Comprehensive Ranking Index for Flexible Pavement Using Fuzzy Sets Model

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Pavement management at the network level usually requires an index to select candidate projects and rank them for scheduling maintenance and rehabilitation activities. Such an index should consider all the factors that affect pavement performance. One of the problems in pavement prioritization is that there is no absolute attribute value at which a pavement has failed. Instead, it is a matter of acceptability. The acceptability of a pavement's condition involves largely the subjective judgment of the pavement engineers and the pavement users. A methodology to develop an index model called the overall acceptability index for flexible pavements using the fuzzy sets concept is presented. The methodology can capture the subjective judgment of the pavement engineer and the pavement user and combine the most important pavement attributes such as roughness, distress, structural capacity, and skid resistance into one index. A case study to apply the methodology is included, and the results are discussed.

The development of systematic procedures for scheduling maintenance and rehabilitation (M&R) activities is one of the major concerns of state and federal highway agencies. Over the years, funding for M&R activities has not been able to keep pace with the needs, resulting in a backlog of projects for many of the agencies. Such problems demand good management of road networks and have led to increased interest in the implementation of pavement management systems (PMSs). FHWA also requires that each state's department of transportation (DOT) have a PMS in use by 1993.

A PMS normally operates at two levels: project and network. Activities at the project level are concerned with specific technical and management decisions for each individual project; activities at the network level are mainly the responsibility of administrators who are primarily concerned with making decisions covering groups of projects or highway links up to an entire highway network (*1,2*). Detailed technical data are not of major concern at this level. At the network level, pavement evaluation measures are used to assess the relative adequacy of each pavement link or section. From this, decisions are made on what projects to include in upcoming M&R work programs. The selection of candidate highway links for M&R work is done through an optimization analysis using condition data. Scores are generally calculated for each evaluation measure per pavement section using a procedure established within the particular agency involved. The scores obtained can then be combined into a single index to establish priorities for M&R work.

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One of the problems in pavement prioritization or optimization is that there is no absolute attribute value at which the pavement has failed. Instead, it is a matter of acceptability. The acceptability of the pavement condition involves largely the subjective judgment of the person or persons using the highway or making the decisions. To develop a rational index for the selection and prioritization of the candidate sections for M&R, such subjective effects must be considered in the index formulation.

Many factors affect the performance of a pavement. Flexible pavements can usually be evaluated by four attributes or evaluation measures:

1. Roughness,
2. Surface distress,
3. Structural capacity, and
4. Skid resistance between the tire and pavement surface.

Each of the four attributes, however, evaluates only one aspect of pavement performance. Therefore, it is necessary to develop an index that considers all four attributes together to give an overall performance evaluation.

The development of a combined performance index for pavements is also a necessary requirement on the system output function for the pavement management process. Such a combined index should take into the consideration both the subjective judgment of decision makers and the most important attributes of pavement.

This paper documents the use of fuzzy set theory to model the subjective decision-making process involved in selecting candidate pavement sections for M&R. The specific application discussed is the formulation of a prioritization index for flexible pavements. The approach adopted is expected to lead to a more realistic and rational way of evaluating candidate sections for priority programming at the PMS network level. A review and evaluation of several approaches to formulating such an index is made to provide background information on existing practices.

The development of a model called the overall acceptability index (OAI), which is based on fuzzy set theory, is discussed. Fuzzy set theory is briefly discussed, and the OAI model is presented. The data for formulating the model are based on a survey of persons who have knowledge and experience in the field of pavement engineering. Data for the model presented in this paper were obtained by surveying faculty and students in the pavement study area at the University of Texas. The four pavement attributes listed earlier were considered.

Regression analysis was conducted on the data from the survey to obtain the membership functions. The results from the regression analysis are discussed, and the conclusions of the study are presented with recommendations for future research activities.

REVIEW OF EXISTING ALTERNATIVE APPROACHES TO FORMULATING A COMBINED INDEX

As discussed earlier, an important phase of M&R programming is the selection of candidate highway links. A combined rating or index is used to express the overall condition of the pavement section or highway link in terms of a combination of selected attributes and the subjective judgment of the decision makers. There are different approaches to develop such a combined index in pavement area; a brief review of several of them follows.

Unique Sums Approach

The unique sums approach is characteristic of a rating system used in Sweden (*3*), in which road sections are classified with respect to the variables pavement wear, deformation (roughness and cracking), and amount of treatment in routine maintenance. For each variable, levels are identified that indicate the extent of distress (none obvious, considerable, serious); for each level, a class number and a rating are assigned.

