FUZZY LOGIC APPLICATION IN PAVEMENT MAINTENANCE AND REHABILITATION

BY

DIEU THI XUAN DUONG

A THESIS SUBMITTED IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE (ENGINEERING AND TECHNOLOGY)

SCHOOL OF MANAGEMENT TECHNOLOGY
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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A Thesis Presented

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DIEU DUONG THI XUAN

Submitted to

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Abstract

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Bachelor of Engineering, Ho Chi Minh University of Technology, 2013

Highway pavement is the main part of highway assets; therefore it needs to be maintained annually by testing and finding out the minor deteriorations to prolong the life time of construction. After a detailed literature review, it was revealed that there was a significant difference on allocation budget and quality, as well as life time of pavement before and after applying the appropriate kind of treatment. Therefore, this study focuses on applying a technique, namely fuzzy logic, in this area and developing it to conduct highway pavement maintenance by utilizing its ability to get the feasible solutions.

The thesis presents the initial step in the chain of determining the optimal treatment in terms of limited budget. Most of this stage is dependent on expert's opinions under the particular analyzing, then building up a model of fuzzy logic with the popular deteriorated index as inputs, applying the raw data from the Department of Highway (DOH), analyzing the data and getting the output as the appropriate applied treatments. Also, the results of the model have been checked by an experienced expert to verify their practical application. This study helps to widen the research direction of fuzzy logic into pavement maintenance management as well as to estimate its applications.

Keywords: Pavement maintenance, Fuzzy logic model

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Chapter 1
Introduction

1.1. Transportation Importance

Transportation plays an important role in creation of employment, globalization and specialization. It gives the opportunity to those who are directly engaged in transport business and to people indirectly in industries that are producing means of transportation or transport equipment. Transportation increases trade and its capacity and rationality determine the growth of the economy in general. Thus, it has become a significant constraint on economic development. In terms of economical evaluation, transportation is seen to be an essential part related to other areas in business, industry, society, etc. The relation between quantity and quality of transport infrastructure is apparent, and vice versa. Issues like the signal control in transportation, especially in each intersection, transportation planning, accident control, maintenance and rehabilitation decide the connection between different areas and the development of civilization. The impact and benefit of modernized transportation on our society is that it helps people to utilize and expand the distribution of occupation.

Also, transportation is important to any nation in social, industrial and economic processes because it helps to move and receive shipments from terminal to retail locations. Additionally, it has a significant role in producing and developing business. Yet another side of transportation is transferring people and enabling trade between countries that is really essential for civilizations. Transportation consists of a variety of complex elements which can be divided into infrastructure, vehicles and operations depending on financing, legalities and policies or other factors. Basically, these factors affect each other and can cause complicated problems. Transportation encounters many factors leading to the decreasing of its quality that demand to be resolved. Ordinarily, because of its importance, durability of transport and its operation always are the first choice in the maintenance process.

1.2. Pavement role, effects and the direction for pavement maintenance and rehabilitation management

In transportation research, pavements can be considered as a significant component in the transport infrastructure system, and they need to be maintained in acceptable condition which helps reduce the life cycle cost of these elements, decrease vehicle operating cost and accident rate, save shipping time of cargo and travel time of passenger, and further positive effects.

Pavements are used in daily life and also are affected directly by environment, temperature and human activity which lead to some problems in the structure of pavement. Most of these issues in pavement management are characterized by uncertainty, ambiguity, imprecision and are difficult to be solved by a crisp value; therefore, we need a tool to cope with these kinds of problem. Over the past few decades, there have been a variety of mathematical models using various formulations and equations (objective knowledge) to solve such problems.

Actually, in real problems an approximated number is used instead of a crisp one for the input parameter because it is impossible to use fixed values to describe complicated traffic and transportation. Nevertheless, to solve these problems we have to record data over a long period of time with various values and we cannot evaluate all of options and fulfil as much as possible of real conditions if we ignore the linguistic information. So, we do need a technique to present the linguistic information and the crucial thing is using a suitable solution to link objective knowledge and subjective knowledge (linguistic information). Fuzzy logic is used to deal with phenomena in pavement maintenance and rehabilitation, which need to be solved by sharing linguistic information between the real experience and the mathematical model. To be more specific, when solving a real problem in transportation, it is inadequate if we just use the various formulations and equations. Fuzzy logic is a technique to combine objective and subjective knowledge to handle the transportation problems that are characterized by uncertainty, ambiguity and vague parameters which are difficult to be solved by a fixed value (crisp value).

1.3. Problem Statement

It is undeniable the importance of the road system in general and pavement management in particular. In Thailand, around 98.5 % of the roads are paved (Thailand Infrastructure Annual Report, 2008). Therefore, this study has been implemented to address some concerns:

- There are some negative effects from some vague sources such as human activities, climate or even overloading of vehicles which let pavement quality gradually be affected adversely. This thesis helps to cope with unclear parameters in this situation.
- Many software programs as well as applications are engaged in development of pavement maintenance and rehabilitation. However, the existing situation still needs to be improved to increase the positive effects on pavement management systems. This study tries to find a useful tool to support such systems.

1.4. Objectives

It is extremely necessary to obtain the suitable treatments and estimate sufficient quality as well as deteriorated situations of pavement. Thus, this study objective to determine the remaining quality of pavement from summary of deterioration parameters and the treatments are got from these obtained situations.

- To estimate current situation of transportation management, especially pavement management using fuzzy logic.
- To develop a Fuzzy model with analysed data and obtained opinion:
    - To determine the appropriate remaining quality of pavement in terms of the distress index in general and for practical problems in Thailand in particular.
    - To identify the treatment for specific cases of deteriorated sections.

1.5. Overview

This thesis contains six chapters as presented below:

Chapter 1 is an introductory part which describes the importance of transportation and pavement. These in turn lead to the importance of maintenance and the demand to research some application to maintain the pavement system, problem statement, objectives and the overview of thesis.

Chapter 2 presents a review of literature as well as a detailed classification of fuzzy logic applications in the different areas of pavement maintenance and rehabilitation. The literatures were classified according to the name of application area, journal name, and publication time together with methodology, which is summarized in tables to be more systematic.

Chapter 3 introduces fuzzy logic including its definition and advantages. Also, a fuzzy logic system and fuzzy operations are mentioned in this chapter.

Chapter 4 refers to fuzzy logic modelling. Such a model would be set up to solve and get the output parameter to find a feasible type of treatment for each grade of deteriorated parameter. To make the model clearer, the thesis covers definitions of distress index and some kinds of treatment. This study will describe in detail the step by step process to build up the model, including membership function, rule base, applied data and pavement maintenance standards.

Chapter 5 presents the results of the Fuzzy Logic Model which are then compared with the results of the HDM-4 software. The evaluation is also expressed to observe the strong and weak points in practical problems.

Chapter 6 discusses the advantages and disadvantages of the model. This chapter involves discussion, limitations, contribution and future study.

Chapter 2

Literature Reviews

The fuzzy logic literatures were reviewed and classified based on two different methods. The first one considered the time frame during which the journals were published. This was to study the change and development of scientific techniques for maintenance and rehabilitation using fuzzy logic over two decades and also to be a foundation for determining the direction for future application.

The other classification approach is based on the areas in pavement management that fuzzy logic has been used in. This section provides an overview and a perspective of the way fuzzy logic is applied.

2.1. Classification by the Time Duration

Apparently, routine maintenance and rehabilitation has not only significant effects for pavement performance but also for the future cost of maintenance activities. Therefore, with outstanding advantages of Fuzzy Logic, more than two decades ago researchers used fuzzy logic techniques for management in general and pavement maintenance and rehabilitation in particular. Fwa and Sinha (1987) analyzed the importance of the annual maintenance process for pavement and presented the way pavement changed its operation in terms of timing, quality and quantity. Hendrickson and Janson (1987) showed the wide range of application of expert systems in pavement management for diagnosing pavement deficiencies, choosing maintenance strategies or estimating cost. In the case of prediction of the pavement performance, Kaur and Tekkedil (2000) found the system predicted the deterioration of road and rut depth to be exact. Moreover, in the period from 2005 to 2013 many technical papers were published for presenting a further literature review related to fuzzy logic application in pavement area, as well as research and conference papers, which are classified by publication year in the first section in table 1. Chandran et al (2007) used fuzzy logic in the mathematical techniques for separating the level of each distress with respect to maintenance which led to ranking pavement sections and prioritizing them for maintenance processes. Meanwhile, Koduru (2010) presented a categorization of distress by using fuzzy logic in C language for seasoning to evaluate the level of distress of pavement systems.

Table 2.1: Classification of articles by publication year

Year	1984-2000	2001-2005	2006-2010	2011-2013
No of articles	16	8	16	2

2.2. Classification by the Applied Areas

2.2.1. Fuzzy Logic in Estimating Deterioration

In maintaining a system, determining the errors not only is the necessary step but also is effective to the chain process. For this purpose, predicting deterioration in road system, as well as evaluating the performance of pavement including material, structure and so on, is taken into account to define the way pavement works to help us estimate better. The great interest in this area obviously is expressed by many papers which have been published used Fuzzy technique to handle the undefinable and non- linear elements, in which there are numerous examples of journal, conference paper, dissertation, thesis or other kinds of research. For instance, Mahmood et al (2013) classified a range of pavement sections by comparing and systemizing based on PCI (pavement condition index).

Fuzzy logic approaches have been used to combine the quantitative and qualitative data with six distress types (alligator crack, block cracking, longitudinal and transverse crack, patching hole, bleeding and ravelling) as inputs and PCI as output. This provides a simpler tool to define the level of distress in pavement systems. Considered as an index to categorize the rank of pavement sector, PCI has been become so popular in this case, Koduru et al (2010) developed and classified distress into low, medium and high levels. In their work, they combined the analyzing result from experts and converted these data to the total deduct point and decided the categorization of the deterioration. Deduct value was taken into consideration on pavement condition rating (PCR) method by Terzi et al (2009) who got the value from modelling a system using fuzzy logic with membership function for distress, severity and extent weight which decide the quality of pavement.

Fuzzy logic is not only used in evaluating the performance from the distress index but also according to the parameter of material the pavement is made from. Kaur and Tekkedil (2000) applied this method to predict the performance of asphalt pavement. They developed a system to optimize the calculation and to be easier to utilize in case of concern about some factor such as total traffic amount, subgrade type, surface thickness and age of analysing pavement. The result was to define the relationship between the material and performance of structure, rut depth to be more precise. In this research, Matlab was used together with fuzzy logic to produce the fuzzy inference system. Tigdemir (2002) also determined the correction of different components in asphalt concrete pavement's design thickness. The proposed estimation presented fatigue life and deformation by a set of fuzzy rules and specifying the fatigue life of bituminous mixture. They determined that the fatigue life is really important to the performance of structure; therefore, the fuzzy set represents a tool to estimate the fatigue life of asphalt pavement and can be used to predict the actual performance of pavement through the analytical result. Saltan et al (2007) simulated a model to estimate the surface deflection behaviour of highway pavement from falling weight deflectometer (FWD) by using fuzzy logic methodology. The model consists of seven load values, three deflections and a rule structure as input, output and rule base, respectively. It is divided into seven subsets from very low to very high depending on the range of load for input variables (from 6-12 tons) and the range of deflections for output (from 0.15-0.6cm). A Fuzzy rule base function is used to predict the output with the assistance of load application. After combining the value according to the membership function, a fuzzy value would be obtained and converted into an output value through an equation to take the average weight. For this case, the output would be combined among seven deflection values for each deflection and presented in an equivalent estimation with the measured data to prove a promising tool which can be helpful in realistic issues.

