NOTTINGHAM TRENT UNIVERSITY

NETWORK-LEVEL MAINTENANCE DECISIONS FOR FLEXIBLE PAVEMENT USING A SOFT COMPUTING-BASED FRAMEWORK

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Abstract

An effective pavement management system (PMS) is one that is guided by a software program that ensures that all pavement sections are maintained at adequately high serviceability levels and structural conditions with a low budget and resource usage, without causing any significant negative effect on environment, safe traffic operations and social activities. PMS comprises of section classification; performance prediction; and optimisation for decision-making.

For section classification, this research presents a fuzzy inference system (FIS), with appropriate membership functions for section classifications and for calculating the pavement condition index (PCI). The severity and extent of seven distress types (alligator cracking, block cracking, longitudinal and transverse cracking, patching, potholes, bleeding and ravelling) were used as fuzzy inputs. The result showed a good correlation for fuzzy model. A sensitivity analysis showed a pavement crack has the greatest influence on section classification compared to the other distress types.

A novel network level deterministic deterioration model was developed for flexible pavement on arterial and collector roads in four climatic zones considering the impact of maintenance, age, area and length of cracks, and traffic loading. The prediction models showed good accuracy with high determination coefficient (R^2). The cross-validation study showed that the models for arterial roads yield better accuracy than the models for collector roads. A sensitivity analysis showed that the area and length of cracks have the most significant impact on the model performance.

A novel discrete barebones multi-objective particle swarm algorithm was applied for a discrete multi-objective problem. Conventional particle swarm optimisation (PSO) techniques require a manual selection of various control parameters for the velocity term. In contrast, the bare-bones PSO has the advantage of being velocity-free, hence, does not involve any parameter selection. The discrete barebones multi-objective PSO algorithm was applied to find optimal rehabilitation scheduling considering the two objectives of the minimisation of the total pavement rehabilitation cost and the minimisation of the sum of all residual PCI values. The results showed that the optimal maintenance plan found by the novel algorithm is the better than found by conventional algorithm. Although the results of performance metrics showed that the both algorithms perform on a par, the novel algorithm is clearly advantageous as it does not need parameter selection.

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Publications

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FHWA	Federal Highway Administration
AASHTO	American Association of State Highway Officials
PMS	Pavement Management System
PMSC	Pavement Management System For Small Communities
PPMS	Portuguese Pavement Management System
BRMS	Beijing Roadway Management System
RPMS	Rigid Pavement Maintenance System
NLEX	North Luzon Expressway
PCPS	Pervious Concrete Pavement Structures
M&R	Maintenance and Rehabilitation
GRC	Gross Replacement Cost
DRC	Depreciated Replacement Cost
GIS	Geographic Information System
LCCA	Life-Cycle Cost Analysis
HIPS	Highway Investment Programming System.
NCDOT	North Carolina Department of Transportation
MCI	Maintenance Control Index
LMI	Specific Maintenance Index
PCR	Pavement Condition Rating
LRM	Linear Reference Method
PRISM	Pavement Rehabilitation and Improvement Strategic Model
AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
UPDI	Unified Pavement Distress Index
FDI	Fuzzy Distress Index
HDM-4	Highway Design And Maintenance Standards Model
RAPP-I	Reliability Analysis and Performance of Pavements
OPAC	Ontario Pavement Analysis of Cost
GP	Genetic Programming
GA	Genetic Algorithm
DMKD	Data Mining and Knowledge Discovery
NPV	Net Present Value
MCA	Multi-Criteria Analysis
FAHP	Fuzzy Analytical Hierarchy Process
DSS	Decision Support System
CBR	Case-Based Reasoning

NLP	Nonlinear Programming Technique
MINLP	Mixed-Integer Nonlinear Programming
MDP	Markov Decision Probabilities
CVaR	Conditional Value at Risk
ESPRESSO	Expert System for Pavement and Rehabilitation Strategy in the State of Ohio
PSI	Present Serviceability Index
SV	Slope Variance %
RD	Rut Depth in inches
C	Square feet of cracking per 1,000 ft2
P	Square feet of patching per 1,000 ft2
IRI	International Roughness Index
PCI	Pavement Condition Index
DP	Deduct Points
TDV	Total Deduct Value
CDV	Corrected Deduct Value
FIS	Fuzzy Inference Systems
LTPP	Long-Term Pavement Performance
SHRP	Strategic Highway Research Program
GPS	General Pavement Studies
GPS-1	GPS for Asphalt Concrete Pavement on Granular Base
SPS	Specific Pavement Studies
μA(x)	Membership Function of Set A
Ci	Cluster Centre
U	Membership Matrix
m_i	Number of Membership Functions for Input i
Y_i	Dependent Variable
X_i	Independent Variable
ε_i	Prediction Error
α, β	Regression Parameters
ESAL	Equivalent Single Axle Load
X_1	Cumulative Equivalent Single Axle Load (ESAL)
X_2	Pavement Age
X_3	Maintenance Effect (Inlay and Overlay Thickness)
X_4	Longitudinal and Transverse Cracking Length
X_5	Cracking Area (Alligator, Edge and Block)
$a_1, a_2, a_3, a_4, a_5, a_6$	Coefficients
SPSS	Statistical Package for the Social Sciences
R^2	Coefficient of Determination

PSO	Particle Swarm Optimisation
CPSO	Chaos Particle Swarm Optimisation
MOPSO	Multi-Objective PSO Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
$X_i(z)$	The position of the ith particle at iteration z
$V_i(z)$	The velocity of the ith particle at iteration z
$V_{i,j}(z+1)$	The velocity of the ith particle at iteration z+1
n	The dimension of the search space, where n = N×T
$Pbest_{i,j}(z)$	The local best position for the *jth* dimension of particle i at iteration z
$Gbest(z)$	The global best position or particle leader at iteration z
w	The inertia weight of the particle
c_1 and c_2	Acceleration coefficients that are positive constants
r_1 and r_2	Random numbers in [0,1]
$\mathbf{x}^*$	Pareto-optimal
$f_k(\mathbf{x})$	An objective vector
$rand()$	a quasi-random number chosen from the continuous uniform distribution [0,1]
$S(V_{i,j})$	The sigmoid function
BBPSO	Barebones Particle Swarm Optimisation
MOPSO	Multi-Objective Particle Swarm Optimisation
DBB-MOPSO	Discrete Barebones Multi-Objective Particle Swarm Optimisation
PWF	Present Worth Factor
T	Time at which the money is spent (in years)
R	Discount rate
m	Treatment type
M	Total number of treatment types
N	Number of sections
T	Analysis period
C_m	Unit cost of treatment type m
L_p	Length of section p
W_p	Width of section p
$PCI_{p,t}$	PCI for section *p* at time *t*
PCI_{max}	Maximum PCI level (100)
$AADT_{p,t}$	Annual average daily traffic for section *p* at time *t*
σ	Sigma value
MS	Maximum Spread
q_i	Minimum value of the sum of the absolute difference for every objective function value between the ith solution and all the non-dominated solutions found

$\bar{q}$	Mean of all q_i
S	Spacing
Δ	Non-uniformity measure
d_i	the Euclidean distance between non-dominated solutions (measured in the objective function space)
D	Number of the Pareto set
d_f, d_l	Euclidean distances between the extreme solutions and the boundary, non-dominated solutions (first and final solutions of the found non-dominated set)
$\bar{d}$	the average of all distances *di*

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Chapter 1

Introduction

1.1 Background

The reviewed version of the *Transport Infrastructure Assets Code* (2009) by HM Treasury defines transport infrastructure as an ‘asset’ and requires it to be maintained at a specified level of service by continuous replacement and refurbishment of its components (Treasury and Transport, 2010). "Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organised, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning" (U.S. Department of Transportation, 1999). The primary objectives of transport asset management are to facilitate an organised and flexible approach to make decisions that are necessary in order to maximise long-term performance while minimising the total cost incurred. The schematic of a generic infrastructure asset management system is given in Figure 1-1 (Dewan, 2004). Every year, authorities spend enormous amounts of public money for the maintenance and rehabilitation (M&R) of transport infrastructure assets to achieve maximum performance with minimum public disruption and expenditure. Figure 1-2 shows the individual processes and components of a typical asset management system (U.S. Department of Transportation, 1999).

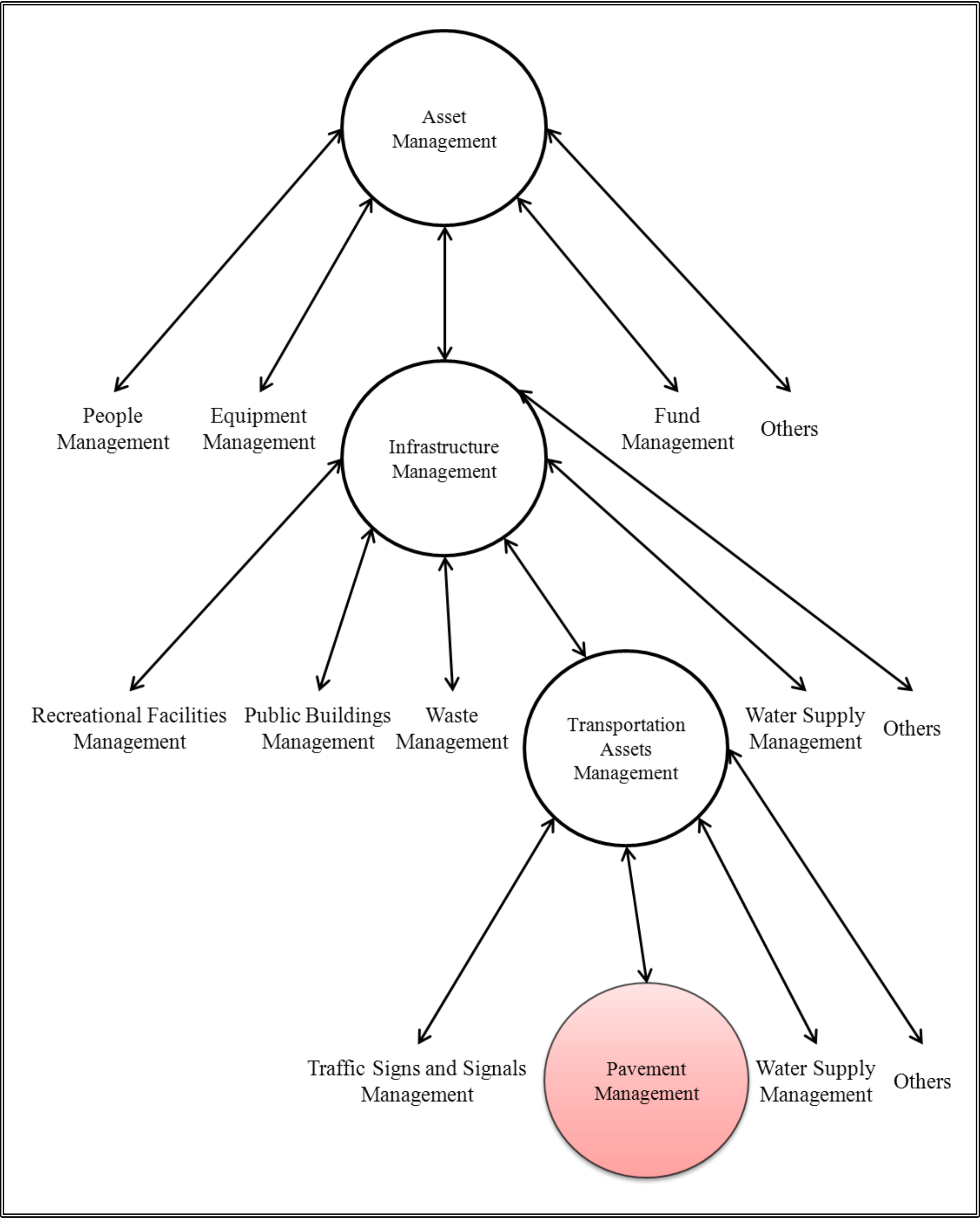

Figure 1-1: Individual components in an overall asset management scheme (Dewan, 2004).

Asset management for transport infrastructure is a large and complex subject. The physical assets in transport infrastructure are divided into two main categories, highway and urban transport systems (Treasury and Transport, 2010). The highway infrastructure includes road pavements, structures and associated elements such as footways, embankments and retaining walls. Urban transport systems, on the other hand, include sub-surface railways, light rail and tramways. This research project mainly concentrates on the pavement asset management, an important component of an overall transportation asset management scheme.

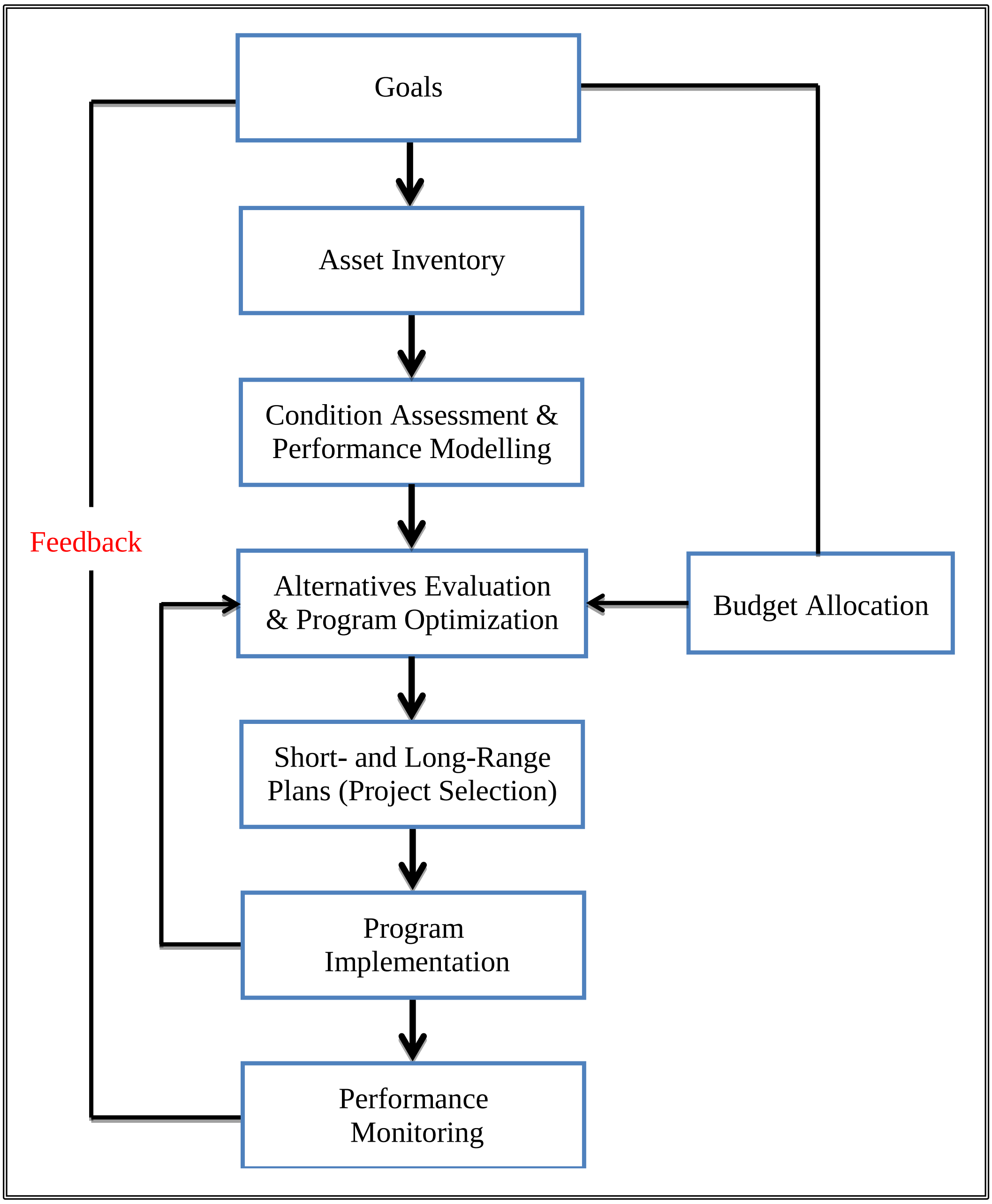

Figure 1-2: Specific components of typical asset management system (U.S. Department of Transportation, 1999).

As a major infrastructure element, the pavements of a road network need to be managed so that they can support broader asset management and standard reporting requirements. Traditionally, the accountability for public assets is expressed in terms of standard reports including financial statements. The new Transport Infrastructure Assets Code requires (as of 2013) a whole life cost approach based on current values rather than historic costs and the cost of next treatment only. The primary aim of this change is to have a long-term approach based on whole life cost and to have a reflection of local standards of service. The requirement also includes the gross replacement cost (GRC) of the asset, based on the cost of constructing an equivalent new asset, and depreciated replacement cost (DRC) which is the current cost of replacing an asset with its GRC, minus deductions for all physical deteriorations and impairments. The difference between the GRC and DRC is the cost of restoring the asset from its present condition to ‘as new’.

1.2 Problem Definition

Highways play an important role in economic and social well-being at the national and local levels. The pavement is a key element of road infrastructure. Increasing traffic volumes, heavier loads and poor reinstatement following excavation by public utility companies allied with repeated adverse weather conditions are causing significant functional and structural deterioration in the pavement such as cracking, localised depression, rutting, potholes, and texture loss. Increasing pavement deterioration is associated with increased demands to repair, as well as deficient resource allocation, which make the task of maintaining the pavement network more challenging and difficult (Chen et al., 2004).

Regular maintenance and rehabilitation (M&R) is essential to preserve and improve a pavement network. Because of ever increasing resource deficiency, maintenance activity must be timely and effective. Unnecessary maintenance increases overall maintenance costs, whereas delayed maintenance may increase rehabilitation costs. In recent years, efficiency has become the overriding issue in highway pavement maintenance planning (Alsherri and George, 1988).

Actually, it is critical to employ the most cost-effective maintenance strategy which is traditionally determined by road authorities for each pavement based on the current and predicted pavement conditions. These classification and prediction models are based on field and laboratory data, and the knowledge of experts. These condition data could be evaluated and forecasted analytically or heuristically by a limited number of pavement engineers who are seldom found in road agencies. The lack of reliable performance prediction models used by road authorities to estimate and request annual budgets lead to funding deficiency. Thus, the deficiency of funding may force an engineer to choose only highly prioritised maintenance and sometimes even leading to temporary works. In the long run, the build-up of pavement deterioration may lead to a more expensive rehabilitation (Shekharan et al., 2010).

An active pavement management system is a program that ensures that all pavement sections are maintained at adequately high service levels and structural conditions with a low budget and resources usage, without causing any significant negative effect on environment, safe traffic operations and social activities. Therefore, the pavement management system must consider multi-objective criteria in the decision making process for the scheduling of pavement maintenance activities.

In the last two decades, several pavement management systems have been developed to determine amount and type of M&R works that would be applied to a given pavement network (Abaza, 2006; Fwa et al., 2000). Despite this development, the majority of PMS systems still use a deterministic approach for data analysis and section classification and then apply regression analysis or an analytical hierarchy method for the decision making. However, M&R decisions based on a deterministic approach tend not to be realistic because of the uncertainty in data and lack of consideration given to the environmental factors, the level of service for the road user and integrated approach to other maintenance activities.

A challenge in a pavement management system is to consider a large number of pavement sections and the associated maintenance and rehabilitation decision variables covering multiple time periods (Javed, 2011). To reach the optimal maintenance decision solutions, it is important to develop an expert system to classify the pavement, predict the performance and then optimise the M&R decision considering multiple objectives such as minimum cost and maximum performance.

1.3 The Research Aim

The primary aim of this research is to introduce an effective approach for the section classification, develop pavement deterioration models, and then develop a multi-objective optimisation algorithm for finding an optimal pavement M&R plan over the analysis period.

1.4 Research Objectives

1. To accomplish a comprehensive literature review on modelling of pavement classification and performance prediction, optimisation techniques and pavement management practices.

2. To develop a simple and effective pavement classification model that is able to deal with uncertain data and subjectivity.

3. To determine accurate pavement performance prediction model considering contribution of the most significant variables such as pavement construction and material, age, traffic, maintenance effect and environmental conditions to pavement deterioration.

4. To establish an optimisation tool for programming pavement maintenance activities based on two objective functions: maximise pavement performance and minimise agency cost (maintenance cost).

5. To verify how well these models can classify, predict and optimise the real solutions by comparing with conventional pavement management models.

1.5 Thesis Structure

The thesis structure is planned to cover the background of pavement asset management issues, the proposed methodology and results of modelling. It is divided into nine chapters as follows:

Chapter 1: Introduction

It introduces background of asset management and pavement management. It also summarises the research aim and objectives.

Chapter 2: Literature Review

It describes the pavement distress types, the techniques of distress identification and inspection and the common indictors of pavement conditions. It also presents summaries of existing articles, papers, and published reports on pavement asset management.

Chapter 3: Basic Components of Pavement Management System

It presents existing journal and conference articles, published reports, design standards and recent developments in pavement condition classification, deterioration models and optimisation techniques used in pavement maintenance decisions. The main contributions to knowledge with pavement section classification, performance prediction, and M&R decision optimisation are described.

Chapter 4: Research Methodology

It presents a brief explanation of main problems in pavement management system. It describes the research aim, and objectives. Moreover, it presents the research methodology for pavement section classification, pavement deterioration and maintenance decision optimisation.

Chapter 5: Pavement Section Classification

This chapter introduces the modelling of pavement section classification by using fuzzy inference system (FIS).

Chapter 6: Pavement Performance Prediction

It presents different types of performance prediction models and the main factors affecting pavement condition. It also introduces the development of new pavement performance prediction models by creating different empirical models.

Chapter 7: Multi-Objective Pavement Maintenance Decision Optimisation

It describes the development procedure of a novel algorithm called discrete barebones multi-objective particle swarm optimisation (DBB-MOPSO). Furthermore, it shows the implementation of DBB-MOPSO algorithm on multi-objective pavement M&R decisions problem and algorithm validation.

Chapter 8: Case Study and Discussions

It present a simple case study of implementation of PMS stages. Moreover, it summarises the main findings of this research.

Chapter 9: Conclusions and Suggestions

It summarises the overall findings of the thesis and presents the final conclusion.

Chapter 10: Limitations and Suggestions for Future Work

It presents recommendations for future research in pavement management system.

Chapter 2

Pavement Deterioration and Management System

2.1 Introduction

Pavement management systems (PMS) are becoming progressively essential tools in the decision-making procedures regarding the preservation of pavement networks. A perfect pavement management system is a program that would keep all pavement segments at satisfactorily high serviceability and structural conditions. However, it needs only reasonable minimum resources (budget, equipment, manpower, etc.) and should not produce any significant negative effect on the environment, safe traffic operations, and social and community activities. Since many of these objectives are conflicting requirements, the decision-making process of PMS for scheduling pavement maintenance activities should involve a multi-objective consideration that handles the competing requirements of different objectives (Fwa et al., 2000).

2.2 Pavement Distress Types

The condition of road pavement deteriorates with time due to one or more causes such as traffic loading, material ageing, environmental effects, construction deficiency, design inadequacy, etc. To assess pavement surface condition at a specific time, pavement condition surveys of distress are periodically conducted. Distress surveys normally provide various deterioration data such as distress types, severity, extent and location. In flexible pavement, distresses can be categorised into five groups (Fwa, 2006):

1. Cracking.
2. Patching and potholes.
3. Surface deformation.
4. Surface defects.
5. Miscellaneous distresses.

2.2.1 Cracking

Cracks are fractures appearing on the pavement surface in different forms, ranging from single cracks to interconnected patterns. There are many possible causes of cracks, such as the fatigue failure of the asphalt concrete, shrinkage, deformation, crack reflection from underlying pavement layers and poor construction joints of the asphalt concrete, and daily temperature cycling. For common types of cracks in flexible pavement, see Table 2-1 (Fwa, 2006; Miller and Bellinger, 2003; Oregon Department of Transportation., 2010; Shahin and Walther, 1990).

2.2.1.1 Alligator Crack

An alligator crack is also known as a crocodile or fatigue crack. It is a single crack or a series of interconnected cracks caused by fatigue failure of the asphalt pavement surface under repeated traffic loading (wheel path). The cracks spread to the pavement surface initially as a series of parallel longitudinal cracks and these cracks connect after repeated traffic loading, hence they form many-sided, sharp-angled patterns, like an alligator skin. Crack is recorded in square feet or metres of fatigue cracking area. The severity level of alligator cracking is grouped in three categories: low, medium, and high (Fwa, 2006;

Miller and Bellinger, 2003; Oregon Department of Transportation., 2010; Shahin and Walther, 1990).

Table 2-1: Flexible pavement distress types (Miller and Bellinger, 2003; Shahin and Walther, 1990).

Distress group	Distress type	Measure unit	Severity level
Cracking	Alligator Cracking	m^2	Low, Medium, High
	Block Cracking	m^2	Low, Medium, High
	Longitudinal and Transverse	m	Low, Medium, High
	Edge Cracking	m	Low, Medium, High
	Joint Reflection Cracking	m	Low, Medium, High
Patching and Potholes	Patching	m^2	Low, Medium, High
	Potholes	number	Low, Medium, High
Surface deformation	Rutting	m^2	Low, Medium, High
	Shoving	m^2	Low, Medium, High
Surface defects	Bleeding	m^2	Low, Medium, High
	Ravelling	m^2	Low, Medium, High
	Polished aggregate	m^2	N/A
Miscellaneous Distress	Lane to shoulder drop-off	m	Low, Medium, High
	Water bleeding and pumping	m	N/A

2.2.1.2 Block Cracking

Block cracking is where interconnected cracks divide the pavement surface into approximately rectangular blocks. The causes of block cracking are asphalt concrete shrinkage and daily temperature cycling. It is measured in square feet or metres of affected surface area at each severity level. It is categorised in three different severity levels based on crack width (Fwa, 2006; Miller and Bellinger, 2003; Oregon Department of Transportation., 2010; Shahin and Walther, 1990).

2.2.1.3 Longitudinal and Transverse Cracks

Longitudinal cracks are one or more cracks parallel to the pavement's centreline, while transverse cracks are mainly perpendicular to the pavement's centreline. They are formed due to the shrinkage of the asphalt concrete surface or a poor joint between pavement lanes or the reflection of the joint in the underlying layer. They are recorded in linear feet or metres at each severity level. The three severity levels of longitudinal and transverse cracks are determined based on crack width, spalling, and faulting (Fwa, 2006; Miller and Bellinger, 2003; Oregon Department of Transportation., 2010; Shahin and Walther, 1990).

2.2.1.4 Edge Cracking

Edge cracks are crescent-shaped cracks or fairly continuous cracks which form only on unpaved shoulders. They are parallel to and located within 1 to 2 ft. (0.3 to 0.6 m) of the outer pavement edge. Traffic loading, or a frost-weakened base or subgrade near the pavement edge, are the main causes of these types of cracks. They are measured by the length of affected pavement edge at each severity level. The severity level is categorised into three levels based on breaks or loss of material (Miller and Bellinger, 2003; Shahin and Walther, 1990).

2.2.1.5 Joint Reflection Cracking

Joint reflection cracks are distresses in asphalt concrete overlay surfaces which occur over joints in concrete slabs. This crack type occurs due to thermal- or moisture-induced movement of the concrete slab beneath the asphalt concrete surface. It is measured in linear feet or metres (Miller and Bellinger, 2003; Shahin and Walther, 1990).

2.2.2 Patching and Pothole

A patch is a portion of the original pavement that has been removed and replaced with new material to repair a lack of serviceability or structural capacity in the pavement. It is measured by square feet of affected surface area at each severity level. A pothole is a shallow or deep hole in the pavement surface resulting from a loss of surface or base course material which is weak and loose because of water entering the pavement layer through cracks. It is quantified by recording the number of potholes at each severity level. The severity level of patching and potholes is categorised in three groups: low, medium and high. The severity level of potholes is determined based on pothole depth, while the severity level of patching is evaluated based on the severity of distresses existing in the patch, and the ride quality of the patch (Fwa, 2006; Miller and Bellinger, 2003; Oregon Department of Transportation., 2010; Shahin and Walther, 1990).

2.2.3 Surface Deformation

Surface deformation is the change in the surface profile of pavement. It can affect roughness and skid resistance, and accelerate crack initiation. There are two common deformation types, rutting and shoving. Rutting is the longitudinal surface depression which occurs in the wheel path because of insufficient surface thickness, high moisture content and poor compaction, and is defined by rut depth. Shoving is the longitudinal displacement of surfacing material occurring generally because of braking or accelerating vehicles. It is measured in square feet or metres of affected area (Fwa, 2006; Miller and Bellinger, 2003; Shahin and Walther, 1990).

2.2.4 Surface Defects

Defects are surface distresses associated with the pavement surface and do not imply structural deterioration in the pavement layers. They do, however, have substantial impact on skid resistance and serviceability. The types of surface defect in flexible pavement are bleeding, ravelling and polished aggregate. Bleeding is excess bituminous material occurring on the pavement surface which becomes a shiny, glasslike, reflecting surface. Ravelling is the wearing away of the pavement surface caused by a loss of asphalt and dislodging of aggregate particles. All surface defect types are measured in square feet or metres of affected surface area (Fwa, 2006; Miller and Bellinger, 2003; Shahin and Walther, 1990).

2.2.5 Miscellaneous Distresses

The other distresses in flexible pavement are lane/shoulder drop-off distress and water bleeding and pumping. The lane/shoulder drop-off distress is the difference between the pavement edge elevation and the shoulder elevation. It is usually caused by erosion and settlement in the shoulder. Water bleeding and pumping occurs where water seeps or ejects from beneath the pavement through cracks (Fwa, 2006).

2.3 Distress Identification Techniques

PMS contains distress surveys to monitor the structural behaviour and its interaction with traffic load and climatic changes (Bianchini and Bandini, 2010). Distress inspection includes the measurement and assessment of the type, extent, and severity of different distress types such as cracking, rutting, cracking, pothole, patching and defects. Such inspection can be performed by walking or driving along a pavement segment (Mallick and El-Korchi, 2013).

2.3.1 Manual Survey Technique

Manual or visual inspection survey is the most widely used method to assess the general surface condition of pavement sections. It is conducted by walking along the pavement segment to supply the detailed information about the pavement surface condition. The main disadvantages of these surveys are time consuming and expensive (Fwa, 2006). Visual survey on such highway network is not just insecure but also produces traffic delays which have caused negative effects on public and economic (Saba, 2011). Moreover, the manual survey is extremely labour-intensive, and a high probability of error-prone (Wang, 2000).

2.3.2 Automated Distress Survey Technique

The main problems and the difficulties of manual distress inspection are data collection costs, survey safety and data reliability. To overcome these problems and difficulties, automated distress inspection methods have been developed (Fwa, 2006). An ideal automated distress inspection system should detect all cracking types, and any other surface defect of any size, at any speed of data collection, and under any climatic conditions. There are many devices and equipment ranging from high-speed contactless laser sensors to equipment recording video images of the asphalt surfaces. The automated equipment should be inexpensive and easy to operate. The recent advancements in computer hardware, and image and video technology have provided opportunities to discover new techniques to automating distress inspection in a cost-effective way (Fwa, 2006; Wang, 2000).

2.4 Data Inventory and Pavement Condition Rating

Pavement condition data are collected by visual and/or automated surveys and numerical values are assigned to each pavement section. Condition data comprises functional features such as ride quality, roughness, skidding resistance and texture; distresses such as cracking, rutting, defects, patching and edge deterioration; and structural condition such as pavement life (Scott Wilson Pavement Engineering Ltd., 2005).

Various condition indicators considering some or all of the deterioration data have been developed to quantify the pavement condition in numerical values. Those pavement condition indicators can be used to describe quantitatively the current pavement condition, predict future deterioration and then optimise the maintenance requirements (Scott Wilson Pavement Engineering Ltd., 2005; Shiyab, 2007).

Generally, the accepted pavement performance measures are safety, structural performance, and functional performance. Safety performance is typically evaluated based on the pavement's frictional characteristics. The skid resistance of the surface under wet conditions and the potential for hydroplaning are the main concerns that are considered in pavement safety evaluation. Functional performance is the pavement's ability to serve pavement users in its main function, that is, to provide a safe and smooth driving surface. It is still one of the most significant measures of pavement performance, and is determined in terms of ride quality of the pavement surface or roughness. Structural performance is the ability of the pavement to sustain the applied traffic load without distress occurring. It is measured in terms of the loading capacity and physical defects (Fwa, 2006; Shiyab, 2007).

Pavement condition can be classified by a range of performance indicators such as pavement condition index (PCI), international roughness index (IRI), and present serviceability index (PSI), by utilising various features of the road surfaces. For highway pavements, these indicators comprise pavement surface deterioration, deflection, rut depth, roughness, and skid resistance (Sun and Gu, 2011). The following are the three most common condition indicators.

2.4.1 Present Serviceability Index (PSI)

In 1960, the concept of Present Serviceability Index (PSI) was introduced by Cary and Irick (Fwa, 2006). PSI, which is one of the most used indicators of pavement functional performance, was developed during an American Association of State Highway Officials (AASHTO) road test. It is measured on a quantitative scale range from 0-5, with 5 being excellent. It is a function of slope variance (i.e. roughness), rutting, cracking and patching, and the following equation is used for flexible pavement (Fwa, 2006; Shiyab, 2007; Ullidtz, 1998):

$$PSI = 5.03 - 1.91\log(1 + SV) - 1.38(RD)^2 - 0.01 \times \sqrt{C + P} \qquad 2\text{-}1$$

Where SV = Slope Variance %, RD = Rut Depth in inches, C = Square feet of cracking per 1,000 ft^2, P = Square feet of patching per 1,000 ft^2.

2.4.2 International Roughness Index (IRI)

The International Roughness Index (IRI), which was developed by the World Bank in Brazil in 1982, is an indicator of pavement roughness, or ride quality. Through this method, the World Bank aimed to determine whether an investment in the construction or maintenance of a highway would have a rate of return high enough to pay for the investment. For determining the rate of return, the World Bank developed the relationship between user cost and pavement condition and found the important measure, which was IRI (Ullidtz, 1998). It is used to define a characteristic of the longitudinal profile of a travelled wheel track and constitutes a standardised roughness measurement. The common IRI units are metres per kilometre (m/km) or millimetres per metre (mm/m).

2.4.3 Pavement Condition Index-PAVER System

In the 1980s, the US Army Corps of Engineers developed the Pavement Condition Index (PCI) rating system. The PCI procedure has been widely adopted and is used for airfield pavements, roads, and parking lots by many highway agencies worldwide. PCI is based on the visual survey results in which distress type, quantity, and severity are identified. The field verification of the PCI inspection approach has shown that PCI gives a good indication of structural integrity and operational condition. In addition, it is a valuable index to determine both the current condition and future performance under existing traffic conditions, without needing additional testing programs such as roughness, skid resistance, and structural capacity (Shahin and Walther, 1990; Shiyab, 2007).

PCI is widely used by the most highway agencies. Compared to others indices, it considers the all types of distresses, their severity and quantities. It also can give a good functional and structural indication of the pavement condition of a network. Therefore, it is adopted in this research.

The pavement deterioration degree is a function of distress type, severity, and distress quantity or density. A major issue which was found in developing PCI was producing a single index that is capable of considering the many potential combinations of all three factors. To overcome this issue, "deduct values" were presented as a kind of weighing factor to combine the effects of each particular distress type, severity level, and distress density on pavement condition (Shahin and Walther, 1990; Shiyab, 2007). PCI is a numerical rating of the pavement condition that ranges from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition, as shown in Figure 2-1. The following is the procedure of calculation for the PCI-PAVER system for flexible pavement (Fwa, 2006):

Step 1: Determine severity, and extent of each distress type for a pavement section. Severity level is expressed by three clusters, namely, low, medium, and high, while the extent is quantified by linear or square metres or feet, or a number, depending on the distress type.

Step 2: Calculate pavement distress density by;

$$\text{Density \%} = (\text{Distress area})/(\text{section area}) * 100 \qquad 2\text{-}2$$

(Distress extent is measured by square metres or feet).

$$\text{Density \%} = (\text{Distress length})/(\text{section area}) * 100 \qquad 2\text{-}3$$

(Distress extent is measured by linear metres or feet).

$$\text{Density \%} = (\text{number of potholes})/(\text{section area}) * 100 \qquad 2\text{-}4$$

(Distress extent is measured by number of potholes).

Step 3: Obtain deduct points (DP) from deduct value curves for each distress type.

Step 4: Determine total deduct value (TDV) for all distresses of each section.

Step 5: Adjust total deduct value (TDV) by calculating corrected deduct value (CDV).

Step 6: Compute PCI for each section by subtracting (CDV) from 100.

