PERFORMANCE MODEL FOR ASPHALT CONCRETE PAVEMENT BASED ON THE FUZZY LOGIC APPROACH

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Abstract. Accurate pavement performance estimation is very important for the managing and maintaining of surface transportation infrastructure. In the present study, a new model for the prediction of present and future performance of flexible pavements is developed using the fuzzy logic approach. The database of the model is able to use numerical measurements and also linguistic statements. Many models developed in the literature neglect the parameters that have little bearing on performance. However, it is a well known fact that these parameters do have an effect on performance to some degree. Different parameters were considered in the model as accepted by the authorities, and as having little bearing on performance. For each parameter, a certain weight was appointed, and the parameters that affected performance were assigned greater weights while the others were assigned smaller weights. As a result, the current model in the fuzzy logic approach is more flexible than the current Pavement Serviceability Index (PSI) and Pavement Condition Index (PCI) models. The model is different from previous fuzzy logic based models. Two stages of the fuzzy logic approach were used in these models. Since this new methodology does not need any mechanical tests, the model can be adopted by the Pavement Management System (PMS) of developing countries.

Keywords: pavement performance, performance prediction, fuzzy logic.

Introduction

Pavement performance is a function of its relative ability to serve traffic over a period of time. Relative ability of pavement in service was determined quite subjectively by visual inspection and experience. However, individual decisions made from similar data were often inconsistent. After the 1950s, measurements such as roughness, deflection and skid resistance began to appear that could quantify pavement performance. After the AASHO Road Test was established (AASHO 1962) the Present Serviceability Rating (PSR) based on individual observation was developed. The PSR ranges from 5 (excellent) to 0 (impassable). Since PSR is based on passenger interpretations of ride quality, it gives us an idea about pavement roughness. The Present Serviceability Index (PSI) is based on the original PSR. Since PSR was a ride quality rating that required a panel of observers and was not practical for large scale networks, a non-panel based system was needed. Therefore PSR values

of various roads in Illinois, Minnesota and Indiana were obtained by a panel of raters and this information was then correlated with various pavement measurements, such as profile and cracking, to develop Pavement Serviceability Index (PSI) equations. PSI is based on the same five-point rating system as PSR.

Setting the priorities for pavement maintenance and rehabilitation depends on the availability of a universal scale for assessing the condition of every element in the network. The condition of a pavement section has traditionally been assessed by several condition indexes. The Present Serviceability Index (PSI) is one common evaluator used to describe the functional condition with respect to ride quality. The Pavement Condition Index (PCI) is another commonly used index to describe the extent of distress on a pavement section (Shoukry *et al.* 1997). PCI is based on the visual inspection of pavement distresses. Although the relationship between pavement distresses and performance is not well defined, there is general agreement that the ability of a pavement to

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sustain traffic loads in a safe and smooth manner is ad-
versely affected by the occurrence of distress. The rating
method provides a procedure for uniformly identifying
and describing pavement distress in terms of severity
and extent. The mathematical expression for PCI pro-
vides an index reflecting the composite effects of various
distress types, their severity and their extent on the over-
all condition of the pavement (Saraf 1998; Shahin 2006).

Prediction of future pavement condition is not only
essential for maintenance budget forecasting at the net-
work level but also for determining the most cost-effec-
tive rehabilitation strategy at the project level (Bandara,
Gunaratne 2001). The knowledge of future pavement
performance is also essential to sound pavement design
and life-cycle economic evaluation at the project level
of pavement management. At the network level, such
information is important to ensure adequate financial
funding and budgeting (Fwa, Sinha 1986).

Pavement failure is a variable event that not only
depends on layer material properties, environmental
and subgrade conditions and traffic loading, but also on
the specific definition of failure adopted by the highway
agency. Failure can be defined in terms of amount of
cracking, rut depth, surface roughness, or combinations
of these or other indicators of performance (Madanat
et al. 2002).

Many pavement deterioration models are based on
regression techniques (AASHO 1962; Akhter, Witczak
1985), neural networks (Attoh-Okine 1999, 2001; Choi
et al. 2004; Terzi 2007; Kargah-Ostadi *et al.* 2010), and
Markovian processes (Haas *et al.* 1994; Butt *et al.* 1995).
The basic shortcoming of current models is the lack of
uniqueness due to their dependency on data used to
generate their formulas. These types of models need
more historical data to predict accurate pavement per-
formance. It can be said that a disadvantage of the mod-
els is that they can only be used in the section where
data are collected since the model calibration is only
valid for the considered section.