2.2.2. Fuzzy Logic in Maintenance and Rehabilitation Planning

Another duty of maintenance management is choosing a suitable solution for pavement deterioration. Each given option is estimated in many ways, but mainly depends on the distressed index which is determined through distress parameter measurement. Although this collected data is a crisp value, it still would possess "fuzziness" because of other factors of the classification process. Fuzzy logic is used to deal with these things and it is mentioned specifically in selecting pavement maintenance treatment. Suman and Sinha (2012) planned the solution for the black topped surface which was based on the drop of quality and age of pavement which lie between the limit intervals for shaping the membership function. Morova et al (2012) showed that fuzzy logic can be used to simulate a model which tries to compare and predict a significant index- Pavement Serviceability Ratio (PSR) which has an important role in designing pavement with low error degree in a short period of time. Using another method according to Fuzzy inference system, some authors had invented by combining both Artificial Neural Network (ANN) and fuzzy logic to predict pavement serviceability ratio. Specifically, to be developed, adaptive neuro-fuzzy inference system (ANFIS) became a successful model with a low error rate in a short time in comparison with measured result (Tabatabaei, S. A.; Khaledi, S. and Jahantabi, A., 2013)

So far, Fwa and Shanmugan (1998) combined a Grade Distance Method and fuzzy logic to represent a distress rating score which evaluates the demand for maintenance of pavement. Fuzzy logic could be used to formulate the membership function and grade distance is considered as the score to transfer equivalently as the severity level. Therefore, the proposed method proved the development had advantages.

2.2.3. Fuzzy Logic in Prioritization and Optimization in Maintenance Process

Most papers consider the most imperative issue to be the limited funding, so maintenance activities are limited as well. Therefore, research has to enable setting up a system or economic solution such that optimal maintenance and rehabilitation will be done. Apparently, the aim of most research works involving real problems is balancing reasonably between cost and benefit. Such a balance is ranked in terms of influencing factors such as traffic loads, the kind of distress and construction's quality. Chassiakos (2006) set a foundation for maintenance planning based on a priority list which concerned three objects: prediction of deterioration and pavement condition judgment, alternative sensible treatment for pavement, and optimization payment allocation according to prioritization. Sandra et al (2007) discussed in detail and analysed the process to develop pavement ranking. They took different functional distress parameters into consideration to select road extensions together with combining expert opinion surveys. This would in turn lead to an overall process and hence a rank of indexes which represent priority order could be computed.

Some studies also considered the cost needed for each kind of treatment on a pavement segment. Hence, comparing among options to optimize the constrained budget was described by Chen and Flintsch (2007) together with Saitoh and Fukuda (2000).)

To get the target, some research used fuzzy and analytical hierarchy process (AHP) in parallel as a technique to organize multi or complicated decisions as well as to set the prioritization in the management process. The relative significance of factors is performed through pairwise assimilation in order to measure the hierarchy index at each level and evaluate alternatives in order to select the optimal solution among alternatives. AHP provides decision makers a way to convert subjective judgments into objective measures. Developed by Thomas L. Saaty in the 1970s, it is a technique which is really useful in providing a comprehensive framework and evaluating alternative solutions to problems (Sipahi and Timor, 2010). However, Moazami and Muniandy (2010) proved the advantage of fuzzy inference in selecting and calculating for prioritization. They presented the results of two methods which illustrated the prioritization in projects together with the limitation in AHP method in comparison to fuzzy logic programming. Furthermore, Moazami et al (2011) used AHP in the first stage to an absolute dimension of priority, after which a fuzzy logic model will be administered to get the most logical prioritization engine. The budget of maintenance and investment is calculated and minimized with this useful model in the future research direction. Sun and Gu (2011) reported a combination of AHP and Fuzzy used in pavement condition estimation and classifying project; AHP is a tool to get the weight vector and fuzzy provides a method to quantify the subjectivity and model the ambiguity connected to a complicated system.

Table 2.2: Classification of literatures by application areas

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
1	Estimating deterioration	• Fuzzy expert system for asphalt pavement performance prediction • Using fuzzy logic and expert system approaches in evaluating flexible pavement distress: case study • Investigation of fatigue behaviour of asphalt concrete pavements with fuzzy logic approach • Universal Pavement Distress Evaluator Based on Fuzzy Set • A fuzzy logic approach for pavement section classification	• Kaur and Tekkedil • Koduru et al • Tigdemir, Karasahin and Sen • Shoukry et al • Mahmood et al	• IEEE Intelligent Transportation Systems Conference Proceedings • Journal of Transportation Engineering • International Journal of Fatigue • Transportation Research Board of the National Academies • International Journal of Pavement Research	22

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
				&Technology	
		• Asphalt pavement evaluation using fuzzy sets	• Elton and Jung	• Journal of the Transportation Research Board	
		• Fuzzy logic modeling of deflection behavior against dynamic loading in flexible pavement	• Saltan, Saltan and Sahiner	• Construction and Building Materials	
		• Determining of Flexible Pavement Condition Rating Deduct Value with Fuzzy Logic Algorithm	• Terzi , Morova and Karasahin	• International Symposium on Innovation in Intelligent System and Application	
		• Fuzzy Expert System for Flexible Pavements Crack Performance Prediction	• Sun and Qiu	• International Conference of Logistics Engineering and Management (ICLEM)	
		• The Use of Fuzzy Set Mathematics in Pavement Evaluation and Management: Interim Report: Executive Summary	• Gunaratne, Altschaeffl and Chameau	• Publication FHWA/IN/JHRP-84/18-2	

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
		• The Use of Fuzzy Sets Mathematics to Assist Pavement Evaluation and Management: Executive Summary • The modeling of wet-pavement related crashes by using fuzzy logic • Estimation of friction coefficient of asphalt concrete road surfaces using the fuzzy logic approach • Pavement performance prediction through fuzzy regression • Prediction of skid resistance coefficient of cement concrete roads with fuzzy logic	• Andonyadis, Altschaeffl and Chameau • Kuang-Yang Kou • Ergun • Nang-Fei Pan et al • Ustuntas	• Publication FHWA/IN/JHRP-85 • Proceeding of: Systems, Man and Cybernetics, 2005 IEEE International Conference • Canadian Journal of Civil Engineering • Expert System with Applications: An International Journal • Civil Engineering and Environmental System	

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
		• Analysis of hot mix asphalt compaction data by means of fuzzy clustering techniques • An approach to predict road accident frequencies: Application of fuzzy neural network • Fuzzy Representation of Pavement Condition for Efficient Pavement Management • Modeling the Deduct Value of the Pavement Condition of Asphalt Pavement by Adaptive Neuro • Application of fuzzy neural network in bitumen pavement performance assessment	• Amadore , Bosurgi and Pellegrino • Zheng and Meng • Bianchini • Tabatabaei, Khaledi, and Jahantabi • He and Huang	• Construction and Building Materials • Submitted to the 3rd International Conference on Road Safety and Simulation • Computer-Aided Civil and Infrastructure Engineering • International Journal of Pavement Research and Technology • Journal of Highway and Transportation Research and	

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
				Development	
		• Fuzzy optimization BP neural network model for pavement performance assessment • Pavement smoothness prediction based on fuzzy and gray theories	• Liu and Sun • Wang and Li	• IEEE International Conference, Nanjing • Computer-Aided Civil and Infrastructure Engineering	
		• Pavement maintenance treatment selection using fuzzy logic inference system • Prediction of the pavement serviceability ratio of ratio of rigid highway pavements by adaptive neuro-fuzzy	• Suman and Sinha • Morova et al	• International Journal of Engineering and Innovative Technology • SDU International Technology Science	

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
2	Maintenance and rehabilitation planning	• Fuzzy logic technique for pavement condition rating and maintenance-needs assessment • Developing a Novel Method for Road Hazardous Segment Identification Based on Fuzzy Reasoning and GIS • The Use of Fuzzy Sets Mathematics in Performance Evaluation and Maintenance and Reconstruction Strategy Selection of Asphalt Pavements • Angular fuzzy logic application for pavement maintenance and rehabilitation strategy in Ohio • A fuzzy linguistic approach of preventive maintenance scheduling cost optimization	• Fwa and Shamugam • Effati et al • Sun-Lijun and Yao-Zukang • Wee and Kim • Oke, Charles and Owaba	• 4^{th} International Conference on Managing Pavement • Journal of Transportation Technologies • Tongji Daxue Xueb • KSCE Journal of Civil Engineering • Kathmandu University Journal of Science	8

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
		• Modeling deflection basin using neurofuzzy in backcalculating flexible pavement layer moduli	• Saltan	• Pakistan Journal of Information and Technology	
3	Prioritization and optimization	• Prioritization of low-volume pavement sections for maintenance by using fuzzy logic • Current and Future Pavement Maintenance Prioritization Based on Rapid Visual Condition Evaluation • A fuzzy-based System for Maintenance Planning of Road Pavements • Prioritization of pavement stretches using fuzzy MCDM approach - a case study	• Chandran et al • Bandara and Gunaratne • Chassiakos • Sandra et al	• Journal of the Transportation Research Board • Journal of Transportation Engineering • 10th WSEAS International Conference on Computers • Soft Computing in Industrial Applications	18

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
		• Automated real-time pavement distress detection using fuzzy logic and neural network • Fuzzy Logic Pavement Maintenance and Rehabilitation Triggering Approach for Probabilistic Life-Cycle Cost Analysis • Modeling an Asphalt Pavement Repair System Considering Fuzziness of Budget Constraints • Comprehensive ranking index for flexible pavement using fuzzy sets model • Fuzzy Set-Based and Performance-Oriented Pavement Network Optimization System	• Cheng • Chen and Flintsch, • Saitoh and Fukuda • Zhang, Singh and Hudson • Wang and Liu	• Proc. SPIE 2946 • Journal of the Transportation Research Board • Computer-Aided Civil and Infrastructure Engineering • Journal of the Transportation Research Board • Journal of Infrastructure System	

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
		• Ranking versus simple optimization in setting pavement maintenance priorities: a case study from Egypt • Fuzzy Logic-based Life-Cycle Costs Analysis model for Pavement and Asset Management • Development of Pavement Performance Models using Fuzzy Systems • Fuzzy Inference and Multi-criteria Decision Making Applications in Pavement Rehabilitation Prioritization • Pavement rehabilitation and maintenance prioritization of urban roads using fuzzy logic	• Sharaf • Chen, Flintsch and Al- Qadi • Loukeri and Chassiakos • Moazami and Muniandy • Moazami, Behbahani and Muniandy	• Journal of the Transportation Research Board • 6th International Conference on Managing Pavements • 4th International Conference on Engineering Computational Technology • Australia Journal of Basic and Applied Sciences • Expert Systems with Applications	

Number	Research Areas	Title	Authors	Journal/Conference Proceeding/Book	Total
		• Pavement Condition Assessment using Fuzzy Logic Theory and Analytic Hierarchy Process • Priority Ranking Model for Managing Flexible Pavements at Network Level • Fuzzy set- based and performance-oriented pavement network optimization system • Fuzzy multi-attribute decision making in pavement management	• Sun and Gu • Reddy and Veeraragavan • Wang and Liu • Gunaratne et al	• Journal of Transportation Engineering • Journal of Indian Road Congress • Journal of Infrastructure Systems • Journal of Civil Engineering System	