Each road section is therefore characterized by the three ratings, which are then added to give a composite rating. The rating numbers were chosen in such a way that the sum of numerical values for every combination of variable levels is unique, that is, each sum is different from the other sums.

Utility Theory

Texas DOT is using the utility theory to develop a measure of overall pavement performance (*4*). Basically, the procedure involves the establishment of utility functions that express a decision maker's preference over different levels of selected attributes. These functions are developed by acquiring expert opinion through interviews. A utility curve will be constructed for each pavement attribute selected. A composite measure of pavement performance can then be obtained by combining the utility curves into a single equation. The procedure assumes mutual preferential independence between attributes. The intuitive meaning of this condition is that there is no interaction of preference between attributes. Priority can then be established by comparing the relative values obtained from the combined multiattribute utility function.

Delphi Method

The Delphi technique is another method that can be used to formulate a prioritization index. This method has been used in Texas and Maine to evaluate pavement condition (*5,6*). In it, an attempt to achieve a consensus among a group of experts is made through cycles of intensive questioning interspersed with controlled opinion feedback. The technique avoids the direct confrontation of experts with one another, which is the traditional method of pooling individual opinions. In this way, some of the serious difficulties inherent in face-to-face interaction are circumvented. The final output of the process is a set of importance ratings reflecting the group consensus that may be used for establishing priorities.

Factorial Rating Method

The factorial rating method was proposed by Fernando (*7*). Essentially, the formulation of an index using this method is based on a factorial design consisting of the following factors:

1. Degree of pavement distress,
2. Present serviceability index (PSI),
3. Traffic, and
4. Environmental condition of rainfall and freeze-thaw cycles.

The application of the method involved the participation of many highway engineers, who were asked to give their opinions on the establishment of rehabilitation priorities. The responses obtained were then evaluated with the hope of gaining a better understanding of the ways in which pavement engineers establish priorities in actual practice. The prioritization procedure was based on the results of the survey.

BASIC CONCEPTS OF FUZZY SET THEORY

The concepts of fuzzy set theory were introduced by Zadeh in 1965 (*8*). It is especially useful for the representation of imprecise knowledge of the type that is prevalent in human concept formulation and reasoning. For example, the linguistic terminology of old and young, good and bad, acceptable and unacceptable, and so on are all imprecise concepts.

Concept of Classical Set and Fuzzy Set

A fuzzy set, in its basic sense, is a set in which objects have a gradual rather than an abrupt transition from membership to nonmembership. In conventional (classical) set theory, either an object belongs to a set U or it does not; the characteristic (membership) function f_u can be represented as:

$$f_u = \begin{cases} 1 & u \text{ belongs to } U \\ 0 & u \text{ does not belong to } U \end{cases}$$

The concept of fuzzy sets extends the range of membership value for f_u and allows graded membership transition, usually defined on an interval [0,1]. Consequently, an object may belong to a set with a certain degree of membership. Figure 1 illustrates this concept.

Methods for Determination of Membership Function

The membership function can be determined in actual applications with several methods; a few of them are briefly described in the following.

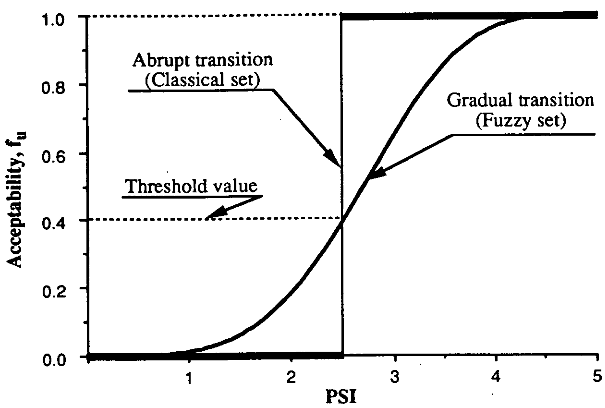

FIGURE 1 Concept of classical set and fuzzy set.

Normative Method

In the normative method, the membership function is defined or selected directly by the users according to the nature of the problem and the user's experience in the field. Membership function tables are also available in some of the fuzzy set references (*9*).

Binary Direct Rating

For the binary direct rating, a group of persons is asked to answer yes or no according to whether the linguistic term describes the element or not. Regression analysis is then used to obtain the membership functions.

