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Fuzzy Logic Techniques for Maintenance Assessment

Rajender Singh

Research Scholar, Singhania University, Rajasthan, India

Abstract This paper discusses the development of a fuzzy logic-based system of pavement condition rating and maintenance-needs assessment for a road network of an industrial park. These two aspects constitute the backbone of the entire project that was undertaken with the aim to streamline the pavement condition survey and reporting procedure, and the decision making process of pavement maintenance. Fuzzy mathematics offers a convenient tool to incorporate subjective analysis and uncertainty in pavement condition rating and maintenance-needs assessment. Computer programs have been developed for PC operation that allows for easy revisions of the assessment basis, and has a module for training of new staff.

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1. INTRODUCTION

This paper reports the application of fuzzy logic concept to the condition rating and maintenance-needs assessme 1. the road network of a large industrial park located c island. The total length of the road network is about 200 km. The objective of the project was to streamline the pavement condition survey and reporting procedure, and the decision making process of pavement maintenance of the entire industrial park. The main elements of works involved setting up of a routine pavement condition survey procedure, a systematic procedure for pavement distress measurement, a standard form for pavement distress reporting, a procedure for assigning a severity level to each distress, and a procedure for assessing the urgency of maintenance needs for each distress reported.

The main focus of this paper is on the development of the fuzzy logic-based systems of pavement condition rating and maintenance-needs assessment. These systems were introduced to strengthen the pavement distress assessment procedure and the decision making process of pavement maintenance. User friendly PC based computer programs have been developed to accept directly and process pavement condition survey data, and produce the required pavement distress rating and recommended maintenance actions. A special PC program module was also developed for the purpose of training new maintenance staff.

2. CONSIDERATIONS FOR ADOPTION OF FUZZY LOGIC TECHNIQUE

Existing Maintenance Practice and Condition Rating System

The existing pavement condition rating system at the industrial park follows the conventional practice of classifying pavement distresses into three different severity levels, namely low, medium and high severity. Table 1 shows some of the classification criteria adopted by the road maintenance division of the industrial park. These criteria have been derived by the maintenance engineers mainly from literature and reports, and modified slightly to reflect the local conditions.

The routine maintenance program was planned based on the subjective Judgment of the maintenance engineers, using the severity classifications of reported pavement distresses as a guide. So far, it is found that high severity distresses have been repaired within a week or two after reporting, while medium severity distresses have been attended to within a period of about a month. The experience gathered from using the pavement condition rating system described has indicated that there are two aspects for which improvements are desired:

- The distress parameter values (such as crack width for cracks and stone exposed depth for ravelling) specified for differentiating low, medium and high severity levels are subjectively selected. The difference between two pavement distresses may be negligible, yet one could be classified as low severity and the other medium severity.

- The classifying criterion for each severity level of a given distress covers a relatively wide range. For example, a rut depth with a depth equal to 11 mm and another rut that measures 20 mm deep would both be classified as medium severity.

It is apparent that the discrete classification rules as depicted in Table 1 do not adequately represent the actual relative severity of different pavement distresses. They tend to exaggerate minute differences of similar distresses in some instances. In other instances, they conceal major differences of those distresses with distinctly different distress severity. Since pavement maintenance program is planned based on the severity assessment of pavement distresses, it is conceivable that with the above-mentioned deficiencies of the pavement condition rating procedure, a cost-effective maintenance program cannot be achieved.

2. Improvements Achievable by Using Fuzzy Logic Technique

The assessment and rating of pavement distresses requires engineering judgement of experienced pavement engineers and maintenance personnel. As explained in the preceding section, the conventional discrete classification rules as shown in Table 1, while convenient to use for pavement maintenance management operations, are not ideal because the true conditions of the various pavement distresses are not satisfactorily represented.

