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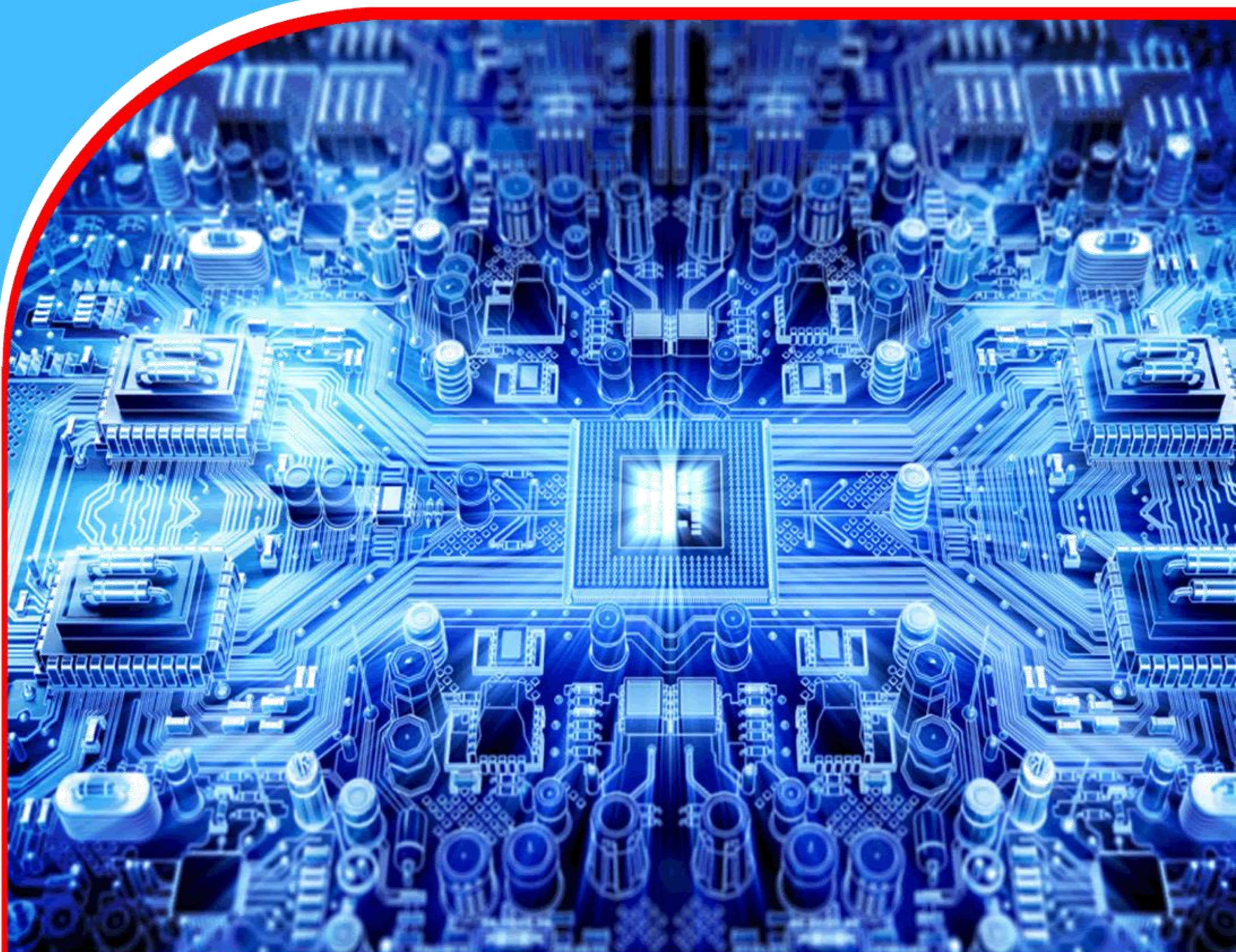

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Fuzzy Rule Based System of Optimal Pavement Maintenance and Rehabilitation Strategies for Yangon-Mandalay Expressway

Nan Htike Yee Mon[1*], Dr. Kyaing[2] & Dr. Moe Thet Thet Aye[3]
[1*]Ph.D Candidate, Transportation Engineering (Civil), Yangon Technological University
[2]Professor, Department of Civil Engineering, Yangon Technological University
[3]Lecturer, Department of Civil Engineering, Yangon Technological University

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Abstract

Purpose: Systematic pavement management plays a vital role in the better Road Asset Management system. The lifespan of pavement can be preserved and prolonged by adequate maintenance measures in proper time. By early detection and repair of defects at initial stages with predictive maintenance reduces the rapid deterioration of the pavement. Moreover, inaccuracy in pavement deterioration prediction leads to an improper maintenance with wastage of time, cost and labor strength. To overcome all of these obstacles, this paper attempts an approach on optimal pavement maintenance strategy by means of fuzzy rule-based system.

Materials and Methods: In this research, four pavement indicators of PCI, IRI, PSR and PSI have been taken into account as antecedents and five different types of pavement maintenance as consequents. In this research, ASTM D-6433, Road Lab Pro software, AASHTO guidelines and Fuzzy Logic (Mamdani) model have been used to evaluate the current pavement condition and optimal pavement maintenance strategies.

Findings: According to research area, 130 total pavement sample units were undertaken to study for the mean pavement condition of PCI value 54.93 (poor), IRI 7.01 (fair), PSR 3.33 (fair) and PSI 3.35 (fair). Due to 13 years-old life span of traffic volume, temperature and other external factors, this expressway is suffering from potholes, bleeding, longitudinal and transverse cracking, weathering, joint reflection cracking for Asphalt Concrete (AC) overlay and linear cracking, joint seal failure, scaling, faulting, depression, lane/shoulder drop off for existing concrete pavement. According to the fuzzy logic model results, 42 numbers of fuzzy If-Then maintenance rules were verified as the most relevant pavement maintenance and rehabilitation strategies for Yangon-Mandalay Expressway.