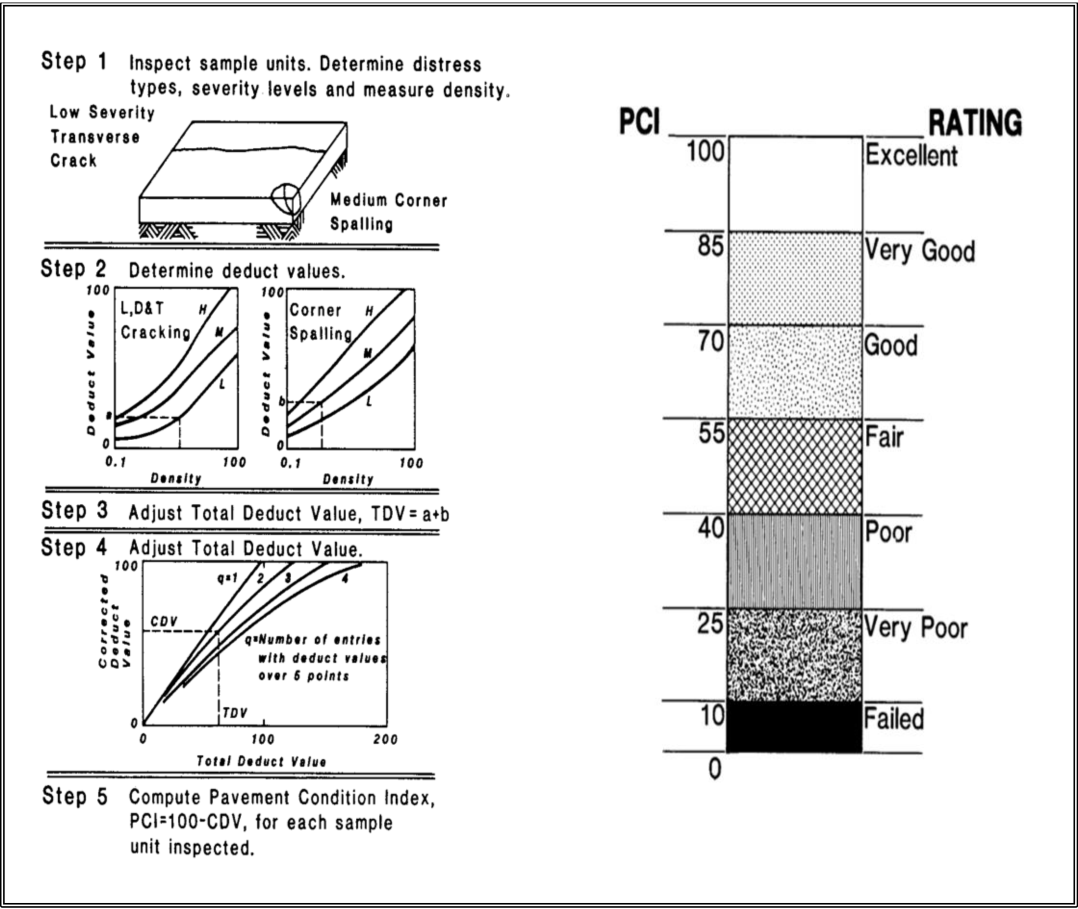

Figure 2-1: Pavement condition index (PCI) calculation procedure (Fwa, 2006).

2.4.4 The UK System of Pavement Condition Evaluation

PMS in the UK adopts the threshold levels or assessment criteria for evaluating the extent of pavement deterioration. The allowable threshold levels are numerical value of either 0 (Pass) or 100 (Fail) to specify whether a distress has exceeded it. The pavement is then classified based on these threshold levels, with the maximum value used to determine the overall index of pavement condition. For example, if a pavement has failed due to any individual defect then the resultant condition index will be 100). This system does not allow single defects to be evaluated individually (Department for Transport (England)., 2008; Scott Wilson Pavement Engineering Ltd., 2005).

2.5 A Brief Overview of Asset Management and Pavement Management Development and Application

Effective asset management can offer improved efficiency in terms of services from assets, and assist decision makers in preserving their assets with minimum possible costs. There are different types of assets such as physical, people, fund, document, etc., and for each asset type, the asset management formulation cannot be the same. Pavement is a physical asset. Hence, an operative PMS should support a whole asset management process and assist managing authorities to show better responsibility to asset owners (public). Therefore, as a key infrastructure component, a pavement network requires to be managed in a way that supports wide asset management (Dewan, 2004).

In the last few decades, many pavement management systems have been established and applied, ranging from very simple systems to the most sophisticated one. Dewan (2004) described the major confusions accompanying the application of asset management concept for managing pavements. The components that should be included in either pavement or assessment management, or in both, were highlighted to simplify the tools employed in communicating messages clearly to infrastructure assets stakeholders (Dewan, 2004). Lim (2009) defined the efficiency of a highway management system integrated with intelligent transportation systems (ITS). The expectations of an integrated system were reductions in traffic delay costs, travel time and accidents, and also an improvement of highway management (Lim, 2009). In 2010, Haas highlighted the main achievements of pavement management and the reasons for periodic improvements in technical, economic and life-cycle, and institutional aspects. Future expectations for PMS were considered in many aspects such as service quality, safety goals, asset valuation, preservation of investment, productivity, and efficiency (Haas, 2010). Xie and Li (2010) examined the application of Web-GIS to a pavement management system to link highway geographic data and attribute data. They found that it enhanced the efficiency of the management system and offered timely and accurate decision support information (Xie and Li, 2010).

Pavement management systems have been developed and applied in differently sized cities. Kilareski and Churilla (1983) developed a PMS in Pennsylvania, a heavily industrialised state with a large highway network. The developed PMS was implemented in other states and evaluated by surveying them, and also by various in-house PMS techniques like "Mays Meter roughness", "Road Rater deflections" and "distress surveys". The implementation of the system was monitored through two modules: a network serviceability inventory by present serviceability index, and a distress progression survey for prioritising projects, optimisation of repair decisions, and budget needs estimation (Kilareski and Churilla, 1983). Suzuki et al. (2010) suggested a methodology to shift pavement maintenance management based on the soundness of the maintenance control hindex (MCI) of the top layer to MCI of base course on major roads, MCI was measured from a cracking ratio, a rut depth and a flatness. In addition, the maintenance management of community roads based on specific maintenance index (LMI) which was measured from a cracking ratio, and a patching ratio (Suzuki et al., 2010).

In addition, Tavakoli et al. (1992) demonstrated a pavement management system for small communities (PMSC) comprising of seven modules. These modules are inventory, distress survey, maintenance/rehabilitation, unit costs, deterioration rates, priority scheme and goals, and backup. The PMSC is a user-friendly and practice-oriented system to make recommendations and decisions about the timing and budget allocation of various treatment actions for each section of the local transportation network (Tavakoli et al., 1992). Goh and McManus (1994) established an intelligent pavement management system to help decision makers of local municipalities to find appropriate treatment activities and estimation of costs. The developed system was based on a pavement database system and an expert system. It comprised of five modules: a database system, a pavement distress algorithm considering pavement condition rating (PCR), a pavement maintenance algorithm based on the decision tree, a pavement costs algorithm and an output system (Goh and McManus, 1994). In 1996, Sachs and Sunde examined the modification of the pavement management system implemented in many larger cities of Washington State to accommodate smaller city agencies. A simple procedure was created to determine the PCR easily by identifying five distress types with three severity levels, and then using a look-up table for the three severity levels of alligator cracking with different percentage ranges to find the total corrected deducted value (Sachs and Sunde, 1996). Sarsam (2008) developed a methodology for a pavement management system based on visual data and distress analysis, using an expert system for evaluating pavement conditions. A small pavement network on Baghdad University campus was selected as a case study to examine the developed system in assessing pavement conditions. In this system, maintenance strategy was determined based on distress type, severity, extent and the required extension in pavement life (Sarsam, 2008).

A number of pavement management systems were applied at both network and project levels. Gharaibeh et al. (1999) proposed a management system integrating analytical procedures and data, presentation methods, and the geographic information system (GIS). This system was applied for five highway infrastructure components (pavements, bridges, culverts, intersections, and traffic signs) of at network and project levels in central Illinois.

The integrated network-level system was used to conduct a trade-off analysis to find the feasible maintenance options for five infrastructure components, while the integrated project-level system was to implement maintenance projects for these components simultaneously to minimise traffic disruptions (Gharaibeh et al., 1999). Sebaaly et al. (1996) presented the development of Nevada's pavement management system at both the network and project levels. This system integrated performance modelling by considering traffic and environment, life-cycle cost analysis (LCCA), and network optimisation methods for rehabilitation and maintenance alternative prioritisation. In addition, extensive pavement evaluation was performed by non-destructive deflection testing at the project level (Sebaaly et al., 1996).

Each highway authority and agency in the world has developed and implemented its own pavement management system. Kanto and Männistö (1993) defined a pavement management system at network level in Finland called the "highway investment programming system (HIPS)" to optimise pavement treatment decisions and budgeting. In this system, the current and optimal pavement condition distributions were determined by classifying pavement conditions based on roughness, defects, rutting, and structural condition. In addition, the allocation of the total fund between different sub-networks of Finland's pavement network was based on pavement network length (Kanto and Männistö, 1993). In 2000, Rasdorf et al. highlighted the issues and needs which occurred in the development of a unified information management system in the North Carolina Department of Transportation (NCDOT). The unified information management system provided an environment that allowed a standardisation of data formats, that supported data sharing, and that diminished training necessities across the organisation. The major development of the unified highway database was the use of the linear reference method (LRM) and GIS (Rasdorf et al., 2000). Golabi and Pereira (2003) examined the development and implementation of the Portuguese pavement management system (PPMS). The key modules of PPMS included a database, a geographical information system, a pavement rehabilitation and improvement strategic model (PRISM), and a pavement quality evaluation model. A Markov modelling approach, using probabilistic prediction models that assign the state transition probabilities based on experience and knowledge, was considered in predictive, optimisation models (Golabi and Pereira, 2003).

In 2003, Xiong et al. presented a generic and comprehensive network-level framework for the Beijing Roadway management system (BRMS). The BRMS comprised these key modules: database, condition survey, condition assessment, deterioration prediction, and optimisation process. For distress surveys, laser sensors integrated with DIS Digital were adopted in the BRMS. A pavement condition index (PCI) was considered for both the flexible and rigid pavement condition assessment. The Markov chain technique was used for performance prediction, while integer programming was adopted for optimising the M&R plan by maximising the average condition under the budget constraints (Xiong et al., 2003). In 2005, Muhmood suggested a new pavement management system for the city of Mosul in Iraq. The new management system consisted of highway referencing, data collection by visual survey, pavement classification based on pavement condition rating (PCR), and decision making (Muhmood, 2005). Lee and Yoo (2008) presented the advantage of the pavement management system implementation in Korea. The efficiency of the PMS was examined by comparing the situations of the pre and post implementation of the PMS. The results of the comparison between 1987 (pre-PMS) and 2006 (post-PMS) showed a reduction of annual maintenance length and cost, with a large increase in traffic volume (Lee and Yoo, 2008).

In Thailand, Suanmali and Ammarapala developed the rigid pavement maintenance system (RPMS) to evaluate rigid pavement conditions, determine the most suitable repair strategy, and prioritise pavement sections by optimising limited budgets. The developed system comprised two units: a pavement condition index (PCI) unit to analyse the collected deterioration data, and an optimisation unit to help the highway authority to organise the maintenance efficiently for all rigid pavement sections. The maintenance decisions optimisation was conducted to decide whether to minimise the budget with the pavement performance as the constraint, or maximise the PCI of the entire network with the budget as the constraint. The RPMS was not used for long-term maintenance planning because of inadequate deterioration data and limited time (Suanmali and Ammarapala, 2010). Punzalan (2010) highlighted the management system of the newly rehabilitated North Luzon Expressway (NLEX), a privately operated toll highway. The maintenance management of this expressway was divided into two groups: heavy maintenance including total pavement overlay and rehabilitation, and routine maintenance including the day-to-day maintenance activity (Punzalan, 2010). In 2005, Webster and Allan conducted a questionnaire among various road authorities in the UK. The objective of that was to show how advanced asset management procedures and techniques acquired in other engineering sciences could be transferred effectively to the road sector to support the optimisation process. They found that there were cost savings in applying advanced techniques of asset management, especially in local agencies where the savings reached 15% (Webster and Allan, 2005). Finnie (2012) explored the challenges facing highway authorities currently in the UK with two conflicting criteria: reducing pavement asset budgets, and minimising carbon footprints in response to climate change. URS developed an application (app), branded WLCO2T, to determine easily the whole-life cost and whole-life carbon emissions for pavement maintenance activities over 60 years. In addition, it was able to identify the optimum year for maintenance by analysing the effect of continuing with routine maintenance to delay the capital expenditure (Finnie, 2012).

2.6 Summary

This chapter described the deterioration of flexible pavement, distress types, severity level, the distress inspection techniques and the common pavement performance indices. The pavement management system concepts were presented and the existing pavement asset management systems used by highway agencies throughout the world were described. The following chapter presents the literature review of basic components of pavement management system and the main contribution to knowledge of this research.

Chapter 3

Basic Components of Pavement Management System

3.1 Introduction

The basic components of a typical PMS consist of a centralised database, performance models, analysis methods, and reporting mechanisms (Dewan, 2004). There are two major components compulsory in a pavement management system to handle the whole pavement management process. The first element is a prediction tool that is capable of forecasting future pavement performance, especially after applying an active M&R program. The second is an optimisation procedure considered to yield best pavement conditions based on a defined decision policy (Abaza et al., 2004).

Overall, a complete PMS system has three main components:

- Pavement classification or section classification;
- Pavement deterioration model;
- Maintenance and rehabilitation decision policy.

3.2 Pavement Classification

A pavement condition assessment is an important element of the decision-making procedure of pavement management systems. It presents a quantitative criterion for assessing pavement section deterioration for the whole pavement network (Sun and Gu, 2011). There are two purposes behind the pavement classification: to observe the pavement network condition, and to identify maintenance and rehabilitation requirements (Hein and Watt, 2005). Pavement condition can be categorised by a range of performance indices. For highway pavements, these indicators comprise pavement surface deterioration, deflection, rut depth, roughness, and skid resistance (Sun and Gu, 2011).

Some of the pavement classification researches were based on exploiting the knowledge of experts or data. In 2008, Sagheer et al. developed a knowledge-based system for pavement deterioration classification using a logic programming language to identify distresses in flexible pavement. The literature and the knowledge of Iraqi pavement engineers were employed to construct an expert system of pavement distress (Sagheer et al., 2008). Khurshid et al. (2011) established an analytical methodology to find a candidate performance threshold for a highway-based cost-effectiveness analysis concept. This methodology was applied using a case study to demonstrate the benefit of candidate threshold levels for popular pavement rehabilitation actions (Khurshid et al., 2011). Terzi (2006) applied a data mining process for modelling the present serviceability index (PSI) for flexible pavements by using a regression tree model. This model has a good ability to estimate pavement surface layer thickness compared with the AASHTO model (Terzi, 2006).

3.2.1 Soft Computing Techniques

For solving complex problems, significant achievements for pavement classification in algorithmic development have been made through modelling techniques based on biological mechanisms and natural intelligence. These algorithms of soft computing comprise artificial neural networks, fuzzy logic, swarm intelligence and evolutionary computation (Engelbrecht, 2007).

Due to the advancement of computational power, the use of soft computing techniques in the field of pavement engineering is gaining popularity owing to its data processing speeds, good learning and adaptive abilities (for the classification system), and efficient data storage and management. Since the real-life engineering decisions are made in an ambiguous environment that requires a very high level of human expertise, which must be consistent, the application of soft computing can be an attractive option for practicing engineers.

3.2.1.1 Fuzzy Logic

Classical (crisp) set theory, or the binary system, considers elements or values to be either completely true (1) or completely false (0). However, human reasoning does not always follow this logic and usually includes a measure of uncertainty. Fuzzy logic presented by Zadeh in 1965 makes a significant improvement from conventional binary logic to address the issue of partial truth values between completely true and completely false. Fuzzy logic provides a modelling tool with the imprecision and uncertainty of reality and an easy interpretation or reflection for human thinking. "Fuzzy logic is determined as a set of mathematical principles for knowledge representation based on the degree of membership rather than on crisp membership of classical binary logic" (Engelbrecht, 2007; Negnevitsky, 2002; Xie, 2006).

Pavement condition and distress assessment and rating needs the subjective judgement of pavement experts and engineers. Therefore, fuzzy logic provides an appropriate tool to deal with the subjective judgement and uncertainty involved in pavement condition assessment.

Juang and Amirkhanian (1992) developed a simple performance index called the unified pavement distress index (UPDI) using a fuzzy set (membership functions). This index considered six distress types and weighted the different distress types for assessing overall pavement distress conditions (Juang and Amirkhanian, 1992). Shoukry et al. (1997) created a universal indicator called the fuzzy distress index (FDI), capable of evaluating pavement section conditions. This index combined the quantitative and qualitative distress data based on fuzzy logic to assess overall conditions of pavement sections. The FDI was a consistent and accurate index compared with the present serviceability index (Shoukry et al., 1997).

For overcoming the differences in distress assessments among experts and assessment uncertainty, Fwa and Shanmugam (1998) developed a distress condition rating procedure using a fuzzy-logic-based system. The membership function was employed to handle a relatively wide range of distress conditions for each distress and also to compute the severity rating scores (Fwa and Shanmugam, 1998). In 2001, Bandara and Gunaratne suggested a new subjective pavement evaluation procedure considering predominant distress types, severity and extent observed in flexible pavements based on the membership function. Then, a weighted fuzzy pavement condition index was developed for ranking pavement segments with respect to rehabilitation requirements (Bandara and Gunaratne, 2001).

Arliansyah et al. (2003) developed a way to calculate a fuzzy set of linguistic terms in pavement condition evaluation based on an expert`s judgement about the range values of these linguistic terms of pavement distress parameters. The influences of inclusion or neglect of pavement parameters on pavement condition assessment were examined. In addition, the effects of parameter weight change on pavement condition assessment were studied by comparing the results of the initial weight of pavement parameters with subsequent weight changes (Arliansyah et al., 2003). In addition, Golroo and Tighe (2009) developed a comprehensive fuzzy condition index for "pervious concrete pavement structures (PCPS)" based on membership functions considering distress types, severities, densities, and weighting factors. This condition index was converted to an individual value that allowed the ranking of pavements for network-level maintenance treatment (Golroo and Tighe, 2009).

In 2010, Koduru et al. suggested a methodology for classifying four pavement distresses based on a knowledge-based system and fuzzy logic, using condition data gathered by an automated survey (Koduru et al., 2010). A recent study by Sun and GU (2011) combined the advantages of analytical hierarchy process (AHP) and fuzzy logic to develop a new pavement condition assessment model. A fuzzy set was employed to assign different memberships to five categories of performance indicators: roughness, structural bearing capacity, surface distress, rutting, and skid resistance. The AHP was adopted to estimate weight vectors associated with these performance indicators (Sun and Gu, 2011). Fuzzy logic is a classification approach whose work has shown to be closer to the way of the human brain function. It has the ability to deal with uncertainty and subjectivity, and transfer the knowledge and experience to the less experienced engineers. It has been used widely by researchers in pavement section classification.

The main limitations of the previous mentioned researches are pavement condition assessment models developed based on the fuzzy sets theory especially on membership function concept to deal with the subjectivity associated with expert judgment of distress extent and severity. In addition, fuzzy set theory was used for ranking and finding the relative importance of different distress types on overall pavement condition performance.

Moreover, the previous researches have not developed fuzzy inference system in pavement classification.

3.2.1.2 Artificial Neural Network (ANN)

Neural networks are computational models that model the relationship between a number of input variables and output variables. "A neural network can be defined as a model of reasoning based on the human brain" (Negnevitsky, 2002). Similar to the human brain, an artificial neural network comprises a number of simple, highly interconnected processors which are called neurons. Neurons are connected together by a large amount of weighted links, with each neuron receiving input from various sources. The weights, called synaptic weights, further increase the correspondence between the real and artificial neurons. The input components obtain their inputs from exterior sources whereas other components obtain their inputs from the particular output that each component produces. The path of this output is split and terminates, through the weighted link, at the input of the receiving unit (Manwaring, 1995). Figure 3-1 shows a typical neuron.

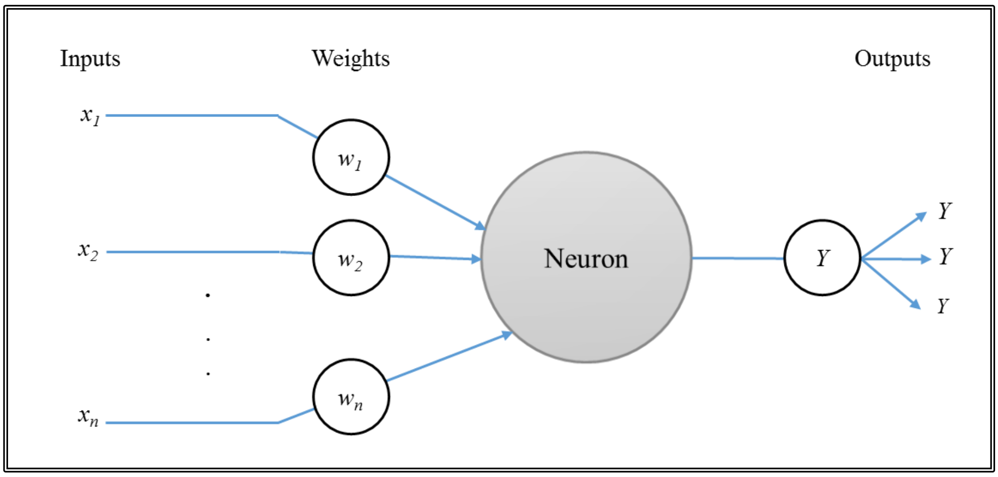

Figure 3-1: Neuron Diagram (Negnevitsky, 2002).

A neural network is an interconnected network of neurons where one neuron’s output acts as a stimulus to another one. During the connection it can obtain more than a single input, but it is not permitted to give more than a single output (Agatonovic-Kustrin and Beresford, 2000). The advantage of artificial neural networks is the ability to compute nonlinear functions, and detect all potential interactions between predictor variables by learning from experience.

Pavement condition assessment is subjectively evaluated by road experts and engineers. Therefore, the artificial neural network technique has adopted as a computational model to mimic the human decision-making process. Eldin and Senouci (1995) employed a back-propagation neural network technique to find a pavement condition rating index for rigid pavement. The distress types and severity levels were considered as inputs in formulating the condition rating model (Eldin and Senouci, 1995). Moreover, Terzi (2007) established a new methodology for determining a present serviceability index (PSI) by using artificial neural network (ANN) techniques rather than the AASHTO equation. The ANN model had better PSI values compared with the AASHTO equation (Terzi, 2007).

Liu and Sun (2007) applied a fuzzy optimisation back-propagation neural network (FOBPNN) model to evaluate the performance of expressway pavement. The maximum crack ratio, rut depth, roughness, strength coefficient and skidding resistance capacity, and expert scores were considered in the model's development (Liu and Sun, 2007). Although ANN is a widely used learning algorithm to solve different pavement classification problems, it cannot interpret relationships between inputs and outputs ("black box" learning method).

3.3 Pavement Deterioration Models

An accurate deterioration model, minimising the error of deterioration prediction, is vital for effective pavement management at both project and network levels because it leads to the creation of a timely and accurate intervention program and thus to a reduction in maintenance costs. These deterioration models should be capable of incorporating the contribution of the most effective variables such as pavement structure, traffic, and climatic effect on pavement deterioration. Prediction of pavement deterioration at the network level is important for adequate treatment programming, plan prioritisation and resource allocation. At the project level, it is required for finding the specific maintenance actions that are necessary, like maintenance and rehabilitation (Lytton, 1987; Prozzi and Madanat, 2004). Therefore, numerous highway authorities have developed various pavement deterioration models for use in their pavement management systems. These deterioration models are essential and valuable in forecasting at least individual distress type. Some of these models are simple and limited in their applications, while others are comprehensive and suitable for a wide range of applications (Haas et al., 1994; Lytton, 1987). The pavement deterioration models can be categorised into two main groups: deterministic and probabilistic, as shown in Table 3-1.

3.3.1 Deterministic Deterioration Models

Deterministic deterioration model types are those which predict a single value of the response variable such as a performance indicator, distress quantity, pavement life, etc., for a specified number of independent variables like time, age, traffic loading, usage rate, environmental effect, level of preservation activity, etc. For deterministic models, the most common analysis method is statistical regression (Haas et al., 1994; Lytton, 1987).

The majority of deterministic deterioration models were established based on linear or nonlinear statistical analysis methods. Fwa and Sinha (1986) found a linear relationship between present serviceability index-equivalent single axle-loads (PSI-ESAL) losses and unit maintenance expenditure. The data of the Indiana pavement network system, including rigid pavement, overlay pavement and flexible pavement routes, were used as a case study to apply this concept. The conclusion of statistical analysis showed that this linear relationship is not statistically powerful because of limited available data (Fwa and Sinha, 1986). Abaza (2004) presented a deterioration model by generating a unique performance curve for a particular pavement structure. This model was developed based on the serviceability PSI adopted by the AASHTO for flexible pavement design (Abaza, 2004).

Al-Mansour et al. (1994) developed linear maintenance-effect models to estimate the changes in pavement roughness with different maintenance treatments. These models were formulated for two highway classes and for two climatic regions. It was found that linear maintenance-effect model values vary significantly among the maintenance types (Al-Mansour et al., 1994). In addition, linear distress models were developed by Obaidat and Al-Kheder (2006) to forecast the pavement distresses quantities considering the effect of traffic, distance from maintenance unit, section area, and pavement age. The results of these statistical models showed that traffic and pavement age were the most important variables in forecasting distresses quantities (Obaidat and Al-Kheder, 2006). Ahmed et al. (2008) established a linear deterioration model to forecast the pavement condition index (PCI) in Baghdad by considering various distresses quantities. It was found that the developed model was able to predict pavement condition for the local flexible pavements network (Ahmed et al., 2008). To improve the predictions accuracy for incomplete data available, Luo 2013 proposed pavement deterioration model by applying an auto-regression method (Luo, 2013).

Table 3-1: A summary of different pavement deterioration models

Author	Model Name	Model Type	Traffic	Age	Distress	Construction & properties	M&R	Climate	Output
Fwa & Sinha 1986	PSI-ESAL loss curve	Deterministic	×						PSI loss
AI-Mansour et al. 1994	Linear maintenance-effect	Deterministic	×	×				×	Roughness/maintenance
Kerali et al. 1996	Linear rutting model	Deterministic	×			×			Rut depth
Ningyuan et al. 2001	Dynamic prediction model	Deterministic		×		×			Performance index/treatment
Prozzi & Madanat 2004	Recursive non-linear	Deterministic	×			×		×	Serviceability
Abaza 2004	unique performance curve	Deterministic	×	×		×			PSI
Obaidat & Al-kheder 2005	Multiple regression	Deterministic	×	×			×		Distresses quantities
Jain et al. 2005	Calibrated HDM-4	Deterministic	×	×		×		×	Distress progression
Ahmed et al. 2008	Linear model	Deterministic			×				PCI
Martin 2009	Mechanistic–empirical models	Deterministic	×	×	×	×	×	×	Rutting, roughness and structural deterioration
Khraibani et al. 2012	Nonlinear mixed-effects	Deterministic		×					Cracking progression
Luo 2013	auto-regression method	Deterministic		×					PCR
Alsherri & George 1988	Simulation model	Probabilistic	×	×		×		×	Serviceability index
Bandara & Gunaratne 2001	Fuzzy Markov model	Probabilistic			×				Degradation rates/distress
Hong & Wang 2003	Nonhomogeneous continuous Markov chain	Probabilistic		×					Pavement performance degradation
Hong & Prozzi 2006	AASHO Model based Bayesian	Probabilistic	×			×		×	Serviceability loss
Park et al. 2008	Bayesian distress prediction	Probabilistic		×					Longitudinal cracking
Henning 2008	Logit model	Probabilistic	×	×	×	×		×	Crack initiation & accelerated rutting
Amador-Jiménez & Mrawira 2009	Markov chain deterioration	Probabilistic		×					PCI
Amador-Jiménez & Mrawira 2012	Bayesian regression	Probabilistic	×			×			Rut depth
Anyala et al. 2012	Bayesian regression	Probabilistic	×			×		×	Rutting
Abaza 2014	discrete-time Markov	Probabilistic			×				Deterioration rate
Lethanh and Adey 2013	exponential hidden Markov	Probabilistic		×					Deterioration progression

Author	Model Name	Model Type	Traffic	Age	Distress	Construction & properties	M&R	Climate	Output
Kaur & Tekkedil 2000	Fuzzy expert	AI*	×	×		×			Rut depth
Chang et al. 2003 & Pan et al.2011	Fuzzy regression	AI			×				PSI
Bianchini & Bandini 2010	Neuro-fuzzy	AI	×		×	×			ΔPSI
Kargah-Ostadi et al. 2010	Roughness model-based ANN	AI	×	×		×	×	×	IRI
Shahnazari et al. 2012	Model-based ANN and GP	AI			×				PCI
Ziari et al. 2015	artificial neural networks and group method of data handling	AI	×	×		×		×	IRI

* Artificial Intelligence

Kerali et al. developed a nonlinear regression model to predict rut depth by considering traffic loading, base materials and thickness. It was found that the combined effects of the base layer materials and base layer thickness influence rutting (Kerali et al., 1996). Ningyuan et al. (2001) presented a dynamic prediction model considering specific treatment effects to predict a condition index for each treatment (Ningyuan et al., 2001). Prozzi and Madanat (2004) developed a nonlinear deterioration model to estimate pavement serviceability by using the experimental and field data of the American Association of State Highways Officials (AASHO) Road Test. The developed model had less prediction error than existing prediction models (Prozzi and Madanat, 2004). One of the common deterministic models is the HDM-4 pavement deterioration models. Jain et al. (2005) calibrated these models to be used in local conditions in the Indian National Highway Network (Jain et al., 2005). Martin (2009) developed mechanistic–empirical deterministic deterioration models at network level for rutting, roughness and the structural deterioration of sealed granular pavements. The long-term observational deterioration data were collected from the Australian arterial highway (Martin, 2009). Moreover, Khraibani et al. (2012) developed a nonlinear model for explaining cracking behaviour with time, and also to study the effects of several factors on this behaviour (Khraibani et al., 2012). The deterministic models of pavement deterioration were developed to forecast specific distress progression without considering other distress types. Moreover, most of these models could not consider the contribution of the most significant variables to pavement deterioration.

3.3.2 Probabilistic Deterioration Models

The probabilistic deterioration model is different from deterministic models in that it predicts a distribution of such events. To deal with limited availability of historical data, the majority of probabilistic deterioration models were developed using the Markov chain technique for predicting distress quantity or an overall performance index (Lytton, 1987).

Alsherri and George (1988) established a simulation model for calculating the reliability-performance of pavements and also the expected pavement life. The program, Reliability Analysis and Performance of Pavements (RAPP-I), employs Monte Carlo simulation method to solve the AASHTO design equations (Alsherri and George, 1988). Henning established continuous probabilistic models to predict the crack initiation and accelerated rutting for New Zealand’s pavement network. A Logit model form, which is especially effective in forecasting the likelihood of a defect event occurring, was used (Henning, 2008).

The most popular method of probabilistic modelling is the Markov chains method. For the application of Markov chains, the state transition probabilities are assigned on the basis of experience (Bovier, 2012). Bandara and Gunaratne (2001) formulated an efficient fuzzy Markov chain model as a future pavement condition prediction model. It was based on expert knowledge in assessments of pavement deterioration rates associated with each distress type (Bandara and Gunaratne, 2001). Hong and Wang (2003) developed a simple probabilistic deterioration model based on a nonhomogeneous continuous Markov chain. The parameters of the developed model were found by matching the mean value of the process to the Ontario Pavement Analysis of Cost (OPAC) model or the AASHTO model (Hong and Wang, 2003). In 2012, Lethanh and Adey developed a new model for estimating the deterioration progression over time using exponential hidden Markov method from the incomplete data (Lethanh and Adey, 2012). Abaza (2014) introduced a new approach called ‘back-calculation’ to evaluate the transition probabilities used in the discrete-time Markov-based pavement deterioration models. In addition, a simple procedure was presented for estimating the pavement state of distress using the two pavement defect groups, called cracking and deformation (Abaza, 2014).

"Another method of probabilistic modelling is Bayesian analysis approach which extends maximum likelihood estimation by assigning a prior probability over the interaction parameters and considering their posterior probability" (Chipman et al., 2001). Hong and Prozzi (2006) improved the AASHTO deterioration model by using a Bayesian approach with a Markov chain Monte Carlo simulation to determine serviceability loss. The three main factors, structural properties, environmental effects, and traffic loading, were combined in this model (Hong and Prozzi, 2006). To deal with the limited availability of two years' historical data, Jiménez and Mrawira (2009) suggested a novel methodology based on Markov chains to estimate an initial condition index at the network level (Jiménez and Mrawira, 2009).

Park et al. (2008) developed a distress prediction model based on a Bayesian analysis method for predicting the future pavement condition of discrete sections' distresses. The prediction model is based on individual pavement distress measurement such as longitudinal cracking (Park et al., 2008). Jiménez and Mrawira (2012) introduced a more reliable framework for the rut depth progression prediction by using Bayesian regression modelling. This framework was validated by comparing with the AASHTO Road Test regression model (Jiménez and Mrawira, 2012). Anyala et al. (2012) introduced a new deterioration model for predicting rutting in asphalt surfacing considering the effects of future climate predictions. For each asphalt surface group, a Bayesian regression method was used to determine the distribution of the model coefficients. The developed model was applied within a Monte Carlo simulation to find the probabilistic distributions of pavement rutting progression under the predefined scenarios of future climate conditions

(Anyala et al., 2012). To overcome the limitation of data availability, the probabilistic approaches were used in pavement deterioration prediction. The majority of probabilistic models were based on the deterioration rate remaining unchanged during the study period. Furthermore, all affective parameters on pavement deterioration were not considered in these models.

3.3.3 Soft Computing Techniques

To address uncertainty and nonlinearity, soft computing techniques were employed in studying pavement deterioration. The techniques of soft computing comprise artificial neural networks, fuzzy logic, swarm intelligence and evolutionary computation.

Kaur and Tekkedil (2000) created a new model based on fuzzy logic to forecast the rut depth of flexible pavement. The subgrade type, surface layer thickness, road age and total traffic volume were considered as inputs for this model (Kaur and Tekkedil, 2000). To handle the uncertainties in pavement condition data, Chang et al. (2003) developed a fuzzy regression model to predict the pavement serviceability index (PSI) (Chang et al., 2003). Moreover, Pan et al. (2011) established fuzzy linear regression equations to estimate future pavement conditions and the PSI (Pan et al., 2011).

Bianchini and Bandini (2010) proposed a hybrid prediction model based on a neuro-fuzzy technique to forecast effectively the change in the present serviceability index (ΔPSI) in five years. Climatic effects, traffic, and parameters acquired by conducting falling weight deflectometer tests were considered as input variables for the model (Bianchini and Bandini, 2010).

Kargah-Ostadi et al. (2010) employed an artificial neural network (ANN) to develop an empirical model for international roughness index (IRI) progression. The data of variables affecting pavement roughness such as initial roughness, pavement age, traffic, climatic conditions, structural properties, subgrade properties, drainage type and conditions, and maintenance effects were extracted from the LTPP SPS-5 database (Kargah-Ostadi et al., 2010). Shahnazari et al. (2012) developed two pavement deterioration models to forecast a pavement condition index (PCI). One of them was developed using ANNs and the other was based on genetic programming (GP). In both models, the input variables were distress quantities, severity levels and types. The results showed that both models had high precision, but the ANN model was more reliable and precise than the GP model (Shahnazari et al., 2012). In 2015, Ziari et al. used artificial neural networks (ANNs) and group method of data handling (GMDH) approaches to develop pavement condition prediction models. It was found that the ANN model can predict international roughness index (IRI) accurately in the short and long terms while the GMDH model has unaccepted accuracy (Ziari et al., 2015). Compared to the deterministic and probabilistic models, soft computing techniques were not widely used in pavement deterioration prediction due to insufficient data availability for training. The main limitation of the majority of the existing prediction models is the maintenance and rehabilitation effect not considered in prediction of pavement conditions.

3.4 Maintenance and Rehabilitation Decision Policy

Basically, it is important to select feasible maintenance plans that are best able to maintain the conditions of the pavement network above the minimum acceptable performance level during its lifetime. Therefore, some pavement management systems use priority approaches, while other management systems employ optimisation models (Javed, 2011). A variety of methods have been used for prioritisation or optimisation maintenance and rehabilitation decision policy, as shown in Figure 3-2.

3.4.1 Prioritisation Models

At both network and project levels, many highway agencies employ priority programming models to compare pavement investment alternatives. In prioritisation models, the pavement condition data are used to find a factor or index to represent the present pavement condition. Prioritisation is done by ranking all the pavement segments based on a priority-ranking index. This ranking index usually considers different parameters such as highway class, traffic volume, quality index, etc. The maintenance and rehabilitation needs selection and budget allocation are conducted based on this priority-ranking index. There are many methods to find priority programming, ranging from a simple subjective ranking method to the mathematical method (Haas et al., 1994; Meneses et al., 2012).

