

A DEVELOPMENT OF FUZZY PAVEMENT CONDITION ASSESSMENT

Joni Arliansyah¹, Teruhiko MARUYAMA² and Osamu TAKAHASHI³

¹Student Member of JSCE, M.T., Dr. Candidate, Dept. of Civil & Environmental Eng., Nagaoka University of Technology (1603-1 Tomioka-cho, Nagaoka-shi, 940-2188, Japan)

²Member of JSCE, Dr. Eng., Professor, Dept. of Civil & Environmental Eng., Nagaoka University of Technology

³Member of JSCE, Dr. Eng., Associate Professor, Dept. of Civil & Environmental Eng., Nagaoka University of Technology

The pavement condition assessment (PCA) based on fuzzy set theory is presented. A method to determine membership functions used in PCA is proposed. The effects of inclusion or omission, weight changes and linguistic rating terms' range values changes of pavement parameters on PCA using fuzzy weighted average (FWA) operation are analyzed. The proposed method is compared with the MCI model.

In developing this case, it is found that the proposed method gives more reliable results. Inclusion or omission, weight changes and linguistic rating terms' range values changes of pavement parameters can cause the differences in PCA. The recommendations with respect to PCA using FWA operation are given.

Key Words: membership functions, linguistic term expression, pavement parameters, fuzzy weighted average and pavement condition assessment.

1. INTRODUCTION

Pavement Management Systems (PMS) are widely used in the world to assist administrators of pavement networks in making consistent and cost effective decision about public investment in highways. One of the basic and important features of PMS is their ability to represent the condition of pavement networks, and various pavement condition indices, such as PCI, PSI, and MCI, are used for this purpose. In recent years, the fuzzy set theory that can account for human subjectivity and impressions associated with the evaluation of engineering parameters is used in pavement condition assessment. Fuzzy Weighted Average (FWA) operation has been used by several researchers to assess pavement condition using various combinations of selected pavement parameters¹⁾⁻⁵⁾.

The most important part of FWA operation is determination of membership functions that represent the linguistic rating terms and weights of parameters used. Usually, some existing membership functions are selected, and trial and error procedures are used to determine the best membership functions in the pavement condition assessment and other applications^{2), 6), 7)}. However, more accurate results may be or not be obtained using other membership functions.

Shoukry et al.⁴⁾ mentioned that flexibility to allow the inclusion or omission of pavement parameters can be achieved in determination of pavement condition through application of fuzzy set theory. Elton et al.¹⁾ and Shoukry et al.⁴⁾ also mentioned that with application of fuzzy set theory, the weight of pavement parameters that indicate their significance to the overall condition could be changed according to the policies of pavement agencies. However, these changes could produce the differences in pavement condition assessment results. In further research on the PMS such as the development of pavement deterioration models that can be applied universally, the effects of these changes must be carefully considered.

In Japan, the pavement surface condition evaluation using fuzzy quantification theory and its application to pavement surface condition data that collected subjectively by pavement engineers and airport administrators through visual survey have been reported⁸⁾. The concern of our study is to develop a pavement condition assessment method in Japan using FWA operation, where the use of existing pavement database and practical aspects are the major considerations of the study.

The purposes of this study are: (1) to propose a method to determine membership functions used in pavement condition assessment based on experts' opinions about the range values of linguistic rating

terms of pavement parameters; (2) to investigate the effects of the inclusion or omission of pavement parameters on pavement condition assessment, the effects of weight changes of pavement parameters on pavement condition assessment and the sensitivity of linguistic rating terms' range values of pavement parameters on pavement condition assessment using FWA operation; and (3) to compare the results of pavement condition assessment determined using the membership functions of proposed method with the results of maintenance control index (MCI) model developed by Japanese Ministry of Construction.

The rest of the paper proceeds as the followings. Section 2 presents the methodology that used in this study, section 3 discusses the analysis on the results of pavement condition assessment, section 4 discusses the comparison of fuzzy pavement condition index (FPCI) and MCI, and section 5 summarizes the findings of the study.

2. METHODOLOGY

(1) Fuzzy pavement condition assessment

In this study, the FWA operation was used to assess pavement condition. The FWA operation has a simple mathematical form⁹⁾:

$$R = \frac{\sum_{i=1}^n R_i \times W_i}{\sum_{i=1}^n W_i} \quad (1)$$

Where,

- R : the fuzzy set that represents the final assessment of pavement condition,
- R_i : the fuzzy set that represents the linguistic rating term of a pavement parameter i ,
- W_i : the fuzzy set that represents the weight of pavement parameter i ,
- n : number of pavement parameter used.

The final assessment of pavement condition is mainly depending on the membership function of fuzzy sets that represent the linguistic rating terms and weights of pavement parameters. The method to determine more rational membership function of fuzzy sets, rather than using existing membership functions, was proposed in this study to get the better results in pavement condition assessment.

In this study, pavement parameters used to assess pavement condition were determined after considering the most important aspects that influence the pavement condition and the

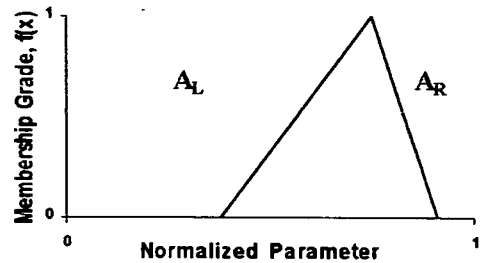


Fig. 1 Definition of fuzzy pavement condition index.

availability of pavement parameter data in the Japanese database. Pavement parameters used were cracking ratio, rutting and roughness (standard deviation of surface profile).

The pavement condition assessment rating for a particular pavement parameter was estimated using one of the following linguistic terms: excellent, very good, good, fair and poor. Similarly the weighting of the pavement parameter was determined using one of the following linguistic terms: extremely important, very important, important, moderately important and not important.

