{(patching,\ \lambda = 0.50)}$ (on Right).

Therefore, the contribution of the parameter "patching" to the overall pavement membership function at a lambda-cut level of $\lambda = 0.50$ can be obtained from:[1]

$$\begin{aligned} C_{(patching,\ \lambda=0.50)} &= P_{(patching,\ \lambda=0.50)} \times W_{(patching,\ \lambda=0.50)} \\ &= (\ 0.0900,\ 0.1100\ ) \times (\ 0.9900,\ 1.0\ ) \\ &= (\ 0.0891,\ 0.1100\ ) \end{aligned}$$

[1]This calculation requires multiplication using interval analysis. The arithmetic operation is determined as follows for elements *a*, *b*, *c*, and *d*: if $a < b$ and $c < d$, then $[a, b] * [c, d] = [\min(ac, ad, bc, bd), \max(ac, ad, bc, bd)]$ (Ross, 1995).

Similar values are computed for all other significant distress parameters. Table 3.3 lists the maximum number of membership grades used to classify each parameter, the actual measurements as recorded in the pavement condition data base, and the membership grade determined for each distress according to its associated measurement. The final column of Table 3.3 lists the importance weighting assigned to each parameter. The weightings are pre-determined, and can be set accordingly by individual highway agencies.

Table 3.3 Maximum Number of Membership Functions, Measurement, Grade Assignment, and Importance Weighting for Each Parameter

Pavement Section - ELFR428 00100E				
PARAMETER	**MAX. NO. OF GRADES USED TO DEFINE PARAMETER**	**PARAMETER MEASUREMENT**	**GRADE ASSIGNMENT ACCORDING TO MEASUREMENT**	**IMPORTANCE WEIGHTING ASSIGNED TO PARAMETER**
Alligator Cracking Type	5	C	D	P
Alligator Cracking Severity	11	0.25	M	P
Alligator Cracking Extent	11	850	P	P
Linear Cracking Type	4	C	D	M
Linear Cracking Severity	11	0.25	M	N
Linear Cracking Extent	11	65	B	N
Sealing	3	N	C	M
Average Rut-Depth	11	0.23	M	N
Patching	11	60	B	P
Appearance	11	10	N	P
Raveling / Flushing	3	19	C	M
Shoulder Condition	8	24	F	H
Roughness	11	292	N	P
Skid	11	0	P	P

3.3.4 Development of Final Membership Function

A range for the overall distress condition at a particular λ value is found from the weighted average equation (Ross 1995):

$$R_{(section,\lambda)} = \frac{\sum_i (C_{i,\lambda} * W_{i,\lambda})}{\sum_i W_{i,\lambda}} \qquad (3.2)$$

where: $R_{section,\,\lambda}$ = the overall rating of a particular pavement section at membership level λ, and I represents different distress parameters.

$C_{i,\,\lambda}$ = the contribution of parameter I to the overall distress membership function of a particular pavement section at lambda-cut level λ.

$W_{i,\lambda}$ = an interval representing the importance weighting (or significance) of parameter I at lambda-cut level λ.

Continuing with pavement section ELFR428 00100E, Table 3.4 shows each parameter and its measured value, the corresponding membership grade, the range for this grade at cut $\lambda = 0.50$, the importance weighting assigned to the parameter, and the range for this weighting at cut $\lambda = 0.50$.

Table 3.4 Lambda-Cut Ranges for Each Parameter Grade and Weighting

Pavement Section - ELFR428 00100E					
DISTRESS	**VALUE**	**MEMBERSHIP GRADE**	**RANGE FOR GRADE AT $\lambda = 0.50$**	**IMPORTANCE WEIGHTING**	**RANGE FOR WEIGHTING AT $\lambda = 0.50$**
Alligator Cracking Type	C	D	[0.74, 0.76]	P	[0.99, 1.0]
Alligator Cracking Severity	0.25	M	[0.79, 0.81]	P	[0.99, 1.0]
Alligator Cracking Extent	850	P	[0.99, 1.0]	P	[0.99, 1.0]
Linear Cracking Type	C	D	[0.99, 1.0]	M	[0.79, 0.81]
Linear Cracking Severity	0.25	M	[0.79, 0.81]	N	[0.89, 0.91]
Linear Cracking Extent	65	B	[0.09, 0.11]	N	[0.89, 0.91]
Sealing	N	C	[0.99, 1.0]	M	[0.79, 0.81]
Average Rut-Depth	0.23	M	[0.79, 0.81]	N	[0.89, 0.91]
Patching	60	B	[0.09, 0.11]	P	[0.99, 1.0]
Appearance	10	N	[0.89, 0.91]	P	[0.99, 1.0]
Raveling / Flushing	19	C	[0.99, 1.0]	M	[0.79, 0.81]
Shoulder Condition	24	F	[0.7043, 0.7243]	H	[0.69, 0.71]
Roughness	292	N	[0.89, 0.91]	P	[0.99, 1.0]
Skid	0	P	[0.99, 1.0]	P	[0.99, 1.0]

Using the information shown in Table 3.4, the range for the overall distress rating at lambda-cut level $\lambda = 0.50$ is calculated as follows:[2]

$R_{(ELFR428\ 00100E,\ 0.50)}$ = { [0.74, 0.76]*[0.99, 1.00] + [0.79, 0.81]*[0.99, 1.00] + [0.99, 1.00]*[0.99, 1.00] + [0.99, 1.00]*[0.79, 0.81] + [0.79, 0.81]*[0.89, 0.91] + [0.09, 0.11]*[0.89, 0.91] + [0.99, 1.00]*[0.79, 0.81] + [0.79, 0.81]*[0.89, 0.91] + [0.09, 0.11]*[0.99, 1.00] + [0.89, 0.91]*[0.99, 1.00] + [0.99, 1.00]*[0.79, 0.81] + [0.70, 0.72]*[0.69, 0.71] + [0.89, 0.91]*[0.99, 1.00] + [0.99, 1.00]*[0.99, 1.00] } ÷ { [0.99, 1.00] + [0.99, 1.00] + [0.99, 1.00] + [0.79, 0.81] + [0.89, 0.91] + [0.89, 0.91] + [0.79, 0.81] + [0.89, 0.91] + [0.99, 1.00]

[2]This calculation requires addition, multiplication, and division using interval analysis. The arithmetic operations are calculated as follows for elements *a*, *b*, *c*, and *d*, where $a < b$ and $c < d$: Addition $[a, b] * [c, d] = [a+c, b+d]$; Multiplication $[a, b] * [c, d] = [\min(ac, ad, bc, bd), \max(ac, ad, bc, bd)]$; Division $[a, b] \div [c, d] = [ab] * [1/d, 1/c]$ (Ross 1995).

+ [0.99, 1.00] + [0.99, 1.00] + [0.79, 0.81] + [0.69, 0.71] + [0.99, 1.00] + [0.99, 1.00] }

$R_{(ELFR428\ 00100E,\ 0.50)}$ = { [0.73, 0.76] + [0.78, 0.81] + [0.98, 1.00] + [0.78, 0.81], + [0.70, 0.74] + [0.08, 0.10] + [0.78, 0.81] + [0.09, 0.11] + [0.78, 0.81] + [0.48, 0.51] + [0.88, 0.91] + [0.98, 1.00] } ÷ { [0.99, 1.00] + [0.99, 1.00] + [0.99, 1.00] + [0.79, 0.81] + [0.89, 0.91] + [0.89, 0.91] + [0.79, 0.81] + [0.89, 0.91] + [0.99, 1.00] + [0.99, 1.00] + [0.99, 1.00] + [0.79, 0.81] + [0.69, 0.71] + [0.99, 1.00] + [0.99, 1.00] }

$R_{(ELFR428\ 00100E,\ 0.50)}$ = [9.64, 10.02] ÷ [12.66, 12.87]

$R_{(ELFR428\ 00100E,\ 0.50)}$ = [0.75, 0.79]

This process is repeated for all levels of lambda, from zero to one, at an interval of 0.01. Table 3.5 displays the intervals for $R_{(ELFR428\ 00100E,\ \lambda)}$ at sample λ-cut levels of 0.0, 0.25, 0.50, 0.75, and 1.0.

Table 3.5 Sample of Ranges for Different Lambda-Cut Levels

λ	$R_{(ELFR428\ 00100E,\ \lambda)}$
0.0	[0.2957, 1.0]
0.25	[0.7333, 0.8056]
0.5	[0.7494, 0.7914]
0.75	[0.7576, 0.7812]
1.0	[0.7719, 0.7719]

The overall distress membership curve is developed by plotting the end points of the distress ranges for every level of lambda. Figure 3.5 shows the overall distress membership curve for this pavement section. The ranges displayed in Table 3.5 are highlighted in the graph. Note that the shape of the final membership function is dependent on the original weights assigned to each parameter, and therefore may or may not be symmetrical.

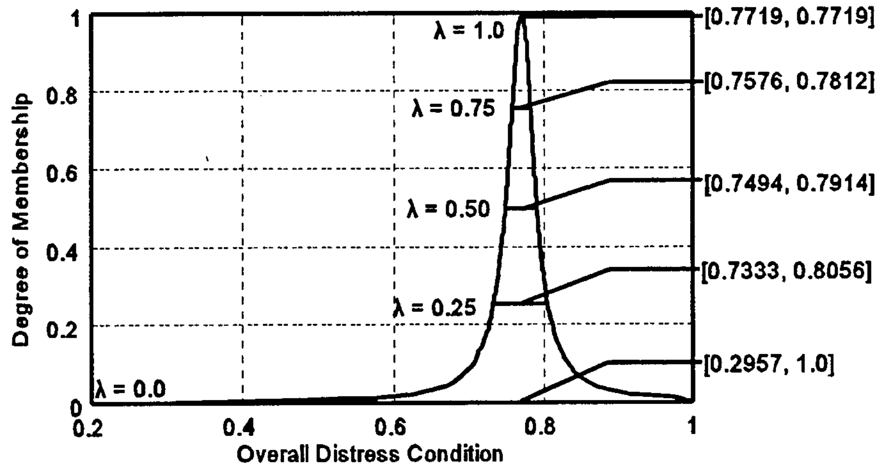


Figure 3.5 Final Membership Function with λ-cut Ranges.

3.3.5 Defuzzification of Final Membership Function

If fuzzy set c represents all possibilities for the overall distress condition within the universe of distress conditions, then c would consist of all values which lie on the horizontal axis of Figure 3.6. Also, suppose that a membership function describing the distress of a particular pavement section is written as c_z. For example, one possible distress condition, z, within the universe of all possible distress conditions is $c_z = 0.7719$, which is the peak of the membership function shown in Figure 3.6. The degree of membership of a particular condition z along membership function c_z is written as $\mu(c_z)$. At distress condition 0.7719 on the membership function in Figure 3.6, the degree of membership is 1.0; therefore, $\mu(c_z) = 1.0$. This illustration is used to clarify the method of calculation of the Fuzzy Distress Index.

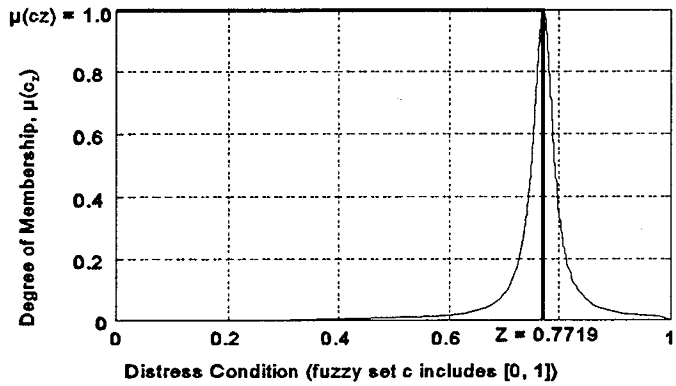


Figure 3.6 Final Membership Function for Pavement Section ELFR428 00100E.

3.3.6 Calculating the Fuzzy Distress Index (FDI)

The Fuzzy Distress Index (FDI) is calculated from the final membership function, resulting in a ranking for each pavement section. The FDI is defined as the center of the area of the overall pavement condition membership function. It is given by the expression (Ross 1995):

$$\mathrm{FDI} = \frac{\int_{-\infty}^{\infty} \mu(c_z) \times z \, dz}{\int_{-\infty}^{\infty} \mu(c_z) \, dz} \times 10 \qquad (3.3)$$

where: c = fuzzy set representing all overall conditions within the universe of overall pavement conditions;

z = particular condition contained in fuzzy set c;

c_z = a membership function describing the overall condition of a particular pavement section; and

$\mu(c_z)$ = the degree of membership of each pavement condition z contained along membership function c_z.

The FDI is a value which ranges from zero to ten, where zero represents the best possible pavement condition and ten represents the worst possible pavement condition. A factor of 10 was used to increase the range of possible conditions for the FDI. Once the FDI is calculated, pavements can be ranked to determine which pavement sections require maintenance immediately and which sections do not require immediate maintenance attention. The importance of the FDI is its role in resource allocation and planning. Highway agencies can determine which areas are in most need of funding and maintenance at a particular point in time, and which areas are in less need of immediate maintenance and funding.

Using the same pavement section from above, the FDI is calculated by applying the center of area method (Equation 3.3) to the overall membership curve. The resulting FDI for pavement section ELFR428 00100E for year 1986 is: FDI = 7.5903. Notice that if the interval for $R_{(ELFR428\ 00100E,\ 0.0)}$ is multiplied by a factor of 10, as is done in the calculation of FDI, the resultant FDI value of 7.5903 falls within this range. The FDI is not, however, located at the maximum peak of the membership curve because, as mentioned previously, the final membership function may not be symmetrical due to the original assignment of importance weightings for each parameter. The final membership function and associated FDI value are shown in Figure 3.7.

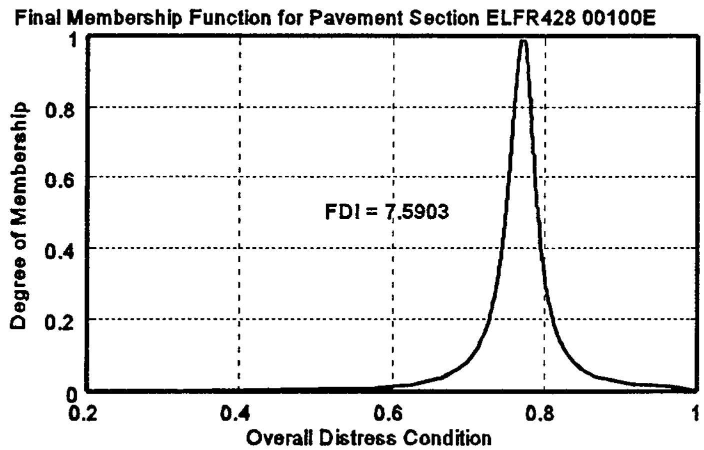


Figure 3.7 Final Membership Function and FDI.

3.4 Conclusions

This chapter first introduced the concept of developing a universal index for the assessment of the overall condition of a pavement section, including the objectives of this work and the motivation behind developing such an index. Next, a simplified numerical example is presented, illustrating the step-by-step procedure for calculating the Fuzzy Distress Index of a particular pavement section. The remainder of this report describes a detailed study on the development of the FDI model, and the accuracy and consistency of the FDI as compared to a condition assessment index currently being used by a particular highway agency.

CHAPTER 4

SENSITIVITY ANALYSIS OF THE FDI

4.1 Introduction

The output from the model is the Fuzzy Distress Index (FDI), a pavement condition assessment based on the following parameters: alligator cracking type, alligator cracking severity, alligator cracking extent, linear cracking type, linear cracking severity, linear cracking extent, sealing, rut-depth, patching, appearance, raveling/flushing, shoulder condition, roughness, and skid number. For this study, a random sample of 80 pavement sections was chosen from the 1986 pavement condition data base provided by the Nevada Department of Transportation.

A model validation is obtained by plotting the FDI verses the Present Serviceability Index (PSI) from the original database. The PSI is a measure of pavement condition, with ride being the major factor in the equation, and is used to monitor the condition of the pavement (Rideability History of the Nevada Department of Transportation, 1995). The current PSI equation used by the Nevada Department of Transportation is the following:

$$PSI = 5 \times e^{(-0.0041 \times IRI)} - 0.09(C+P)^{1/2} \quad (4.1)$$

where: IRI = International Roughness Index;

C = Cracked area in square feet per 1000 square feet of pavement area; and

P = Patched area in square feet per 1000 square feet of pavement area.

A basic computer program (Appendix B) was developed and then modified accordingly to examine the sensitivity of membership functions, weighting factors, and defuzzification techniques.

4.2 Sensitivity of Membership Functions

Program 1: 3 membership functions, varied weighting

First, the sample data was used in a program, referred to as Program 1, containing three (3) membership functions describing each parameter. The exact number of membership grades used to characterize each parameter is the first entry shown in Table 4.2. The significance weighting for each parameter was characterized according to the following scale:

Table 4.1 Guidelines for Significance Weightings

Significance	Grade
Extremely Important	E
Very Important	D
Important	C
Moderately Important	B
Relatively Unimportant	A

For all programs in this study with varied weighting, the weighting for each parameter is CDDCDCBCDBCADB, respectively. This information is also shown as the second entry in Table 4.2. The output of the Program 1 is shown in Figure 4.1. The sample consists of 80 points, of which only 62 appear on the scatter plot: the remaining 18 points are repeated values and therefore are plotted on top of each other.

Table 4.2 Number of Membership Functions (First Entry) and Importance Weighting (Second Entry) Assigned to Each Parameter for Computer Programs 1-5

Comparison of Number of Membership Functions and Importance Weighting Assigned to Each Parameter.					
PARAMETER	**Program 1**	**Program 2**	**Program 3**	**Program 4**	**Program 5**
Alligator Cracking Type	3, C	5, C	5, C	5, C	5, E
Alligator Cracking Severity	3, D	5, D	8, D	11, D	11, E
Alligator Cracking Extent	3, D	5, D	8, D	11, D	11, E
Linear Cracking Type	3, C	4, C	4, C	4, C	4, E
Linear Cracking Severity	3, D	5, D	8, D	11, D	11, E
Linear Cracking Extent	3, C	5, C	8, C	11, C	11, E
Sealing	3, B	3, B	3, B	3, B	3, E
Average Rut-Depth	3, C	5, C	8, C	11, C	11, E
Patching	3, D	5, D	8, D	11, D	11, E
Appearance	3, B	5, B	8, B	11, B	11, E
Raveling / Flushing	3, C	3, C	3, C	3, C	3, E
Shoulder Condition	3, A	5, A	8, A	8, A	8, E
Roughness	3, D	5, D	8, D	11, D	11, E
Skid	3, B	5, B	8, B	11, B	11, E

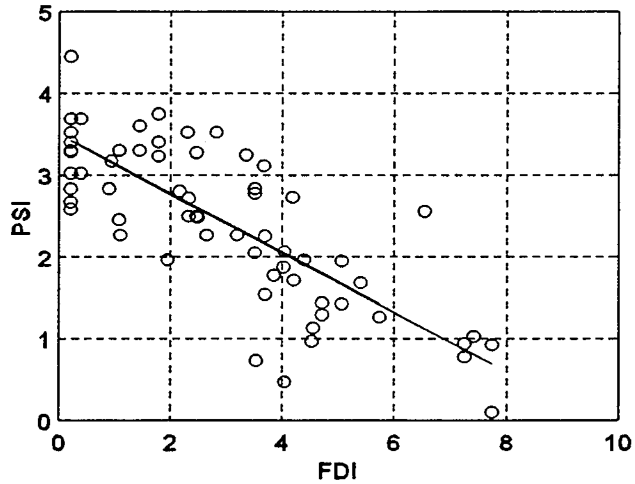


Figure 4.1 3 Membership Functions, Varied Weighting.

The minimum FDI obtained from the sample data is 0.2085, and the maximum FDI is 7.7259. The range from best possible condition to worst possible condition within the universe of distress conditions using this particular model is 0.2085 to 9.2027. Notice that the best possible condition is obtained when the pavement section receives the best rating for the measurement of each individual distress parameter, and the worst condition is obtained when each measurement of a pavement section is assigned the worst rating possible. For example, Table 4.3 lists the best and worst condition ratings for each parameter for Program 1. The resultant membership functions for the best and worst conditions are shown in Figures 4.2 and 4.3, respectively.

Table 4.3 Best and Worst Condition Ratings for 3 Membership Functions, Varied Weighting

Best and Worst Possible Condition Ratings for Program 1		
PARAMETER	**Best Condition**	**Worst Condition**
Alligator Cracking Type	A	C
Alligator Cracking Severity	A	C
Alligator Cracking Extent	A	C
Linear Cracking Type	A	C
Linear Cracking Severity	A	C
Linear Cracking Extent	A	C
Sealing	A	C
Average Rut-Depth	A	C
Patching	A	C
Appearance	A	C
Raveling / Flushing	A	C
Shoulder Condition	A	C
Roughness	A	C
Skid	A	C

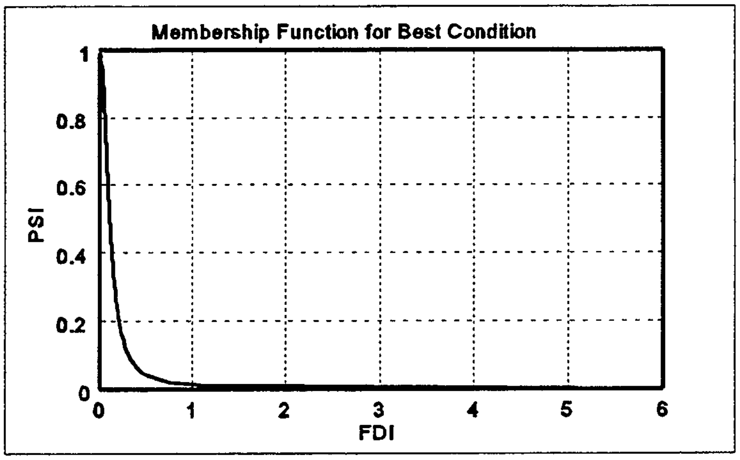


Figure 4.2 Membership Function for Best Condition Using 3 Membership Functions, Varied Weighting.