Table 2.3: Classification of literatures by applied methodology

Methodology	Title	Research Area	Publication year
• Fuzzy logic	• The Use of Fuzzy Set Mathematics in Pavement Evaluation and Management: Interim Report: Executive Summary	• Estimating deterioration	• 1984
	• Angular fuzzy logic application for pavement maintenance and rehabilitation strategy in Ohio	• Maintenance and rehabilitation planning	• 2006
	• A fuzzy linguistic approach of preventive maintenance scheduling cost optimization	• Maintenance and rehabilitation planning	• 2007
	• Pavement maintenance treatment selection using fuzzy logic inference system	• Maintenance and rehabilitation planning	• 2012
	• Fuzzy logic technique for pavement condition rating and maintenance-needs assessment	• Maintenance and rehabilitation planning	• 1998
	• The use of fuzzy sets mathematics in performance evaluation	• Maintenance and rehabilitation	• 1990

	and maintenance and reconstruction strategy selection of asphalt pavements	planning	
	• Developing a Novel Method for Road Hazardous Segment Identification Based on Fuzzy Reasoning and GIS	• Maintenance and rehabilitation planning	• 2011
	• Fuzzy multi-attribute decision making in pavement management	• Prioritization and optimization	• 1985
	• Fuzzy set- based and performance- oriented pavement network optimization system	• Prioritization and optimization	• 1997
• Fuzzy logic	• Modelling an Asphalt Pavement Repair System Considering Fuzziness of Budget Constraints	• Prioritization and optimization	• 2000
	• Current and Future Pavement Maintenance Prioritization Based on Rapid Visual Condition Evaluation	• Prioritization and optimization	• 2001
	• A fuzzy-based System for Maintenance Planning of Road Pavements	• Prioritization and optimization	• 2006

• Fuzzy logic	• Prioritization of low-volume pavement sections for maintenance by using fuzzy logic • The Use of Fuzzy Sets Mathematics to Assist Pavement Evaluation and Management: Executive Summary • Universal Pavement Distress Evaluator Based on Fuzzy Set • Fuzzy expert system for asphalt pavement performance prediction • Investigation of fatigue behaviour of asphalt concrete pavements with fuzzy logic approach • The modelling of wet-pavement related crashes by using fuzzy logic • Fuzzy logic modelling of deflection behaviour against dynamic loading in flexible pavement	• Prioritization and optimization • Prioritization and optimization • Estimating deterioration • Estimating deterioration • Estimating deterioration • Estimating deterioration • Estimating deterioration	• 2007 • 1986 • 1997 • 2000 • 2002 • 2005 • 2006

• Fuzzy logic	• Determining of Flexible Pavement Condition Rating Deduct Value with Fuzzy Logic Algorithm	• Estimating deterioration	• 2009
	• Estimation of friction coefficient of asphalt concrete road surfaces using the fuzzy logic approach	• Estimating deterioration	• 2007
	• Prediction of skid resistance coefficient of cement concrete roads with fuzzy logic	• Estimating deterioration	• 2007
	• Using fuzzy logic and expert system approaches in evaluating flexible pavement distress: case study	• Estimating deterioration	• 2010
	• A fuzzy logic approach for pavement section classification	• Estimating deterioration	• 2013
	• Pavement performance prediction through fuzzy regression	• Estimating deterioration	• 2011
	• Analysis of hot mix asphalt compaction data by means of fuzzy clustering techniques	• Estimating deterioration	• 2012

	• Fuzzy Representation of Pavement Condition for Efficient Pavement Management	• Estimating deterioration	• 2012
• Fuzzy logic and Life- cycle Cost Analysis	• Fuzzy Logic Pavement Maintenance and Rehabilitation Triggering Approach for Probabilistic Life-Cycle Cost Analysis • Fuzzy Logic-based Life-Cycle Costs Analysis model for Pavement and Asset Management	• Prioritization and optimization • Prioritization and optimization	• 2007 • 2004
• Fuzzy and Artificial Neural Network	• Prediction of the pavement serviceability ratio of ratio of rigid highway pavements by adaptive neuro-fuzzy • Modelling deflection basin using neurofuzzy in backcalculating flexible pavement layer moduli • Automated real-time pavement distress detection using fuzzy logic and neural network • Application of fuzzy neural network in bitumen pavement performance assessment	• Maintenance and rehabilitation planning • Maintenance and rehabilitation planning • Prioritization and optimization • Estimating deterioration	• 2012 • 2002 • 1996 • 2000

	• Fuzzy optimization BP neural network model for pavement performance assessment • An approach to predict road accident frequencies: Application of fuzzy neural network • Modeling the Deduct Value of the Pavement Condition of Asphalt Pavement by Adaptive Neuro	• Estimating deterioration • Estimating deterioration • Estimating deterioration	• 2007 • 2011 • 2013
• Fuzzy logic and AHP	• Fuzzy Inference and Multi-criteria Decision Making Applications in Pavement Rehabilitation Prioritization • Pavement Condition Assessment using Fuzzy Logic Theory and Analytic Hierarchy Process • Pavement rehabilitation and maintenance prioritization of urban roads using fuzzy logic	• Prioritization and optimization • Prioritization and optimization • Prioritization and optimization	• 2010 • 2011 • 2011

Chapter 3
Methodology

3.1. Fuzzy Logic

Throughout the years since 1965 when Zadeh (1965) set forth a basic foundation for fuzzy logic theory and its operation in his famous paper "Fuzzy Sets", Fuzzy logic has been applied in many of fields such as automatic machines economics, transportation, etc. Because of the increasing number of fuzzy logic applications, it has be considered as a tool to cope with the issues whose boundaries are not precise and not easy to determine. For instance, Swain (2006) stated that "instead of determining the exact boundaries as in an ordinary set, a fuzzy set allows no sharply defined boundaries because of generalization of a characteristic function of a membership function".

As mentioned above, fuzzy logic was considered as a mathematical tool which allowed us to describe and deal with vague or ambiguous notions. After this foundation, Zadeh (1973) continued to develop the technique for the use of linguistic variables and fuzzy algorithms.

Basically, classic set theory decides whether an element belongs to a set or not with definition for only value of 0 or 1. An element's membership function in a set is defined in set theory as below:

$$\mu F(x) = \begin{cases} 1, if\ and\ if\ only\ x\ is\ a\ member\ of\ F \\ 0, otherwise \end{cases}$$

Whereas, fuzzy logic theory giv es a definition for a set which is more precise and suitable for ambiguous options like "What happens for an element that lies in the interval of 0 and 1?" So that, fuzzy set F is described:

x: a real number, $x \in F$

$\mu_F(x)$:a membership function of set F that assigns value to every $x \in F$ into [0, 1]

$F = \{x, \mu_F(x) \mid x \in F\}$

for values from 0 to 1 with 0 representing no membership and 1 is complete membership in set F.

There are 4 forms which are used more than others: Triangular, Trapezoidal, Gaussian and Bell-shaped forms.

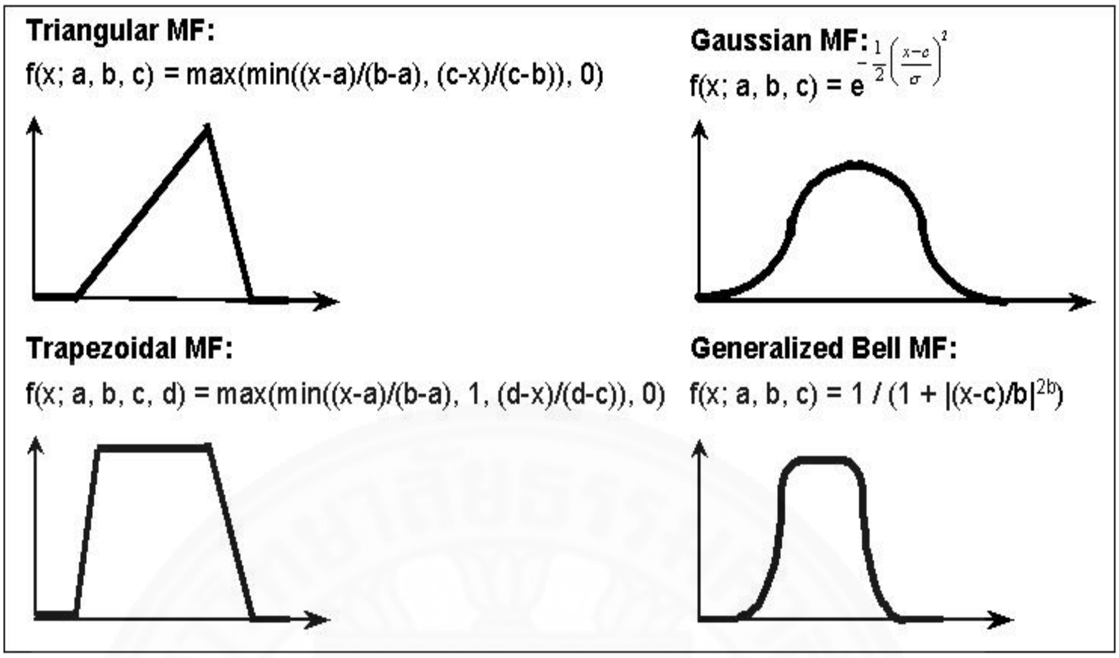

Figure 3.1: Four popular kinds of fuzzy logic membership functions

Source: http://wing.comp.nus.edu.sg/pris/FuzzyLogic/DescriptionDetailed2.htm

3.2 Fuzzy Set Linguistic

One powerful function of fuzzy sets is the ability to deal with the linguistics quantifiers or hedges such as *more* or *less*, *very*, *not very*, *slightly*, etc., which cause modification in the membership function of the fuzzy set involved. Depending on the application, fuzzy hedges may be defined in different ways to meet the requirements of the process being controlled.

3.3 Fuzzy Logic System

The main elements of a fuzzy logic system are a fuzzification unit, a fuzzy inference engine, a knowledge base and a defuzzification unit.

- Fuzzification: Convert crisp value (fixed number) as input variable into fuzzy value.
- An inference engine consists of a rule base and data base: a data base defining the membership function of the fuzzy sets used as values for each system variable and an If-then format rule base which maps fuzzy values of the input to fuzzy values of the output. Depending on the complexity of the fuzzy system, the number of

variables will change. The fuzzy knowledge base consists of a number of fuzzy rules with several sentence connectives, namely AND, OR and ALSO:

IF x_1 is A_1 OR x_2 is A_2 AND x_3 is A_3 THEN y_1 is B_1 ALSO y_2 is B_2

where the "If" part is called the antecedent part describing causes, and the rest is called a consequent part describing results.

- Defuzzification: one crisp value is converted for the output variable by taking a weighted average of the various recommendations by 2 ways: Center of Gravity (COG) defuzzification and Center Average (CA) defuzzification.

For several decades, fuzzy logic has been applied in some areas of maintenance management. As discussed above, a fuzzy logic system consists of 3 main parts: fuzzification, fuzzy inference and defuzzification. Most research methodologies are built according to this process and developed in the different direction based on their own target. Also, with the same target, the author can try different methods. In order to enlarge the applicators, researchers gradually have upgraded the applications day by day. Nevertheless, they still depend on the basic foundations such as some indicators, process or value which have been evaluated widely such as PCI, PSI, deduct value, etc. The development could be the combination of fuzzy and other techniques, fuzzy in more precise realizable phenomenon, or changing the representation of fuzzy to be easier for users in applicators, respectively.

3.4 Fuzzy Logic Operation

Referring to Jun Yan et al (1994), these are some popular operations used in rule base knowledge which will be mentioned in 2.4

Union: $\mu_{AUB}(x) = \max\{\mu_A(x), \mu_B(x)\}$ (minimum)

$\mu_{AUB}(x) = \mu_A(x) + \mu_B(x) - \mu_A(x).\mu_B(x)$ (algebraic product)

Intersection: $\mu_{AUB}(x) = \min\{\mu_A(x), \mu_B(x)\}$ (minimum)

$\mu_{AUB}(x) = \mu_A(x).\mu_B(x)$ (algebraic product)

Complement: $\mu_{A'}(x) = 1-\mu_A(x)$

Chapter 4
Fuzzy Model

4.1 Research Model Direction

In recent times, despite the rise in the number of vehicles, especially in developing countries, the infrastructure is decaying faster than it is being renewed and is leading to inferior installation, inadequate inspection and maintenance, and lack of investment maintenance system and also increasing the social and monetary cost. Historically, most local highway departments emphasized building new roads but nowadays they intentionally focus on maintenance and rehabilitation of existing pavement surfaces except in the case of ridiculously serious damages. As with the majority of structures, such as buildings, every highway pavement requires routine maintenance (Burningham, S and Stankevich, N (2005)) each day to check minor pavement distresses such as cracks, potholes, patches, etc. Such checks increase the serviceability of the pavement which in turn increases others benefits such as users' safety, reduced maintenance costs, and improved pavement life (W. James Wilde, 2014). Besides, in the long-term consideration, it will provide sustainable strategies for improving the infrastructure performance at the best available cost. All kinds of maintenance in general and treatment as well as distress are needed in a corresponding pavement maintenance program.