In this study, because experts' opinions about the range values of linguistic terms for rating the pavement parameters were collected, pavement parameter data can be directly classified into suitable linguistic terms of rating. If the membership functions of linguistic rating terms and weights of pavement parameters are already determined, the FWA operation to assess pavement condition can be carried out.

The Vertex method¹⁰⁾ was used to calculate the FWA operation. A computational algorithm of this method is based on the α cut representation of fuzzy sets and the interval analysis.

The fuzzy pavement condition index (FPCI) was calculated based on the final fuzzy set result of FWA operation. The index model proposed by Elton et al.¹⁾ were modified and used. (See Fig. 1.)

$$FPCI = \frac{A_L - A_R + 1}{2} \times 10 \quad (2)$$

Where,

- A_L : the area enclosed to the left of the membership function that represents the final assessment of pavement condition,
- A_R : the area enclosed to the right of the membership function that represents the final assessment of pavement condition.

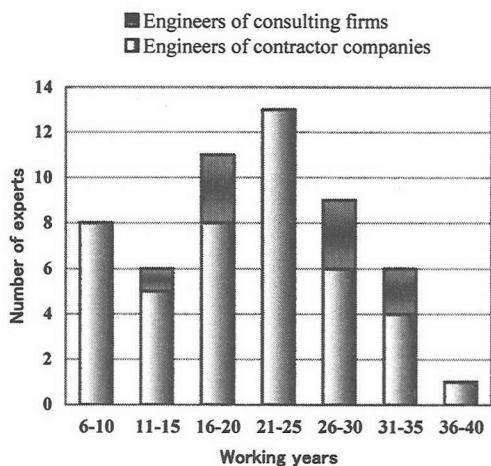


Fig. 2 The distribution of working years of experts

In addition to the value indicated by FPCI, in this study the final assessment of pavement condition was also expressed in linguistic term. α -Level (α -cut) distance¹¹⁾ was used to translate the final fuzzy set result into appropriate linguistic term.

The α -level distance is defined as follows:

$$d_j = \frac{\sum_{\alpha=0}^{1.0} \sqrt{(a_{\alpha, \min} - j_{\alpha, \min})^2 + (a_{\alpha, \max} - j_{\alpha, \max})^2}}{N} \quad (3)$$

Where,

- d_j : α -level distance between the output fuzzy number A and the predefined standard fuzzy number j ,
- $a_{\alpha, \min}$: lower bound of the α -cut interval of the fuzzy number A ,
- $a_{\alpha, \max}$: upper bound of the α -cut interval of the fuzzy number A ,
- $j_{\alpha, \min}$: lower bound of the α -cut interval of the predefined standard fuzzy number j ,
- $j_{\alpha, \max}$: upper bound of the α -cut interval of the predefined standard fuzzy number j ,
- N : Number of the α -cut intervals taken.

The most appropriate translation is the linguistic term whose fuzzy set has the smallest α -level distance to the output fuzzy set.

The use of both FPCI and its linguistic term expression in final assessment of pavement condition is more sophisticated than the use of a single index, because the linguistic term can directly express the condition of pavement.

Table 1 The linguistic rating terms' range values of cracking ratio.

Linguistic rating term	Range value (%)
Excellent	0.00 - 3.46
Very Good	3.46 - 9.16
Good	9.16 - 17.12
Fair	17.12 - 27.88
Poor	>27.88

Table 2 The linguistic rating terms' range values of rutting

Linguistic rating term	Range value (mm)
Excellent	0.00 - 4.49
Very Good	4.49 - 9.53
Good	9.53 - 16.59
Fair	16.59 - 26.14
Poor	> 26.14

Table 3 The linguistic rating terms' range values of roughness (σ).

Linguistic rating term	Range value (mm)
Excellent	0.00 - 0.89
Very Good	0.89 - 1.53
Good	1.53 - 2.21
Fair	2.21 - 3.00
Poor	> 3.00

The effects of omission or inclusion and weight changes of pavement parameters on pavement condition can be clearly analyzed using linguistic term expression.

(2) Membership functions determination

The proposed method to determine membership functions that represent linguistic rating terms and weights of pavement parameters, based on Japanese experts' opinions about the range values of linguistic rating terms of pavement parameters, is presented in this section. Using this method, the output of pavement condition assessment could be more accurate than using existing membership functions, due to its ability to represent experts' opinions in pavement condition assessment.

The first step of this method is collecting the experts' opinions about the range values of linguistic rating terms of pavement parameters. For this purpose, a questionnaire survey, written in Japanese, was widely conducted to Japanese highway engineering experts who have a sufficient practical career in pavement condition evaluation. Fifty-four highway engineering experts, who work at contractor companies and consulting firms, were surveyed. Their average working career as highway engineers was twenty-one years. The distribution of their working years is shown in Fig. 2.

The average values of experts' opinions about linguistic rating terms' range values of pavement parameters were used in this study. The linguistic rating terms' range values of cracking ratio, rutting and roughness are shown in Tables 1 - 3, respectively.