The approaches based on expert knowledge such as decision trees and expert systems were employed to rank or prioritise pavement treatment decisions. In 1985, Darter proposed a simple decision tree assignment procedure for the network level to select the most cost-effective maintenance strategy for each section over the analysis period (Darter et al., 1985). Ritchie (1987) presented the PARADIGM system, integrating a set of expert systems for the pavement rehabilitation prioritisation and pavement surface condition assessment (Ritchie, 1987). In addition, Helali et al. (1996) developed a network-level pavement management system for the steel slag dense friction course/open friction course (DFC/OFC) hot mix surface pavements of Toronto’s highway network. This pavement system consisted of a pavement condition evaluation, empirical deterministic deterioration models, maintenance prioritisation and budget priority analysis. The optimal budget and feasible rehabilitation plans over 10 years were estimated by the decision trees generated based on engineering experience and life-cycle economic analysis (Helali et al., 1996). Zhou et al. (2010) integrated data mining and knowledge discovery (DMKD) with

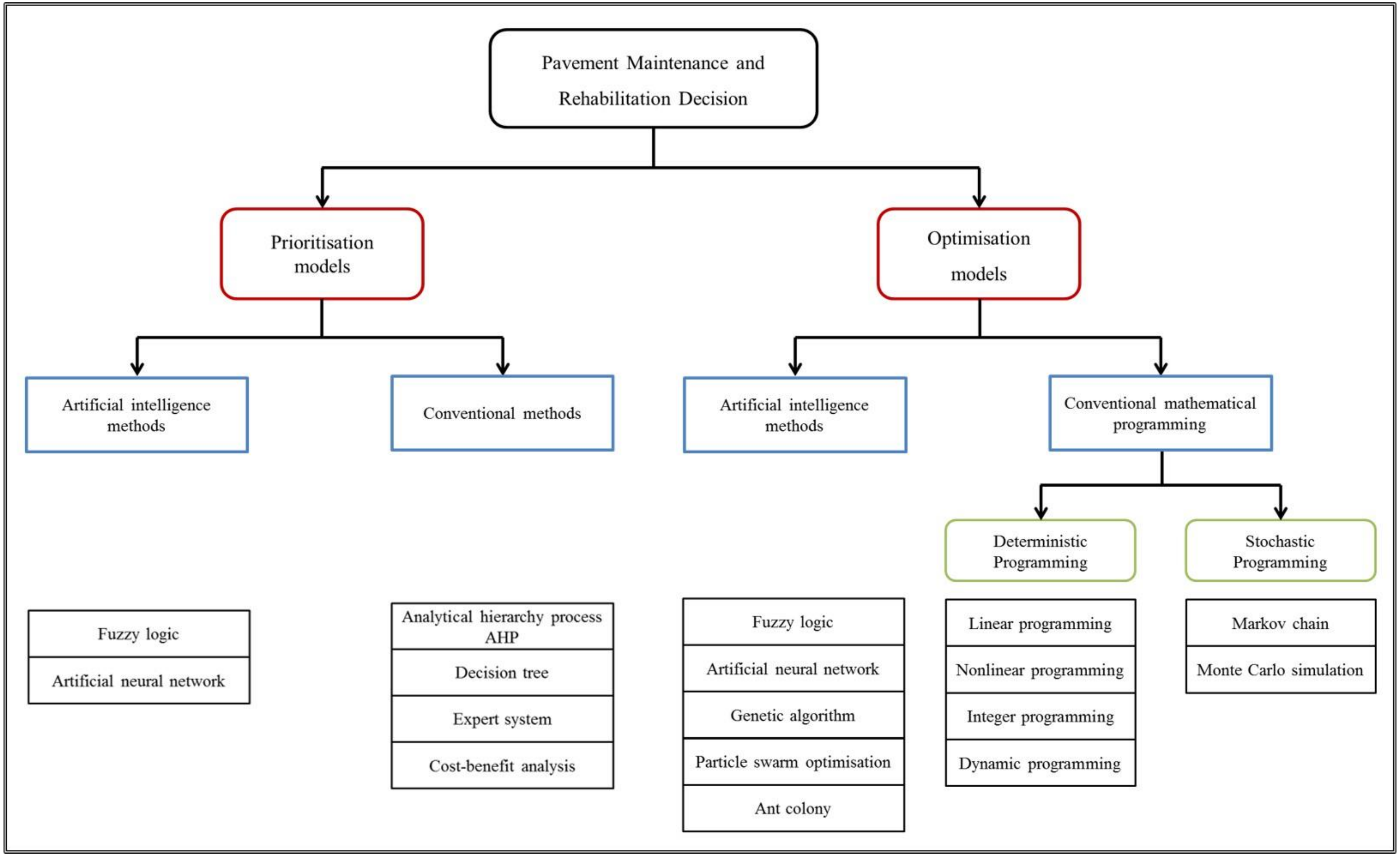

Figure 3-2: Flowchart of M&R decision prioritisation and optimisation methods

Geographic Information System (GIS) technology to the pavement management system to make the treatment decisions prioritisation (Zhou et al., 2010). "Data mining is defined as the process of discovering patterns in data. The process must be automatic or (more usually) semiautomatic. The patterns discovered must be meaningful in that they lead to some advantage, usually an economic one. The data is invariably present in substantial quantities" (Witten et al., 2011).

The finance criterion, the net present value (NPV), was used as a priority factor to rank maintenance strategies and allocate resources. In 2004, Fakhri and Rooeinbakht identified the optimum treatment standards for Iranian pavement conditions by using the "Programme Analysis" application within the HDM-4 model. The proposed maintenance standards assist in prioritising maintenance strategies based on maximum net present values (Fakhri and Rooeinbakht, 2004). Moreover, Tsunokawa and Hiep (2008) proposed a unified methodology for determining the optimal budget allocation among all highway subsystems. The NPV was used as a criterion to allocate the budget among all subsystems (Tsunokawa and Hiep, 2008).

The common indicators like the cost/benefits ratio and trade-offs are valuable to adopt as priority or rank criterion. Krueger and de la Garza (2010) introduced a technique to compute the decision-making process effectiveness, represented by the service level, and efficiency, represented by the cost/benefit ratio, for a predetermined yearly budget and a specific funding allocation strategy among treatment actions. The best budget allocation scenario was identified by determining the minimum cost/benefits ratio (Krueger and Garza, 2010). Furthermore, Moazami et al. (2010) applied alternative, unlimited and annual budgets in pavement management software called Micro-

PAVER. Mozami et al. examined various trade-offs among budget scenarios to obtain the best pavement performance in the entire Tehran network (Moazami et al., 2010).

One of the most common methods used in pavement treatment prioritisation is the analytical hierarchy process (AHP). The AHP is a multi-criteria decision model, designed to assist decision makers. Ramadhan et al. (1999) used the AHP to create a priority index that determines the importance weight of pavement maintenance. The highway class, condition index, traffic, riding quality, skid resistance, cost, and the overall importance of the section to the public were considered in the priority index (Ramadhan et al., 1999). Cafiso et al. (2001) developed a maintenance prioritisation model called multi-criteria analysis (MCA) within HDM-4 by including criteria such as environmental effects, safety impact, and social benefits. Then, the AHP was chosen to determine the relative importance of these criteria (Cafiso et al., 2001). In 2010, Farhan and Fwa proposed two methods, the fuzzy analytical hierarchy process (FAHP) and the fuzzy arithmetic approach, to prioritise maintenance activities in pavement maintenance programming. The FAHP was employed to overcome a degree of uncertainty in judgements and the large amount of information. The goal of the study was to identify a method that would allow engineers and agencies to be more accurate in the decision-making process (Farhan and Fwa, 2010). Moazami et al. (2011) determined a pavement maintenance prioritisation index for the Tehran road network by using the AHP, considering the pavement condition index (PCI), traffic volume (TV), and road class. Fuzzy logic modelling related to human inference was employed as a next step to finding precise results of the maintenance prioritisation engine (Moazami et al., 2011).

In 2008, Lamptey et al. formulated the decision support system (DSS) model to select the optimal combination of preventive treatment types and timings in the interval between two resurfacing actions (Lamptey et al., 2008). The concept of a decision support system (DSS) is defined as "an interactive, flexible, and adaptable computer-based information system, especially developed for supporting the solution of a non-structured management problem for improved decision making. It utilises data, provides an easy-to-use interface, and allows for the decision maker’s own insights" (Turban, 1995). Šelih et al. (2008) established a multi-criteria decision model that was able to make decisions of maintenance and rehabilitation prioritisation at different highway facilities (Šelih et al., 2008). Morgado and Neves (2010) applied a multi-criteria decision analysis model to the evaluation of pavement maintenance investments to estimate total agency cost, works’ duration and average user delay (Morgado and Neves, 2010). In 2011, Augeri et al. introduced a multiple-criteria decision model to distribute the allocated budget to various pavement sections according to the degree of urgency of maintenance activities (Augeri et al., 2011).

There were other approaches used in maintenance decision prioritisation. In 1993, Fwa and Chan used neural network models to estimate the priority rating scheme of highway pavement maintenance needs. A simple back-propagation neural network model was tested separately with three priority-setting schemes: linear and nonlinear condition index functions, and subjective priority ratings (Fwa and Chan, 1993). Chou (2008) used a case-based reasoning (CBR) method to calculate the initial pavement maintenance project costs by considering the past knowledge of experts and the important weights of attributes determined by the AHP (Chou, 2008). Pantha et al. (2010) created a GIS-based prioritisation model for establishing a pavement maintenance priority map. This model was developed by integrating pavement condition, the international roughness index (IRI), and roadside slope failure (Pantha et al., 2010). The aforementioned prioritisation models involved ranking candidate pavement sections requiring preservation based on decision makers preference or the "worst first" concept. Therefore, they did not considered single or multi-objective functions. In addition, they could not find the maintenance type and timing just finding the worst first section.

3.4.2 Optimisation Models

"Optimisation is the act of obtaining the best result under given circumstances" (Rao, 2009). Optimisation models have been applied in different engineering topics such as construction, design, maintenance management, etc. The main objective of all optimisation decisions is either maximisation of the desired benefit or minimisation of the required cost or effort (Rao, 2009).

In pavement management, optimisation decision models can be executed to either single-year or multi-year M&R programming. Optimisation models can be used to select alternatives to satisfy a single or multi-specific objective functions, such as effectiveness maximisation and/or cost minimisation (Haas et al., 1994). Many mathematical programming techniques (e.g. linear programming, dynamic programming, etc.), soft computing methods (e.g. genetic algorithms, particle swarm optimisation, etc.) or hybrid models that combine the two techniques have been used in pavement maintenance optimisation (Fwa et al., 2000).

3.4.2.1 Classical Mathematical Programming Models

There are different ways to classify optimisation problems. They are classified based on constraints, as constrained and unconstrained, or the nature of their design variables, or the nature of their objective functions as linear, nonlinear, quadratic or geometric problems, or the values of their design variables as real-valued and integer programming problems, or the deterministic nature of their variables as deterministic and stochastic (probabilistic) programming problems. A variety of mathematical techniques have been developed to solve the different optimisation problems. The classical mathematical techniques such as linear, nonlinear, quadratic and integer programming can be used for solving specific optimisation problems (Rao, 2009).

3.4.2.1.1 Stochastic Programming Techniques

One of most popular stochastic programming techniques is the Markov chain or Markov decision process. This technique has the ability to overcome a deficiency of data availability. For the application of the Markov decision, the state transition probabilities are assigned based on expert knowledge or experience, and it can also estimate a set of transition probabilities (Butt et al., 1994; Yang, 2004). Golabi et al. (1982) described the development of the pavement management system in the state of Arizona to find optimal repair strategies for each mile of the 7,400-mile pavement network. The developed system consisted of a mathematical model which could deal with the dynamic and probabilistic features of pavement maintenance. Therefore, the Markov decision method was considered for both the short-term and long-term management system (Golabi et al., 1982). Mbwana and Turnquist (1996) formulated a network-level pavement management system (PMS) model that reduced the gap between network-level policies and project-level decisions. This system adopted a Markov decision approach to find optimal treatment decisions for each section or link in the pavement network of Nassau County, New York (Mbwana and Turnquist, 1996). To overcome the insufficient availability of pavement condition and road user cost data, Chen et al. (1996) introduced a global optimisation model based on the Markov decision process to estimate benefits of pavement M&R treatments for independent pavement groups. The entire network was divided into a number of groups by highway class, traffic, pavement type, and geographic or climatic zones (Chen et al., 1996). Veeraragavan (1998) proposed an optimisation methodology based on the Markov decision process for a pavement management system at the project level to determine the most cost-effective rehabilitation programme for the pavement at each cycle time. The sections of a national network in India were categorised into forty-five condition states based on roughness level, cracking area and rutting. It was found that the optimal proportion of pavement sections in different condition states with correct activities applied for each state leads to the lowest cost rehabilitation strategy with the minimum future treatment cost (Veeraragavan, 1998).

Li and Madanat (2002) developed a deterministic Markov decision process integrated with a steady-state optimisation approach to find the overlay frequency and intensity over infinite (continuous) time. The resurfacing action optimisation was conducted by minimising the net present value of agency and user costs (Li and Madanat, 2002). In 2006, Abaza established and applied a stochastic pavement management model (SPMM) to a particular pavement system containing homogenous sections in pavement structure and loading conditions. The SPMM was developed to find optimal M&R actions and their timing, and determine optimal M&R fund allocations over the long term at network-level by using a nonhomogeneous discrete Markov chain. The maintenance decision optimisation was done by maximising the expected pavement conditions or minimising the total M&R costs (Abaza, 2006). Li (2009) formulated a stochastic optimisation model, and an efficient solution algorithm for a project-level road asset management system. The developed model can select the optimal subset of varied types of road facilities (pavement, bridge, roadside, etc.) from many candidate projects, considering the maximisation of overall project benefits under different scenarios of budget constraint (Li, 2009). Babaei and Naderan (2012) proposed a network-level management model based on Markov chains that was able to predict pavement conditions and optimise resources simultaneously. To ensure the maximum possible amount of pavement network above the minimum acceptable level, this model was employed on multi-objective functions: minimisation of the ratio of the worst condition in the network and minimisation of the pavement quantity of all the states exceeding the critical threshold except for the worst state (Babaei and Naderan, 2012).

3.4.2.1.2 Deterministic Programming Techniques

One of the common mathematical programming methods is the linear programming method, which is used to solve particular optimisation problems where all functions of objectives and constraints are linear functions. Hugo et al. (1989) proposed a pavement management system to support decisions on the programming of rehabilitation projects over the planning period. The proposed system was able to predict the pavement conditions and find optimal decisions based on a linear programming method with logical constraints (Hugo et al., 1989). De La Garza et al. (2011) developed a simpler network-level decision-making model for pavement maintenance optimisation, based on linear programming subject to annual budget constraints and the agencies' pavement performance target. It was then applied on the interstate pavement network to examine the following number of single objectives: minimise the number of pavement sections in different conditions with budget constraints or performance targets; minimise the required budget over the planning period to satisfy the constraints; and minimise the limited annual budget required to satisfy the constraints (de la Garza et al., 2011).

The nonlinear programming technique (NLP) is used when any of the functions among the constraints and objectives is a nonlinear function (Rao, 2009). To reduce pavement life-cycle costs for continuous time and continuous pavement states, Gu et al. (2012) incorporated the effects of maintenance actions on pavement resurfacing scheduling decisions by developing a nonlinear mathematical program. The results show the advantage of applying a sufficient quantity of maintenance actions to minimise the overall life-cycle costs by more than 6% (Gu et al., 2012).

Quadratic programming is used to solve nonlinear programming problems with a quadratic objective function and linear constraints. Durango-Cohen and Sarutipand (2009) proposed a quadratic programming optimisation model to determine optimal maintenance plans for multi-facility transportation systems. The developed model has the ability to capture the functional interdependencies that exist between facilities in transportation systems and also to capture the bidirectional relationship between traffic and deterioration (Durango-Cohen and Sarutipand, 2009).

The values of design variables in all the optimisation methods are considered to be continuous. However, the main concept of the integer programming method is that some or all of the design variables are assumed to be integer (discrete). If some of the design variables are restricted to discrete values, this method is called mixed integer programming. For solutions of linear programming problems, the integer linear programming technique is used (Rao, 2009). Fwa et al. (1988) developed a network-level pavement management system based on integer linear programming for programming routine maintenance actions of a pavement network in Indiana. This system helps decision makers find quantities of various routine treatment types to be executed over a planning period under a number of constraints (Fwa et al., 1988). In

2003, Wang et al. introduced a selection problem of candidate treatment projects at the network level, which was solved by employing an integer linear programming method. The multi-objective functions, the maximisation of total treatment effectiveness and minimisation of treatment disturbance cost, were solved by adopting a weighting formulation and the decision maker's value judgment (Wang et al., 2003). Wu and Flintsch (2008) proposed a decision support methodology for selecting the optimal pavement treatment projects based on the combination of three techniques: k-means clustering, the analytic hierarchy process (AHP), and integer linear programming. The k-means clustering was used to categorise maintenance projects into different homogeneous groups, while the AHP was used to determine the importance of each group. The integer linear programming was used to select optimal projects by maximising the M&R benefit within the budget constraint (Wu and Flintsch, 2008). Scheinberg and Anastasopoulos (2010) developed a network-level multi-constraint pavement management system by using mixed integer programming with different predefined multi-year maintenance strategies. The goal of the proposed system was to generate an optimal maintenance plan that satisfied a single objective and multiple constraints across two or more years (Scheinberg and Anastasopoulos, 2010).

Another integer programming type, the integer nonlinear programming method, is considered if there is at least one nonlinear function among the constraints and objective functions. In 2004, Ouyang and Madanat proposed a mixed-integer nonlinear programming (MINLP) model to find optimal pavement rehabilitation scheduling by minimising discounted total life-cycle costs including user and agency costs over the planning period. The nonlinear deterioration, rehabilitation effectiveness models and integer decision variables were extended and incorporated into the MINLP model (Ouyang and Madanat, 2004). In 2008, Priya et al. employed mixed-integer nonlinear programming to find the optimum treatment alternatives and their timing for the assigned budget. The objective of optimisation was to maximise the total benefit, the area between the performance curve and threshold values. Moreover, the optimal required budget for project-level pavement management was estimated by considering the structural and functional pavement conditions at different levels of traffic volumes (Priya et al., 2008). Ng et al. (2011) proposed two M&R models based on integer nonlinear programming to incorporate uncertainties in pavement upgrading due to treatment solutions and deterioration rate. In addition, the price of uncertainty, that is, the additional required funding when treatment solutions are applied if uncertainty is considered against the case where uncertainty is totally ignored, was quantified (Ng et al., 2011).

There are particular optimisation problems named multistage decision problems. In these problems, the decisions are made at sequential stages. Therefore, the dynamic programming is designed for solutions of these problems. Camahan et al. (1987) developed a new methodology to find an optimal preservation program by integrating a cumulative damage model based on a Markov chain with dynamic programming. The damage model was employed to estimate pavement deterioration, while the dynamic programming was used to find the optimal maintenance plan with the minimum cost over the planning period (Camahan et al., 1987). Butt et al. (1994) combined Markov chains-based prediction model with a dynamic programming model for a pavement management system at the network level. A nonhomogeneous Markov chain was used to develop a condition prediction model, while dynamic programming was employed for finding the optimal budget requirements (Butt et al., 1994).

Yin et al. (2008) proposed an integrated and robust optimisation system for estimating the maintenance investment required to reach the desired serviceability levels and facility conditions of the highway network. The proposed system considered the uncertainties of both demand growth (volume/capacity ratio) and facility deterioration level (pavement roughness) (Yin et al., 2008). In 2008, Gao and Zhang suggested a robust optimisation system to estimate the future budget for project-level M&R pavement programming. This system consisted of three function modules: a prediction module, a maintenance effect module and a robust optimisation module. Linear regression models were used for both the performance prediction module and the maintenance prediction module (Gao and Zhang, 2008). There are various optimisation algorithms that have been used for pavement management system. Tsunokawa and Schofer (1994) proposed a new optimisation model called the "control theoretic dynamic model" for optimising the frequency and thickness (intensity) of overlay actions over a continuous period. To mitigate the problem difficulty, the developed model used a smooth trend curve for approximating a sawtooth-like pavement serviceability trajectory curve as shown in Figure 3-3 (Tsunokawa and Schofer, 1994).

To simplify the complexity of the optimisation model, Worm and Harten (1996) developed a "four-phased optimisation approach", with associated operational research (OR) methods in each phase. The proposed approach was developed for multi-period pavement maintenance programming by minimising the net present value (NPV) of all present and future maintenance costs (Worm and van Harten, 1996). Li and Haas (1998) developed an optimisation system for multiple years of pavement maintenance and rehabilitation programming at the network level through integrating homogeneous Markov transition process deterioration models. The maximisation of the total benefit-cost ratio for the pavement network, obtained from cost-effectiveness-based priority analysis on a year by year basis, was the objective of the maintenance decisions optimisation (Li and Haas, 1998).

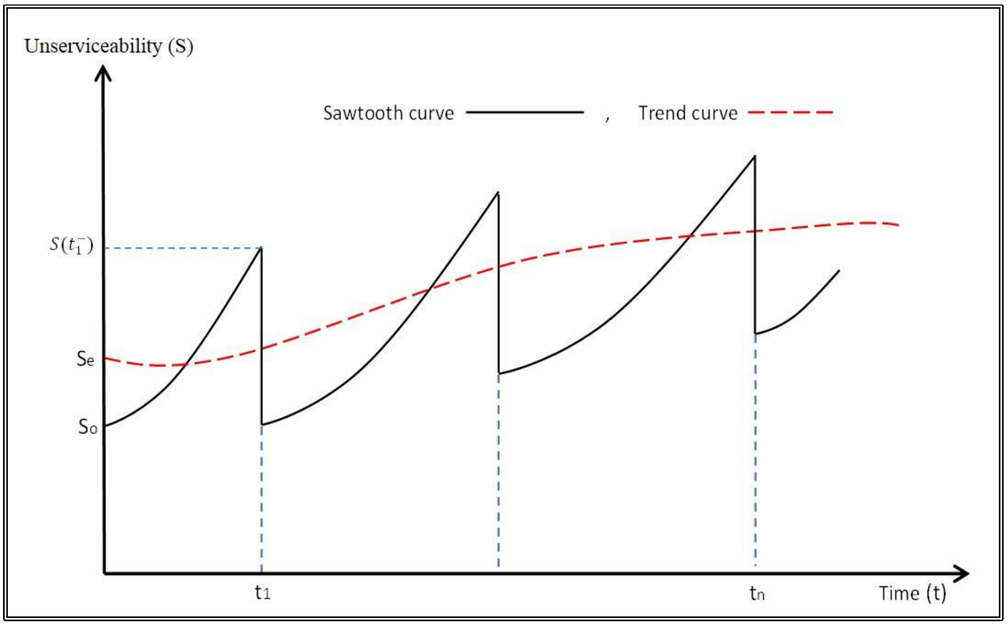

Figure 3-3: Sawtooth curve and trend curve of pavement serviceability (Tsunokawa and Schofer, 1994).

Abaza and Ashur (1999) formulated an integrated decision policy optimisation model which applied a discrete-time Markov chain model to predict future pavement condition state. The nonlinear optimisation approach was used with two options of maintenance decision policy: optimisation of a particular state probability under budget constraints, and minimisation of total maintenance costs under predefined condition states (Abaza and Ashur, 1999).

Abaza et al. (2001) established a macroscopic optimisation approach, using a long pavement section, to find optimal decision policy by maximising the annual average network present serviceability index (PSI) when subjected to budget constraints. For predicting pavement performance, AASHTO serviceability curves were employed. Then, the pavement sections having similar performance curves were categorised into six classes with only four classes with the worst performance levels (Abaza et al., 2001). Hiep and Tsunokawa (2005) introduced a systematic methodology for the Vietnamese pavement network by combining the HDM-4 model with gradient methods to determine the optimal treatment alternative decisions corresponding to three traffic levels and different initial pavement conditions. After calibration of the HDM-4 model according to Vietnam's conditions, the optimal solution was optimised to maximise the net benefit to society, the difference in the total transport costs between a specified maintenance decision and a do-minimum decision (Hiep and Tsunokawa, 2005). In 2006, Ouyang and Madanat proposed an optimisation model for multiple pavement resurfacing actions by minimising life-cycle costs in a discrete period. The simple analytical method was used to find optimal conditions that can be subsequently employed to develop a simple algorithm to find an optimal resurfacing solution (Ouyang and Madanat, 2006).

In 2008, Durango-Cohen and Madanat developed an integrated optimisation methodology, based on latent Markov decision process formulations and adaptive control formulations, to find inspection decisions and treatment strategies simultaneously in infrastructure management under performance model uncertainty. The performance model uncertainty represented the facility deterioration process by using a finite mixture of Markov Decision Probabilities (MDP) (Durango-Cohen and Madanat, 2008). Wu et al. (2008) proposed and applied a decision-support model for finding the optimal short-term preservation budgeting across districts for the interstate and primary flexible pavement network. The programming was integrated to handle multiple objectives while the analytical hierarchy process (AHP) was used to determine the relative importance of each district for receiving funds. The two conflicting optimisation objectives, maximisation of the total expected age gain for the network and minimisation of total preservation costs, were considered (Wu et al., 2008). Wu and Flintsch (2009) proposed an approach for pavement maintenance scheduling of using multi-objective optimisation and chance constraints. The weighting sum method was considered to simplify the multi-objective optimisation problem by using a weighting factor to change the multi-objectives to a single objective. The Markov transition probability method was employed as a pavement deterioration model (Wu and Flintsch, 2009).

Seyedshohadaie et al. (2010) suggested a general methodology based on the Conditional Value at Risk (CVaR) measure for creating short- and long-term optimal risk-based maintenance and rehabilitation policies for transportation infrastructure. The proposed methodology was to ensure a particular performance level across the network under a predefined risk level. The Markov Decision Process was used to formulate a long-term model with risk-averse actions and transitional probabilities representing the deterioration process uncertainty. Two linear programming models were used to address the short-term budget allocation problem (Seyedshohadaie et al., 2010). Jorge and Ferreira (2011) introduced a new maintenance optimisation system, called "GENEPAV-HDM4", which was developed to combine the pavement management system of Viseu municipality in Portugal and to comply with recent Portuguese legislation. The proposed model was to bridge the gap between project and network management levels and to find the best solutions of not only corrective M&R actions but also routine maintenance actions (Jorge and Ferreira, 2011). Sathaye and Madanat (2011) presented a simple methodology based on a greedy algorithm for determining the overlay timing and thickness for several road facilities, continuous-state over the infinite period (Sathaye and Madanat, 2011). Meneses et al. (2012) applied a multi-objective decision-aid tool (MODAT) and tested with data of PMS in

Oliveira do Hospital in Portugal. The MODAT used a deterministic section-linked optimisation model with three different objectives: minimisation of maintenance and rehabilitation costs, minimisation of user costs, and maximisation of the residual value of pavements. The MODAT used the pavement performance model of the AASHTO flexible pavement design method to bridge the gap between network and project management. Then, the best M&R solutions produced by the MODAT were presented on the map using GIS (Meneses et al., 2012).

The main limitation of aforementioned optimisation algorithms is that the selection of the logarithm is restricted and depended on the nature of optimisation problem. For example, linear programming is not able to solve the problem when the objective and/or constraints are nonlinear functions and integer programming is not able to solve continuous optimisation problems. Therefore, the optimisation method must be selected based on the nature of the objective and constraints equation, and the values of design variables. In addition, these programming techniques could not address the high dimensional optimisation problems.

3.4.2.2 Soft Computing Techniques for M&R Decisions Optimisation

Soft computing techniques consist of knowledge-based expert systems such as fuzzy logic and artificial neural networks, evolutionary computing algorithms such as genetic algorithms, swarm intelligence, and the ant colony algorithm. These techniques differentiate from the other optimisation techniques by their ability to deal with uncertain and incomplete data. The data used to produce and develop maintenance and rehabilitation decision standards and policy may include a mixture of objective measurements, subjective assessments, and expert contributions.

Therefore, these techniques are appropriate to deal with these data and handle the uncertainty and subjectivity (Fwa, 2006).

3.4.2.2.1 Knowledge-Based Expert Systems

The popular examples of knowledge-based expert systems being used for solving engineering problems through simple decision rules are artificial or soft computing technologies such as fuzzy logic and artificial neural networks (ANN). The main advantage of these techniques is their ability to handle subjectivity and uncertainty of data. Therefore, ANN and fuzzy logic techniques have been employed for pavement maintenance needs, analysis and strategy selections (Fwa, 2006).

Flintsch et al. (1996) developed and applied an artificial neural network method in a pavement management system in Arizona for identifying pavement sections that should be programmed for maintenance (Flintsch et al., 1996). Wang and Liu (1997) introduced a fuzzy set based network optimisation system (NOS) by converting the objective of the existing system adopted in Arizona. The optimisation process targeted a minimisation of annual maintenance cost and a maximisation of pavement performance over the analysis period. In order to predict accurately pavement deterioration, a fuzzy set was employed to represent three pavement condition factors to estimate the performance ratings for different condition states. For each highway category, the alternative model was utilised to allocate the annual budget for several maintenance actions and also find the minimum annual required budget for the desired level of service (Wang and Liu, 1997).

To handle the subjectivity and uncertainty of pavement data, Chen et al. (2004) developed fuzzy logic model based life-cycle cost analysis (LCCA) for pavement maintenance management at project level. The LCCA was employed to estimate future costs for five maintenance and rehabilitation policies based on the membership function (Chen et al., 2004). Wee and Kim (2006) developed a new pavement management system, the "expert system for pavement and rehabilitation strategy in the state of Ohio (ESPRESSO)", using angular fuzzy logic to generate an optimal M&R strategy. Three treatment strategies: major rehabilitation, minor rehabilitation, and maintenance, were selected to analyse the types and causes of distress affecting pavement layers through use of an angular fuzzy logic model (Wee and Kim, 2006). For classifying a historical pavement management database, Kaur and Pulugurta (2007) used fuzzy logic to create fuzzy decision trees which were subsequently converted into fuzzy rules. Then, these rules were utilised to support a decision-making procedure for choosing a specific treatment type on a pavement section based on its condition (Kaur and Pulugurta, 2007). Bohdanovich (2008) presented the simplest application of fuzzy logic in making decisions on the necessity of maintenance solutions for the pavement sections. The rate of defects and the longitudinal roughness were considered as fuzzy inputs, and confidence in maintenance necessity was considered as fuzzy output (Bohdanovich, 2008). The objective of research by Chen and Flintsch (2008) calibrated a fuzzy-logic-based rehabilitation decision model by establishing a systematic approach and extracting real examples of overlay action from the Long Term Pavement Performance (LTPP) database (Chen and Flintsch, 2008).

3.4.2.2.2 Evolutionary Algorithms

One of the common evolutionary algorithms used in pavement maintenance management is the genetic algorithm. It is based on the mechanics of natural genetics and natural selection. The development of the genetic algorithm was through the basic principle of Darwin’s theory of "survival of the fittest". The main elements of natural genetics to produce the new generation of solutions are reproduction, crossover, and mutation. This algorithm is characterised by its ability to generate efficient heuristics to find ideal solutions to complex and large-scale optimisation problems (Fwa, 2006; Rao, 2009).

In pavement asset management, the genetic algorithm was repeatedly used at both the network and the project levels. The genetic algorithm (GA) was adopted to solve single-objective problems, or multi-objective optimisation problems, or different objectives, or find an optimal M&R program or budget allocation. Fwa et al. (1994) presented a single-objective optimisation model based on the genetic algorithm called "PAVENET" to analyse the pavement maintenance programming problems at the network level. PAVENET was used to examine the effects of network parameters, resource parameters and maintenance-policy parameters (Fwa et al., 1994). Moreover, in 1994, Chan et al. demonstrated the formulation and characteristics of the “PAVENET” genetic algorithm, to solve the pavement management problem at the network level. The objective of this model was to assist engineers in treatment-budget scheduling and maintenance activity programming (Chan et al., 1994). Fwa et al. (1996) developed another model-based genetic algorithm called "Pavenet_R" for solving the pavement maintenance–rehabilitation trade-off problems at the network level (Fwa et al., 1996). In 1998, Fwa et al. demonstrated the utility of genetic algorithms in the network-level pavement management system by analysing three problems considering different objectives and system parameters (Fwa et al., 1998). Pilson et al. (1999) illustrated the formulation of a simple pavement optimisation problem at the project level by using a genetic algorithm to consider the single and the multi-objective functions. The interactivity model was used to predict the deterioration of different pavement structure components (Pilson et al., 1999). In 2000, Fwa et al. formulated a genetic algorithm optimisation model to find an optimal solution for network-level pavement maintenance considering multi-objective functions. The concepts of Pareto frontier and rank-based fitness evaluation were used to solve two- and three-objective function problems (Fwa et al., 2000). Chan et al. (2001) developed a new method called the prioritised resource allocation method (PRAM) for handling genetic algorithm resource constraints for a pavement maintenance program problem (Chan et al., 2001).

Ferreira et al. (2002) introduced a new single-objective optimisation model, a "probabilistic segment-linked mixed-integer optimisation model", for the network-level pavement management system in Portugal. The main assumptions were that the pavement condition states were evolved probabilistically, and also that M&R activities could be defined for particular pavement sections (Ferreira et al., 2002). Chan et al. (2003) used a genetic-algorithm optimisation to develop a multi-district highway management system for allocating the total available budget procedure to different regional agencies. The proposed procedure could improve pavement conditions between 5% and 20% compared to the conventional procedures (Chan et al., 2003). Cheu et al. (2004) proposed a hybrid framework combining a traffic simulation model with a genetic algorithm to determine the total travel time of network users for programming maintenance actions relating to lane closures in the network. The optimisation objective to find an optimal lane closure schedule was the minimisation of the total network travel time of all vehicles in a 24-hour period (Cheu et al., 2004). Herabat and Tangphaisankun (2005) formulated a single- and multi-objective optimisation model based on genetic algorithms to support the decision-making process of the pavement management in Thailand and select the optimal multi-year maintenance plans. The minimisation of vehicle operating cost (VOC) and pavement condition maximisation were considered as objective functions (Herabat and Tangphaisankun, 2005).

To improve the capability and efficiency of the optimisation model in infrastructure management systems, Morcous and Lounis (2005) proposed a new approach combining a genetic algorithm with the Markov-chain model. The genetic algorithm was able to determine optimal maintenance solutions by minimising the life-cycle cost, while the Markov-chain model was used to predict infrastructure performance. The proposed approach was applied to schedule treatment actions of concrete bridge decks protected with asphaltic concrete overlay (Morcous and Lounis, 2005). Chootinan et al. (2006) developed simulation-based optimisation framework programming by combining stochastic simulation with a genetic algorithm for multi-year pavement maintenance programming. The stochastic simulation technique simulated the uncertainty of future pavement conditions based on a calibrated deterioration model. The genetic algorithm addressed the combinatorial nature of pavement treatment programming at the network level. For programming pavement maintenance activities, a different range of pavement management objectives were applied as single-objective functions (Chootinan et al., 2006). In order to improve road life-cycle, Jha and Abdullah (2006) formulated an optimisation model, based on the Markov decision process, for minimising repair costs of roadside appurtenances. A genetic algorithm was employed to overcome the complexity of the optimisation formulation. A probabilistic model was formulated to estimate the deterioration function for roadside appurtenances (Jha and Abdullah, 2006).

To minimise the application effort and time of the optimisation process in pavement management systems at both the project and the network level, Golroo and Tighe

(2012) developed an optimum genetic algorithm system. The optimum genetic algorithm setting consisted of the simulation number, the GA operators (mutation and crossover) and the operator's probability established by experimental design (Golroo and Tighe, 2012). Farhan and Fwa (2012) examined different priority score schemes in pavement preservation scheduling to overcome suboptimal solutions. These priority weighting schemes were applied to show how these preferences would affect optimal solutions of a conventional optimisation approach based genetic algorithm (Farhan and Fwa, 2012). Jawad and Ozbay (2006) developed a hybrid optimisation model (LCCOM) for project-level pavement management to identify a life-cycle strategy that maximises the benefit to society. The hybrid model was formulated mathematically as a mixed-integer non-linear optimisation model. Moreover, a genetic algorithm was used as a search algorithm for finding optimal solutions, and a Monte Carlo simulation functioned as a risk analysis method to handle the uncertainty (Jawad and Ozbay, 2006). In 2013, Chikezie et al. developed a project-level multi-objective maintenance pavement programming system based on a genetic algorithm. Two objective optimisation functions, maximisation of pavement performance and minimisation of maintenance costs, were considered (Chikezie et al., 2013).

Mathew and Isaac (2014) used genetic algorithm to develop a deterministic optimisation model considering the objectives of the condition maximisation and the maintenance cost minimisation. For finding the optimal maintenance strategy plans, the proposed model was applied on the rural pavement network of Kerala state in India (Mathew and Isaac, 2014). Elhadidy et al. (2014) introduced a multi-objective optimisation model for programming the maintenance and rehabilitation (M&R) actions using genetic algorithm in conjunction with deterioration model based Markov-chain. The developed model was implemented on highway network in Egypt considering minimum maintenance costs and maximum PCI (Elhadidy et al., 2014). Yang et al. (2015) introduced a new system combining probabilistic pavement age gain models with a type of genetic algorithm called NSGA-II. This system was applied on multi-objective and multi-constrained optimisation problems for scheduling pavement maintenance and rehabilitation (M&R) actions (Yang et al., 2015).

The particle swarm optimisation PSO algorithm is an evolutionary computation or population–based search algorithm. It was developed by Kennedy and Eberhart to simulate the simplified social behaviour of birds or fish within a flock or school. The main concept of this algorithm is that each particle (solution) in the swarm moves with an adjustable velocity through the search space. The position of a particle in the search space is adjusted according to the experiences of the particle and its neighbour. The particles move towards the global minimum, while still searching a wide space around the optimal solution. The robust and quick search capability of the PSO allows it to effectively address highly constrained problems that have an extremely large solution space (Engelbrecht, 2007; Kennedy and Eberhart, 1995; Tayebi et al., 2010).

Wang and Goldschmidt (2008) proposed a project interaction pre-optimisation model that integrates the project interaction, traffic-demand prediction interaction and maintenance-condition interaction into the decision optimisation process. Cluster models with similarity and dissimilarity analysis were employed in the project interaction pre-optimisation process to avoid roadwork on two paths between origin and destination at similar times. The pre-optimisation model was used as an input of a global multi-objective optimisation model-based particle swarm optimisation (PSO). The multi-objective PSO problem was converted into a single-objective problem by using the weighted aggregation method (Wang and Goldschmidt, 2008). Shen et al.

(2009) used chaos particle swarm optimisation (CPSO), a new random global optimisation algorithm which has strong local searching capability, in their pavement maintenance decision programming. It was applied on an expressway network to satisfy just a single objective, which was maximisation of economic benefit. The pavement maintenance decision results proposed by the CPSO were validated by comparing with the results of the NSGA-II algorithm. It was found that the convergence speed of CPSO to reach the optimal solution was quicker than the convergence speed of NSGA-II (Shen et al., 2009). In 2010, Tayebi et al. used PSO with single-objective function scenarios for a pavement management system at the network level. The same hypothetical problem formulation of the Pavenet_R model by Fwa was used to apply a PSO algorithm for pavement maintenance programming (Tayebi et al., 2010). Chou and Le (2011) formulated a classical multi-objective PSO algorithm MOPSO to find the timing of maintenance action and the overlay layer thickness. The objective of this research is to study the effect of overlay maintenance activities on the performance pavement reliability with an optimised treatment cost. The maintenance cost and performance reliability of the pavement were considered simultaneously in the developed algorithm as multi-objective functions. For considering uncertainties of input parameters and maintenance effect on pavement service life, a probabilistic model integrated with a Monte Carlo simulation was proposed to predict performance reliability (Chou and Le, 2011).