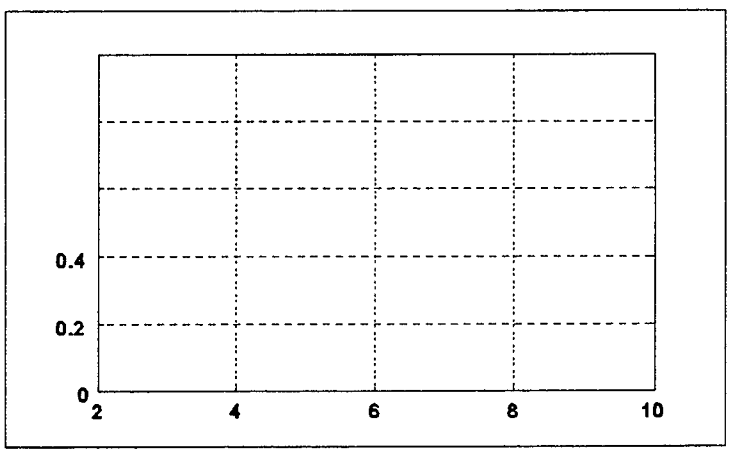


Figure 4.3 Membership Function for Worst Condition Using 3 Membership Functions, Varied Weighting.

The coefficient of determination (r^2) is a measure between 0 and 1 which describes how much of the total variation in data is explained by the regression equation. The closer r^2 is to 1, the more the variability in data is explained. For Program 1, the coefficient of determination is calculated as $r^2 = 0.6945$, and is listed in Table 4.4. Note that a higher correlation between FDI and PSI can be achieved simply by increasing the weighting of the parameters included in the PSI equation: roughness, cracking, and patching, and decreasing the importance weighting of other parameters. However, this concept merely increases the correlation: it is not a valuable solution.

The standard deviation of a set of data is a measure of the spread, or deviation, of values from the mean. The larger the deviation, the more the values fluctuate around the mean value. This measure is used as a guideline for determining the optimal number of membership functions to use in the program. A small standard deviation for PSI and a larger standard deviation for FDI shows a wider spread for FDI and therefore a greater measure of sensitivity. The standard deviation is calculated for both the FDI and PSI. For the PSI, the standard deviation of the 80 values in the sample set of data is 0.9696. The standard deviation for the FDI values is 2.2144, showing that the FDI does, in fact, yield a greater measure of sensitivity.

Table 4.4 Coefficient of Determination and Standard Deviations for the FDI

Program #	**Coefficient of Determination r^2**	**Standard Deviation of FDI s**
1	0.6945	2.2144
2	0.6888	2.1569
3	0.6806	1.9513
4	0.7007	2.1609
5	0.6947	2.2441

Program 2: 5 membership functions, varied weighting

In Program 2, the number of membership functions used to describe each parameter, as shown in Table 4.2, is increased to a maximum of five (5) membership functions. The significance weightings are varied, ranging from grades A through E, and are also listed in Table 4.2. The output (Figure 4.4) shows a minimum and maximum FDI of 0.2123 and 7.5092 respectively, and an FDI range from best possible condition to worst possible condition of 0.2123 to 9.1925. Upon observation of the scatter plot, only 61 out of the 80 total data points appear on the graph. The coefficient of determination for the output of Program 2 is $r^2 = 0.6888$, and the standard deviation for the new FDI values is 2.1569 (Table 4.4).

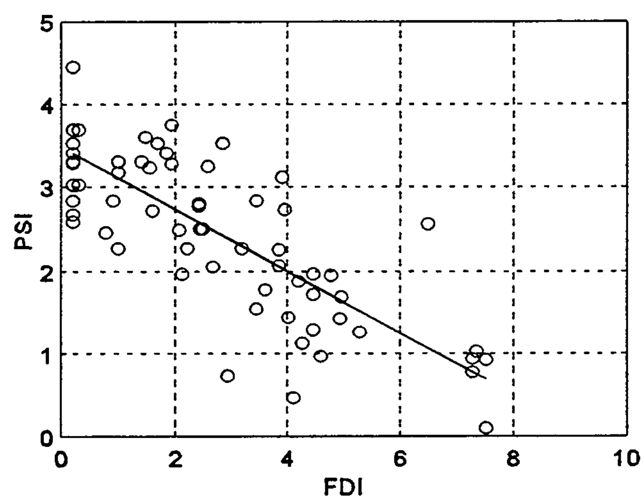


Figure 4.4 5 Membership Functions, Varied Weighting.

Program 3: 8 membership functions, varied weighting

Program 3 includes a maximum of eight (8) membership functions defining each parameter, and variable weighting for the significance of each individual parameter. The exact number of membership functions used for each parameter along with the corresponding weighting factor are listed in Table 4.2. The program output is shown in Figure 4.5, where the minimum and maximum FDI of the 80-pavement-section sample are 0.8986 and 7.6996, respectively. The maximum FDI range possible for Program 3 is 0.8824 to 9.2027. The coefficient of determination is $r^2 = 0.6806$, while the standard deviation of the FDI values is s = 1.9513. A total of 65 out of the 80 data points appear on the scatter plot; therefore, 15 data points are repeated values.

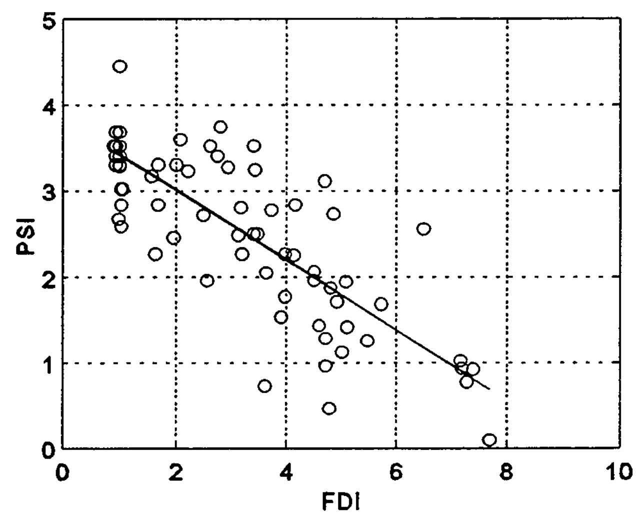


Figure 4.5 **8** Membership Functions, Varied Weighting.

Program 4: 11 membership functions, varied weighting

The number of membership functions describing a single parameter is next increased to a maximum of eleven (11) in Program 4, and the weighting again varies for each individual parameter. The maximum possible range for FDI is 0.2085 to 9.2027, which is the greatest range determined so far. The minimum and maximum FDI values for the sample data are 0.2502 and 7.4709. The coefficient of determination is $r^2 = 0.7007$ and the standard deviation of the FDI values is 2.1609. The output is shown in Figure 4.6. A total of 67 out the 80 data points appear on the plot.

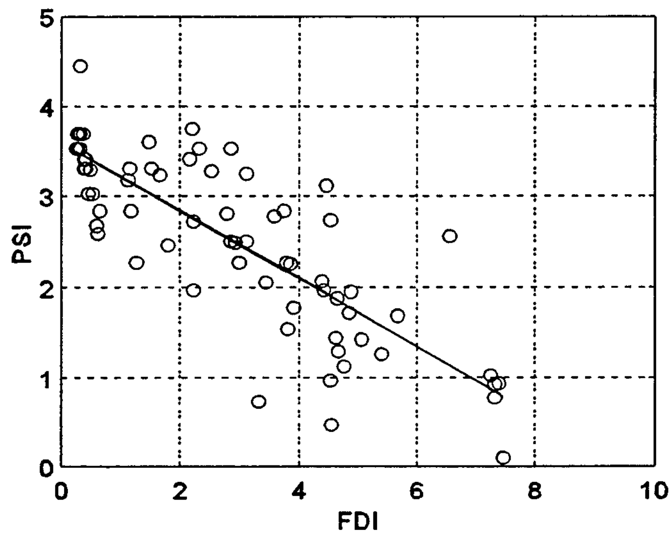


Figure 4.6 11 Membership Functions, Varied Weighting.

At this point it is clear that the coefficient of determination and the standard deviation of FDI values change only slightly when additional membership functions are inserted into the computer program (see Table 4.4). The ranges of possible FDI values are very similar, and the minimum and maximum FDI values calculated from the sample data also differ only slightly. Upon observation of the scatter plots, a comparison between the output in Figures 4.1 and 4.6 show that a greater number of data points appear in Figure 4.6 than in Figure 4.1. Therefore, an increase in the number of membership functions used to define each parameter results in a greater scatter, or spread, of the FDI. This is shown by the vertical straight line pattern at the left-hand side of Figure 4.1, which spreads into a scatter of points in Figure 4.6. From these observations, a maximum of eleven (11) membership functions are used in the remainder of the studies in this chapter.

4.3 Sensitivity of Importance Weighting

After determining the optimal number of membership functions to use to describe each parameter, the individual weightings were considered. Up to this point, all programs used varied significance weightings which were dependent on the parameter itself, but were consistent for each parameter in every program. This section compares the varied weighting with maximum weighting for each parameter.

Program 5: 11 membership functions, maximum weighting

Program 4 was then compared to Program 5, which is a modified program with a maximum of eleven (11) membership functions and maximum weighting assigned to each parameter, as listed in Table 4.2. The output of Program 5 is shown in Figure 4.7. The maximum possible range for FDI

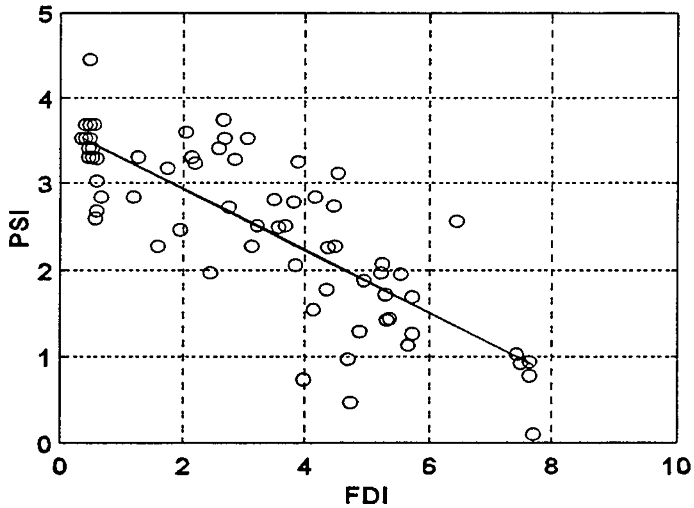


Figure 4.7 11 Membership Functions, Maximum Weighting.

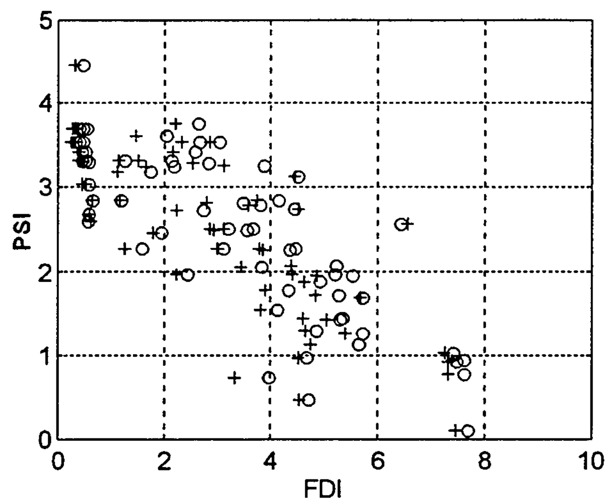


Figure 4.8 Comparison between 11 Membership Functions, Varied Weighting (+) and Maximum Weighting (o)

is 0.1948 to 9.4919, while the minimum and maximum values for FDI determined from the sample data are 0.3374 and 7.6837, respectively. The correlation between FDI and PSI is $r^2 = 0.6947$, and the standard deviation of the FDI values is $s = 2.2441$ (see Table 4.4).

Figure 4.8 shows a comparison between Program 4 and Program 5. Both have a maximum number of eleven (11) membership functions describing each parameter. The difference between the two outputs is caused by the initial importance weighting of the parameters. One program assigns a varied significance level, depending on the individual parameter, and the second program simply assigns the highest significance level to every parameter.

Results are very similar, and both programs yield high correlations between FDI and PSI; therefore, Program 4 was selected for the remainder of the study. It contains a maximum of eleven (11) membership functions and the weighting levels are dependent upon the individual parameters. This allows the user to choose individual parameter weightings as he or she deems appropriate.

The maximum possible range for FDI in Program 4 spreads from 0.2085 to 9.2027, as opposed to the range for PSI which spreads only from 0.10 to 4.46. Notice that increasing the range of assessment possibilities increases the sensitivity of the FDI model; hence the interpretation of the overall assessment carries more significance.

4.4 Effect of Membership Function Shape

The shape of the membership function was considered next, and a comparison was made using the identical sample of 80 pavement sections randomly selected from the 1986 pavement condition data base. The two membership function shapes are shown in Figure 4.9. Program 4 was used for this study (11 membership functions, varied weighting): the only difference between the two computer runs was the equation which defined the membership function shape. The first run contained the wider, more rounded membership function shape (top graph in Figure 4.9), and the second run contained the thinner, sharper membership function shape (bottom graph in Figure 4.9). The results for each alternative shape were similar, and are listed in Table 4.5. Figure 4.10 is a comparison plot of the data points.

The range between best and worst possible conditions is greater for the skinnier, nonlinear membership Gaussian shape as opposed to the wider, nonlinear Gaussian curve. This demonstrates that sharper, skinnier membership functions yield a more sensitive FDI result; thus this shape is chosen as the best membership function curve for the remainder of the analyses.

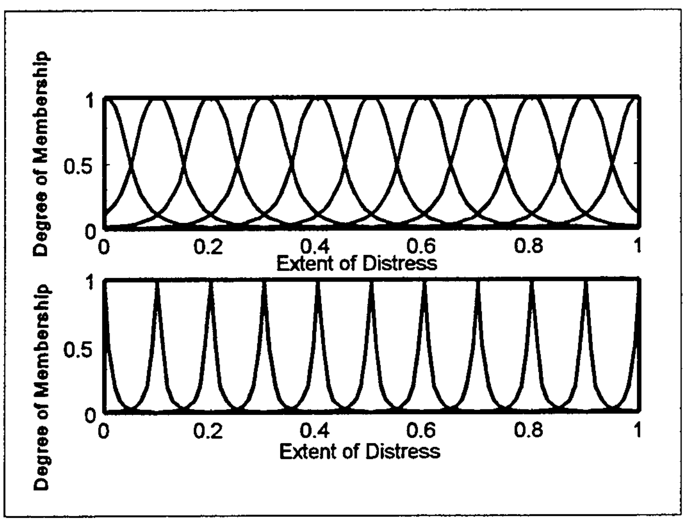


Figure 4.9 Example of Round, Wide Membership Curves (top) versus Sharp, Skinny Membership Curves (bottom)

Table 4.5 Comparison of Wide Versus Skinny Bell-Shaped Membership Curves

Description of Curve	Minimum FDI From Sample Data	Maximum FDI From Sample Data	Maximum Possible Range From Best To Worst Condition	Coefficient of Determination r^2	Standard Deviation s
Round, Wide Curve	0.9125	7.4198	[0.8795, 8.4315]	0.6999	1.9949
Sharp, Skinny Curve	0.2502	7.4709	[0.2085, 9.2027]	0.7007	2.1609

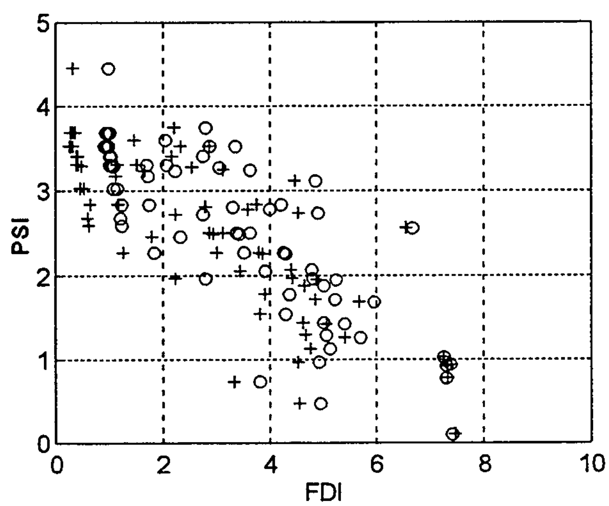


Figure 4.10 Comparison of FDI verse PSI for Round, Wide Membership Curves (o) and Sharp, Skinny Membership Curves (+).

4.5 Sensitivity of Defuzzification Techniques

Defuzzification techniques are used to convert fuzzy results to crisp results. For example, the computer program in this study first determines a final membership function which describes the overall distress of a pavement section. This membership function represents a fuzzy set containing many possible distress conditions, each with an associated degree of membership. In other words, each distress condition contained in the fuzzy set represents the actual distress of a pavement section with a certain degree of acceptance. The user, however, is interested in finding a specific distress condition of the pavement section, particularly the condition which best represents the actual distress of the pavement. Defuzzification techniques do exactly that: they assign a crisp number to a fuzzy measurement. In this case, a numerical rating of the distress condition for a pavement section is assigned to represent its corresponding membership function developed in the computer program. This rating, called the Fuzzy Distress Index (FDI) is used to prioritize the pavement sections from those sections with a high degree of distress to those with a low degree of distress.

Several defuzzification techniques include: the weighted average method, maximum height (or max-membership) principle, the center of area (or centroid method), and an approximation of the center of area method.

The weighted average method is given by equation 4.2 (Ross, 1995). This method is formed by weighting each membership function in the output by its respective maximum membership value. The weighted average method is only valid for symmetrical output membership functions. Since the final membership functions in this study may not be symmetrical due to the importance weighting assigned to each parameter initially, this method is not applicable.

$$z* = \frac{\Sigma\ \mu(c_z) \cdot z}{\Sigma\ \mu(c_z)} \tag{4.2}$$

where: c = a fuzzy set representing all distress conditions within the universe of distress conditions;

z = a particular distress condition contained in fuzzy set c;

c_z = a membership function describing the overall distress condition of a particular pavement section; and

$\mu(c_z)$ = the degree of membership of a particular distress condition z contained along membership function c_z.

The second method, the max-membership principle, is limited to peaked output functions, and is determined by simply choosing the value of the fuzzy set which yields the maximum membership. The drawback to this defuzzification method is that it is not dependent on the shape of the membership function, therefore resulting in a less sensitive measure.

The third technique, the center of area, is found by the integral expression as described in the previous chapter (Ross, 1995):

$$z* = \frac{\int_{-\infty}^{\infty} \mu(c_z) \cdot z\ dz}{\int_{-\infty}^{\infty} \mu(c_z)\ dz} \tag{4.3}$$

where: c = a fuzzy set representing all possible conditions within the universe of overall pavement conditions;

z = a particular condition contained in fuzzy set c;

c_z = a membership function describing the overall condition of a particular pavement section; and

$\mu(c_z)$ = the degree of membership of each condition z contained along membership function c_z.

The fourth method is an approximation of the center of area method, and is found by (Elton and Juang, 1988):

$$z* = \frac{(A_L - A_R + 1)}{2 \times A_U} \tag{4.4}$$

where: AL = area to the right of the membership function;

AR = area to the left of the membership function; and

AU = area enclosed by the universe.

A comparison was performed on the last two defuzzification methods described above. Ten (10) pavement sections were chosen randomly from the sample of 80 sections from the 1986 data base. The FDI was calculated using both methods: the resultant FDI values for each method are listed in Table 4.6 and a comparison plot is shown in Figure 4.11.

The results are very similar. Since (Equation 4.4) is an approximation of the center of area method, yet both methods are simple to solve in the computer program, the center of area method (Equation 4.3) was chosen as the best defuzzification method for this study.

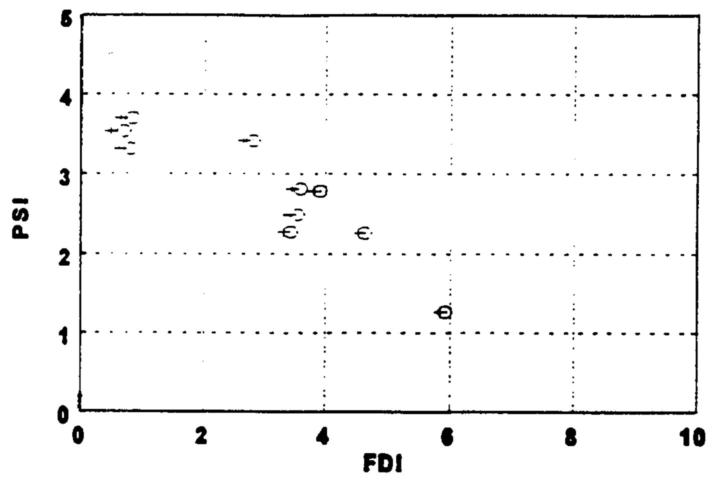


Figure 4.11 Comparison of Center of Area (+) and Approximated Center of Area (o) Defuzzification Techniques.

Table 4.6 Comparison of FDI Values for Center of Area (Eqn 3) and Approximated Center of Area (Eqn 4) Defuzzification Techniques

Pavement Section	Center of Area (Eqn 3)	Approximated Center of Area (Eqn 4)
1	0.8421	0.6373
2	4.6111	4.5238
3	3.5255	3.4019
4	2.7969	2.6399
5	3.9087	3.8055
6	3.4291	3.3138
7	3.5742	3.4453
8	0.6932	0.4849
9	5.9064	5.8457
10	0.8136	0.6186

4.6 The FDI Verse PSI

Program 4 was run using all 10,817 pavement sections available in the Nevada pavement condition data base. A maximum of eleven (11) membership functions were used to describe the different extents of distress of each parameter, while five (5) membership functions were used to define the perception of significance of each parameter. The sharp, skinny curves described in Section 4.4 were used in this program. Finally, the center of area defuzzification technique was implemented in the program to determine the FDI value for each pavement section. A plot of the FDI versus PSI for all pavements is shown in Figure 4.12. Linear regression analysis was performed to determine the correlation between the FDI and PSI. The equation of the fitted line for this sample of pavement sections is:

$$y = -0.3003x + 3.3982 \tag{4.5}$$

The correlation coefficient is r = -0.6127, where the negative sign represents the negative slope of the fitted line. This correlation between FDI and PSI is neither particularly high nor low. There are several outliers that were found in the scatter plot of data points which have high PSI ratings (good conditions) as well as high FDI ratings (bad conditions). Examination of these few data points reveal the following conditions:

1). The deviant pavement section records are found in sequential order in the data base.