Fuzzy logic has been used widely as a tool to solve issues in this area. In this research, Fuzzy Logic Modelling is an application in pavement maintenance and rehabilitation, as well as a tool to connect the pavement condition to the judgement of quality to improve the management system (Moazami et al (2011)). Due to fuzzy logic's capability and the current situation of pavement systems, the application of Fuzzy Logic Modelling is definitely necessary. Fuzzy logic would help to deal with the ambiguous variables problem. Furthermore, it would be easier for users to work interactively with their data in the software and produce their results in a timely manner. Matlab also is an appropriate tool in this case because of its large database for built-in image and computer vision applications. The fuzzy logic toolbox in Matlab adapts to these demands, especially with the Graphical User Toolbox. The applied fuzzy logic model is simple enough for users to get familiar with the working environment easily.

4.2 Research Data

The model requires input data in order to build up information and get the output. There are two sources of data; one is based on the opinion of experts who have done jobs related to highway projects. After determining which factors are important, the raw data to apply in the model is obtained from Survey Data of the Department of Highway. After the interviewing of experts, the membership function is built up based on their experience. The opinions have been used to estimate the difference distress parameters on the functional condition of the pavement. There are four types of distress: potholes, crack, roughness and rutting. These are assigned to the different severity classes, namely Very Good, Good, Fair, Poor, and Very Poor. The responses given by experts have been summarized and are shown in Table 4.1.

Table 4.1: Summary of Experts Opinion

Criteria	Expert opinion	Pot hole	Crack	Roughness	Rutting	Quality
Very Good	E1			IRI<2	RUT<5	>90%
	E2		0%	IRI<2.5		
Good	E1	0	0-5%	2<IRI ≤3	5≤ RUT ≤25	>80%
	E2	0	<5%	2.5<IRI≤3.5	RUT<5	>80%
Fair	E1	<20	5-20%	3<IRI≤4	10<RUT≤25	60%-80%
	E2	<20	5-10%	3.5<IRI≤5	5≤ RUT <25	60%-80%
Poor	E1	>20	>20%	4<IRI≤6	25<RUT≤50	40%-60%
	E2	>20	>10%	IRI>5	25≤ RUT <50	40%-60%
Very Poor	E1			IRI>6	RUT>50	<40%
	E2				RUT>50	<40%

4.3 Fuzzy numbers

The distressed parameters are chosen based on the influence of each kind. In this study, the deterioration is caused mostly by current situations which are affected by traffic volume and age of the pavement. Therefore, traffic volume and age are elements that are indirectly related to pavement quality. To evaluate the deteriorated level and find the appropriate kind of treatment for each case, this model just considered 4 factors: Pothole, Roughness, Rutting and Crack.

4.3.1 Pothole

According to expert opinion, a pothole is the most dramatic indication of pavement failure. It also causes the break point in traffic density and accidents for vehicles driving at high speed. The level of potholes can be classified in two ways: size and qualification. The first way, it is separated depending on how dangerous the pothole is and the second is based on the distress density while ignoring the small size. In terms of pavement standard, classifying by size is more useful because it covers most sorts of potholes and leads to 3 classes of pothole deterioration. To be more specific, they are: None, Low and High size of pothole.

Figure 4.1: Pothole

(Internet source: http://oppositelock.kinja.com)

4.3.2 Roughness

Roughness is a crucial pavement characteristic because of its effect not only on ride quality but also on vehicle delay costs, fuel consumption and maintenance costs. In this study, International Roughness Index (IRI) with the unit of slope (m/km) stands for roughness. Since 1986, IRI has been considered as the most popular index and is used worldwide for evaluating and managing road systems. Experts have separated roughness into 5 classes in order of higher rate of roughness.

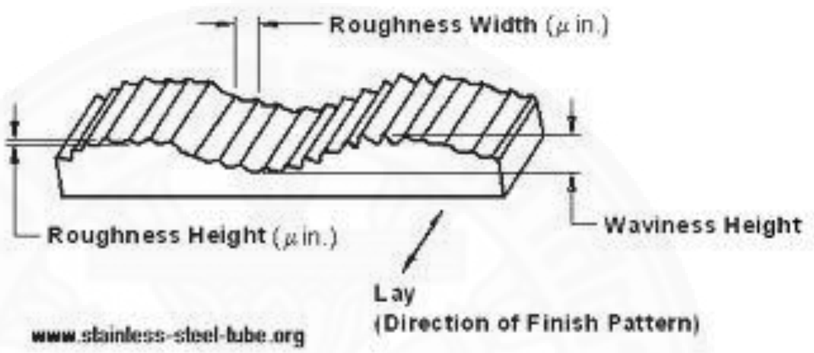

Figure 4.2: Surface roughness

(Internet source: stainless-steel-tube.org)

4.3.3 Rutting

Rutting is also estimated as a main distress of pavement; it results from the overload of vehicles or the effects of temperature. There are some ways to evaluate the difference among each kinds of rutting; however, this research focuses on the rut depth and involves 5 levels of rut depth: Very Poor, Poor, Fair, Good, and Very Good.

Figure 4.3: Rutting Pavement

(Internet source: http://www.pavementinteractive.org)

4.3.4 Crack

In asphalt pavement, a crack is a kind of distress most often instigated by failure in the surface owing to traffic loading. While the environment and other factors could affect the crack situation, traffic loading remains the direct cause; therefore, it is calculated in this model.

Figure 4.4: Cracked Pavement

(Internet source:wallpaperweb.org)

4.3.5 Quality of Pavement

After combining all kinds of deterioration, each case should be treated in a way which is appropriate to the remaining quality of pavement. Quality of pavement is judged by a scale from 0-100% on which 100% represents the best possible condition and 0% the worst.

4.4. Fuzzy Logic Membership Function

A linear membership function is widely used is triangular membership function and the corresponding fuzzy numbers are called Triangular Fuzzy Numbers.

From expert opinions taken from Table 4.1, values of each kind of membership function are compared, and assisted by maintenance standards to get the final value for building up the model. The type of membership function is Triangular, the analyzed value is the boundary value, and the mean is the central value, marking the shape and interval of each membership function in the Fuzzy Logic Model.

Table 4.2: Fuzzy Sets for Remaining Quality of Estimating Pavement

Parameter	**MF**	**Attribute**	**Function value**			**Universe of discourse**
			Left	central	Right	
Pothole	Triangular	None	0	0	0	0-30 cm
		Low	0	10	20	
		High	20	30	30	
Crack	Triangular	Good	0	0	5	0-20%
		Fair	5	7.5	10	
		Poor	10	15	20	
		Very poor	20	40	40	
Roughness	Triangular	Very good	0	0	2	0-6 m/km
		Good	2	2.5	3	
		Fair	3	3.5	4	
		Poor	4	5	6	
Rutting	Triangular	Very good	0	0	5	0-100mm
		Good	5	7.5	10	
		Fair	10	17.5	25	
		Poor	25	37.5	50	
		Very poor	50	100	100	
Quality	Triangular	Very good	100	100	90	0-100%
		Good	90	85	80	
		Fair	80	70	60	
		Poor	60	50	40	
		Very poor	40	40	0	

4.5. Fuzzy logic Inference System

The fuzzy logic inference engine consists of a rule base and a data base. The data base defines the membership function of the fuzzy sets used as values for each system variable and the rule base maps fuzzy values of the input to fuzzy values of the output. These rules are expressed in an If-Then format.

However, to be simpler, the model uses only the AND operation among input parameters, And method is Min, Implementation method is Min, Aggregation method is Max and in Defuzzification operator is recommended by ways: Center of Gravity (COG) Defuzzification (Centroid). Analysis of adopted parameters was carried out on MATLAB software.

Table 4.3: Rule Base of Fuzzy logic Inference System

If Pothole	**And Crack**	**And Rutting**	**And Roughness**	**Then Quality**
None	Good	RUT≤5	≤2	Very Good
Low	Good	RUT≤5	≤2	Fair
High	Good	RUT≤5	≤2	Poor
None	Poor	5< RUT≤10	2<IRI≤3	Poor
Low	Poor	5< RUT≤10	2<IRI≤3	Poor
High	Poor	5< RUT≤10	2<IRI≤3	Very Poor
None	Fair	5< RUT≤10	3<IRI≤4	Fair
Low	Fair	5< RUT≤10	3<IRI≤4	Fair
High	Fair	5< RUT≤10	3<IRI≤4	Poor
None	Poor	10<RUT≤25	3<IRI≤4	Poor
Low	Poor	10<RUT≤25	3<IRI≤4	Poor
High	Poor	10<RUT≤25	3<IRI≤4	Poor
None	Fair	25<RUT≤50	4<IRI≤6	Poor
Low	Fair	25<RUT≤50	4<IRI≤6	Poor
High	Fair	25<RUT≤50	4<IRI≤6	Poor

4.6. Pavement Maintenance Standards

During the data analysis period, because experts' opinions are different, opinions are chosen and analyzed completely based on the pavement maintenance standards to confirm their opinions. The interval of Fuzzy membership function is dependent on both experts' experience and existing documents which are used widely in the same research area. These are some documents that are related to the applied data in this study:

- **Pavement Maintenance Standards for classifying input factors:**

-Paterson, W. D. O., "Prediction of Road Deterioration and Maintenance Effects: Theory and Quantification". *Highway Design and Maintenance Study, Vol. 3,* World Bank, Transportation Department, Washington, D.C. 1986.

-American Association of State Highway And Transportation Officials-AASHTO (1983), "Interim Guide for Design of Pavement Structure", Washington, D.C.

- "Guidelines for Maintenance Management of Primary, Secondary and Urban Roads"; *Published in Indian Roads Congress – 2004.*

- "Manual of Uniform Minimum Standards for Design", Construction and Maintenance for Streets and Highways

- **Pavement Maintenance Standards for classifying applying treatments:**

- Kerali, Henry.G.R,2000, "Overview of HDM-4", *Calibration of HDM-4 model, Vol 1,* International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

- Kerali, Henry.G.R.; McMullen, Derek ; Odoki J.B, " Applications Guide", *Calibration of HDM-4 model, Vol 2,* International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

-Kerali, Henry.G.R,; Odoki,J.B, "Analytical Framework and Model Descriptions", *Calibration of HDM-4 model, Vol 4,* International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

-Bennet, Christopher. R. and Paterson, William D.O.(2000), " A Guide to Calibration of HDM-4 model", *Calibration of HDM-4 model, Vol 5*, International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

- N.D.Lea International (1992), "Thailand Road Maintenance Project: Draft Final report", Volume 2, *Main Report*, Ministry of Communications, Department of Highways, Kingdom of Thailand.

4.7. Treatments for Problems Detected by Fuzzy Logic Model

4.7.1. Rehabilitation

Rehabilitation is considered a major kind of pavement treatment and causes significant effects to the traffic. Some kinds of pavement rehabilitation are based on type of material such as asphalt, concrete or bituminous, or available funding and expected service life. However, most cases which require rehabilitation treatment involve the pavement being in unacceptable condition for use, and such conditions normally can be predicted and planned for by using engineering and pavement techniques.