The ant colony optimisation algorithm is a metaheuristic algorithm developed by Marco Dorigo in 1992. The main concept of the algorithm is a simulation of the ability of an ant to find the shortest path between its colony or nest and a food source. In recent research, Terzi and Serin developed a pavement management system at the network level based on the ant colony optimisation method. A single-objective function, maximisation of pavement treatment work, was considered for programming routine maintenance actions (Terzi and Serin, 2014).

To overcome the mathematical programming problems, the soft computing and evolutionary computation techniques such as the genetic algorithm and particle swarm optimisation were commonly used in pavement management systems. Most previous researches in pavement maintenance management were based on the evolutionary algorithms with different problem formulation, different objectives, single or multi objective, or different methods of constraints handling. These algorithms involving many parameters (such as mutation operator, crossover operator, mutation probability, crossover probability and population size),were necessary to be considered. In addition, in a few studies, PSO was used for solutions of hypothetical pavement optimisation problems considering single-objective functions.

3.5 Discrete Particle Swarm Optimisation for Multi–Objective Functions (DMOPSO)

3.5.1 Particle Swarm Optimisation

Particle swarm optimisation (PSO) is a simulation of social behaviour of birds or fish within a flock or school. The PSO was developed by Kennedy and Eberhart in 1995. The swarm of PSO consists of a set of particles. In addition, each particle represents a possible solution of an optimisation problem. Each particle moves in the search space, and this movement is achieved by an operator that is directed by a local and by social elements. Each solution or particle is assumed to have a position and a velocity. The position of particle is denoted at iteration *t* by $X_i(t) = \{X_1(t), X_2(t), \ldots, X_n(t)\}$ and the velocity is denoted by $V_i(t) = \{V_1(t), V_2(t), \ldots, V_n(t)\}$. Then, each particle updates its position and velocity at iteration *t+1* by using the following equations (de Carvalho and Pozo, 2012; Rao, 2009; Zhang et al., 2012):

$$V_{i,j}(t+1) = w\,V_{i,j}(t) + r_1\,c_1\left[Pbest_{i,j}(t) - X_{i,j}(t)\right] + r_2\,c_2\left[Gbest(t) - X_{i,j}(t)\right] \quad 3\text{-}1$$

$$X_{i,j}(t+1) = X_{i,j}(t) + V_{i,j}(t+1) \quad 3\text{-}2$$

Where $Pbest_i(t)$ = local or personal best position for particle i at iteration *t*; $Gbest(t)$ = global best position or particle leader at iteration *t*; w = the inertia weight of the particle; c_1 and c_2 = acceleration coefficients (positive constants); r_1 and r_2 = random numbers within [0, 1].

In the velocity update equation 3-1, the leader particle *Gbest* in each generation guides the particles to move towards the optimal positions. In each generation, a particle’s memory is updated. For each particle in the swarm, its performance is estimated according to the fitness or objective of the optimisation problem. The inertia weight *w* is used to regulate the effect of the previous velocities on the current velocity. This has the effect of producing a trade-off between the global and local exploration abilities of the particles (de Carvalho and Pozo, 2012).

The multi-objective optimisation problems consider the simultaneous satisfaction of two or more objective functions. Furthermore, the objectives of optimisation problems are in general conflicting objectives, which means there is no single optimal solution. Therefore, it is necessary to find a decent trade-off of solutions that represent the compromise between the objectives. In multi-objective particle swarm optimisation (MOPSO) problems, the main challenge is to determine the best global particle "leader" at each generation. In a single-objective problem, the leader particle is found easily by choosing the particle that has the best position. In multi-objective problems, a set of non-dominated solutions called "Pareto optimal solutions" are the best solutions (de Carvalho and Pozo, 2012).

The most common optimisation problems have either discrete or qualitative distinctions between variables. In the discrete PSO, the solutions can be assumed to be one of several discrete values. The most common example of discrete PSO is binary optimisation where all solutions will take only 0 or 1. Fundamentally, the original PSO is different from discrete PSO in two features. Firstly, the particle coordinate is composed of binary values. Secondly, the velocity must be transformed into the probability change that is the chance of the binary variable taking 1 (Liao et al., 2007; Pugh and Martinoli, 2006).

The original algorithm of PSO for continuous optimisation problems was modified for solving discrete (binary) optimisation problems by changing the position equation to the new one. The following is an equation for the modified algorithm (Kennedy and Eberhart, 1997; Liao et al., 2007; Pugh and Martinoli, 2006):

$$X_{i,j} = \begin{cases} 1 & if\ rand < S(V_{i,j}) \\ 0 & Otherwise \end{cases} \quad 3\text{-}3$$

Where $S(V_{i,j})$ is the sigmoid function given by

$$S(V_{i,j}) = {}^{1}/_{(1+e^{-X_{i,j}})} \quad 3\text{-}4$$

3.5.2 A Review on Particle Swarm Optimisation Algorithms

There are many different particle swarm optimisation algorithms to solve single- or multi-objective optimisation problems.

A. Multi-Guider and Cross-Searching Techniques (MGC-MOPSO)

In multi-objective particle swarm optimisation (MOPSO), one particle is considered as a global leader to minimise the number of non-dominated solutions for additional diversity in the external archive. For improving the diversity of the particles over the entire Pareto front, while ensuring the inclusion of the extreme solutions, the new algorithm of Gaussian multi-objective particle swarm optimisation (G-MOPSO) was developed using multi-guiders and cross-searching techniques.

The MGC-MOPSO algorithm proposed two particles (guiders) rather than one guider. Guider is a particle having the global optimal location. In addition, the cross-searching factor is used to control the second guider and also provide a good diversity over the whole Pareto front regarding all objectives. The function of cross-searching factor is to control the effect of the second guider and make a decent distribution of the solutions over the whole Pareto-front concerning all objectives (Pham et al., 2012).

B. A Bare-Bones Multi-Objective Particle Swarm Optimisation Algorithm

A new optimisation algorithm called the bare-bones particle swarm optimisation (BBPSO) was developed by Kennedy. The BBPSO is beneficial as the information of inertia weights and acceleration coefficients are not needed. The BBPSO uses a Gaussian distribution based on global best position ($Gb_j(t)$) and local best position ($Pb_{i,j}(t)$) instead of the particle velocity. The particle positions in any dimensions have a 50% chance to update and change to the corresponding personal best position as in the following equation (Zhang et al., 2012):

$$X_{i,j}(t+1) = \begin{cases} N\left(\frac{Pb_{i,j}(t)+Gb_j(t)}{2}, \left|Pb_{i,j}(t) + Gb_j(t)\right|\right) & if\ U(0,1) < 0.5, \\ Pb_{i,j}(t) & \end{cases} \quad 3\text{-}5$$

Where $N\left(\frac{Pb_{i,j}(t)+Gb_j(t)}{2}, \left|Pb_{i,j}(t)+Gb_j(t)\right|\right)$ is a Gaussian distribution, and $U(0,1)$ is a uniform distribution between 0 and 1.

The main feature of BBPSO is that a particle can update without needing to tune up control parameters. Moreover, to avoid early convergence and increase the search capability, the effect mutation operator on all particles in the swarm is changeable based on the number of generations. Another feature of BBPSO is the updating of the global best particle based on the diversity of non-dominated solutions. Furthermore, it has good performance on multi-objective optimisation problems, and is also easy to implement (Zhang et al., 2012).

C. Competitive and Cooperative Co-Evolutionary Multi-Objective Particle Swarm Optimisation Algorithm (CCPSO)

The competitive and cooperative co-evolutionary multi-objective particle swarm optimisation algorithm (CCPSO) was developed to overcome the complexity and dimensionality of multi-objective optimisation problems and also handle premature convergence because of high convergence speeds. The cooperative model was employed to direct the evolution of isolated species called sub-swarms to create higher diversity across the various species. In addition, competitive co-evolutionary technique was adopted to allow particles to compete amongst sub-swarms for the right to represent particular variables, and the winners work together to answer the entire problem (Goh et al., 2010).

D. Dynamic Self-Adaptive Multi-Objective Particle Swarm Optimisation (DSAMOPSO)

The Dynamic Self-Adaptive MOPSO (DSAMOPSO) method was developed to address different optimisation constraints in multi-objective problems. This algorithm is capable of solving discrete (binary) multi-objective optimisations. The main characteristics of DSAMOPSO, like fast-ranking, elitism, crowding distance, and a leader particle selection method, make it a robust and competitive optimisation algorithm. These properties of the proposed algorithm improve the procedure of re-producing the original Pareto front of the multi-objective optimisation problems with lowest error and better diversity (Khalili-Damghani et al., 2013).

E. Time Variant Multi-Objective Particle Swarm Optimisation (TV-MOPSO)

For obtaining better convergence to the Pareto front, while attaining sufficient diversity, the time variant MOPSO algorithm (TV-MOPSO) was developed. TV-MOPSO allows the vital parameters, inertia weight, and acceleration coefficients, to change with each iteration. The objective of the proposed algorithm is to achieve a decent balance between the exploration and the exploitation of the search space and assist the algorithm in efficiently exploring the search space. A mutation operator is adopted, to obtain adequate diversity amongst the Pareto non-dominated solutions while maintaining the same convergence to these solutions (Tripathi et al., 2007).

F. A Pareto-Adaptive Metaheuristic To Multi-Objective Optimisation

An interactive particle-swarm metaheuristic algorithm for multi-objective optimisation features interaction with the decision maker to explore Pareto non-dominated solutions by updating its members as per the preference data delivered by the decision maker. The proposed algorithm aggregates different properties of multi-objective optimisation and decision-making strategy. In addition, it does optimisation based on the opinion of the decision maker. The interactive particle-swarm metaheuristic algorithm for multi-objective optimisation comprises an adaptive-grid mechanism, a self-adaptive mutation operator, and a new decision-making component (Agrawal et al., 2008).

G. Sigma Multi-Objective Particle Swarm Optimisation (MOPSO)

In multi-objective particle swarm optimisation (MOPSO), the selection of the local best particle or the global best particle (leader), for each iteration, from a set of non-dominated (Pareto-optimal) solutions is important to increase the convergence and solution diversity. The new technique, called the Sigma method, was developed for selecting the local best position for each particle in the swarm. The key concept of this method is that a value σ is calculated for each particle in the archive by the following formula (Mostaghim and Teich, 2003):

$$\sigma = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \quad 3\text{-}6$$

Where σ is sigma value; f_1, f_2 is objective functions.

H. Dynamic Particle Swarm Optimisation

In contrast to the simple algorithm of PSO, where swarm size and topological environment are fixed, the dynamic particle swarm optimisation algorithm varies the parameters of PSO with time. The main concept of this algorithm is that the velocity of each particle changes toward its global and local best positions during process iterations. The velocity updating is carried out by weighting acceleration by random best values at each iteration (Urade and Patel, 2012).

I. Control Of Dominance Area Of Solutions Multi-Objective Particle Swarm Optimisation (CDAS-MOPSO)

The key challenges faced by multi-objective optimisation problems are the restrictions of the search ability which occur because of the growth of the non-dominated solutions number with the objectives number. For that reason, to overcome these restrictions, the control of dominance area of solutions (CDAS), a new method based on the particles cooperation rather than their competition, limits the capacity of the non-dominated solutions. The proposed algorithm adopts a user-defined parameter to restrict the contraction and expansion levels of the dominance capacity of solutions (de Carvalho and Pozo, 2012).

J. Hierarchy Particle Swarm Optimisation Algorithm (HPSO)

A hierarchy particle swarm optimisation (HPSO) is proposed to effectively address the multi-objective optimisation problem having very complex constraints (Yang, 2012). This algorithm can work by using the adaptive inertia weight algorithm (AWA) and mutative scale local search algorithm (MSLSA). The AWA is adopted to regulate inertia weight adaptively for each particle based on the global and local searching abilities of the algorithms during iteration. The MSLSA is employed to find global best solutions during the evolution process (Yang, 2012).

K. Proportional Distribution And Jump Improved Operation (PDJI-MOPSO)

For improving the ability of the PSO algorithm to avoid the local optimum staying on the same convergence speed, the proportional distribution and jump improved operation algorithm (PDJI-MOPSO) was developed for multi-objective optimisation problems. The proposed algorithm ensures diversity of new Pareto non-dominated solutions by proportional distribution. In addition, to improve the solution-searching abilities of particles, it combines the jump improved operation with advantages of extensive exploration and exploitations of the PSO algorithm in the external repository. The jump improved operation technique can produce new Pareto non-dominated solutions in the external repository without doing the mutation process (Tsai et al., 2010).

L. *Fuzzy-Pareto-Dominance (FPD)*

The fuzzy-Pareto-dominance technique (FPD) is applied in multi-objective particle swarm optimisations to effectively maintain the repository containing Pareto non-dominated solutions obtained during iterations. The FPD, fuzzified format of the Pareto dominance solutions relationship, is employed to estimate a dominance degree between two Pareto solutions. The ranking for each solution is done according to the solution, with a maximum dominance degree to overall solutions. This ranking scheme is further employed to keep sufficient capacity for an archive (Ganguly et al., 2013).

M. *Pareto Archive Particle Swarm Optimisation For Multi-Objective Problems*

Pareto archive particle swarm optimisation is established as one of the solutions to handle the capacity of the memory (archive) when it reaches a predetermined maximum capacity. The concept of the Pareto archive is that the algorithm updates the archive when the new Pareto solution dominates some solutions of the memory or the memory capacity is less than or equal to the maximum (Lei, 2008).

N. *Dynamic Neighbourhood Particle Swarm Optimisation*

The dynamic neighbourhood method is used to find the Pareto non-dominated solutions of multi-objective particle swarm optimisation problems. The dynamic neighbourhood concept is that each particle finds different neighbours in each iteration based on the fitness values. Then, each particle discovers the local best particle among the new neighbours (Hu and Eberhart, 2002).

O. *Particle Swarm Optimisation And Fitness Sharing To Solve Multi-Objective Optimisation Problems (MOPSO-fs)*

The particle swarm optimisation algorithm and fitness sharing are combined to handle multi-objective optimisation problems for selecting a small number of Pareto non-dominated solutions. The selection mechanism of Pareto solutions is applied firstly by filling the archive with non-dominated solutions, and secondly by removing non-dominated solutions that have lower fitness sharing. “The fitness sharing concept is to distribute a population of individuals along a set of resources. When an individual *i* is sharing resources with other individuals, its fitness f_i is degraded in proportion to the number and closeness to individuals that surround it” (Salazar-Lechuga and Rowe, 2005). The following is the fitness sharing formula:

$$fShar_i = \frac{f_i}{\sum_{j=0}^{n} sharing_i^j} \qquad 3\text{-}7$$

Where $fShar_i$ is fitness sharing for individual i; n is the number of individuals in the population.

$$sharing_i^j = \begin{cases} 1 - \left(d_i^j / \sigma_{share}\right)^2 & if\ d_i^j < \sigma_{share} \\ 0 & otherwise \end{cases} \qquad 3\text{-}8$$

σ_{share} is the distance we want the individuals to remain distant from each other, d_i^j is a measure of distance between individual *i* and *j*.

P. Multi-objective Particle Swarm Optimisation Algorithm Using Clustering (ClustMPSO)

The new multi-objective optimisation algorithm is developed by combining the PSO algorithm with clustering methods. Clustering techniques such as the *k*-means algorithm are used to cluster all particles into separated swarms (sub-swarms) in each generation (Janson and Merkle, 2005).

Q. A Multi Objective Multi-Leader Particle Swarm Optimisation Algorithm On NLP And MINLP Problems

A new multi-leader particle swarm optimisation algorithm is developed for tackling both single and multi-objective mixed-integer nonlinear optimisation problems having equality and inequality constraints. The proposed algorithm allows each particle to update its position based on the experience of several selected leaders, not only its closest leader (Shokrian and High, 2014).

R. Particle Swarm Optimizer For Multi-Objective Problems Based On Proportional Distribution And Cross-Over Operation

The proportional distribution and cross-over operation are combined with the particle swarm optimisation algorithm for wide exploration and maintenance of diversity for new Pareto non-dominated solutions in the external memory (Sun et al., 2008). The cross-over operation technique produces new non-dominated solutions in the external memory while maintaining the same convergence speed, while the proportional distribution technique distributes numbers of particles to the memory member based on its solution distance (Sun et al., 2008).

3.6 Knowledge Gap

3.6.1 Pavement Section Classification

Pavement sections are normally classified based on their pavement condition index in order to categorize them as “good”, “moderate” or “poor”. Conventionally, this has been done by comparing various pavement distress data against threshold values. However, borderline values between two categories have significant influence on the subsequent pavement maintenance and rehabilitation decision. Traditional crisp classification fails to address this issue.

The heuristic knowledge is possessed by a limited number of pavement engineering specialists, who use their knowledge, judgment and experience to evaluate pavement conditions and investment decisions. These experts are seldom found in road agencies, and their all-important skill in diagnosing the pavement distress, condition evaluation and determining the proper treatments is difficult to pass on to the less experienced engineers. As they retire, their knowledge and experience may be lost forever. Therefore, it is necessary to capture the knowledge, experience and thought processes used by pavement engineering experts.

In order to deal with these issues, previous studies, as reported earlier (Arliansyah et al., 2003; Bandara and Gunaratne, 2001; Fwa and Shanmugam, 1998; Golroo and Tighe, 2009; Juang and Amirkhanian, 1992; Koduru et al., 2010; Shoukry et al., 1997; Sun and Gu, 2011), used fuzzy logic together with a linear classification model, expert system, or artificial neural network to deal with the uncertainty and subjectivity involved in the classification. However, expert systems require data training to cope with a given problem, which is time-consuming.

3.6.2 Pavement Deterioration Model

Until now, the majority of deterministic and probabilistic deterioration models at the network level were developed to forecast distress progression or to predict overall pavement conditions (Abaza, 2014, 2004; Ahmed et al., 2008; Al-Mansour et al., 1994; Alsherri and George, 1988; Anyala et al., 2012; Fwa and Sinha, 1986; Henning, 2008; Hong and Prozzi, 2006; Jain et al., 2005; Jiménez and Mrawira, 2012, 2009; Kerali et al., 1996; Khraibani et al., 2012; Lethanh and Adey, 2012; Luo, 2013; Ningyuan et al., 2001; Obaidat and Al-Kheder, 2006; Park et al., 2008; Prozzi and Madanat, 2004), but not while considering all contributory factors on performance. Although the soft computing techniques can deal with uncertainty and nonlinearity, there are limitations to using them in pavement deterioration models because of the need for huge data quantities for training.

3.6.3 Multi Objective Pavement Maintenance Decision Optimisation

The main objective of pavement management systems is to determine the maintenance work quantity and type which should be applied to a particular pavement network. Therefore, a variety of mathematical optimisation techniques have been used in an attempt to schedule pavement maintenance and rehabilitation solutions and allocate resources. To reach the optimal solutions of maintenance decisions, the big challenge is to deal with high-dimensional problems which consider many pavement sections and the associated treatment decision variables covering multiple time periods.

The mathematical programming techniques are designed for particular optimisation problems. For example, linear programming is not able to solve the problem when the objective and/or constraints are nonlinear functions and integer programming is not able to solve continuous optimisation problems. Therefore, the optimisation method must be selected based on the nature of the objective and constraints equation, and the values of design variables.

To overcome these issues, the soft computing and evolutionary computation techniques such as the genetic algorithm and particle swarm optimisation are commonly used (Chan et al., 2003, 2001, 1994; Cheu et al., 2004; Chikezie et al., 2013; Chootinan et al., 2006; Chou and Le, 2011; Elhadidy et al., 2014; Farhan and Fwa, 2012; Ferreira et al., 2002; Fwa et al., 2000, 1998, 1996, 1994; Golroo and Tighe, 2012; Herabat and Tangphaisankun, 2005; Jawad and Ozbay, 2006; Jha and Abdullah, 2006; Mathew and Isaac, 2014; Morcous and Lounis, 2005; Pilson et al., 1999; Shen et al., 2009; Tayebi et al., 2010; Terzi and Serin, 2014; Wang and Goldschmidt, 2008; Yang et al., 2015) in pavement management systems. Most previous researches (Chan et al., 2003, 2001, 1994; Cheu et al., 2004; Chikezie et al., 2013; Chootinan et al., 2006; Elhadidy et al., 2014; Farhan and Fwa, 2012; Ferreira et al., 2002; Fwa et al., 1998, 1996, 1994, 2000; Golroo and Tighe, 2012; Herabat and Tangphaisankun, 2005; Jawad and Ozbay, 2006; Jha and Abdullah, 2006; Mathew and Isaac, 2014; Morcous and Lounis, 2005; Pilson et al., 1999; Yang et al., 2015) in pavement maintenance management have been based on the genetic algorithm with different problem formulation, different objectives, single or multi objective, or different methods of constraints handling. Since the genetic algorithm involves many parameters (such as mutation operator, crossover operator, mutation probability, crossover probability and population size), an algorithm is required that has few parameters to modify that is easy to implement. In a few studies (Shen et al., 2009; Tayebi et al., 2010; Wang and Goldschmidt, 2008) PSO was used for solutions of hypothetical pavement optimisation problems considering single-objective functions.

3.7 Summary

This chapter presented the exiting papers, articles, reports and design standards on the main components of PMS: pavement section classification; pavement performance prediction; maintenance and rehabilitation decision optimisation. The models of three components were classified into different groups based on the technique or algorithm type used in development of these models. The next chapter presents the research methodology.

Chapter 4

Research Methodology

4.1 Introduction

This chapter presents a brief overview of the main problems in pavement management systems. It provides a description of the research aim and objectives. Furthermore, it describes the key stages of the methodology.

4.2 Problem Definition

Roads are by far a nation’s biggest capital asset, and play an important role in economic and social well-being at both national and local levels. Pavement is a key element of road infrastructure. Increasing traffic volumes, heavier loads, and poor reinstatement following excavation by public utility companies - allied with repeated adverse weather conditions - are cumulatively causing significant deterioration in the pavement, resulting in millions of failed areas (cracking, localised depression, rutting, potholes, texture loss, etc.). These failed areas not only reduce the ride quality, but also potentially create dangerous driving conditions. Additionally, increased pavement deterioration, increasing demands for repair, and deficient resource allocation have made the task of maintaining pavement networks more challenging (Chen et al., 2004).

Regular maintenance and rehabilitation (M&R) is essential to preserve and improve a pavement network. Because of ever increasing resource deficiency, maintenance activity must be timely and effective. Unnecessary maintenance increases overall maintenance costs, while delayed maintenance may increase rehabilitation costs. In recent years, therefore, efficiency has become a key issue in highway pavement maintenance planning (Alsherri and George, 1988).

For a good return on the investment, it is critical to employ the most cost-effective method of M&R. Traditionally, appropriate M&R activities are determined by road authorities for each pavement section based on the current and predicted condition of the pavement. This prediction is based on field and laboratory data, the knowledge and expertise of the organisation's staff, and the research. Some of these condition data can be solved analytically because of uncertainty while the others must be solved heuristically because of complexity. The heuristic knowledge is possessed by a limited number of pavement engineering specialists, who use their knowledge, judgment and experience to make inferences and reach design and investment decisions. These experts are seldom found in road agencies and their all-important skill in diagnosing pavement distress and determining the proper treatments is difficult to pass on to the less experienced engineers. As they retire, their knowledge and experience may be lost forever. So, it is necessary to capture the knowledge, experience and thought processes used by pavement engineering experts as much as possible, for the benefit of engineers with less experience, through seminars or questionnaires.

In situations where there is a lack of reliable performance prediction models, many road authorities use a need-based budgeting process, namely, annual budget requests. Need-based budgets are developed on the basis of pavement maintenance needs derived from pavement inventory and annual or biannual condition data. This allocation of funding across maintenance activities is challenging and often involves negotiation and balancing. This is because there is a tendency to exaggerate true needs for maintenance, and consequently there is the possibility of a budget request that may not be directly linked to the optimal benefit of the overall pavement network (Shekharan et al., 2010). Funding restrictions also have a significant effect on the pavement M&R. The deficiency of funding may force an engineer to choose only highly prioritised maintenance and can sometimes even lead to temporary works. In the long run, the build-up of pavement deterioration may lead to a more expensive rehabilitation.

Pavement asset management is a set of analytical tools or methods that assist the decision makers in finding optimum strategies for M&R of pavements to maintain serviceable conditions over a given period of time (Haas et al., 1994). Therefore, for an effective classification, knowledge about the condition of the assets, the effectiveness of the corrective strategies, and the impact of a given action on the system performance are vital.

In the last two decades, several pavement management systems have been developed to determine a solution which defines the amount and type of M&R works that should be applied to a given pavement network. These models applied different approaches to achieve similar objectives but the biggest challenge across all of them is how to efficiently solve an optimally formulated model. Therefore, several advanced optimisation methods have been used in an attempt to solve the pavement management problem (Abaza, 2006; Fwa et al., 2000).

An active pavement management system (PMS) is one that is guided by a software program that ensures that all pavement sections are maintained at adequately high levels of service and structural conditions with a low budget and low resource usage, without causing any significant negative effect on environment, safe traffic operations and social activities. Unfortunately, many of these are conflicting requirements. For example, resource allocation and funds will be needed if the pavement networks are to be maintained at a higher level of serviceability, and a software program with more pavement maintenance actions would, in general, cause longer traffic delays, increased environmental pollution, more disruption of social activities, and greater inconvenience to the community. However, if repairs are made early enough, it can actually reduce costs as it can avoid major maintenance action. Therefore, the PMS (i.e. the software program) must consider multi-objective criteria in the decision-making process for the scheduling of pavement maintenance activities.

Optimum decision policy, which is key for the successful implementation of any PMS, requires the ability to predict future asset conditions under each repair strategy (Jiménez and Mrawira, 2009). In addition, a pavement performance model that is used to evaluate and predict current and future pavement deterioration is a very important stage in the PMS, because many other functions and stages, like determination of the pavement's future needs, and maintenance and rehabilitation priority programming, depend mainly on the results of the selected pavement performance model (Li and Haas, 1998).

The pavement performance is calculated based on pavement deterioration data, like the type of distress and the level of severity, which are collected by visual and machine-based surveys, with the results being compared against threshold values. The three main components of an effective PMS are:

a) Data inventory and pavement condition rating or section classification;

b) Pavement performance prediction;

c) Optimisation for decision making.

Good-quality data is at the heart of the functionality of any PMS. Although the recent advancements in machine-based surveys has made it possible to collect data with acceptable repeatability, the majority of PMSs use a deterministic approach for data analysis and section classification, and then apply regression analysis or an analytical hierarchy method for decision making. However, M&R decisions based on this approach tend not to be realistic because of the lack of consideration given to the environmental factors, the level of service for the road user, and an integrated approach to other maintenance activities. A deterministic approach to the data analysis may lead to inappropriate section classification because of the influence of borderline (upper or lower limit) condition data.

Different PMSs use different condition indices for the classification of pavements. Examples include the Pavement Condition Index (PCI), used in the USA (ASTM D6433–09), the Present Serviceability Index (PSI), also used in the USA, and the International Roughness Index (IRI), used by the World Bank and many developing countries. In the UK, however, the pavements are first assessed against the various investigatory levels (good, moderate, poor) of the condition data, and then are classified according to an approved set of rules and parameters to provide condition indices and priority levels for network sections based on their condition (Roads Liaison Group, 2011).

The challenge in pavement management is to consider a large number of pavement sections and the associated maintenance and rehabilitation decision variables covering multiple time periods (Javed, 2011). To reach the optimal maintenance decision solutions, it is important to develop an expert system to classify the pavement and then optimise the M&R decision, considering multiple objectives such as minimum cost and maximum performance.

4.3 The Research Aim and Objectives

The primary aim of this research is to introduce an effective approach for the section classification, develop pavement deterioration models, and then develop a multi-objective optimisation algorithm for finding an optimal pavement M&R plan over the analysis period.

In order to develop an effective pavement management system, this study will be divided into three main parts: section classification, pavement performance prediction, and the M&R decision optimisation.

A comprehensive literature review is undertaken on pavement management practices and procedures - published in scientific journals, reports, and international standards - namely, the evaluation and classification techniques of pavement sections, the optimisation algorithms, and the life-cycle analyses that have been used to forecast pavement performance and compute near-optimal M&R decisions.

For pavement section classification, a simple and effective model is developed that is able to deal with uncertain data and transfer the knowledge and experience to the less experienced engineers. This study proposes a fuzzy rule-based system or fuzzy inference system (FIS) for estimating the pavement condition index (PCI) for pavement, considering various distresses, their severity, and extent as input variables. A FIS is one of the most popular methods used in classification problems. The FIS is a technique which interprets the values in the input vector and, based on predefined rules, assigns quantities to the output vector. The advantage of this approach is that knowledge can be represented in the form of If–Then rules.

To determine timely and accurate intervention programs, and thus to reduce maintenance costs, a precise pavement performance prediction model at the network level is developed. The developed deterioration model is a deterministic model called Multi-Input Deterioration Prediction Model (MID-PM), for flexible pavement evaluating the changes of overall PCI over a period of time. It considers the combined effect of distress quantity such as the area and length of cracked pavement, pavement age, traffic loading, maintenance effects, climatic conditions, pavement construction and materials.

The final stage of the pavement management system is the selection of maintenance, rehabilitation, and reconstruction options and analysis of the associated costs for all candidate sections needing treatment. A multi-objective optimisation algorithm considering two objective functions, maximise pavement performance and minimise agency cost, is developed to find an optimal maintenance strategies plan. This multi-objective decision policy optimisation is a complex optimisation problem. Therefore, particle swarm optimisation (PSO), which is a relatively modern technique, is used to solve the multi-objective optimisation problem for programming pavement maintenance activities over a period of years. PSO is an increasingly popular method for global optimisation. This method deals with a non-differentiable, nonlinear optimisation problem and enables the effective handling of the pavement management problem, which has an extremely large solution space (Shen et al., 2009; Tayebi et al., 2010).

The final objective of this research is to verify how well these models can determine the best solutions by comparing the results obtained from these models with conventional techniques and algorithms for section classification, condition prediction, and binary multi-objective optimisation problems.

4.4 Methodology

This research was based on optimisation algorithm development and quantitative methodology. The main aspects of the methodology are to develop a section classification model based on fuzzy logic theory for flexible pavements, to establish an accurate deterioration model based on deterministic techniques, and to develop a multi-objective optimisation algorithm for maintenance decision policy. The Figure 4-1 shows the schematic diagram of three stages of this research. The methodology procedures of this research are as given below.

4.4.1 Pavement Section Classification

Firstly, the long-term pavement performance (LTPP) data for monitoring modules are selected to build a fuzzy rule-based system for pavement section classification. For a specific year, the extracted monitoring data are seven distress types (alligator cracking, block cracking, longitudinal and transverse cracking, patching, potholes, bleeding, and ravelling), with a severity level and extent for each section.

To develop a new section classification model, the distress density for each type and severity level is determined by using the distress equations for the PAVER system. Then, the pavement condition index (PCI) is calculated for each pavement section with the Micro-Paver software. The densities of all distress types are used as FIS inputs and PCI is the output of the FIS.

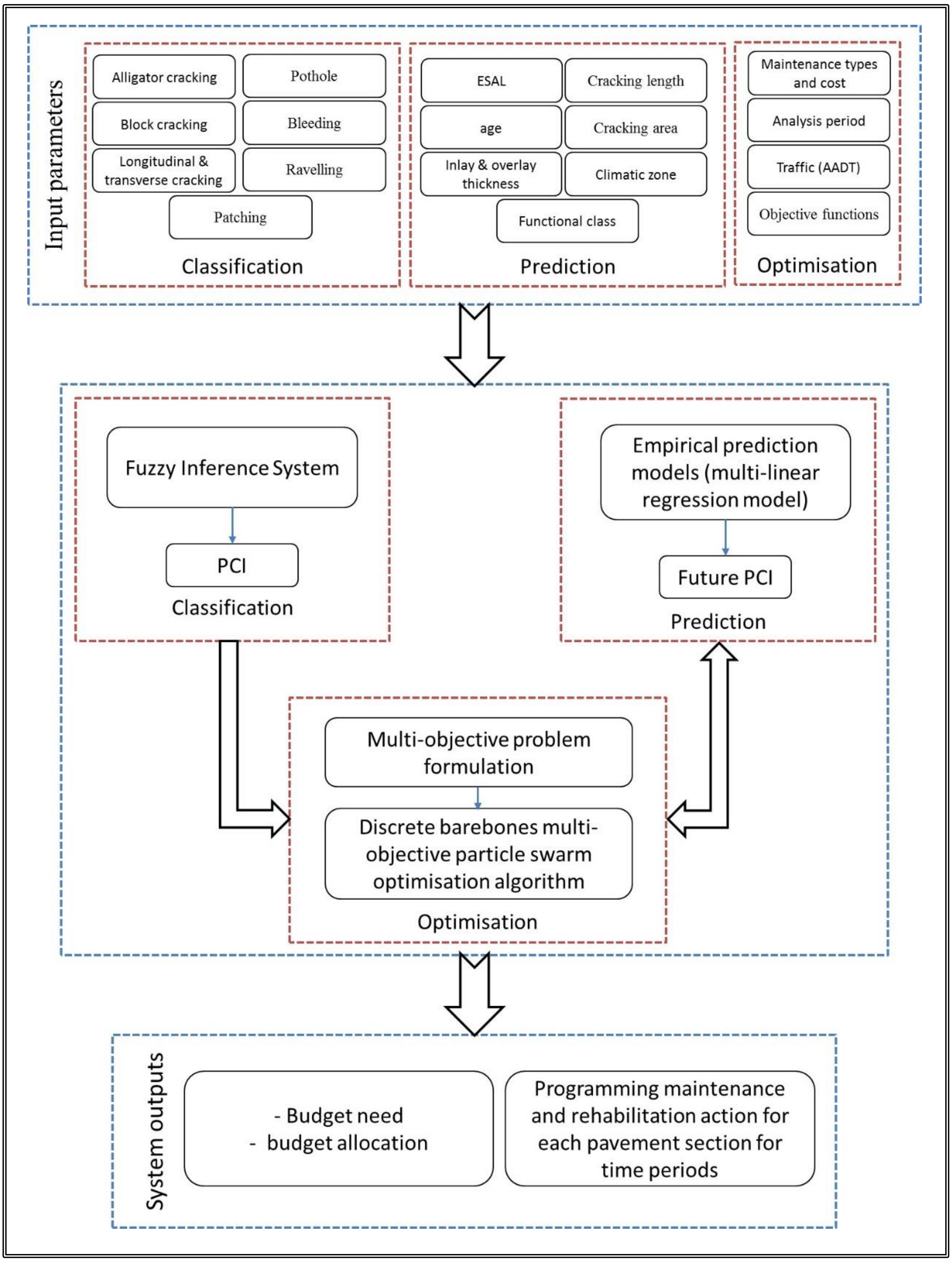

Figure 4-1: The schematic diagram of three research stages.

Then there is the challenge of the generation of the fuzzy rules and membership functions in FIS with a high-dimensional problem. To overcome this problem, the membership functions of inputs are established based on the *k*-means clustering method using the Fuzzy Inference System Professional (FISPro) software. "FISPro offers the possibility to generate fuzzy inference systems and to use them for reasoning purposes, especially for simulating a physical or biological system" (Guillaume et al., 2013). It has ability to design a fuzzy inference system from the expert knowledge or from the numerical data. For each distress type, three triangular membership functions representing different severity levels (low, medium, and high) are created. The seven triangular membership functions of output (PCI) are created manually. Additionally, to address the challenge of fuzzy rules generation, the Wang & Mendel method is adopted to generate fuzzy rules automatically from numerical data. Eventually, to reduce time and effort, the FISPro software is used for the generation of membership functions and fuzzy rules from the numerical data.

4.4.2 Pavement Performance Prediction

The main challenge in developing pavement deterioration models is the existence and use of different factors affecting pavement condition that need to be considered in model development. These factors are pavement age, traffic loading, climate effect, initial design and construction, and maintenance effect [Fwa 2006, Al-Mansour et al. 1994]. For building the deterioration model, these five parameters are considered as model inputs. Pavement age is measured from the construction date or the last rehabilitation date. Cracking has the most severe effect on pavement conditions, and therefore cracking area (alligator, block, and edge) and cracking lengths (longitudinal and transverse) are used as two parameter inputs. For the inclusion of traffic loading effects on the deterioration models, the cumulative equivalent single axle load (ESAL) is used as another input. One of the pavement deterioration modelling difficulties is how to include the maintenance actions mathematically in deterioration modelling. To overcome this difficulty, the maintenance effect is included in the modelling by considering the inlay and overlay thickness as a variable input.

The main challenge of pavement deterioration modelling is the mathematical representation of the environmental effects in pavement deterioration. Therefore, the environmental effects are embedded by generating a prediction model for each of the four climatic zones in the LTTP study area. These are wet freeze, wet non-freeze, dry freeze, and dry non-freeze zones. Since pavement structure and construction have a significant effect on deterioration, highway functional classification is employed to reflect the structural design variation. For simplification, the deterioration model is developed for the two functional classes (arterial and collector roads).

To develop deterioration models, data for arterial and collector roads are considered individually for three climatic zones (wet Freeze, wet non freeze, and dry Freeze). For dry non freeze zone, due to the availability of limited data, only arterial roads are considered. Then, for each subgroup, the required data are extracted from the database of asphalt concrete pavement on granular base (GPS-1) in LTPP.

Multi-regression analysis is used to build empirical pavement performance prediction models for each region and functional class by calculating the coefficients of independent variables in deterministic mathematical statements which can describe most variations in the dependent variable. The independent variables of the linear prediction model are distress quantities (length and area of cracked pavement), pavement age, maintenance intervention (inlay and overlay thickness), and cumulative ESAL.