Implications to Theory, Practice and Policy: This research provide implications to the study and contributions to theory, practice and policy. This research paper insights into effective infrastructure maintenance and investment, emphasizing the role of advanced computational techniques in transportation economics. The key advantage of this research paper is to be effective, supportive, easy and accessible decision-making tool for transportation and pavement engineers, expressway planners and highways department authorities especially from developing countries.

Keywords: *PCI, IRI, PSR, PSI, Fuzzy Logic (Mamdani), Optimal Pavement Maintenance*

JEL codes: R42, C63, H54

1.0 INTRODUCTION

Regular investigation of pavement deterioration is an important part of pavement management system because poorly maintained pavement can induce accident severity and excessive road users cost over a period of time. Thus, pavement performance is usually evaluated either by the drivers' or passengers' view point of comfort and safety, or by the infrastructure administrators from their technological viewpoint of structural and functional performance (Himeno et al. 1996). Abdulhaq and Israa (2018) also proposed that many research works have been conducted to link the objective and subjective judgments with observed physical pavements condition. Depending on these studies, various performance indices have been evaluated for current pavement quality, such as Pavement Condition Index (PCI), International Roughness Index (IRI), Present Serviceability Rating (PSR), Present Serviceability Index (PSI) and so on. This research was undertaken to develop optimal pavement maintenance strategy with Fuzzy Logic (Mamdani) model for Yangon-Mandalay Expressway (YME). The Fuzzy Logic model with Fuzzy Rule-Based system is an effective tool for transportation engineering researchers. It can convert quantitative values into linguistic or qualitative variables by fuzzy membership degrees. Its feature makes it possible to gather experts' experience about the technical rule base knowledge and pavement condition database in fuzzy inference engine to determine the optimal pavement maintenance strategies for study area.

Problem Statement

Existing pavement and shoulder of YME are needed to consider maintenance and rehabilitation because the life span of pavement is over 13 years. So, now it is the time to consider optimal maintenance plan for YME. There is a limitation of the budget allocations for pavement maintenance thus effective and efficient pavement maintenance plan is certainly needed for decision makers. Moreover, frequent repairs before pavement deterioration can reduce life cycle costs without extensive rehabilitation. Therefore, it is necessary to switch from post-event/corrective maintenance to preventive maintenance strategy. Pavement inspection methods are needed as a first step to access Pavement Management System (PMS). Systematic selection of the most required road sections to rehabilitate is also very important. In addition, prioritizing the pavement maintenance sections is one of the challenges for both clients and contractors. These are the main facts for the depth of this research.

Study Area

Yangon - Mandalay Expressway (YME) is 4 lanes divided expressway and it locates between Yangon and Mandalay cities. The total length is 368 miles (589 km) for each way and from 0/0 mile to 365/3 miles (supervised by Department of Highways, Ministry of Construction, Myanmar) is chosen for study area. In this research, both ways of YME and total pavement sample units of 130 units were studied for research analysis. This expressway is earliest expressway and one of the central backbones of Myanmar. It has been constructed with AC overlay and existing concrete pavement.

Aim and Objectives

The main aim of this research is to provide effective and efficient pavement maintenance decision-making tool for transportation engineers, expressway planners and highways department authorities. The specific objectives of this research are as follows: 1. To identify the current condition of pavement according to theorize standards, 2. To propose fuzzy rule-based systems for pavement maintenance system, 3. To determine the optimal pavement maintenance and rehabilitation strategies for YME.

2.0 LITERATURE REVIEW

Pavement Condition Index (PCI)

A study by Sabaruddin and A Deni (2019 cited Hardiyatmo H.C 2007) discussed that pavement Condition Index (PCI) is a system for assessing pavement conditions by type, the level of damage that occurs and can be used as a reference in the maintenance plan. Standard practice for roads and parking lots pavement condition index surveys is issued under the fixed designation ASTM D-6433. The PCI method provides information on pavement conditions only at the time of the survey, but cannot provide a predictive picture in the future. However, by periodically conducting condition surveys, information on pavement conditions can be useful for predicting future performance, as well as being able to be used as a more detailed measurement input [24].

International Roughness Index (IRI)

The international roughness index (IRI) was developed by the World Bank in the 1980s. IRI is used to define a characteristic of the longitudinal profile of a travelled wheel track and constitutes a standardized roughness measurement. The commonly recommended units are meters per kilometre (m/km) or millimetres per meter (mm/m). The IRI was defined as a mathematical property of a two-dimensional road profile (a longitudinal slice of the road showing elevation as it varies with longitudinal distance along a travelled track on the road). As such, it can be calculated from profiles obtained with any valid measurement method, ranging from static rod and level surveying equipment to high-speed inertial profiling systems [22].

Present Serviceability Rating (PSR) and Present Serviceability Index (PSI)

One of the earliest pavement condition indices was the Present Serviceability Rating (PSR) developed at the AASHTO Road Test. The PSR was developed at the AASHTO Road Test by having raters riding in an automobile assign a pavement condition value that indicated the level of service the pavement provided. Researchers wanted, however, to measure this index objectively. Therefore, a relationship was developed between the mean PSR assigned by the panel, and some objective measurements such as roughness, rutting and cracking. The new index, which was based on the values of pavement smoothness, rutting cracking and patching was called the Present Serviceability Index (PSI) [20].

Road LabPro Software

Road Lab Pro is designed as a data collection tool for engineer by the World Bank in collaboration with Beldor Center, Softteco and Progress Analytics LLC. With accelerometers on smartphones, this app evaluates road conditions, map road networks, detects major road bumps, and reports road safety hazards. The Road Lab Pro app estimates the road roughness based on kinematic and GPS sensors in smart phones [22].