Subjective evaluations can be analysed using fuzzy
set mathematics. Therefore, in response to the need for
analytical tools that can incorporate subjective judgment
and qualitative evaluations in pavement management
systems, several researchers in recent years have ex-
plored the use of fuzzy sets (Juang, Amirkhanian 1992;
Shoukry *et al.* 1997; Cheng *et al.* 1996; Bandara, Gu-
naratne 2001; Bianchini, Bandini 2010; Pan *et al.* 2011;
Moazami *et al.* 2011).

In the present study, a fuzzy logic approach was de-
veloped to predict pavement performance without us-
ing any mechanistic measurements, such as deflection or
profile data. The model contains all possible distresses in
asphalt pavements and allows predictions of the present
and future performance of the pavement. The model is
especially suitable for the PMS of developing countries
and low volume roads. Many developing countries have
a limited number of road rater equipment to collect data
for all networks. Therefore, highway agencies generally
use the equipment to collect data for high volume roads
rather than low volume roads.

1. Pavement Performance

Performance is a general term for pavements in chang-
ing conditions or serving an intended function with ac-
cumulative use (Lytton 1987). For performance analysis,
some information is needed on the history of the riding
quality of a particular section of pavement for a chosen
time period, and the traffic during that time. This can be
determined by periodic observations or measurements
of the pavement riding quality coupled with records of
traffic history and time. It is the history of deterioration
of the ride quality or serviceability provided for the user,
which defines pavement performance, as shown in Fig. 1
(Haas *et al.* 1994).

The Present Serviceability Index (PSI) is based on
the original AASHO Road Test. Basically, the PSI was
a ride quality rating that required a panel of observers
to actually ride in an automobile over the pavement in
question. Since this type of rating is not practical for
large-scale pavement networks, a transition to a non-
panel based system was needed. Table 1 shows PSI rating
scale.

Table 1. PSI rating scale

PSI	Ride rating	Appearance rating
100	New – no roughness or cracks	Looks dark and smooth
80	Minor roughness	Cracks cannot be felt while driving; Minor cracks are barely visible
60	Noticeably rough	Cracks can be felt while driving; Cracks are clearly visible; Weathered surface
40	Very rough	Transverse cracks at short intervals; Longitudinal cracks present
20	Very rough	Difficult to maintain speed; Heavily distressed; Transverse, longitudinal and block cracking present

To transition from a PSR serviceability measure
(panel developed) to a PSI serviceability measure (no
panel required), a panel of raters during 1958 to 1960
rated various roads for PSR. This information was then
correlated to various pavement measurements (such as
slope variance (profile), cracking, etc.) to develop PSR
equations. Thus, although PSI is based on the same
5-point rating system as PSR it goes beyond a simple
assessment of ride quality (AASHO 1962; Nakamura
1962):

$$PSR = 5.03 - 1.91 \cdot \log(1 + SV) - 0.01 \cdot \sqrt{C + P} - 1.38 \cdot RD,$$

where: *PSI* – the Present Serviceability Index; *SV* – the
mean of the Slope Variance in the two wheel paths;
C + *P* – a measure of cracking and patching in the pave-
ment surface; *RD* – a measure of rutting in the wheel
paths.

The PCI is a numerical index, ranging from 0 for a
failed pavement to 100 for a pavement in perfect condi-

tion. Calculation of the PCI is based on the results of a visual condition survey in which distress type, severity, and quantity are identified. The PCI was developed to provide an index of the pavement's structural integrity and surface operational condition. The distress information obtained as part of the PCI condition survey provides insight into the causes of distress and whether it is related to load or climate.

The degree of pavement deterioration is a function of distress type, distress severity, and amount or density of distress. Producing one index that would take into account all three factors was a considerable challenge. To overcome this challenge, 'deduct values' were introduced as a type of weighing factor to indicate the degree of effect that each combination of distress type, severity level, and distress density has on pavement condition. The deduct values were developed based on in-depth knowledge of pavement behaviour, input from many experienced pavement engineers, field testing and evaluation of the procedure, and accurate descriptions of distress types and severity levels. The sum of the deduct values is corrected based on the number and value of the deducts and the corrected sum is subtracted from 100 to obtain the PCI (Shahin 2006; Saraf 1998) The mathematical expression for PCI is as follows:

$$PCI = 100 - \sum_{i=1}^{n} Deduct_i,$$

where: n – number of observable distresses; *Deduct* – weight for distress, weight for severity, weight extent.