4.4.3 Decision Policy Optimisation

In the final stage of a pavement management system, the pavement sections' treatment needs are selected based on the minimum acceptable level of PCI for individual sections, where the pavement sections under this level need treatment.

Initially, five pavement sections are selected for formulating a pavement maintenance decision optimisation problem. These sections are uniform and homogeneous in climatic zone, road functional class, material and structural properties. The total length of the analysis period and the unit analysis period are specified. For determining the sections' maintenance needs, the minimum acceptable level of pavement condition data is selected based on the previous researches.

Maintenance and rehabilitation investment type, frequency, and degree, have a significant effect on pavement conditions. In addition, the overlay or reconstruction of the pavement is the best maintenance solution to restore or upgrade the pavement to a perfect or excellent condition level. Therefore, the five overlay maintenance treatment strategies, shown in Table 4-1, are employed to calculate future pavement performance. The agency cost for each selected conservation action and the annual budget are determined based on historical data.

Table 4-1: Pavement rehabilitation options

No.	Rehabilitation Options
1	Do nothing
2	AC overlay 1 in (25 mm)
3	AC overlay 2 in (50 mm)
4	AC overlay 4 in (100 mm)
5	AC overlay 6 in (150 mm)

It is essential to determine the future deterioration for the programming of maintenance options over the study period. Therefore, this research has developed network-level deterministic deterioration models for flexible pavement, with the capability to predict pavement deterioration by considering distress, pavement age, traffic loading, and maintenance effects. The network-level deterministic deterioration model for arterial roads in the wet freeze climatic region is used to estimate future pavement condition:

$$PCI = 97.744 - 0.15\, X_5 - 0.064\, X_4 - 0.515\, X_2 + 3.748\, X_3 \qquad 4\text{-}1$$

Where *PCI* = Pavement condition index*;* X_2 = Pavement age; X_3 = Maintenance effect (inlay and overlay thickness); X_4 = Longitudinal and transverse cracking length; X_5 = Cracking area (alligator, edge, and block).

To find the optimal treatment decisions, it is important to optimise the treatment options considering multiple objectives. The maintenance decision-making model is formulated to achieve the following two objective functions:

1. Minimise the total pavement maintenance cost;
2. Minimise the sum of all residual PCI values.

This multi-objective maintenance decision model is complex and nonlinear, thus the optimisation algorithm group known as particle swarm optimisations (PSO) are used to overcome this complexity and nonlinearity. Therefore, the bare-bones algorithm is at first selected to solve pavement maintenance decision problem. However, this algorithm has the capability to solve only continuous optimisation problems, while the pavement maintenance decision problem is a discrete (binary) optimisation problem. Therefore, a new algorithm called discrete barebones multi-objective particle swarm optimisation (DBBMOPSO) is developed in this thesis. In addition, new MATLAB code is created for DBBMOPSO.

4.5 Summary

The applied methodology of this study has been summarised in this chapter. The aim was to introduce fuzzy logic for the section classification, develop pavement deterioration models, and then develop a multi-objective optimisation algorithm for finding an optimal pavement M&R plan over the analysis period. Moreover, a brief explanation of main problems in pavement management system has been presented. The following chapters describe the proposed methodology.

Chapter 5

Pavement Section Classification

5.1 Introduction

Generally, pavement condition comprises four key components; load bearing capacity, riding comfort, safety, and aesthetics. The ability to assess the current pavement condition is an important feature of the decision-making procedure of a pavement management system. It presents a quantitative measure for evaluating pavement section deterioration for the whole pavement network (Shahin, 2005; Sun and Gu, 2011). The primary purpose behind the assessment of pavement condition is to recognise the maintenance and rehabilitation requirements of the pavement network. To determine preservation needs, especially preventive treatment needs, the condition assessment must be detailed and on time (annually or biennially) (Hein and Watt, 2005).

A pavement network is divided into a number of pavement sections. Pavement sections with the worst assessment classes will have a high probability of being programmed for maintenance and rehabilitation, depending on the resources available and the importance of the highway. Due to limited preservation funding, the role of pavement condition assessment in pavement management is essential for prioritising treatment projects (Sun and Gu, 2011).

Highway pavement condition can be characterised through different performance indicators assessing different aspects of pavement performance. For highway pavements, these indicators may take account of surface deterioration, pavement deflection, roughness, and skid resistance. For airfield pavements, these indicators may comprise the structural index, the pavement condition index, friction characteristics, and foreign object damage potential (Sun and Gu, 2011).

5.2 Long-Term Pavement Performance (LTPP) Data

One of the major sources of pavement performance data for researchers is the Long-Term Pavement Performance (LTPP) program that was created to collect pavement condition information as one of the main research areas of the Strategic Highway Research Program (SHRP). The LTPP program was funded and managed by SHRP for the first five years, and by the Federal Highway Administration (FHWA) since 1990 (Elkins et al., 2011).

The LTPP program is an enormous study project which contains two major kinds of studies and some minor studies to explore particular pavement with details that are important to pavement performance. The two major studies are the General Pavement Studies (GPS) and the Specific Pavement Studies (SPS). The pavement sections of both GPS and SPS studies comprise over 2500 in-service test sections located on highways of the North American networks. The LTPP program monitors and collects pavement condition information on whole in-service sections. The collected data contain information on seven modules: Inventory, Maintenance, Monitoring, Rehabilitation, Materials Testing, Traffic, and Climatic (Elkins et al., 2011).

The LTPP Information Management System (IMS) is the central database where all the data collected under the LTPP program is stored. The LTPP IMS was established in 1988, and is continuously being developed as more data is collected and processed. Four regional offices are established under the LTPP program to coordinate and communicate LTPP-related activities throughout the U.S. and Canada (Elkins et al., 2011).

In this study, the LTPP data from the monitoring module is chosen as the pavement classification system. 180 test sections which contain seven distress types (alligator cracking, block cracking, longitudinal and transverse cracking, patching, potholes, bleeding, and ravelling) were first selected for this study, and then an extra 291 sections were extracted. This study is conducted on those two data groups (180 sections and 291 sections). The raw data of these sections were extracted from the Access file format of the monitoring module database, and also from images of each section found on LTPP Product online. Some of these monitoring data need manipulation and calculation before using them, and therefore the distress quantities of each severity level (low, medium, and high) are extracted and determined from LTPP survey images for each section as shown in Figure 5-1. Appendix A shows the distress quantity for each section based on the severity level.

The test sections have the same length, 500 feet (152.5m), but they have different widths. After preparing the distress data for each section, the density of each of the seven distress types for each severity level and PCI are determined by using the equations and procedures of the PAVER system as explained before in Section 2.4.3. Appendix B shows the density of each distress type and PCI.

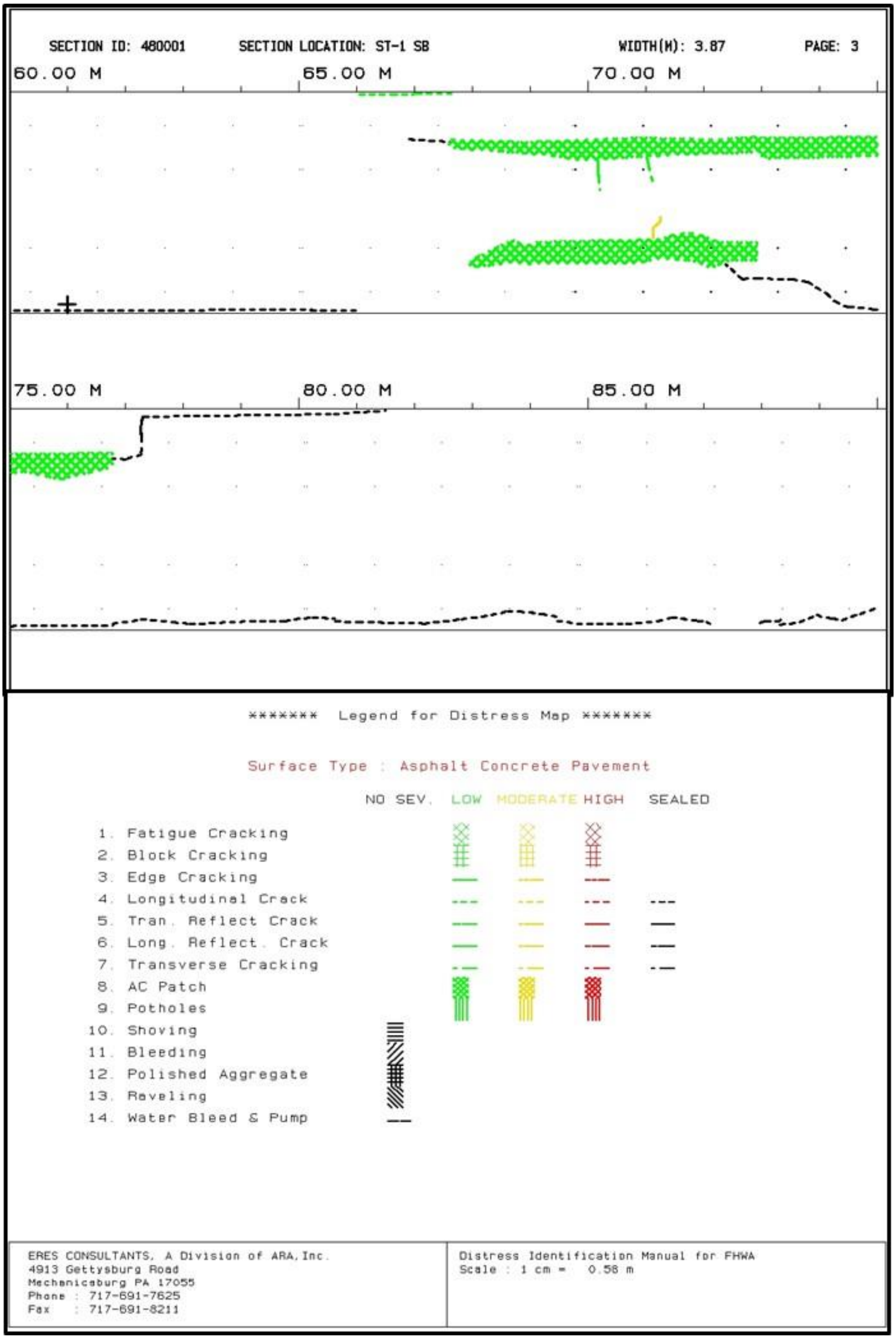

Figure 5-1: LTPP survey image sample (FHWA, 2012).

5.3 Model Formulation

Figure 5-2 shows the flowchart of the proposed model developed for pavement section classification using a fuzzy inference system. Initially, for building a pavement classification model based on a fuzzy inference system, the density of alligator cracking, block cracking, longitudinal and transverse cracking, patching and potholes, bleeding, and ravelling are determined as FIS inputs, and a calculated PCI is determined as the FIS output. Fuzzy Inference System Professional (FISPro) version 3.4 is then employed to design a fuzzy inference system from the numerical data. This software is one of many automatic learning methods, was created using the C++ language and has a graphical Java interface. It is not a "black box" system like other learning methods such as neural network, and contains algorithms to make the reasoning rules easy to interpret, so that the user understands how the fuzzy system operates (Guillaume et al., 2013).

5.3.1 Fuzzy Rule-Based System

A fuzzy rule-based system is one of the most popular methods used in classification problems. Fuzzy inference is a method that interprets the values in the input vector and, based on user-defined rules, assigns values to the output vector. The advantages of this approach are firstly that knowledge is represented in the form of If–Then rules, rendering the mechanism of reasoning in human-understandable terms, secondly that it has the capacity to take linguistic information from human experts and combine it with numerical information, and thirdly that it has the ability to approximate complicated nonlinear functions with simpler models (Dehzangi et al., 2007).

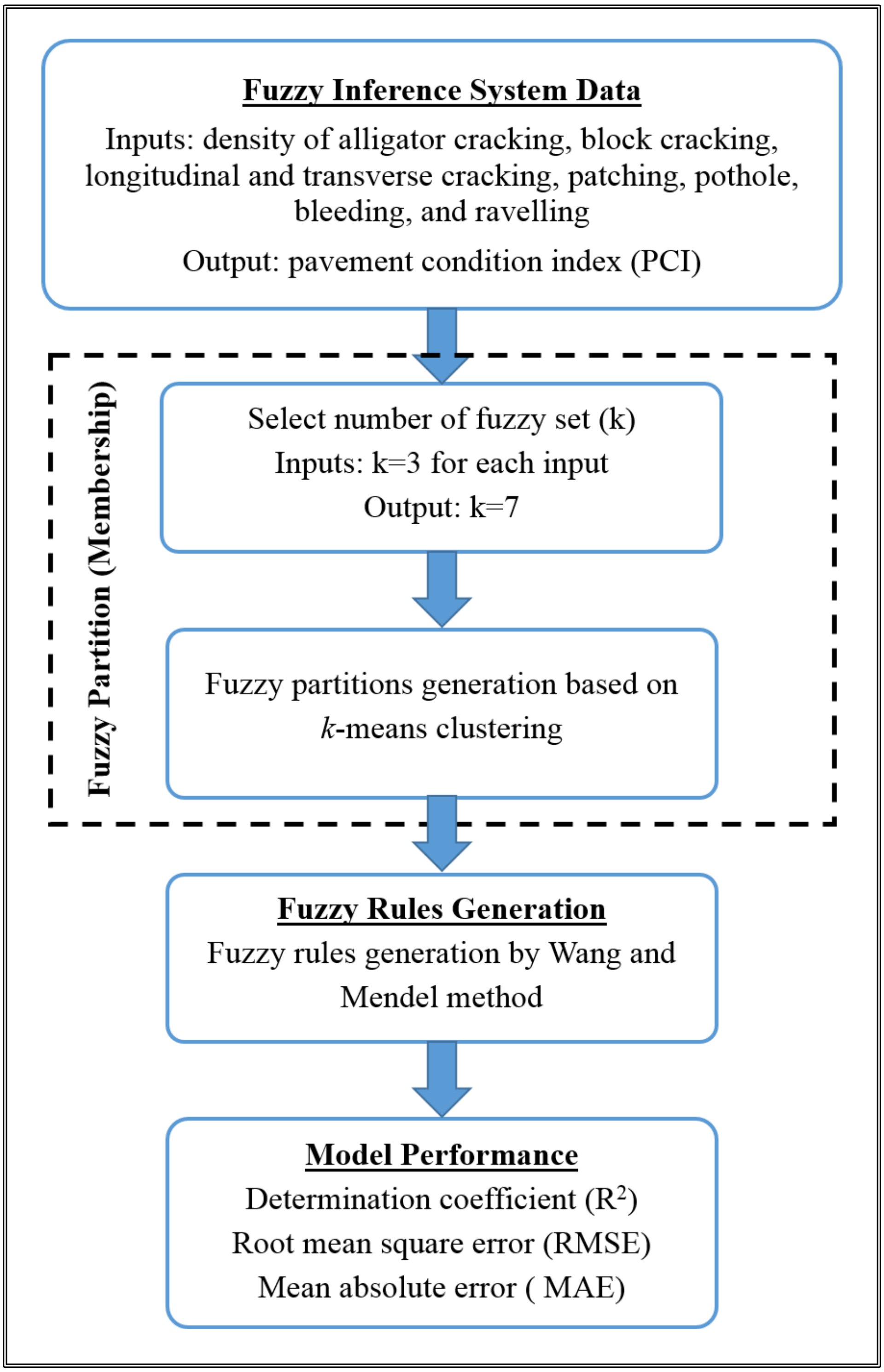

Figure 5-2: Flow chart of a pavement classification model based on FIS.

Fuzzy inference systems (FIS) are also known as fuzzy-rule-based systems, fuzzy models, fuzzy associative memories (FAM), or fuzzy controllers when used as controllers. Basically a fuzzy inference system is composed of five functional blocks (see Figure 5-3):

- a rule base containing a number of fuzzy If-Then rules;
- a database which defines the membership functions of the fuzzy sets used in the fuzzy rules;
- a decision-making unit which performs the inference operations on the rules;
- a fuzzification interface which transforms the crisp inputs into degrees of match with linguistic values;
- a defuzzification interface which transform the fuzzy results of the inference into a crisp output (Jang, 1993).

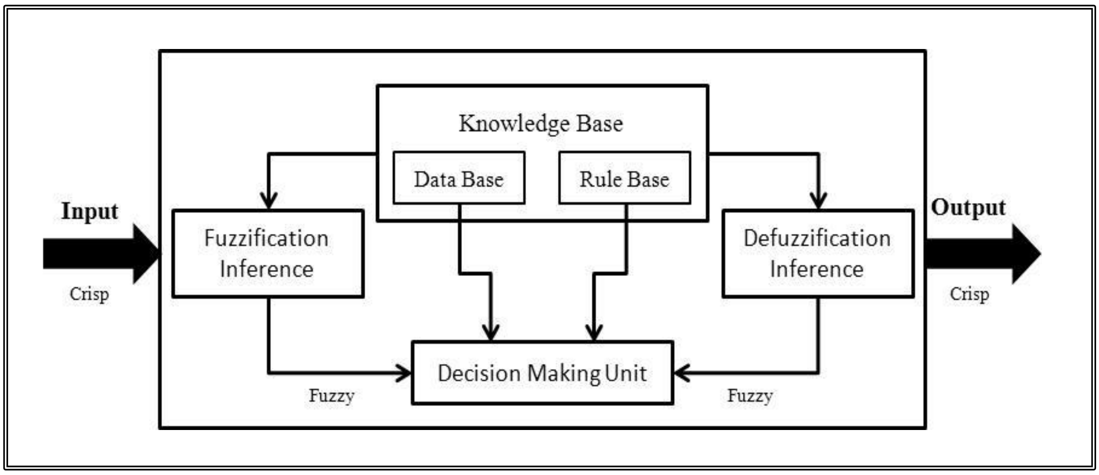

Figure 5-3: Fuzzy inference system structure (Jang, 1993).

5.3.1.1 Membership Functions Generation

"In fuzzy theory, the fuzzy set *A* of universe *X* is defined by the function $\mu_A(x)$, called the membership function of set *A*" (Negnevitsky, 2002).

$$\mu_A(x): X \rightarrow [0, 1]$$

Where $\mu_A(x) = 1$ if x is totally in A; $\mu_A(x) = 0$ if x is not in A; $0 < \mu_A(x) < 1$ if x is partly in A.

The degree of membership, or membership value, represents or equals the membership function $\mu_A(x)$ for an element x of set A, and has a value between 0 and 1. The membership function is a graphical representation which defines how each point in the variable space is mapped to the membership degree, or a value between 0 and 1. This graphical representation has different shapes such as triangular, trapezoidal, Gaussian, etc. (Negnevitsky, 2002). The membership function is determined by knowledge acquisitions or numerical data. There are many methods to generate membership functions of each variable based on numerical data.

5.3.1.1.1 Data Clustering Algorithms

Numerical data clustering is the foundation of various different system modelling and classification algorithms. The aim of clustering is to categorise a huge data set to natural groups of data to generate a brief demonstration of a model's behaviour. It divides the data set into a number of data subsets, such that the similarity inside a subset is greater than between the subsets. A similarity among elements of input vectors is an essential feature to achieve data clustering. Generally, clustering methods are categorised as either hard clustering or fuzzy clustering (Naik, 2004).

The most popular clustering method, one has been used in various areas, is *k*-means clustering, also known as *C*-means clustering. The basic concept of this clustering method is to randomly select *k* initial cluster means, or centres. After a number of repetitions, these initial cluster means are updated in such a way that they represent the data clusters as much as possible. A disadvantage of the *k*-means clustering algorithm is that the number of clusters is constant; after *k* is selected there will always be k cluster means or centres. The k-means algorithm can avoid this problem by eliminating the excess clusters. A cluster centre may be eliminated if it does not have enough samples. Selecting the initial number of clusters is a problem that is still unsolved. However, it is possible to avoid this problem by choosing a large enough k (Naik, 2004).

1. Initialise C_i by randomly choosing C points from among all the data points.
2. Compute the membership matrix (U),

Where the element (u_{ij}) is 1 if the j^{th} data point x_j belongs to the group i and 0 otherwise.

3. Compute the fitness function by using the following equation. Stop if the fitness function value is lower than a certain threshold value:

$$J = \sum_{i=1}^{c} Ji = \sum_{i=1}^{c} \left(\sum_{k, X_k \in C_i} \|X_k - C_i\|^2 \right) \tag{5-1}$$

4. Update the cluster centre C_i and calculate the new matrix (U).

Basically, the k-means clustering algorithm is iterative. Therefore, it is difficult to forecast its convergence to the best solution. The performance of this algorithm depends on the position of the initial centres, and therefore the initial position of the cluster centres are forecasted by a front-end tool, which creates them iteratively (Naik, 2004).

5.3.1.1.2 Membership function

The membership functions of inputs are generated by using FISPro. In distress identification manual, there are three severity levels for each distress (Miller and Bellinger, 2003). Therefore, three triangular membership functions (low, medium, and high) are created for each input, while the seven triangular membership functions of

PCI are created as shown in Figure 5-4, Figure 5-5, Figure 5-6, Figure 5-7, Figure 5-8, Figure 5-9, Figure 5-10, and Figure 5-11 for the 180 and 291 sections respectively. In these figures, the x-axis represents the distress density (see Section 2.4.3) for each input and PCI for output, while the y-axis is a membership function ranging between 0 and 1. Where '0' means no relation and '1' means maximum relation.

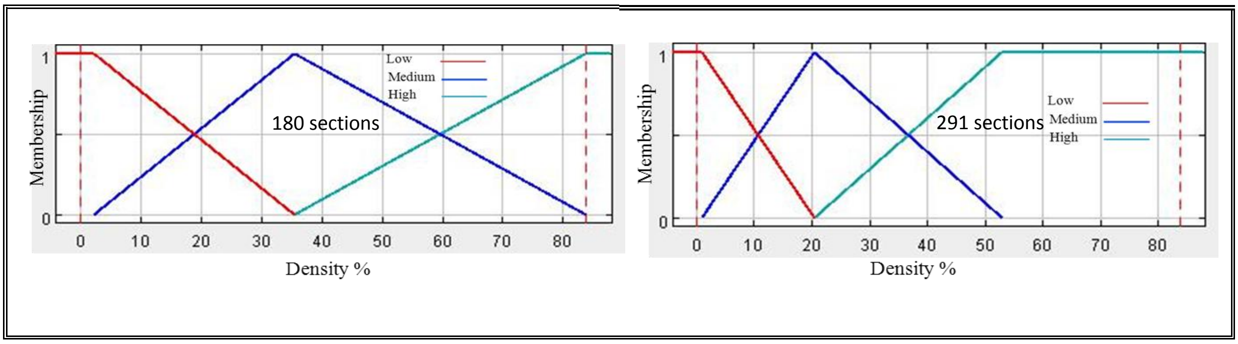

Figure 5-4: Membership functions for Alligator cracking.

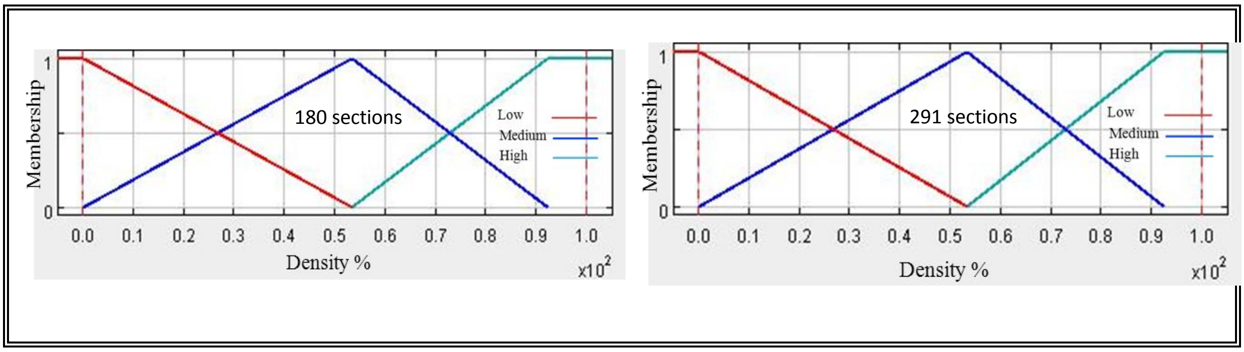

Figure 5-5: Membership functions for Block cracking.

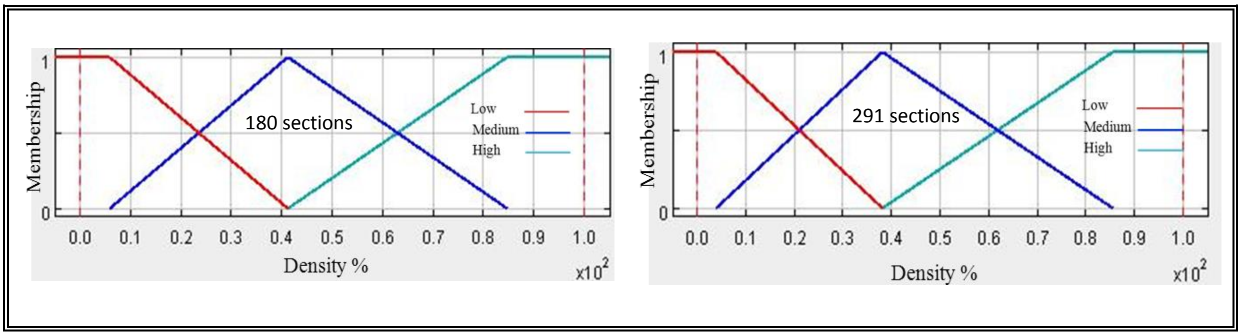

Figure 5-6: Membership functions for Longitudinal and Transverse cracking.

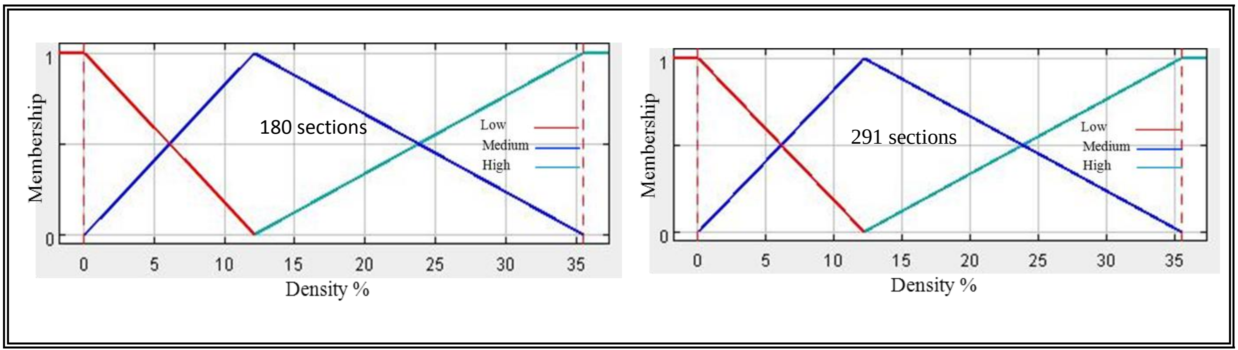

Figure 5-7: Membership functions for Patching.

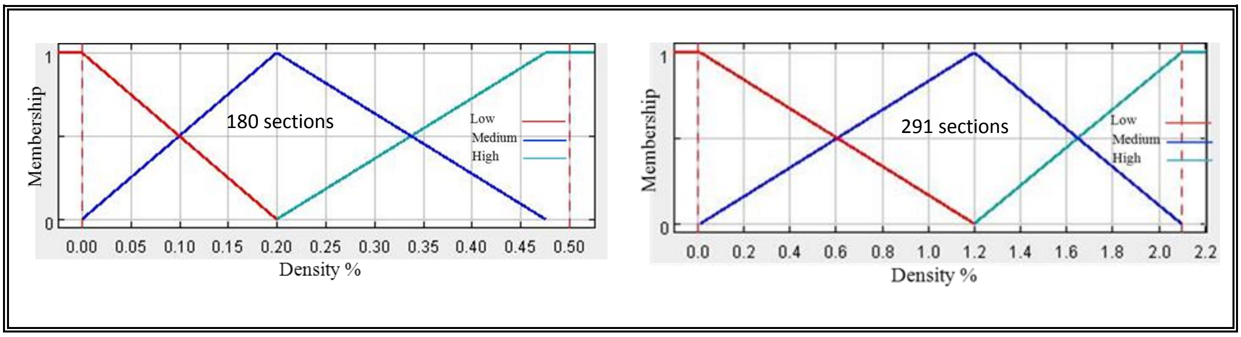

Figure 5-8: Membership functions for Potholes.

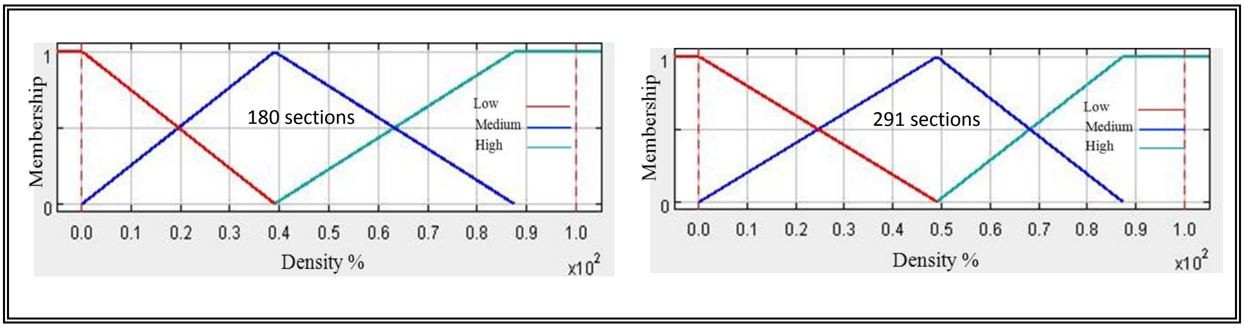

Figure 5-9: Membership functions for Bleeding.

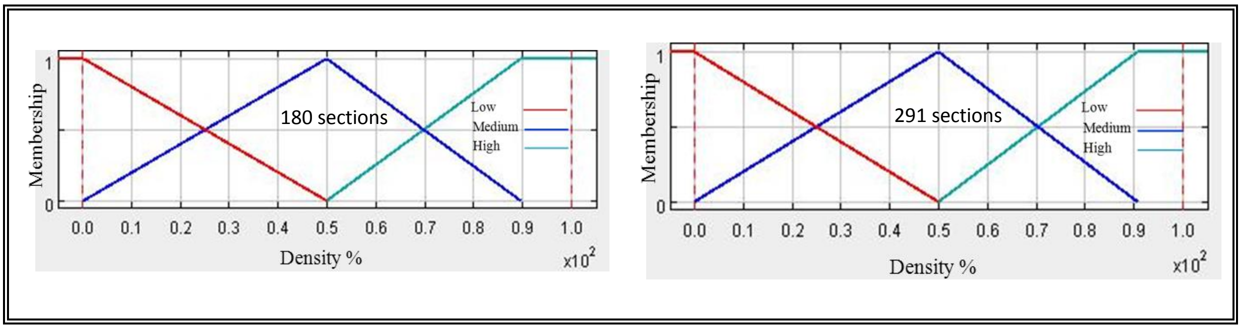

Figure 5-10: Membership functions for Ravelling.

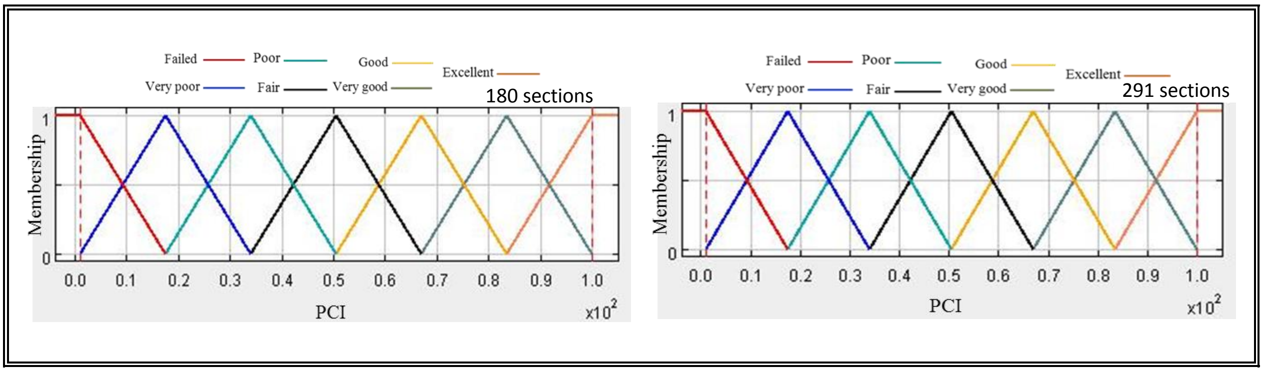

Figure 5-11: Membership functions for PCI.

5.3.1.2 Fuzzy Rule Generation:

The second stage of FIS based section classification is rule generation. The major challenge in FIS is generating the rules. In high-dimensional problems, it is very difficult to generate every possible rule with respect to all antecedent combinations. The number of rules of a complete rule set is equal to

$$\prod_{i=1}^{n} m_i \qquad 5\text{-}2$$

Where *m* is the number of membership functions for input *i*, and *n* is the number of inputs.

The fuzzy rules are generated either from expert knowledge or numerical data (Nelles et al., 1996). The generation rules of the classification model described in this work are difficult and complex because it consists of seven inputs and one output. Therefore, FISPro is employed to overcome this problem. FISPro (Fuzzy Inference System Professional) is used to design and produce fuzzy systems from numerical data (Guillaume et al., 2013). The fuzzy rules are generated based on Wang & Mendel's method. This method needs predefined fuzzy membership functions for each input and output. It can automatically generate rules from data. It starts by creating one rule for each data pair of the training set. The i^{th} pair rule is as follow:

$$IF\ x_1\ is\ A_1^i\ AND\ x_2\ is\ A_2^i\ \ldots\ AND\ x_p\ is\ A_p^i\ THEN\ y\ is\ C^i$$

The fuzzy sets A_1^i are those for which the degree of match of X_j^i is maximum for each input variable j from pair i. The fuzzy set C^i is the one for which the degree of match of the observed output, y, is maximum (Guillaume et al., 2013). The Table 5-1 and Table 5-2 show the fuzzy rules for the two data sets of 180 sections and 291 sections respectively. There are significant difference among fuzzy rules in Table 5-1 and Table 5-2. That is because the fuzzy rules are generated automatically by learning from data examples and the 291 sections are the same 180 sections plus another 111 sections. Therefore, the new fuzzy rules are generated from 111 sections.

Table 5-1: Fuzzy If-Then rules generated by 180 pavement sections

Rule No.	Input rule - *If "Alligator cracking" is … and "Block cracking" is …*							Output rule - *Then "PCI" is…*
	Distress type							
	Alligator Cracking	Block Cracking	Long. & Trans. Cracking	Patching	Potholes	Bleeding	Ravelling	
1	**High**	**Low**	**Low**	**Low**	**Low**	**Low**	**Lothrow**	**Failed**
2	**Medium**	**Low**	**Medium**	**Low**	**Low**	**Medium**	**Low**	**Failed**
3	**Medium**	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Failed**
4	**Medium**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Low**	**Failed**
5	**Medium**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Medium**	**Failed**
6	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**High**	**Failed**
7	**Medium**	**Low**	**Low**	**Low**	**Medium**	**Low**	**Low**	**Very poor**
8	**Low**	**High**	**Low**	**Low**	**High**	**Low**	**Low**	**Very poor**
9	**Medium**	**Low**	**Low**	**High**	**Low**	**Low**	**High**	**Very poor**
10	**Medium**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Poor**
11	**Medium**	**Low**	**Low**	**Low**	**High**	**Low**	**Low**	**Poor**
12	**Low**	**Low**	**Medium**	**Medium**	**Low**	**Low**	**Low**	**Poor**
13	**Low**	**Low**	**Medium**	**Low**	**High**	**Medium**	**High**	**Poor**
14	**Low**	**Low**	**High**	**Low**	**Low**	**High**	**Low**	**Fair**
15	**Low**	**Low**	**Medium**	**Low**	**Medium**	**Low**	**Low**	**Fair**
16	**Medium**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Fair**
17	**Low**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Medium**	**Fair**
18	**Low**	**Medium**	**High**	**Low**	**Low**	**Low**	**Low**	**Fair**
19	**Low**	**Low**	**Medium**	**Low**	**Low**	**Medium**	**Low**	**Fair**
20	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Medium**	**Good**
21	**Low**	**Low**	**High**	**Low**	**Low**	**Low**	**Low**	**Good**
22	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Good**
23	**Low**	**High**	**Low**	**Low**	**Low**	**Low**	**Low**	**Good**
24	**Low**	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Good**
25	**Low**	**Low**	**Low**	**Low**	**High**	**Low**	**Low**	**Very good**
26	**Low**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Low**	**Very good**

27	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Very good**
28	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**High**	**Very good**
29	**Low**	**Low**	**Low**	**Low**	**Low**	**High**	**Low**	**Very good**
30	**Low**	**Low**	**Low**	**Medium**	**Medium**	**Low**	**Low**	**Very good**
31	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Excellent**

Table 5-2: Fuzzy If-Then rules generated by 291 pavement sections.

