Asphalt Pavement Evaluation Using Fuzzy Sets

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A new method of asphalt pavement evaluation using fuzzy sets is proposed. The purpose is to provide a simple, consistent, cost-effective procedure for pavement evaluation. Consistent pavement evaluation is needed for adequate pavement maintenance. The large turnover pending in the pavement engineering field over the next five years will leave many pavement agencies without adequate expertise to evaluate their pavement systems. A computer program, Fuzzy Evaluation of Asphalt Pavement Systems (FEAPS), is presented to facilitate the method. The program uses the fuzzy weighted average operation to combine distress ratings for five different types of pavement distress (roughness, alligator cracks, transverse cracks, longitudinal cracks, rutting). A fuzzy set representing the pavement condition is produced. This final fuzzy set can be translated to a natural language descriptor. A new function for comparing the final fuzzy sets is described, allowing ranking of the pavements. With FEAPS, the user can change the pavement weights reflecting the local expert opinions to allow for differences of interpretation of local pavement distress types.

Asphalt pavement maintenance is a very important issue facing the state and local highway engineer today (*1*, *2*). Proper maintenance requires proper pavement evaluation. Unfortunately, the wide variety of pavement types, loading conditions, and soil types makes pavement evaluation a complex task. Current effective pavement evaluation methods require the services of a highly trained and experienced expert, which entails significant costs in time and money. The methods proposed by Shahin and Kohn (*3*) and the U.S. Department of Transportation (*4*) are examples which, while effective, are also time-consuming, expensive, and often unsuitable for many agencies responsible for pavement maintenance and repair. This paper proposes a new evaluation procedure that reduces the need for an expert to perform the pavement evaluation. The procedure uses the experience of past experts and fuzzy arithmetic. Fuzzy sets, introduced by Zadeh (*5*), fuzzy arithmetic, and fuzzy logic have been applied to many areas of engineering problems where the inputs are vague or ill-defined (*6–9*). A recent National Science Foundation workshop at Purdue University examined areas in civil engineering where fuzzy sets could be applied and included pavement evaluation as one of those areas (*6*).

Many large highway structures in the U.S. are reaching the end of their design lives and thus are requiring more maintenance. The problem is exacerbated by the anticipated retirement in the near future of large numbers of experienced pavement engineers and experts (*10–12*). Many of these engineers were hired by highway departments at the start of the National System of Interstate and Defense Highways, which was created by the Federal-Aid Highway Act of 1956. Because the interstate system has grown slowly, hiring and turnover rates have been low. Consequently, few new pavement engineers have been available to become expert at pavement evaluation. The low turnover in these positions has led to low job demand, and many universities have removed pavement engineering from their curricula. Finally, the dropping enrollments in civil engineering curricula at universities have reduced the supply of potential pavement engineers (*13*). These factors accentuate the need for a consistent and simple pavement evaluation procedure that reduces the need for an expert. The procedure proposed here does not require an expert.

Pavement evaluation schemes are very local in character and can vary even from county to county. Only local knowledge of the relative importance of such factors as soil type, weather, asphalt types, significance of distress types, and seasonal variations and magnitudes of pavement loadings is useful at a given location. Therefore, pavement evaluation procedures must be tailored to every locale.

The combination of these factors has created an impending crisis in pavement engineering. In order to avert the crisis, a method of preserving the knowledge of pavement evaluation experts must be found and implemented.

A procedure employing fuzzy logic can be a great aid in solving this problem. The procedure presented herein can capture local knowledge about the importance of various forms of pavement distress in the form of weights for distress types. This knowledge is stored in a computer program and can be recalled. Each type of pavement distress is rated for severity, which is represented as a fuzzy set and then combined with the severity of other distress types, using fuzzy arithmetic to produce the pavement rating. The procedure for capturing knowledge and manipulating it is explained below.

METHODOLOGY

Use of Fuzzy Sets

Fuzzy set theory can account for the uncertainty associated with the evaluation of engineering parameters. There is considerable uncertainty in pavement evaluation, as is evidenced by the unclear terms used to describe pavement condition. For example, such general terms as "real bad," "poor," "good," and "excellent" are often used, and a range of pavement conditions is associated with each descriptor. Fuzzy sets describe that range well.

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In conventional mathematics, a single numerical rating might be assigned to each descriptive term. This number might represent the mean value, for example, when in reality some range of values might all be classified with that same number. Fuzzy sets can be used to describe this uncertainty. Rather than assigning a single number to represent the pavement rating, a fuzzy set is used. This is a set of numbers that describe the "degree of belonging" or "support" (*14*) to each level of rating to which the particular pavement belongs. In this study, a computer program performs fuzzy operations on the linguistic assessments of the pavement condition to produce the pavement rating.