Fuzzy mathematics offers a convenient tool to better represent the subjective assessment and uncertainty involved in pavement condition rating and assessment. Besides, it is common that the condition assessments of a given pavement distress by different pavement experts are not the same. This is not surprising because there is an element of uncertainty concerning the

(a) Single or Multiple Cracks

Severity	Crack Width
Low	1 mm or less No edge sapling
Medium	1 to 3 mm Some edge sapling
High	More than 3 mm & Edge sapling

(b) Alligator Cracks

Severity	Crack Features
Low	Hairline cracks, mostly non-interconnecting
Medium	Well-defined pattern of lightly spalled interconnected cracks
High	Pattern cracking with edge sapling & rocking pieces

Table 1: Classification criteria for severity levels of selected pavement distresses

(c) Shoving

Severity	Heave Height
Low	Less than 15 mm
Medium	15 to 30 mm
High	More than 30 mm

(d) Rutting

Severity	Rut Depth
Low	10 mm or less
Medium	10 to 20 mm
High	More than 20 mm

(e) Corrugation

Severity	Mean Depth
Low	Less than 6 mm
Medium	6 to 12 mm
High	More than 12 mm

(f) Pothole

Severity	Pothole Diameter
Low	Less than 20 mm
Medium	20 to 80 mm
High	More than 80 mm

(g) Ravelling

Severity	Stone Exposed Depth
Low	¼ diameter or less
Medium	¼ to ½ diameter
High	Loss of stones

(h) Bleeding

Severity	Bled Asphalt Diameter
Low	Less than 20 mm
Medium	20 to 60 mm
High	More than 60 mm

"true value" of the severity level of ant pavement distress. The differences in distress assessments among experts and the uncertainty involved in their assessments can be easily incorporated into the analysis using fuzzy logic concepts.

As will be shown in the later sections, the use of fuzzy mathematics enables a distress rating score to be computed for each pavement distress. This effectively eliminates the problem associated with the existing pavement condition rating system wherein many pavement distresses with discernible differences in severity are grouped under a single classification of low, medium or high severity level. With the better ability to differentiate the differences in severity of various distresses, a more effective maintenance program can be planned.

3. FRAMEWORK OF FUZZY LOGIC-BASED MAINTENANCE MANAGEMENT

The main objective of the present project was to improve, streamline and rationalize the maintenance management of the pavement network. It was not the aim of project to change the management structure of pavement maintenance unit. The three distress severity levels (low, medium and high severity) have been used as the basis for maintenance activity programming, although the programming was performed non-vigorously by subjective Judgments.

The proposed fuzzy logic-based framework retains the use of the three severity levels, as they provide an easy-to-understand general description that would be useful in budget planning and presentation of management report. However, additional meaning and significance are now attached to them. From the analysis of past maintenance program and interviews with the civil engineers in charged, it was concluded that the three distress severity levels should be defined on the basis of their respective needs for maintenance treatment. This has led to the definition for the three severity levels shown in Table 2.

Severity Level	Maintenance Needs
Low	No maintenance treatment needed, monitoring is necessary
Medium	Maintenance treatment needed
High	Mandatory repair required

Table 2: Severity levels defined in terms of maintenance needs

The difference between the distress severity classification criteria given by Table 1 and Table 2 is significant. Besides having the limitations identified in Sec. 2.1, the conventional criteria of Table 1 also do not ensure a uniform relationship of distress severity level and the urgency of needs for maintenance among different distress types. In other words, since the maintenance needs are not a criterion for severity classification in Table 1, the urgency of needs for maintenance of different distresses having the same severity level may not be the same. This presents problems in maintenance activity programming. The use of the definitions given by Table 2 ensures consistency in the meaning of the three severity levels across all distress types. The direct link between severity level and maintenance needs facilitates logical programming and scheduling of maintenance activities.

The proposed framework consists of a fuzzy logic-based micro-computer algorithm that analyzes the pavement condition survey data and computes a severity rating score for each pavement distress. The severity rating scores are related directly to the severity level as defined in Table 2. This is achieved through expressing the engineering judgement and assessment of pavement maintenance engineers by means of fuzzy mathematics concepts. It is important to note that this procedure no longer relies on discrete classification rules such as those depicted in Table 1. In other words, rules like those in Table 1 are not a component of a fuzzy mathematics-based pavement distress rating system.

4. CONDITION RATING USING FUZZY MATHEMATICS

In assessing the pavement distress condition using fuzzy mathematics, the three general definitions of distress severity levels given in Table 2 are followed. The concepts of fuzzy mathematics, however, enables addition information on each assessment to be contained in the form of member functions [Novak 1990]. A membership function provides information concerning the judgement and uncertainty associated with the distress severity assessment given by an expert. This section explains how these membership functions are established for distress severity assessment.