Table 4 Membership functions of the fuzzy sets that represent the linguistic rating terms and weights

Linguistic rating term and weight	Membership function $f(x)$	
A	$f(x) = 5(x-0.80)$,	$0.80 \leq x \leq 1.00$
B	$f(x) = 5(x-0.60)$,	$0.60 \leq x \leq 0.80$
C	$f(x) = 1 - 5(x-0.80)$,	$0.80 \leq x \leq 1.00$
	$f(x) = 3.85(x-0.34)$,	$0.34 \leq x \leq 0.60$
D	$f(x) = 1 - 5(x-0.60)$,	$0.60 \leq x \leq 0.80$
	$f(x) = 2.94(x)$,	$0.00 \leq x \leq 0.34$
E	$f(x) = 1 - 3.85(x-0.34)$,	$0.34 \leq x \leq 0.60$
	$f(x) = 1 - 2.94(x)$,	$0.00 \leq x \leq 0.34$

A: Excellent/Extremely Important; B: Very Good/Very Important; C: Good / Important; D: Fair/Moderately Important; E: Poor/ Not Important

Table 5 The weights of pavement parameters used

No.	Pavement parameter	Weight
1.	Cracking ratio	Very Important
2.	Rutting	Extremely Important
3.	Roughness (σ)	Very Important

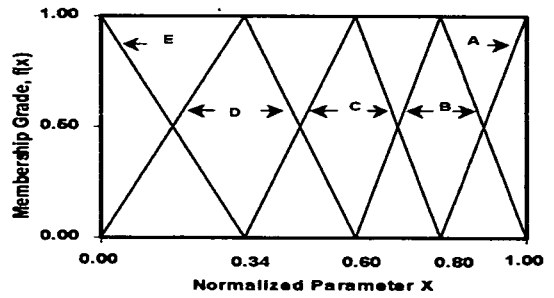
Table 6 The examples of FPCI calculation

No	Section	Cracking ratio		Rutting		Roughness (σ)		FPCI	α - cut distance from					Linguistic term of FPCI
		(%)	LT	(mm)	LT	(mm)	LT		A	B	C	D	E	
1	5+1800 - 5+1900	0.7	A	4	A	1.48	B	8.99	0.07	0.13	0.41	0.75	1.02	A
2	7+200 - 7+300	41	E	17	D	4.94	E	1.78	0.98	0.79	0.51	0.19	0.13	E
3	37+600 - 37+700	0	A	5	B	3.23	E	6.20	0.43	0.23	0.05	0.39	0.67	C
Weight		Very Important		Extremely Important		Very Important								

LT: Linguistic Term; A: Excellent; B: Very Good; C: Good; D: Fair; E: Poor.

These opinions were then used to determine the membership functions of linguistic terms used in the pavement condition assessment. The procedure is described as follows:

1. Normalize the linguistic rating terms' range values of each pavement parameter, ranging from 0 for poor to 1 for excellent.
2. The average of the maximum normalized value of each linguistic rating term of all pavement parameters is determined as the maximum point of membership function (membership function = 1) of each linguistic rating term that used to assess pavement condition. If linguistic rating terms' range values of pavement parameter are a decrease from maximum value for excellent to minimum value for poor, minimum normalized value of each linguistic rating term is used to substitute for the maximum normalized value. The average maximum normalized value of excellent, very good, good, fair and poor is 1.00, 0.80, 0.60, 0.34 and 0.00, respectively.
3. The membership function shape has usually a triangle, a π curve, a bell shape or other shapes. In this study the triangular shape was used.



A: Excellent/Extremely Important; B: Very Good/Very Important; C: Good / Important; D: Fair/ Moderately Important; E: Poor/Not Important

Fig. 3 Graphical shapes of linguistic terms' membership functions determined by proposed method.

The final membership functions were used to characterize the fuzzy sets that represent linguistic rating terms and weights of pavement parameters. Their graphic shapes are shown in Fig. 3. The final membership functions, which were determined based on their graphic shapes, are defined in Table 4. The reliability of this method will be discussed in section 3.

The weights of pavement parameters were also asked in the survey. The average values were used, and these are shown in Table 5.

(3) Data used

The pavement data from the database of Hokuriku Region pavement management support system were used in this study. The data contained in this database include pavement condition data, maintenance history, pavement material types, traffic, pavement geometric, and road map. 1920 pavement sections data of route 8 in Niigata Prefecture were retrieved and used. The local influence in Hokuriku Region is not extreme. In this study, we assume the local influence is not significant, and we don't take into account the local influence in the FPCI calculation.

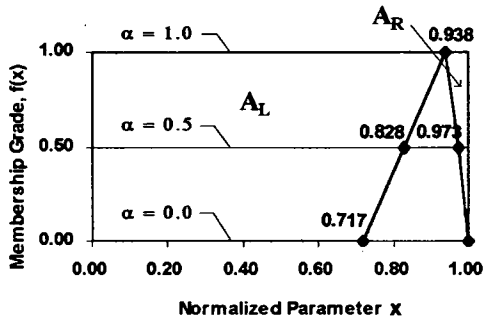


Fig. 4 The final fuzzy set of section No. 1

(4) Example application

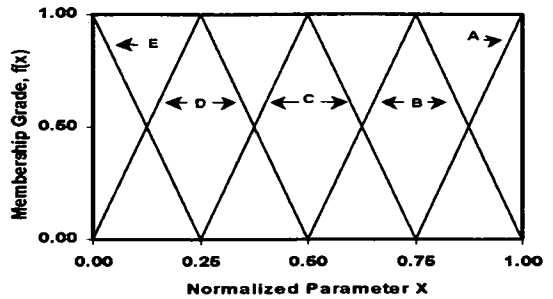
To demonstrate the procedure used, the calculation examples are presented. Three pavement sections data of route 8 were used, and Table 6 shows the summary of their FPCI calculation. The calculation procedure is described as follows.