Rule No.	Input rule - *If "Alligator cracking" is … and "Block cracking" is …*							Output rule - *Then "PCI" is…*
	Distress type							
	Alligator Cracking	Block Cracking	Long. & Trans. Cracking	Patching	Potholes	Bleeding	Ravelling	
1	**High**	**Low**	**Medium**	**Low**	**Low**	**Medium**	**Low**	**Failed**
2	**Medium**	**Low**	**High**	**Low**	**Low**	**Low**	**Low**	**Failed**
3	**Medium**	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Failed**
4	**Medium**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Low**	**Failed**
5	**High**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Medium**	**Failed**
6	**High**	**Low**	**Low**	**High**	**Low**	**Low**	**High**	**Very poor**
7	**Low**	**Low**	**High**	**Low**	**Low**	**Low**	**High**	**Very poor**
8	**Low**	**Low**	**Medium**	**Low**	**Medium**	**Low**	**Low**	**Very poor**
9	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**High**	**Poor**
10	**High**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Poor**
11	**Low**	**Low**	**Medium**	**Medium**	**Low**	**Low**	**Low**	**Poor**
12	**Medium**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Poor**
13	**Low**	**Low**	**Medium**	**Low**	**Low**	**Medium**	**High**	**Poor**
14	**High**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Poor**
15	**Low**	**Low**	**Low**	**Low**	**High**	**Low**	**Low**	**Poor**
16	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Low**	**Poor**
17	**Medium**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Poor**
18	**Low**	**Low**	**High**	**Low**	**Low**	**High**	**Low**	**Fair**
19	**Low**	**Medium**	**High**	**Low**	**Low**	**Low**	**Low**	**Fair**
20	**Low**	**Low**	**Medium**	**Low**	**Low**	**Medium**	**Low**	**Fair**
21	**Medium**	**Low**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Fair**
22	**Medium**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Low**	**Fair**
23	**High**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Low**	**Fair**
24	**Low**	**Low**	**High**	**Low**	**Low**	**Low**	**Low**	**Good**
25	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Medium**	**Good**
26	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Good**
27	**Low**	**High**	**Low**	**Low**	**Low**	**Low**	**Low**	**Good**
28	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**High**	**Very good**
29	**Low**	**Low**	**Low**	**Low**	**Low**	**High**	**Low**	**Very good**
30	**Low**	**Low**	**Low**	**Medium**	**Low**	**Low**	**Low**	**Very good**
31	**Low**	**Low**	**Low**	**Low**	**Low**	**Medium**	**Low**	**Very good**
32	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Low**	**Excellent**

5.4 The Results of Pavement Section Classification

Initially, 180 flexible pavement sections were selected for building the fuzzy rules. The number of sections was then increased to 291 in order to further improve the accuracy of the model. For each section, seven types of distress (alligator cracking, block cracking, longitudinal and transverse cracking, patching, potholes, bleeding, and ravelling), the severity level, and the extent of each section as defined in the LTTP were used.

5.4.1 Pavement Condition Index (PCI)

After generating membership functions and rules, the system is tested for two section data sets by calculating the performance of the fuzzy pavement classification. Figure 5-12 and Figure 5-13 show the relation between the observed PCI and fuzzified PCI for both the 180 and the 291 section sets. It can be seen that a correlation of approximately 73.5% was achieved for the 180 section set, while the model's accuracy improved to 76% with 291 sections. This means that the classification model improved as the number of sections increased, as more sections represent more possible variations of the distress types and severities, which helps the model to learn and create additional fuzzy rules.

Table 5-3 shows the coefficient of determination together with the root mean square error (RMSE) and mean absolute error (MAE) to show the level of agreement of the PCI values in the two data sets calculated by two different methods. The performance of the fuzzified PCI calculation improved by approximately 3% with 111 additional sections. It is expected that the level of accuracy will improve with further increases in the number of sections.

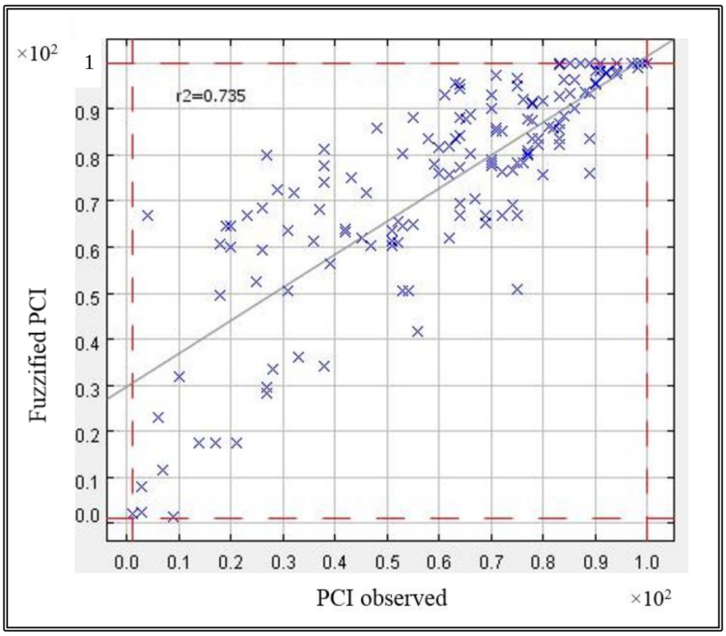

Figure 5-12: The performance of a fuzzy inference system based PCI for 180 sections.

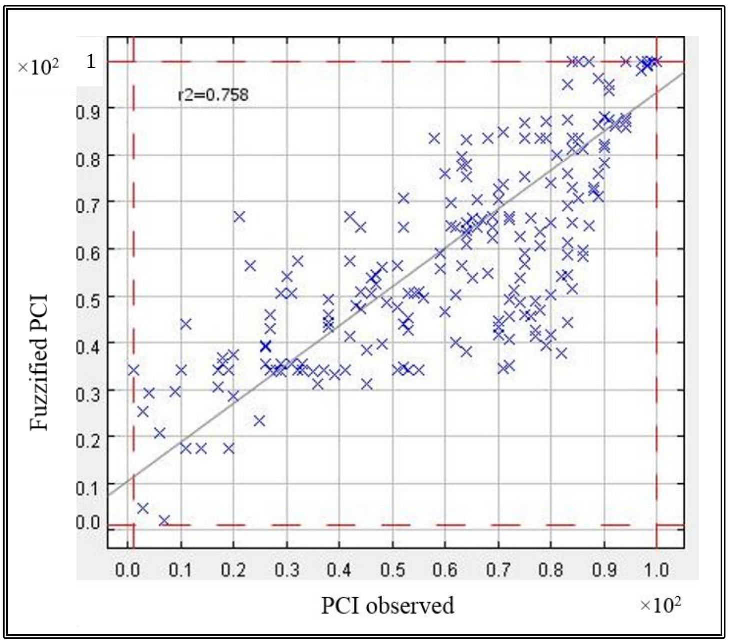

Figure 5-13: The performance of a fuzzy inference system based PCI for 291 sections.

Table 5-3: The improvement of model performance with number of sections.

Number of sections	R^2 (%)	RMSE	MAE
180	73.5	17.869	12.186
291	75.8	13.925	9.077

5.4.2 Error Levels

To understand the level of error for each PCI category, the error levels are plotted for both data sets in Figure 5-14 and Figure 5-15. The error level is the percentage difference between the fuzzified PCI (calculated by the fuzzy system) and the observed output (PCI calculated by PAVER software). It can be seen that the errors in the 'excellent' and 'very good' PCI classes are high compared to the 'medium' and 'worst' classes. Moreover, the errors in the first data set are larger than those in the second data set because the distribution of raw data in each PCI category is better in the second set than in the first, as shown in Figure 5-16 and Figure 5-17.

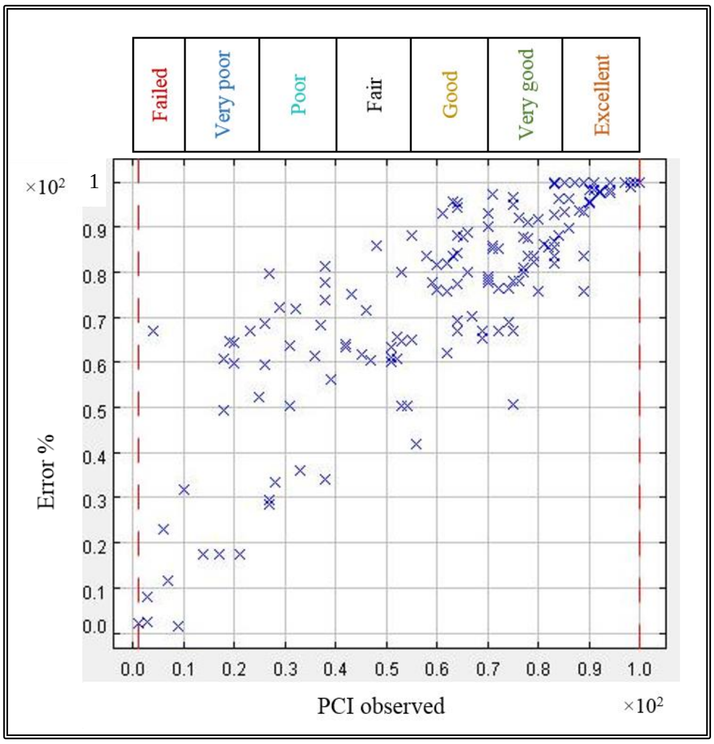

Figure 5-14: Error levels in the pavement classification system for 180 sections.

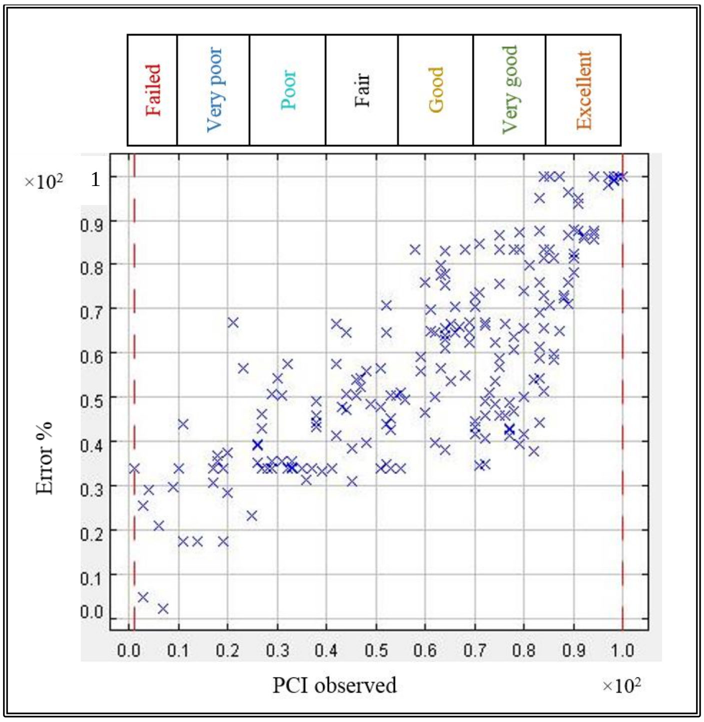

Figure 5-15: Error levels in the pavement classification system for 291 sections.

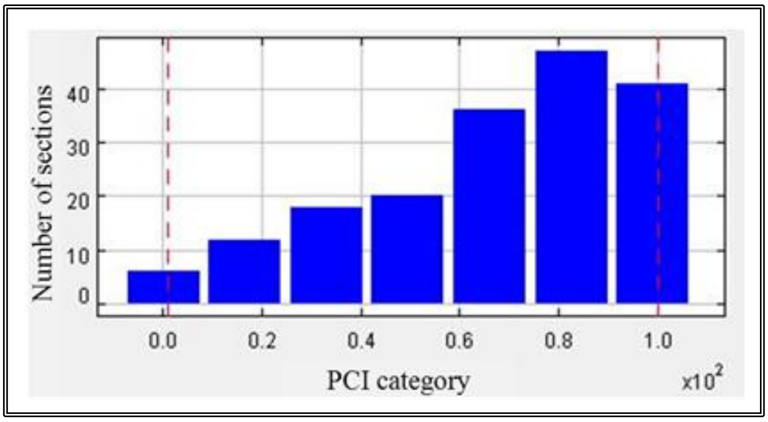

Figure 5-16: Pavement distress data for each PCI category (180 sections).

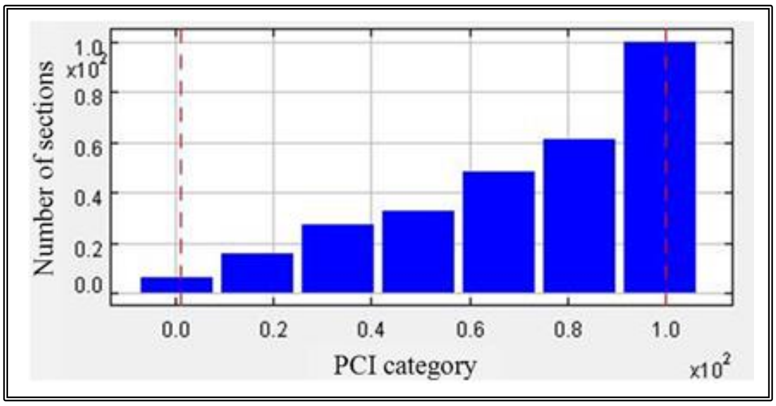

Figure 5-17: Pavement distress data for each PCI category (291 sections).

5.4.3 Sensitivity of Distress Types

A sensitivity analysis was carried out to examine the effect of input variables on the efficiency of the fuzzy pavement classification system in the calculation of PCI. For example, the sensitivity analysis was conducted by generating the FIS model by considering effect of individual input and cancelling effects of other inputs. The sensitivity analysis was done considering the following points:

- The effect of each input separately;
- The effect of all cracks (alligator, block, and longitudinal and transverse);
- The effect of patching and potholes;
- The effect of bleeding and ravelling.

The correlation between the fuzzified and conventional PCI calculations for each distress type and their level of influence on the PCI calculation are shown in Table 5-4. It can be seen from these figures that the determination coefficients for cracking, patching and potholes, and surface defects are 73, 4.7, and 6.4 per cent respectively. It was found that for this given data set, the influence of alligator cracking is significantly higher than that of other types of distress. Therefore, the majority of the effect on the PCI calculation comes from cracking, while patching, potholes, and surface defects have very little effect on the classification model.

Table 5-4: Sensitivity level for each input variable.

Input variable	R^2 (%)	Sensitivity level
Alligator cracks	**56**	**High**
Block cracks	2.8	Low
Longitudinal and transverse cracks	8	Low
Patching	4.3	Low
Potholes	0.6	Low
Bleeding	1.2	Low
Ravelling	5.6	Low
All Cracks	**73**	**High**
Patching and potholes	4.7	Low
Bleeding and ravelling	6.4	Low

5.5 Summary

This chapter presented the development of a new and simplified section classification model for flexible pavement. It also introduced a brief summary of the FIS mechanism. The density of alligator cracking, block cracking, longitudinal and transverse cracking, patching and potholes, bleeding and ravelling were considered as FIS inputs while a calculated PCI was considered as the FIS output. Then, the FIS model was formulated for two data groups through two stages. The first stage was the fuzzy partition generation for inputs and output by using clustering algorithm. The second stage was fuzzy rule generation from numerical data by using Wang & Mendel’s method. The results showed that the fuzzy pavement classification has good accuracy compared to PCI calculated by the commercial MicroPAVER software. The following chapter presents the development of pavement deterioration models for flexible pavement at the network level.

Chapter 6

Pavement Performance Prediction

6.1 Background

An accurate pavement performance prediction model is necessary for pavement management at both the project and the network level. Prediction of pavement performance at the network level is important for adequate activity programming, plan prioritisation and resource allocation. At the project level, it is necessary for finding the particular conservation actions that need to be taken, such as maintenance and rehabilitation (Lytton, 1987; Prozzi and Madanat, 2002).

Performance is defined as "a general term for how pavements change their condition or serve their intended function with accumulating use" (Lytton, 1987). Performance is different in meaning and definition between the project and the network level. At the project level, it is defined by distress, skid resistance, loss of serviceability index, loss of general condition, and by the deterioration caused by the estimated traffic. Performance at the network level is stated not only in terms of the condition and trends of single projects, but also in terms of the general condition of the pavement network, and the performance level provided by each kind and functional class of highway (Lytton, 1987).

Models of performance prediction are employed in various ways based on whether they are utilised at the project or network level. At the project level, these models are employed for designing pavements and carrying out life-cycle cost analyses. Moreover, they are adopted for determining optimal designs with the smallest entire costs including users costs, and in trade-off analyses in which the annualised costs of new construction, maintenance, rehabilitation, and user costs are summed for a specific pavement design to calculate the optimal time and pavement condition to perform each task (Lytton, 1987).

At the network level there are various uses for pavement performance models, such as the choosing of best maintenance and rehabilitation plans; investigations of pavement cost responsibilities for different legal vehicle weights and sizes, tyre pressures, and suspension systems; determination of equitable permit fees for overweight vehicles; budget allocation studies utilising load equivalence factors and, in the future, marginal load equivalence factors; and network-level trade-off analysis of the optimum level and timing of pavement deterioration, treatment, and user costs. All these uses of performance models at the network level affect taxation levels and public travelling fees, and thus establish the rational basis for all public highway transportation investments (Lytton, 1987).

6.2 Types of Pavement Performance Prediction Models

Numerous highway authorities have established different pavement performance models for use in their pavement management systems, sometimes focused on a specific type of performance or model to the exclusion of others. However, all performance model types are essential and useful in forecasting at least one type of performance. Some of these models are very simple and limited in their applications, while other models are comprehensive and suitable for a wide range of applications.

Pavement performance prediction models can be classified into two main groups: deterministic and probabilistic (Haas et al., 1994; Lytton, 1987). Deterministic models forecast a particular number for a pavement's life or its level of distress or other indicators of its condition, while the probabilistic models expect a distribution of such events. Deterministic models comprise primary response, structural performance, functional performance, and damage models. Probabilistic models comprise survivor curves and Markov transition process models (Haas et al., 1994; Lytton, 1987). These models are described briefly here.

6.2.1 Empirical Models

These models are used to find the empirical (regression) relationship between the dependent variable, which is the condition index, and one or more explanatory variables. Both subjective indices such as riding quality, condition index, and serviceability, and objective indices such as rutting, roughness, and cracking, are utilised as dependent variables. These performance indices are related to one or more independent variables, such as structural strength, traffic loading and climatic effects (Prozzi and Madanat, 2002). The simplest empirical model is linear regression analysis, which is described as follows:

$$Y_i = \alpha + \beta X_i + \varepsilon_i \qquad \text{6-1}$$

Where Y = dependent variable; X = independent variable; ε = prediction error; α, β = regression parameters.

Nonlinear regression analysis is necessary when the empirical relationship is not linear. In this case, a linear regression analysis may underestimate or overestimate the pavement's condition during its life (Shahin, 2005).

6.2.2 Mechanistic Models

These models are able to determine pavement responses such as stress, strain, and deflection. These models represent the real behaviour of the pavement structure under the effects of either traffic, or the environment, or both. Many attempts have been made to create this type of model, but a comprehensive and credible mechanistic performance model has not yet been established (Prozzi and Madanat, 2002).

6.2.3 Mechanistic-Empirical Models

These types of models are capable of determining pavement response or behaviour parameters such as stress, strain, or deflection. This pavement response is related to measured structural or functional damage, such as distress or roughness, through regression equations. These models are calibrated to a real pavement structure, and both test and in-service pavement sections are considered for this calibration. The calibration of these models is commonly done using a bias correction factor (shift factor) (Haas et al., 1994; Prozzi and Madanat, 2002; Shahin, 2005).

Regardless of their limitations, empirical and mechanistic-empirical models are presently the most popular prediction methods. Empirical (regression) models have been employed for a long time and are one of the most widely used deterioration models. Nevertheless, highway authorities have changed the direction of their efforts toward mechanistic-empirical models over the past 20 years because they come the closest to matching the engineering reality (Prozzi and Madanat, 2002).

6.3 Data Requirements for Performance Models

The common types of pavement data are inventory, monitoring, and maintenance costs. Inventory data are constant data which do not change with time or traffic, or represent a prior condition of the pavement such as geometry, layer thickness, material properties, age, etc. Monitoring data, by contrast, change with time or traffic and represent the dependent variables of performance equations. Examples of monitoring data include distress, traffic, deflection, profile, friction, etc. Cost data consist of initial construction cost, maintenance cost and rehabilitation cost (Lytton, 1987).

6.3.1 LTTP Database

The Long Term Pavement Performance (LTPP) database was described in section 5.2. In the LTPP program, investigation continues on the in-service pavement sections to understand the behaviour under real-life traffic loading. These pavement sections are categorised in the LTPP program as General Pavement Studies (GPS) and Specific Pavement Studies (SPS). GPS comprises a study series on approximately 800 in-service pavement test sections in all parts of the United States and Canada, while SPS are studies of particular pavement parameters involving new construction, maintenance and rehabilitation actions. The LTPP database is separated into seven modules: Inventory, Maintenance, Monitoring, Rehabilitation, Materials Testing, Traffic, and Climatic (Elkins et al., 2011). This research uses the data of asphalt concrete pavement on granular base (GPS-1).

6.3.2 Input Parameters

The main challenge in developing pavement deterioration models is the existence and use of the different factors affecting pavement condition that need to be considered.

These factors are pavement age, traffic loading, climatic effects, initial design and construction, and maintenance effects (Al-Mansour et al., 1994; Fwa, 2006). In this research, the following parameters are considered as inputs for the deterioration models.

6.3.2.1 Pavement Age

Asphalt stiffness increases with age, makes it brittle and prone to cracking. In addition, adverse environmental effects and interaction with traffic loads accelerates “ageing”. Pavement age is measured from the construction date or from the date of the last rehabilitation (Al-Mansour et al., 1994; Fwa, 2006).

6.3.2.2 Traffic Load

Traffic loading will generate stresses and strains within the bituminous/concrete layers, causing fatigue and eventually cracks, and bituminous surface rutting due to the plastic cumulative deformation of the pavement layers including the foundation. The classical design approach addresses two forms of failure in pavements, fatigue cracking in the bituminous/concrete material and overstressing of the subgrade (Fwa, 2006).

The traffic module is adopted to extract ESAL, and then cumulative ESAL is calculated. The pavement surface carries different traffic loads, ranging from light passenger cars to heavy trucks, heavy traffic loads having more harmful influence on pavement than light loads. Moreover, a high repetition of the same traffic load category has a harmful effect on the pavement. The pavement deterioration caused by the application of all axle loads on the pavement during its service life must be considered in pavement design. Knowledge of the axle loads and the repetition of these loads is required in structural pavement analysis (Fwa, 2006).

Two types of traffic surveys are conducted in the field to collect traffic loading data. The first type counts the number of different vehicle types, while the other measures the axle or wheel loads of each vehicle type. In pavement design, the combination of the loading effects of various axle types in the expected traffic is considered (Fwa, 2006).

In the AASHTO (1993) design method, the different magnitudes of axle loads and different repetition numbers are converted to an equivalent repetition number of a standard axle load which causes the same deterioration to the pavement. The load of a standard axle is defined as being equal to 18000lb (80 kN) of a single axle with a dual wheel at each end. "The equivalent single axle load (ESAL) is the equivalent number of repetitions of the 18000lb (80kN) standard axle load that causes the same damage to the pavement caused by one pass of the axle load in question" (Fwa, 2006).

6.3.2.3 Pavement Design and Construction

A pavement section's design and construction have significant influence on its performance. In general, pavement design consists of two main parts, pavement type and asphalt layer thickness. In performance prediction analysis, all pavement sections should be the same pavement type, either flexible or rigid pavement. Road functional classification was employed to reflect the structural design variation (Al-Mansour et al., 1994).

6.3.2.4 Maintenance and Rehabilitation (M&R)

Maintenance type, frequency and degree, and rehabilitation (overlay) time, have a significant effect on pavement performance. Generally, there are two groups of maintenance activity, namely, a) preventive (periodic) and b) corrective maintenance. The objective of preventive maintenance is to limit the deterioration rate of pavement structure, while corrective maintenance can be remedial, or performed in an emergency to keep the pavement structure in a serviceable state (Al-Mansour et al., 1994; Haas et al., 1994).

Sometimes, when pavement contains one or more distresses, a pavement might be sufficiently maintained but repair costs may be too high and the structural capacity for expected future traffic loads may be insufficient. Therefore, rehabilitation (overlay) or reconstruction of the pavement is the best solution to restore or upgrade the pavement to its required condition and serviceability level (Fwa, 2006). For this study, only inlay and overlay rehabilitation options are considered, as these are expected to improve pavement condition. It should be noted that depending on the construction and level of deterioration, the thickness of inlay and overlay will be different and consequently the benefit will be variable. One of the main limitations of the model is to mathematically incorporate the benefit of preventive maintenance like crack sealing, patching etc. on pavement performance. Therefore, to avoid model complications in the PCI calculation, the benefit of preventive maintenance to the pavement was not considered.

6.3.2.5 Climatic Effect

One of the main factors contributing to pavement deterioration is environmental variation, or climatic effect. This includes temperature, which causes a bituminous bound surfacing to rut under traffic in hot weather, and cracking of the age-hardened brittle bituminous surface in cold weather. Climatic effects also include precipitation quantities and freeze-thaw cycles. The climate is one of key contributors to pavement structural distress. Structural damage decreases the load carrying capacity of the pavement, which leads to failures such as cracking (Al-Mansour et al., 1994; Fwa, 2006). It is difficult to represent the environmental effects mathematically in a prediction model. Therefore, the environmental effects are embedded by generating a prediction model for each of the four climatic zones in the LTTP study area as shown Figure 6-1. These are wet freeze, wet non-freeze, dry freeze, and dry non-freeze zones.

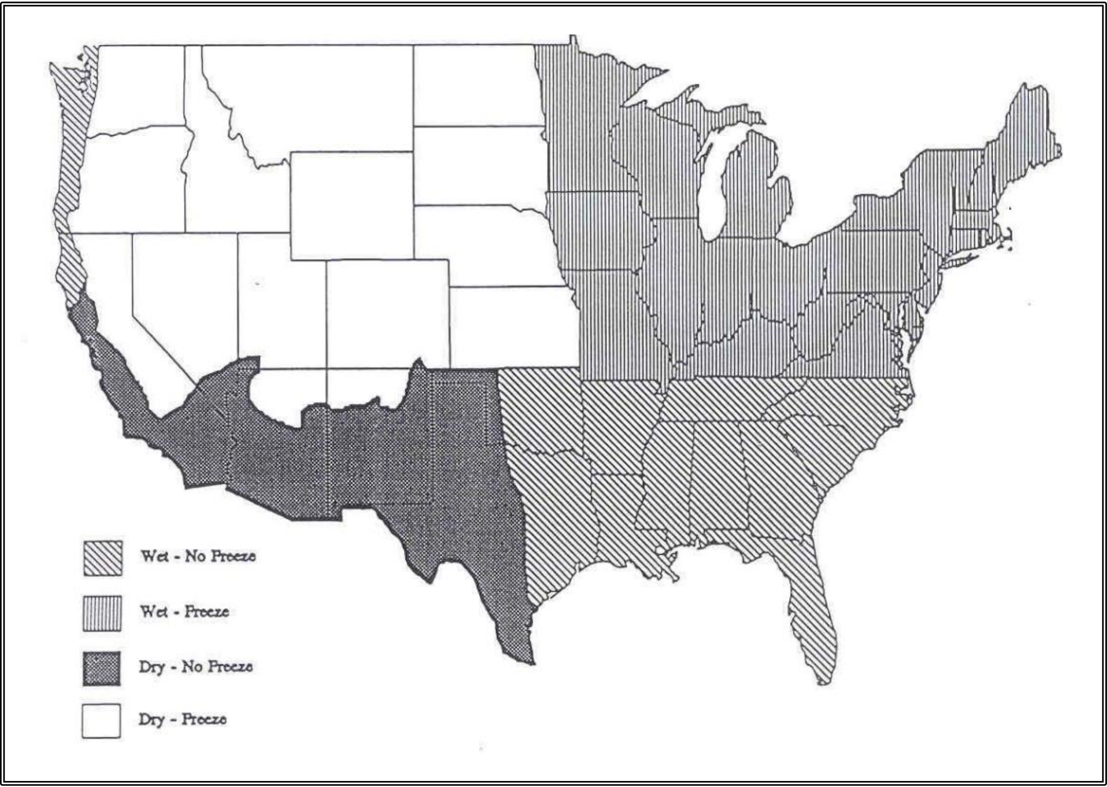

Figure 6-1: Map of climate regions in the United States and Canada based on LTPP (Perera and Kohn, 2001).

6.3.2.6 Distress Quantity

Distress is any physical deterioration of the pavement surface, such as cracking, potholes, and rutting, and is generally but not necessarily visible (Haas et al., 1994). At the project level, pavement performance is expressed by evaluating the pavement distresses separately, while at the network level it is essential to find a composite measure of performance that considers most distresses (Litzka, 2006). In section classification of this thesis, it was found that cracking has the most severe effect on overall pavement performance, or PCI. Furthermore, as shown in Figure 6-2, the occurrence frequency of cracking distress is high compared with any other distress. Therefore, only cracking area (alligator, block, and edge) and cracking length (longitudinal and transverse) are considered in the development of the deterioration prediction models.

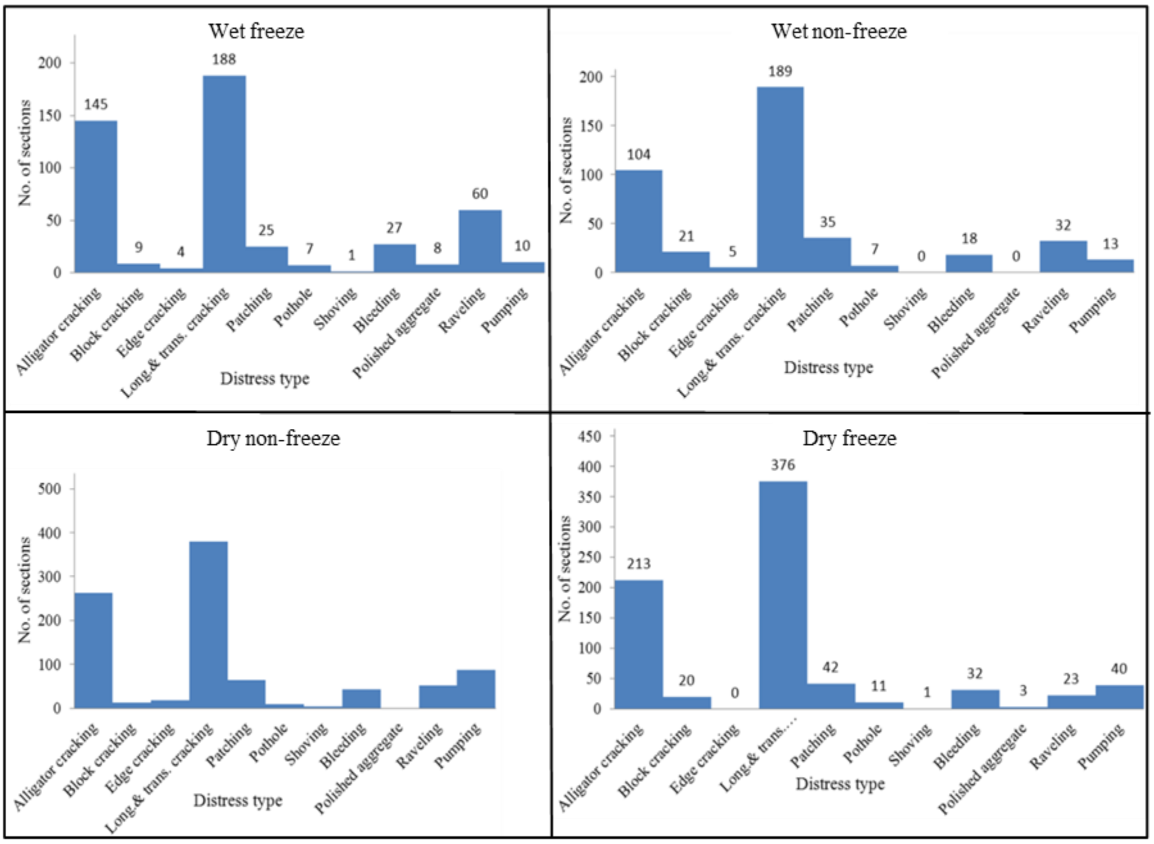

Figure 6-2: Occurrence frequency of distress types in all climatic zones.

6.4 Development of a Multi-Input Deterioration Prediction Model (MID-PM)

Deterministic models are commonly used to find the empirical relationship between the dependent variable, which is distress progression or a condition index, and one or more explanatory variables, such as cracking area, age and ESAL. Subjective indices such as ride quality, condition index, and serviceability, and objective indices such as rutting, roughness, and cracking, are utilised as dependent variables. These performance indices are related to one or more independent variables like structural strength, traffic loading and climatic effects (Prozzi and Madanat, 2004). The simple equation of the prediction model is described thus:

$$PCI = a_1 + a_2\, X_1 + a_3\, X_2 + a_4\, X_3 + a_5\, X_4 + a_6\, X_5 \qquad 6\text{-}2$$

Where PCI = Pavement condition index; X_1 = Cumulative Equivalent Single Axle Load (ESAL); X_2 = Pavement age; X_3 = Maintenance effect (inlay and overlay thickness); X_4 = Longitudinal and transverse cracking length; X_5 = Cracking area (alligator, edge and block); $a_1, a_2, a_3, a_4, a_5, a_6 =$ Coefficients.

The flowchart of the formulation procedure of an empirical pavement performance prediction is presented in Figure 6-3.

To develop empirical models, the collected condition data are separated into four groups, each representing a different climatic zone (wet freeze, wet non-freeze, dry freeze and dry non-freeze), to embed climatic effects into the prediction model. Then, each group is divided into two subgroups to consider the road's functional class (arterial and collector). The five independent variables, cracking area, length of crack, pavement age, cumulative equivalent single axle load (ESAL), and maintenance effect (inlay or overlay thickness), are used to develop network-level empirical deterioration models for each road class. Table 6-1 shows the number of sections and number of data samples used in the study. The number of sections in the LTTP database for collector roads was significantly lower than for arterial roads, which may affect the accuracy of the model. It is also noted that the model was verified by predicting separate data sets, which were not included in the model's development. The parameters data of deterioration model for each climatic region and functional class are presented in Appendix C, Appendix D, Appendix E, Appendix F, Appendix G, Appendix H, Appendix I.

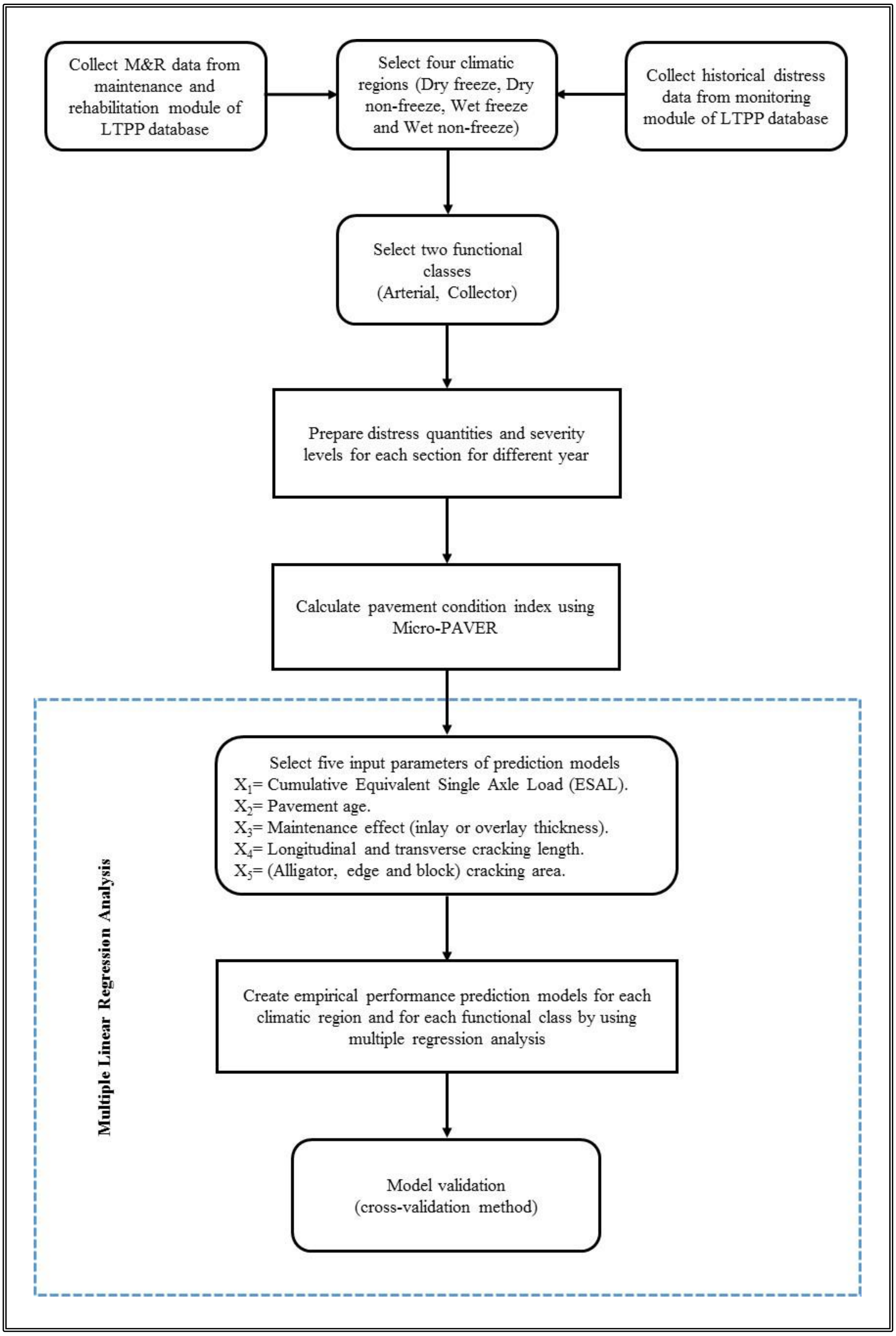

Figure 6-3: Flowchart for a Multi-Input Deterioration Prediction Model (MID-PM).

Table 6-1: A summary of pavement condition data samples.