Fuzzy Rule-Based Systems (FRBSs)

S.K. Suman and S. Sinha (2012) have discussed that Fuzzy Rule-Based Systems as the following. This system is a design methodology that can be used to solve real life problems. Fuzzy sets theory resembles human decision making in its use of approximate information. It was basically used to mathematically represent uncertainty and vagueness and provide tools to deal with the imprecision in many problems. A fuzzy logic technique has the advantage of lower development costs, superior features and better end product performance [27]. The following discussion introduces the four-step fuzzy inference system employed in implementing FL efficiently: Fuzzification, Fuzzy Inference Engine, Fuzzy Rules and Defuzzification.

Fuzzification

The function of the fuzzifier is to convert a crisp numerical value from the universe of discourse of the input variable into a linguistic variable and corresponding level of belief. This step takes the current value of a process state variable and gives levels of belief in input fuzzy sets, in order to make it compatible with the fuzzy set representation of the process state variables in the rule-antecedent. The level of belief is equal to the degree of membership in the qualifying linguistic set which can take any value from the closed interval (0, 1) [27].

Fuzzy Inference Engine

The basic function of the inference engine is to compute level(s) of belief in output fuzzy sets from the levels of belief in the input fuzzy sets. The output is a single belief value for each output fuzzy set. In this stage, the fuzzy operator is applied in order to gain a single number that represents the result of the antecedent for that rule. The inference engine is mainly based on rule [27].

Fuzzy Rules

The fuzzy rules are based on expert opinion, operator experience, and system knowledge. The basic function of the rule base is to represent in a structured way the control policy of an experienced process operator and/or control engineer in the form of a set of production rules such as if (process state) and then (control output). The if-part of such a rule is called the rule-antecedent and is a description of a process state in terms of a logical combination of fuzzy propositions. Moreover, the then-part of the rule is called the rule consequent and is again a description of the control output in terms of a logical combination of fuzzy propositions [27].

Defuzzification

The function of defuzzifier is to convert the levels of belief in output fuzzy sets to a crisp decision variable of some kind. In practice, the output of the defuzzifier process is a single value from the set. There are several built-in defuzzifier methods. The centre of gravity method is the most commonly used for extracting a crisp value from a fuzzy set [27].

The Mamdani Model

This model type was introduced by Mamdani (1974) and Mamdani and Assilian (1975). It is built by linguistic variables in both the antecedent and consequent parts of the rules. So, considering multi-input and single-output (MISO) systems, fuzzy IF-THEN rules are of the following form:

IF X1 is A1 and . . . and Xn is An THEN Y is B,

where Xi and Y are input and output linguistic variables, respectively, and Ai and B are linguistic values. The standard architecture for the Mamdani model is displayed in Figure 1. It consists of four components: fuzzification, knowledge base, inference engine, and defuzzifier. The fuzzification interface transforms the crisp inputs into linguistic values (Lala Septem et al. 2015). The knowledge base is composed of a database and a rule base. While the database includes the fuzzy set definitions and parameters of the membership functions, the rule base contains the collections of fuzzy IF-THEN rules. The inference engine performs the reasoning operations on the appropriate fuzzy rules and input data. The defuzzifier produces crisp values from the linguistic values as the final results. Since the Mamdani model is built out of linguistic variables it is usually called a linguistic or descriptive system. A key advantage is that its interpretability and flexibility to formulate knowledge are higher than for other FRBSs by Lala Septem et al. (2015 cited Cordon et al. 2001) [14].

Types of Maintenance Strategy

Routine Maintenance consists of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service [7]. Preventive Maintenance is a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without significantly increasing the structural capacity) [7].

Minor rehabilitation consists of non-structural enhancements made to the existing pavement sections to eliminate age-related, top-down surface cracking that develop in flexible pavements due to environmental exposure. Because of the non-structural nature of minor rehabilitation techniques, these types of rehabilitation techniques are placed in the category of pavement preservation [7]. Major rehabilitation consists of structural enhancements that both extend the service life of an existing pavement and/or improve its load-carrying capability [7].

Pavement Reconstruction is the replacement of the entire existing pavement structure by the placement of the equivalent or increased pavement structure. Reconstruction usually requires the complete removal and replacement of the existing pavement structure. Reconstruction may utilize either new or recycled materials incorporated into the materials used for the reconstruction of the complete pavement section. Reconstruction is required when a pavement has either failed or has become functionally obsolete [7].