The next step involves computing rating scores from the membership functions. Termed as membership grade, each rating score provides a measure of the severity of the distress concerned. These rating scores are used the basis for maintenance activity programming. In short, the procedure of pavement distress condition rating using fuzzy mathematics consists of two main steps: (a) establishment of pavement distress severity rating membership functions for individual pavement distresses; and (b) determination of the severity rating scores based on the membership functions.

4.1 Membership Functions for Distress Severity Rating

It is seen from Table 2 that each of the three severity levels (low, medium and high severity levels) for a given pavement distress covers a relatively wide range of distress condition. For example, a rut with a depth of 12 mm and another with a depth of 18 mm will both be classified under medium severity, although the latter is obviously having a much more sever rutting problem and is likely to reach high severity level and receive maintenance treatment sooner. Applying fuzzy mathematics, it is possible to incorporate this difference by means of membership functions.

The severity of a pavement distress can be represented by a fuzzy set A characterized by a membership function as shown below:

$$A = \{ a(x_1)/x_1, a(x_2)/x_2, \ldots\ldots, a(x_n)/x_n \} \qquad \text{(Eq. 1)}$$

where xi, x_2,............, and x_n are the various possible pavement distress levels, and $a(x_i)$, $1 \leq i = \leq n$, denotes the membership grade of x_i. In the present application, there are three levels of pavement distress severity levels and the number of n is 3. The value of $a(x_i)$ represents the degree of belonging that the distress severity level is xi. It varies from 0 to 1. The larger the value of $a(x_i)$, the higher is the degree of belonging. As an example, the severity of a rut as assessed by an expert may be described by a fuzzy set $A_{(rut)}$ as follows:

$$A_{(rut)} = \{ 0/Low, 0.8/Medium, 0.5/High \} \qquad \text{(Eq. 2)}$$

This expression says that the expert has judged the rut to be not of low severity. He feels very likely that it is of medium severity, and much less likely to be of high severity. Graphically, the membership function of $A_{(rut)}$ given by Eq. (2) is shown in Fig. 1.

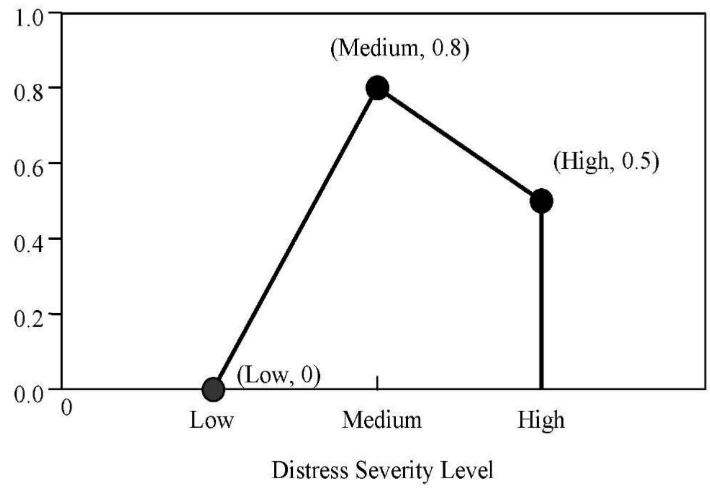


Figure 1. Graphical representation of membership function $A_{(rut)}$

4.2 Establishment of Membership Functions

The first step of the proposed fuzzy mathematics-based pavement condition rating procedure requires establishing a database of severity membership functions of individual distress types. A number of methods for determining membership functions of fuzzy sets have been employed by various researchers [Chameau and Gunaratne 1984, Tee et al. 1988, Novak 1990]. In the present study, the required membership function database is developed by interviewing with pavement maintenance engineers. Three pavement engineers of the industrial park, each with at least 5 years of working experience in the field, took part in this phase of the project. This project established the initial database of distress severity membership functions over a period of 6 months using the actual pavement distresses found in the industrial park. Table 3 shows the distress parameters recorded in the pavement condition survey. Based on the recorded distress parameters and field inspection of the distresses concerned, the three engineers were asked to award the degree of belonging to each severity level for each distress.