Pavement Evaluation

Five forms of visual distress of asphalt pavements were selected for this study: rutting, longitudinal cracks, transverse cracks, alligator cracks, and roughness. All are indicators of structural distress. Although safety conditions are also important in evaluating pavements and could be included in the procedure proposed herein, they were not included, for the sake of brevity and clarity. A more complete list of pavement distress is given by the Asphalt Institute (*15*) and Turner et al. (*16*).

The various forms of distress were weighted to reflect their relative importance, and the weights were determined through the collection of expert knowledge. Several experienced experts in asphalt pavement analysis were interviewed for this study, in order to ascertain the importance of particular distress types. The experts used natural language terms, such as "not important" or "very important," which reflected the fuzziness associated with pavement evaluation. Each distress type was given a weight, shown in table 1, that reflects the experience of the local experts and was incorporated in the Fuzzy Evaluation of Asphalt Pavement Systems (FEAPS) program. However, the user can easily change the weights to accommodate his or her own experience. The weights reflect the differing importance of the same distress in different locales. For example, where the soils are very susceptible to pumping, small cracks in the pavement assume more significance. Similarly, where the soils are very susceptible to the formation of ice lenses, cracks allowing infiltration might have more significance than in soils where ice lenses do not form. This feature of the procedure allows for important local variations in soil types, weather, asphalt types, significance of distress types, and seasonal variations and magnitudes of pavement loadings to be incorporated in the methodology. Such flexibility makes FEAPS very versatile.

It is important to note that the results obtained are a direct function of the experts chosen to assign weights. While agreement in the selection of experts is not likely to be unanimous, some measure of expertise can be applied to aid in the selection of experts. Unfortunately, the profession still awaits a perfect method to select and evaluate experts.

The pavement rating is assigned based on visual criteria established by the agency conducting the survey. A trained individual is required to identify the kind and degree of distress. The training for this task can be done in a short period of time, whereas the training to understand the significance of distress may take years and is expert knowledge. The computer program described herein provides the pavement evaluation, a much more difficult task than distress evaluation.

Once the linguistic ratings are obtained, they are entered into the computer program. The ratings are represented internally by fuzzy sets. The overall rating of the pavement is determined from the fuzzy weighted average described below and defined in equation 1 by Schmucker (*17*) as

$$R = \frac{\Sigma R_i * W_i}{\Sigma W_i} \tag{1}$$

where

R = the fuzzy set that represents the overall rating of the pavement,
R_i = the fuzzy set that represents the linguistic rating of a particular distress i, and
W_i = the fuzzy set that represents the weight (or relative importance) of a particular distress i, as compared to other distress.

The five major distress types have varying importance. The weight of each type is shown in table 1. The fuzzy sets representing each weight are given in table 2. Note that the weight indicates the relative importance of one distress type compared to the others. The weight is not an absolute scale. Thus, the table does not, for example, imply that transverse cracks are absolutely "not important."

The shape of the membership functions shown in figure 1 (as indicated by the fuzzy set) has been shown to have little effect on the fuzzy weighted average operation used in this study (*18*). Figure 1 shows that the relative importance of each distress ranges from 1 to 9, with 9 representing the domain element of greatest importance. "Support" values, which express membership, range from 0.0 to 1.0. Thus, for example, in table 2 the weight "not important" is fully supported (1.0) at domain element 1 and also partially supported (0.5) at domain element 2. No support (0.0) is indicated at domain elements 3 and above, indicating that there is no high level importance associated with the rating "not important."

TABLE 1 WEIGHT SCALE FOR PAVEMENT DISTRESS

Distress	Weight
Rutting	important
Longitudinal cracks	moderately important
Transverse cracks	not important
Alligator cracks	extremely important
Roughness	very important

TABLE 2 WEIGHTS USED TO EVALUATE PAVEMENT DISTRESS

Weight	Symbol	Fuzzy Set Representation
not important	A	{1.0/1, 0.5/2, 0/3}
moderately important	B	{0/1, 0.5/2, 1.0/3, 0.5/4, 0/5}
important	C	{0/3, 0.5/4, 1.0/5, 0.5/6, 0/7}
very important	D	{0/5, 0.5/6, 1.0/7, 0.5/8, 0/9}
extremely important	E	{0/7, 0.5/8, 1.0/9}