3.0 MATERIALS AND METHODS

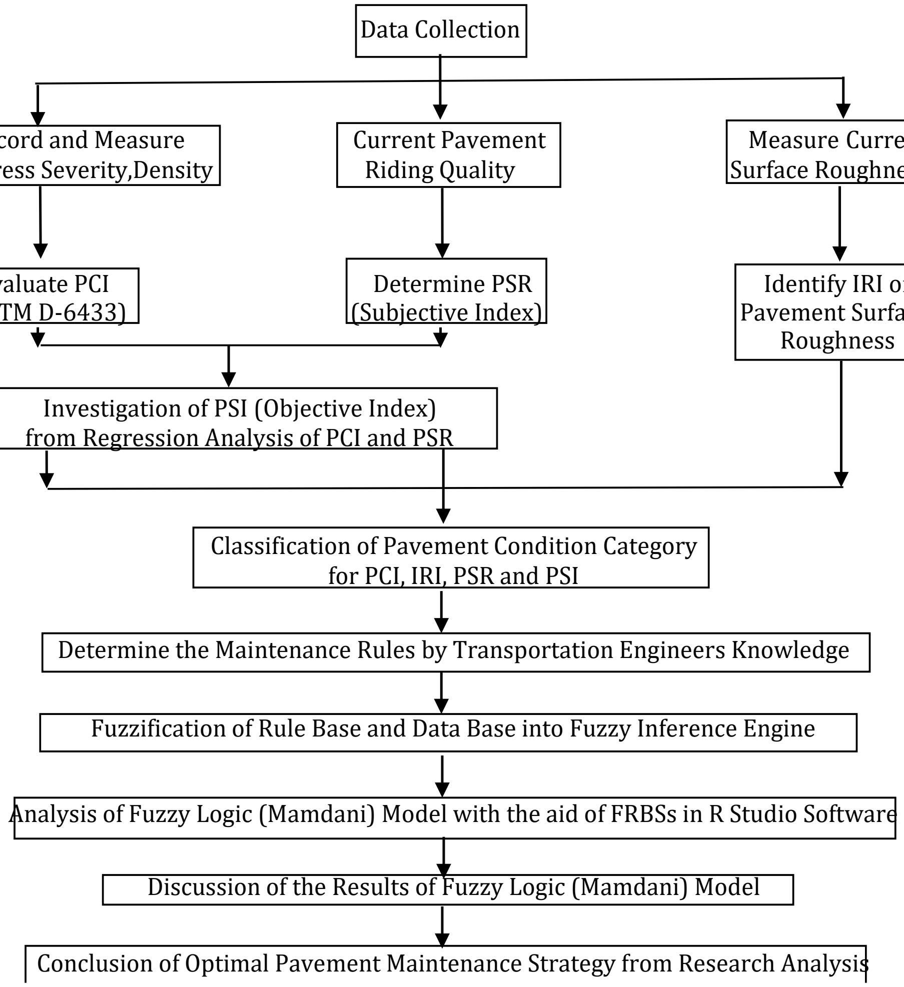

Figure 1: Methodology Flow Chart of Research

Input Data of Fuzzy Logic Model

In this research, both ways of Yangon-Mandalay Expressway (730/6 miles in length for both ways) and total 130 pavement sample units were studied for analysis. Along expressway, four road sections can be divided for each way as Yangon-Phyu, PhyuNaypyitaw, Naypyitaw-Meiktila, Meiktila-Mandalay and reversely for opposite way. Since the expressway has been constructed two pavement types, the number of pavement sample units for AC overlay pavement is 64 units and 66 units for existing concrete pavement. Review and check of sample sizes in accordance with ASTM D 6433 standard by actual standard deviation method and it was enough sample sizes for my research area. The following figure shows the PCI values of sample units from unit 1 to 60 of Yangon to Mandalay direction. Among them, unit 3, 23, 30, 43 and 53 are the highest PCI values that describe these sections are the best pavement condition. On the other hand, unit 2, 6, 11, 19, 33, 35 and 39 are the lowest PCI values which mean these sections are the poorest.

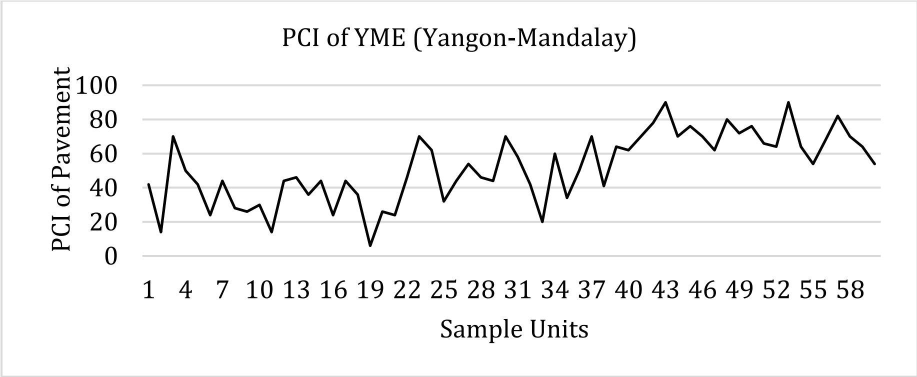

Figure 2: PCI Values of Sample Unit from 1 to 60 (Yangon-Mandalay)

The following figure presents the PCI values of sample units from unit 1 to 70 of Mandalay to Yangon direction. Among them, unit 8, 34, 36, 58 and 61 are the highest PCI values that represent these road sections are the best pavement condition. On the other hand, unit 5, 16, 24, 30, 33, 35, and 57 are the lowest PCI values which mean these sections are the worst pavement condition.

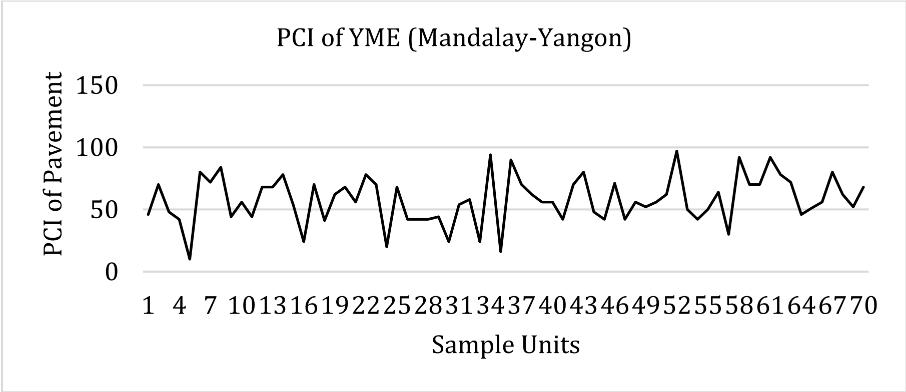

Figure 3: PCI Values of Sample Unit from 1 to 70 (Mandalay-Yangon)

IRI values of 130 pavement sample units for Yangon-Mandalay Expressway are shown in following figures. The smoothest pavement units are 49, 42, 45, 48, 50 and the roughest pavement units are 14, 35, 9, 11, 8 for Yangon to Mandalay direction.