Distress Type	Distress Parameters
Single crack	Crack width, crack length, crack orientation, edge sapling
Multiple cracks	Maximum crack width, width & length of affected area, crack orientation, edge sapling
Alligator cracks	Maximum crack width, width & length of affected area, number of polygons in the affected area
Slippage cracks	Maximum crack width, width & length of affected area
Rutting	Maximum rut depth, width & length of affected area, presence of cracks
Shoving	Height of heaved area, width & length of affected area, presence of cracks
Corrugation/ undulations	Mean channel depth, width & length of affected area
Ravelling	Degree of surface materials lost, width & length of affected area, average exposed stone depth
Depression	Maximum depth, dimension of affected area
Pothole	Depth of largest pothole, radius of largest pothole, width & length of affected area, number of potholes in affected area
Ponding	Depth of pool, dimensions of pool
Bleeding	Equivalent radius of largest patch, width & length of affected area, number of patches in affected area
Oil spill	Equivalent radius of largest patch, width & length of affected area, number of patches in affected area

Table 3: Parameters for physical measurements of distresses in pavement condition survey

The membership grade $a(x_i)$ of a pavement distress with respect to a severity level x_i, is computed by the following equation:

$$a(x_i) = \left[\sum_{j=1}^{n} w_j \cdot {}_j(x_i)\right]\left[\sum_{j=1}^{n} w_j\right]^{-1} \quad \text{(Eq. 3)}$$

where $0 \leq \chi(x_i) \leq 1$ is the membership grade awarded by engineer j, n is the total number of engineers interviewed, and W_i is the weight given to the answer by engineer j. A different weight may be assigned to the assessment of each of the engineers. In this study equal weights have been assigned to the three engineers interviewed. Table 4 presents some of the membership functions obtained using the procedure described in this section. In these membership functions, numerical numbers 1, and 2 and 3 have been used to represent low, medium and high severity levels respectively. The micro-computer database of distress severity membership functions consists of the following entries: distress type, measurements of the distress parameters listed in Table 3, the membership grade assessments by the three engineers, and the membership function. As the actual pavement distresses found during the 6-month period did not cover the full range of possible parameter measurements for each distress, the initial database was extended by conducting further interviews with the three engineers to seek their assessments based on values of distress parameters alone.