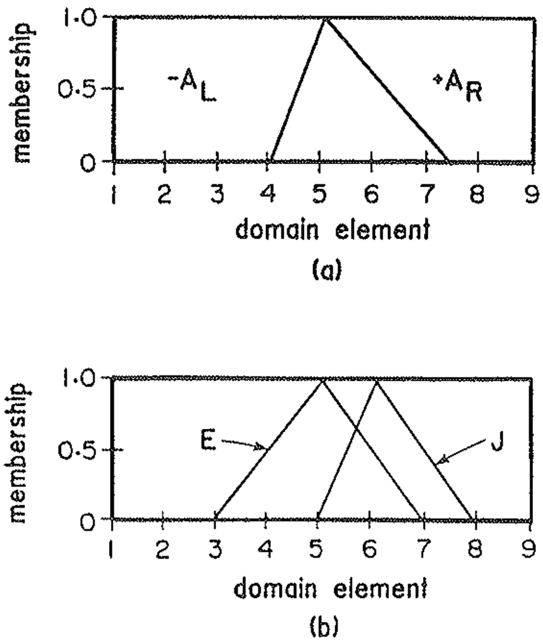

FIGURE 1 (a) Model of the distress index. (b) Comparison of fuzzy sets for the distress index calculation.

As mentioned above, the rating of the evaluated pavement was expressed in linguistic terms. Because rating of the pavement by individuals is very subjective, use of linguistic terms appears to be more natural and appropriate than use of single numeric values. Consequently, fuzzy set representations of these linguistic ratings have been used in the proposed evaluation procedure. Table 3 gives the fuzzy sets corresponding to the linguistic rating grades used in this study. The domain elements for these rating grades range from 1 to 9, with 9 representing the domain element of greatest severity. As before, "support" values, which express membership, range from 0.0 to 1.0. Thus, for example, in table 3, the rating "slight" is unsupported (0.0) at domain element 1, partially supported (0.5) at domain element 2, fully supported (1.0) at domain element 3, partially supported (0.5) at domain element 4, and unsupported (0.0) at domain element 5. No support (0.0) is indicated at domain elements 5 and above, indicating that there is no high level severity associated with the rating "slight."

Tables 1, 2, and 3 represent the opinion of the experts used in this study. Other fuzzy sets could be used in the computer program to describe the pavement rating and weights, as desired. Once these opinions are in place, and the pavements ratings have been obtained, equation 1 can be used to calculate the final fuzzy set which represents the overall pavement rating.

TABLE 3 RATING SCALE: QUALITATIVE RATING OF THE DISTRESS

Rating Grade	Symbol	Fuzzy Set Representation
none	A	{1.0/1, 0.5/2, 0/3}
slight	B	{0/1, 0.5/2, 1.0/3, 0.5/4, 0/5}
significant	C	{0/3, 0.5/4, 1.0/5, 0.5/6, 0/7}
severe	D	{0/5, 0.5/6, 1.0/7, 0.5/8, 0/9}
extremely severe	E	{0/7, 0.5/8, 1.0/9}

Several pavements can be rated with this method, and their final results compared, resulting in a ranking of pavements for use in maintenance strategies. This comparison is a rational way to establish the repair priority of each pavement, based on structural evaluation of the pavement. The comparison is facilitated by the establishment of a distress index, explained below.

DISTRESS INDEX FOR COMPARISON OF PAVEMENTS

Pavements can be compared using a ranking index based on the fuzzy sets representing the pavement condition. This index is a quantitative measure of pavement distress. The ranking index, here called the distress index (*DI*), can also be used as an absolute measure of the pavement condition, based on local criteria.

The proposed distress index is based on a model proposed by Juang and Kalidindi (*19*). Referring to Figure 1a, the distress index is

$$DI = \frac{A_L - A_R + C}{2C} \quad (2)$$

where

DI = distress index,
A_R = area to the right of the membership function which characterized the final fuzzy set,
A_L = area to the left of the membership function which characterized the final fuzzy set, and
C = a constant, equal to the area enclosed by the universe.

The distress index value ranges from 0.0 to 1.0. A low index indicates better pavement condition, while a high index indicates worse condition. For example, pavements with overall ratings represented by fuzzy sets *E* and *J*, given in figure 1b, are readily compared as follows:

E = {0/3, 0.5/4, 1.0/5, 0.5/6, 0/7}

For *E*,

$$DI = \frac{3 - 3 + 8}{2(8)} = 0.50$$

J = {0/5, 1.0/6, 0.5/7, 0/8}

For *J*,

$$DI = \frac{4.5 - 2 + 8}{2(8)} = 0.66$$

Thus, the pavement represented by fuzzy set *J* is in worse condition than the pavement represented by fuzzy set *E*.