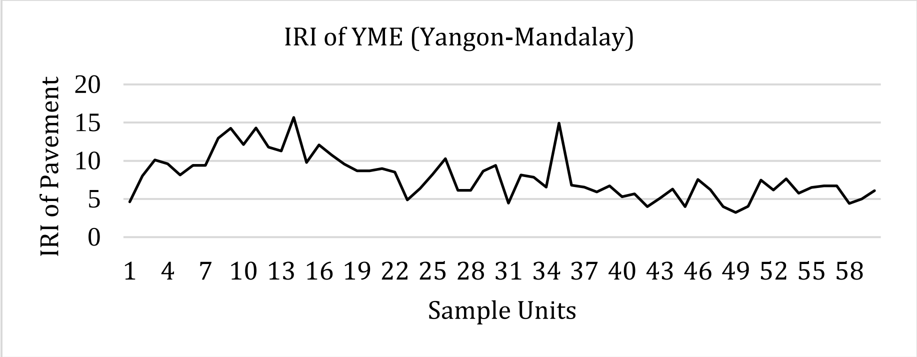

Figure 4: IRI Values of Sample Unit from 1 to 60 (Yangon-Mandalay)

The smoothest pavement units are 34, 63, 8, 36, 6 and the roughest pavement units are 30, 39, 1, 4, and 33 for Mandalay to Yangon way.

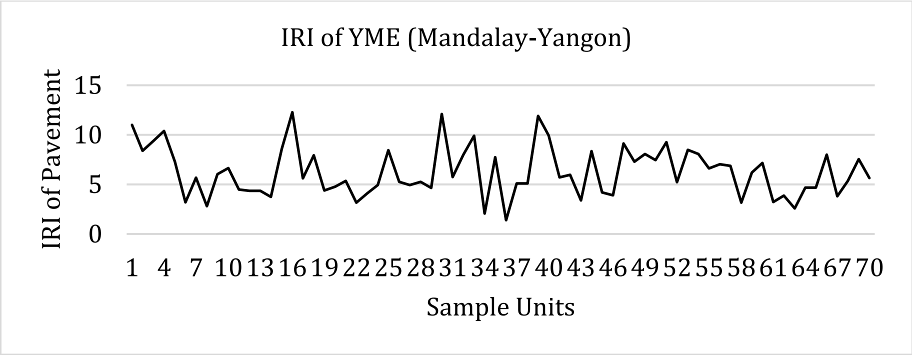

Figure 5: IRI Values of Sample Unit from 1 to 70 (Mandalay-Yangon)

The following line charts show the present serviceability rating (PSR) and the present serviceability index (PSI). Prediction of PSI is the regression analysis results of the relation between present serviceability rating (PSR) and pavement condition index (PCI).

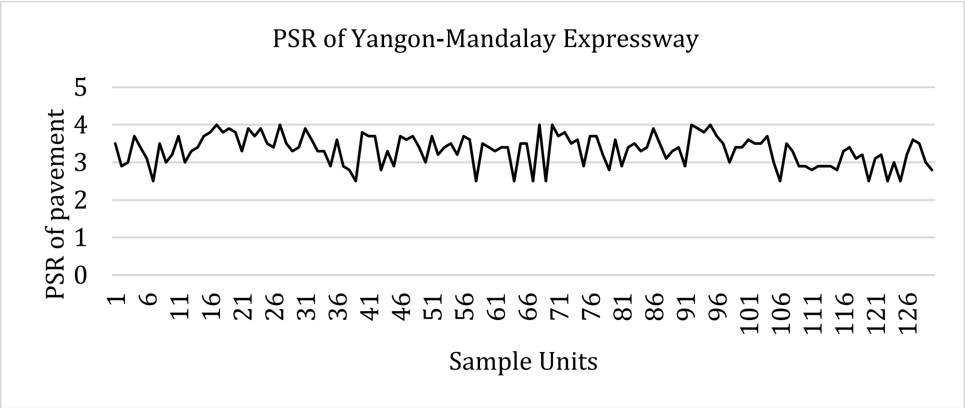

Figure 6: Present Serviceability Rating (PSR) of YME

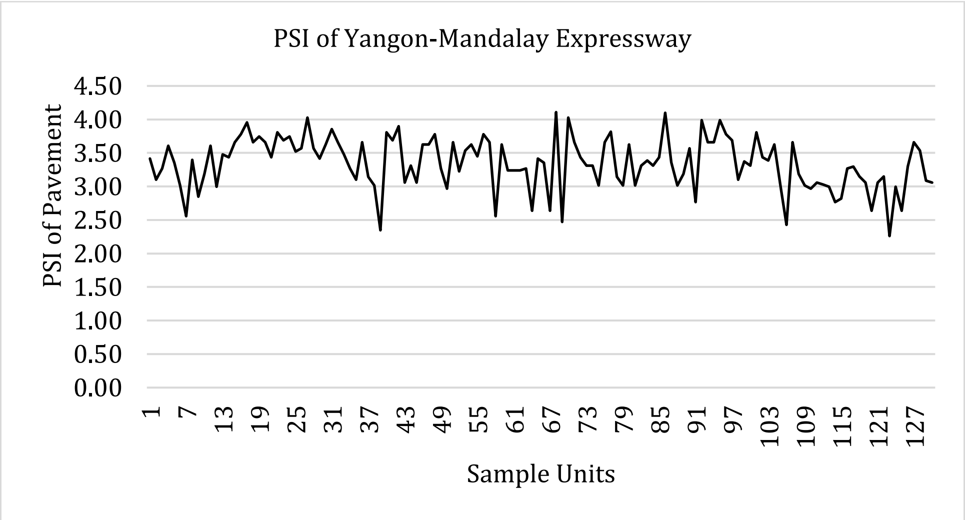

Figure 7: Present Serviceability Index (PSI) of YME

According to Table 1, pavement performance indicators rating of PCI, IRI, PSR and PSI are categorized into group 1, 2, 3, 4, 5, 6, 7 for very good, good, fair, poor, very poor, serious and failed condition respectively. The numerical values of these indices with their respective condition rating and category group are shown in Table 1.