1. Classify the pavement parameters into suitable linguistic rating terms. The experts' opinions about the range values of linguistic rating terms of pavement parameters, as shown in Tables 1 to 3, are used for this purpose. For section No. 1, cracking ratio is classified as excellent, rutting is classified as excellent and roughness is classified as very good. The weights of pavement parameters, as shown in Table 5, are used.
2. Translate the linguistic rating terms and weights of pavement parameters into fuzzy sets by using membership functions. The membership functions, as shown in Fig. 3, are used.
3. Calculate the fuzzy set representing the condition of each section by using FWA operation defined in Equation (1). The Vertex method¹⁰ is used to calculate the FWA operation. The final fuzzy set of section No. 1 is shown in Fig. 4.
4. Calculate FPCI using Equation (2). For section No. 1:

$$A_L = (0.717 \times 1.00) + (0.50 \times (0.938 - 0.717) \times 1.00) = 0.828;$$

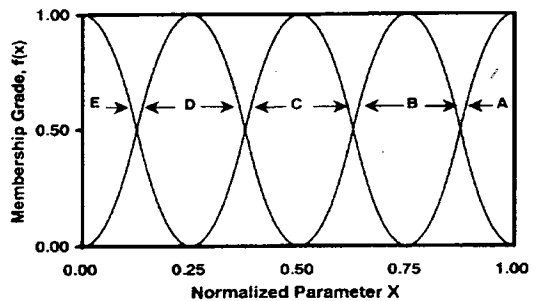
$$A_R = (0.50 \times (1.00 - 0.938) \times 1.00) = 0.031;$$

$$FPCI = (0.828 - 0.031 + 1.00) \times 10 / 2 = 8.99.$$
5. Translate the final fuzzy set into appropriate linguistic term. This process involves the determination of distance between final fuzzy set and fuzzy sets representing linguistic terms expression (Fig. 3). The α -level distance¹¹ defined in Equation (3) is used. The α values of 0, 0.5 and 1.0 are used. As shown in Table 6, the final fuzzy set of section No. 1 has the smallest α -distance with fuzzy set representing excellent. Therefore, the linguistic term



A: Excellent/Extremely Important; B: Very Good/Very Important; C: Good / Important; D: Fair /Moderately Important; E: Poor /Not Important

Fig. 5 Graphical representation of linguistic term's membership functions used by Juang et al.^{2,7)}



A: Excellent/Extremely Important; B: Very Good/Very Important; C: Good / Important; D: Fair /Moderately Important; E: Poor/Not Important

Fig. 6 Graphical representation of linguistic term's membership functions used by Juang et al.⁶⁾

expression of pavement condition of this section is classified as excellent.

3. ANALYSIS ON THE RESULTS OF PAVEMENT CONDITION ASSESSMENT

(1) Reliability of proposed method

To evaluate the reliability of the proposed method, the linguistic term expressions of pavement condition assessment results determined using proposed membership functions were compared with the results determined using existing membership functions. Existing linear membership functions used by Juang et al.^{2,7)} and non-linear π -curve membership functions used by Juang et al.⁶⁾, as shown in Figs. 5 and 6, were selected. The pavement parameters used were cracking ratio, rutting and roughness.

Table 7 The differences in pavement condition assessment results.

No.	Existing membership functions (MF) used	The pavement condition assessment results that are not in the same linguistic term expression with the results determined using MF of proposed method.	
		Number of sections	(%)
1	Linear MF ²⁾⁷⁾	307	$307/1920^{1)} \times 100\% = 15.99\%$
2	Non linear MF ⁶⁾	307	15.99 %

¹⁾1920 is the number of pavement sections that were evaluated

Table 7 summarizes the number of pavement condition assessment results determined using selected existing membership functions that are not in the same linguistic expression with the results determined using membership functions of proposed method.

From **Table 7**, it can be seen that there are significant differences between the results of pavement condition assessment determined using both selected existing membership functions and the results determined using membership functions of the proposed method. From the evaluation results of 1920 pavement sections, there are 307 pavement sections with different pavement condition assessment in both cases. This indicates that the use of the inappropriate membership functions could lead to the wrong assessment of pavement condition networks.

Table 8 summarizes the combination of pavement parameter data that have different pavement condition assessment results. In a combination, the pavement parameter data have the same linguistic rating term of cracking ratio, rutting and roughness. The pavement condition assessment results determined using selected existing membership function and proposed membership functions were analyzed by comparing the linguistic term expression of the results and using the pairwise comparison method (PCM)¹²⁾. The membership

functions being more accurate and appropriate to assess pavement condition were considered as the best membership functions.

The results of linguistic term expression comparison of final pavement condition assessment results indicate that the use of membership functions of the proposed method can give more reasonable and appropriate pavement condition assessment results rather than using selected existing membership functions. The followings can be seen from **Table 8**:

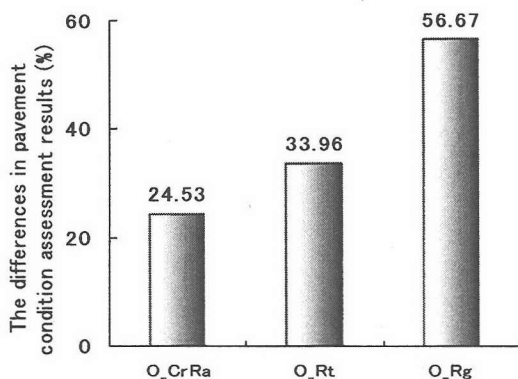
- Pavement sections in combination No 1 that have excellent condition of cracking ratio, poor condition of rutting and fair condition of roughness, are better or more reasonable to be classified as fair rather than good because the pavement that have poor condition of rutting and fair condition of roughness can not be classified as good. The similar indications are found from pavement sections in combination No. 2 and 3.
- Pavement sections in combination No 4 that have excellent condition of cracking ratio, excellent condition of rutting and poor condition of roughness are better to be classified as good rather than very good because pavement has poor condition in roughness. The similar indications are found from pavement sections in combination No. 5.
- Pavement sections in combination No 6 that have excellent condition of cracking ratio, good condition of rutting and good condition of roughness are better to be classified as good rather than very good because although the pavement sections have only a little amount of cracking, these sections have only good condition of rutting and roughness.

The pairwise comparison method¹²⁾ was done by comparing the result of existing MF with the result of proposed MF at a time for their accuracy to represent the pavement condition with respect to a particular combination. If linguistic term of

Table 8 The combination of pavement parameter data that have different pavement condition assessment result.