The distress index can be translated back into the natural language rating, if desired, by assigning natural language descriptions to "standard" fuzzy sets representing different pavement conditions. The *DI* for each of these fuzzy sets is calculated, and the *DI* of the pavement under consideration is compared to the *DI* of the standard. Table 4 gives standard fuzzy sets that might be assigned the natural language descriptions shown there.

TABLE 4 NATURAL LANGUAGE TRANSLATION OF THE DISTRESS INDEX (*DI*)

Final Evaluation Descriptor	Fuzzy set	DI
no distress	= {1.0/1, 0.5/2, 0/3}	0.06
moderate distress	= {0/1, 0.5/2, 1.0/3, 0.5/4, 0/5}	0.25
distress	= {0/3, 0.5/4, 1.0/5, 0.5/6, 0/7}	0.50
severe distress	= {0/5, 0.5/6, 1.0/7, 0.5/8, 0/9}	0.75
total distress	= {0/7, 0.5/8, 1.0/9}	0.94

FUZZY WEIGHTED AVERAGE

The fuzzy weighted average (FWA) operation is defined in equation 1. The summation, multiplication, and division in equation 1 are fuzzy arithmetic operations and are defined by Schmucker (*17*) as follows:

First, let

$$X = \{x(i) \quad | \quad i\,;\, 1 \le i \le n\}$$

$$Y = \{y(j) \quad | \quad j\,;\, 1 \le j \le n\}$$

where i, j and n are integers, and $x(i)$ and $y(i)$ are membership functions that characterize fuzzy sets X and Y respectively. Then, fuzzy addition is defined as

$$X + Y = \{\min\,[x(i), y(j)] \quad | \quad (i + j)\,;\; 1 \le i, j \le n\} \qquad (3)$$

The fuzzy summation is simply fuzzy addition repeated. Fuzzy multiplication is defined as

$$X * Y = \{\min\,[x(i), y(j)] \quad | \quad (i * j)\,;\; 1 \le i, j \le n\} \qquad (4)$$

Lastly, fuzzy division is defined as

$$X/Y = \{\min\,[x(i), y(j)] \quad | \quad (i/j)\,;\, 1 \le i, j \le n\} \qquad (5)$$

The implementation of fuzzy addition and multiplication is straightforward; fuzzy division, however, is less so. For many applications, the Clements algorithm may be sufficient to solve this problem. Mullarkey and Fenves (*20*) consider this algorithm to be the best for fuzzy division.

The Clements algorithm involves two assumptions: (1) any division (i/j) not resulting in an integer is deleted, and (2) any division resulting in a quotient greater than n is discarded.

Another concern in the implementation of equation 1 is whether the fuzzy "normalization" should be conducted after each fuzzy operation (addition, multiplication, or division). Earlier studies (*17, 20*) have indicated that more reasonable results can be obtained with normalization than without normalization. Fuzzy normalization is defined by Schmucker (*17*) as follows. Let

$$Z = \text{NOR}\,[X]$$

then

$$Z = \{z(i)/i\,;\, 1 \le i \le n\} \qquad (6)$$

where

$$z(i) = x(i)/\max\,[x(i),\, 1 \le i \le n] \qquad (7)$$

Fuzzy normalization was used in this study.

COMPUTER PROGRAM

Created to perform the pavement evaluation, the FEAPS program was written in FORTRAN 77 and, using the WATFOR77 compiler (*21*), runs on IBM PC and IBM-compatible microcomputers.

The simplified flowchart for the program is shown in figure 2. The first part of the program accepts information from the user. The program then allows the user to tailor the evaluation by assigning linguistic weights to the five different distress types, based on his or her experience. The user can also

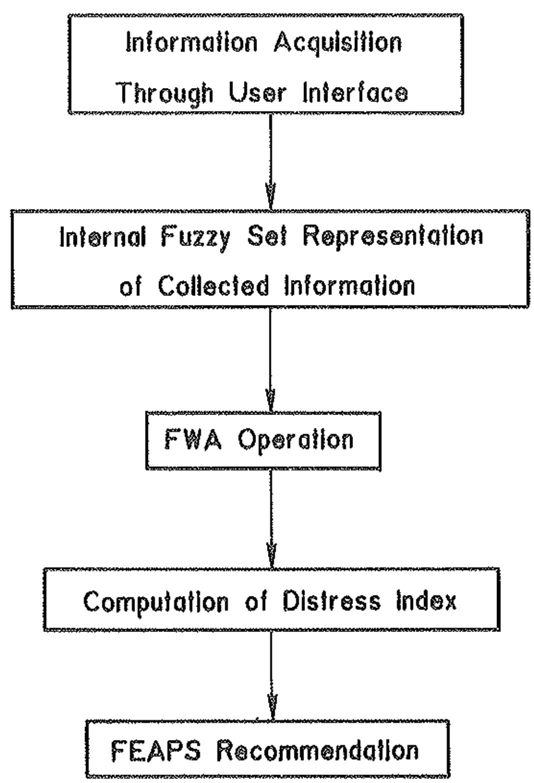

FIGURE 2 General flowchart for FEAPS.