2). Each record description is similar; all showing zero alligator cracking and high levels of linear cracking, no sealing on several of the sections, good ratings for appearance, zero flushing/raveling, low measures of roughness, and moderate skid numbers.

The PSI values for these pavement sections do not reflect their true distress conditions: the sections were rated extremely high, although they deserve lower ratings for their recorded measurements. This is, however, reflected in the FDI ratings, which indicate that the sections are in moderately bad condition. The placement of the regression line shows that the PSI may be an over-estimator for poor overall pavement conditions, and an under-estimator for excellent pavement conditions.

As mentioned previously, a higher correlation between the FDI and PSI can be achieved by increasing the importance weighting of the parameters included in the PSI equation and decreasing the weighting of the other parameters. However, this concept merely increases the correlation, and is not a valuable solution.

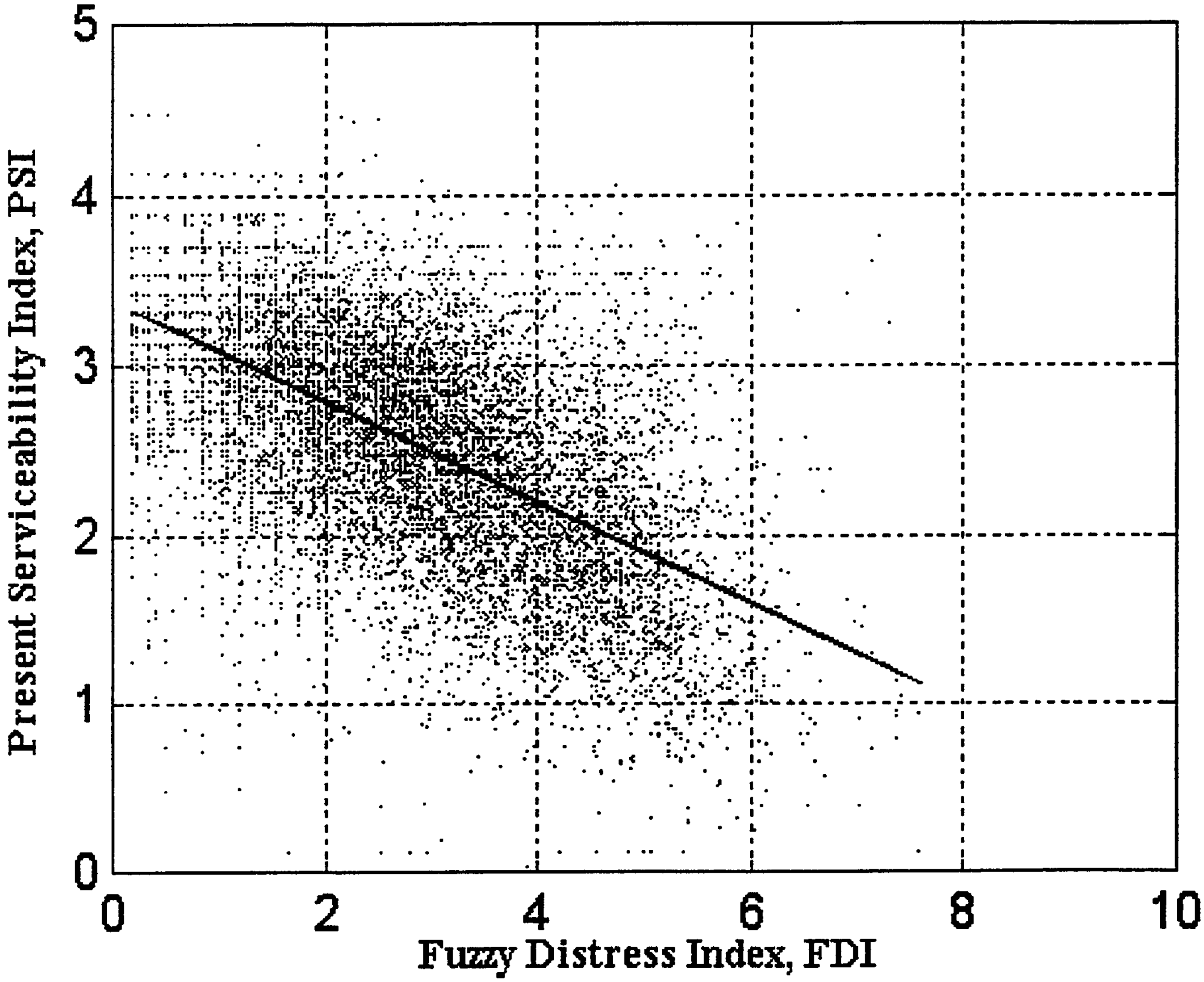


Figure 4.12 FDI versus PSI for all pavement sections in year 1986.

4.7 Conclusions

Sensitivity analyses for membership functions, weighting factors, and defuzzification techniques, reveal the following conclusions relating to the Fuzzy Distress Index (FDI):

• *The greater the number of membership functions used to describe each parameter, the more sensitive the measure for FDI.* This is shown in a comparison between a program using a maximum of 3 membership functions and program using a maximum of 11 membership functions, where the importance weighting varies among the individual parameters, but each parameter carries the same degree of weighting in both programs. Although correlation coefficients and standard deviations yield slight differences, the most insight is gained by observing the plots of FDI output. The FDI spread is greater for the program consisting of 11 membership functions (Figure 4.6) than the program consisting of 3 membership functions (Figure 4.1).

• *The importance weighting for each parameter can be assigned according to the individual parameter.* The effect of maximum versus varied importance weighting is minimal, thus the conclusion is to implement the model using varied importance weighting. This allows the user to choose the level of importance for each individual parameter as he or she deems appropriate.

• *The sharper and skinner the membership curves, the more sensitive the measure for FDI.* Two curves were compared: a rounded, wide bell-shaped curve and a sharp, skinny bell curve. The results show that the sharper and skinnier the membership curve, the greater the FDI range, and therefore, the greater the sensitivity of FDI.

• *The center of area method is the most accurate method for defuzzification of the final membership function.* Several methods were studied and a comparison was made between two techniques: the center of area and an approximation of the center of area. The center of area equation resulted in a slightly greater range of FDI values than the approximation equation. Since the second method is an approximation of the first, the center of area is believed to be the more accurate defuzzification technique, yielding the more sensitive FDI measure.

CHAPTER 5

ANALYSIS OF FDI AND PSI OVER TIME

5.1 Introduction

This chapter presents a comparison analysis of the Fuzzy Distress Index (FDI) and Present Serviceability Index (PSI) over a given time period. Appendix D contains the actual analyses of a random sample of 13 pavement sections selected from the Nevada Department of Transportation pavement condition data base. A table is displayed for each pavement section, complete with all parameters included in the calculations of the FDI and PSI, as well as traffic loading, environmental conditions, and maintenance actions for years 1980 through 1989. An outline of the abbreviations and a brief description for each parameter can be found in Appendix E. The FDI and PSI for each pavement section are plotted individually against time for the years under examination. Following the table and plots for each pavement section are remarks pointing out interesting features and inaccurate measures of each rating method, as well as behavior discrepancies between the two indices. In this chapter, results from the study are analyzed in detail, followed by a summary of conclusions.

5.2 Comparison of FDI and PSI

For the FDI, pavement deterioration is represented by an increase in the range from 0 to 10; however, an increase in PSI (ranging from 0 to 5) represents an improvement in pavement condition.

Therefore, there exists a negative correlation between the FDI and PSI. This means that if the PSI increases (pavement condition improves), the FDI is expected to decrease. However, the plots in Appendix D show several years where there are contradictions in the behavior of the FDI and PSI. These time periods are carefully analyzed in an attempt to fully understand the behaviors and attributes of both the FDI, based on fuzzy logic, and PSI, based on regression, and then in turn, ascertain the optimal technique for determining the overall distress of a pavement section.

The first observation is that many cases (D2-D13) show one or more years where the PSI value is equal to 0.1, which is a very low condition rating. None of the cases show an FDI value corresponding to such a low rating. The PSI does not reflect the parameter measurements listed in the tables for any of these instances. For example, year 1983 in Table D7 shows a PSI value of 0.1 and an FDI value of 0.5600. The data for this particular pavement section indicates no alligator cracking, linear cracking, rutting, patching, or raveling/flushing. It also received excellent condition ratings for appearance and shoulder condition, and the roughness and skid number are average or above. The extremely poor PSI rating clearly does not reflect the data presented in the table, while the excellent FDI rating does accurately represent the data. For all cases such as this, it must be assumed that the PSI values are incorrect: the values may have been miscalculated or entered into the data base incorrectly.

It is extremely important to consider the validity of the data base. After all, maintenance decisions are based on indices such as the FDI or PSI. Since these indices are developed from information contained in pavement condition data bases, it is vital that the data base contains accurate information and measurements. Therefore, the collection of data and the entry of the measurements into the data base are critical processes in the pavement management system. Billions of dollars are spent on maintenance and rehabilitation actions every year. An erroneous data base will result in the determination of imprecise pavement serviceability indices. This leads to inaccurate decision-making in addition to incorrect allocation of funds.

There is reason to believe that the Nevada pavement condition data base is not an accurate data base. Table D4 and Figure D4 in Appendix D yields one justification. The first error is found in the table in year 1980, where the parameters precipitation, number of wet days, and freeze-thaw are all equal to zero. Continuing down these columns for years 1981-1989, the numbers recorded for each parameter are 19.5, 65, and 158, respectively, and remain constant for each year. Another discrepancy in the data is found in the PSI column, where PSI is equal to 0.1 for years 1980-1983. This PSI value is an extremely low condition rating, and does not reflect the parameter measurements shown for these years. Finally, there is inconsistency between the maintenance column and the PSI. For example, the maintenance column for the first four years (1980-1983) shows that rehabilitation was performed on this pavement section; however, the PSI value remains low and constant (PSI = 0.1), not reflecting this rehabilitation action. Later, year 1986 shows no corrective measures were taken, although the PSI reflects a significant improvement in pavement condition.

Similar circumstances are found in Table D6 and Figure D6 (Appendix D). Again, the parameters precipitation, number of wet days, and freeze-thaw for the year 1980 are all zeros. The remainder of the years (1981-1989) contain constant values of 7.95, 56, and 216 for each parameter, respectively. The PSI value of 0.1 for year 1980 is not reflective of the parameter measurements, and the PSI values show an improvement in pavement condition between years 1896 to 1987, although no corrective actions were undertaken during this time, as indicated in the maintenance column (year 1986). Also note that year 1984 contains zeros for the parameters alligator cracking severity and extent, linear cracking severity and extent, rut depth, patching, appearance, raveling/flushing, and shoulder condition. The PSI is 3.69, an above-average value, but not an excellent rating. However, the FDI is 0.6448, which is an extremely good rating, reflecting the very low measures of distress for the aforementioned parameters. Extremely important results can be concluded from this example. First, the FDI is determined directly from the information contained in the data base, expressing once again the importance of the accuracy of the data base. However, the FDI is most likely an incorrect measure of the actual distress, because the ratings for appearance and shoulder condition are rated according to pictures in a manual, thus the value of zero is not a reasonable rating for these parameters.

Each one of the thirteen randomly selected pavement sections in Appendix D show one or more inconsistencies within the pavement condition data base. Thus, it is difficult to draw conclusions on the accuracy of either the FDI or the PSI. However, the comparisons of the FDI and PSI are carried out based on the given information.

The PSI is calculated by the Nevada Department of Transportation (1995) using the following equation, which is discussed in the previous chapter:

$$PSI = 5 * e^{(-0.0041 * IRI)} - 0.09(C+P)^{1/2} \qquad (5.1)$$

where: PSI = Present Serviceability Index;

IRI = International Roughness Index;

C = Cracked area in square feet per 1000 square feet of pavement area; and

P = Patched are in square feet per 1000 square feet of pavement area.

Many discrepancies in the change of FDI and the change of PSI can be explained by this equation. The PSI considers only those parameters identified above. However, the FDI considers all of the above in addition to other significant parameters: a total of 14 parameters all together. Therefore, a slight decline in the condition of one of the three parameters listed above may have a significant impact on the change in PSI over a year: however, when all 14 conditions are considered, the overall condition may not necessarily change in the same manner. For example, suppose the roughness condition becomes slightly worse from one year to the next, but the cracks are sealed, and rut depth, raveling/flushing, and shoulder condition all improve significantly. In this case, the PSI (using equation 5.1) reflects only the small change in roughness, and in turn, has a slightly poorer rating. However, the FDI considers the decline in roughness in addition to all of the significant condition improvements, as well as the importance of each parameter to the overall distress of the pavement section, and reflects a combination of all of these factors in its rating. Although the final condition rating depends on the extent of deterioration or improvement of each parameter as well as the perception of each parameter's importance to the overall pavement condition, the FDI in this case will most likely show an improvement in pavement condition over the year. Cases such as this are described in the "Remarks" paragraphs for the thirteen pavement sections in Appendix D.

For example, Table D4 and Figure D4 illustrate a similar inconsistencies. In Figure D4 between years 1986-1987, the FDI shows pavement deterioration while the PSI shows an improvement in pavement condition. The measurements in the table indicate a decline in the parameters alligator cracking type, severity, and extent with no sealing, rutting, appearance, raveling/flushing, and roughness. In addition, the maintenance column shows that no corrective measures were taken in year 1986. Therefore, the overall distress condition should reflect the deterioration represented in these measures, as exhibited in the FDI. There is no evidence that the pavement condition should improve over this time period, thus the validity of the PSI is questionable.

Another example is found in Table D9 and Figure D9 for years 1986-1987. The FDI shows significant deterioration (from 0.4844 to 2.3142), while the PSI shows a very small decline in pavement condition (from 3.54 to 3.52). The data in the table indicates a decline in linear cracking type, severity, and extent with no sealing, appearance, shoulder condition, and roughness, justifying the significant decrease in the overall distress rating given by the FDI.

Finally, careful observation of Table D11 and Figure D11 reveals another discrepancy between the FDI and PSI. Years 1982-1983 both have identical PSI ratings of 2.9; however, it is clear that several measurements provided in the table change over this time period. There is a significant decline in linear cracking type, severity, and extent (with no sealing), while the roughness becomes slightly greater. There are also small improvements in rut depth, appearance, and raveling/flushing. The PSI does not reflect any of these changes in condition; however, the FDI does reflect the changes by indicating a slight decrease in the overall distress condition. Years 1987-1988 show an improvement in condition according to the PSI, while the FDI shows pavement deterioration. The data in the table indicates a decline in alligator cracking type, severity, and extent, linear cracking type, severity, and extent (with no sealing), appearance, raveling/flushing, and shoulder condition. The roughness rating becomes slightly smoother, although it is still a good rating. The only parameter which shows improvement is rut depth. Clearly the FDI better represents the actual condition of this pavement section over these years. Examples of similar situations can be found in the "Remarks" sections located in Appendix D.

5.3 Conclusions

Several results have been discussed above, and specific examples supporting each statement are included in Appendix D. Important conclusions from this study are summarized below.

• *The PSI does not consistently reflect the information provided in the data base, while the FDI does represent this data both accurately and consistently.* The PSI is based on regression and considers only three parameters. However, the FDI is based on fuzzy logic and makes full use of the data base by including fourteen parameters which are significant in the overall pavement condition. Twelve out of the thirteen cases show inconsistencies between the given data and the corresponding PSI values. On the other hand, the FDI is consistent in accurately reflecting the information in the data base.

• *A condition index must consist of all parameters which are significant to that particular condition.* The PSI used by the Nevada Department of Transportation (equation 5.1) includes only three parameters: roughness, cracking, and patching. Therefore, a slight change in one of these parameters may cause a significant increase or decrease in PSI. However, these three parameters are not the only variables which affect pavement deterioration and the overall condition of a pavement. The FDI developed in this study includes a total of fourteen parameters which are all significant in determining the extent of distress on a pavement section. It is a more accurate measure because it is based on the combination of a number of significant parameters, in addition to the perception of importance of each parameter.

• *The clarity and validity of the data base is fundamental in the development of condition indices, such as the FDI or PSI, and ultimately has an effect on decision-making for maintenance and rehabilitation actions.* The condition indices are developed directly from measurements and ratings collected and stored in a data base. Therefore, it is important that the information gathered is accurate and entered into the data base correctly. It is also important that the information contained in the data base is explained clearly and in detail. For example, the Nevada pavement condition data base shows a maintenance column which consists of rehabilitation (R), maintenance (M), overlay (O), or no maintenance (N). Knowledge of the exact type of maintenance and corresponding cost would be helpful in understanding and explaining the behavior of the PSI and FDI in this study, as well as aid in future studies. The condition indices need to be precise, since maintenance decisions are based upon these indices. Ultimately, decision making becomes ambiguous when a great number of inconsistencies and vagueness exist in the data base.

CHAPTER 6

CONCLUSIONS

Pavement evaluation modeling plays an important role in pavement management systems. Knowledge of the extent of deterioration on a pavement section compared to other sections in the transportation network is a primary motivation for decision making and initiating maintenance actions. Since the introduction of the concept of the prediction of pavement performance, many pavement condition indices have been developed, such as the Present Serviceability Index (PSI). However, these indices lack uniqueness due to their dependency on the type of data used to generate their formulas. Although they may function on a state level, they cannot be applied to a national or international scale without calibration.

The global scale of this work is the development of a universal index which represents the overall condition of any pavement section, independent of its location, use, or design. The assessment of a pavement section should include as many elements as possible that affect its overall condition. This study introduces the use of fuzzy sets in the development of such a universal measure. This development is based on membership functions for each condition parameter and the perception of the significance of each parameter. The Fuzzy Distress Index (FDI) is used as a measure of the membership function, and thus is a unique measure of the overall condition of a particular pavement section.

There are several advantages of incorporating fuzzy logic into this distress assessment model, including the following:

- This method produces a universal index that would be suitable to any pavement of the same construction anywhere on the globe.
- The data base can consist of numeric and/or linguistic measurements.
- Membership functions can be built for all significant parameters contributing to the distress of pavement section.
- Weights are assigned to each parameter, allowing for more significant parameters to have a greater contribution to the overall distress of the pavement section, and less significant parameters to have a smaller contribution to the overall distress.
- Ideas and policies for a particular highway agency can be easily implemented in a universal program. The impact of different policies can be studied by adjusting the significance weightings for particular parameters.
- On a local and state level, decision makers can easily identify the areas that are in most need of maintenance.
- For a particular country, the government would be able to identify and allocate funding for the locations in most need of maintenance.

For the development of an optimal condition assessment model, the study in Chapter 4 examined how each of the following effects the behavior of the FDI:

- the number of membership functions used to define each parameter;
- maximum versus varied weightings used to describe the perception of the significance of each parameter;
- the shape of membership functions used to describe each parameter and its corresponding significance weighting; and

• the different methods used for defuzzification of the final membership function describing the overall distress condition of a particular pavement section.

The data base used in this study was provided by the Nevada Department of Transportation. Close examination of this information revealed inconsistencies and vagueness within the data base, as documented in Chapter 5. A well-defined, valid data base is fundamental in the development of condition indices, such as the FDI and PSI, because the condition indices are the basis of decision making for present and future maintenance and rehabilitation activities.

Another important finding in Chapter 5 is that the PSI calculated by the Nevada DOT does not consistently reflect the information provided in the data base, while the FDI does represent this data both accurately and consistently. The PSI is based on regression, and includes only three parameters in an overall assessment of pavement condition. However, the FDI is a unique and extremely flexible measure which is consistent in accurately reflecting the information in the data base, while possessing all of the advantages of fuzzy set theory described above. The set of generated membership functions describing the different extent of every distress type are standardized over the 50 states, allowing the model to be implemented on any pavement in any location. Also, the parameter weights used in the assessment may be easily adjusted to reflect changes in maintenance policies or budget at the local, state, or national decision-making level.

As stated in the introduction, the first task of transportation is to maintain the assets that already exist. Therefore, a pavement management system is needed which concentrates on maximizing the number of pavements in "good" condition, minimizing the number of pavements in "medium" condition, and eliminating the number of pavements in "bad" condition. The idea is to develop a pavement management system that does not allow pavements to deteriorate below a pre-determined level. Pavements in need of maintenance should be identified before they deteriorate below this level and become unsatisfactory.

This study has focused on the development of a unique measure for determining the overall condition of a particular pavement section. As a continuation of the study, a combination of pavement design, use, traffic loading, environmental conditions, and maintenance history may be added to the FDI. Knowledge of the present condition of a pavement section leads to the ability to predict the future condition of the pavement. If future conditions are known with a certain degree of confidence, the effects of implementing different highway policies can be examined. In addition, planning and decision making for maintenance actions as well as for the allocation of funds becomes an easier, more accurate task for highway agencies.

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APPENDIX A

PARAMETER DESCRIPTIONS AND MEMBERSHIP FUNCTIONS

ALLIGATOR CRACKING TYPE

Description: Longitudinal cracking in a wheel path and interconnected or interlaced fatigue cracks forming a series of small polygons are load associated cracking and are identified as Type A and Type B Alligator Cracking respectively. Initially, a single longitudinal crack appears in one or both wheel paths (Type A). Upon further wheel load repetitions parallel longitudinal cracks will develop which then interconnect forming the typical pattern resembling an alligators skin (Type B). Alligator pattern cracking that covers a large portion or all of the surface is cracking caused by age hardening and shrinkage of the asphalt and is not directly related to the loading of the pavement. It is identified as either Type C or Type D alligator cracking.

Type A Alligator Cracking: The initial appearance of fatigue cracks in the wheel paths. This is manifest as a single longitudinal crack in one or both wheel paths. The most Type A alligator cracking that can exist in the rating section is 200 ft.