Traffic data is used in pavement management for the prediction of performance and the assignment of priorities during the selection of rehabilitation projects. For the selection of projects, a measure of traffic volumes is suitable. The Average Annual Daily Traffic (AADT) is a common measure of total traffic on the section (Jung *et al.* 1976; Haas *et al.* 1994; Tavakoli *et al.* 1992). It is the total volume of vehicle traffic of a highway or road for a year divided by 365 days. Performance modelling, on the other hand, requires an estimate of heavy vehicle traffic, which generates the majority of distress. The usual measure is total 8.2 t (18-kip) Equivalent Single-Axle Loads (ESAL) which can be used to estimate the quantity of vehicles that damage the pavements or that the pavement has carried or is expected to carry (Fwa, Sinha 1991, 1992; Berger *et al.* 1991; Owusu-Ababio 1998; Prozzi, Madanat 2003). However, in some of the studies, only pavement age or traffic was considered (Figs 1 and 2), (Shahin, Becker 1984). In the development of this model, ESAL was considered. ESAL was calculated as flexible pavement ESAL equation (AASHTO 1993) that was given in below:

$$\frac{W_x}{W_{18}} = \left(\frac{L_{18} + L_{2s}}{L_x + L_{2x}} \right)^{4.79} \cdot \left(\frac{10^{\frac{G}{\beta_x}}}{10^{\frac{G}{\beta_{x18}}}} \right) \cdot (L_{2x})^{4.33};$$

$$G = \log \left(\frac{4.2 - pt}{4.2 - 1.5} \right);$$

$$\beta = 0.4 + \frac{0.081 \cdot (L_x + L_{2x})^{3.23}}{(SN + 1)^{5.19} \cdot L_{2x}^{3.23}},$$

where: W – axle applications inverse of equivalency factors (where W_{18} = number of 18000 lb (80 kN) single axle loads); L_x – axle load being evaluated (kips); L_{18} – 18 (standard axle load in kips); L_2 – code for axle configuration (1 – single axle, 2 – tandem axle, 3 – triple axle); x – axle load equivalency factor being evaluated; s – code for standard axle (1 – single axle); G – a function of the ratio of loss in serviceability at time t, to the potential loss taken at a point where $p_t = 1.5$; p_t – 'terminal' serviceability index (point at which the pavement is considered to be at the end of its useful life); β – function which determines the relationship between serviceability and axle load applications; SN – structural number.

Material and construction quality can also affect performance; therefore, any pavement performance model should contain these factors, which may be obtained from pavement construction records. These parameters are especially important in predicting the future performance of newly constructed or rehabilitated pavements. If high quality materials were used in the pavement construction, one could expect to see a long-lasting pavement that is performing well. Therefore, if pavement history is available, the pavement performance model should contain these parameters.

Environmental factors are also considered regarding pavement performance and pavement structure de-
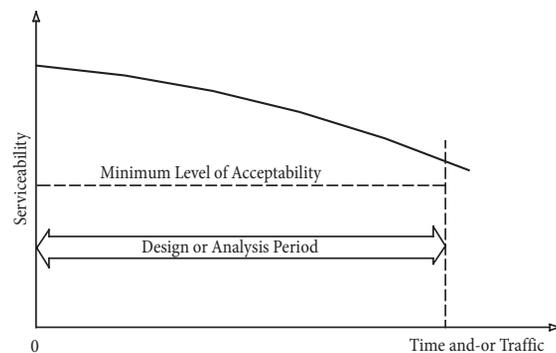
Fig. 1. Deterioration of ride quality or serviceability (Haas *et al.* 1994)
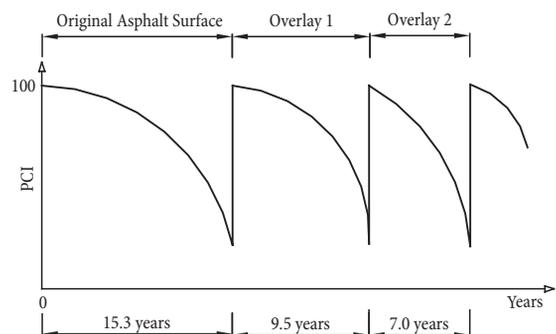
Fig. 2. Average age of asphalt surface before overlay (Shahin, Becker 1984)

sign. For instance, temperature affects the creep properties of asphalt concrete, thermal-induced stresses in asphalt concrete, and the freezing and thawing of roadbed soil. Since temperature is one of the main reasons for many distresses, care was taken to include it in the model.

Drainage of water from pavements has always been an important consideration in road design; however, current methods of design have often resulted in base courses that do not drain well. This excess water combined with increased traffic volumes and loads often leads to early pavement distress in the pavement structure (AASHTO 1986). As the water content of bases and subbases increases, there is a reduction in supporting power and an increase in the rate of loss of serviceability of the pavements. Free water in hot-mix asphalt (HMA) pavements contributes to shrinkage cracking and to oxidation and loss of flexibility, which can lead to cracking and general deterioration of wearing courses and stabilized bases. Free water is almost always associated with the breaking out of chunks of pavements constructed of two or more successive layers of similar paving material (Cedergren 1974). Therefore, since the drainage is generally neglected in developing countries, many asphaltic-concrete pavements lose service capability at a relatively early stage. For this reason drainage needs to be included in any pavement performance model.