Climatic Zone	**Road Class**	**Number of Sections**	**Number of Data Samples**
Wet freeze	Arterial	13	224
	Collector	3	38
Wet non freeze	Arterial	8	91
	Collector	3	32
Dry freeze	Arterial	22	314
	Collector	2	25
Dry non freeze	Arterial	8	111

6.5 The Results of Pavement Performance Prediction

6.5.1 Empirical Models

Seven network-level deterioration prediction models for flexible pavement were created by using a multiple regression analysis technique using the statistical software SPSS (Field, 2009). The models and their corresponding coefficients of correlation (R^2) are shown in Table 6-2. It can be seen that with the exception of "Wet Freeze Arterial" and "Dry Non-Freeze Arterial", the models have very good accuracy, with R^2 values greater than 70%. Despite the relatively poor correlation compared to other models, the R^2 values for "Wet Non-Freeze Arterial" and "Dry Freeze Arterial" were still 52 and 62% respectively. These results indicate a good correlation for a network-level prediction model.

Furthermore, as in Table 6-2, the results show that empirical models for collector roads have a better correlation than models for arterial roads. This is likely to be because the characteristics of arterial roads are different from collector roads. Arterial roads carry heavier traffic, thus their pavement design and construction is different from that of collector roads, and the deterioration behaviour is also consequently different; for these reasons arterial road deterioration appears to be nonlinear. Further research work is required to study the characteristic variations between arterial and collector roads.

Table 6-2: Empirical pavement performance prediction models for each subgroup.

Climatic Zone	Road Class	Prediction Model	R^2
Wet Freeze	Arterial	$PCI = 97.744 - 0.15\ X_5 - 0.064\ X_4 - 0.515\ X_2 + 3.748\ X_3$	0.70
	Collector	$PCI = 100.257 - 3.45\ X_2 - 0.168\ X_5 - 0.04\ X_4 + 0.814\ X_3 + 0.062\ X_1$	0.88
Wet non freeze	Arterial	$PCI = 93.546 - 0.175\ X_2 - 0.083\ X_5 - 0.038\ X_4 + 1.073\ X_3$	0.52
	Collector	$PCI = 104.336 - 0.15X_5 - 1.122\ X_2 - 0.194\ X_4$	0.95
Dry Freeze	Arterial	$PCI = 97.252 - 0.245\ X_5 - 0.074\ X_4 - 0.359\ X_2 + 2.967X_3$	0.62
	Collector	$PCI = 94 - 0.628\ X_2 + 0.072\ X_5 - 0.055\ X_4 + 23.603\ X_3 - 0.013\ X_1$	0.7
Dry non freeze	Arterial	$PCI = 98.861 - 0.407\ X_2 - 0.235\ X_5 - 0.065\ X_4 + 3.404\ X_3 - 0.003\ X_1$	0.79

6.5.2 Cross Validation

The cross-validation technique is used either to assess how well models can predict PCI or to assess the model's accuracy across various data samples. 80% of the data samples for each subgroup (as shown before in Table 6-1) are randomly selected to create deterioration models. The remaining 20% of the data samples are used to evaluate the accuracy of empirical models.

As shown in Table 6-3, after validation, the reduction in R^2 value and mean square error (MSE) value for arterial roads in the four climatic zones is not significant; accuracy reduction is less than 20% in R^2 value and 35% in MSE value. This means that the deterioration models for arterial roads have the ability to predict PCI accurately. However, the loss in R^2 value and MSE value for collector roads is significant, especially in the dry freeze and wet freeze zones, though it is insignificant in the wet non freeze zone. The Figure 6-4, Figure 6-5, Figure 6-6, Figure 6-7, Figure 6-8,

Figure 6-9, and Figure 6-10 show the errors and linear relation in each subgroup. These show that empirical models for both the dry freeze zone and the wet freeze zone have not good level of accuracy.

Table 6-3: Validation results of empirical deterioration models for each subgroup.

Climatic zone	Road class	Linear regression		Cross-validation	
		R^2	MSE	R^2	MSE
Wet freeze	Arterial	0.69	205.9	0.59	252.2
	Collector	0.88	85.1	0.31	258.7
Wet non freeze	Arterial	0.52	181.5	0.45	178.5
	Collector	0.95	38.2	0.82	71.2
Dry freeze	Arterial	0.62	182.1	0.74	134.
	Collector	0.7	133.7	0.35	617.4
Dry non freeze	Arterial	0.79	86.6	0.64	136.2

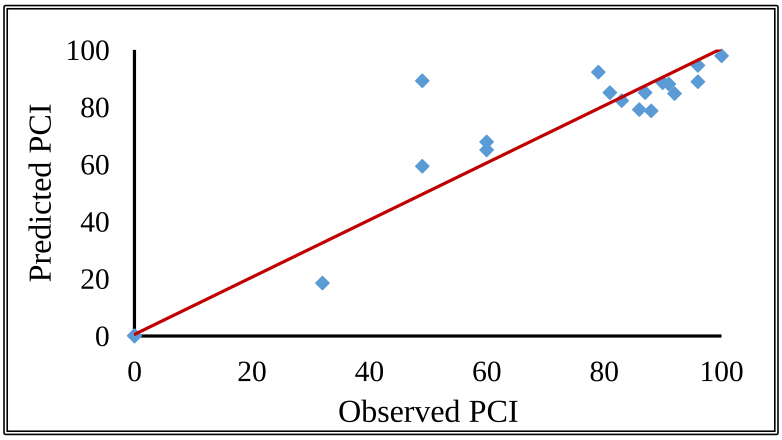

Figure 6-4: Accuracy of the empirical deterioration model for wet freeze - arterial.

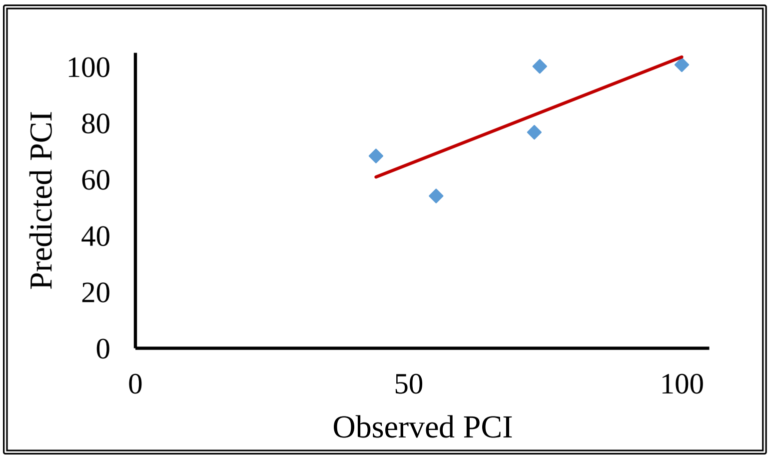

Figure 6-5: Accuracy of the empirical deterioration model for wet freeze - collector.

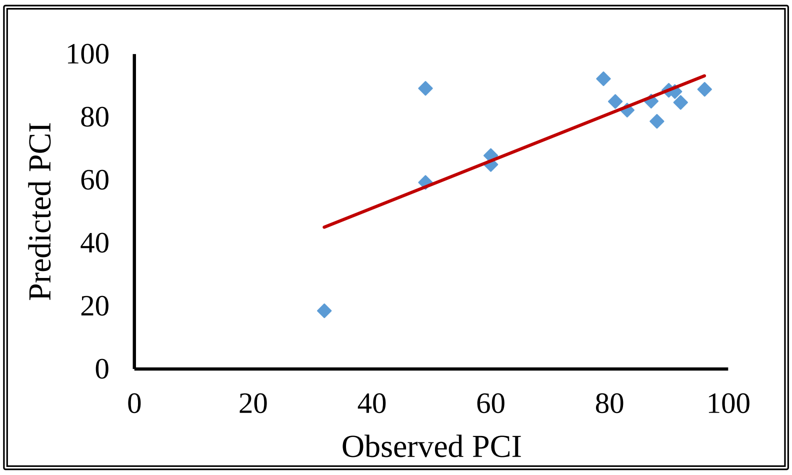

Figure 6-6: Accuracy of the empirical deterioration model for wet non freeze - arterial.

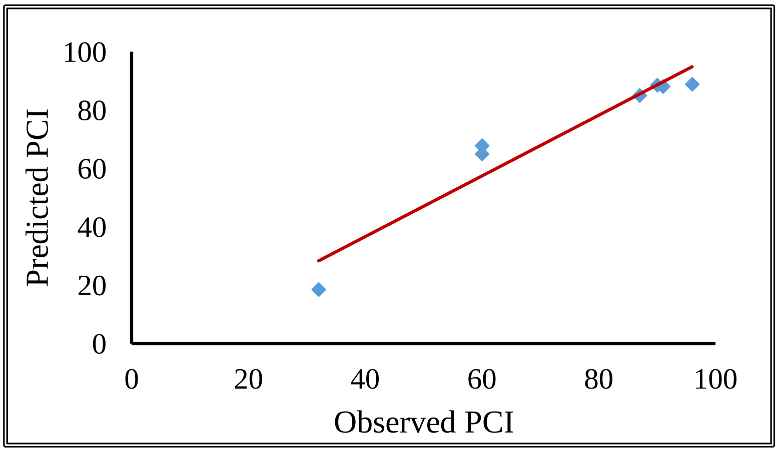

Figure 6-7: Accuracy of the empirical deterioration model for wet non freeze - collector.

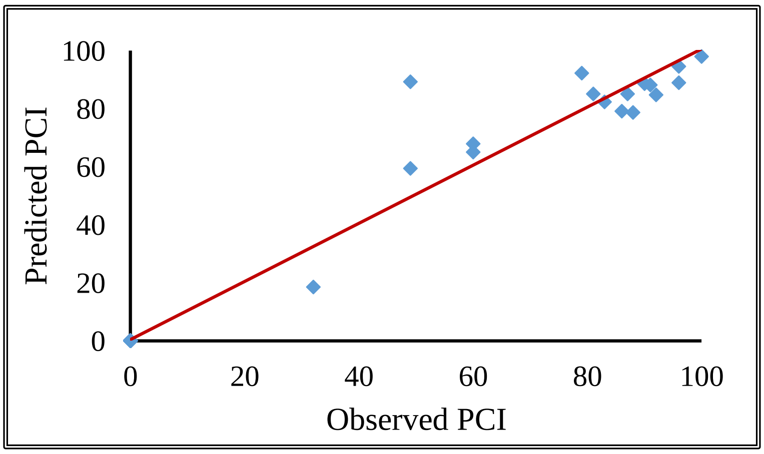

Figure 6-8: Accuracy of the empirical deterioration model for dry freeze - arterial.

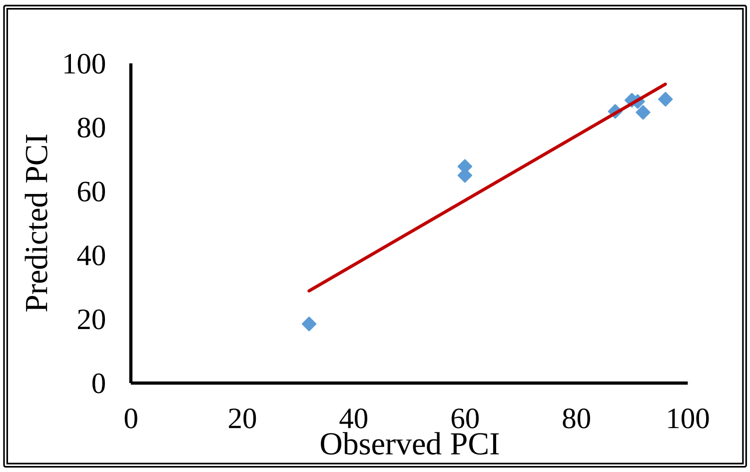

Figure 6-9: Accuracy of the empirical deterioration model for dry freeze - collector.

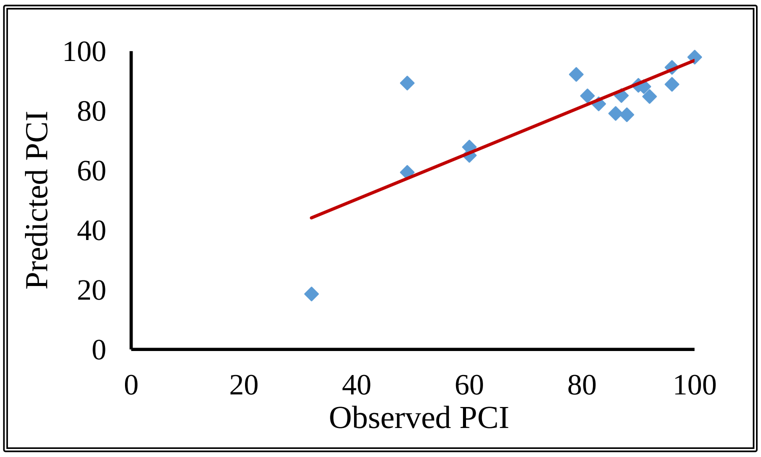

Figure 6-10: Accuracy of the empirical deterioration model for dry non freeze - arterial.

6.5.3 Statistical Test

To check the significance of estimates of each parameter (a_1,… a_i) as in equation 6-2, the F-test and t-test were used. Generally, in the multiple-regression model, the null hypothesis was applied: H0: $a_i = 0$, HA: $a_i \neq 0$. When the empirical models were created by using a multiple regression analysis technique using the statistical analysis software SPSS, the t-test and the F-test were calculated at the same time. The t-test for each independent parameter and the F-test for the overall linear model were estimated as shown in Table 6-4. The results of the F-test and t-test with probability level α =

0.05 show that the null is rejected in all empirical models. Therefore, the independent variables ($X_1, \ldots X_i$) have an influence on the dependent variable Y. However, the test also shows that the traffic parameter does not have an effect on PCI in the majority of the models.

Table 6-4: The results of the t-test and F-test.

Climatic zone	Road class	*t-test*						*F-test*
		Constant	X_1	X_2	X_3	X_4	X_5	
Wet freeze	Arterial	38.428	0	-3.91	2.676	-9.948	-12.868	94.811
	Collector	25.496	4.617	-4.737	0.518	-5.141	-3.792	40.482
Wet non freeze	Arterial	29.281	-0.542	-0.822	1.237	-4.965	-5.627	15.122
	Collector	46.123	0	-5.676	0	-3.941	-15.463	120.065
Dry freeze	Arterial	52.999	0	-3.409	2.176	-10.143	-11.156	96.204
	Collector	13.118	-0.302	-0.463	1.717	-1.91	0.551	5.125
Dry non freeze	Arterial	49.51	1.809	-2.379	1.229	-6.936	-12.975	66.827

6.5.4 Sensitivity Analysis

A sensitivity analysis was conducted to study the influence of input variables on the efficiency of empirical prediction models in the calculation of PCI. The sensitivity analysis was conducted by generating the empirical models by considering the effect of individual input and by neglecting the effects of other inputs. The results of the sensitivity analysis are shown in Table 6-5. It can be seen that the cracking area and cracking length are the most significant factors in the prediction model's performance. The pavement's age and maintenance also have an influence to some extent, while the cumulative ESAL has only a minor effect on the model's performance.

Table 6-5: Sensitivity analysis of input variables on prediction.

Climatic zone	Road class	R^2(%)				
		Pavement Age	Cracking Area	Cracking Length	Maintenance Effect	Cum. ESAL
Wet freeze	Arterial	11	40	30	6	0
	Collector	23	50	40	7	0
Wet non freeze	Arterial	9	25	25	4	0
	Collector	20	71	19	0	0
Dry freeze	Arterial	13	40	33	3	0
	Collector	17	14	82	13	16
Dry non freeze	Arterial	12	39	41	2	0.1

6.6 Summary

This chapter described different types of performance prediction models and presented contributory factors on pavement deterioration, such as pavement construction and material, age, traffic, maintenance effect and environmental conditions. For developing empirical models, ESAL, age, rehabilitation thickness, cracking area, and length were considered as independent variables to find future PCI. For each climatic region, by using linear regression analysis, the two empirical models were crated for arterial and collector roads. It was found the models of collector roads have better correlation than the models of arterial roads. The next chapter describes the final stage of PMS, which is multi-objective pavement maintenance actions decision optimisation.

Chapter 7

Multi-Objective Pavement Maintenance Decision Optimisation

7.1 Introduction

The next stage after the condition evaluation for all pavement sections in the highway network is the selection of maintenance, rehabilitation, and reconstruction options, and analysis of the associated costs for all nominated sections in need of treatment. The selection of the most appropriate treatment options for nominated sections at planned times requires consideration of several factors that can significantly affect the performance of these pavement sections and long-term costs. The appropriate treatment options are generated by the application of knowledge-based decision making methods. The knowledge of treatment selection is represented by heuristic methods, which consider al1 other treatment policies in order to meet the requirements for repairing the deteriorated pavements in a network (Fwa, 2006; Li, 1997). This chapter presents key parameters needed for multi-objective pavement maintenance, and then describes the development and analysis of a novel pavement maintenance optimisation using PSO technique.

7.2 Multi-Objective Pavement Maintenance Optimisation

Optimisation models of pavement management systems (PMS) at the network level attempt to optimise some objectives, subject to a number of constraints or resource restrictions. A single objective such as agency cost, user cost, or network performance is optimised. The constraints regularly represent resource limitations of the highway agency, threshold conditions of a network, etc. Commonly, the nature of optimisation problems are combinatorial and the decision variables are discrete.

The satisfaction of single-objective optimisation systems is seldom acceptable just because the decision maker is satisfied with optimising a single objective. Often there are many objectives needing to be optimised, and these various objectives could have considerable influence on the optimisation solutions (Mbwana, 2001).

7.2.1 Optimisation Problem Parameters

The M&R analysis procedure depends on the following data and decision criteria: current state of the pavement based on distresses, minimum acceptable serviceability level, treatment cost and budget, and analysis period. For determining the treatment needs, the highway network is divided into a number of pavement segments of same length (Fwa et al., 1996; Haas et al., 1994).

Agency cost of highway asset are the interventions which are necessary to construct and invest a highway network. It consists of highway maintenance, rehabilitation and reconstruction cost. Rehabilitation is necessary for the highway asset at least one time over its lifetime to keep it above the minimum acceptable serviceability and safety level. The cost of any particular rehabilitation activity, which is a form of construction, comes from: materials, preliminary engineering, and construction management (Chen, 2007). If a rehabilitation action is to be applied in subsequent years, then the costs of it can be discounted to present worth in the following manner:

$$\text{Present cost} = \text{Future cost} \times \text{PWF} \qquad 7\text{-}1$$

Where, PWF is the present worth factor, given by:

$$\text{PWF} = \frac{1}{(1+R)^t} \qquad 7\text{-}2$$

The typical range of discount rates R recommended by FHWA is 3 to 5% (FHWA, 1998), t = time at which the money is spent (years).

Depending on the situation, highway agencies have the option to choose a rehabilitation action from a list of activities. One such list, which is also used in this work, is given in Table 7-1. It is also essential to specify the warning level for each treatment action. A warning level is defined as the minimum level of pavement performance, such that the treatment must be applied when the pavement reaches it. The total span of the analysis period is commonly specified by the highway authority concerned. Furthermore, the unit study period, which might be a week, a month, or a year, is selected depending on the requirements of the highway authority (Fwa et al., 1996).

Table 7-1: The rehabilitation strategies

No.	Treatment action
1	Do nothing
2	AC* overlay 1in (25mm)
3	AC overlay 2in (50mm)
4	AC overlay 4in (100mm)
5	AC overlay 6in (150mm)

* Asphalt Concrete

7.2.2 Objectives Functions

The common objectives of pavement maintenance systems as identified by road authorities comprise the following: to minimise the present worth of overall treatment costs over the analysis period; to minimise user costs by choosing and scheduling treatment actions to decrease delays and disruptions to traffic; and to keep the serviceability of the pavement network over the minimum acceptable level with the resources available. Commonly, two or more of these objectives are combined by allocating a proper weighting factor to each (Fwa et al., 1996).

The main challenge in pavement management is the selection of maintenance investment alternatives for a large number of pavement sections over multiple time periods (Javed, 2011). To reach the optimal maintenance investment decisions, it is important to optimise the M&R decision considering multiple objectives such as minimum cost and maximum performance, etc. Therefore, multi-objective programming of pavement management activities is developed using the particle swarm optimisation technique.

The multi-objective programming of pavement management can be presented mathematically as the following:

Minimise the total pavement maintenance cost

$$f_1(x) = \sum_{t=1}^{T} \sum_{p=1}^{N} \sum_{m=1}^{M} x_{m,p,t}\, C_m\, L_p\, W_p\, (1+R)^{-t} \qquad 7\text{-}3$$

And minimise the sum of all residual PCI values

$$f_2(x) = \sum_{t=1}^{T} \sum_{p=1}^{N} \sum_{m=1}^{M} x_{m,p,t} \left[\left(\mathrm{PCI}_{max} - \mathrm{PCI}_{p,t} \right) L_i\, W_p\, \mathrm{AADT}_{p,t} \right] \qquad 7\text{-}4$$

Where, $x_{m,p,t} = \begin{bmatrix} 1 & \text{if treatment } m \text{ for section } p \text{ at time } t \text{ is selected} \\ 0 & \text{otherwise} \end{bmatrix}$

In the equations above, m is the treatment type; M stands for the total number of treatment types; p is the pavement section number under consideration; N is the total number of pavement sections; t is any time in the analysis period, and T is the total analysis period (both are usually specified in years); C_m is the unit cost of treatment type m; L_p is the length of pavement section p; W_p stands for the width of section p; R is the discount rate; $\text{PCI}_{p,t}$ = PCI for section p at time t; PCI_{max} is the maximum PCI level (100 %); $\text{AADT}_{p,t}$ is the annual average daily traffic for section p at time t.

In this work, the following acceptable level for section performance is chosen: $\text{PCI}_{p,t} \geq 65$ %.

7.2.3 Pavement Deterioration Model

A PMS must predict the performance of a pavement network for the subsequent years in order to evaluate the outcome of a given set of maintenance decisions, thereby enabling it to optimise the maintenance decision. A pavement deterioration model is an essential component when determining treatment needs, and when estimating highway user costs and benefits of the treatment application (Shahin, 2005). In general, deterioration models are established in terms of a pavement condition indicator and the exogenous influences contributing to pavement deterioration (Herabat and Tangphaisankun, 2005). Various researchers have developed network-level deterministic deterioration prediction models for flexible pavement, to predict pavement deterioration by considering distress, pavement age, traffic loading, and maintenance effects. Here, a deterministic deterioration model, as developed in chapter

6 for arterial highways in the wet freeze climatic region, has been designed to estimate future pavement condition:

$$PCI = 97.744 - 0.15\, X_5 - 0.064\, X_4 - 0.515\, X_2 + 3.748\, X_3 \qquad 7\text{-}5$$

Where PCI is the pavement condition index; X_1 is the cumulative equivalent single axle load (ESAL); X_2 is the pavement age; X_3 is the maintenance effect (inlay and overlay thickness, in inches); X_4 is the total longitudinal and transverse cracking length, in inches; X_5 is the cracking area (alligator, edge, and block), in square inches.

7.3 Particle Swarm Optimisation

The background information of particle swarm optimisation (PSO) is given in chapter 3. As mentioned before, PSO is a simulation of the social behaviour of birds or fish within their flock or school, and was developed by Kennedy and Eberhart in 1995. The swarm of PSO comprises a set of particles, each particle representing a possible solution of an optimisation problem. Each particle moves in the search space, and this movement is achieved by the operator that is directed by a local element and by social elements. Each solution or particle is assumed to have a position and a velocity. The position of the *i*th particle is denoted at iteration *z* by $X_i(z) = \{X_{i,1}(z), X_{i,2}(z), \ldots, X_{i,n}(z)\}$ and velocity by $V_i(z) = \{ V_{i,1}(z), V_{i,2}(z), \ldots, V_{i,n}(z)\}$. Here, n is the dimension of the search space, where $n = N \times T$. Then, each particle i updates the position and velocity of its *j*th dimension at iteration $z + 1$ by using the following equations (de Carvalho and Pozo, 2012; Rao, 2009):

$$V_{i,j}(z+1) = w\, V_{i,j}(z) + r_1\, c_1 \left[Pbest_{i,j}(z) - X_{i,j}(z)\right] + r_2\, c_2 \left[Gbest(z) - X_{i,j}(z)\right] \qquad 7\text{-}6$$

$$X_{i,j}(z+1) = X_{i,j}(z) + V_{i,j}(z+1) \qquad 7\text{-}7$$

where $Pbest_{i,j}(z)$ is the local or personal best position for the jth dimension of particle i at iteration z; $Gbest(z)$ is the global best position or particle leader at iteration z; w is the inertia weight of the particle; c_1 and c_2 are acceleration coefficients that are positive constants; r_1 and r_2 are random numbers in [0,1].

In the velocity update equation, the leader particle *Gbest* in each generation guides the particles to move towards the optimal positions. In each generation, the particle memory is updated. For each particle in the swarm, performance is estimated according to the fitness function or objective function of the optimisation problem. The inertia weight *w* is used to regulate the effect of the previous velocities on the current velocity, and hence to effect a trade-off between the global and local exploration abilities of the particles (de Carvalho and Pozo, 2012).

7.3.1 Multi-Objective Optimisation Problems

Multi-objective optimisation problems consider the simultaneous satisfaction of two or more objective functions. Furthermore, the objectives of optimisation problems are usually conflicting objectives, which means there is no single optimal solution. Therefore, it is necessary to find a decent trade-off of solutions that represent a compromise between the objectives. In multi-objective particle swarm optimisation (MOPSO) problems, the main challenge is to determine the best global particle "leader" at each generation. In a single-objective problem, the leader particle is found easily by choosing the particle that has the best position. For multi-objective problems there is a set of non-dominated solutions called "Pareto-optimal solutions", which is the set of best solutions (de Carvalho and Pozo, 2012).

The feasible solutions of a multi-objective optimisation problem are Pareto-optimal solutions if there are no other feasible solutions that can yield progress in one objective without damaging at least one other objective (Osyczka, 1978). The Pareto optimality is named after Vilfredo Pareto. The definition of Pareto optimality is that "A decision vector, $\mathbf{x}^* \in \mathcal{F}$, is Pareto-optimal if there does not exist a decision vector, $\mathbf{x} \neq \mathbf{x}^* \in \mathcal{F}$ that dominates it. That is, $\nexists k : f_k(\mathbf{x}) < f_k(\mathbf{x}^*)$. An objective vector, $\mathbf{f}^*(\mathbf{x})$, is Pareto optimal if $\mathbf{x}$ is Pareto optimal" (Engelbrecht, 2007). For a set of objective functions $\{f_1, f_2, \ldots, f_K\}$, the condition that a feasible solution $\mathbf{x}^*$ dominates another feasible solution $\mathbf{x}$, then it is denoted by $\vec{F}(\mathbf{x}^*) \prec \vec{F}(\mathbf{x})$.

7.3.2 Discrete (Binary) Particle Swarm Optimisation

The most common optimisation problems have either discrete or qualitative distinctions between variables. In the discrete PSO, the solutions can be assumed to be one of the several discrete values. The most common example of a discrete PSO is binary optimisation, where all solutions will be 0 or 1. Fundamentally, the continuous domain PSO is different from a discrete PSO in two ways. Firstly, the particle coordinate is composed of binary values. Secondly, the velocity must be transformed into a probability change, that is, the chance of the binary variable taking the value of 1 (Liao et al., 2007; Pugh and Martinoli, 2006).

The algorithm of PSO for continuous optimisation problems was modified for solving discrete (binary) optimisation problems by changing the position equation to a new one. The following is an equation for the modified algorithm (Kennedy and Eberhart, 1997; Liao et al., 2007; Pugh and Martinoli, 2006):

$$X_{i,j} = \begin{cases} 1 & \text{if } rand() < S(V_{i,j}) \\ 0 & \text{otherwise} \end{cases} \qquad \text{7-8}$$

Where $rand()$ is a quasi-random number chosen from the continuous uniform distribution in the interval [0, 1], i.e. $U[0, 1]$, and $S(V_{i,j})$ is the sigmoid function given by

$$S(V_{i,j}) = \frac{1}{1+e^{-X_{i,j}}} \qquad \text{7-9}$$

7.3.3 Barebones Particle Swarm Optimisation (BBPSO)

The behaviour of a particle is such that it converges to a weighted average between its local best position and the global best position. This behaviour induced Kennedy to modify the original algorithm by replacing the equation of the particle velocity with a Gaussian sampling based on $Pbest_i(z)$ and $Gbest(z)$, resulting in BBPSO. The velocity equation of the original algorithm is replaced by (Engelbrecht, 2007; Zhang et al., 2012):

$$X_{i,j}(z+1) = N\left(\frac{Pbest_{i,j}(z)+Gbest(z)}{2}, \left|Pbest_{i,j}(z) - Gbest(z)\right|\right) \qquad \text{7-10}$$

Based on this equation, the particle position is randomly chosen from the Gaussian distribution with the mean of the local best position and the global best position. In addition, Kennedy developed another version of the BBPSO, symbolised by BBExp, by modifying the equation thus (Zhang et al., 2012):

$$X_{i,j}(z+1) = \begin{cases} N\left(\frac{Pbest_{i,j}(z)+Gbest(z)}{2}, \left|Pbest_{i,j}(z) - Gbest(z)\right|\right) & \text{if } U(0,1) < 0.5, \\ Pbest_{i,j}(z) & \text{otherwise} \end{cases} \qquad \text{7-11}$$

As there is a probability of 50% that the j^{th} dimension of a particle changes to the corresponding local best position, the new version of the algorithm tends to search for local best positions. The main features of BBPSO are that it is parameter-free and appropriate for application to real problems where the information on inertia weights and acceleration coefficients of particles is insufficient or difficult to obtain. In addition, it is easy to implement and performs well when dealing with multi-objective optimisation problems (Zhang et al., 2012).

7.4 Discrete Barebones Multi-Objective Particle Swarm Optimisation (DBB-MOPSO)

In this section a discrete version of the BBPSO, called discrete multi-objective PSO (DBB-MOPSO), is proposed for multi-objective optimisation problems. The process flow of the DBB-MOPSO algorithm is shown in Figure 7-1 and process stages are described in the following sections.

7.4.1 Initialisation

7.4.1.1 Particle Positions

The first step in the initialisation stage of DBB-MOPSO is randomly generating the swarm with a predefined size. For each particle, values are assigned for each dimension randomly from a predefined set of values, as explained in detail below (Zhang et al., 2012).

One of the main steps in designing an effective particle swarm optimisation algorithm is the correct representation of particle positions for finding a proper mapping between the problem solution and the particle. There are two forms of representation, namely direct and indirect representations (Izakian et al., 2010). In this research, a combination of direct and indirect representation is adopted. A problem solution (position) in direct representation is encoded in a one dimensional string of size n, where $n = N \times T$. Every element of the string is a number chosen randomly from the set $\{1, 2, 3, \ldots, M\}$, where for the problem at hand, *M* is the number of pavement maintenance actions. For the current problem, the structure of direct encoding is shown in Figure 7-2:

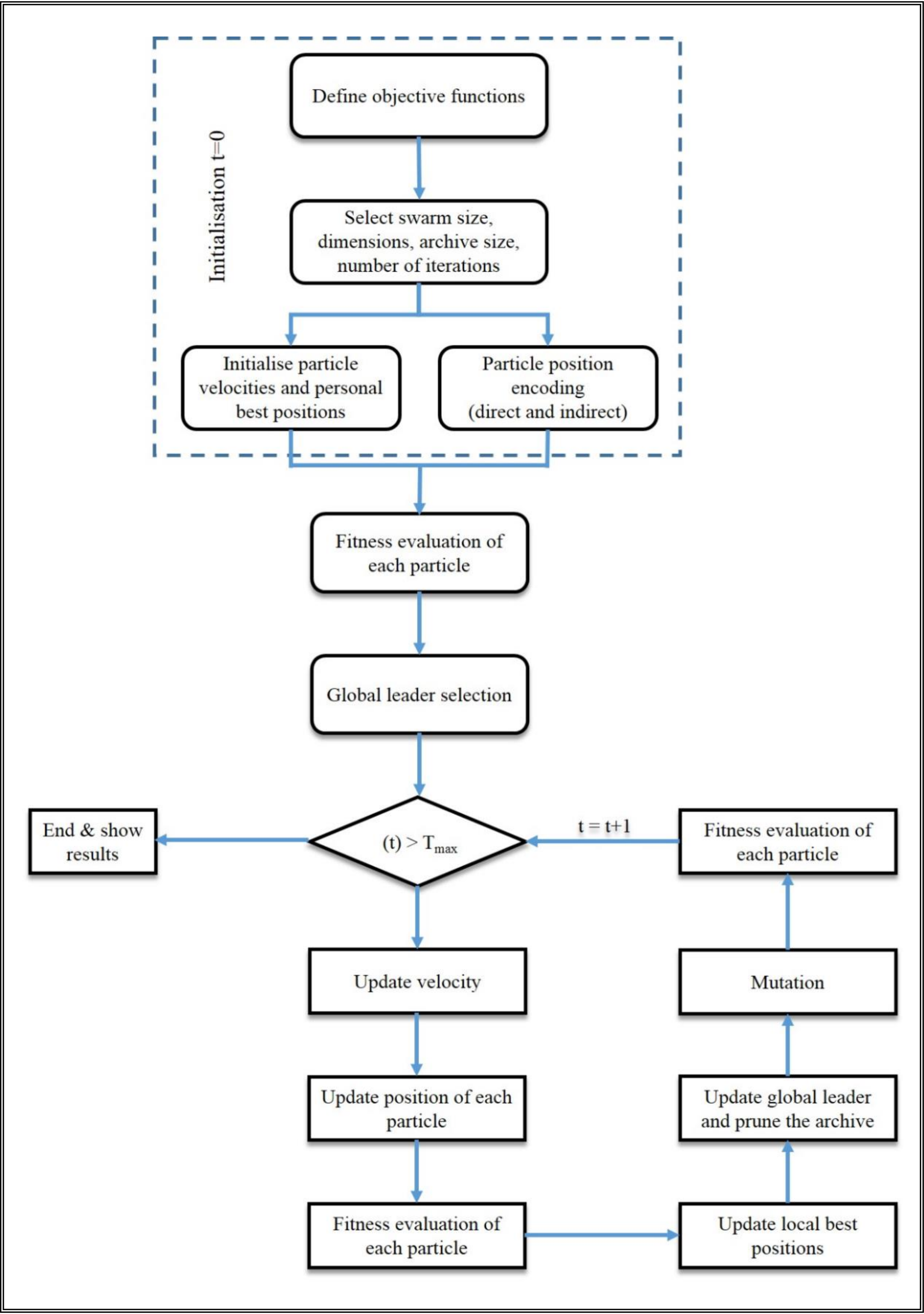

Figure 7-1: Flow chart of the binary barebones particle swarm optimisation algorithm.

Dimension →

Particle i	4	1	5	2	4	3	-----	1	5	2

Figure 7-2: Direct representation (encoding).

In indirect encoding, solutions for each particle are encoded in a position matrix, $n \times M$. In the position matrix, the values of the matrix elements for each particle are binary values, 0 or 1. Moreover, in each column the value of most of the elements is 0; just one element, corresponding to the maintenance action, is 1. For the direct representation in Figure 2, the indirect encoding is shown in Figure 7-3:

Maintenance action 1	0	1	0	0	0	0	-----	0	0	0
Maintenance action 2	0	0	0	1	0	0	-----	0	0	1
Maintenance action 3	0	0	0	0	0	1	-----	0	0	0
Maintenance action 4	1	0	0	0	1	0	-----	0	0	0
Maintenance action 5	0	0	1	0	0	0	-----	1	1	0

Figure 7-3: Indirect representation (encoding) for particle i.

7.4.1.2 Particle Velocity, Local (Personal) Best Position

Indirect encoding is used to initialise the velocity of each particle. The $n \times M$ matrix is generated and all elements of the matrix are assumed to be 0. The initial personal best position of each particle is assumed to be equal to the initial position of the particle, $Pbest_{i,j}(0) = X_{i,j}(0)$, where $X_{i,j}(0)$ is the initial position of the j^{th} dimension of the i^{th} particle and in the swarm. To save the non-dominated solutions found across all iterations, the archive, or memory, is initialised from the initial swarm.

7.4.2 Updating the Local (Personal) Best Positions

The local best position for particle i, $Pbest_i(z)$, is the best position reached by the particle itself to date. The local best position is updated at each iteration according to the equation (12). If the fitness value of the previous $Pbest_i(z)$ is smaller than the fitness value of the current position $X_i(z+1)$, the current $Pbest_i(z)$ will not be replaced. Otherwise, it will be replaced by the current position $X_i(z+1)$ (Zhang et al., 2012).

$$Pbest_i(z+1) = \begin{cases} Pbest_i(z), & if \ \vec{F}(Pbest_i(z)) \prec \vec{F}(X_i(z+1)) \\ X_i(z+1), & otherwise \end{cases} \quad \text{7-12}$$

Where $i = 1, 2, \ldots, I$, and I is the total number of particles in the swarm (i.e. the swarm's size).

7.4.3 Updating the Global Best Positions

The leader particle or global best position $Gbest(z)$ is the best solution found from the swarm of particle neighbours so far. For single-objective optimisation problems it is found in a straightforward manner. Conversely, in multi-objective optimisation problems, the multiple conflicting objectives make it challenging to select a leader solution. To overcome this problem, DBB-MOPSO maintains a memory (archive) with a sufficient capacity to store the non-dominated (Pareto) solutions, as proposed by (Engelbrecht, 2007; Zhang et al., 2012).