Continuous Direct Rating

In the continuous direct rating, a group of persons rates elements on a predesigned continuous scale from "definitely in the concept" to "definitely not in the concept." Regression analysis is then used to obtain the membership functions.

OAI MODEL

Each of the four pavement attributes roughness, distress, structural capacity, and skid resistance has different categories of severity. However, there is not a distinct transition point between the various categories but a gradual transition. For example, in the AASHO road test (*10*) the 50th percentile for acceptability occurs when the present serviceability rating (PSR) is approximately 2.9. This means that the pavement is acceptable, with respect to roughness, when the PSR is above the threshold value of 2.9. This is therefore an ideal opportunity to apply fuzzy set theory to ascertain category membership.

Thus, the next step is to apply the fuzzy set theory to the four pavement attributes that are recognized as the major factors affecting pavement performance. For each of the attributes, the description of the categories will be either "acceptable" or "unacceptable." To consider the relative importance of the attributes, a weighting value will be given to each of them. These weighting values will also be obtained from an opinion survey. With these considerations in mind, the factor set, description set, and weight set will be as follows:

- Factor set = {roughness, distress, structural capacity, skid resistance},
- Description set = {acceptable, unacceptable}, and
- Weight set = $\{w_1, w_2, w_3, w_4\}$ where $\Sigma w_i = 1$.

For each of the factors in the factor set, a membership value A_i can be obtained from the membership curve, and the OAI can be expressed as

$$\text{OAI} = \left(w_1/\sum w_i\right)A_1 + \left(w_2/\sum w_i\right)A_2 + \left(w_3/\sum w_i\right)A_3 + \left(w_4/\sum w_i\right)A_4$$

One of the important advantages of this model is that it will always ensure that the weighting values $(w_i/\Sigma w_i)$ sum to 1, even when one of the attributes is deleted from the model. For example, in a city PMS pavement structural capacity data may not be collected. In this case the index will still be valid. Because of the linear combinations of the individual acceptabilities, the model is easy to understand and operate.

The following section addresses the construction of the practical membership functions for each of the four attributes in the factor set and the corresponding weighting values.

SUBJECTIVE OPINION SURVEY AND DATA PROCESSING

To construct the membership functions for the OAI model, it was decided to conduct a subjective opinion survey about the level of acceptance for the selected pavement attributes and their relative importance.

Roughness is measured by the existing PSI. PSI is primarily a function of pavement roughness and is measured on a scale of 0 to 5. A PSI value of 0.0 indicates an extremely rough pavement and therefore totally unacceptable, and a value of 5.0 corresponds to the roughness of a well-constructed new pavement (*10*).

On asphalt pavements there are many types of distress: fatigue cracking, temperature/moisture cracking, rutting, and so on. However, for network-level purposes it is necessary to perform not detail analysis but analysis suited for overall planning. Therefore, the measures for various distresses are aggregated into a single measure. In this study the aggregated measure is defined as the percentage of distressed area. This means, for example, that if 20 percent or more of the survey section suffers from any type of distress, the entire section will be judged as acceptable or unacceptable.

Structural adequacy is essential for a pavement to serve traffic. It is usually measured using a falling weight deflectometer or a Benkelman beam. In this study, structural capacity of a pavement is measured as a percentage of its capacity when newly constructed or relative to the capacity of some other new pavement having a similar structure.

Skid resistance is an indirect measure of safety. The coefficient of friction determines the skid resistance of a pavement. Theoretically, the maximum coefficient of friction is 1.0 and the minimum is 0.0. In practice, however, the maximum usually attained on a newly constructed, dry pavement is about 0.8. On an old, wet pavement, which represents the worst condition, the coefficient of friction is approximately 0.2.

To characterize the degree of acceptability of the four attributes, it was necessary to obtain subjective opinions of persons having knowledge of pavement design and pavement performance. Therefore, ideal persons to be surveyed should include district engineers from highway agencies such as Texas DOT. However, because of constraints in this study, the persons selected included faculty and students in the pavement study area (pavement design and pavement management systems) at the University of Texas at Austin. Twenty persons were surveyed.

Each person was required to complete rating forms that were specially designed for this study. The forms consists of the four attributes as identified for Interstate and secondary roads. Associated with each attribute is a scale on which the rater can mark the level of acceptability. Also included in the survey is a weight factor to capture the relative importance of the attribute with respect to pavement performance.