Com. No.	Number of section in Com.	Cracking ratio (%)	Rutting (mm)	Roughness (σ) (mm)	Pavement Condition Assessment								PCM Results	
					Using linear MF ^{2),7)}		Using nonlinear MF ⁶⁾		Using MF of proposed method		Existing MF ^{2),6),7)}	Proposed MF		
					FPCI	LT	FPCI	LT	FPCI	LT				
1	6	0 - 3.4	29 - 40	2.25 - 3.0	F	3.86	G	3.83	G	4.25	F	0.0	1.0	
2	72	0 - 3.4	17 - 26	3.06 - 5.62	P	4.04	G	4.02	G	4.42	F	0.0	1.0	
3	9	17.3 - 27.6	7 - 9	3.22 - 7.37	P	3.91	G	3.81	G	4.26	F	0.0	1.0	
4	38	0 - 3.4	2 - 4	3.01 - 7.64	P	6.67	V	6.82	V	6.76	G	0.0	1.0	
5	105	0 - 3.4	5 - 9	2.24 - 2.98	F	6.48	V	6.63	V	6.89	G	0.5	0.5	
6	77	0 - 3.3	10 - 16	1.54 - 2.21	G	6.30	V	6.41	V	6.95	G	0.0	1.0	

Com.: Combination; LT: Linguistic Terms; E: Excellent ; VG: Very Good; G: Good; F: Fair; P: Poor; MF: Membership Functions, PCM: Pairwise Comparison Method.



O_: Omission of; CrRa: Cracking ratio; Rt: Rutting; Rg: Roughness.

Fig. 7 The effects of omission or inclusion of pavement parameter on pavement condition assessment.

pavement condition is judged to be more accurate than the other, a score 1.0 is assigned to the accurate one, while a score of 0.0 is assigned to the other one. If there is no obvious choice both entries are assigned a score of 0.5. The pairwise comparison method results are shown in Table 8. In general, the results also indicate that the use of membership functions of the proposed method can give more reasonable and appropriate pavement condition assessment results rather than using selected existing membership functions

The results indicate that the use of existing membership functions can cause the wrong assessment of the pavement section condition. This may lead to the miss interpretation of pavement section maintenance needs.

There is no difference between the results of pavement condition assessment using existing linear membership functions and non-linear π curve membership functions. Both membership functions have the same range values. If we compare them with the range values of membership functions of the proposed method, it seems that the range values of membership functions have greater effect on the results of pavement condition assessment rather than their shape.

(2) The effects of the inclusion or omission of pavement parameters

To investigate the effects of inclusion or omission of pavement parameters on pavement condition assessment, the linguistic term expressions of pavement condition assessment results determined using cracking ratio, rutting and roughness were compared with the results after omission of cracking ratio, rutting or roughness respectively. Fig. 7 shows the differences in pavement condition assessment results after

omission of cracking ratio, rutting or roughness, respectively.

From Fig. 7, it can be seen that the omission of roughness has more effect on pavement condition assessment than the omission of cracking ratio or rutting. The omission of roughness, rutting and cracking ratio respectively caused 56.67 %, 33.96 %, and 24.53 % differences in pavement condition assessment results.

Clearly, the results indicate that omission or inclusion of pavement parameters in pavement condition assessment using fuzzy weighted operation can cause the differences in pavement condition assessment results. This finding is not consistent with the statement by Shoukry et al.⁴⁾ who mentioned in determination of pavement condition, flexibility to allow the inclusion or omission of pavement parameter can be achieved through the application of fuzzy set theory. It could be happen because linguistic term expression of final pavement condition assessment, which can clearly indicate the effects of inclusion or omission of pavement parameters rather than use an index, was used in this study.

Pavement condition assessment results are the basic information that used in the network level priority analysis of PMS. The different results of pavement condition assessment can lead to the different results of network level priority analysis. The best assessment of pavement condition using fuzzy weighted average operation could be achieved by using all important parameters that influence pavement condition⁴⁾. However, in order to get the results that can be applied universally, using the same pavement parameters in pavement condition assessment is recommended.

(3) The effects of weight changes of pavement parameters

To investigate the effects of weight changes of pavement parameters on pavement condition assessment, linguistic term expressions of pavement condition assessment results determined using initial weight of pavement parameters, as shown in Table 5, were compared with the results determined using combinations of weight after 1 level weight change of 1, 2 and 3 pavement parameters. The combination of weight changes is shown in Table 9. Fig. 8 shows the differences in pavement condition assessment results after weight changes of pavement parameter. Table 10 shows the average value of these differences.

The differences in pavement condition assessment results, as shown in Fig. 8, vary significantly depending on the combination of weight used. The average value of the differences in

Table 9 The weight combination after 1 level weight change

Weight Com.	Number of parameter used in weight change	Pavement parameter weight		
		Cracking ratio	Rutting	Roughness
Initial Weight		VI	EI	VI
Com. 1	1	EI*	EI	VI
Com. 2		I*	EI	VI
Com. 3		VI	VI*	VI
Com. 4		VI	EI	EI*
Com. 5		VI	EI	I*
Com. 6	2	I*	VI*	VI
Com. 7		EI*	VI*	VI
Com. 8		I*	EI	I*
Com. 9		EI*	EI	I*
Com. 10		I*	EI	EI*
Com. 11	3	EI*	EI	EI*
Com. 12		VI	VI*	I*
Com. 13		VI	VI*	EI*
Com. 14		I*	VI*	I*
Com. 15		EI*	VI*	EI*
Com. 16		EI*	VI*	I*
Com. 17		I*	VI*	EI*

* One level weight change; Com: combination; EI: Extremely Important; VI: Very Important; I: Important.

Table 10 The average value of the differences in pavement condition assessment results.

Number of parameter used in weight change	Number of weight combinations	The differences in pavement condition assessment results (%)			
		Ave- rage	Std Dev	Min	Max
1	5	7.80	8.26	0	17.81
2	8	9.27	6.79	0.21	17.66
3	4	9.52	7.71	1.09	19.79

pavement condition assessment results increased with increasing the number of pavement parameter used in weight change, but the increment were not significant.