Table 1: Pavement Performance Indicators Rating with Category Group

Category Group	Pavement Rating	PCI (ASTM D6433)	IRI (DOH, Myanmar)	PSR (Raters)	PSI (Objective Index)
1	Very Good	86-100	< , = 2	> , = 4.1	> , = 4.1
2	Good	71-85	2-4	3.6-4.0	3.6-4.0
3	Fair	56-70	4-8	3.1-3.5	3.1-3.5
4	Poor	41-55	8-12	2.6-3.0	2.6-3.0
5	Very Poor	26-40	12-16	2.1-2.5	2.1-2.5
6	Serious	11 - 25	>16	< , = 2	< , = 2
7	Failed	0 - 10			

The following tables show the category group values of PCI, IRI, PSR and PSI rate with their sample unit in accordance with the reference of Table 1. The black filled in colour is AC overlay pavement units and white filled one means concrete pavement units.

Table 2: Category Group Values of Pavement Performance Indicators for 130 Sample Units

Sample unit	PCI rate	IRI rate	PSR rate	PSI rate	Sample unit	PCI rate	IRI rate	PSR rate	PSI rate
1	4	3	4	4	26	4	4	4	4
2	6	4	5	5	27	4	3	3	3
3	3	4	3	2	28	4	3	4	3
4	4	4	3	3	29	4	4	4	3
5	4	4	4	4	30	3	4	2	2
6	6	4	4	4	31	3	3	3	3
7	4	4	4	4	32	4	4	3	3
8	5	5	4	4	33	6	3	5	5
9	5	5	4	4	34	3	3	3	3
10	5	5	4	4	35	5	5	4	4
11	6	5	4	4	36	4	3	3	3
12	4	4	3	3	37	3	3	2	2
13	4	4	3	3	38	4	3	4	4
14	5	5	3	3	39	3	3	3	3
15	4	4	3	4	40	3	3	3	3
16	6	5	5	4	41	3	3	2	2
17	4	4	3	4	42	2	2	2	2
18	5	4	3	3	43	1	3	2	2
19	7	4	5	5	44	3	3	2	2
20	5	4	4	4	45	2	2	2	2
21	6	4	5	4	46	3	3	2	2
22	4	4	3	3	47	3	3	3	3
23	3	3	2	2	48	2	2	2	2
24	3	3	3	3	49	2	2	2	2
25	5	4	4	4	50	2	2	2	2

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Table 2: Continue

Sample unit	PCI rate	IRI rate	PSR rate	PSI rate	Sample unit	PCI rate	IRI rate	PSR rate	PSI rate
51	3	3	3	3	77	3	3	2	2
52	3	3	3	3	78	4	4	3	3
53	1	3	2	1	79	3	3	3	3
54	3	3	3	3	80	3	3	3	2
55	4	3	3	3	81	3	3	3	3
56	3	3	3	2	82	2	2	2	2
57	2	3	2	2	83	3	3	2	2
58	3	3	2	2	84	6	3	5	5
59	3	3	3	3	85	3	3	3	2
60	4	3	3	3	86	4	3	3	3
61	4	4	4	3	87	4	3	3	3
62	3	3	2	2	88	4	3	3	3
63	4	4	4	3	89	4	3	3	3
64	4	4	4	4	90	6	5	5	4
65	7	3	5	5	91	4	3	3	3
66	2	2	2	2	92	3	3	3	3
67	2	3	2	2	93	6	4	5	4
68	2	2	2	2	94	1	1	2	1
69	4	3	4	4	95	6	4	5	5
70	3	3	3	3	96	1	1	2	2
71	4	3	4	4	97	3	3	2	2
72	3	3	2	2	98	3	3	2	3
73	3	3	2	2	99	3	4	3	3
74	2	2	2	2	100	3	4	2	3
75	4	4	3	3	101	4	3	4	4
76	6	5	4	4	102	3	3	2	2

Table 2: Continue

Sample Unit	PCI rate	IRI rate	PSR rate	PSI rate	Sample Unit	PCI rate	IRI rate	PSR rate	PSI rate
103	2	2	2	2	117	5	3	4	4
104	4	4	3	3	118	1	2	2	2
105	4	3	4	4	119	3	3	2	2
106	2	2	2	2	120	3	3	2	2
107	4	4	4	4	121	1	2	2	2
108	3	3	3	3	122	2	2	2	2
109	4	4	3	3	123	2	2	3	2
110	3	3	3	3	124	4	4	4	3
111	3	4	3	3	125	4	4	3	3
112	1	3	2	1	126	3	4	3	3
113	4	4	3	3	127	2	2	2	2
114	4	4	3	4	128	3	3	3	3
115	4	3	3	3	129	4	4	3	3
116	3	3	3	3	130	3	3	2	2

Discussion

According to statistical description, the minimum value of PCI is 6, maximum is 97 and its mean condition is poor. On the other hand, the minimum and maximum values of IRI are 1.39 and 15.68 respectively. For PSR, the minimum value is 2.5 and maximum is 4. Moreover, the minimum value of PSI is 2.26 and 4.11 is the maximum. Mean condition of IRI, PSR and PSI are the same, fair. All of these discussions are specifically presented in Table 3.

Table 3: Descriptive Statistics of Pavement Performance Indicators

Indicators	N	Minimum	Maximum	Mean	Mean Condition Rating	Std. Deviation
PCI	130	6	97	54.93	Poor	19.699
IRI	130	1.39	15.68	7.01	Fair	2.82
PSR	130	2.5	4.0	3.33	Fair	0.4049
PSI	130	2.26	4.11	3.35	Fair	0.39

Table 4 shows the canonical forms of rule-based system for pavement maintenance types by transportation engineers' opinion. For this rule form, there is a notification that minimum of at least two indices have to meet for one specific rule, then the proposed maintenance type can be considered. (eg. For rule 1, A unit has good PCI rate and very good IRI rate, it should be routine maintenance if PSR and PSI data cannot be available).