In the past, pavement condition was often determined quite subjectively by visual inspection and experience. Therefore, individual decisions made from similar data were often inconsistent. Determination of pavement performance consists of some degree of fuzziness and the fuzzy logic modelling technique is one of the best approaches with which to handle fuzziness.

2. Fuzzy Logic Approach

The basic elements of each fuzzy logic system are, as shown in Fig. 3, rules, fuzzifier, inference engine, and defuzzifier. Input data are most often crisp values. The task of the fuzzifier is to map crisp numbers into fuzzy sets (cases are also encountered where inputs are fuzzy variables described by fuzzy membership functions). Models based on fuzzy logic consist of 'If–Then' rules.

For fuzzy rule-based systems, the rule base is formed with the assistance of human experts. Recently, in some research, numerical data has been used as well as a combination of numerical data-human experts. An interesting case appears when a combination of numerical information obtained from measurements and linguistic information obtained from human experts is used to form the fuzzy rule base. In this case, rules are extracted from numerical data in the first step. In the next step this fuzzy rule base can (but need not) be supplemented with the rules collected from human experts. A fuzzy rule base obtained from numerical data can be used to solve the same type of problem solved by artificial neural networks. The inference engine of the fuzzy logic maps fuzzy sets onto fuzzy sets. A large number of different inferential procedures are found in the literature. In most papers and practical engineering applications, minimum inference or product inference is used.

During defuzzification, one value is chosen for the output variable. The literature also contains a large number of different defuzzification procedures. The final value chosen is most often either the value corresponding to the highest grade of membership or the coordinate of the center of gravity (Teodorovic, Vukadinovic 1998; Teodorović 1999).

3. Previous Pavement Performance Models with The Fuzzy Logic Approach

Generally, regression techniques have been used to obtain functions that are limited to the available database. The functions may suffer from inaccuracies due to error in data collection and recording (Shoukry *et al.* 1997). Therefore, there is a need to develop a more generalized pavement performance model to enable efficient management of large transportation networks. The fuzzy logic approach does not need any data to calibrate the model and therefore the model is universal.

Juang and Amirkhanian (1992) developed a fuzzy based Unified Pavement Distress Index (UPDI), considering the distresses of alligator cracking, rutting, potholes, patching, block cracks and longitudinal cracks that indicates pavement condition. In the developed model each distress has different weights for the calculating of UPDI. If *UPDI* = 0 then the pavement is in perfect condition, if *UPDI* = 1 then the pavement is in the worst condition.

Shoukry *et al.* (1997) developed a Fuzzy Distress Index (FDI) which combines the extent of structural distress with performance parameters such as roughness to describe the overall condition of a pavement section.

Bandara and Gunaratne (2001) used the mathematical techniques of fuzzy sets to deal with the subjectivity associated with the human judgment of distress severity and extent. Finally, a fuzzy pavement condition forecasting model was also developed by incorporating subjective probability assessments regarding pavement condition deterioration rates in the Markov transition process.

Previous fuzzy based pavement performance models mentioned above focused on few parameters, such as alligator cracking, rutting, potholes, patching, block cracks and longitudinal cracks (Juang, Amirkhanian 1992). However, Shoukry *et al.* (1997) proposed another fuzzy based model which has fourteen parameters, namely alligator cracking type, alligator cracking severity, alligator cracking extent, linear cracking type,
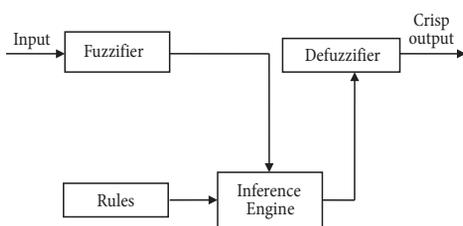
Fig. 3. Basic elements of a fuzzy logic

linear cracking severity, linear cracking extent, sealing, average rut depth, patching, appearance, flushing/ravelling, shoulder condition, roughness and skid number. It is always possible to add another parameter into the model. Previous models were able to predict the current condition of pavement performance at project level. Therefore, there is a need for a new fuzzy logic model that could predict both the present and future performances of a pavement, which is the main aim of this present research.