Type B Alligator Cracking: A series of parallel or interconnected fatigue cracks in one or both wheel paths. The most Type B alligator cracking that can exist in the rating section is 600 ft.

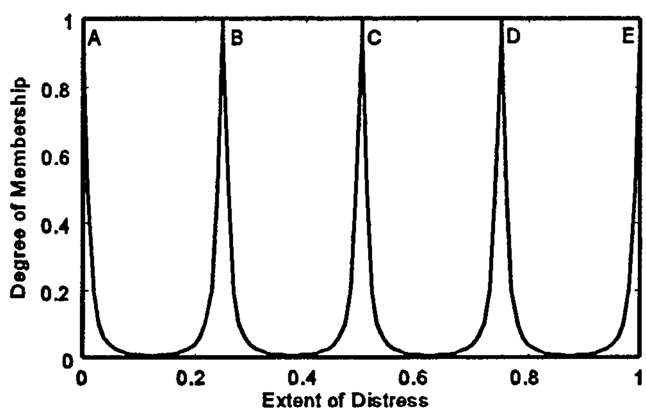
Type C Alligator Cracking: This type of cracking is characterized by the typical alligator cracking pattern which covers large portions or all of the surface. The small segments have sharp corners or angles and range in size up to an average of 1 ft. X 1 ft. The most Type C alligator cracking that can exist in the rating section is 1000 ft.

Type D Alligator Cracking: This type classification is "Block" cracking. Block cracking shows as a network of interconnected cracks forming a series of large polygons, usually with sharp corners or angles. The segments range in size from an average of 1 ft. X 1 ft. up to an average of 5 ft. X 5 ft. If the blocks are larger than 5 ft. X 5 ft., they shall be rated as linear cracking. The most Type D alligator cracking that can exist in the rating section is 1000 ft.

Identified: From the descriptions given, determine which type of cracking is predominant within the rating section, then, record the appropriate code.

Membership function for **Alligator Cracking Type**:

Type	Code	Description	Grade
(blank) " "	1	Very Slight	A
"A"	2	Slight	B
"B"	3	Moderate	C
"C"	4	Severe	D
"D"	5	Very Severe	E



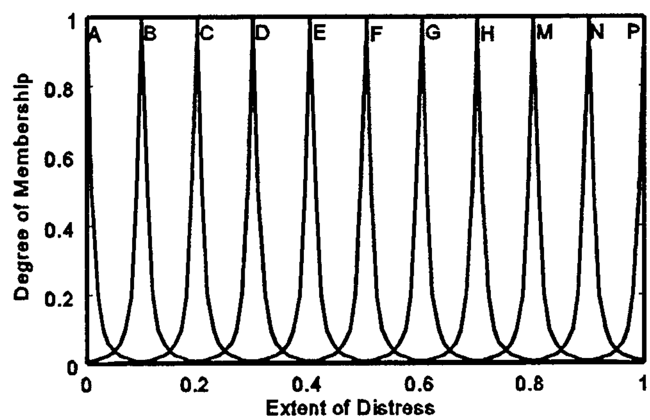
ALLIGATOR CRACKING SEVERITY

Description: Severity pertains to the width of the cracks. The width of the crack is considered to be the total width of the fissure including widening caused by raveling.

How measured: The measurement is a general average of the width of all alligator cracks in the rating section. The measurement is taken at the surface. With the crack width gauge provided, obtain a measurement to the nearest whole number of the gauge and record this number.

Membership function for **Alligator Cracking Severity**:

Width	Description	Grade
w <= 0.025	Very Slight	A
0.025 < w <= 0.050		B
0.050 < w <= 0.075		C
0.075 < w <= 0.100		D
0.100 < w <= 0.125		E
0.125 < w <= 0.150	Moderate	F
0.150 < w <= 0.175		G
0.175 < w <= 0.200		H
0.200 < w <= 0.250		M
0.250 < w <= 0.300		N
w > 0.300	Very Severe	P



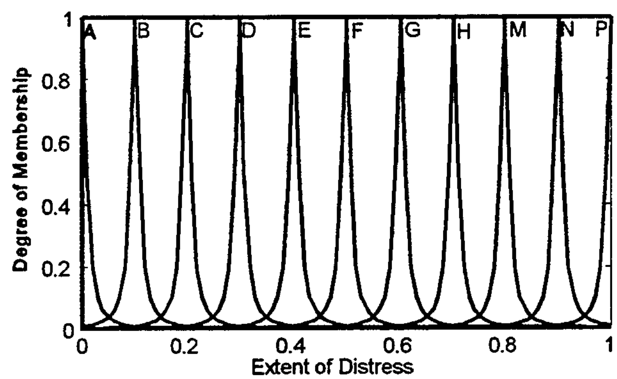
ALLIGATOR CRACKING EXTENT

Description: Extent is the amount of cracking that exists in the rating section.

How measured: Within the rating section, the width and length of the Alligator Cracked area is measured with the "Roll-a-Tape". To record this value, the length and width in feet are multiplied to give the area. The calculated area value is then recorded rounded to the nearest 1 whole square foot.

Membership function for **Alligator Cracking Extent**:

Area (in sq.ft.)	Description	Grade
a<=50	Very Slight	A
50<a<=100		B
100<a<=150		C
150<a<=200		D
200<a<=250		E
250<a<=300	Moderate	F
300<a<=350		G
350<a<=400		H
400<a<=450		M
450<a<=500		N
a>500	Very Severe	P



LINEAR CRACKING TYPE

Description: Longitudinal cracks other than in the wheel paths, and transverse cracks.

Shrinkage cracks forming blocks larger than approximately 5 ft X 5 ft are rated as linear cracks and are not considered Type D cracking.

Type A Linear Cracking: Longitudinal cracking other than in the wheel paths.

Type B Linear Cracking: Cracks that occur at approximately fright angles to the centerline (transverse). They are primarily due to shrinkage of the surface course or reflection cracking.

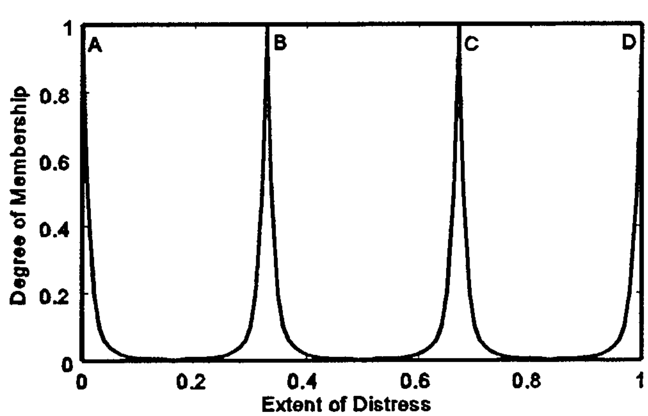
Type C Linear Cracking: Approximately equal amounts of both longitudinal and transverse cracking.

By definition the most linear cracking that can exist in the rating section is 510 feet.

Identified: From the descriptions given, determine which type of linear cracking is predominant within the rating section, then record the appropriate code.

Membership function for **Linear Cracking Type**:

Type	Code	Description	Grade
(blank) " "	1	Very Slight	A
"A"	2	Moderate	B
"B"	3	Severe	C
"C"	4	Very Severe	D



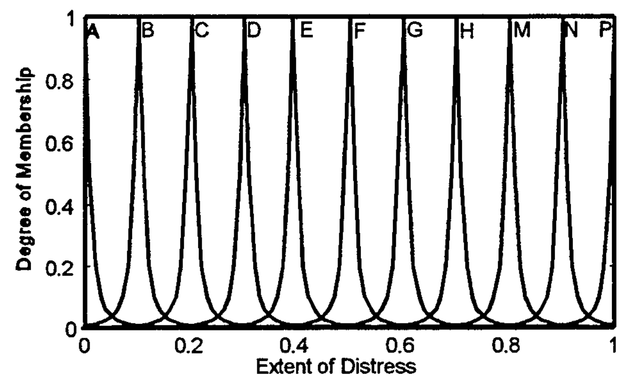
LINEAR CRACKING SEVERITY

Description: Severity pertains to the width of the cracks. The width of the crack is the total width of the fissure, this includes widening caused by raveling.

How measured: The measurement is a general average of the width of all linear cracks in the rating section. The measurement is taken at the surface. With the crack width gauge provided, obtain a measurement to the nearest whole number (1/8 inch) and record this number.

Membership function for **Linear Cracking Severity**:

Width	Description	Grade
w <= 0.025	Very Slight	A
0.025 < w <= 0.050		B
0.050 < w <= 0.075		C
0.075 < w <= 0.100		D
0.100 < w <= 0.125		E
0.125 < w <= 0.150	Moderate	F
0.150 < w <= 0.175		G
0.175 < w <= 0.200		H
0.200 < w <= 0.250		M
0.250 < w <= 0.300		N
w > 0.300	Very Severe	P



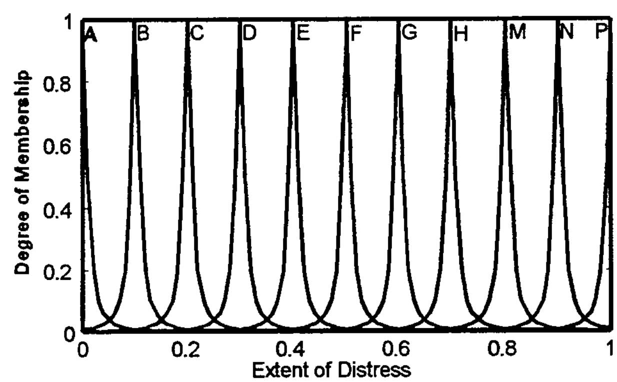
LINEAR CRACKING EXTENT

Description: Extent is the amount of linear cracking that exists within the rating section.

How measured: When the rating section is established, the length of the longitudinal and transverse cracks are measured with the "Roll-A-Tape". The total of their lengths are then reported to the nearest one foot. By definition, the most Linear Cracking that can exist in the rating section is 510 linear feet. Linear and Alligator Cracking are mutually exclusive, for example, there can be no Linear Cracking if there is 1000 square feet of Alligator Cracking.

Membership function for **Linear Cracking Extent**:

Length (in sq.ft.)	**Description**	**Grade**
l <= 50	Very Slight	A
50 < l <= 100		B
100 < l <= 150		C
150 < l <= 200		D
200 < l <= 250		E
250 < l <= 300	Moderate	F
300 < l <= 350		G
350 < l <= 400		H
400 < l <= 450		M
450 < l <= 500		N
l > 500	Very Severe	P



CRACK SEALING

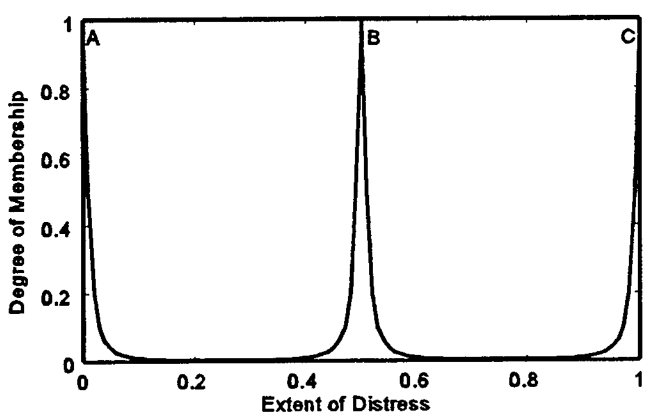
Description: A bituminous or other type material poured into the cracks to prevent the intrusion of moisture and foreign solid material.

Identified: The crack sealing material is easily discernable by observation. The condition, however, is important. If the crack has reopened, it shall be rated as not sealed. In this case the letter "N" shall be entered.

If the cracks are sealed and the material is in good condition, the letter "Y" shall be entered.

Membership function for **Sealing**:

Sealing	Code	Description	Grade
(blank) " "	1		A
"Y"	2	Good	B
"N"	3	Bad	C



RUT DEPTH

Description: A rut is a longitudinal surface depression in the wheel paths. Rutting is usually caused by consolidation or lateral movement of surfacing material under heavy wheel loads.

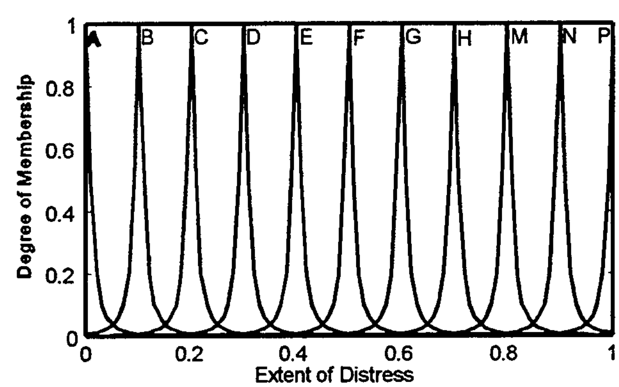
The depths of ruts are measured with the rut depth gauge provided.

Within the rating section, three measurements are taken in the left wheel path 25 feet apart. Likewise, three measurements are taken in the right wheel path 25 feet apart.

How measured: The measurements are to be taken by placing the rut depth gauge over the deepest part of the rut, approximately in the center of the wheel path. The center measuring rod is then lowered to the surface, the wing nut tightened and the reading taken. The scale on the rut gauge is in increments of 1/8 inch. The measurement is to be reported in sequence to the nearest whole number indicated on the rut gauge scale. All six measurements for each pavement section are averaged together resulting in the Average Rut Depth.

Membership function for **Average Rut Depth**:

Rut Depth (in 1/8 in)	**Description**	**Grade**
r <= 0.025	Very Slight	A
0.025 < r <= 0.050		B
0.050 < r <= 0.075		C
0.075 < r <= 0.100		D
0.100 < r <= 0.125		E
0.125 < r <= 0.150	Moderate	F
0.150 < r <= 0.175		G
0.175 < r <= 0.200		H
0.200 < r <= 0.250		M
0.250 < r <= 0.300		N
r > 0.300	Very Severe	P



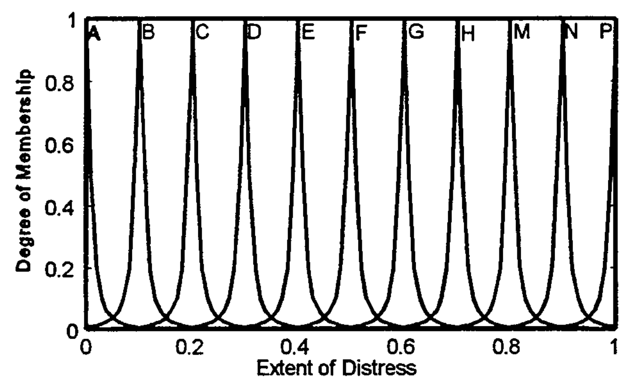
PATCHING

Description: Patches are permanent or temporary corrections to damaged pavement. They vary in size and method of placement.

How measured: For the purposes of this survey, all patches are recorded in square feet per one thousand square feet. Within the rating section, measure the widths and lengths of all patches. Multiply the widths by the lengths and enter the total reporting to the nearest 1 foot. If the rating section is located entirely on a long patch, the amount of patching will be 1000 square feet.

Membership function for **Patching**:

Area (in sq.ft.)	Description	Grade
a <= 50	Very Slight	A
50 < a <= 100		B
100 < a <= 150		C
150 < a <= 200		D
200 < a <= 250		E
250 < a <= 300	Moderate	F
300 < a <= 350		G
350 < a <= 400		H
400 < a <= 450		M
450 < a <= 500		N
a > 500	Very Severe	P



APPEARANCE

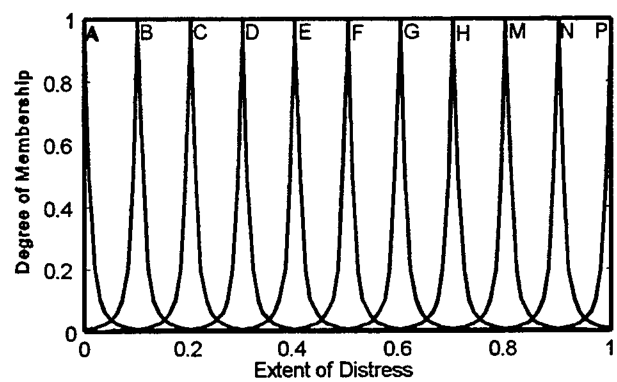
Description: General pavement condition refers to the overall appearance of the roadway surface as already described in the Maintenance Rating Booklet.

Identified: Turn to the series of 19 pavement condition photographs in the back of this manual. From these photographs, depicting varieties of distress with ranges of severity, choose the one photograph which best reflects the overall appearance of the roadway. Record the numerical code of this photograph.

Should there be no discernable distress, as with a recent contract, the numerical code of the photograph illustrating a good pavement condition shall be entered.

Membership function of **Appearance**:

Picture	Description	Grade
0, 1	Very Good	A
2		B
3		C
4		D
5		E
6	Moderate	F
7		G
8		H
9		M
10		N
> 10	Very Bad	P



FLUSHING / RAVELING

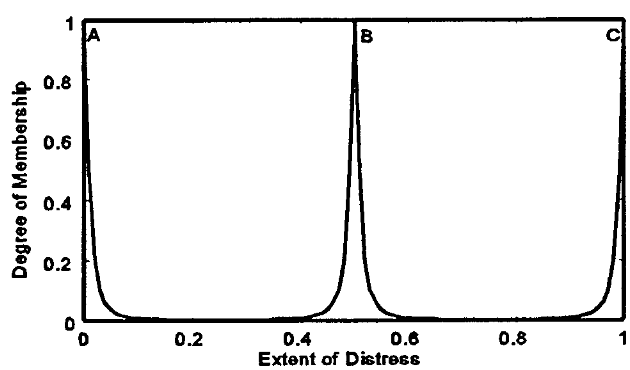
Description: Flushing is a term for a specific condition where there is a film of bituminous material on the pavement surface. This will occur only in the wheel paths. The condition can be seen as just a darkening of the wheel paths ranging up to a very dark shiny mat with no aggregate exposed at all.

Raveling is the wearing away of the pavement surface. It can be caused by weathering and oxidation of the asphaltic binder with subsequent loss of aggregate or be actively worn away as with chain traffic,. The result is the same, the appearance is that of a gross texture, and in more severe cases rutting in the wheel paths.

Identified: Photographs 12, 13, and 14, page 26, illustrate flushing. Photographs 15, 16, and 17, page 27, illustrate raveling. From the description determine if there is flushing or raveling (they do not occur together) or neither condition present. From one of the pavement condition photographs choose and record the one which best reflects the actual pavement condition and level of severity. If there is neither flushing nor raveling, leave a blank space.

Membership function for **Flushing / Raveling**:

Flushing / Raveling	**Description**	**Grade**
<= 12, 15	Slight	A
13, 16	Moderate	B
14, >=17	Severe	C



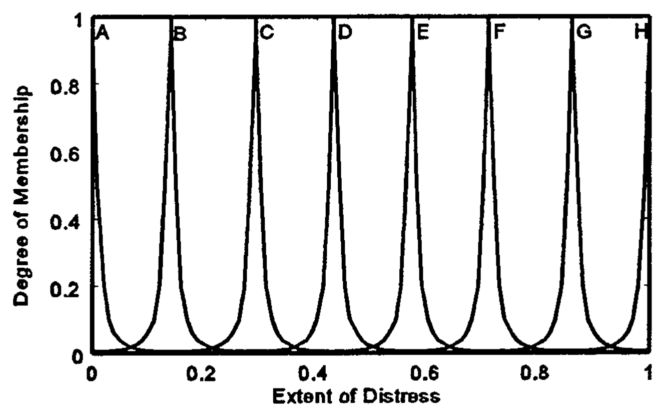
SHOULDER CONDITION

Description: Shoulder condition is the overall appearance and condition of the shoulders or edge of pavement. See page 25, figure 9, for examples of different types of shoulders. The condition of the shoulder is to be rated regardless of its width. On divided highways, only the outside shoulder is to be rated.

Identified: Turn to the shoulder condition photographs in the back of this manual. Make a comparison of the actual shoulder condition with the photographs illustrating shoulder condition. Determine which photograph best represents the actual overall shoulder or edge of pavement condition and record the numeral code for that photograph. All shoulders and pavement edges are to be rated.

Membership function for **Shoulder Condition**:

Condition	Description	Grade
blank " "	Very Good	A
20		B
21		C
22		D
23	Moderate	E
24		F
25		G
> 25	Very Bad	H

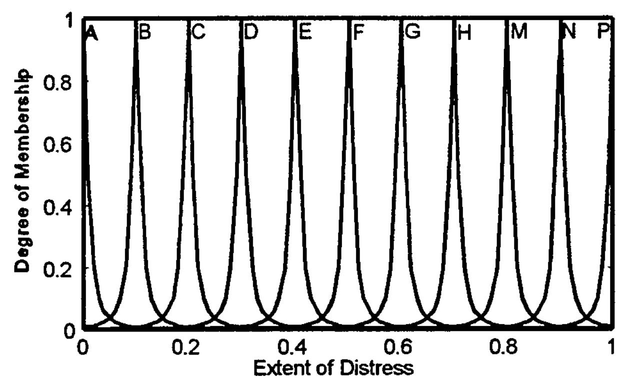


ROUGHNESS

The Nevada State Department of Transportation uses the International Roughness Index for describing the roughness of each pavement section.