Figure 4.5: Pavement Rehabilitation

(Internet source:http://www.vaconsultinginc.com/services)

4.7.2. Slurry seal

Slurry seal is defined as a type of composite element which includes emulsified asphalt, crushed aggregate, water, and set-control additives. Existing pavement surface defects, either a preparatory treatment for other maintenance treatments or as a wearing course, are usually filled by slurry seals. It is one of the most versatile of pavement surface treatment systems, providing low cost, rapid usability, and aesthetic value, while correcting minor deficiencies in the pavement surface and preventing further deterioration. If it is applied at the appropriate time, slurry seal could double the life of distressed pavement and also save money by preventing minor problems from turning into major ones.

Figure 4.6: Slurry Seal

(Internet source: iprslurryseal.com)

4.7.3. Overlay

An overlay is any operation that consists of placing a layer of new material over an existing pavement structure to reduce the tolerable deflection. The thickness of the new surface depends on the level of distress and can be classified into thin overlay and thick overlay treatment. When constructing an overlay, the old surface is typically cleaned by broom, milled or ground off and, finally, a new surface is applied. Overlay is a popular method of pavement preservation because of its effect and obviously economical long-lasting service.

Figure 4.7: Pavement overlay

(Internet source: http://asphaltmagazine.com)

4.7.4. Routine maintenance

Routine maintenance could be defined as the early detection and repair of minor defects to keep the pavement functioning and sometimes is referred to as “reactive maintenance.” It also is performed on pavements as they begin to expose the small deterioration; therefore, routine maintenance is not suitable for pavements that are significantly distressed.

According to expert opinion, routine maintenance is quite significant in some urgent situations, such as a pothole, but not for large numbers of potholes. The main function of this kind of treatment is to maintain the condition of the pavement system as well as to meet the particular conditions in order to upgrade the system to an acceptable level of service.

4.7.5. Reconstruction

When the top surface is severely deteriorated, the pavement has reached the end of its life, and reconstruction treatment should be applied. Reconstruction consists of either replacing the entire existing pavement structure with an equivalent structure or restoring the pavement structure.

Figure 4.8: Pavement Reconstruction
(Internet source: Photo by Scott Oines-
http://www.newsline.dot.state.mn.us/archive/06/jan/18.html)

4.7.6. Crack seal

Crack sealing is a sufficient and economical option for repairing pavement with small size cracks about or equal to 0.1 inch. This kind of modification is simple and helps to extend the lifetime of pavement.

Figure 4.9: Pavement crack seal
(Internet source: http://www.battseal.com/images/residential/crack_sealing_large.jpg)

Chapter 5

Results and Discussions

5.1. Modelling Results

The purpose of this study is to identify the relevant treatment for each case of distressed pavement. In each case, the deterioration will be combined and the remaining quality index will be calculated. Then the applied treatment is chosen based on experts' responses such as sealing, overlay, reconstruction, etc.

Table 5.1: Result of Fuzzy Modelling

Distance (km)	pothole(cm)	Crack	Rutting	IRI	Remaining Quality	Treatment
0	0	0	6.75	1.25	85	None
0.025	0	0	5.75	1.47	85	None
0.05	0	0	4.59	1.39	95.5	None
0.075	0	0	3.57	1.65	95.7	None
0.1	0	0	4.73	1.66	95.5	None
0.125	0	4.16	5.91	1.14	85	Overlay
0.15	0	0	5.21	2.27	85	None
0.175	0.58211	0	2.66	1.34	88.9	Patch+ Crack seal
0.2	0	0	3.58	1.31	95.9	None
0.225	0	0	5.96	1.42	85	None
0.25	0	2.008	5.03	1.7	85	Overlay
0.275	0.2	2.727	5.14	1.21	76	Patch+ Crack seal
0.3	0	4.199	5.06	1.7	85	Overlay
0.325	0	0	4.96	1.3	95.5	None
0.35	0	3.25	6.05	1.51	85	Crack seal
0.375	0	3.88	7.24	1.54	85	Crack seal
0.4	0	3.88	8.98	2.52	83	Crack seal
0.425	0	3.88	7.47	1.89	85	Crack seal
0.45	0	4.838	7.1	3.46	70	Overlay
0.475	0	5.05	6.36	1.68	85	Crack seal
0.5	0	5.05	3.49	2.5	83.7	Crack seal
0.525	0	5.05	5.89	2.11	84.2	Crack seal
0.55	0	8.34	6.24	1.75	83	Crack seal
0.575	0	9.195	5.27	1.53	83	Crack seal
0.6	0	8.981	6.01	1.65	83	Crack seal
0.625	0	0	7.44	1.5	85	None

0.65	0	0	5.17	1.37	87.7	None
0.675	0	0	3.97	1.52	95.8	None
0.7	0	0	3.45	1.73	95.6	None
0.725	0	0	3.99	1.8	95.5	None
0.75	0	0	4.02	1.89	95.5	None
0.775	0	0	2.91	1.76	95.6	None
0.8	0	0	4.37	1.85	95.5	None
0.825	0	0	7.02	1.69	85	None
0.85	0	0	5.03	1.54	87	None
0.875	0	0	4.58	1.73	95.5	None
0.9	0	0	4.3	1.32	95.6	None
0.925	0	0	6.15	1.68	85	None
0.95	0	0	4.9	1.82	95.5	None
0.975	0	0	5.28	1.7	87	None
1	0	0	5.78	1.52	87	None
1.025	0	0	3.66	1.44	95.9	None
1.05	0	0	4.74	2.2	85	None
1.075	0	0	6.3	1.25	87	None
1.1	0	0	4.33	1.53	95.6	None
1.125	0	0	4.47	1.58	95.5	None
1.15	0	0	6.58	2.02	85	None
1.175	0	0	6.23	1.18	87	None
1.2	0	0	6.69	1.67	85	None
1.225	0	0	8.7	1.55	85	None
1.25	0	0	9.75	1.86	85	None
1.275	0	0	5.38	1.81	85	None
1.3	0	0	6.47	3.05	70	Overlay
1.325	0	0	9.8	2.05	85	None
1.35	0	0	6.8	1.8	85	None
1.375	0	0	5.91	2.22	85	None
1.4	0	0	11.67	2.68	81	Overlay
1.425	0	0	10.42	2	85	Overlay
1.45	0	0	7.56	1.93	85	None
1.475	0	0	4.32	3.14	70	Overlay
1.5	0	0	5.33	2.75	85	None
1.525	0	0	6.92	2.23	85	None
1.55	0	0	8.47	2.64	85	None
1.575	0	0	12.24	2.21	85	Overlay
1.6	0	0	14.69	2.83	81	Overlay
1.625	0	0	12.68	3.44	70	Overlay

1.65	0	0	6.18	3.82	70	Overlay
1.675	0	0	5.5	2.66	85	None
1.7	0	0	6.22	1.41	85	None
1.725	0	0	6.24	2.07	85	None
1.75	0	0	5.72	1.84	85	None
1.775	0	0	5.41	1.75	85	None
1.8	0	0	5.02	2.73	85	None
1.825	0	0	7	2.03	85	None
1.85	0	0	7.73	1.51	85	None
1.875	0	0	8.67	1.79	85	None
1.9	0	0	8.13	1.47	85	None
1.925	0	0	9.11	1.75	85	None
1.95	0	0	9.91	1.68	85	None
1.975	0	0	10.61	1.89	83	Overlay
2	0	0	12.65	2.25	85	Overlay
2.025	0	0	11.14	2.43	81	Overlay
2.05	0	0	11.13	2.01	81	Overlay
2.075	0	0	8.12	2.81	85	None
2.1	0	0	10.03	3.58	70	Overlay
2.125	0	0	11.62	1.99	85	Overlay
2.15	0	0	9.78	2.02	85	None
2.175	0	0	10.08	1.83	85	Overlay
2.2	0	0	6.31	2.36	85	None
2.225	0	0	6.82	2.28	85	None
2.25	0	0	6.86	2.69	85	None
2.275	0	0	8.29	2.22	85	None
2.3	0	0	6.98	1.56	85	None
2.325	0	0	6.47	1.8	85	None
2.35	0	0	5.26	1.57	85	None
2.375	0	0	4.93	2.62	85	None
2.4	0	0	4.45	3.17	70	Overlay
2.425	0	0	2.99	1.68	95.7	None
2.45	0	0	5.03	1.58	85	None
2.475	0	0	5.68	1.5	85	None
2.5	0	0	6.83	1.41	85	None
2.525	0	0	8.62	1.93	85	None
2.55	0	0	5.06	1.45	85	None
2.575	0	0	3.35	1.72	95.6	None
2.6	0	0	4.08	1.6	95.7	None
2.625	0	0	4.23	1.82	95.5	None

2.65	0	0	5.28	1.47	85	None
2.675	0	0	8.75	1.92	85	None
2.7	0	0	9.76	1.5	85	None
2.725	0	0	8.8	1.63	85	None
2.75	0	0	6.72	1.46	85	None
2.775	0	0	4.69	1.91	95.5	None
2.8	0	0	4.08	2.2	85	None
2.825	0	0	7.13	1.99	85	None
2.85	0	0	9.78	1.82	85	None
2.875	0	0	7.82	2.08	85	None
2.9	0	0	6.59	1.62	85	None
2.925	0	0	5.58	2.01	85	None
2.95	0	0	6.37	2.67	85	None
2.975	0	0	7.19	1.78	85	None
3	0	0	8.32	2.22	85	None
3.025	0	0	9.04	1.71	85	None
3.05	0	0	9.59	1.81	85	None
3.075	0	0	7.37	1.96	85	None
3.1	0	0	7.45	1.92	85	None
3.125	0	0	7.14	2.46	85	None
3.15	0	0	3.36	1.72	95.6	None
3.175	0	0	1.36	1.84	95.5	None
3.2	0	0	1.66	3.36	70	Overlay
3.225	0	0	3.28	2.35	85	None
3.25	0	0	2.58	1.88	95.5	None
3.275	0	0	3.17	1.69	95.7	None
3.3	0	0	4.49	3.4	70	Overlay
3.325	0	0	3.71	1.67	95.7	None
3.35	0	0	6.8	1.66	85	None
3.375	0	0	5.43	2.29	85	None
3.4	0	0	4.29	1.74	95.6	None
3.425	0	0	5.69	1.53	85	None
3.45	0	0	6	1.86	85	None
3.475	0	0	5.79	1.66	85	None
3.5	0	0	5.9	1.27	85	None
3.525	0	0	5.03	1.15	85	None
3.55	0	0	5.08	1.58	85	None
3.575	0	0	5.16	1.91	85	None
3.6	0	0	3.37	1.96	95.5	None
3.625	0	0	5.67	1.82	85	None

3.65	0	0	4.32	1.64	95.6	None
3.675	0	0	6.6	1.96	85	None
3.7	0	0	5.48	2.4	85	None
3.725	0	0	7.34	2.67	85	None
3.75	0	0	5.73	5.21	50	Rehabilitation
3.775	0	0	3.93	1.98	95.5	None
3.8	0	0	3.38	2.46	85	None
3.825	0	0	7.67	2.63	85	None
3.85	0	0	8.67	1.86	85	None
3.875	0	0	8.22	4.89	50	Rehabilitation
3.9	0	0	10.32	3.52	70	Overlay
3.925	0	0	12.06	1.79	85	Overlay
3.95	0	0	16.12	1.89	85	Overlay
3.975	0	0	17.2	2.56	85	Overlay
4	0	0	13.07	2.44	85	Overlay
4.025	0	0	5.76	4.07	50	Rehabilitation
4.05	0	0	7.03	5.18	50	Rehabilitation
4.075	0	0	8.53	3.73	70	Overlay
4.1	0	0	5.54	2.84	85	None
4.125	0	0	4.97	3.23	70	Overlay
4.15	0	0	3.96	2.26	85	None
4.175	0	0	3.24	1.91	95.5	None
4.2	0	0	2.92	2.14	85	None
4.225	0	0	3.08	1.51	95.9	None
4.25	0	0	3.22	2.58	85	None
4.275	0	0	2.82	1.26	96.1	None
4.3	0	0	4.98	1.83	95.5	None
4.325	0	0	3.69	2.13	85	None
4.35	0	0	4.4	1.74	95.6	None
4.375	0	0	4.93	1.4	95.5	None
4.4	0	0	4.27	1.61	95.6	None
4.425	0	0	4.67	2.7	85	None
4.45	0	0	5.69	1.66	85	None
4.475	0	0	4.73	3.52	70	Overlay
4.5	0	0	5.33	2.42	85	None
4.525	0	0	4.93	2.55	85	None
4.55	0	0	7.09	1.79	85	None
4.575	0	0	6.75	2.97	85	None
4.6	0	0	3.28	7.14	50	Rehabilitation
4.625	0	0	3.21	6.12	50	Rehabilitation