4. Developing a New Software for Pavement Performance

A new fuzzy logic model has been developed to predict both the present and future performance of a pavement. The structure of the model for predicting pavement performance is shown in Fig. 4. The approach used in developing the model is fuzzy logic with two stages that are configured in such a way that it is different from previous fuzzy based models. The inputs to the first part of the model are variables that do not require any mechanistic measurements such as deflection. Output of the first part of the model is all possible distresses that probably occur, and these distresses are also the input for the second part of the model. The output of the second part of the model is the Fuzzy Pavement Serviceability Index (FPSI), that is, the pavement serviceability index based on the fuzzy logic approach. The reason for using the fuzzy logic approach with two stages is that there is no direct relationship between pavement serviceability index and factors causing distress. If only the second part of the model is used, the FPSI can be determined at project level. If the first and second parts of the model are used together, future FPSI can be predicted at network level. The model can also be used to conduct "what if" analyses to study the effects of various budget levels on future pavement condition.

Numerical variables in the model are considered with triangular membership functions and an example is shown in Fig. 5. However, linguistic variables were also used in the rule base. Table 2 shows variables used in the model and the ranges of variables. The effect of distresses on pavement is taken for each distress and rearranged to include other distresses. In the model, the distress having the highest membership degree was considered for each group (Table 3).

It is obvious that causes of distresses that are input in the first part of the model have no effect on any other distresses. Therefore, a sub-model was developed for each distress type to consider the effect of different factors. Some of the sub-models are shown in Fig. 6.
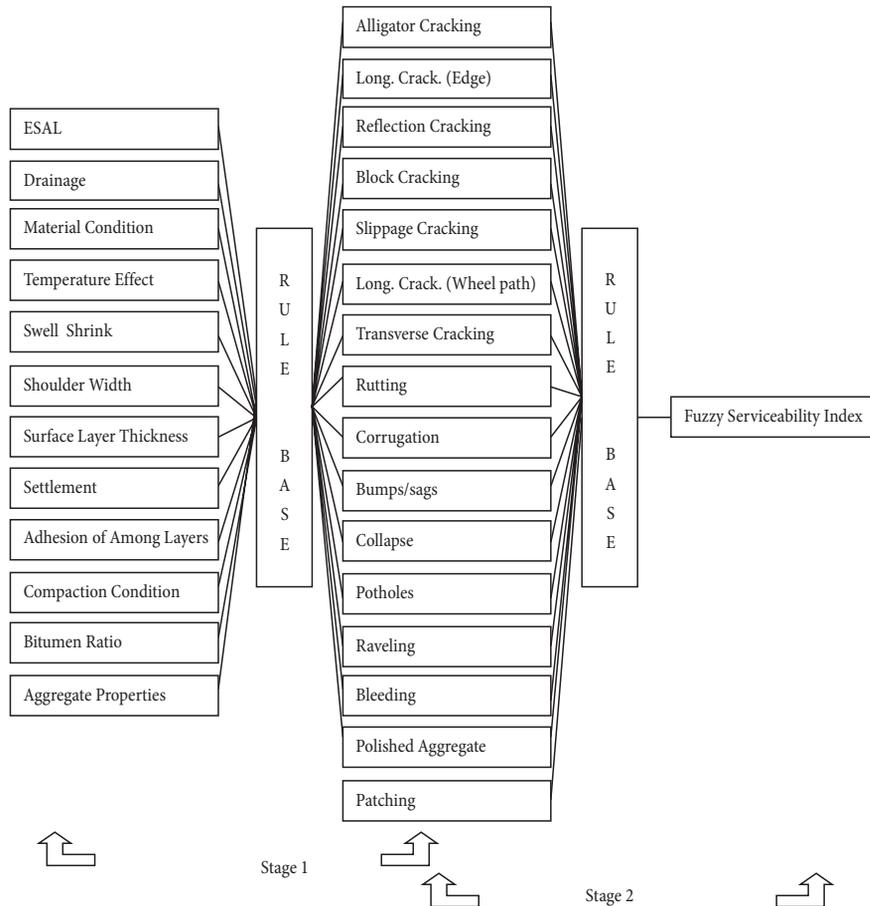
Fig. 4. General structure of the model
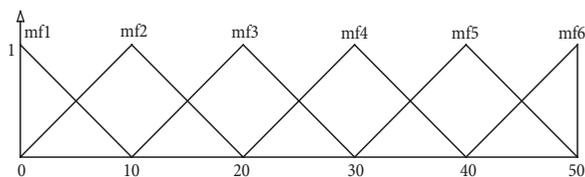
Fig. 5. Membership function of rutting