The rater marked the level considered to be the minimum (or maximum) level of acceptance for each of the four attributes. For example, if the rater thought that the maximum percent of distress tolerable on an Interstate pavement was 20 percent, the rater marked 20 percent. The raters also entered a weight for each of the four attributes to indicate his or her opinion about their relative importance.

From the survey the frequency at each acceptability level for each attribute was determined. The cumulative sum of the number of ratings over the entire rating scale was calculated for each attribute. By dividing cumulative frequency at each acceptability level by the total number of responses per attribute, the degree of acceptability on a 0-to-1 scale was determined. The degree of acceptability was plotted against the attribute scale for each attribute. Nonlinear regression analyses were performed on each of the four attribute plots, and the best-fit function (highest R-squared value) was chosen as the membership function.

RESULTS ANALYSIS

There are two membership functions for each of the four pavement attributes: one for Interstates and the other for secondary roads. The eight membership curves for roughness, distress, structural capacity, and safety and their equations are shown in Figures 2 through 9.

The curves take the general form

$$A = e^{-ax^b}$$

or

$$A = 1 - e^{-ax^b}$$

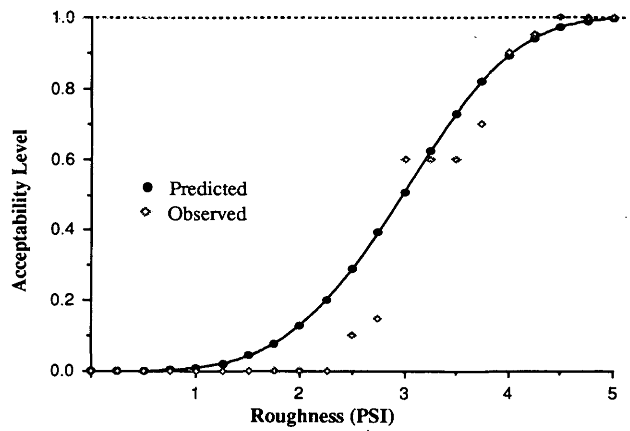

FIGURE 2 Membership curve for pavement roughness, interstate roads.

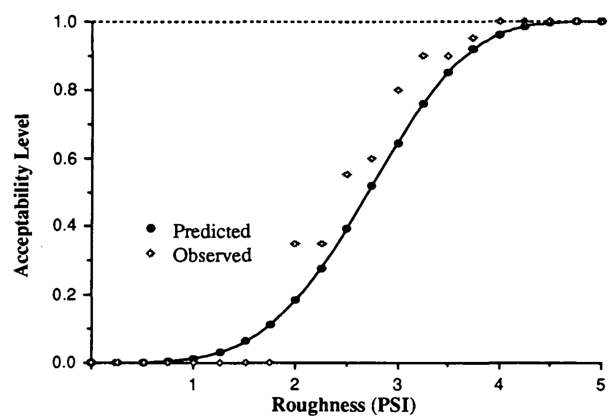

FIGURE 3 Membership curve for pavement roughness, secondary roads.

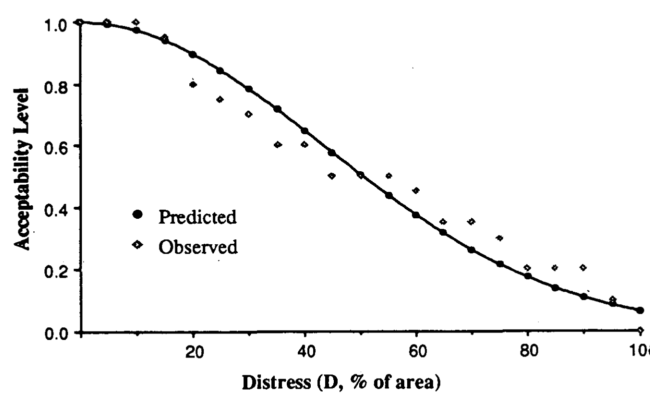

FIGURE 4 Membership curve for distress, interstate roads.

High regression coefficients (R-square) ranging from .955 to .979 were obtained.