The results indicate that the weight changes of pavement parameters can cause the differences in pavement condition assessment results. In pavement condition assessment, however, the weight of pavement parameter can be changed according to maintenance policies of any highway agencies.

(4) The sensitivity of the linguistic rating terms' range values of pavement parameters

To investigate the sensitivity of the linguistic rating term's range values of pavement parameter on pavement condition assessment, sensitivity analysis was done by comparing the results of pavement condition assessment determined using initial linguistic rating terms' range values, as shown in Tables 1 – 3, with the results determined after gradually increasing and decreasing the linguistic rating terms' range values of roughness,

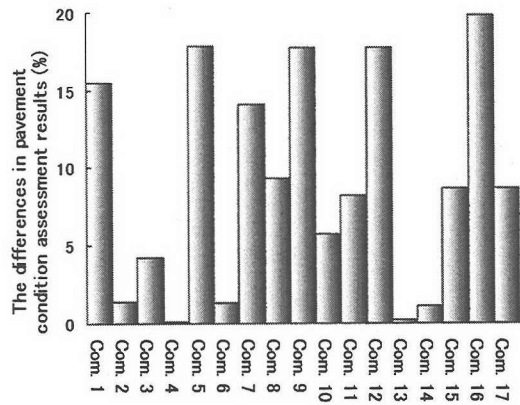


Fig. 8 The effects of the weight changes on pavement condition assessment results.

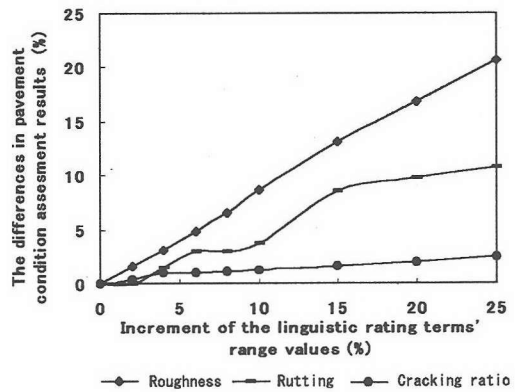


Fig. 9 The effects of the increment of the linguistic rating terms' range values of pavement parameter on pavement condition assessment results.

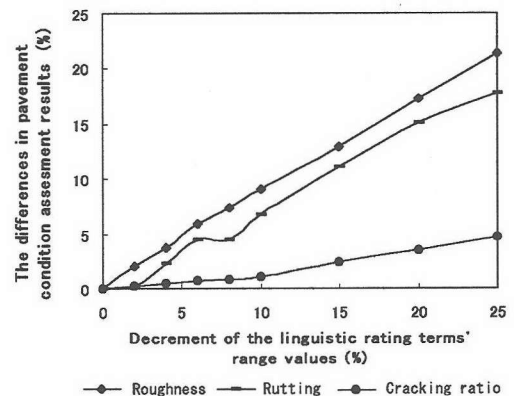


Fig. 10 The effects of the decrement of the linguistic rating terms' range values of pavement parameter on pavement condition assessment results.

rutting or cracking ratio, respectively. Figs. 9 and 10 respectively show the differences in pavement condition assessment results after increasing and

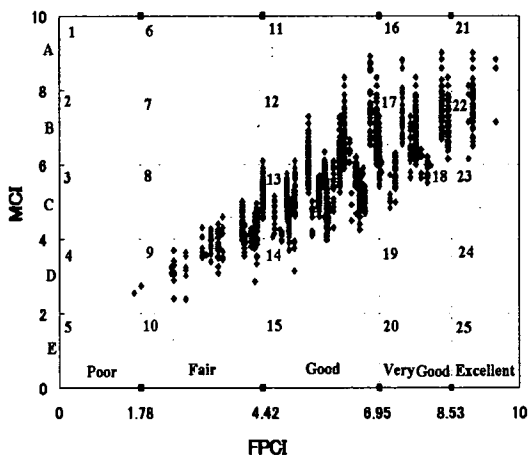


Fig. 11 Comparison analysis for FPCI versus MCI.

decreasing the linguistic rating terms' range values of pavement parameter.

The results indicate that the change of the linguistic rating terms' range values of roughness gave more effect on pavement condition assessment results than the change of the linguistic rating terms' range values of rutting or cracking ratio. 10 % increment of the linguistic rating terms' range values of roughness caused 8.65 % differences in the pavement condition assessment results, and the same increment of the linguistic rating terms' range values of rutting and cracking ratio caused only 3.75 % and 1.25 % differences in the results, respectively. 10 % decrement of the linguistic rating terms' range values of roughness, rutting and cracking ratio respectively caused 9.06 %, 6.82 % and 1.04 % differences in pavement condition assessment results. The cracking ratio has low sensitivity to the change of its linguistic rating terms' range values.

From Figs. 9 and 10, it can be seen that the curves of the differences in pavement condition assessment results, caused by increment or decrement of linguistic rating terms' range values of rutting between interval 5% and 10 %, are not smooth. It happened because in this interval increment or decrement of linguistic rating terms' range values of rutting gave no or a little effect in the changing of linguistic rating terms of rutting data.

4. THE COMPARISON OF FUZZY PAVEMENT CONDITION INDEX (FPCI) AND MCI

To investigate the correlation between FPCI and MCI, a comparison analysis was carried out. The

Table 11 The findings that are revealed from FPCI and MCI comparison.