4.65	0	0	2.68	2.83	85	None
4.675	0	0	3.42	3.04	70	Overlay
4.7	0	0	3.68	2.21	85	None
4.725	0	0	3.67	3.62	70	Overlay
4.75	0	0	2.99	2.17	85	None
4.775	0	0	2.94	3.28	70	Overlay
4.8	0	0	2.89	2.22	85	None
4.825	0	0	3.06	2.38	85	None
4.85	0	0	2.56	3.07	70	Overlay
4.875	0	0	4.63	3.22	70	Overlay
4.9	0	0	4.48	3.29	70	Overlay
4.925	0	0	3.93	2.91	85	None
4.95	0	0	3.16	2.95	85	None
4.975	0	0	2.92	2.65	85	None
5	0	0	4.6	3.14	70	None
5.025	0	0	2.94	1.98	95.5	None
5.05	0	0	4.84	2.35	85	None
5.075	0	0	4.21	2.89	85	None
5.1	0	0	3.23	2.52	85	None
5.125	0	0	3.13	3.72	70	Overlay
5.15	0	0	3.86	3.51	70	Overlay
5.175	0	0	3.52	3.15	70	Overlay
5.2	0	0	3.57	2.57	85	None
5.225	0	0	3.25	2.41	85	None
5.25	0	0	3.32	2.87	70	None
5.275	0	0	3.39	2.79	85	None
5.3	0	0	3.12	2.87	85	None
5.325	0	0	3.83	2.36	85	None
5.35	0	0	2.87	2.07	85	None
5.375	0	0	3.53	2.27	85	None
5.4	0	0	5.1	3.06	70	Overlay
5.425	0	0	4.34	3.03	70	Overlay
5.45	0	0	3.57	2.82	85	None
5.475	0	0	2.66	1.82	96.1	None
5.5	0	0	2	1.86	95.5	None
5.525	0	0	2.55	1.56	95.8	None
5.55	0	0	3.16	1.75	95.6	None
5.575	0	0	3.85	1.51	95.8	None
5.6	0	0	3.04	1.82	95.5	None
5.625	0	0	3.07	2.05	85	None

5.65	0	0	1.93	2.82	85	None
5.675	0	0	1.24	2.86	85	None
5.7	0	0	0.83	2.69	85	None
5.725	0	0	1.1	1.47	95.9	None
5.75	0	0	1.61	2.03	85	None
5.775	0	0	1.47	2.35	85	None
5.8	0	0	2.15	2.32	85	None
5.825	0	0	2.57	1.94	95.5	None
5.85	0	0	2.75	2.26	85	None
5.875	0	0	2.58	2.67	85	None
5.9	0	0	2.05	2.7	85	None
5.925	0	0	2.04	3.5	70	Overlay
5.95	0	0	1.31	3.4	70	Overlay
5.975	0	0	1.47	2.84	85	None
6	0	0	1.47	2.05	85	None
6.025	0	0	1.45	1.82	95.5	None
6.05	0	0	3.77	4.27	50	Rehabilitation
6.075	0	0	2.19	1.43	95.9	None
6.1	0	0	4.39	1.87	95.5	None
6.125	0	0	3.72	1.71	95.6	None
6.15	0	0	3.66	2.84	85	None
6.175	0	0	3.29	2.15	85	None
6.2	0	0	3.97	2.44	85	None
6.225	0	0	3.66	2.16	85	None
6.25	0	0	2.41	2.23	85	None
6.275	0	0	3.49	1.68	95.7	None
6.3	0	0	3.34	2.4	85	None
6.325	0	0	4.12	3.45	70	Overlay
6.35	0	0	6.47	5.33	50	Rehabilitation
6.375	0	0	1.63	6.05	50	Rehabilitation
6.4	0	0	1.03	3.03	70	Overlay
6.425	0	0	1.6	4.41	50	Rehabilitation
6.45	0	0	2.02	4.09	50	Rehabilitation
6.475	0	0	3.14	3.69	70	Overlay
6.5	0	0	4.9	2.69	85	None
6.525	0	0	3.6	5.53	50	Rehabilitation
6.55	0	0	4.36	6.04	50	Rehabilitation
6.575	0	0	2.9	3.16	70	Overlay
6.6	0	0	2.65	3.61	70	Overlay
6.625	0	0	2.37	3.49	70	Overlay

6.65	0	0	2.41	4.04	50	Rehabilitation
6.675	0	0	1.98	3.9	85	Overlay
6.7	0	0	2.16	3.03	70	Overlay
6.725	0	0	2.8	3.46	85	Overlay 51
6.75	0	0	3.43	4.51	50	Rehabilitation
6.775	0	0	3.39	4.9	50	Rehabilitation
6.8	0	0	2.62	4.81	50	Rehabilitation
6.825	0	0	4.86	5.11	50	Rehabilitation
6.85	0	0	3.99	3.59	70	Overlay
6.875	0	0	4.17	3.85	70	Overlay
6.9	0	0	2.92	3.08	70	Overlay
6.925	0	0	2.84	2.52	85	None
6.95	0	0	3.17	2.41	85	None
6.975	0	0	1.4	3.2	70	Overlay
7	0	0	1.98	2.26	85	None
7.025	0	0	1.89	2.51	85	None
7.05	0	0	2.26	2.56	85	None
7.075	0	0	1.82	2.16	85	None
7.1	0	0	2.15	4.09	50	Rehabilitation
7.125	0	0	1.15	1.72	95.6	None
7.15	0	0	2.8	1.86	95.5	None
7.175	0	0	2.41	1.84	95.5	None
7.2	0	0	3.34	1.81	95.5	None
7.225	0	0	3.21	3.46	85	Overlay
7.25	0	0	3.91	3.47	70	Overlay
7.275	0	0	2.96	3	85	Overlay
7.3	0	0	3.8	1.8	95.5	None
7.325	0	0	2.38	1.9	95.5	None
7.35	0	0	3.51	1.75	95.6	None
7.375	0	0	2.54	2.08	85	None
7.4	0	0	2.45	1.89	95.5	None
7.425	0	0	3.07	1.93	95.5	None

5.2. HDM-4 evaluating results

5.2.1. HDM-4 definition

The Highway Development and Management Tools (HDM-4) system is a software package produced by The International Study of Highway Development and Management (ISOHDM) for analyzing road network strategy, investment alternatives and managing pavement maintenance system. HDM-4 focuses on the functions of highway management, including planning, programming, and preparation (Kerali, Henry.G.R, 2000).

HDM-4 can process detailed information from road network, traffic data, vehicle fleet data, etc. HDM-4 is considered a powerful tool to support project level analysis, programme analysis under constrained allocation budget, and planning of medium to long term investment strategy.

5.2.2. Evaluating results

The results of the Fuzzy Model are evaluated by using HDM-4 software and by comparing to observe similarities or differences.

Generally, the input data for HDM-4 software is uniform with the Fuzzy Logic Model to compare two results consistently. The result indicates that each section requires a different kind of treatment corresponding to the variety of input sources. The compared sections are divided equally into seven 1- kilometre sections and the software helps find the appropriate maintenance type.

Firstly, the software includes the input parameters which describe the details of programme analysis:

- Road network: pavement type, speed flow pattern, traffic flow pattern, climate zone, road class and AADT.
- Vehicle fleets: types of vehicle, class of vehicle, and vehicle category.
- Maintenance standards: HDM-4 software requires the base alternative and maintenance alternative. To compare with the Fuzzy Logic Model, the maintenance standard consists of some basic situations with the Fuzzy Model.

Next, the value from analysed data is modified and applied into the software section Condition (in the Road network criteria). The last step is generating the programme.

The result obtained from HDM-4 is presented below.

H D M - 4

HIGHWAY DEVELOPMENT & MANAGEMENT

Work Programme Unconstrained by Section

Study Name: thesis 1

Run Date: 28-05-2015

All costs are expressed in: US Dollar (millions)

Section	Road Class	Length (km)	AADT	Surface Class	Year	Work Description	NPV/CAP	Financial Costs	Cumulative Costs
42500030702-1	Primary or Trunk	1.0	8000	Bituminous	2015	PATCH+ CRACK	0.000	0.000	0.000
42500030702-2	Primary or Trunk	1.0	8000	Bituminous	2015	NONE	0.000	0.000	0.000
42500030702-3	Primary or Trunk	1.0	8000	Bituminous	2015	NONE	0.000	0.000	0.000
42500030702-4	Primary or Trunk	1.0	8000	Bituminous	2015	NONE	0.000	0.000	0.000
42500030702-5	Primary or Trunk	1.0	8000	Bituminous	2015	NONE	0.000	0.000	0.000
42500030702-6	Primary or Trunk	1.0	8000	Bituminous	2015	NONE	0.000	0.000	0.000
42500030702-7	Primary or Trunk	1.0	8000	Bituminous	2015	OVERLAY3	0.000	0.000	0.000

Figure 5.1: Result from the HDM4 Software

Also, the results of the Fuzzy Logic Model are incorporated by each 1km, in different ways for 40 detailed segments of 25 meters. Input values are calculated from the original source, summed up and the average value taken every 1km of a whole section. The results are similar in comparison to HDM-4. The full result of the Fuzzy Logic Model is expressed in Table 5.2.

Table 5.2*:* Summarised results of Fuzzy Logic Model

Distance (km)	Pothole (cm)	Crack	Rut Lane	IRI	Remaining Quality	Treatments
1	0.39	2.13	5.434	1.73	75.2	Patch + Crack seal
2	0	0	7.75	2.13	85	None
3	0	0	7.025	2	85	None
4	0	0	6.43	2.2	85	None
5	0	0	4.27	2.83	85	None
6	0	0	2.813	2.49	85	None
7	0	0	3.11	3.4	70	Overlay

Chapter 6
Conclusions and Recommendation

6.1. Conclusion

This study has investigated the applied areas of fuzzy logic to find out the potential for applying fuzzy logic to pavement maintenance. The research has covered the major kinds of pavement's distresses and proposed the treatment for deterioration of pavement using a fuzzy logic system. Rules based responses were obtained from 2 experts and the answers were classified based on scale ranging from Poor to Good. The Fuzzy Model is applied primordially in Pavement Maintenance and Rehabilitation in Thailand.

- The Fuzzy Logic Model shows the results for each 25 meters with each remaining quality variable ranging from 50 to 96.1 with some overlap in values. The input values of sections ranged in the same membership function value were calculated into not too much different result. Generally, each segment has its own modification, and modifications can be combined together in a specific way, such as Do-Nothing for first 100 meters, Patch and Crack seal for next 75 meters, etc. But in combined section of 1 kilometre, the treatment is combined and chosen as shown in Table 5.2.
- Apply the specific technique to practical concept in Thailand and evaluate its application by comparing to other techniques used widely in the same field. The results obtained from the Fuzzy Logic Model are similar in comparison to HDM-4.
- Fuzzy requires less input parameters than HDM-4, has a friendlier user interface, which involves the required input data. Whereas, HDM-4 covers many types of parameter, from vehicle fleet, traffic flow, climate zones and so on.
- The Fuzzy Model has achieved the final result that expresses the quality of pavement and treatments.
- Fuzzy Logic Modelling is easy to understand and it can cover multiple objects that need to be considered. This study has connected great features, presented the relationship among them and obtained the expected target for each relationship.