Though the curves for roughness, distress, and structural capacity appear to be S-shaped, the curve for skid resistance demonstrates a linear membership transition for both Interstate and secondary roads. For the same attribute value, the degree of acceptance for Interstate roads is normally lower

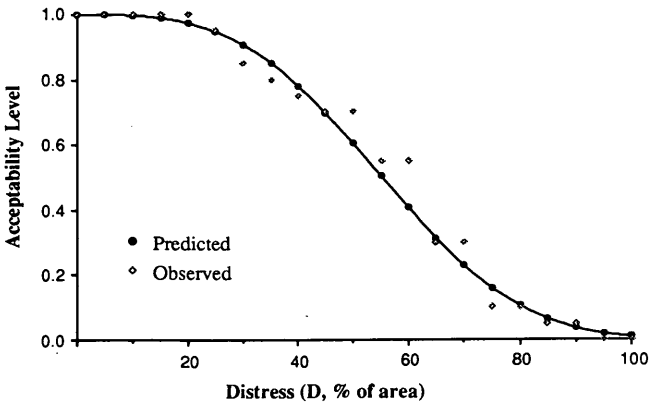

FIGURE 5 Membership curve for distress, secondary roads.

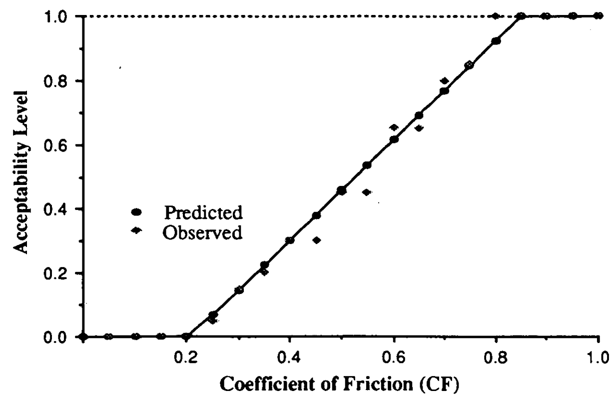

FIGURE 8 Membership curve for skid resistance, Interstate roads.

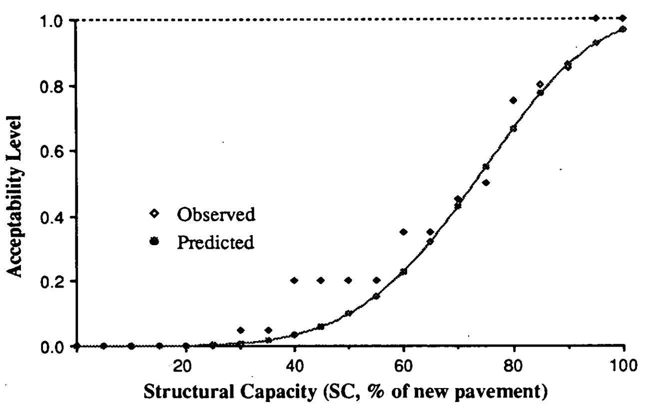

FIGURE 6 Membership curve for structural capacity, Interstate roads.

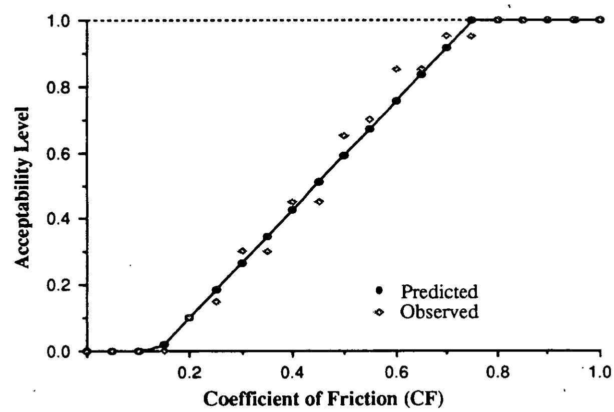

FIGURE 9 Membership curve for skid resistance, secondary roads.

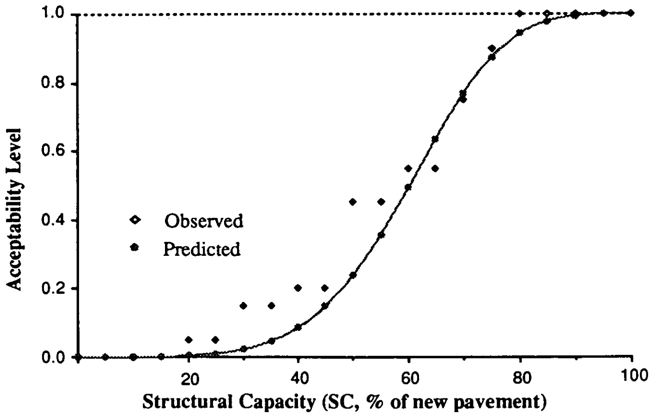

FIGURE 7 Membership curve for structural capacity, secondary roads.

than that for secondary roads. This means that the performance requirements for Interstate highways are higher than those for secondary roads, which is consistent with the real situation.