Finding		Number of section	%	Location of data in Fig 11 (Box no.)
No	Condition			
1.	Pavement sections are classified as excellent in FPCI model but have MCI value less than 8.	42	2.19	22
2.	Pavement sections are classified as good in FPCI model but have MCI value greater than 8.	40	2.08	11
3.	Pavement sections are classified as very good in FPCI model but have MCI value less than 6.	44	2.29	18
4.	Pavement sections are classified as good in FPCI model but have MCI value less than 4.	9	0.49	14
5.	The results of FPCI model are in agreement with the results of MCI model.	1785	92.97	4, 8, 9, 12, 13, 16,17,21
Total		1920	100	

comparison was obtained by floating FPCI versus MCI as shown in Fig. 11. FPCI values are classified from excellent to poor, and MCI values are classified from A to E according to Handbook of Pavement Testing Method, 1988¹³. Examination of all data points reveals several findings. These are summarized in Table 11.

As shown in Table 11, the results of FPCI model, which are not in agreement with the results of MCI model, are found in finding No. 1 to 4. There are 135 pavement sections found in these findings. To determine which index gives more reliable results, pavement parameter data and their pavement condition assessment results determined using FPCI model and MCI model were analyzed. The pavement parameter data and their pavement condition assessment results are summarized in Table 12.

The results indicate that MCI values for the pavement sections in findings No. 1, 2 and 3 do not reflect their true condition. The followings can be seen from Table 12:

- In case No. 2 of finding No. 1, pavement sections are classified as excellent by FPCI model because they have excellent condition of cracking ratio, excellent condition of rutting and very good condition of roughness, but in MCI model these sections are represented by low index values between 6.63 and 7.99. The similar facts are found in cases No. 1, 3 and 4 of finding No.1.
- In case No. 1 of finding No. 2, pavement sections are classified as good by FPCI model

Table 12 The pavement parameter data and their pavement condition assessment results

Finding No.	Case No	The example of pavement section that represents the finding									Number of section	MCI range in the case	Total Number of section
		Cracking ratio		Rutting		Roughness (σ)		FPCI		MCI			
		(%)	LT	(mm)	LT	(mm)	LT	LT	LT				
1	1	1.40	E	4	E	0.88	E	9.50	E	7.14	1	7.14	42
	2	3.20	E	4	E	1.40	VG	8.99	E	6.63	37	6.63-7.99	
	3	0.90	E	6	VG	0.48	E	8.90	E	7.14	3	6.16-7.89	
	4	4.30	VG	4	E	0.87	E	8.99	E	6.49	1	6.49	
2	1	0	E	3	E	5.62	P	6.76	G	8.71	14	8.53-8.93	40
	2	0	E	5	VG	2.39	F	6.89	G	8.33	14	8.11-8.33	
	3	0	E	6	VG	3.08	P	6.20	G	8.11	12	8.11-8.33	
3	1	3.40	E	9	VG	1.64	G	7.75	VG	5.99	1	5.99	44
	2	3.40	E	10	G	0.85	E	8.08	VG	5.96	1	5.96	
	3	2.30	E	15	G	1.37	VG	7.63	VG	5.67	3	5.63-5.73	
	4	8.60	VG	3	E	1.72	G	7.86	VG	5.75	1	5.75	
	5	8.40	VG	4	E	2.79	F	7	VG	5.78	1	5.78	
	6	7.70	VG	6	VG	1.33	VG	8.0	VG	5.76	7	5.51-5.98	
	7	8.80	VG	7	VG	2.21	G	7.31	VG	5.48	21	5.34-5.95	
	8	8.70	VG	14	G	1.46	VG	7.18	VG	4.82	5	4.82-5.72	
	9	9.40	G	4	E	1.19	VG	7.86	VG	5.63	1	5.63	
	10	14.70	G	4	E	1.94	G	7.18	VG	5.01	1	5.01	
	11	10.90	G	5	VG	1.42	VG	7.31	VG	5.43	2	5.00-5.43	
4	1	1.40	E	33	P	2.09	G	5.10	G	3.76	1	3.76	9
	2	27.50	F	8	VG	2.03	G	5.80	G	3.97	1	3.97	
	3	24.10	F	15	G	1.92	G	4.99	G	3.69	3	3.69-3.92	
	4	13.70	G	19	F	2.03	G	4.83	G	3.94	1	3.94	
	5	42.10	P	9	VG	1.73	G	5.10	G	3.15	3	3.15-3.95	
5	1	0	E	3	E	1.45	VG	8.99	E	8.83		8.00-9.03	1785
	2	0	E	4	E	1.61	G	8.31	VG	8.57		6.68-9.02	
	3	0.50	E	4	E	2.26	F	7.45	VG	7.48		6.56-8.82	
	4	0.90	E	5	VG	1.48	VG	8.44	VG	7.16		6.14-8.33	
	5	2.60	E	11	G	1.99	G	6.95	G	5.94		5.42-7.29	
	6	2.40	E	12	G	2.74	F	6.10	G	5.85		5.27-7.29	
	7	0.30	E	19	F	2.49	F	5.12	G	5.76		4.62-6.08	
	8	0.70	E	4	E	5.19	P	6.76	G	7.25		6.51-7.97	
	9	12.40	G	12	G	4.99	P	4.30	F	4.55		3.91-4.95	
	10	11.60	G	19	F	2.40	F	4.01	F	4.07		3.54-4.41	
	11	24.70	F	17	F	3.63	P	2.51	F	3.41		2.89-3.70	
	12	29.50	P	12	G	4.22	P	2.75	F	3.64		2.37-3.64	
	13	0.10	E	21	F	3.50	P	4.42	F	5.45		4.54-5.92	
	14	41	P	17	F	4.94	P	1.78	P	2.74		2.74	

LT : Linguistic Term; E : Excellent ; VG : Very Good; G : Good; F: Fair; P : Poor.

but they are represented by high index value between 8.53 and 8.93 in MCI model. These sections are classified as good, because even they have excellent condition of cracking ratio and rutting, they have poor condition of roughness. The similar facts are found in cases 2 and 3 of finding No. 2.