6.2. Recommendation

The thesis illustrates both advantages and limitations. Specifically, test results indicated that the model can support the useful tool for pavement maintenance when considering some factors:

- The data is interpreted in the model and identifies the existing quality which represents which section should be defined. However, we need the corresponding relationship between the remaining quality and treatment that is suggested by experts in this area.
- The model focuses on finding the result in a single year and ignores the annual cost constraint. The maintenance activities need to be identified and carried out with a priority order. Because there are some sensitive options of distress, such as a pothole which is tremendously dangerous to vehicles, they have to be fixed as soon as possible during routine maintenance. However, routine maintenance is dependent on the budget of a project or government's capital. In real situations, there is an absolute link between the priority of treatment and budget which partly affects treatment choices that has not been mentioned to in this study recently.
- Additionally, even the climate and AADT, or the age of pavement are considered as indirect aspects that affect pavement quality or pavement deterioration. They should be considered along with the factors.
- Despite some difficulties, with the ability of the fuzzy technique to contain a large set of information (variables), a better fuzzy system can be built up. The obtained results still get stuck at some points with the same number because of the simplicity of the membership function. In addition to the triangular membership function and other operations used, this model could install other shapes of membership function to qualify the minor point together and to compare the advantage of the application model. A more complicated membership function requires a more detailed interval value and more pieces of information are covered.

As discussed, this research covers the initial stage of pavement maintenance to find the treatment for each pavement section. After building up the model and applying the survey data in real situations, it is obvious that fuzzy logic can provide useful information for the problem of pavement performance prediction. However, it needs to be developed to access a particular kind corresponding to a particular option. This proposed approach should be extended and verified to evaluate its results as well as realistic.

In summary, this research helps ensure the most necessary activities are done from the maintenance budget for Thailand’s Department of Highway by supplementing other methods that they use, such as HDM-4 or Thailand Pavement Management System (TPMS). The findings are also of interest to organizations and companies that are interested in pavement maintenance research.

References

Books and Book Articles

American Association of State Highway and Transportation Officials-AASHTO (1983), *Interim Guide for Design of Pavement Structure*, Washington, D.C.

Jun Yan, Michael Ryan and James Power. (1994), *Using Fuzzy Logic* , Prentice Hall

Articles

Amadore, A., Bosurgi, G. and Pellegrino, O. (2013). Analysis of hot mix asphalt compaction data by means of fuzzy clustering techniques. *Construction and Building Materials*, Volume 40, March 2013, pp. 430–437.

Andonyadis, M., Altschaeffl, A. G. and Chameau, J. (1986). The Use of Fuzzy Sets Mathematics to Assist Pavement Evaluation and Management: Executive Summary. *Publication FHWA/IN/JHRP-85/14-1. Joint Highway Research Project*, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Bandara, N. and Gunaratne, M. (2001). Current and Future Pavement Maintenance Prioritization Based on Rapid Visual Condition Evaluation. *Journal of Transportation Engineering*, Vol. 127, No. 2, January, 2001, pp.116-123.

Bianchini, A. (2012). Fuzzy Representation of Pavement Condition for Efficient Pavement Management. *Computer-Aided Civil and Infrastructure Engineering 27*, pp. 608–619.

Burningham, S and Stankevich, N (2005). *Why road maintenance is important and how to get it done*, The World Bank, Washington DC, Transport Note No. TRN-4, June 2005.

Chandran, S., Isaac, K.P. and Veeraragavan, A. (2007). Prioritization of low-volume pavement sections for maintenance by using fuzzy logic. *Transportation Research Record: Journal of the Transportation Research Board, No. 1989,* Vol. 1, Transportation Research Board of the National Academies, Washington, D.C., pp. 53–60.

Chassiakos, A. P. (2006). A fuzzy-based System for Maintenance Planning of Road Pavements. *Proceedings of the 10th WSEAS International Conference on Computers*, Vouliagmeni, Athens, Greece, July 13-15, 2006, pp 535-540, Chen, C. and Flintsch, G. W. (2007). Fuzzy Logic Pavement Maintenance and Rehabilitation Triggering Approach for Probabilistic Life-Cycle Cost Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1990, Transportation Research Board of the National Academies, Washington, D.C. ISSN: 0361-1981. pp. 80–91.

Chen, C., Flintsch, G. W. and Al- Qadi, I. L. (2004). Fuzzy Logic-based Life-Cycle Costs Analysis model for Pavement and Asset Management. *6th International Conference on Managing Pavements*, Oct. 19-24, 2004. Brisbane, Australia.

Duong, D. T. X. and Ammarapala, V. (2013). Fuzzy logic application in transportation problems. *Proceedings of the 4th International Conference on Engineering, Project, and Production Management (EPPM 2013)* ,23-25 October 2013, Bangkok, Thailand, pp. 395-402.

Effati, M. et al (2011). Developing a Novel Method for Road Hazardous Segment Identification Based on Fuzzy Reasoning and GIS. *Journal of Transportation Technologies*, December 15, 2011, Vol. 2, pp.32-40

Elton, D.J., and C.H. Jung. (1992). Asphalt pavement evaluation using fuzzy sets. *Transportation Research Record: Journal of Transportation Research Board, No. 1196*, National Research Council, Washington D.C, pp 686- 699.

Ergun, M. (2007). Estimation of friction coefficient of asphalt concrete road surfaces using the fuzzy logic approach. *Canadian Journal of Civil Engineering*, Vol 34, number 9, September 2007,pp. 1110-1118.

Fwa, T.F. and Shamugam, R. (1998). Fuzzy logic technique for pavement condition rating and maintenance-needs assessment. *4th International Conference on Managing Pavement*, 1998.

Fwa, T. F. and Sinha, K. C. (1987). Effects of maintenance on pavement performance. *2nd North American Pavement Management Conference,* 1987.

Gunaratne, M., Altschaeffl, A. G. and Chameau, J. (1984). The Use of Fuzzy Set Mathematics in Pavement Evaluation and Management: Interim Report: Executive Summary. *Publication FHWA/IN/JHRP-84/18-2. Joint Highway Research Project*, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 1984.

Gunaratne, M., Altschaefflf, A. G. and Chameaut, J. (1985). Fuzzy multi-attribute decision making in pavement management. *Civil Engineering Systems*, Vol. 2, Issue 3, 1985.

He, T. and Huang, W. (2000). Application of fuzzy neural network in bitumen pavement performance assessment. *Journal of Highway and Transportation Research and Development*, Aug. 2000, Vol. 17, no. 4, pp. 15-18.

Heng-Da Cheng (1996), Automated real-time pavement distress detection using fuzzy logic and neural network., *Proc. SPIE 2946, Nondestructive Evaluation of Bridges and Highways*, ", Utah State Univ. (USA), 140 (November 13, 1996).

Hendrickson, C.T. and Janson, B. N. (1987). Expert systems and pavement management. *2nd North American Pavement management Conference*, 1987.

Kaur, D. and Tekkedil, D. (2000), Fuzzy expert system for asphalt pavement performance prediction, *2000 IEEE Intelligent Transportation Systems Conference Proceedings, USA*, 01 -03 Oct.

Koduru, H. K., Xiao, F., Amirkhanian, S. N. and Juang, C. H (2010**).** Using fuzzy logic and expert system approaches in evaluating flexible pavement distress: case study. *Journal of Transportation Engineering*, Vol. 136, No. 2, February 1.

Kuang-Yang Kou, The modeling of wet-pavement related crashes by using fuzzy logic, Proceeding of: Systems, Man and Cybernetics, *2005 IEEE International Conference*, Vol 2, 11/2005; ISBN: 0-7803-9298- 1.

Liu, Y. and Sun, M. (2007), "Fuzzy optimization BP neural network model for pavement performance assessment", *Grey system and intelligent services GSIS, IEEE International Conference*, Nanjing, China, pp.1031-1034.

Loukeri, E.D. and Chassiakos, A.P. (2004), Development of Pavement Performance Models using Fuzzy Systems, in B.H.V. Topping, C.A. Mota Soares, (Editors), *Proceedings of the Fourth International Conference on Engineering Computational Technology*, Civil-Comp Press, Stirlingshire, UK, Paper 129.

Mahmood, M., Radman, M., Nolle, L. and Mathavan, S. (2013), A fuzzy logic approach for pavement section classification", *International Journal of Pavement Research & Technology*. September 2013, Vol. 6, Issue 5, pp.620-626.

Moazami, D., Behbahani, H and Muniandy, R. (2011). Pavement rehabilitation and maintenance prioritization of urban roads using fuzzy logic. *Expert Systems with Applications*, Vol. 38, pp. 12869–12879.

Moazami, D and Muniandy, R. (2010). Fuzzy Inference and Multi-criteria Decision Making Applications in Pavement Rehabilitation Prioritization. *Australia Journal of Basic and Applied Sciences*, Vol.4, No.10, ISSN 1991-8178. Pp.4740-4748,

Morova, N. et al (2012). Prediction of the pavement serviceability ratio of ratio of rigid highway pavements by adaptive neuro-fuzzy. *SDU International Technology Science,* November 2012, Vol. 4, No.2, pp. 96-101.

Nang-Fei Pan, Chien-Ho Ko, Ming-Der Yang, Kai-Chun Hsu (2011). Pavement performance prediction through fuzzy regression. *Expert System with Applications: An International Journal*, Vol. 38, Issue 8, August, 2011, pp. 10010-10017.

Paterson, W. D. O., Prediction of Road Deterioration and Maintenance Effects: Theory and Quantification. *Highway Design and Maintenance Study, Vol. 3,* World Bank, Transportation Department, Washington, D.C. 1986.

Oke, S.A, Charles, E. and Owaba, O. E. (2007). A fuzzy linguistic approach of preventive maintenance scheduling cost optimization. *Kathmandu University Journal of Science, Engineering and Technology*, Vol. 1, No.3, January.

Reddy, B.B. and Veeraragavan, A. (2001). Priority Ranking Model for Managing Flexible Pavements at Network Level. *Journal of Indian Road Congress*, Vol. 62, issue 3, page no. 379.

Saitoh, M. and Fukuda, T. (2002), “Modelling an Asphalt Pavement Repair System Considering Fuzziness of Budget Constraints*”, Computer-Aided Civil and Infrastructure Engineering* , 12/2002, Vol. 15, issue 1, pp.39 – 44.

Saltan, M. (2002). Modelling deflection basin using neurofuzzy in backcalculating flexible pavement layer moduli. *Pakistan Journal of Information and Technology*, Vol 1, issue 2, pp 180-187.

Saltan, M., Saltan, S. and Şahiner, A. (2007), “Fuzzy logic modeling of deflection behavior against dynamic loading in flexible pavement”, *Construction and Building Materials,* 01/2007,Vol. 21, issue 7, pp. 1406-1414.

Sandra, A.K. et al (2007), “Prioritization of pavement stretches using fuzzy MCDM approach - a case study”, *Soft Computing in Industrial Applications*, Vol 39, pp. 265-278.

Sharaf, E. (1993). Ranking versus simple optimization in setting pavement maintenance priorities: a case study from Egypt. *Transportation Research Record 1397, Transportation Research Board*, Washington DC, pp. 34-8.

Shoukry, S.; Martinelli, D. and Reigle, J. (1997). Universal Pavement Distress Evaluator Based on Fuzzy Set. *Transportation Research Board of the National Academies.* No. 1592, ISSN 0261-1981, pp. 180-186.

Sipahi, S. and Timor,M. (2010). The analytic hierarchy process and analytic network process: an overview of applications. *Management Decision*, Vol. 48, Issue 5, pp.775 – 808.

Suman, S.K. and Sinha, S. (2012). Pavement maintenance treatment selection using fuzzy logic inference system. *International Journal of Engineering and Innovative Technology*, Vol. 2, Issue 6, December 2012.