Figures 10 through 13 show the comparisons of the acceptability for roughness (PSI), distress, structural capacity, and skid resistance between Interstate and secondary roads. The average acceptability is 0.5, which means that 50 percent of the pavement engineers accept the pavement condition at this attribute level. Taking roughness as an example, the PSI value corresponding to an acceptability of 0.5 is 3.0 for Interstate and 2.7 for secondary, as shown in Figure 10. The 50 percent acceptance values for all four attributes for Interstate and secondary roads are presented in Table 1. It can be seen that the expected performance for Interstate is generally higher than that for secondary. Summaries of the membership functions and weights are given in Tables 2 and 3.

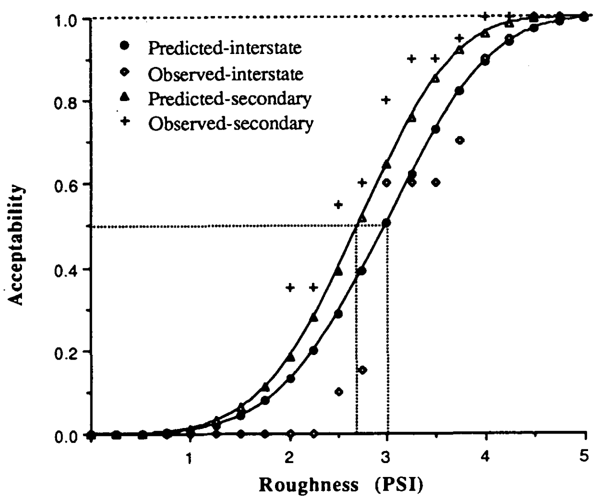

FIGURE 10 Comparison of Interstate and secondary roads for PSI.

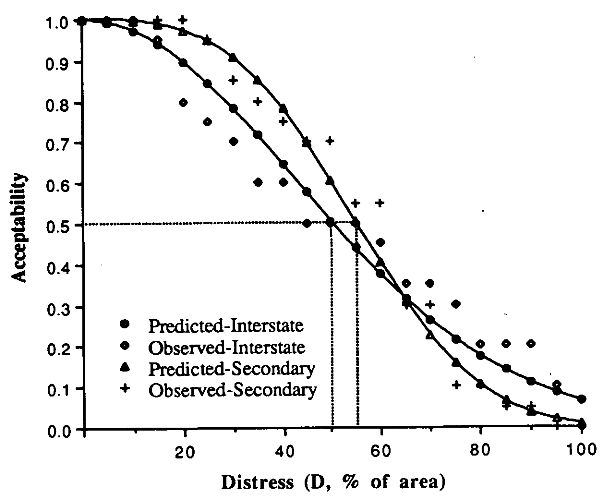

FIGURE 11 Comparison of Interstate and secondary roads for distress.

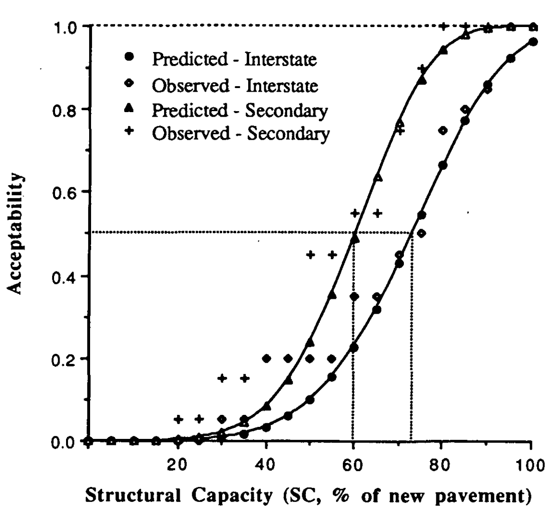

FIGURE 12 Comparison of Interstate and secondary roads for structural capacity.