Table 4: Canonical Forms of Rule-Based System by Transportation Engineers' Opinion

Rule	PCI	IRI	PSR	PSI	Maintenance Types
1.	Good	Very Good	Very Good	Very Good	Routine
2.	Good or Satisfactory	Good	Good	Good	Preventive
3.	Fair or Poor	Fair or Poor	Fair or Poor	Fair or Poor	Minor Rehabilitation
4.	Very Poor or Serious	Poor	Poor	Poor	Major Rehabilitation (Initial Stage)
5.	Very Poor or Serious or Failed	Very Poor	Very Poor	Very Poor	Major Rehabilitation (Heavy Stage)
6.	Failed	Serious	Serious	Serious	Reconstruction

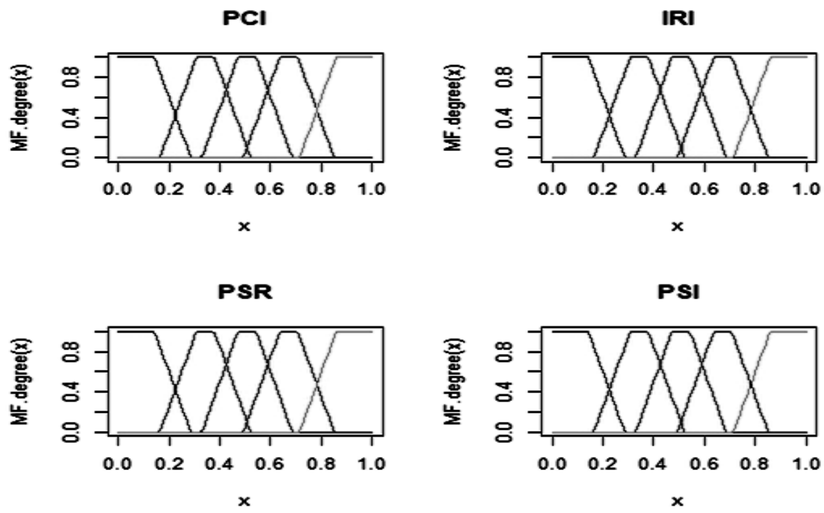

Figure 8: Fuzzy Logic (Mamdani) Model Plot: Membership Function (MF) Degrees

At first, actual numerical values of pavement performance indices (not category) were put in data preprocessing. After data preprocessing, the data base and rule base were altogether put into fuzzy inference engine with the aid of FRBSs package and R studio software. Then, analysis of Fuzzy Logic (Mamdani) model was developed and the following fuzzy IF-THEN rules for optimal pavement maintenance strategies were generated. Fuzzy Logic (Mamdani) model plot of fuzzy membership function (MF) degrees is presented in Figure 9. According to following generated fuzzy rules, there are five pavement maintenance strategies depending on the performance data of pavement.

Maintenance strategies in fuzzy IF-THEN rules are discussed below, namely:

Pavement maintenance strategy 1 - Routine maintenance,

Pavement maintenance strategy 2 - Preventive maintenance,

Pavement maintenance strategy 3 - Minor rehabilitation,

Pavement maintenance strategy 4 - Major rehabilitation (initial stage) and

Pavement maintenance strategy 5 - Major rehabilitation (heavy stage).

Generated fuzzy IF-THEN rules:

IF PCI value is	AND IRI value is	AND PSR value is	AND PSI value is	THEN Strategy is
1 very.small	medium	very.small	very.small	5
2 very.large	very.small	very.large	very.large	1
3 medium	small	medium	medium	3
4 large	small	medium	large	3
5 very.large	very.small	very.large	very.large	1
6 large	small	large	large	3
7 medium	small	medium	large	3
8 medium	medium	medium	medium	3
9 small	medium	medium	medium	3
10 small	small	small	small	3
11 small	very.large	small	medium	5
12 medium	medium	large	large	3
13 medium	large	large	medium	3
14 small	medium	small	small	3
15 large	medium	large	large	3
16 large	very.small	large	large	2
17 medium	small	large	medium	3
18 medium	medium	large	medium	3

IF PCI value is	AND IRI value is	AND PSR value is	AND PSI value is	THEN Strategy is
19 small	small	large	medium	3
20 small	large	small	medium	3
21 medium	medium	small	medium	3
22 medium	large	small	medium	3
23 medium	small	small	medium	3
24 very.large	very.small	large	very.large	2
25 small	large	small	small	5
26 very.large	small	very.large	very.large	2
27 large	small	very.large	large	3
28 large	medium	very.large	large	3
29 very.small	large	small	small	5
30 small	small	very.small	medium	3
31 small	medium	very.small	medium	3
32 small	large	very.small	medium	3
33 small	very.small	very.small	small	3
34 small	large	very.small	small	3
35 small	small	medium	medium	3
36 very.small	large	very.small	very.small	5
37 large	very small	very.large	large	2
38 medium	very.small	large	large	3
39 medium	small	large	large	3
40 small	very.small	small	medium	3
41 very.small	very.large	small	small	5
42 very.small	medium	small	small	4

Model Validation Process

Certainty Factor (CF) is the fuzzy reasoning about probability and it is one of the important indicators of model accuracy. CF value ranges from -1 to +1 depending on the term of accuracy. In this research, the output value of certainty factor (CF) of Fuzzy Logic (Mamdani) model is + 0.863 (almost certainly condition) and it indicates the positive strength and accuracy of model because the higher the certainty factor, the better and stronger the model results.

Validation of pavement maintenance strategies were investigated with the tests of correlations and regression analysis by means of the substitution of data input as 100%, 80% and 20% in the development of three (3) Fuzzy Logic models totally. Consequently, three (3) Fuzzy Logic models testified that the above-mentioned 42 fuzzy rules (100% data input) are the most accurate and relevant for the optimal pavement maintenance strategies for Yangon-Mandalay Expressway certainly.

Thus, the validated correlations and regression analysis results are shown from Table 5 to Table 10. Among these tests, correlations and regression analysis between 100% and 80% of data input is the best result than others. It means that the most of the fuzzy rule's characteristics and pavement maintenance strategies are almost the same for this analysis with adjusted R square value of 1. The second-best result is the analysis of 100% and 20% and its adjusted R square value is 0.971. The last one is analysis between 80% and 20% with adjusted R square value of 0.96.