Sun-Lijun and Yao-Zukang. (1990).The Use of Fuzzy Sets Mathematics in Performance Evaluation and Maintenance and Reconstruction Strategy Selection of Asphalt Pavements. *Tongji Daxue Xueb*, Vol. 18. No. 2. pp. 167–176.

Sun, B. and Qiu, Y. (2010). Fuzzy Expert System for Flexible Pavements Crack Performance Prediction. *International Conference of Logistics Engineering and Management (ICLEM) 2010*, pp. 2415-2421.

Sun, L. and Gu,W. (2011). Pavement Condition Assessment using Fuzzy Logic Theory and Analytic Hierarchy Process. *Journal of Transportation Engineering*, Vol.137. No.9, September 1, 2011, pp.648-655.

Swain, N. K. (2006). A survey of application of fuzzy logic in intelligent transportation systems (ITS) and rural ITS. *Proc., IEEE Southeastcon*, IEEE, New York, pp. 85–89.

Tabatabaei, S. A.; Khaledi, S. and Jahantabi, A. (2013). Modeling the Deduct Value of the Pavement Condition of Asphalt Pavement by Adaptive Neuro Fuzzy Inference System. *International Journal of Pavement Research and Technology* , Vol. 6, Issue 1, ISSN: 1996-6814, January, 2013, pp. 59-65.

Terzi, S., Morova, N., Karasahin, M. (2009). Determining of Flexible Pavement Condition Rating Deduct Value with Fuzzy Logic Algorithm. *International Symposium on Innovation in Intelligent System and Application*, Trabzon, pp.161-168.

Tigdemir,M ; Karasahin,M and Sen,Z (2002). Investigation of fatigue behaviour of Asphalt concrete pavements with Fuzzy logic approach. *International Journal of Fatigue*, Vol 24. Issue 8, August 2002, pp. 903-910.

Ustuntas, T. (2007). Prediction of skid resistance coefficient of cement concrete roads with fuzzy logic. *Civil Engineering and Environmental Systems,* Vol. 24. No. 3, September 2007, 233–246.

Wang, K. and Liu, F. (1997). Fuzzy Set-Based and Performance-Oriented Pavement Network Optimization System. *Journal of Infrastructure Systems*, Vol. 3, No.4. December. 1997, pp. 154–159.

Wang, K. C. P. and Li, Q. (2011). Pavement smoothness prediction based on fuzzy and gray theories. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 26, issue 1, pp. 69–76.

Wee, S. and Kim,N. (2006). Angular fuzzy logic application for pavement maintenance and rehabilitation strategy in Ohio. *KSCE Journal of Civil Engineering* ,Vol. 10 .No 2, March 2006, pp. 81-89.

Zadeh, L.A. (1965). Fuzzy sets. *Information and Control.* Vol. 8. 1965, pp. 338–353.

Zadeh, L.A. (1973). Outline of a new approach to the analysis of complex systems and decision processes. *IEEE Trans. Systems, Man and Cybernetics*. 1973, Vol. 3, pp. 28–44.

Zhang, Z., Singh, N. and Hudson, W. R. (1993), Comprehensive ranking index for flexible pavement using fuzzy sets model, *Transportation Research Record: Journal of Transportation Research Board, No. 1397*, National Research Council, Washington D.C, pp. 96-102.

Zheng, L. and Meng, X. (2011 September 14-16). *An approach to predict road accident frequencies: Application of fuzzy neural network.* Submitted to the 3rd International Conference on Road Safety and Simulation, 2011, Indianapolis, USA.

Technical report from an online source

W. James Wilde, Luke Thompson, and Thomas J. Wood. (2014, September).Cost-Effective Pavement Preservation Solutions for the Real World (Report No. MN/RC 2014-33)

Other Materials

Bennet, Christopher. R. and Paterson, William D.O.(2000), " A Guide to Calibration of HDM-4 model", *Calibration of HDM-4 model, Vol 5,* International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

Guidelines for Maintenance Management of Primary, Secondary and Urban Roads"; Published in Indian Roads Congress – 2004.

Manual of Uniform Minimum Standards for Design, Construction and Maintenance for Streets and Highways

N.D.Lea International (1992), "Thailand Road Maintenance Project: Draft Final report", Volume 2, *Main Report,* Ministry of Communications, Department of Highways, Kingdom of Thailand

Kerali, Henry.G.R, "Overview of HDM-4",2000, *Calibration of HDM-4 model, Vol 1*, International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

Kerali, Henry.G.R.; McMullen, Derek ; Odoki J.B, " Applications Guide", *Calibration of HDM-4 model, Vol 2,* International Study of Highway Development and Management Tools (ISOHDM), Birmingham

Kerali, Henry.G.R,; Odoki,J.B, 2000, "Analytical Framework and Model Descriptions", *Calibration of HDM-4 model, Vol 4*, International Study of Highway Development and Management Tools (ISOHDM), Birmingham.

Buildings and Infrastructure Protection Series, "Aging Infrastructure: Issues, Research, and Technology", BIPS 01 / December 2010.

Appendix A
Expert Qualification

Dr. Amnart Khampanit

1. Position : Civil Engineer

2. Name : **Mr. Amnart Khampanit**

3. Date of Birth : July 5, 1978

4. Nationality : Thai

5. Education : Ph.D (Civil Engineering), 2015
King mongkut's university of technology Thonburi
M.Eng. (Civil Engineering), 2003
Mahanakorn University of technology
B.Eng. (Civil Engineering), 2001
Mahanakorn University of technology

6. Registered Member : The Engineering Institute of Thailand
Council of Engineering of Thailand,
Professional engineer license No.สย.8790 and ภส.132
Department of Public Works and Town & Country Planning
Auditor license No. บ.1862/2557

7. Experience

2007 – 2015 Transportation Research Center (TREC),
Sirindhorn International Institute of Technology (SIIT)

Position and responsibility : Researcher, Project Engineer

1) Perform analysis and assessment infrastuctures, espicially, highway and bridge. The scope of

work also include developing the infomation technology for highway maintenance.

2) Prepare the technical and financial proposal using for bidding.
3) Perform managing the projects.

2005– 2006 Planning and Design Co., Ltd.

Position and responsibility : Structural Engineering

Perform analysis, design and assessment the infrastructure and managing the construction projects.

2003– 2004 IMMS Co., Lts.

Position and responsibility : Structural Engineering

Perform analysis, design and assessment the infrastructure and building.

8. Research

Khampanit, A., Leelataviwat, S., Kochanin, J., Warnitchai , P., 2014, "Energy-based seismic strengthening design of non-ductile reinforced concrete frames using buckling-restrained braces" **Engineering Structures**, Vol. 81 (2014). pp. 110–122.

Khampanit, A., Ngamsagiem, C., Leelataviwat, S. and Warnitchai, W., 2013, "Cyclic Response of a Non-ductile Reinforced Concrete Frame Strengthened with Buckling restrained Braces", **Steel and Composite Structures,** Vol 12(4), pp.72-83.

Khampanit, A., and Leelataviwat, S., 2013, "Seismic Strengthening of a Non-Ductile Reinforced Concrete Frame with Soft-Story Mechanism Using Buckling-Restrained Braces", The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), Sapporo, Japan.

Nakano T, Khampanit A, Leelataviwat S, Njamsanjeim C, 2013, A Study on soft story RC frame strengtened with buckling restrained brace, **JCI Annual Conference**, Nagoya, Japan.

Ammarapala, V, Chinda, T, Udomworarat, P, Rongwiriyapanich, T, Khampanit A, Suanmali, S and Samphanwattanachai, B, 2012 "**Selection of weigh station locations in Thailand using the analytic hierarchy process" Songklanakarin J. Sci. Technol., 35 (1), 81-90.**

Khampanit, A., Ngamsagiem, C., Leelataviwat, S. and Warnitchai, W., 2011, "Cyclic testing of Non-ductile Reinforced Concrete Frame Strengthened with Buckling-restranied Braces", **The 2011 World Congress on Advance in Structural Engineering and Mechanics (ASEM 11^{+})**, Seoul, Korea.

Ngamsagiem, C., Khampanit A., Leelataviwat, S. and Warnitchai, W., 2010, "Development of Steel Buckling-restrained Braces for Seismic Retrofitting of RC Frame Structure**"**, **6th Annual Concrete Conference**, Petchaburi, Thailand.

Warawigsit A, Phanthuthecha K, Ratanachote W, Ammarapala V, Chinda T, Khampanit A., 2014, "Feasibility study of weigh Station of DRR using analytic hierarchy process" 19th National Convention on Civil Engineering , Khon Kaen, Thailand

Dr. Tunwin Svasdisant

1. Position : Civil Engineer

2. Name **: Mr. Tunwin Svasdisant**

3. Nationality **:** Thai

4. Education **:** Ph.D. in Pavement Engineering, 2002-2003
Michigan State University, USA
M.S.in Geotechnical and Pavement Engineering, 2000- 2002
Michigan State University, USA
B.Eng. (Civil Engineering), 1993-1997
Chulalongkorn University, Thailand

5. Experience

Nov 2009 - Present : Senior Professional Civil engineer,
Head of Maintenance Development Section,
Bureau of Highway Maintenance Management,
Department of Highways, Sri Ayudhaya Rd, Ratchathewee,
Bangkok, Thailand 10400

Nov 2003 – Nov 2009 :Professional Civil Engineer
Bureau of Road Research and Development and Bureau of Maintenance Management, Department of Highways, Thailand

Jan 2001 – Aug 2003 **:** Research Assistance
Department of Civil and Environmental Engineering,
Michigan State University, USA.

Aug 1997 – Aug 2000 **:** Civil Engineer 5
The Expressway and Mass Rapid Transit Authority of Thailand.

Appendix B
Survey form

How many elements to evaluate the level of highway? What are they? Which are the most important? (Circle the factor which you think it is worth to consider and prioritize it by giving the number in the list)
a. Age
b. Rutting
c. Roughness
d. Pothole
e. Texture Depth
g. Traffic volume
f. Crack

1. How many levels in quality of highways that the Departments of Highways (DoH) normally classifies? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

2. If we will have to classify the highways for maintenance purpose, by looking at the age of the highways? How many classes should we classify them? And what would be the duration is each class? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

3. If we will have to classify the highways for maintenance purpose, by looking at the roughness condition of the highways? How many classes should we classify them? And how distressed they are for each class? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

4. If we will have to classify the highways for maintenance purpose, by looking at the rutting condition of the highways, how many classes should we classify them? And how distressed they are for each class? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

5. If we will have to classify the highways for maintenance purpose, by looking at the traffic condition of the highways with data of traffic volume (AADT), how many classes should we classify them? And how different they are for each class? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

6. If we will have to classify the highways for maintenance purpose, by looking at the pothole condition of the highways, how many classes should we classify them? And how different they are for each class? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

7. If we will have to classify the highways for maintenance purpose, by looking at the cracking conditions of the highways, how many classes should we classify them? And how different they are for each class? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

8. How many kinds of treatment we can apply to maintain the road? Which standard you based on?

☐ 3 ☐ 4 ☐ 5 ☐ Others

9. What is the relationship between road deterioration (roughness, pot hole, rutting,) and selected kind of treatment? Besides, please evaluate the remained quality of highway after being affected by these kinds of deteriorations?

Appendix C

Publications

- Duong, D. T. X. and Ammarapala, V. (2013). Fuzzy logic application in transportation problems. *Proceedings of the 4th International Conference on Engineering, Project, and Production Management (EPPM 2013)* ,23-25 October 2013, Bangkok, Thailand, pp. 395-402.

- Duong, D. T. X. and Ammarapala, V. (2015). A Fuzzy logic model for maintenance planning of road pavements. *International Research Conference on Engineering and Technology (IRCET 2015)*, June 27 -June 29, 2015, Bangkok, Thailand.