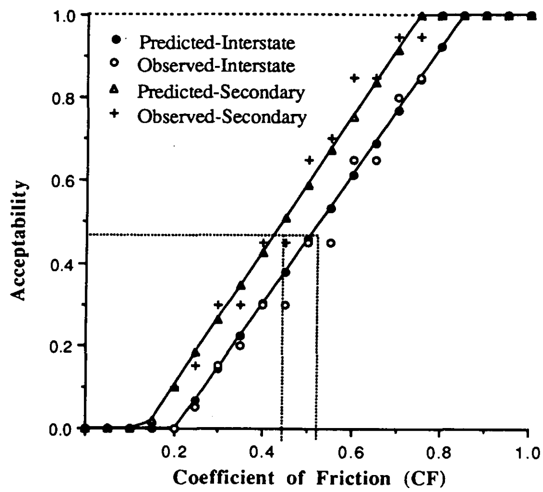

FIGURE 13 Comparison of Interstate and secondary roads for skid resistance.

TABLE 1 Attribute Values for Acceptability of 0.5

Attribute	Interstate	Secondary
Roughness (PSI)	3.0	2.7
Distress (% of area)	50	55
Structural Capacity (% of new)	73	60
Skid Resistance (Coefficient of friction)	0.51	0.45

TABLE 2 Membership Functions and Weights for Interstate Roads

Attribute	Membership Function	R-square	Weight
Roughness	$A = 1\text{-}\exp(-0.008688*PSI^4)$	0.995	0.344
Distress	$A = \exp(-0.000002729*D^2)$	0.965	0.203
Structural Capacity	$A = 1\text{-}\exp(-0.104*(SC/50)^5)$	0.972	0.222
Skid Resistance	$A = -0.32231+1.5582*CF$	0.977	0.236

TABLE 3 Membership Functions and Weights for Secondary Roads

Attribute	Membership Function	R-square	Weight
Roughness	$A = 1\text{-}\exp(-0.01274*PSI^4)$	0.970	0.306
Distress	$A = \exp(-0.00000185*D^2)$	0.971	0.244
Structural Capacity	$A = 1\text{-}\exp(-0.207*(SC/50)^5)$	0.960	0.225
Skid Resistance	$A = -0.2246+1.6308*CF$	0.979	0.231

CONCLUSIONS

Pavement management is an area in which imprecise concepts and subjective knowledge exist. In an attempt to model this knowledge and concepts, fuzzy set theory can be used.

The OAI model using fuzzy set theory combined 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. The concept is simple and practical to use.

The membership functions are the basis of the OAI model. The methodology for establishing the membership functions is presented with examples. The procedures can be applied to any other similar problem.

The OAI model is independent of the number of pavement attributes included because the sum of the weighting values is always 1.

REFERENCES

1. R. Haas and W. R. Hudson. *Pavement Management System.* Robert E. Krieger Publishing Company, Inc., Melbourne, Fla., 1982.
2. W. R. Hudson, R. Haas, and R. D. Pedigo. *NCHRP Report 215: Pavement Management System Development.* TRB, National Research Council, Washington, D.C., Nov. 1979.
3. O. Anderson. *Features of the Swedish Triennial Road Inventory System.* Bulletin 10. Department of Highway Engineering, Royal Institute of Technology, Stockholm, Sweden, 1979.
4. W. R. Hudson, R. D. Pedigo, and E. G. Fernando. *Development of an Initial Pavement Management System for Texas.* Research Report 307-1. Center for Transportation Research, University of Texas, Austin, May 1982.
5. R. A. Bush. *Influence of Cognitive Style in a Methodology for Data Base Design.* Research Report 123-27. Center for Transportation Research, University of Texas, Austin, Feb. 1975.
6. W. J. Verrill and P. E. Theberge. *Pavement Surface Condition Rating.* Interdepartmental Memorandum. State of Maine, Sept. 1981.
7. E. G. Fernando. *Development of a Prioritization Procedure for the Network Level Pavement Management System.* M.Sc. thesis. University of Texas, Austin, Dec. 1982.
8. P. P. Wang. *Advances in Fuzzy Sets, Possibility Theory, and Applications.* Plenum Press, New York, N.Y., 1983.
9. Z. X. He. *Fuzzy Sets and Their Applications.* Tianjing Science and Technology Press, Tianjing, P.R. China, 1984.
10. W. N. Carey Jr. and P. E. Irick. The Pavement Serviceability-Performance Concepts. *Bulletin 250*, HRB, National Research Council, Washington, D.C., 1960.