Membership function for **Roughness**:

Roughness	Description	Grade
a <= 50	Very Smooth	P
50 < a <= 53		N
53 < a <= 56		M
56 < a <= 59		H
59 < a <= 62		G
62 < a <= 65		F
65 < a <= 68		E
68 < a <= 71		D
71 < a <= 74	Moderate	C
74 < a <= 77		B
77 < a <= 95		A
95 < a <= 105		B
105 < a <= 115	Moderate	C
115 < a <= 120		D
120 < a <= 125		E
125 < a <= 130		F
130 < a <= 135		G
135 < a <= 140		H
140 < a <= 145		M
145 < a <= 150		N
a > 150	Very Rough	P

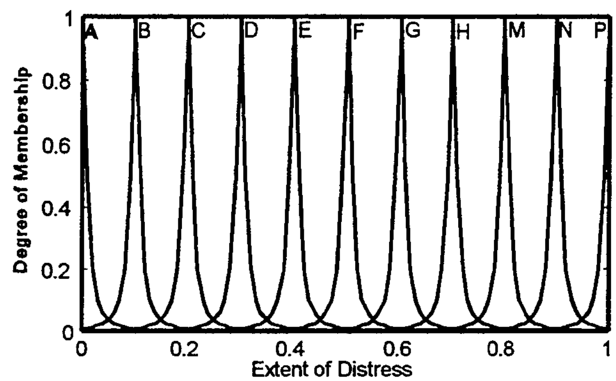


SKID

The Nevada State Department of Transportation supplied no additional information for the skid measurement. However, the membership functions were defined in the program as the following:

Membership Functions for **SKID**:

Skid	Description	Grade
a > 70	Very Good	A
65 < a <= 70		B
60 < a <= 65		C
55 < a <= 60		D
50 < a <= 55		E
45 < a <= 50	Moderate	F
40 < a <= 45		G
35 < a <= 40		H
30 < a <= 35		M
25 < a <= 30		N
a <= 25	Very Bad	P



APPENDIX B

COMPUTER PROGRAM AND SAMPLE INPUT/OUTPUT

```
%Program GRD8011b.m reads a data base and calculates the FDI for pavements one section at a
%time, and then plots FDI versus PSI.

%Read in coded data from data base.
M=csvread('c:\jenifer\d801986.csv',0,0);

%Define variables and arrays.
ndx=[];fdi=[];psi=[];

%Read one record at a time and calculate its corresponding FDI.
for i=1:length(M)

  GRD=[];

  %Define guidelines for ALLIGATOR CRACKING TYPE
  if M(i,2)==1 GRD=[GRD 'A'];
  elseif M(i,2)==2 GRD=[GRD 'B'];
  elseif M(i,2)==3 GRD=[GRD 'C'];
  elseif M(i,2)==4 GRD=[GRD 'D'];
  elseif M(i,2)==5 GRD=[GRD 'E'];
  end

  %Define guidelines for ALLIGATOR CRACKING SEVERITY
  if M(i,3)<=0.025 GRD=[GRD 'A'];
  elseif M(i,3)>0.025&M(i,3)<=0.05 GRD=[GRD 'B'];
  elseif M(i,3)>0.05&M(i,3)<=0.075 GRD=[GRD 'C'];
  elseif M(i,3)>0.075&M(i,3)<=0.1 GRD=[GRD 'D'];
  elseif M(i,3)>0.1&M(i,3)<=0.125 GRD=[GRD 'E'];
  elseif M(i,3)>0.125&M(i,3)<=0.15  GRD=[GRD 'F'];
  elseif M(i,3)>0.15&M(i,3)<=0.175 GRD=[GRD 'G'];
  elseif M(i,3)>0.175&M(i,3)<=0.2 GRD=[GRD 'H'];
  elseif M(i,3)>0.2&M(i,3)<=0.25 GRD=[GRD 'M'];
  elseif M(i,3)>0.25&M(i,3)<=0.3 GRD=[GRD 'N'];
  elseif M(i,3)>0.3 GRD=[GRD 'P'];
  end

  %Define guidelines for ALLIGATOR CRACKING EXTENT
  if M(i,4)<=50 GRD=[GRD 'A'];
  elseif M(i,4)>50&M(i,4)<=100 GRD=[GRD 'B'];
  elseif M(i,4)>100&M(i,4)<=150 GRD=[GRD 'C'];
  elseif M(i,4)>150&M(i,4)<=200 GRD=[GRD 'D'];
  elseif M(i,4)>200&M(i,4)<=250 GRD=[GRD 'E'];
  elseif M(i,4)>250&M(i,4)<=300 GRD=[GRD 'F'];
```

```
elseif M(i,4)>300&M(i,4)<=350 GRD=[GRD 'G'];
elseif M(i,4)>350&M(i,4)<=400 GRD=[GRD 'H'];
elseif M(i,4)>400&M(i,4)<=450 GRD=[GRD 'M'];
elseif M(i,4)>450&M(i,4)<=500 GRD=[GRD 'N'];
elseif M(i,4)>500 GRD=[GRD 'P'];
end

%Define guidelines for LINEAR CRACKING TYPE
if M(i,5)==1 GRD=[GRD 'A'];
elseif M(i,5)==2 GRD=[GRD 'B'];
 elseif M(i,5)==3 GRD=[GRD 'C'];
elseif M(i,5)==4 GRD=[GRD 'D'];
end

%Define guidelines for LINEAR CRACKING SEVERITY
if M(i,6)<=0.025 GRD=[GRD 'A'];
elseif M(i,6)>0.025&M(i,6)<=0.05 GRD=[GRD 'B'];
elseif M(i,6)>0.05&M(i,6)<=0.075 GRD=[GRD 'C'];
elseif M(i,6)>0.075&M(i,6)<=0.1 GRD=[GRD 'D'];
elseif M(i,6)>0.1&M(i,6)<=0.125 GRD=[GRD 'E'];
elseif M(i,6)>0.125&M(i,6)<=0.15  GRD=[GRD 'F'];
elseif M(i,6)>0.15&M(i,6)<=0.175 GRD=[GRD 'G'];
elseif M(i,6)>0.175&M(i,6)<=0.2 GRD=[GRD 'H'];
elseif M(i,6)>0.2&M(i,6)<=0.25 GRD=[GRD 'M'];
elseif M(i,6)>0.25&M(i,6)<=0.3 GRD=[GRD 'N'];
elseif M(i,6)>0.3 GRD=[GRD 'P'];
end

%Define guidelines for LINEAR CRACKING EXTENT
if M(i,7)<=50 GRD=[GRD 'A'];
elseif M(i,7)>50&M(i,7)<=100 GRD=[GRD 'B'];
elseif M(i,7)>100&M(i,7)<=150 GRD=[GRD 'C'];
elseif M(i,7)>150&M(i,7)<=200 GRD=[GRD 'D'];
elseif M(i,7)>200&M(i,7)<=250 GRD=[GRD 'E'];
elseif M(i,7)>250&M(i,7)<=300 GRD=[GRD 'F'];
elseif M(i,7)>300&M(i,7)<=350 GRD=[GRD 'G'];
elseif M(i,7)>350&M(i,7)<=400 GRD=[GRD 'H'];
elseif M(i,7)>400&M(i,7)<=450 GRD=[GRD 'M'];
elseif M(i,7)>450&M(i,7)<=500 GRD=[GRD 'N'];
elseif M(i,7)>500 GRD=[GRD 'P'];
end
```

```
%Define guidelines for SEALING
if M(i,8)==1 GRD=[GRD 'A'];
elseif M(i,8)==2 GRD=[GRD 'B'];
elseif M(i,8)==3 GRD=[GRD 'C'];
end

%Define guidelines for RUT-DEPTH
if M(i,9)<=0.025 GRD=[GRD 'A'];
elseif M(i,9)>0.025&M(i,9)<=0.05 GRD=[GRD 'B'];
elseif M(i,9)>0.05&M(i,9)<=0.075 GRD=[GRD 'C'];
elseif M(i,9)>0.075&M(i,9)<=0.1 GRD=[GRD 'D'];
elseif M(i,9)>0.1&M(i,9)<=0.125 GRD=[GRD 'E'];
elseif M(i,9)>0.125&M(i,9)<=0.15  GRD=[GRD 'F'];
elseif M(i,9)>0.15&M(i,9)<=0.175 GRD=[GRD 'G'];
elseif M(i,9)>0.175&M(i,9)<=0.2 GRD=[GRD 'H'];
elseif M(i,9)>0.2&M(i,9)<=0.25 GRD=[GRD 'M'];
elseif M(i,9)>0.25&M(i,9)<=0.3 GRD=[GRD 'N'];
elseif M(i,9)>0.3 GRD=[GRD 'P'];
end

%Define guidelines for PATCHING
if M(i,10)<=50 GRD=[GRD 'A'];
elseif M(i,10)>50&M(i,10)<=100 GRD=[GRD 'B'];
elseif M(i,10)>100&M(i,10)<=150 GRD=[GRD 'C'];
elseif M(i,10)>150&M(i,10)<=200 GRD=[GRD 'D'];
elseif M(i,10)>200&M(i,10)<=250 GRD=[GRD 'E'];
elseif M(i,10)>250&M(i,10)<=300 GRD=[GRD 'F'];
elseif M(i,10)>300&M(i,10)<=350 GRD=[GRD 'G'];
elseif M(i,10)>350&M(i,10)<=400 GRD=[GRD 'H'];
elseif M(i,10)>400&M(i,10)<=450 GRD=[GRD 'M'];
elseif M(i,10)>450&M(i,10)<=500 GRD=[GRD 'N'];
elseif M(i,10)>500 GRD=[GRD 'P'];
end

%Define guidelines for APPEARANCE
if M(i,11)<=1 GRD=[GRD 'A'];
elseif M(i,11)>1&M(i,11)<=2 GRD=[GRD 'B'];
elseif M(i,11)>2&M(i,11)<=3 GRD=[GRD 'C'];
elseif M(i,11)>3&M(i,11)<=4 GRD=[GRD 'D'];
elseif M(i,11)>4&M(i,11)<=5 GRD=[GRD 'E'];
elseif M(i,11)>5&M(i,11)<=6 GRD=[GRD 'F'];
elseif M(i,11)>6&M(i,11)<=7 GRD=[GRD 'G'];
elseif M(i,11)>7&M(i,11)<=8 GRD=[GRD 'H'];
```

```
elseif M(i,11)>8&M(i,11)<=9 GRD=[GRD 'M'];
elseif M(i,11)>9&M(i,11)<=10 GRD=[GRD 'N'];
elseif M(i,11)>10 GRD=[GRD 'P'];
end

%Define guidelines for RAVELING/FLUSHING
if M(i,12)<=12 GRD=[GRD 'A'];
elseif M(i,12)==15 GRD=[GRD 'A'];
elseif M(i,12)==13 GRD=[GRD 'B'];
elseif M(i,12)==16 GRD=[GRD 'B'];
elseif M(i,12)==14 GRD=[GRD 'C'];
elseif M(i,12)>=17 GRD=[GRD 'C'];
end

%Define guidelines for SHOULDER CONDITION
if M(i,13)<=19 GRD=[GRD 'A'];
elseif M(i,13)>19&M(i,13)<=20 GRD=[GRD 'B'];
elseif M(i,13)>20&M(i,13)<=21 GRD=[GRD 'C'];
elseif M(i,13)>21&M(i,13)<=22 GRD=[GRD 'D'];
elseif M(i,13)>22&M(i,13)<=23 GRD=[GRD 'E'];
elseif M(i,13)>23&M(i,13)<=24 GRD=[GRD 'F'];
elseif M(i,13)>24&M(i,13)<=25 GRD=[GRD 'G'];
elseif M(i,13)>25 GRD=[GRD 'H'];
end

%Define guidelines for ROUGHNESS
if M(i,14)<=50 GRD=[GRD 'P'];
elseif M(i,14)>50&M(i,14)<=53 GRD=[GRD 'N'];
elseif M(i,14)>53&M(i,14)<=56 GRD=[GRD 'M'];
elseif M(i,14)>56&M(i,14)<=59 GRD=[GRD 'H'];
elseif M(i,14)>59&M(i,14)<=62 GRD=[GRD 'G'];
elseif M(i,14)>62&M(i,14)<=65 GRD=[GRD 'F'];
elseif M(i,14)>65&M(i,14)<=68 GRD=[GRD 'E'];
elseif M(i,14)>68&M(i,14)<=71 GRD=[GRD 'D'];
elseif M(i,14)>71&M(i,14)<=74 GRD=[GRD 'C'];
elseif M(i,14)>74&M(i,14)<=77 GRD=[GRD 'B'];
elseif M(i,14)>77&M(i,14)<=95 GRD=[GRD 'A'];
elseif M(i,14)>95&M(i,14)<=105 GRD=[GRD 'B'];
elseif M(i,14)>105&M(i,14)<=115 GRD=[GRD 'C'];
elseif M(i,14)>115&M(i,14)<=120 GRD=[GRD 'D'];
elseif M(i,14)>120&M(i,14)<=125 GRD=[GRD 'E'];
elseif M(i,14)>125&M(i,14)<=130 GRD=[GRD 'F’];
elseif M(i,14)>130&M(i,14)<=135 GRD=[GRD 'G'];
```

```
    elseif M(i,14)>135&M(i,14)<=140 GRD=[GRD 'H'];
    elseif M(i,14)>140&M(i,14)<=145 GRD=[GRD 'M'];
    elseif M(i,14)>145&M(i,14)<=150 GRD=[GRD 'N'];
    elseif M(i,14)>150 GRD=[GRD 'P'];
    end

    %Define guidelines for SKID
    if M(i,15)>70 GRD=[GRD 'A'];
    elseif M(i,15)>65&M(i,15)<=70 GRD=[GRD 'B'];
    elseif M(i,15)>60&M(i,15)<=65 GRD=[GRD 'C'];
    elseif M(i,15)>55&M(i,15)<=60 GRD=[GRD 'D'];
    elseif M(i,15)>50&M(i,15)<=55 GRD=[GRD 'E'];
    elseif M(i,15)>45&M(i,15)<=50 GRD=[GRD 'F'];
    elseif M(i,15)>40&M(i,15)<=45 GRD=[GRD 'G'];
    elseif M(i,15)>35&M(i,15)<=40 GRD=[GRD 'H'];
    elseif M(i,15)>30&M(i,15)<=35 GRD=[GRD 'M'];
    elseif M(i,15)>25&M(i,15)<=30 GRD=[GRD 'N'];
    elseif M(i,15)<=25 GRD=[GRD 'P'];
    end


%Use assigned grades in array (GRD) in function fun8011b.m to determine (v), the FDI value.
  v=fun8011b(GRD);

%Save FDI (fdi) and index (ndx) for all pavement sections in data base in separate arrays.
  fdi=[fdi;v];
  ndx=[ndx;i];

end

%Save corresponding PSI values from data base in array (psi).
psi=M(:,16);

%Plot FDI versus PSI for all pavement sections within data base.
plot(fdi,psi,'w.')
axis([0 10 0 5])
grid
xlabel('FDI')
ylabel('PSI')
title('FDI vs PSI for sample of 80 pavement sections')
```

```
%Save M, ndx, fdi, and psi matrices as data11b.mat.
save c:\jenifer\data11b M ndx fdi psi
```

```
%Function fun8011b.m calculates the FDI for a single pavement section and returns this value
%(to program GRD8011b.m) as variable (v).

function v=fun8011b(X)

%Define grades for parameter weightings.
[y,A]=lcut(0.01);
[y,B]=lcut(0.25);
[y,C]=lcut(0.5);
[y,D]=lcut(0.75);
[y,E]=lcut(1.0);

%Assign each grade in array (GRD) to its corresponding parameter and go to the appropriate
%function to determine the membership function for each parameter.
X2=X(1);X3=X(2);X4=X(3);X5=X(4);X6=X(5);X7=X(6);
X8=X(7);X9=X(8);X10=X(9);X11=X(10);X12=X(11);X13=X(12);
X14=X(13);X15=X(14);

z=gatrtypb(X2,X3,X4);        x2=z(:,1:2);x3=z(:,3:4);x4=z(:,5:6);
z=lintypb(X5,X6,X7);         x5=z(:,1:2);x6=z(:,3:4);x7=z(:,5:6);
z=sealng(X8);                x8=z;
z=rutdpthb(X9);              x9=z;
z=patchngb(X10);             x10=z;
z=apearncb(X11);             x11=z;
z=flushrav(X12);             x12=z;
z=shouldrb(X13);             x13=z;
z=roghnesb(X14);             x14=z;
z=skidb(X15);                x15=z;

%Define vector (mb) which will contain values of the final overall distress membership function
%for a particular pavement section.
mb=[];

%Calculate the value of membership for all possible extents of distress at all lambda-cut levels.
%There are a total of 100 lambda-cut levels, from 0.001 to 1.0 with a step of 0.01.
for i=1:length(y)
```

```
%Calculate the numerator of the weighted average equation, (J) at a certain lambda-cut level.
  I=find(y==y(i));
  J=mul(x2(I,:),C(I,:))+mul(x3(I,:),D(I,:))+mul(x4(I,:),D(I,:));
  J=J+mul(x5(I,:),C(I,:))+mul(x6(I,:),D(I,:))+mul(x7(I,:),C(I,:));
  J=J+ mul(x8(I,:),B(I,:));
  J=J+ mul(x9(I,:),C(I,:));
  J=J+ mul(x10(I,:),D(I,:));
  J=J+ mul(x11(I,:),B(I,:));
  J=J+ mul(x12(I,:),C(I,:));
  J=J+ mul(x13(I,:),A(I,:));
  J=J+ mul(x14(I,:),D(I,:));
  J=J+ mul(x15(I,:),B(I,:));

%Calculate the denominator of the weighted average equation, (K), at a certain lambda-cut level.
  K=C(I,:)+D(I,:)+D(I,:)+C(I,:)+D(I,:)+C(I,:);
  K=K+B(I,:)+C(I,:)+D(I,:)+B(I,:)+C(I,:)+A(I,:);
  K=K+D(I,:)+B(I,:);

%Determine the value of the overall distress membership function, (J), of a particular pavement
%section at a certain lambda-cut and store it in matrix (mb), which contains all values for the
%final membership function.
  J=mul(J,(1./K));
  mb=[mb;J];
end

%Store the values of the final membership function in variable (z), a 100x2 matrix.  This
%includes values at every lambda-cut level.
z=mb;

%(z1) is a 200x1 array containing the values from (z), which are the values of extent of distress
%of the final membership function, within the universe of extent of distress.
z1=[];z1=z(:,1);
for i=100:-1:1
  z1=[z1;z(i,2)];
end

%(y1) is a 200x1 array containing the values from (y), which are the lambda-cut levels.
y=y';y1=[];y1=y;
for i=100:-1:1
  y1=[y1;y(i)];
end
```

```
%(y2) is a 200x1 array containing y1(i)*z1(i) for all i from 1 to 200.
y2=[];
for i=1:200
  y2=[y2;y1(i)*z1(i)];
end

%Calculate the FDI by center of area defuzzification method and return FDI in variable (v).
num=trapz(y2,z1);denom=trapz(y1,z1);
v=(num/denom)*10;
```

```
%Function lcut.m performs the lambda-cuts on membership functions for each parameter and
%corresponding weightings, where variable c represents the center of the original membership
%function representing a particular grade.

function [y,z]=lcut(c)

y=[];z=[];
x=0:0.01:1.0;

%(a) and (b) are constants which determine the shape of the membership functions.
a=0.01;b=1.0;

%Determines the nonlinear Gaussian bell-shaped membership function describing the
%association between specific parameter values and their degrees of membership, given
%variables (a), (b), and (c).
y=gbellmf(x,[a,b,c]);

%Perform the lambda-cut operation for the derived membership function.  Lambda levels range
%from 0 (in this case 0.001) to 1 with a step of 0.01.
for cut=0.001:0.01:1

%Given constants (a) and (b) and lambda-cut level (cut), determine the corresponding parameter
%value.  (x2) is the right-hand side parameter value of the membership function.
  x2=c+(a*(((1/cut)-1)^(1/(2*b))));

%Determine (x1), which is the left-hand side parameter value of the membership function at a
%particular lambda-cut level.  The defined membership functions are symmetrical, so (xx) is the
%center of the membership function, (xy) is the distance from the center to the right-hand side
%parameter value, and (x1) is the left-hand side parameter value, determined by finding the
%value at the same distance from the center of the membership curve as distance (xy).
  xx=x(find(y==max(y)));
```

```
xy=x2-xx;
x1=xx-xy;

%Normalization - minimum parameter value on left side is 0.
if x1<0
  x1=0;
end

%Normalization - maximum parameter value on right side is 1.
if x2>1
  x2=1;
end

%(z) is a 100x2 matrix which contains the overall condition values for the final membership
%function at each level of lambda.
z=[z;x1 x2];
end

%(y) is a 100x1 array containing all of the lambda-cut levels used, from 0 to 1.0.
y=0.001:0.01:1;
```

```
%Function gatrtypb.m inputs assigned membership grades for parameters alligator cracking type,
alligator cracking severity, and alligator cracking extent, respectively. It then calculates each
corresponding membership function and returns (z), consisting of membership function values
for all parameters.

function z=gatrtypb(X1,X2,X3)

%Defines membership function for alligator cracking type depending on grade assigned in
GRD8011b.m.
[y,A]=lcut(0);
[y,B]=lcut(0.25);
[y,C]=lcut(0.5);
[y,D]=lcut(0.75);
[y,E]=lcut(1.0);

x1=eval(X1);

%Defines membership functions for alligator cracking severity and extent depending on grades
%assigned in GRD8011b.m.
[y,A]=lcut(0);
```

```
[y,B]=lcut(0.1);
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);

x2=eval(X2); x3=eval(X3);
```
z=[x1 x2 x3];

%Function lintypb.m inputs assigned membership grades for parameters linear cracking type, linear cracking severity, and linear cracking extent, respectively. It then calculates each corresponding membership function and returns (z), consisting of membership function values for all parameters.

function z=lintypb(X1,X2,X3)

```
%Defines membership function for linear cracking type depending on grade assigned in
%GRD8011b.m.
[y,A]=lcut(0);
[y,B]=lcut((1/3));
[y,C]=lcut((2/3));
[y,D]=lcut(1.0);

x1=eval(X1);

%Defines membership functions for linear cracking severity and extent depending on grades
%assigned in GRD8011b.m.
[y,A]=lcut(0);
[y,B]=lcut(0.1);
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
```

```
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);

x2=eval(X2); x3=eval(X3);
```
z=[x1 x2 x3];

%Function sealng.m uses the grade assignment for the parameter sealing. It calculates a membership function according to this grade, and returns the values of the membership function in (z).

function z=sealng(X1)

```
[y,A]=lcut(0);
[y,B]=lcut(0.5);
[y,C]=lcut(1.0);
```

z=eval(X1);