Table 2. Variables used in the model and ranges

Linguistic Variables	Range	
Drainage	Sufficient–Insufficient	
Material condition	Bad–Average–Good	
Swelling–shrinking	Little–Average–Much	
Settlement	Little–Average–Much	
Adhesion of among layers	Little–Average–Much	
Compaction condition	Bad–Average–Good	
Bitumen ratio	Little–Average–Much	
Aggregate properties	Bad–Average–Good	
Numerical Variables	Range (min÷max)	Unit
Cumulative equivalent axle load number	0÷150000000	Number
Climate	0÷40	°C
Shoulder with	50÷300	cm
Surface layer thicknesses	19÷27	cm
Alligator cracking	0÷60	m^2
Longitudinal cracking (edge)	0÷20	mm
Reflection cracking	0÷20	mm
Block cracking	0÷20	mm
Slippage cracking	0÷20	mm
Longitudinal cracking (wheel path)	0÷20	mm
Transverse cracking	0÷20	mm
Rutting	0÷50	mm
Corrugation	0÷10	mm
Bumps/sags	0÷20	mm
Collapse	0÷50	mm
Potholes	0÷50	mm
Raveling	0÷10	m^2
Bleeding	0÷100	m^2
Polished aggregate	0÷100	m^2
Patching	0÷100	m^2
Serviceability index	1.25÷4.14	

All inputs and outputs are connected to each other with rules in the sub-models. Some rules related to Fig. 6c are shown:
– if ESAL is much and compaction condition is bad and temperature is much then rutting is much;
– if ESAL is low and compaction condition is good and temperature is normal then rutting is little.

Table 3. Weights among different types of distresses for assessment of pavement conditions

Distress Type	Weight	
	Description	Letter Grade
Alligator cracking	Extremely important	E
Rutting Potholes Collapse	Very important	D
Patching Block cracking Longitudinal cracking (wheel path)	Important	C
Longitudinal cracking (edge) Reflection cracking Slippage cracking Transverse cracking Corrugation	Moderately important	B
Bleeding Raveling Polished aggregate Bumps/sags	Relatively unimportant	A

a)

b)

c)
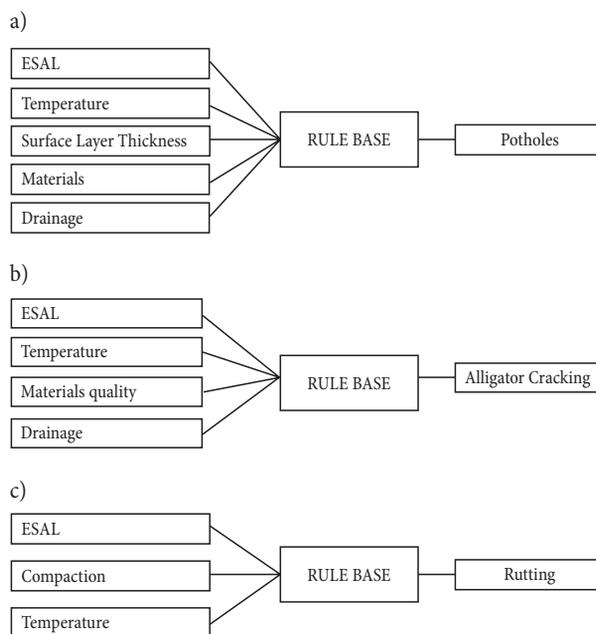
Fig. 6. Sub models of: a – potholes; b – alligator cracking; c – rutting

To combine all sub-models, a computer program was developed in *Visual Basic* programming language. Fuzzy mathematics was used in calculations. The algorithm used in the program is shown in Fig. 7 and an output of the program is shown in Fig. 8. The user can select either project level or network level pavement performance prediction. If the project level is chosen, distress type and its extent needs to be entered. However, if network level, in other words future pavement performance prediction is chosen, factors causing distresses need to be known.

Fig. 7. Algorithm used in the program

Fig. 9. Relationship of ESAL with FPSI of drainage
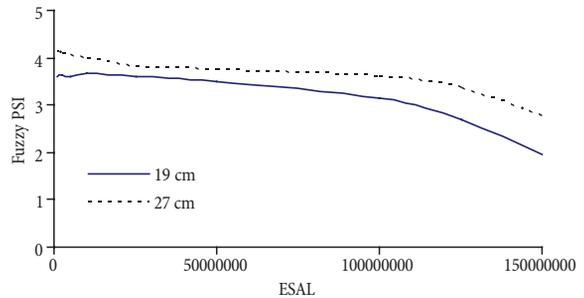
Fig. 10. Relationship of ESAL with FPSI of various layer thicknesses values
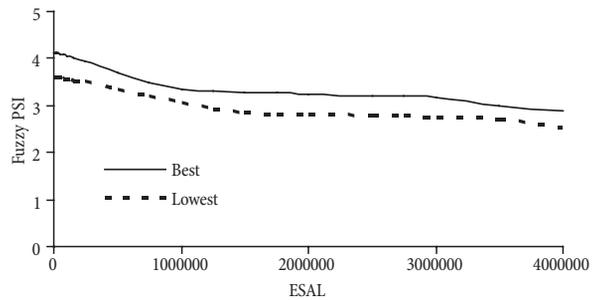
Fig. 11. Relationship of ESAL with FPSI of various materials quality