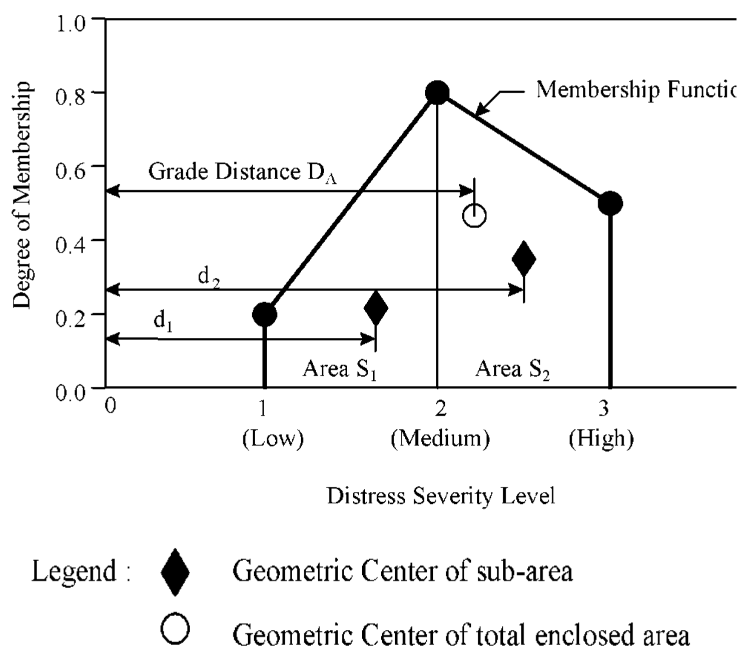
Pavement Distress and Distress Parameter Measurements	Membership Function
<u>Single crack</u>	
• Crack width 0.5 mm, crack length 0.8 m, no edge sapling	{ 1.0/1, 0/2, 0/3 }
• Crack width 1.1 mm, crack length 1.2 m, no edge sapling	{ 0.7/1, 0.5/2, 0/3 }
• Crack width 1.2 mm, crack length 3.4 m, no edge sapling	{ 0.4/1, 0.7/2, 0/3 }
• Crack width 1.6 mm, crack length 1.4 m, slight edge sapling	{ 0.3/1, 0.8/2, 0/3 }
• Crack width 2.1 mm, crack length 1.8 m, slight edge sapling	{ 0.1/1, 0.8/2, 0/3 }
• Crack width 3.3 mm, crack length 2.7 m, some edge sapling	{ 0/1, 0.5/2, 0.7/3 }
• Crack width 5.2 mm, crack length 3.6 m, some edge sapling	{ 0/1, 0.4/2, 0.9/3}
<u>Rutting</u>	
• Maximum rut depth 6 mm, width affected 0.5 m, no cracks	{1.0/1, 0/2, 0/3}
• Maximum rut depth 11 mm, width affected 0.7 m, no cracks	{0.9/1, 0.2/2, 0/3}
• Maximum rut depth 16 mm, width affected 0.9 m, no cracks	{0/1, 0.8/2, 0.3/3}
• Maximum rut depth 20 mm, width affected 0.8 m, no cracks	{0.1/1, 0.7/2, 0.5/3}
• Maximum rut depth 27 mm, width affected 0.8 m, intermittent cracks on both sides	{0/1, 0/2, 1.0/3}
<u>Corrugation</u>	
• Mean depth 4 mm, width affected 0.6 m, length affected 1.8 m	{0.7/1, 0.2/2, 0/3}
• Mean depth 7 mm, width affected 0.5 m, length affected 1.1 m	{0.7/1, 0.3/2, 0/3}
• Mean depth 11 mm, width affected 0.4 m, length affected 1.4 m	{0.4/1, 0.8/2, 0.3/3}
• Mean depth 12 mm, width affected 1.1 m, length affected 2.1 m	{0.2/1, 0.6/2, 0.6/3}
• Mean depth 17 mm, width affected 0.8 m, length affected 3.1 m	{0/1, 0/2, 1.0/3}

Table 4: Examples of severity membership functions for pavement distresses

Recognizing that the distress severity database possesses a good training value, this project developed a separate micro-computer training module complete with the colour photographs and images of those actual pavement distresses assessed. As the membership functions and individual distress assessment data are available in the database, revision and updating of the membership functions can be carried out quite easily.

4.3 Computation of Distress Rating Scores

The proposed fuzzy mathematics-based pavement condition assessment procedure expresses the final distress severity rating of a pavement distress by numerical scores. In the membership functions shown in Table 3, the low, medium and high severity levels have been assigned numerical values of 1, 2 and 3 respectively. The concept of grade distance is adopted to compute the final distress rating score. The definition of grade distance of a membership function is depicted in Fig. 2.



$$\text{Grade Distance } D_A = \frac{(S_1 * d_1) + (S_2 * d_2)}{(S_1 + S_2)}$$

Figure 2. Definition of grade distance

It is equal to the distance from the vertical membership axis to the geometric center of the enclosed areas s_1 and s_2. Mathematically, it is computed as

$$D_A = \frac{\sum_{i=1}^{m}(s_i . d_i)}{\sum_{i=1}^{m} s_i} \qquad \text{(Eq. 4)}$$

where m is the number of sub-areas, s_i the area of sub-area i, d_i the distance from the vertical membership axis to the geometric center of sub-area s_I and D_A the grade distance of the membership function.

The grade distance DA computed according to Eq. (4) gives the severity rating score for the pavement distress considered. Having set the ratings for low, medium and high severity levels as 1, 2 and 3 respectively, it means that the minimum value of the distress severity rating score is 1.0, and the maximum value is 3.0. The larger the value of the rating score, the more severe is the distress condition.

Table 5 gives the rating scores for the membership functions presented in Table 4. The value of the rating scores increases as the distress condition becomes more severe. The qualitative distress level classifications (i.e. low, medium or high severity level as defined in Table 2) are entered in the last column of Table 5. It is seen from Table 5 that the rating scores provide useful additional information to differentiate the different distress conditions of distresses within the same severity levels. This makes priority setting of pavement distress treatments in maintenance activity programming a rather straight-forward matter .