%Function rutdpthb.m inputs assigned membership grades for the parameter rut depth. It then calculates the corresponding membership function and returns (z), consisting of membership function values at all levels of lambda for the parameter rut depth.

function z=rutdpthb(X1)

```
[y,A]=lcut(0);
[y,B]=lcut(0.1);
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);
```

z=eval(X1);

%Function patchngb.m inputs assigned membership grades for the parameter patching. It then calculates the corresponding membership function and returns (z), consisting of membership function values at all levels of lambda for the parameter patching.

```
function z=patchngb(X1)

[y,A]=lcut(0);
[y,B]=lcut(0.1);
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);


z=eval(X1);
```

%Function apearnceb.m inputs assigned membership grades for the parameter appearance. It then calculates the corresponding membership function and returns (z), consisting of membership function values at all levels of lambda for the parameter appearance.

```
function z=apearncb(X1)

[y,A]=lcut(0);
[y,B]=lcut(0.1);
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);

z=eval(X1);
```

%Function flushrav.m inputs assigned membership grades for the parameter flushing/raveling. It then calculates the corresponding membership function and returns (z), consisting of membership function values at all levels of lambda for the parameter flushing/raveling.

```
function z=flushrav(X1)

[y,A]=lcut(0);
[y,B]=lcut(0.5);
[y,C]=lcut(1.0);

z=eval(X1);
```

%Function shouldrb.m inputs assigned membership grades for the parameter shoulder condition. It then calculates the corresponding membership function and returns (z), consisting of membership function values at all levels of lambda for the parameter shoulder condition.

```
function z=shouldrb(X1)

[y,A]=lcut(0);
[y,B]=lcut((1/7));
[y,C]=lcut((2/7));
[y,D]=lcut((3/7));
[y,E]=lcut((4/7));
[y,F]=lcut((5/7));
[y,G]=lcut((6/7));
[y,H]=lcut(1.0);

z=eval(X1);
```

%Function roghnesb.m inputs assigned membership grades for the parameter roughness. It then calculates the corresponding membership function and returns (z), consisting of membership function values at all levels of lambda for the parameter roughness.

```
function z=roghnesb(X1)

[y,A]=lcut(0);
[y,B]=lcut(0.1);
```

```
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);

z=eval(X1);
```

```
%Function skidb.m inputs assigned membership grades for the parameter skid number. It then
calculates the corresponding membership function and returns (z), consisting of membership
function values at all levels of lambda for the parameter skid number.

function z=skidb(X1)

[y,A]=lcut(0);
[y,B]=lcut(0.1);
[y,C]=lcut(0.2);
[y,D]=lcut(0.3);
[y,E]=lcut(0.4);
[y,F]=lcut(0.5);
[y,G]=lcut(0.6);
[y,H]=lcut(0.7);
[y,M]=lcut(0.8);
[y,N]=lcut(0.9);
[y,P]=lcut(1.0);

z=eval(X1);
```

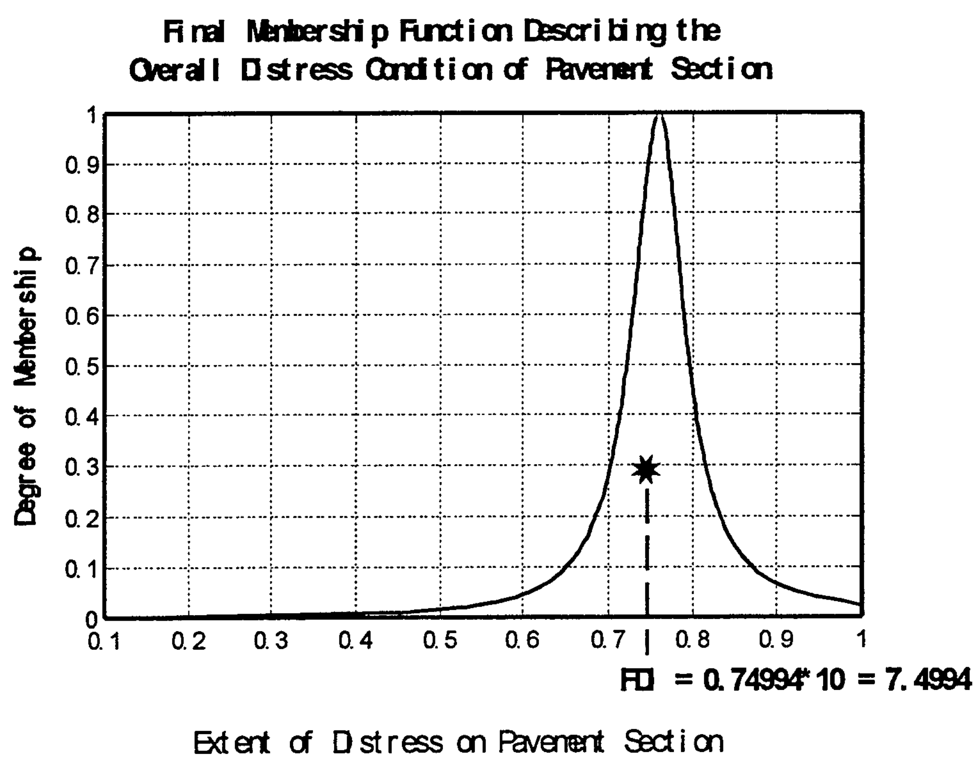
```
%The function mul.m performs interval multiplication on intervals (a) and (b) and returns the
%result in variable (y).

function y=mul(a,b)

a=a(:);b=b(:);
c=[a(1)*b;a(2)*b];
```

```
c=c';
y=[min(c) max(c)];
```

PROGRAM INPUT: (bottom row of data)

	all type	all sev	all ext	lin type	lin sev	lin ext	seal	rut	patch	appr	rav/fl	shldr	rough	skid	PSI
Data base	C	0.38	300	C	0.38	200	No	0.61	0	8	18	25	255	24	0.77
Program Input	4	0.38	300	4	0.38	200	3	0.61	0	8	18	25	255	24	0.77

PROGRAM OUTPUT: FDI = 7.4994



APPENDIX C

FUZZY SETS AND MEMBERSHIP FUNCTIONS

FUZZY SETS AND MEMBERSHIP FUNCTIONS

Conventional, or "classical," set theory is binary: an element either belongs to a specific set or does not belong to the set. The characteristic function f_a is represented as:

$f_a =$ 1 if *a* belongs to set A

0 if *a* does not belong to set A

A "fuzzy" set is a set without a crisp, clearly defined boundary. It contains elements with only a partial degree of membership. Its membership function extends the range of membership of the characteristic function f_a, and is defined on the interval [0,1]. Therefore, a fuzzy set may contain an element that belongs to the set with only a partial degree of membership. For example, suppose x1, x2, and x3 represent the parameters alligator cracking, traffic loading, and precipitation, respectively. A fuzzy set A, representing a particular pavement section, may then be described by the following:

$$A = \frac{0.2}{x1} + \frac{0.8}{x2} + \frac{0.5}{x3}$$

where alligator cracking has a degree of membership of 0.2 to the pavement section, traffic loading has a degree of membership of 0.8 to the pavement section, and precipitation has a degree of membership of 0.5 to the pavement section. The symbol (-) does not represent division, but instead is used to separate the parameter (the denominator) from its degree of membership (the numerator). Similarly, the symbol (+) does not represent addition, but is a notation for function-theoretic union, which is read as "and."

A membership function is a unique relation between specific parameter values and their degree of "belongingness" to a set that describes the physical aspect of this parameter. For example, it is difficult to clearly identify the boundaries of the set of heights which define a "tall" person. The transition between membership and nonmembership to this set is gradual. "Tall" may be defined as a height of 6 ft. or greater. However, a person who is 6 ft., 5 in. may not consider a 6 ft. individual to be "tall." Since different individuals have different perceptions when specifying these boundaries, it is impossible to define the set "tall" in this manner. Fortunately, this parameter can be uniquely characterized through the use of fuzzy sets. An individual with a modest height may be considered as "really not very tall at all," and that person's height would belong to the fuzzy set "tall" with a degree of 0.20. Similarly, an individual with ample height may be considered as "definitely a tall person," and the corresponding height would belong to the fuzzy set "tall" with a degree of membership of 0.90.

The same concept can be applied when describing characteristics of pavement sections. For example, it is difficult to quantify the amount of alligator cracking necessary in order for a pavement section to be considered as having the characteristic "alligator cracking." Fuzzy sets can be used to describe this parameter in the same manner as above for the set "tall." A pavement section containing a very small amount of alligator cracking (Type B alligator cracking) may belong to the set "alligator cracking" with a degree of membership of 0.2. A pavement consisting almost entirely of alligator cracking (Type D alligator cracking) may belong to that set with a degree of membership of 0.90.

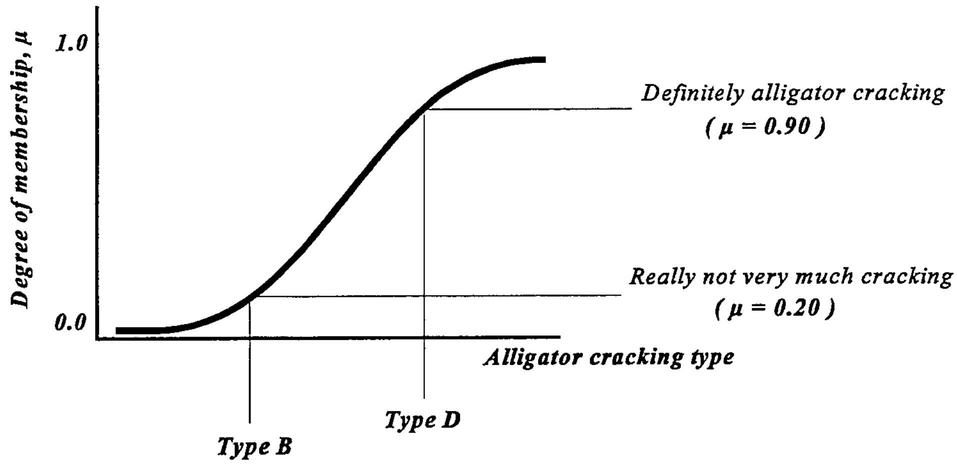


Figure C1 Continuous Membership Function for Alligator Cracking Type.

There are numerous alternatives for membership function generation found in the literature, including exemplification, rank ordering, neural networks, and inductive reasoning (Tee et al. 1989, Ross 1995). Exemplification is a method of membership function generation in which a number of experts are asked whether or not a certain element belongs to an ill-defined set. Some examples of responses include "true," "false," "more or less true," and "more or less false." A pre-determined numerical value is associated with each response. The membership function for the element is the average of the numerical values. The advantage of this approach is that the membership function is directly determined from the responses, however, the disadvantage is that it is cumbersome.

Rank ordering is another method of assigning membership values to fuzzy variables where preferences are determined by pairwise comparisons. The preferences are based on the opinions of an individual, committee, poll, etc. Pairwise comparisons are used to determine the ordering of membership.

Membership functions can also be generated through the use of neural networks. Data is divided into two sets: a training-data set and a checking-data set. The training-data set is used to train the neural network. The input data, such as alligator cracking, linear cracking, and patching, are fed into the network. The result is the network output; for example, an overall condition such as Present Serviceability Index (PSI). After the network is trained, meaning it performs under a standard error level, it is tested using the checking data set to determine its accuracy. Although neural networks have been proven to show very powerful results, there are several disadvantages to this approach. For example, the architecture of a neural network model is determined by trial and error. Also, the models require a large data base and a convergence algorithm, which can be computationally very expensive.

Inductive reasoning is a method of automatic membership function generation used particularly with static parameters. Based on the entropy minimization principle, this method minimizes the randomness between different clusters of classes by utilizing the actual data base. A membership function based on the data base appears to be a promising concept: however, this would require a data base which includes data from all over the globe, and not just a single region or state. This makes data collection difficult, since all states have unique data collection methods and data bases. It should be noted that this method is not appropriate for dynamic parameters. If a parameter continuously changes over time, such as the increase in traffic loading over the years, the corresponding membership function will change with time since it is developed directly from the data base.

APPENDIX D

PAVEMENT SECTION ANALYSIS OF FDI AND PSI OVER TIME

Table D1 State Route CHSR722 00900W

PAVEMENT SECTION - STATE ROUTE CHSR722 00900W																						
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980	D	2.5	1000		0	0	N	0.94	0	10	0	0	84	0	1.13	5.1539	45	60	0	0	0	R
1981	D	3.13	1000		0	0		0	0	2	17	25	77	69	2.47	3.6524	25	60	10.35	50	183	O
1982	D	3.13	1000		0	0	N	0.52	12	7	19	25	83	69	1.98	5.3189	15	60	10.35	50	183	R
1983	D	0.13	1000		0	0	N	0.08	0	9	19	25	77	69	1.98	4.6258	20	60	10.35	50	183	R
1984		0	0	C	0.25	400	N	0	0	8	19	25	80	69	2.82	4.1373	25	60	10.35	50	183	R
1986	C	0.5	1000		0	0	N	0	0	8	19	25	194	69	1.29	4.8449	22	9	10.35	50	183	R
1987	C	0.25	1000		0	0	N	0.02	0	7	19	25	99	69	2.09	4.3254	25	8	10.35	50	183	R
1988		0	0	C	0.02	200	N	0	0	4	18	22	90	69	2.78	2.7645	30	8	10.35	50	183	O
1989	C	0.01	1000		0	0	N	0	0	8	14	25	179	69	2.02	4.1053	30	8	10.35	50	183	O

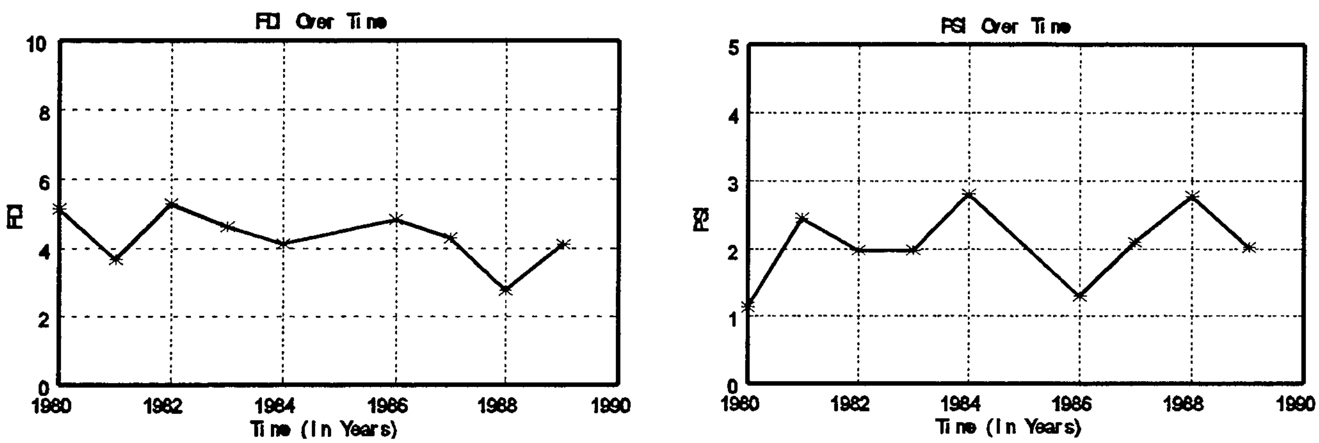


Figure D1 State Route CHSR722 00900W

Remarks:

The graphs above show that for every increase in FDI over a year's time, there is a decrease in PSI. This means that every year the FDI shows deterioration of this pavement section, the PSI shows deterioration as well. However, there is one discrepancy in the representation of pavement improvement. The PSI remains the same from 1982 to 1983, while the FDI decreases slightly, representing a small improvement in pavement distress condition. The table above suggests the overall improvement may have come from improvements in alligator cracking severity, rut-depth, or patching: all of which were initially assigned maximum importance weightings.

Table D2 US Route CHUS050 01600W

PAVEMENT SECTION - US ROUTE CHUS050 01600W																						
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLD R	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	B	2.5	9	N	5.52	0	13	0	23	88	0	0.1	4.3904	4515	11	0	0	0	R
1981		0	0	B	3.13	20	N	1.98	0	13	14	21	107	57	0.1	4.3952	2298	13	5.55	38	119	R
1982	D	2.5	810		0	0	N	0.84	0	8	18	22	90	57	1.39	5.3118	2495	13	5.55	38	119	R
1983		0	0		0	0		0.04	0	1	0	20	50	57	1.39	1.2743	2353	13	5.55	38	119	R
1984		0	0		0	0		0	0	1	17	20	71	57	3.54	1.0805	2415	13	5.55	38	119	M
1986		0	0		0	0		0.02	0	1	0	20	78	57	3.42	0.5485	3315	12	5.55	38	119	N
1987		0	0		0	0		0	0	1	0	20	65	57	3.69	0.4844	3385	12	5.55	38	119	N
1988		0	0	C	0	150	Y	0	0	4	17	21	68	57	3.32	2.4064	3180	13	5.55	38	119	M
1989		0	0	B	0.04	15	N	0	0	8	14	21	136	57	3.07	2.5835	3477	13	5.55	38	119	M

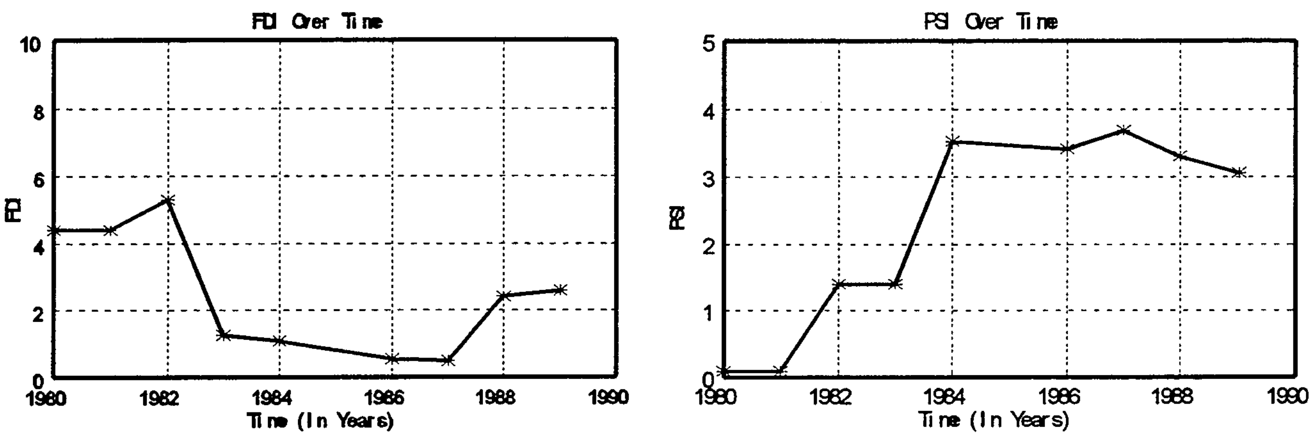


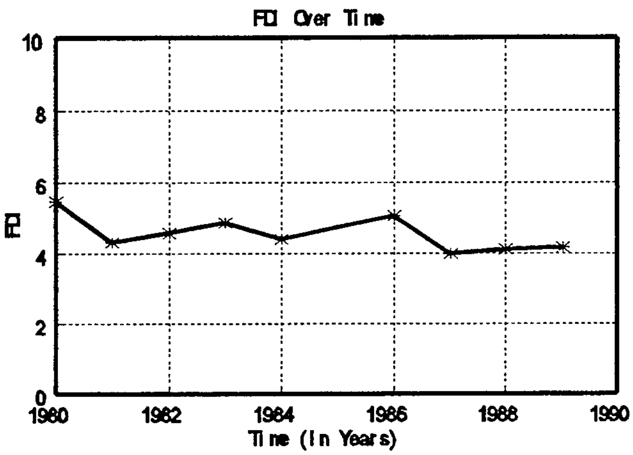
Figure D2 US Route CHUS050 01600W

Remarks:

The first observation to notice on the graphs above is that the PSI is 0.1 for both years 1980 and 1981. This is an extremely poor distress rating, yet the table of measurements shows good to medium conditions for all parameters. Therefore, the FDI ratings of 4.3904 and 4.3952 correspond to the actual conditions more accurately. The next discrepancy is found between years 1981 and 1982, where the FDI shows deterioration and the PSI shows improvement in pavement condition. The table shows sharp declines in alligator cracking type, severity, and extent, as well as declines in raveling/flushing and shoulder condition. Although several parameters do show slight improvements in condition, the FDI appears to be a more accurate representation of the actual distress condition since a small amount of deterioration is accounted for, while a significant improvement in pavement condition does not correspond to the actual measurements. The final major difference between FDI and PSI behavior is found from year 1982 to 1983. The FDI improves while the PSI remains the same. However, each parameter in the table shows an improvement in condition which justifies the improved distress rating given by the FDI.