5. Case Study

To show pavement performance change with different variables, user friendly software was developed in *Visual Basic* programming language. A change in serviceability index could be obtained for each variable causing distresses and ESAL. It is possible to obtain many graphics to show the effect of all variables, and some of them are shown here. Fig. 9 shows the effect of drainage on the FPSI. As the number of ESAL was increased, the FPSI considerably decreased, and distresses such as alligator cracking, edge cracking and settlement may occur. Fig. 10 shows the effect of pavement thickness on the FPSI. As the pavement thickness increased, the FPSI increased. The effect of material quality used in pavement structure on the FPSI is shown in Fig. 11.

As expected, low quality material gives a lower FPSI and at high ESAL values, the FPSI decreases considerably. Fig. 12 shows the effect of compaction of pavement materials. Low compaction causes a dramatic decrease in the FPSI from the beginning and shows how compaction is important for the FPSI. Because of this difference, the FPSI results were multiplied by 20.

Fig. 13 shows effect of adhesion of between layers. As it can be seen in this figure, adhesion is one of the important factors for pavement performance. The adhesion inadequate is decrease of the pavement performance with ESAL value.

Another important factor is compaction of the pavement layers. Effect of compaction was given in

Fig. 8. Result of the calculation of FPSI value

Fig. 14. The compaction inadequate is dramatically decreased of the pavement performance more than adhesion inadequate. Weather conditions are one of the important factors for pavement performance because of the characteristics of bitumen change depending on the temperature.

Fig. 15 shows that effect of temperature. As it can be seen in this figure, more high and low temperature is negative effect of the pavement performance. Also this negative effect is increase with traffic value.

To demonstrate model validation, data (Table 4) from Jahren *et al.* (1998) were compared to the model
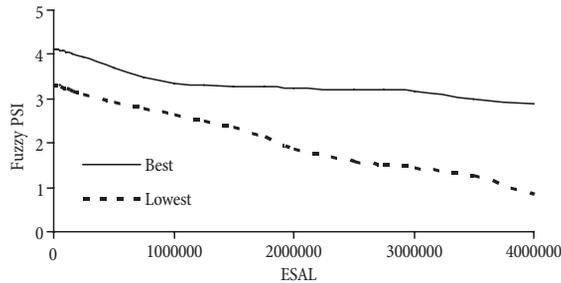
Fig. 12. Effect of compaction of pavement materials
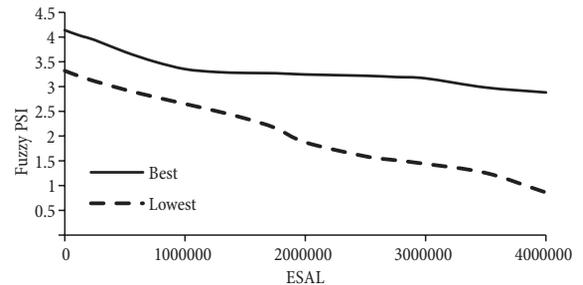
Fig. 14. Effect of Compaction

Fig. 13. Effect of adhesion of between layers
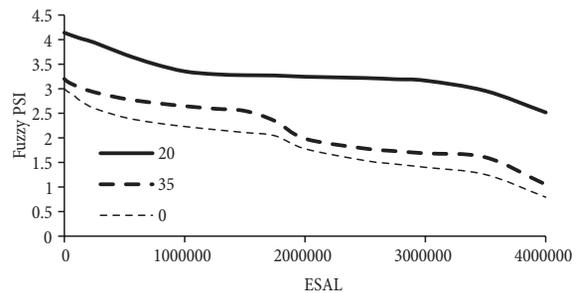
Fig. 15. Effect of Temperature

Table 4. Road surveyed 1996 and 1997 (Jahren *et al.* 1998)