Table 5: Correlations of 100% and 80 % of Data Input

Correlations of Maintenance Strategies			
		100 % of Data	**80 % of Data**
Pearson Correlation	100 % of Data	1.000	1.000
	80 % of Data	1.000	1.000

Table 6: Regression Analysis of 100% and 80 % of Data Input

Model Summary[b]				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	1.000[a]	1.000	1.000	0.000
a. Predictors: (Constant), 80 % of Data				
b. Dependent Variable: 100 % of Data				

Table 7: Correlations of 100% and 20 % of Data Input

Correlations of Maintenance Strategies			
		100 % of Data	**20 % of Data**
Pearson Correlation	100 % of Data	1.000	0.986
	20 % of Data	0.986	1.000

Table 8: Regression Analysis of 100% and 20 % of Data Input

Model Summary[b]				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	.986[a]	0.972	0.971	0.153
a. Predictors: (Constant), 20 % of Data				
b. Dependent Variable: 100 % of Data				

Table 9: Correlations of 80% and 20 % of Data Input

Correlations of Maintenance Strategies			
		80 % of Data	**20 % of Data**
Pearson Correlation	80 % of Data	1.000	0.981
	20 % of Data	0.981	1.000

Table 10: Regression Analysis of 80% and 20 % of Data Input

Model Summary[b]				
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**
1	.981[a]	0.962	0.960	0.175
a. Predictors: (Constant), 20 % of Data				
b. Dependent Variable: 80 % of Data				

Table 11: Root Mean Square Error (RMSE) Check

No.	Pair of Data Input	RMSE Value
1.	100 % and 80 %	0
2.	100 % and 20 %	0.189
3.	80 % and 20 %	0.189

As next validation of Fuzzy Logic (Mamdani) model, calculated Root Mean Square Error (RMSE) values are 0, 0.189 and 0.189 for checking the results of fuzzy rules' characteristics and maintenance strategies of data input paired 100% - 80%, 100% - 20% and 80% - 20% respectively. Acceptable values of RMSE are from 0.2 to 0.5 according to Rule of Thumb. Thus, these calculated RMSE values are satisfactory for this research. Results of RMSE values are shown in Table 11.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Firstly, the introduction about importance of pavement maintenance system, reliable pavement performance indicators (PCI, IRI, PSR, PSI), measurement of pavement surface roughness (RoadLab Pro software), the components of fuzzy rule-based systems (FRBSs) and types of maintenance strategies were discussed with the reference of literature review. Secondly, the research methodology flow chart including step by step detailed research works were presented. Then, practical survey data, secondary data collections, research findings and calculations were discussed with figures and tables specifically. Based on the consideration of these statistical data base and transportation engineers' knowledge rule base, Fuzzy Logic (Mamdani) model was developed with the aid of FRBSs package and R studio software. After that, the discussion of developed model with certain 42 generated fuzzy rules of maintenance strategies. Then, validation of these generated fuzzy rules of maintenance strategies was testified by certainty factor (CF), correlations, regression analysis with adjusted R square value, Root Mean Square Error (RMSE) values by result tables and discussions. Moreover, it can be clearly seen that there is satisfactory approval for developed Fuzzy Logic (Mamdani) model.

The author presented that the optimal pavement maintenance strategies through the development of Fuzzy Logic (Mamdani) model by using pavement performance indicators for Yangon-Mandalay Expressway. The generated fuzzy rules of this research can also be used for the same characteristics of other roadways. The main goal of this research paper is to be effective, easy, supportive and accessible decision-making tool of optimal pavement maintenance strategies for transportation engineers, expressway planners, decision makers and highways department authorities especially from developing countries. In addition, the results can also provide an appropriate and economically viable maintenance strategy for future. By the limitation of research time and scope, a comparative study of other pavement indices, software and models should be researched for further study.

Implications of the Study

This study provides significant contributions to the fields of theory, practice, and policy, particularly in the realm of infrastructure maintenance and transportation economics. By integrating reliable pavement performance indicators such as PCI, IRI, PSR, and PSI with advanced computational techniques like the Fuzzy Logic (Mamdani) model, this research offers a robust framework for optimal pavement maintenance strategies.

Theoretical Contributions: The development and validation of a Fuzzy Logic (Mamdani) model using FRBSs package and R Studio software represent a substantial advancement in the application of fuzzy logic to infrastructure maintenance. This study enriches the theoretical discourse by demonstrating the efficacy of integrating statistical data and expert knowledge bases to generate and validate maintenance strategies. The methodological rigor, including the use of certainty factors, correlations, regression analysis, and RMSE values, underscores the model's robustness and reliability, setting a new standard for future research in this domain.

Practical Contributions: Practically, this study equips transportation engineers and highway authorities with a powerful decision-making tool. The model's application to the Yangon-Mandalay Expressway showcases its practical relevance and adaptability to similar roadways. By offering an easy-to-use and accessible tool for devising maintenance strategies, the study addresses the practical challenges faced by engineers and planners, particularly in developing countries. The practical survey data, secondary data collections, and detailed figures and tables provide a comprehensive guide for implementing the model in real-world scenarios.

Policy Contributions: From a policy perspective, the study's recommendations highlight the importance of adopting advanced modeling techniques for infrastructure maintenance. The findings advocate for economically viable and effective maintenance strategies, supporting policymakers in making informed decisions that enhance road safety and longevity. The study's emphasis on developing countries underscores its relevance in addressing the unique challenges faced by these regions, promoting sustainable and cost-effective infrastructure management.

In summary, this study not only advances the theoretical understanding of pavement maintenance systems but also offers practical solutions and policy recommendations that can transform infrastructure management practices. By validating the Fuzzy Logic (Mamdani) model and demonstrating its applicability, the research provides a valuable tool for transportation professionals and policymakers, paving the way for more reliable and efficient road maintenance strategies in the future.

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