Table D3 Frontage Road CLFR444 00090N

PAVEMENT SECTION - FRONTAGE ROAD CLFR444 00090N																					
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980	B	3.13	50	B	3.13	267	N	1.88	0	6	0	22	107	0	0.1	5.4737	0	0	0	0	0	R
1981		0	0	B	3.13	237	N	0.83	0	8	0	22	67	0	3.03	4.3040	75	3	3.97	18	43	O
1982		0	0	C	3.75	250	N	0.63	0	8	0	22	99	0	2.03	4.5641	75	3	3.97	18	43	O
1983		0	0	C	0.38	510	N	0.13	0	8	0	24	118	0	2.03	4.8645	90	3	3.97	18	43	O
1984		0	0	C	0.38	360	N	0.06	0	4	0	25	161	0	1.89	4.3851	90	3	3.97	18	43	R
1986		0	0	C	0.38	510	N	0.17	0	8	0	24	151	0	1.96	5.0871	45	3	3.97	18	43	R
1987		0	0	C	0.25	250	N	0	0	8	0	24	105	0	2.57	3.9894	45	3	3.97	18	43	M
1988	D	0.03	1000		0	0	N	0	0	8	0	25	77	0	1.78	4.1102	45	2	3.97	18	43	R
1989	D	0.03	1000		0	0		0	0	8	0	25	377	0	1.38	4.1774	45	2	3.97	18	43	R



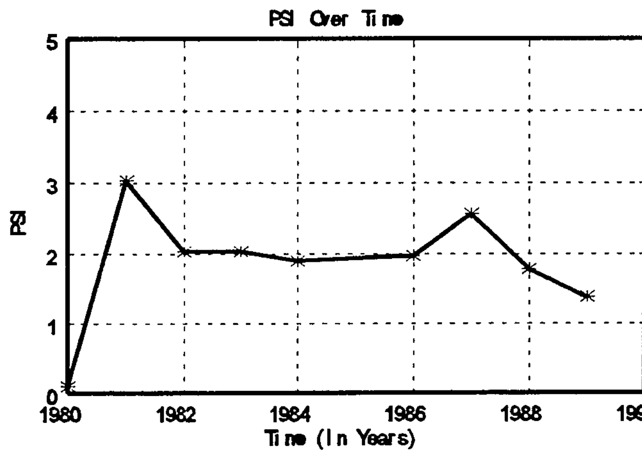


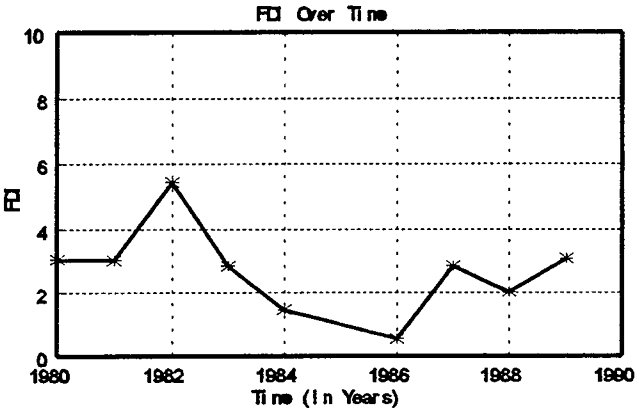
Figure D3 Frontage Road CLFR444 00090N

Remarks:

The PSI rating of 0.1 for year 1980 is not justified by the measurements given in the table. The measurements show average conditions, making the FDI rating of 5.4737 a more acceptable representation of the actual distress. There are three minor discrepancies in FDI and PSI behavior; however, careful observation of the measurements given in the table reveal that the FDI describes pavement distress conditions more accurately than the PSI.

Table D4 State Route DOSR028 00123S

PAVEMENT SECTION - STATE ROUTE DOSR028 00123S																							
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	B	6.25	22		1.46	0	3	0	21	99	0	0.1	3.0392	4900	5	0	0	0	R
1981		0	0	B	0	51	Y	3.44	0	3	18	20	190	60	0.1	3.0310	2500	7	19.25	65	158	R
1982	D	9.38	1000		0	0	N	5.63	0	5	18	23	198	60	0.1	5.4641	2840	7	19.25	65	158	R
1983		0	0		0	0	Y	0	0	11	117	20	444	60	0.1	2.8467	2617	7	19.25	65	158	R
1984		0	0		0	0		0	0	1	17	22	136	60	2.68	1.4535	2312	7	19.25	65	158	M
1986		0	0		0	0		0	0	1	0	20	79	60	3.42	0.5485	2360	6	19.25	65	158	N
1987	A	0.25	33		0	0	N	0.15	0	2	14	20	62	60	3.92	2.8583	2430	6	19.25	65	158	M
1988		0	0	C	0.02	140	N	0	0	4	0	20	68	58	3.53	2.0240	2395	6	19.25	65	158	M
1989	B	0.02	400		0	0	N	0	0	6	14	20	108	58	2.79	3.0760	2395	12	19.25	65	158	R



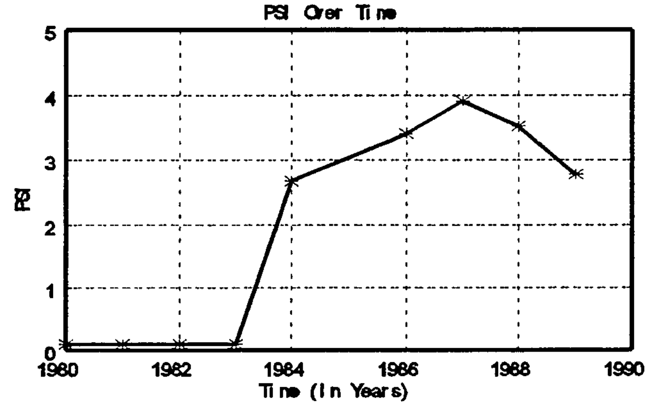


Figure D4 State Route DOSR028 00123S

Remarks:

The PSI rating of 0.1 for years 1980, 1981, 1982, and 1983 does not reflect the measurements given in the table, whereas the FDI is very sensitive to the actual measurements shown above. There is a contradiction of FDI and PSI ratings between the years 1986 and 1987: the FDI shows pavement deterioration while the PSI shows an improvement in pavement condition. Careful observation of the table shows a decline in the parameters alligator cracking type, severity, and extent with no sealing, rutting, appearance, raveling/flushing, and roughness. Also note that the maintenance column shows no corrective measure is applied to the pavement section in 1986: therefore, the distress rating should not show an improvement in the condition of the pavement section in year 1987. The discrepancy of rating indices for years 1987 - 1988 may be caused by the equation used to calculate the PSI. For example, the FDI shows an improvement in pavement condition while the PSI shows a decline in pavement condition. Notice that alligator cracking type, severity, and extent, rutting, and raveling/flushing all improve over this time span. However, linear cracking type, severity, and extent, and appearance decline. Since these parameters plus roughness and patching are the only variables in the PSI equation, PSI shows a decrease. However, other parameters may influence the deterioration of the pavement section; therefore the addition of all significant parameters results in an overall decrease in pavement distress as represented in the FDI rating.

Table D5 Interstate Route ELIR080 06000E

PAVEMENT SECTION - INTERSTATE ROUTE ELIR080 06000E																					
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	B	0	129	N	3.33	0	13	0	21	96	0	0.1	3.6874	3650	34	0	0	0	R
1981		0	0	B	2.5	20	N	1.05	0	3	17	21	106	47	1.33	3.9520	1862	43	7.95	56	216	R
1982		0	0	C	3.13	42	N	1.77	0	3	18	21	104	47	0.1	4.1454	2045	43	7.95	56	216	R
1983		0	0		0	0		0.02	0	1	0	20	50	47	0.1	1.3656	1870	43	7.95	56	216	R
1984		0	0		0	0		0	0	0	0	0	100	47	3.04	0.6332	1802	43	7.95	56	216	M
1986		0	0	B	0.25	20	N	0	0	4	0	21	72	47	3.41	2.4844	2005	40	7.95	56	216	N
1987		0	0	C	0.13	135	Y	0.13	0	4	17	21	67	47	3.32	3.2373	1992	40	7.95	56	216	M
1988	A	0.05	100	C	0.04	150	N	0	0	5	0	21	72	47	3.07	2.7036	2257	40	7.95	56	216	M
1989		0	0	B	0.04	50	N	0	0	3	0	21	122	47	3.09	2.0614	2535	40	7.95	56	216	M

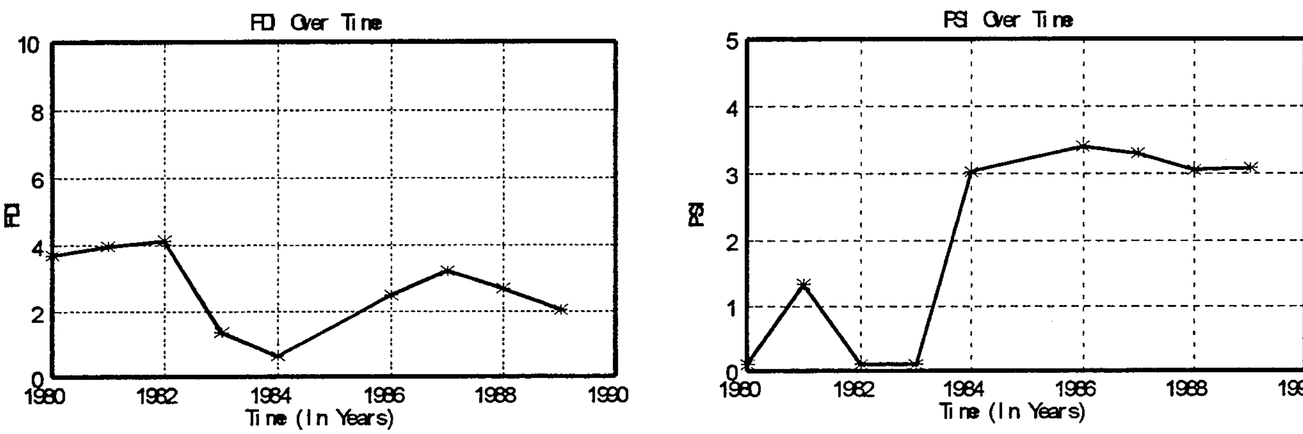


Figure D5 Interstate Route ELIR080 06000E

Remarks:

The PSI values of 0.1 for years 1980, 1982, and 1983 do not reflect the condition data given in the table above: however, the FDI values for these years appear to be acceptable according to the parameter measurements. The PSI improves from year 1984 to 1986: however, the table shows decreases in linear cracking, appearance, shoulder condition, and roughness. Therefore, the deterioration reflected in the change of the FDI value is a more reasonable distress behavior of the pavement section. Both indices for year 1987 show deterioration from the previous year: a logical result since no corrective measure was applied to the pavement in 1986. For 1987-1988, the FDI rating shows improvement while the PSI rating shows deterioration. Notice that linear cracking severity and extent improve, as well as rutting, raveling/flushing, and roughness. There is a decline in condition for alligator cracking and appearance. The equation for calculating the PSI includes only the parameters cracking, patching, and roughness. Since alligator cracking became significantly worse over the year, the PSI shows a decline in the overall condition, and does not consider the affects of other significant parameters. The FDI considers all condition parameters, and the result in this case is an overall increase in distress condition.

Table D6 Interstate Route ELIR080 06100W

PAVEMENT SECTION - INTERSTATE ROUTE ELIR080 06100W																						
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	B	7.5	23	N	2.71	0	13	0	20	74	0	0.1	4.0880	3650	34	0	0	0	R
1981		0	0	C	1.25	31	N	0.31	0	4	18	22	75	44	3.11	4.2325	1862	43	7.95	56	216	M
1982		0	0	C	3.13	45	N	0.83	0	3	17	21	73	44	2.38	4.0796	2045	43	7.95	56	216	O
1983		0	0		0	0		0	0	1	0	20	93	44	2.38	0.7756	1870	43	7.95	56	216	O
1984		0	0		0	0		0	0	0	0	0	66	44	3.69	0.6448	1802	43	7.95	56	216	N
1986		0	0	C	0	90	Y	0	0	4	0	21	63	44	3.6	1.9663	2005	40	7.95	56	216	N
1987		0	0	C	0.13	123	Y	0.13	0	4	17	23	58	44	3.76	3.4675	1992	40	7.95	56	216	M
1988	A	0.04	100	B	0.05	40	N	0	0	5	0	21	70	51	3.32	2.3051	2257	40	7.95	56	216	M
1989		0	0	B	0.05	30	N	0	0	3	0	21	108	51	3.2	1.9855	2535	40	7.95	56	216	M

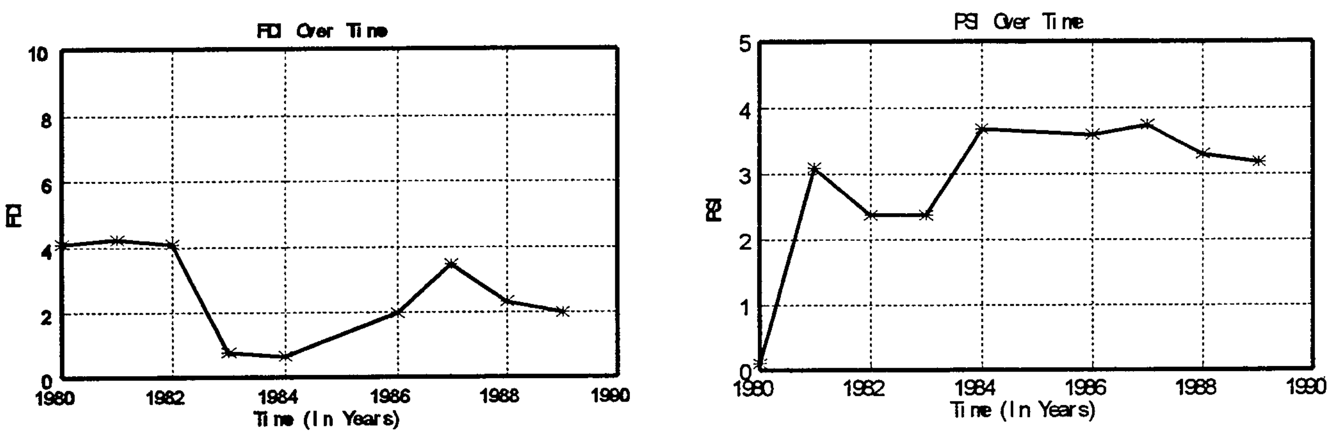


Figure D6 Interstate Route ELIR080 06100W

Remarks:

The data in the table above shows average conditions for year 1980; therefore an extremely low PSI value of 0.1 is not an accurate rating for the distress of this pavement section. There is a discrepancy between FDI and PSI for years 1981-1982, where the FDI shows a slight improvement in pavement condition while the PSI shows a significant amount of deterioration. The table reveals a decline in linear cracking severity and extent, although the rating of Type C remains the same. There is a very slight decline in roughness, and rutting also declines, however, appearance, raveling/flushing, and shoulder condition all show an improvement. The FDI measure considers all of these measures, and is more sensitive to the overall distress condition. Years 1986 through 1989 also show discrepancies in distress conditions ratings between the FDI and PSI. Careful observation of the table and the measurements recorded for each parameter reveal that the FDI ratings yield more accurate and sensitive measurements for the overall distress of the pavement section based on the given data.

Table D7 US Route HUUS095 00100N

PAVEMENT SECTION - US ROUTE HUUS095 00100N																					
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980	B	1.25	210	C	2.5	70	N	2.29	0	7	0	21	81	0	0.1	5.6068	4755	12	0	0	0	R
1981	D	5	1000		0	0	N	1.77	10	8	0	22	161	51	0.1	5.0122	2256	10	6.65	41	154	R
1982	D	6.25	1000		0	0	N	2.71	0	9	0	22	131	51	0.1	5.0123	1045	26	6.65	41	154	R
1983		0	0		0	0		0	0	1	0	20	71	51	0.1	0.5600	962	26	6.65	41	154	R
1984		0	0		0	0		0.13	0	1	14	20	50	51	4.43	2.2268	1006	25	6.65	41	154	N
1986		0	0		0	0		0	0	14	14	20	259	51	1.97	2.4847	3975	8	6.65	41	154	O
1987		0	0		0	0	N	0	0	1	0	20	89	51	3.42	1.2211	2520	10	6.65	41	154	N
1988		0	0	B	0.01	3	N	0	0	1	15	20	108	35	3.06	2.0075	2695	10	6.65	41	154	M
1989		0	0	B	0.01	12	N	0	0	3	14	21	236	35	2.62	3.2073	4505	10	6.65	41	154	M

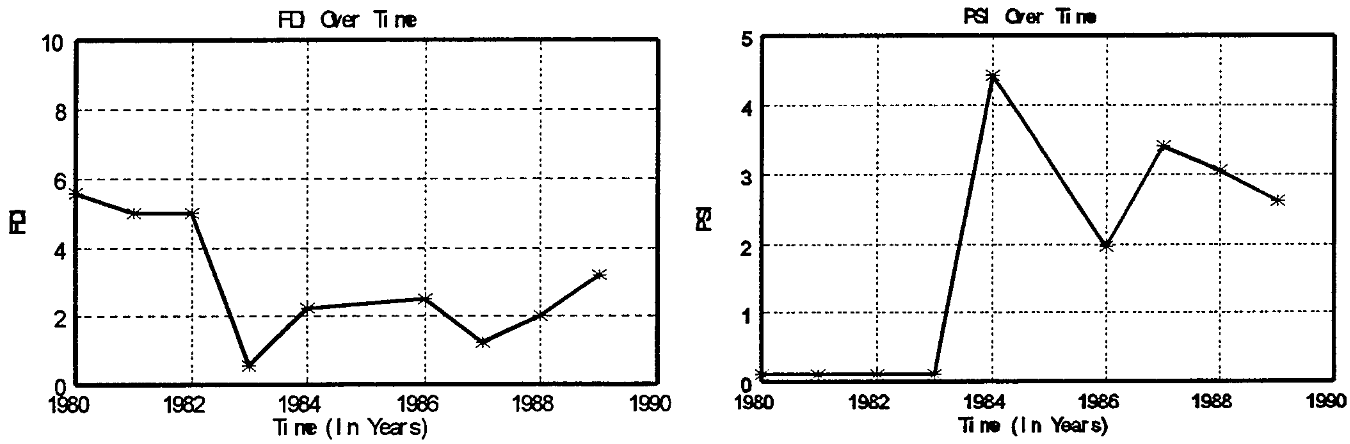


Figure D7 US Route HUUS095 00100N

Remarks:

The PSI values for years 1980, 1981, 1982, and 1983 are all recorded as 0.1, which do not reflect the measurements provided in the table. In particular, the pavement section appears to be in excellent condition in year 1983, which is reflected in the FDI value. It is clear that a very poor PSI rating of 0.1 is incorrect. Otherwise, both indices reflect similar behavior of pavement distress over the years, including indicating pavement deterioration over years which no corrective measures were taken to improve conditions.

Table D8 Frontage Road LAFR402 01700W

PAVEMENT SECTION - FRONTAGE ROAD LAFR402 01700W																						
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECIP	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0		0	0	N	2.81	0	1	0	20	67	0	0.1	2.2696	0	0	0	0	0	R
1981		0	0		0	0	N	1.77	0	1	17	23	113	50	0.1	2.8776	80	10	6.25	50	230	R
1982		0	0		0	0		2.09	0	13	17	22	94	50	0.1	2.8606	112	10	6.25	50	230	R
1983	B	0.38	236		0	0	N	0.38	0	5	18	22	91	50	0.1	4.4219	120	10	6.25	50	230	R
1984		0	0		0	0		0.09	0	1	17	25	125	50	2.72	1.9629	70	10	6.25	50	230	M
1986		0	0	C	0.25	90	N	0.13	0	4	14	25	141	50	2.28	4.2078	35	10	6.25	50	230	M
1987		0	0		0	0	N	0.17	0	1	17	21	78	50	3.27	2.3852	50	10	6.25	50	230	M
1988	A	0.02	150		0	0	N	0	0	7	14	22	93	50	2.24	2.8162	25	10	6.25	50	230	M
1989		0	0	B	0.01	10	Y	0	0	12	16	21	236	50	2.1	2.9750	25	10	6.25	50	230	O

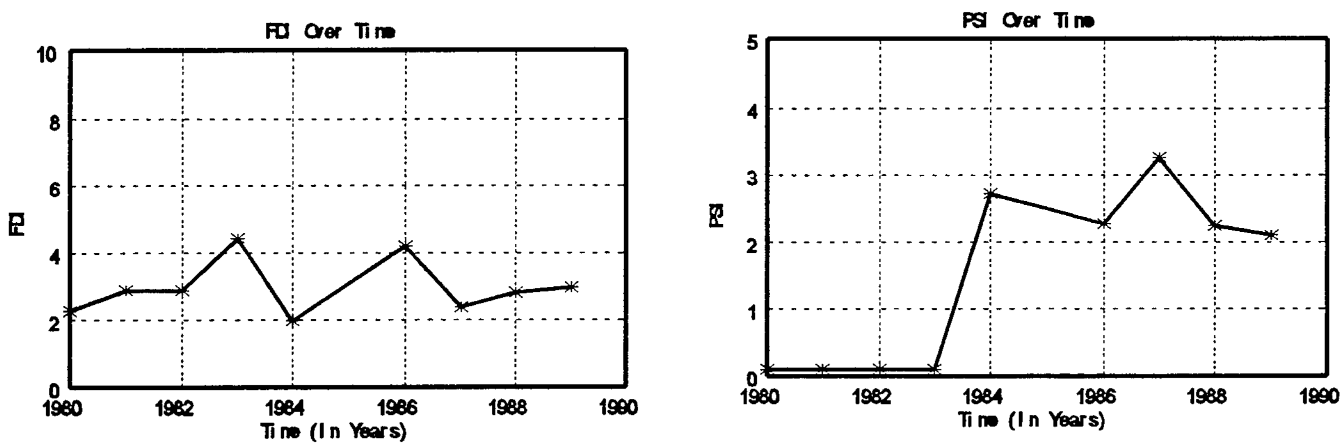


Figure D8 Frontage Road LAFR402 01700W

Remarks:

The PSI value of 0.1 for years 1980, 1981, 1982, and 1983 are inaccurate measures of the data provided in the table. Although the pavement section is not in perfect condition, the parameter measurements indicate better-than-average conditions, as reflected in the FDI ratings. For each year after 1983, the FDI and PSI values show similar patterns of overall distress for this pavement section.