- In case No. 6 of finding No. 3, pavement sections are classified as very good by FPCI model because they have very good condition of cracking ratio, rutting and roughness, but in MCI model these sections are represented by low index value between 5.51 and 5.98. The similar facts are found in other cases of finding No. 3.

The above facts could be happen because MCI model was developed by specific pavement database. It is possible that this model fail to give appropriate pavement condition assessment in some sections in other pavement database.

In finding No. 4, the FPCI model gave the appropriate pavement condition assessment in cases No. 2, 3, and 4 because the good conditions of pavement sections are represented by low index value in MCI model. MCI model gave the appropriate pavement condition assessment in cases No. 1 and 5. In these cases, the pavement sections that have poor condition of rutting or cracking ratio are represented by low index value in MCI model, but they are classified as good in FPCI model.

In finding No. 5, it was found that the results of FPCI model are in agreement with the results of MCI model. There are totally 93 cases in this finding, and 14 cases that represent all the facts found are presented in **Table 12**.

In general, the results indicate that FPCI model results are in agreement with the results of MCI model. In some sections, however, FPCI model gave more appropriate pavement condition

assessment comparing with MCI model. The FPCI model gave the appropriate pavement condition assessment in 99.8 % of pavement sections, and MCI model gave the appropriate pavement condition assessment in 93.2 % of pavement sections.

5. CONCLUSIONS

A method to determine membership functions of linguistic terms used in pavement condition assessment based on expert's opinion data were proposed and evaluated. The effects of inclusion or omission, weight changes and linguistic rating terms' range values changes of pavement parameters on pavement condition assessment using fuzzy weighted operation were analyzed. Pavement condition assessment results using the membership functions of proposed methods were compared with the results of MCI model. The major findings and the recommendations to get the better results of pavement condition assessment are summarized as follows:

- The membership functions of the proposed method can provide more reliable results in pavement condition assessment. The better results can be found because the proposed method can accommodate the experts' opinions about the linguistic rating terms' range values of pavement parameters that used to assess pavement condition.
- Inclusion or omission of pavement parameter can cause the significant differences in pavement condition assessment results. In order to get pavement condition assessment results that can be applied universally, we should use the same pavement parameters.
- The weight changes of pavement parameters also can lead to the different results in pavement condition assessment. In order to get pavement condition assessment results that can be applied universally, we should use the same pavement parameters weight for specified condition of pavement or policies of highway agency.
- The differences of the linguistic rating terms' range values of pavement parameter can also cause the changes in pavement condition assessment results. In order to get the best results of pavement condition assessment, these values must be determined based on the information collected from the experts of pavement condition evaluation.
- The FPCI model seems to be able to give better results in pavement condition assessment compare with existing MCI model.

ACKNOWLEDGMENT: The data used in this study were provided by Hokuriku Regional Development Bureau and Nagaoka National Highway Work Office of Ministry of Land, Infrastructure and Transport. Their cooperation is gratefully acknowledged. The authors are also grateful to all highway engineering experts who shared their knowledge in this study.

REFERENCES

- 1) Elton, D. J. and Juang, C. H.: Asphalt Pavement Evaluation Using Fuzzy Sets, *Transportation Research Record 1196*, Transportation Research Board, Nat. Res. Council, Washington, D.C., pp.1-6, 1988.
- 2) Juang, C.H. and Amirhanian, S.N.: A Unified Pavement Distress Index for Managing Flexible Pavements, *Journal of Transportation Engineering*, ASCE, Vol. 118, pp. 686-699, 1992.
- 3) Zhang, Z., Singh, N. and Hudson, W. R.: Comprehensive Ranking Index for Pavement Using Fuzzy Sets Modes, *Transportation Research Record 1397*, Transportation Research Board, Nat. Res. Council, Washington, D.C., pp. 96-102, 1993.
- 4) Shoukry, S.N., Martinelli, D.R., Reigle, J. A.: Universal Pavement Distress Evaluator Based on Fuzzy Sets, *Transportation Research Record 1592*, Transportation Research Board, Nat. Res. Council, Washington, D.C., pp. 180-186, 1997.
- 5) Wang, K. and Liu, F.: Fuzzy Set-Based and Performance-Oriented Pavement Network Optimization System, *Journal of Infrastructure system*, December 1997, pp.154-159, 1997.
- 6) Juang, C.H., Lee, D.H. and Sheu, C.: Mapping Slope Failure Potential Using Fuzzy Sets, *Journal of Geotechnical Engineering*, ASCE, Vol 118, No.3, pp. 475-494, 1992.
- 7) Juang, C.H.: A Performance Index for The Unified Rock Classification System, *Bull. Assoc. of Engrg. Geologist*, 27(4), pp. 497-540, 1990.
- 8) Kenji Himeno, Tsuyoshi Kamijima and Yoshitaka Hachiya: A New Method for Evaluating Pavement Surface Using Fuzzy Sets Theory, *Journal of Materials, Concrete Structures and Pavement of JSCE*, No. 538, V-31, pp. 207-213, 1996.
- 9) Schumucker, K. J.: *Fuzzy Sets, natural language computations, and risk analysis*, Computer Science Press, Inc., Rockville, Maryland, 1984.
- 10) Dong, W.M. and Wong, F.S.: Fuzzy weighted average and implementation of extension principle, *Fuzzy Sets and Systems*, (21), pp. 183-199, 1987.
- 11) Juang, C.H., Clark, J.E. and Ghost, P.: Representation, Processing and Interpretation of Fuzzy System in Civil Engineering, *Transportation Research Record 1123*, Transportation Research Board, Nat. Res. Council, Washington, D.C., pp. 20-26, 1993.
- 12) Saaty, T.L.: A Scaling Method for Priorities in Hierarchical Structure, *Journal of Math. Psych.*, 15(3), pp. 234-281, 1977.
- 13) Japan Road Association: *Handbook of Pavement Testing Method*, pp. 1012, 1988 (in Japanese).

(Received February 18, 2003)