County	Road	AADT	Age	Alligator cracking	Block cracking	Edge cracking	Longitudinal cracking	Raveling	Rutting	Slippage	Shoving	Transverse cracking	PSI	PCI	(PSI + PCI)/2
Guthrie	IA–4	820	2	0	0	0	0	0	0	0	0	0	90	100	95.0
Butler	T–16	470	3	0	0	0	0	0	0	0	0	0	81	100	90.7
Calhoun	IA–175	1920	3	0	0	0	0	0	0	0	0	0	81	100	90.7
Muscatine	F–70	950	3	0	0	0	0	0	0	0	0	0	82	100	90.8
Hardin	D–35	665	4	0	8	0	0	0	3	0	0	8	65	85	75.0
Boone	E–52	290	5	0	0	3	0	0	0	0	0	2	73	95	83.8
Muscatine	G–28	940	5	0	0	0	0	0	0	0	0	2	73	98	85.3
Tama	V–18	550	5	0	0	0	0	0	0	0	0	0	70	100	85.0
Cerro	Gordo S.S	600	6	0	0	0	4	0	1	0	0	14	61	81	71.2
Tama	E–66	1080	6	0	0	0	0	0	0	0	0	6	61	94	77.0
Winnebago	R–34	620	6	0	0	0	0	0	0	0	0	10	63	90	76.3
Winnebago	R–60	340	6	0	28	0	0	0	0	0	0	0	63	72	67.3
Cerro	Gordo B–43	570	7	0	12	0	11	0	8	0	14	3	68	77	72.3
Clinton	Z–30	850	7	0	0	0	0	0	0	6	0	1	64	93	78.4
Greene	IA–144	1110	7	33	1	0	4	0	17	0	0	7	58	60	59.0
Boone	198TH	300	8	18	0	0	3	0	17	0	0	0	59	71	64.9
Muscatine	Y–14	990	9	0	0	0	5	16	9	54	0	7	61	52	56.4
Clinton	E–50	520	10	0	0	0	1	0	10	0	0	15	51	81	66.2

results (Fig. 16). To this aim, the FPSI was estimated only for use at network level (second level). As seen in Table 2, the serviceability index (FPSI) was estimated using 0÷5 ranges. However, Jahren *et al.* (1998) estimated the PCI (pavement condition index) using 0÷100 ranges. As a result of this difference, the FPSI results were multiplied by 20. The comparison thus resulted in a regression value of 0.80. Actually, if Jahren *et al.* (1998) were to not use cold in-place asphalt recycling in their work, it could be of more value. Also, they obtained to regression value as 0.78 for PSI and 0.49 PCI using linear regression lines extrapolating into the future and 95% confidence intervals. Our model has more high regression value than that work. Some statistical compares are given in Table 5. As seen in the Table, our model has more successful values than the PCI calculations.
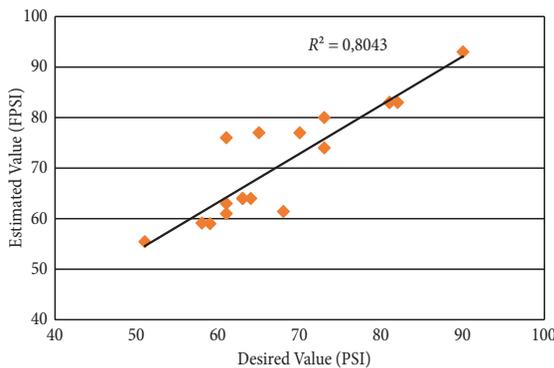
Fig. 16. Comparison of desired value with estimated value

Table 5. Comparing of models statistical values

	PSI	PCI	FPSI
Mean (average)	68	86.05556	70.94267
Standard deviation	10.1865	14.79059	10.93558
Variance (standard deviation)	103.76471	218.76144	119.587
Population standard deviation	9.89949	14.37387	10.62748
Variance (population standard deviation)	98	206.60802	112.94328
Sum of Squared Error (SSE)	1764	3718.9445	2032.979
Mean Squared Error (MSE)	98	206.60803	112.94328

Conclusions

A new model for performance prediction of flexible pavements was developed using the fuzzy logic approach. The model is different from previous fuzzy based performance models since it has two stages to predict both the current and future performance of asphalt pavements. The addition of a new parameter or excluding a parameter is always possible, therefore the model is more flexible than previous flexible pavement performance models based on a specific dataset. Another advantage of the model is it finds answers to 'what–

if' scenarios. The model developed in the research work considers all distresses in the pavement and causes of these distresses. Therefore, the model allows predicting the present condition of the pavement at project level, and in addition, the future condition of the pavement can also be predicted at network level.

Considering all the work, this model is more suitable for network level. The model can also predict the performance of new and rehabilitated pavements.

The new methodology proposed in the paper can be used in developing countries and small municipalities where only limited resources and datasets are available. A possible limitation of the model may be that collecting the required date using the model as input may be more costly and time consuming. The use of automatic equipment is more useful in some conditions for collecting pavement performance data.

The fuzzy logic model with two layers can be easily used when there is no relationship between inputs and outputs.

Nowadays, there is a lot of automatic equipment for pavement performance measurement. But they are so expensive and complicate. Excellent condition is use of all mechanistic equipment and all parameters effecting to pavement performance if it possible.

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