Table D9 US Route LYUS095A01800S

PAVEMENT SECTION - US ROUTE LYUS095A01800S																					
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	C	2.5	356	N	0.83	0	3	0	21	90	0	1.68	4.3160	2015	8	0	0	0	R
1981	D	3.13	1000		0	0	N	1.88	0	9	17	21	90	58	0.1	5.3114	1002	10	6.65	41	154	R
1982	D	3.13	1000		0	0	N	1.77	0	8	14	21	91	58	0.1	5.2346	937	10	6.65	41	154	R
1983	D	0.25	950		0	0		0	0	9	0	22	99	58	0.1	3.3629	912	10	6.65	41	154	R
1984		0	0		0	0		0	0	0	0	0	89	58	3.31	0.4820	983	10	6.65	41	154	M
1986		0	0		0	0		0	0	1	0	20	71	58	3.54	0.4844	1175	10	6.65	41	154	N
1987		0	0	C	0.13	35	N	0	0	4	0	21	66	58	3.52	2.3142	1267	10	6.65	41	154	N
1988		0	0	C	0	150	Y	0	0	4	0	20	67	51	3.18	1.8023	785	13	6.65	41	154	N
1989		0	0	C	0.02	510	Y	0	0	4	0	21	122	51	2.63	2.5682	882	13	6.65	41	154	O

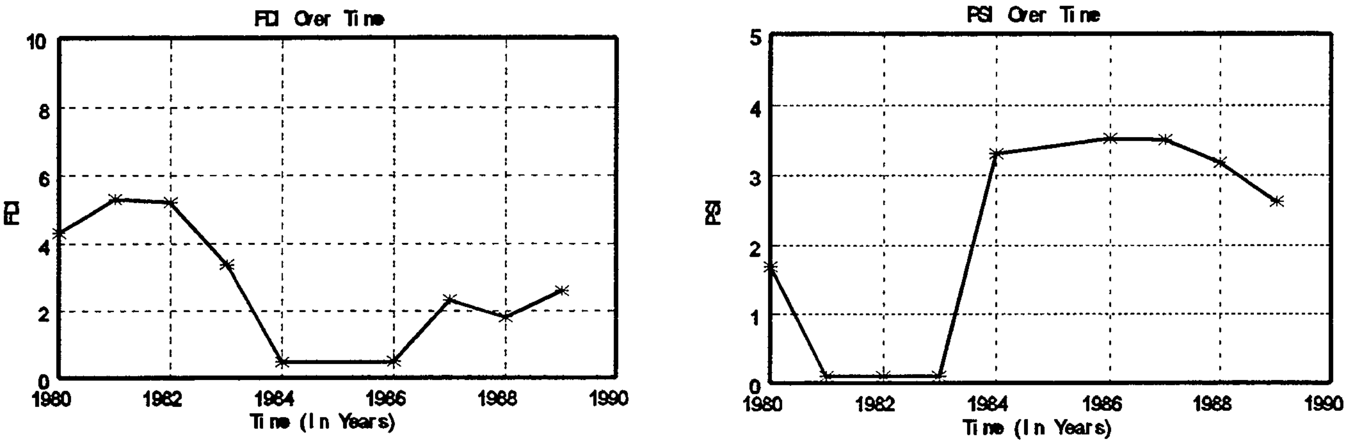


Figure D9 US Route LYUS095A01800S

Remarks:

The data in the table above shows average or less than average distress conditions for years 1981, 1982, and 1983, and the PSI value of 0.1 is too low of a rating to accurately describe the overall distress conditions for this pavement section. The FDI and PSI ratings are inconsistent over years 1986-1987, where the FDI gets significantly worse while the PSI shows only a slight decline in pavement condition. The table shows a decline in linear cracking type, severity, and extent, appearance, shoulder condition, and roughness, justifying the more significant change in the FDI value. Between 1987 and 1988, linear cracking severity improves while the extent gets worse, the cracking is sealed, and shoulder condition and roughness improve slightly. This accounts for the improvement in FDI over this time period. Notice that the maintenance column shows no corrective measures were taken during years 1986, 1987, and 1988. Therefore, any increase in distress condition over this time period is not logical, including the increase in PSI in year 1987. However, year 1988 shows improvements in cracking measurements and shoulder condition, and records that the cracks were sealed. This means that either some corrective measure was taken (to seal the cracks) or that sealing is not considered.

Table D10 Access Road NYAR503 00200W

PAVEMENT SECTION - ACCESS ROAD NYAR503 00200W																						
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECIP	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	A	3.75	150	N	1.67	0	9	0	0	121	0	0.1	3.9423	0	0	0	0	0	R
1981	A	1.88	66		0	0	N	0.42	0	2	14	20	67	0	3.97	3.9162	300	3	7.71	40	156	M
1982	B	0.63	201	B	0.63	41	N	0.83	0	6	18	21	111	62	1.47	5.3563	435	3	7.71	40	156	R
1983		0	0	A	0.25	39	N	0.04	0	2	18	20	134	62	1.47	2.6900	960	3	7.71	40	156	R
1984		0	0	B	0.25	310	N	0.08	0	2	17	21	152	62	2.09	3.6086	985	3	7.71	40	156	R
1986		0	0	A	0.13	82	N	0	0	2	0	20	127	62	2.46	1.8800	492	3	7.71	40	156	M
1987		0	0	C	0.38	79	N	0.02	0	4	17	21	89	62	2.94	3.2999	480	3	7.71	40	156	M
1988		0	0	C	0.04	115	N	0	0	4	18	24	95	62	2.8	2.9837	240	3	7.71	40	156	O
1989		0	0	C	0.01	124	N	0	0	4	17	0	221	62	2.38	2.9235	240	3	7.71	40	156	M

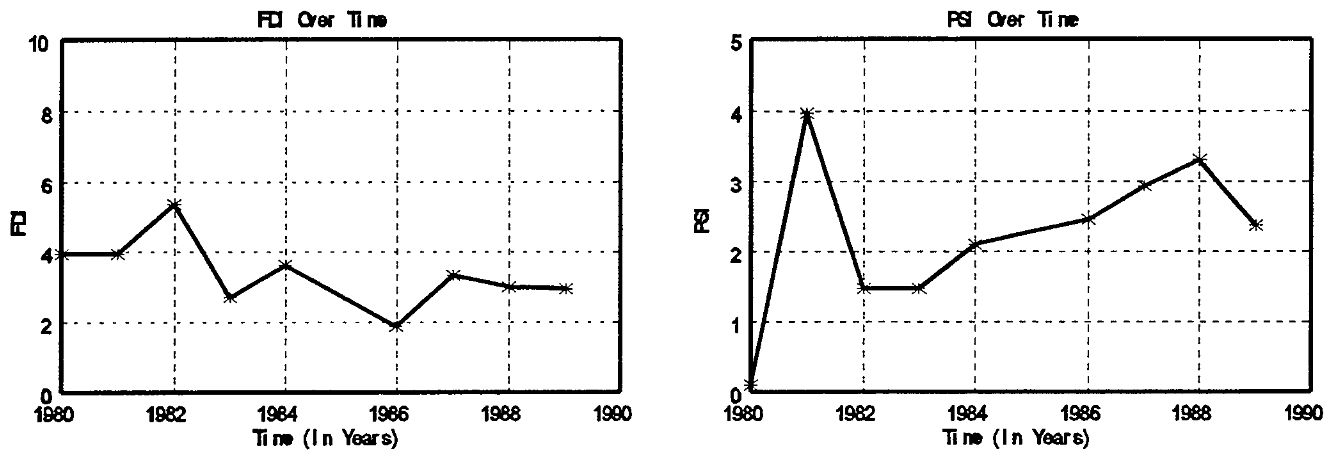


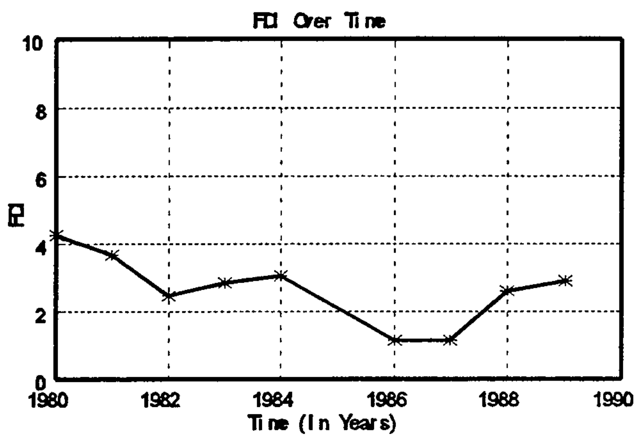
Figure D10 Access Road NYAR503 00200W

Remarks:

The PSI rating of 0.1 for year 1980 is not consistent with the condition data provided in the table. There are also discrepancies between FDI and PSI for several different years for this pavement section. First, for 1982-1983, the FDI shows an improvement in the distress condition which is reasonable with the changes in individual parameters. Alligator cracking type, severity, and extent, linear cracking type, severity, and extent, rut-depth, appearance, and shoulder condition all improve from year 1982 to 1983. The PSI stays the same because the only considerations of this index are cracking (which improves), patching (which remains the same), and roughness (which becomes slightly worse): therefore the conditions "balance out" and result in no change. The FDI recognizes all factors which contribute to pavement distress, resulting in a more accurate measure and indicating an overall improvement of distress over the year. Similar explanations exist for the discrepancies found in years 1983-1984, 1986-1987, and 1988-1989.

Table D11 Access Road NYAR503 00300E

PAVEMENT SECTION - ACCESS ROAD NYAR503 00300E																						
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980	B	3.13	120		0	0	N	1.88	0	11	0	0	90	0	0.1	4.2479	0	0	0	0	0	R
1981		0	0	B	1.88	25	N	0.11	0	17	0	20	67	0	4.29	3.6799	300	3	7.71	40	156	N
1982		0	0		0	0		0.31	0	17	18	20	97	61	2.9	2.4766	435	3	7.71	40	156	O
1983		0	0	B	0.25	26	N	0	0	3	17	20	115	61	2.9	2.8406	960	3	7.71	40	156	O
1984		0	0	B	0.25	106	N	0.02	0	3	17	21	121	61	2.59	3.0513	985	3	7.71	40	156	M
1986		0	0		0	0		0.02	0	1	14	20	116	61	2.84	1.1453	492	3	7.71	40	156	M
1987		0	0		0	0		0.02	0	1	14	20	116	61	2.84	1.1453	492	3	7.71	40	156	M
1988	B	0.02	100	A	0.02	28	N	0	0	6	18	24	85	61	2.95	2.6067	240	3	7.71	40	156	O
1989		0	0	C	0.03	92	N	0	0	4	17	0	207	61	2.53	2.9150	240	3	7.71	40	156	M



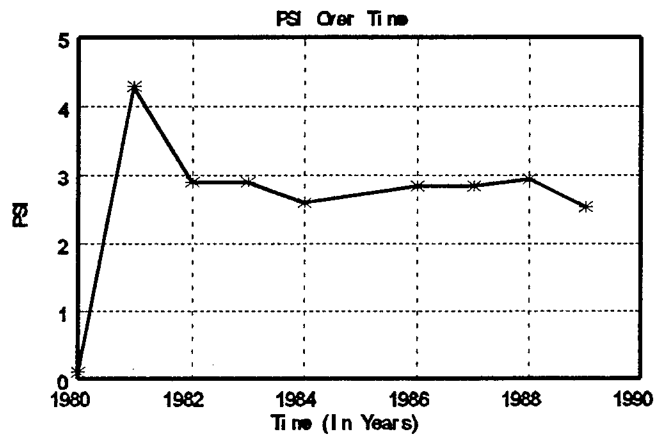


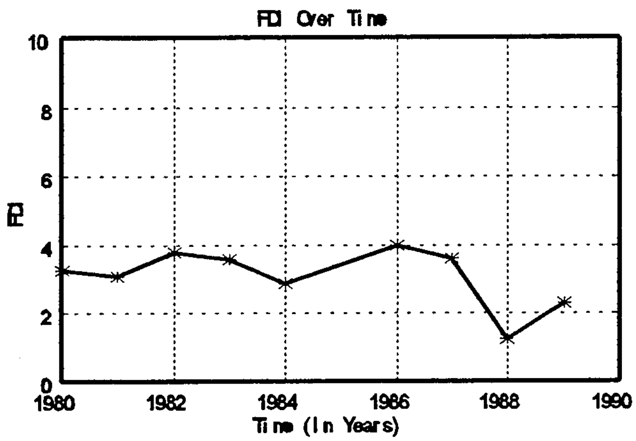
Figure D11 Access Road NYAR503 00300E

Remarks:

The PSI value of 0.1 for year 1980 is not reflective of the data provided in the table. Also, the PSI remains at a rating of 2.9 for years 1982-1983 and a rating of 2.84 for 1986-1987. Referencing the table, it is clear that there is a change in data for years 1982-1983, as is reflected in the change in FDI. The data for years 1986-1987 is identical for each parameter, which is also reflected in the FDI rating. Another discrepancy of distress behavior is found for years 1987-1988, where the FDI shows pavement deterioration while the PSI shows an improvement in the distress condition. The data in the table shows a decline in alligator cracking type, severity, and extent, linear cracking type, severity, and extent, appearance, raveling/flushing, and shoulder condition, which justifies the rating given by the FDI.

Table D12 Interstate Route PEIR080 05400W

PAVEMENT SECTION - INTERSTATE ROUTE PEIR080 05400W																					
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLD R	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980		0	0	A	1.5	96	N	2.5	0	2	0	20	67	0	0.1	3.2675	4390	35	0	0	0	R
1981		0	0	A	1.25	28	N	2.71	0	3	0	20	68	39	0.1	3.0680	2205	34	6.65	41	154	R
1982	A	6.25	91		0	0	N	3.96	0	2	14	21	73	39	0.1	3.7831	2385	34	6.65	41	154	R
1983		0	0	B	0.13	33	N	0.27	0	3	14	21	74	39	0.1	3.5716	2237	34	6.65	41	154	R
1984		0	0	A	0.13	85	N	0.27	0	2	0	22	78	38	3.04	2.8857	2235	34	6.65	41	154	M
1986		0	0	B	0.25	137	N	0.27	0	3	14	21	85	39	2.85	3.9793	2450	34	6.65	41	154	M
1987		0	0	B	0.25	310	N	0.25	0	3	0	22	69	39	3.08	3.5979	2362	34	6.65	41	154	M
1988		0	0		0	0		0	0	1	14	20	84	53	3.27	1.2211	2670	34	6.65	41	154	M
1989		0	0		0	0	N	0	0	1	14	22	179	53	2.66	2.2789	2940	34	6.65	41	154	M



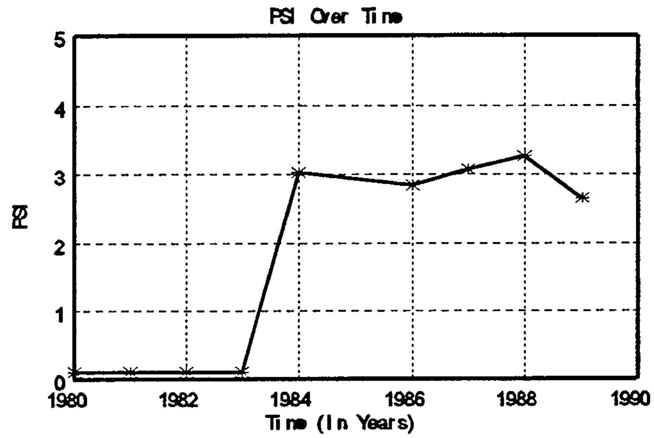


Figure D12 Interstate Route PEIR080 05400W

Remarks:

The PSI value of 0.1 for years 1980, 1981, 1982, and 1983, does not reflect the measurements in the table above. Careful observation of the table shows that the FDI, however, does accurately represent the pattern of distress condition behavior of this pavement section over time.

Table D13 State Route WPSR892 00600N

PAVEMENT SECTION - STATE ROUTE WPSR892 00600N																					
YEAR	ALLIGATOR CRACKING			LINEAR CRACKING			SEAL	RUT	PATCH	APPEAR	RAV/ FL	SHLDR	ROUGH	SKID #	PSI	FDI	ADT	% TRKS	PRECI P	#WET DAYS	FRZ THAW	MAINT
	TYPE	SEV	EXT	TYPE	SEV	EXT																
1980	A	2.5	25	C	5.63	145	N	1.25	0	3	0	0	161	0	0.1	4.9623	50	41	0	0	0	R
1981	D	8.75	400		0	0	N	2.92	0	9	12	21	167	31	0.1	5.1041	32	41	10.6	63	189	R
1982	A	0.63	40	B	2.5	83	N	2.4	0	4	0	21	171	31	0.1	4.7870	32	41	10.6	63	189	R
1983	A	0.25	100	C	0.38	136	N	0	0	4	17	22	256	31	0.1	5.2868	17	41	10.6	63	189	R
1984	B	0.75	150	C	0.25	180	N	0.09	0	7	14	22	220	31	1.55	5.9112	22	41	10.6	63	189	R
1986	C	0.38	300	C	0.38	200	N	0.19	0	8	18	25	318	31	1.03	7.3411	25	7	10.6	63	189	R
1987		0	0	C	0.38	190	N	0	0	4	14	24	147	31	2.13	4.2802	20	7	10.6	63	189	O
1988		0	0	B	0.02	71	N	0	0	3	17	21	86	31	2.95	2.8135	20	5	10.6	63	189	M
1989		0	0	C	0.03	204	N	0	0	4	14	21	207	31	2.41	3.7323	22	7	10.6	63	189	M

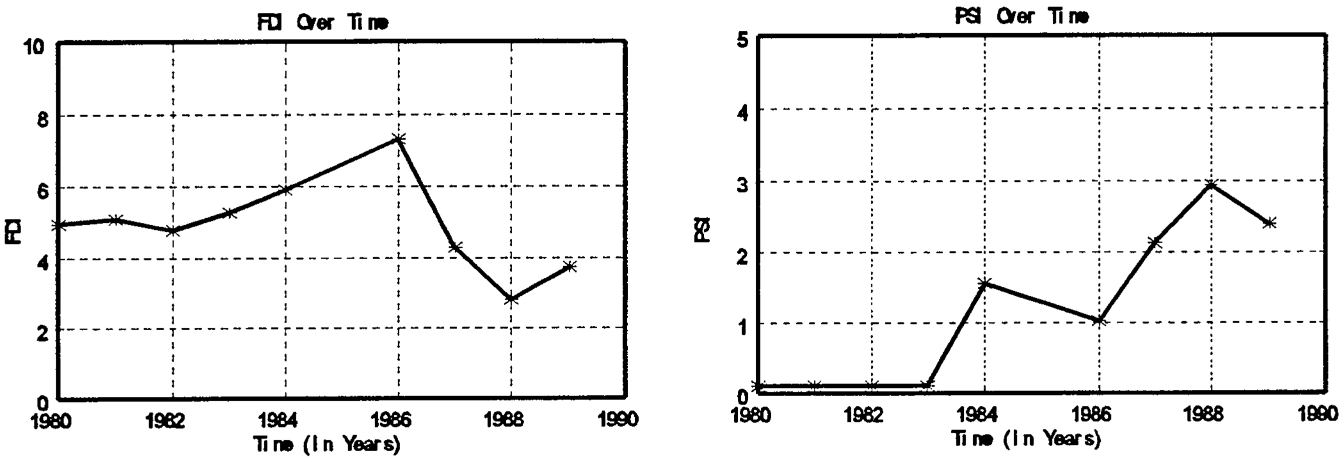


Figure D13 State Route WPSR892 00600N

Remarks:

The PSI yields an extremely poor serviceability rating of 0.1 for the years 1980, 1981, 1982, and 1983, respectively. Although the data provided in the table reveals a significant amount of distress for this pavement section over these years, the rating should not be this low. More reasonable ratings for this condition data are reflected in the FDI values. The only other discrepancy between the two distress rating indices is found for years 1983-1984; where the FDI reflects pavement deterioration while the PSI reflects an improvement in distress condition. However, a logical analysis cannot be carried out for this difference since the PSI for year 1983 is not valid.

APPENDIX E

DESCRIPTION OF DATA BASE

Abbreviation Used in Table	Meaning	Description of Data
Alligator Cracking **TYPE**	Alligator Cracking Type	Longitudinal cracking in a wheel path and interconnected or interlace fatigue cracks forming a series of small polygons are load associated cracking and are identified as Type A and B respectively. Type C and D alligator cracking covers a large portion or all of the surface and is caused by age hardening and shrinkage of the asphalt and is not directly relation to the loading of the pavement.
Alligator Cracking **SEV**	Alligator Cracking Severity	Severity pertains to the width of the cracks. The width of the crack is considered to be the total width of the fissure including widening caused by raveling.
Alligator Cracking **EXT**	Alligator Cracking Extent	Extent is the amount of cracking that exists in the rating section.
Linear Cracking **TYPE**	Linear Cracking Type	Longitudinal cracks other than in the wheel paths, and transverse cracks.
Linear Cracking **SEV**	Linear Cracking Severity	Severity pertains to the width of the crack.
Linear Cracking **EXT**	Linear Cracking Extent	Extent is the amount of linear cracking that exists within the rating section.
SEAL	Linear Seal	A bituminous or other type material poured into the cracks to prevent the intrusion of moisture and foreign solid material.
RUT	Average Rut Depth	A rut is a longitudinal surface depression in the wheel paths. Rutting is usually caused by consolidation or lateral movement of surfacing material under heavy wheel loads. The depths of ruts are measured with the rut depth gauge. Within the rating section, three measurements are taken from the right wheel path and three measurements are taken from the left wheel path. The measurements are averaged to determine the average rut depth.
PATCH	Patching	Patches are permanent or temporary corrections to damaged pavement . They vary in size and method of placement.
APPEAR	Appearance	Refers to the overall appearance of the roadway surface as already described in the Maintenance Rating Booklet ( )
RAV/FL	Bleed-Ravel	Flushing is a specific condition where there is a film of bituminous material on the pavement surface (occurs only in the wheel paths). Raveling is the wearing away of the pavement surface.
SHLDR	Shoulder Condition	Shoulder condition is the overall appearance and condition of the shoulders or edge of pavement.
ROUGH	Roughness	The International Roughness Index.

Abbreviation Used in Table	Meaning	Description of Data
SKID#	Skid Number	The skid number.
PSI	Present Serviceability Index	The Present Serviceability Index as calculated by the Nevada Department of Transportation.
FDI	Fuzzy Distress Index	The Fuzzy Distress Index as calculated by the model developed in this study.
ADT	ADT	The average annual daily traffic (ADT) for the most recent year; one directional in the given direction.
%TRKS	Percent Trucks	The percentage of the current ADT represented by trucks: one directional in the given direction.
PRECIP	Precipitation	The annual precipitation.
#WET DAYS	Wet Days	The number of wet days.
FRZ THAW	Freeze Thaw	The number of freeze thaw cycles.
MAINT	Maintenance	Maintenance category based on the following: " " - Not corrected N - No action (preventive maintenance) M - Maintenance (corrective) O - Overlay R - Reconstruction