5. MAINTENANCE-NEEDS ASSESSMENT FOR MAINTENANCE PROGRAMMING

The results of fuzzy logic-derived pavement distress rating as depicted in Table 5 produce two decision parameters, namely distress rating score and severity level, that are useful for planning and programming of maintenance activities. While the qualitative distress severity levels are practical classifications useful as broad indications of the overall state of pavement condition and for the purpose of management presentation, the distress rating scores are more appropriate for maintenance needs assessment and programming of maintenance activities. For instance, consider distresses A, B and C with distress rating scores of 2.50, 2.20 and 1.80 respectively. In terms of qualitative classification, A is a high severity distress, whereas B and C are medium severity distresses. However, when it comes to maintenance activity programming based on distress rating score, B would receive a priority much ahead of C and not far behind A.

The distress severity rating procedure as proposed provides a logical basis for programming maintenance activities. Currently the maintenance program is still being planned manually based on the information of the distress rating scores. The pavement maintenance division of the industrial park is considering further upgrading of the maintenance management operation by adding an optimal programming module to improve maintenance productivity and the overall level of service of the road network.

Pavement Distress and Distress Parameter Measurements	Distress Rating Score	Severity Level
Single crack		
• Crack width 0.5 mm, crack length 0.8 m, no edge sapling	1.33	Low
• Crack width 1.1 mm, crack length 1.2 m, no edge sapling	1.73	Low
• Crack width 1.2 mm, crack length 3.4 m, no edge sapling	1.85	Medium
• Crack width 1.6 mm, crack length 1.4 m, slight edge sapling	1.89	Medium
• Crack width 2.1 mm, crack length 1.8 m, slight edge sapling	1.96	Medium
• Crack width 3.3 mm, crack length 2.7 m, some edge sapling	2.27	High
• Crack width 5.2 mm, crack length 3.6 m, some edge sapling	2.35	High
Rutting		
• Maximum rut depth 6 mm, width affected 0.5 m, no cracks	1.33	Low
• Maximum rut depth 11 mm, width affected 0.7 m, no cracks	1.54	Low
• Maximum rut depth 16 mm, width affected 0.9 m, no cracks	2.11	Medium
• Maximum rut depth 20 mm, width affected 0.8 m, no cracks	2.18	Medium
• Maximum rut depth 27 mm, width affected 0.8 m, intermittent cracks on both sides	2.67	High
Corrugation		
• Mean depth 4 mm, width affected 0.6 m, length affected 1.8 m	1.58	Low
• Mean depth 7 mm, width affected 0.5 m, length affected 1.1 m	1.64	Low
• Mean depth 11 mm, width affected 0.4 m, length affected 1.4 m	1.97	Medium
• Mean depth 12 mm, width affected 1.1 m, length affected 2.1 m	2.13	Medium
• Mean depth 17 mm, width affected 0.8 m, length affected 3.1 m	2.67	High

Table 5: Distress rating scores for selected pavement distresses

6. SUMMARY AND CONCLUSIONS

The development of a fuzzy logic-based pavement distress condition rating procedure has been presented. Compared with the conventional methods of classifying pavement distress severity based on physical measurements of distress parameters, the proposed approach has the following advantages: (a) Artificial rules with rigid limits to separate different distress levels are not required; (b) Discrete grouping of distresses into classes covering broad ranges of distress parameters is not necessary; (c) Opinions and assessments of more than one expert can be incorporated; (d) Uncertainty involved in distress severity assessments can be included; and (e) More logical priority setting and maintenance programming are achieved.

The procedure described was programmed to permit user-friendly processing of pavement condition survey data on a micro-computer. It includes a distress severity membership functions database that contains information such as the aggregated membership functions of distresses as well as the original individual assessments by different experts. Changes and revisions can be easily made to the database should the need arise. An interactive training module meant for new maintenance staff has also been developed for distress recognition and distress severity assessment. The proposed procedure has a sound and logical decision framework, and it generates useful information that can be used for optimal programming of maintenance activities at the network level.

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