TABLE 5 CASE STUDY 1: FOUR PAVEMENT RATINGS

Distress	Pavement 1	2	3	4
Rutting	B	C	C	D
Longitudinal cracks	C	B	C	C
Transverse cracks	D	E	B	C
Alligator cracks	B	C	E	E
Roughness	B	B	C	D
Distress Index	0.32	0.43	0.60	0.74

[a] NOTE: pavement ratings made according to the following scale -
A - none
B - slight
C - significant
D - severe
E - extremely severe

select default weights embodied in the program, which are expressed in linguistic terms (or phrases) for ease of use. Similarly, the rating of any pavement evaluated according to each of the distress criteria is expressed in linguistic terms.

The second part of the program translates the input linguistic expressions into fuzzy sets. Once the required data are input and translated into fuzzy sets, the FWA operation is performed. The result is a final fuzzy set that represents the pavement rating.

Finally, the distress index of the final fuzzy set is calculated, and this process is repeated for each pavement evaluated. The pavement with the lowest *DI* is in the best condition.

CASE STUDIES

The procedure explained above was evaluated by selecting and rating four pavements. The default weights shown in table 1 and the rating scale shown in table 3 were used.

Case 1

Four pavements are shown in table 5: each exhibited a different combination of distress. Pavements with different degrees of distress were chosen to show how the proposed procedure could be used to differentiate among them. Pavement 1 ratings intuitively indicate good condition. In particular, the small amount of alligator cracks indicates good condition. Visual inspection of the ratings for pavements 2, 3, and 4 indicates that the condition of these pavements decreases with increasing pavement number.

Evaluation using FEAPS was performed. The *DI* for each is shown in table 5. As expected, pavement 1 is in the best condition (lowest *DI*), while pavement 4 is in the worst condition (highest *DI*). Pavements 2 and 3 are arranged in order of decreasing condition.

Case 2

Four more pavements are shown in table 6, each again exhibiting a different combination of distress. Intuitively, pavement 8 is in better condition than pavement 5, the only difference between the two being the lower rating given for alligator cracks for pavement 5. Pavement 6 is in worse condition than pavement 5, since all the ratings for pavement 6 are less than or equal to the rating for pavement 5, except for the alligator cracks. Although pavement 6 has a better rating for alligator cracks than pavement 5, the overall rating is less, because of the lower ratings for several other distresses (particularly roughness, which is heavily weighted). The FEAPS evaluation ranks the pavements 8, 7, 5, and 6 from best to worst, as indicated by their respective distress indices.

Pavements 2 and 7 had very similar distress indices. However, they had different amounts of distress. Although pavement 2 had a much better rating for longitudinal cracks (which were weighted as "moderately important"), it had a slightly lower rating for alligator cracks (which were weighted as "very important"). This heavy weight resulted in the lower overall rating. The similarity in *DI* with pavement 7 indicates that FEAPS was able to weight longitudinal and alligator cracks properly. Pavements 1 and 8 have different amounts of transverse cracks and roughness distress, but similar distress indices. This indicates that FEAPS was able to weight these types of distress properly.

CONCLUSION

A computer program for the structural evaluation of asphalt pavements has been presented that captures the knowledge of experts and puts it in a fuzzy framework. The pavement ratings, also represented by fuzzy sets, are used as program input. The knowledge and the ratings are combined using the fuzzy weighted averaging technique in the computer program FEAPS to produce a fuzzy set that represents the pavement condition. The program provides a consistent, reliable, and facile method of evaluating pavements. As such, it provides a tool that many pavement agencies—especially those with limited resources—can use to reduce the impact of the loss of expertise during the next few years.

TABLE 6 CASE STUDY 2: FOUR PAVEMENT RATINGS

Distress	Pavement			
	5	6	7	8
Rutting	B	D	C	B
Longitudinal cracks	C	D	E	C
Transverse cracks	A	A	E	A
Alligator cracks	E	D	B	B
Roughness	C	D	B	C
Distress Index	0.55	0.70	0.41	0.35

[a] NOTE: pavement ratings made according to the following scale -
A - none
B - slight
C - significant
D - severe
E - extremely severe

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