To find the leader particle, the Sigma method is used here. This method was developed by (Mostaghim and Teich, 2003). In this method, a value σ_i is assigned to each solution with coordinates $(f_{1,i}, f_{2,i})$, and thus all the solutions that are on the line

$(f_1 = \sigma f_2)$ have the same σ value. The sigma value (σ) can be determined for two objectives as follows:

$$\sigma = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \qquad 7\text{-}13$$

For more than two objective functions, Mostaghim and Teich [2003] provide the formulae for the estimation of σ. The leader particle $Gbest(z)$ among the archive members of each generation is selected as follows. Firstly, the sigma value σ is assigned to each non-dominated solution e in the archive. Secondly, the sigma value is determined for particle a of the current generation. Then, the distance between them (σ_e , σ_a) is calculated. Finally, solution g in the archive that has the lowest distance to solution a is chosen as the global best position or leader particle. Therefore, each solution which has a closer sigma value to the sigma value of a non-dominated solution must choose that non-dominated solution as the leader solution (Mostaghim and Teich, 2003).

7.4.4 Updating the Particle Velocities and Positions

To handle the multi-objective optimisation problem, a new version of BBExp, namely BBVar, has been proposed to update a particle's position by (Zhang et al., 2012), and it works as shown below:

$$X_{i,j}(z+1) = \begin{cases} N\left(\frac{r_3\, Pbest_{i,j}(z) + (1-r_3)\, Gbest(z)}{2}, \left|Pbest_{i,j}(z) - Gbest(z)\right|\right), & \text{if } U(0,1) < 0.5, \\ Gbest(z), & \text{otherwise} \end{cases} \qquad 7\text{-}14$$

Where, r_3 is a random number chosen from $U[0, 1]$. This formulation avoids the use of particle velocities used in the regular PSO algorithm.

For discrete problems the definition in equation (7.14) is of not much use as the resulting positions, for each dimension of a particle, will have to be either 0 or 1. In this work, the velocity term is reintroduced for the discrete barebones algorithm. However, rather than using the parameters as defined in equation (7.6), it is proposed to make use of equation (7.14), where the difference between the current particle position and the estimated position in the next iteration, by using equation (7.14), is defined as the equivalent velocity of the particle. Hence, it is proposed here to make the change in the following manner to update a particle's velocity, to deal with discrete multi-objective problems: In this research, to deal with DBB-MOPSO problems, the BBVar algorithm is modified to update a particle's velocity:

$$V_{i,j}(z+1) = \begin{cases} N\left(\frac{Pbest_{i,j}(z)+Gbest(z)}{2}, \left|Pbest_{i,j}(z) - Gbest(z)\right|\right) - X_{i,j}(z), & if\ U(0,1) < 0.5 \\ Gbest(z) - X_{i,j}(z), & otherwise \end{cases}$$

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After (Izakian et al., 2010), the particle's position is proposed to be updated as follows:

$$X_{i,j}(z+1) = \begin{cases} 1 & if\ V_{i,j}(z+1) = max\{V_{i,j}(z+1)\},\ \forall j \in \{1, 2, \ldots, n\} \\ 0 & otherwise \end{cases} \quad 7\text{-}16$$

For particle *i*, the values of most elements in each column *j* of the position matrix are 0, and only the element that has the maximum velocity is assigned 1. If, in a given column, there is more than one element with the maximum velocity value, then one of these elements is assigned 1 randomly (Izakian et al., 2010). The same method is used by the DBB_MOPSO algorithm presented here.

7.4.5 Mutation Operator

The main feature of PSO is the fast speed of convergence. However, in multi-objective optimisation, the PSO algorithm could converge to non-optimal solutions. To prevent a premature convergence to non-optimal solutions in the MOPSO, a mutation operator is used to control convergence speed. In addition, it allows the MOPSO algorithm to expand the search capability, thus gaining better diversity. At the beginning of the generation process, all particles of the swarm are affected by the mutation operator with the full range of decision variables, with the influence of the mutation operator declining as the iteration number increases (Zhang et al., 2012). The procedure of mutation operation is given by the following pseudo-code:

FUNCTION MUTATION: Out = MUTATE (X, Z) //X = any particle in the swarm; Z = max. no. of iterations//

```
FOR i = 1 TO I                        // For all the particles //
    IF e^((−8*z)/Z) > r_4             // r_4 is a random number chosen from U[0,1] //
        FOR j = 1 TO n                // Do it for all the dimensions //
        Position X_{i,j} == 1         // j number chosen randomly from the set
                                         {1,2,3,….,M} randomly //
        END FOR
    END IF
End FOR                               // Return the swarm after mutation //
```

7.4.6 External Archive Pruning

In multi-objective optimisation algorithms, it is necessary to retain the non-dominated solutions generated across all iterations of the search. In each generation, all new non-dominated solutions are stored in the external archive, while all solutions which became dominated are eliminated. It is common to adopt an external archive with limited capacity characteristics (Silva and Bastos-filho, 2013; Zhang et al., 2012). To avoid reaching the maximal capacity of the external archive, crowding distance is used to eliminate some solutions without a negative effect on its distribution. When the archive capacity has reached the maximum limit, the solutions that have the largest crowding distance values are retained in the archive (Zhang et al., 2012). The following pseudo-code is the pruning archive procedure.

FUNCTION PRUNING ARCHIVE: Opt = PRUNE_ARCHIVE (*C*, *Xc*, *arch_cap*)
// *C*: fitness values of non-dominated solutions; *Xc*: non-dominated solutions; *arch_cap*: maximum capacity of the archive; *B*: the number of the non-dominated solutions //

```
CDA = zeros(B)                 //CDA: crowding distance; initialise as a 2D matrix//
FOR k = 1 TO K                 // K: number of objectives//
    C_k = C(k)                 //consider the fitness value for the kth objective//
    [C_k_sort, sorted_indices] = sort(C_k)  //sort the kth objective in ascending order and get
                                              the sorted particle indices//
    CDA(sorted_indices_first,k) = 10000     // particle corresponding to the largest objective
                                              function is given a large crowding distance
    CDA(sorted_indices_final,k) = 10000     // particle corresponding to the smallest objective
                                              function is also given a large crowding distance
    FOR b = 2 to (B-1)     // the 1st and the last ones are excluded//
        CDA(sorted_indices(b)) = CDA(sorted_indices(b))
                    +(C_k_sort(b+1) – C_k_sort(b-1))/(C_k_sort(1) –
                                                       C_k_sort(end))
                    //crowding distance calculation - normalized//
    END FOR
END FOR
[CDA, particle_indices_sorted] = sort (CDA)     // Sort in descending order using each objective
                                                   value//
particle_indices_pruned = particle_indices_sorted(1: arch_cap)   // Retain the first (number of
                                                   solutions = maximum capacity
                                                   of archive) with the largest
                                                   crowding distance values in the
                                                   archive//
Out ← particle_indices_pruned       // output the Pareto (non-dominated) optimal solutions //
```

7.4.7 Compromise Solution

To avoid the subjective judgment of decision makers, a fuzzy set function is employed to mimic the agency preferences and to find the compromise solution from the non-dominated solutions in the archive. Therefore, at the final generation of algorithm, the compromise solution is identified from the equation (17) (Zhang et al., 2012):

$$\mu_k^i = \begin{cases} 1, & F_k(X_i) \le F_k^{min} \\ \frac{F_k^{max} - F_k(X_i)}{F_k^{max} - F_k^{min}}, & F_k^{min} < F_k(X_i) < F_k^{max} \\ 0, & F_k(X_i) \ge F_k^{max} \end{cases} \qquad 7\text{-}17$$

Where μ_k^i = membership value of the *kth* objective function and particle *ith*. X_i = non-dominated solution ith in the archive. F_k^{min} and F_k^{max} = the minimum and maximum of the *kth* objective function.

Then, the normalised fuzzy set function μ^i of non-dominated solution *ith* is estimated by:

$$\mu^i = \frac{\sum_{k=1}^{K} \mu_k^i}{\sum_i^B \sum_{k=1}^{K} \mu_k^i} \qquad 7\text{-}18$$

Where *K* = the total number of objectives. *B* = the total number of the non-dominated solutions in the archive. The particle *ith* having the maximum μ^i in the archive is selected as the compromise solution (Zhang et al., 2012).

7.5 Problem Description

The applied problem of pavement network consists of 5 pavement sections which have the same length and width (152.5m×3.6m). These sections are uniform in construction and structural design which is asphalt concrete pavement on granular base (GPS-1), climatic zone, and functional class. The 5 overlay maintenance actions will be scheduled over 10 years for these pavement sections (as shown in Table 7-1).

The adopted objective functions are the minimisation of the rehabilitation costs and the minimisation of the sum of all residual PCI values over the planning horizon of 10 years. The discount rate employed in the analysis is 4%. The cost of each overlay actions is measured by unit cost (dollar per section area). The other data to calculate the PCI values for each section is given in Table 7-2.

7.6 Implementation of the Problem

The developed DBB-MOPSO algorithm is applied to a pavement maintenance decision optimisation problem. This problem is the selection of the optimal treatment action from 5 maintenance actions for 5 pavement sections over 10 years. The decision variables are encoded by direct and indirect representations as shown in Figure 7-4.

Table 7-2: Pavement section details.

Year	Section	AADT	Age	Cracking Area	Cracking Length
1	1	3674	7.26	15.6	232.9
	2	4325	14.92	0	586.9
	3	9140	8.61	0	1.4
	4	2054	2.08	0	0
	5	2880	5.02	0	0
2	1	5820	8.35	12.1	252.4
	2	2975	16.01	1.57	589.5
	3	9362	9.67	0	11.3
	4	2456	3.16	0	0
	5	2949	6.02	0	0.8
3	1	5830	9.31	0.8	323.4
	2	3067	16.97	2.62	585.7
	3	9608	10.64	1.15	66.3
	4	2485	4.02	0	13.8
	5	3000	7.09	0	22.7
4	1	6068	10.42	28.3	249
	2	3163	18.08	13.8	579.1
	3	9854	11.75	12.32	35.2
	4	2515	5.02	0	4.95
	5	3063	8.09	0	68.8
5	1	6306	11.42	0	0
	2	3227	19.08	13	588.9
	3	10100	12.75	22.7	38.5
	4	2329	5.58	0	0
	5	3123	8.74	0	98.8
6	1	6558	12.03	47	370.7
	2	3291	20.08	12.1	598.7
	3	10570	13.62	31.8	41.4
	4	2143	7.09	0	1
	5	3183	9.81	73.9	64.8
7	1	6831	13.06	522.1	138.2
	2	3355	21.15	11.2	608.5
	3	11270	14.41	117.5	25
	4	1957	7.89	0	3.5
	5	3243	10.74	64.3	94.1
8	1	7104	14.44	144.9	718.4
	2	3415	22.14	122.1	159.1
	3	11800	15.87	66.9	131.5
	4	1771	8.97	0	16.7
	5	3303	12.21	31.8	169.9
9	1	7377	15.36	92	457.2
	2	3517	23.14	111.4	221.1
	3	12100	16.80	117.2	108.2
	4	1847	9.97	0	23.4
	5	3363	13.23	73.2	172.8
10	1	7672	16.36	92	457.2
	2	3615	23.79	104.5	261.4
	3	12500	17.80	73.6	111.7
	4	1999	10.65	0.8	27.9
	5	3423	13.85	66.6	171.9

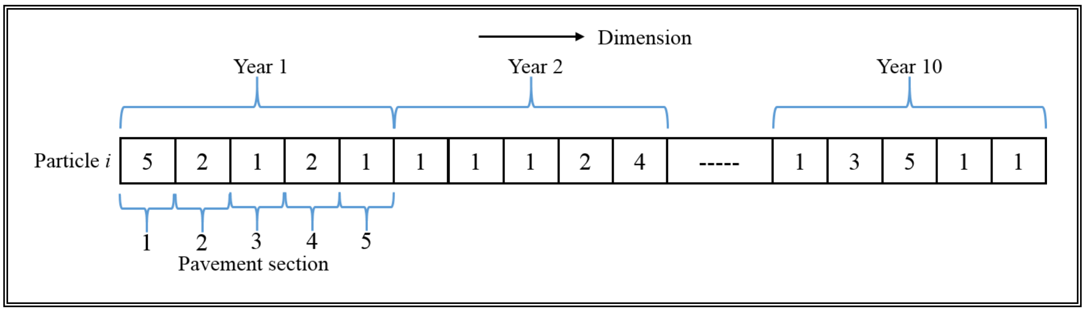

Figure 7-4: Particle position encoding for the pavement maintenance optimisation problem.

The particle swarm optimisation algorithm for discrete optimisation problem developed by Izakian *et al*. (2010) is used to evaluate the performance of the developed algorithm. Both the proposed algorithm and the one Izakian *et al*. are coded in MATLAB, as shown in (Appendix J, Appendix K, Appendix L, Appendix M, Appendix N, and Appendix O) and applied to the same optimisation problem. The parameters of the problem are given below:

- A swarm size of 100, archive size of 100, number of iterations of 100 are assumed for both algorithms.
- A velocity range [6, -6], is assumed for the DMOPSO algorithm. This velocity range is recommended by Kennedy and Eberhart (1995) for discrete problems. The values of $c_1 = 2$, $c_2 = 2$ are recommended by Izakian *et al*. (2010).

7.7 Performance Metrics

The concept of performance is used to compare different optimisation methods. The quality definition for multi-objective optimisation problems is ultimately more complex than for single-objective optimisation problems, because the goal of optimisation comprises many objectives. The distance of the found non-dominated solutions to the Pareto-optimal front should be minimised. A strong uniformity of the solutions is required. The evaluation of this measure might be based on a distance index. The extent of the found non-dominated solution set should be maximised (Zitzler et al., 2000). There are different metrics to examine the accuracy and the diversity of different procedures in regenerating the Pareto front of multi-objective optimisation problems. Some of these metrics are described below, before employing these to perform an evaluation of the effectiveness of the proposed method.

7.7.1 Maximum Spread

This measure was developed by Zitzler *et al*. (2000). "This index is utilised to estimate the maximum extension covered by the non-dominated solutions in the Pareto front. In a two objective problem, the Maximum Spread corresponds to the Euclidean distance between the two farther solutions" (Salazar-Lechuga and Rowe, 2005; Santana et al., 2009).

$$MS = \sqrt{\sum_{k=1}^{K}[\max(f_k^b) - \min(f_k^b)]^2} \qquad \forall b \in \{1, 2, \dots, B\} \qquad 7\text{-}19$$

Where B = the number of the non-dominated solutions. K = the total number of objectives. Larger values of this index indicate better performance.

7.7.2 Spacing

Spacing is a measure to determine how well distributed (spaced) the solutions are in the non-dominated set obtained. It is defined as:

$$S = \sqrt{\frac{1}{D}\sum_{i=1}^{D}(q_i - \bar{q})^2} \qquad 7\text{-}20$$

Where q_i = the minimum value of the sum of the absolute difference for every objective function value between the i^{th} solution and all the D non-dominated solutions found.

$$q_i = min_{l=1 \wedge l \neq i}^{D} \left(\sum_{k=1}^{K} \left| f_k^i - f_k^l \right| \right) \qquad 7\text{-}21$$

The $\bar{q}$ = mean of all q_i, and is defined as:

$$\bar{q} = \sum_{i=1}^{D} {q_i}/{D} \qquad 7\text{-}22$$

If the value of this metric is smaller, the solutions will be uniformly spaced (Salazar-Lechuga and Rowe, 2005).

7.7.3 Generational Distance (GD)

Generational distance was proposed by Van Veldhuizen and Lamont (1998). It is a method to evaluate the Euclidean distance between each element in the non-dominated solution found until now and its nearest element in the Pareto-optimal set. It is defined as:

$$GD = \frac{\sqrt{\sum_{i=1}^{D} d_i^2}}{D} \qquad 7\text{-}23$$

Where D = the number of members in the set of non-dominated solutions found to date. d_i = the Euclidean distance between non-dominated solutions (measured in the objective function space). All members found are in the Pareto-optimal set if the GD value is equal to zero (Tsai et al., 2010).

7.7.4 Diversity (D)

The diversity metric was developed by Deb *et al*. (2002). It is used to estimate the extent of spread among the found solutions. It is defined as follows (Tsai et al., 2010):

$$\Delta = \frac{d_f + d_l + \sum_{i=1}^{D-1} |d_i - \bar{d}|}{d_f + d_l + (D-1)\,\bar{d}} \qquad 7\text{-}24$$

Where, $\bar{d} = \frac{\sum_{i=1}^{D-1} d_i}{D-1}$ 7-25

d_f, d_l are the Euclidean distances between the extreme solutions and the boundary, non-dominated solutions (first and final solutions of the found non-dominated set). $\bar{d}$ = the average of all distances d_i, i = 1, 2, ..., (D - 1), assuming that there are D solutions on the best non-dominated front.

7.8 The Results of Multi-Objective Pavement Maintenance Decisions Optimisation

7.8.1 Compromise Solution

To simulate agency preferences, a compromise solution is applied by both algorithms as shown in Figure 7-5 and Figure 7-6. The solution having the maximum membership value (μ^i) in the archive is selected as the optimal pavement maintenance by both algorithms. Table 7-3 shows the optimal maintenance programme found by both algorithms. It can be seen that the sum of all residual PCI values found by the DBB-MOPSO algorithm is approximately the same to the sum of all residual PCI values found by DMOPSO, but the cost value of DMOPSO is slightly larger than the novel algorithm. Consequently, there is no significant difference between both algorithms. In the optimal maintenance plan found by the DBB-MOPSO algorithm, as shown in Table 7-4, there is heavier investment in the pavement maintenance of all sections at the beginning of the plan period compared with the end of period. By contrast, in the optimal maintenance programme found by the DMOPSO algorithm, as shown in Table 7-5, there is heavy investment in maintenance of most sections during the middle years.

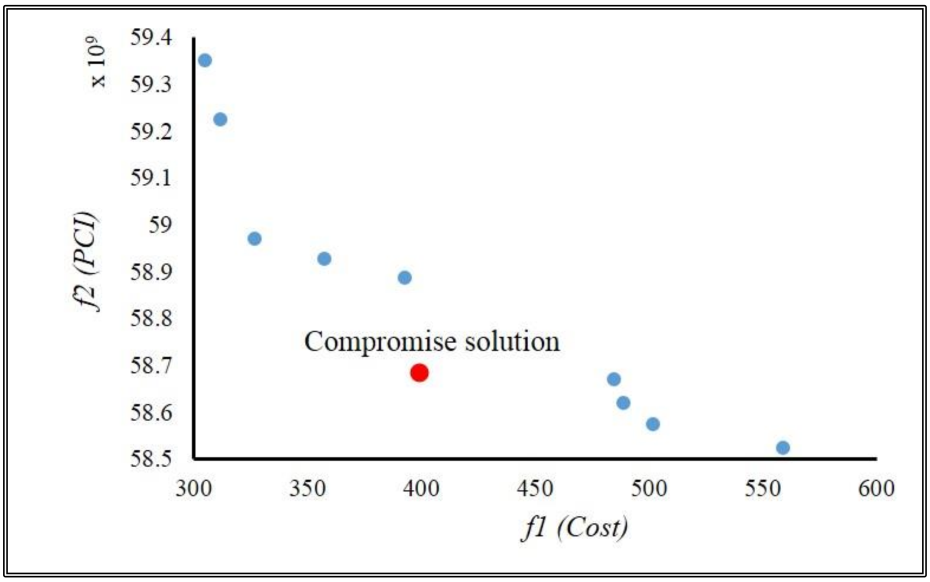

Figure 7-5: Compromise solution of DBB-MPSO at 100 generations.

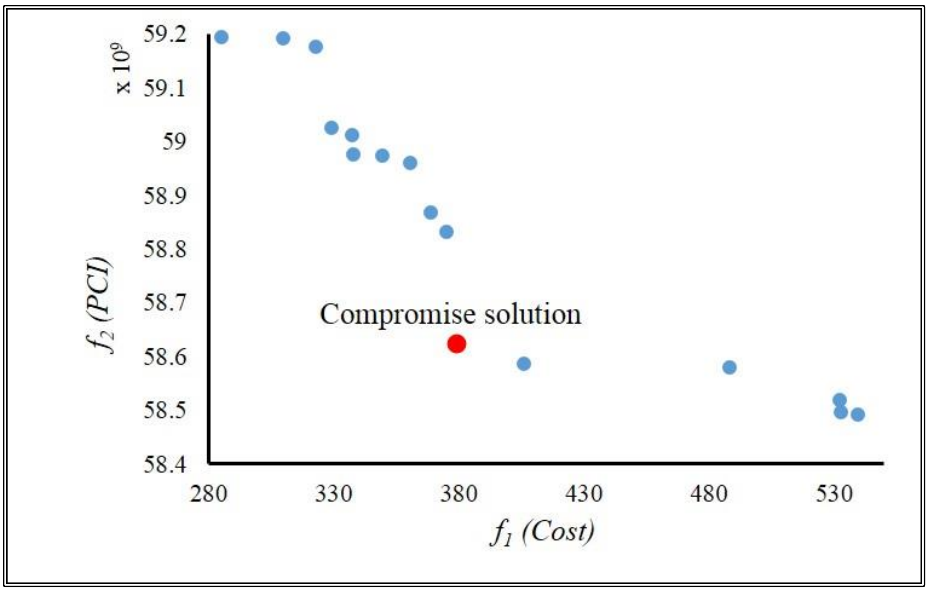

Figure 7-6: Compromise solution of DMOPSO at 100 generations.

Table 7-3: Optimal maintenance plans found by both algorithms.

Algorithm	Objective functions		μ
	Total Cost	Sum of all residual PCI values	
DBB-MOPSO	399.25	5.87E+10	0.121
DMOPSO	379.22	5.86E+10	0.077

Table 7-4: The pavement maintenance plan based on the DBB-MOPSO algorithm.

Year 1					Year 2					Year 3					Year 4					Year 5					Year 6					Year 7					Year 8					Year 9					Year 10				
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	1	0	1	1	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0
0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0
0	0	1	0	0	1	1	0	1	1	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1
1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7-5: The pavement maintenance plan based on the DMOPSO algorithm.

Year 1					Year 2					Year 3					Year 4					Year 5					Year 6					Year 7					Year 8					Year 9					Year 10				
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0
1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
0	1	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	1	0	1	0	0	1	0	1	0	0	0	0	0	0	0
0	0	1	0	1	0	1	0	0	1	1	0	1	0	1	0	1	0	1	0	0	1	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

7.8.2 Algorithms Comparison Results

The novel algorithm called discrete barebones multi-objective particle swarm optimisation (DBB-MOPSO) is developed to schedule the rehabilitation actions over ten years for five sections of flexible pavement. The DBB-MOPSO optimisation framework is implemented by generating code in MATLAB. After five generations, thirteen non-dominated solutions from 100 solutions were found as shown in Figure 7-7. After 100 generations, ten non-dominated solutions were found as shown in Figure 7-8.

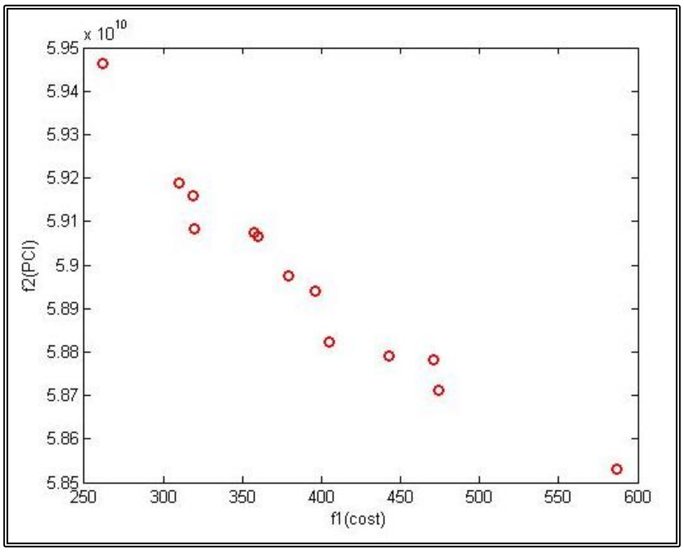

Figure 7-7: Pareto solutions of DBB-MOPSO after five iterations.

The effectiveness of the DBB-MOPSO algorithm is demonstrated by comparing this algorithm to the existing discrete multi-objective particle swarm optimisation (DMOPSO) algorithm developed by Izakian *et al*. (2010). In this algorithm after five generations, fifteen non-dominated solutions were found as shown in Figure 7-9, while after 100 iterations, seventeen non-dominated solutions were found as shown in Figure 7-10.

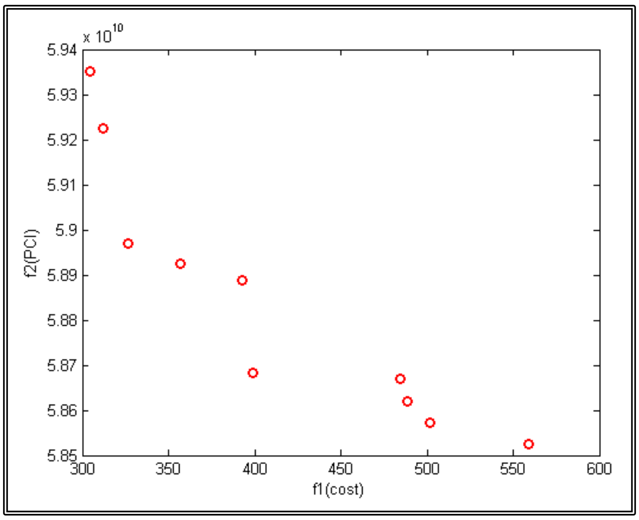

Figure 7-8: Pareto solutions of DBB-MOPSO after 100 iterations.

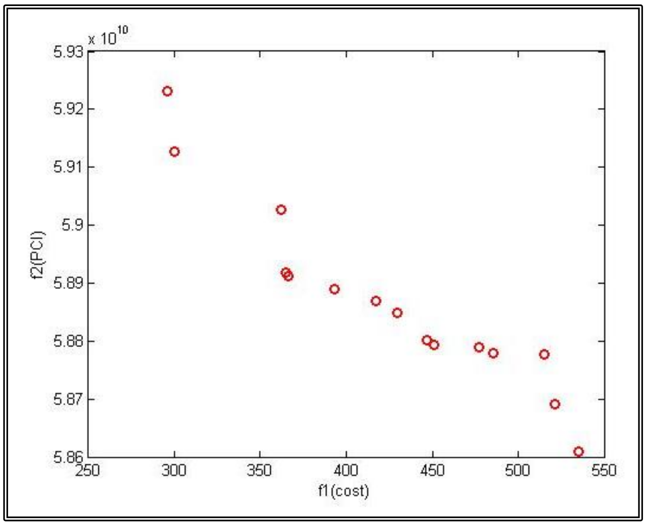

Figure 7-9: Non-dominated solutions of DMOPSO after 5 iterations.

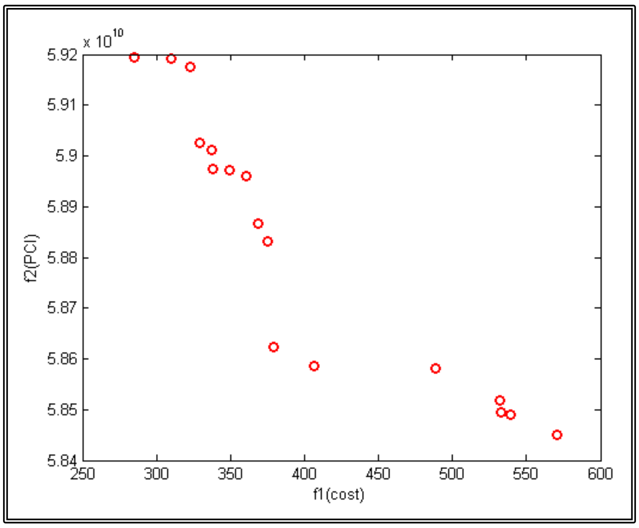

Figure 7-10: Non-dominated solutions of DMOPSO after 100 iterations.

7.8.3 Performance Metrics

To test the novel algorithm, the performances of both algorithms are estimated with respect to the following performance metrics: spacing, maximum spread, generational distance (GD), and diversity. The results of the different metrics are plotted against iterations as shown in Figure 7-11, Figure 7-12, Figure 7-13, and Figure 7-14.

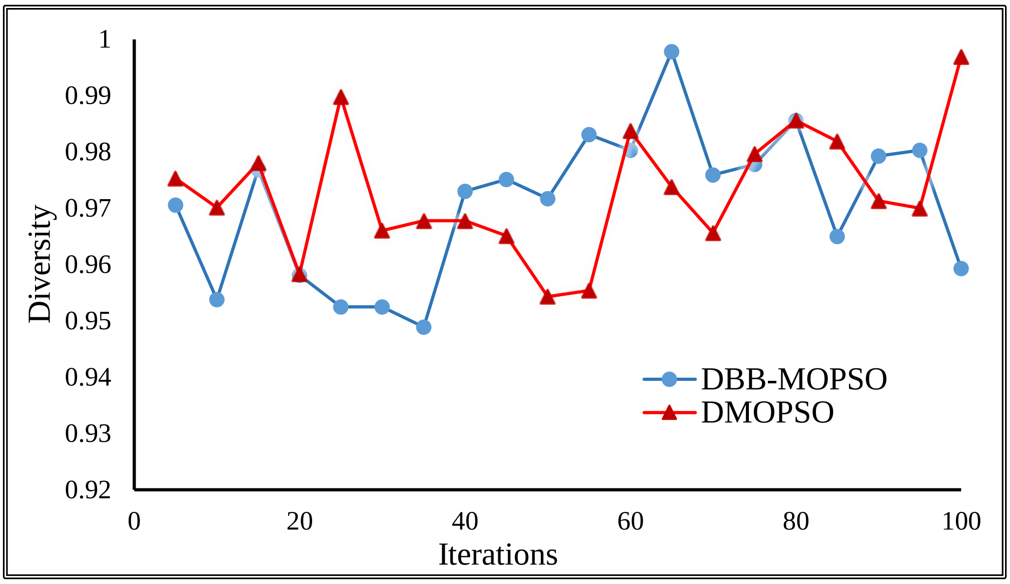

Figure 7-11: The diversity metric of both algorithms.

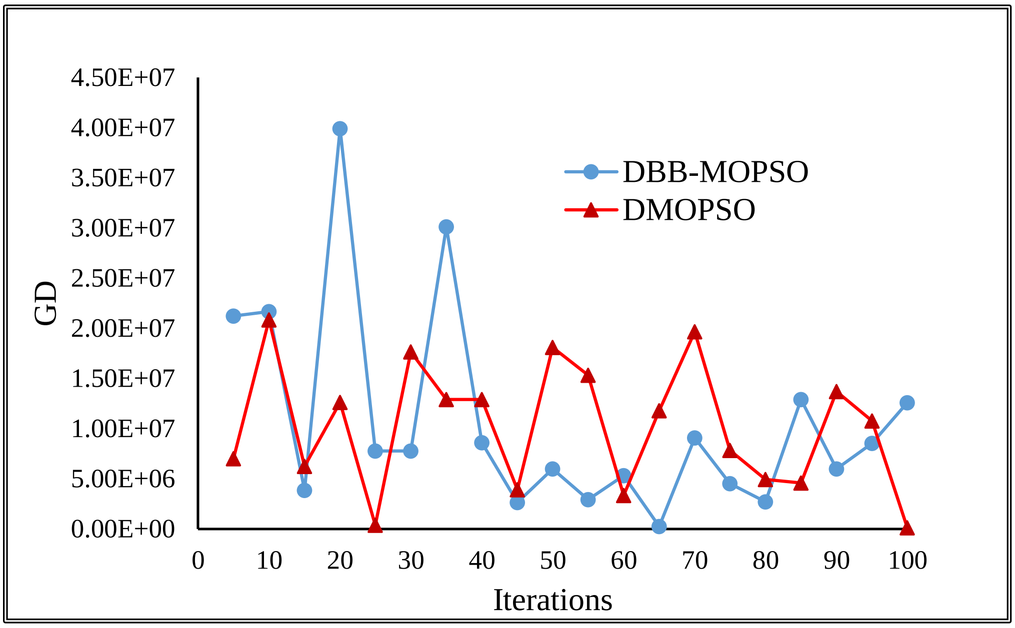

Figure 7-12: The generational distance metric of both algorithms.

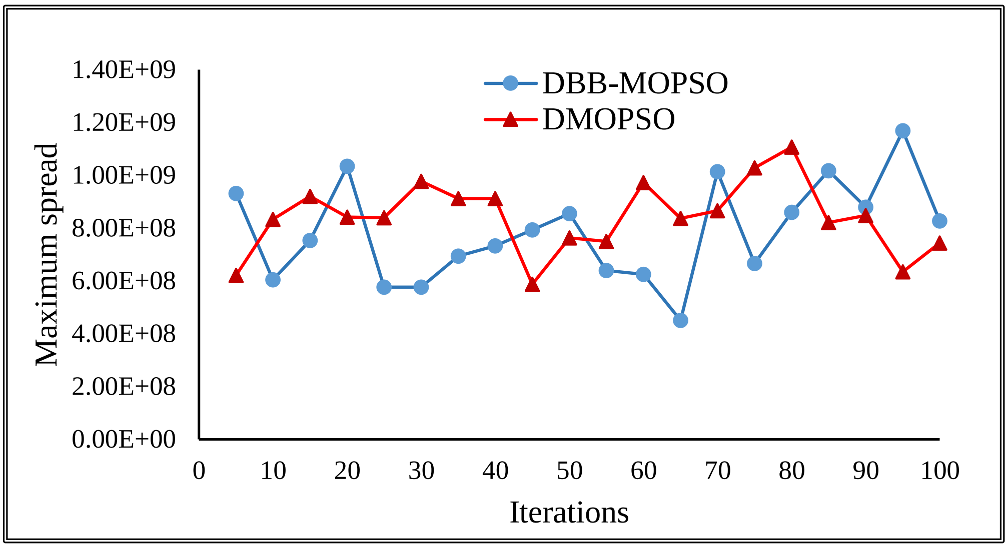

Figure 7-13: The maximum spread metric of both algorithms.

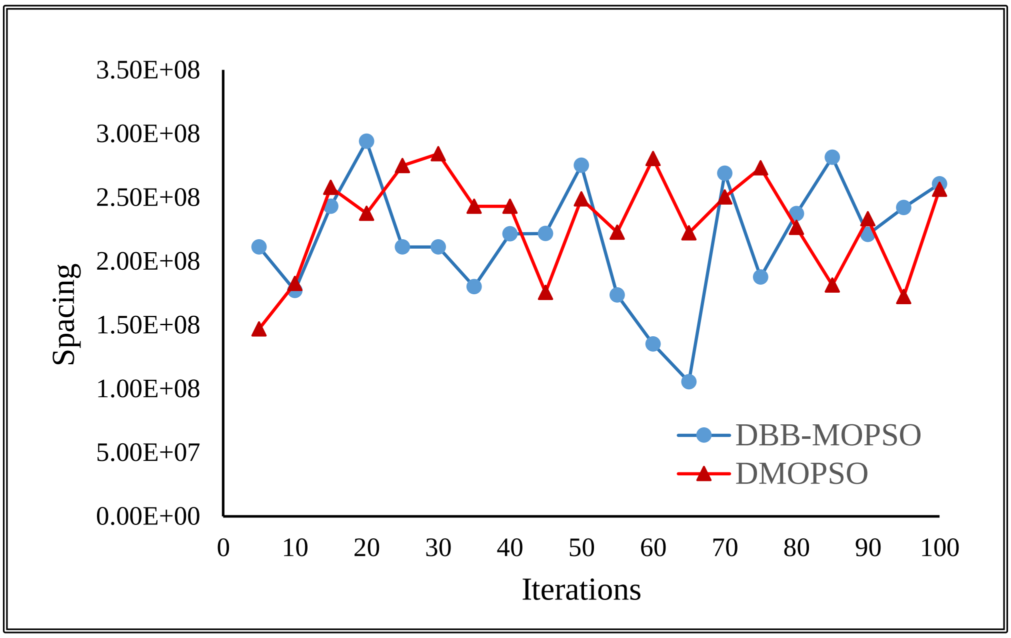

Figure 7-14: The spacing metric of both algorithms.

The diversity metric is estimated to ensure the non-dominated solutions spread across the entire region of the true front. Figure 7-11 shows that the DBB-MOPSO algorithm has lower diversity at 100 generations than the DMOPSO algorithm. DBB-MOPSO after 100 iterations, as shown in Figure 7-12, has a small value of generational distance (GD) while DMOPSO has the same range of GD, but it becomes larger at the end of the generations. Therefore, the convergence speed of DBB-MOPSO to the Pareto front is slightly higher than that of DMOPSO. As shown in Figure 7-13, the maximum spread of DBB-MOPSO at 100 iterations is approximately the same as DMOPSO at 100 iterations. Figure 7-14 shows that DBB-MOPSO has slightly smaller values of spacing. This indicates that the solutions of DBB-MOPSO are more uniformly spaced than those of the DMOPSO algorithm.

The results are reported in terms of the mean and standard deviation of the performance metrics for both algorithms in Table 7-6. For the four performance metrics, Table 7-6 shows that the mean and variance are approximately the same for the DBB-MOPSO and DMOPSO algorithms at 100 iterations.

Table 7-6: The mean and variance of both algorithms for different performance metrics.

Algorithms		Performance Metrics			
		Spacing	Maximum Spread	Generational distance	Diversity
DBB-MOPSO	Mean	2.18E+08	7.85E+08	1.07E+07	0.971
	SD	4.86E+07	1.87E+08	1.01E+07	0.0131
DMOPSO	Mean	2.31E+08	8.41E+08	1.02E+07	0.973
	SD	3.97E+07	1.33E+08	6.32E+06	0.0112

7.9 Summary

This chapter described the process of M&R decision optimisation development. The novel algorithm called discrete barebones multi-objective particle swarm optimisation (DBB-MOPSO) was developed for finding optimal M&R actions scheduling over analysis period. Particle initialisation stage, updating local position global leader and velocity, mutation operator, and pruning the external archive were described in detail. The two objective functions, minimisation of the rehabilitation costs and the minimisation of the sum of all residual PCI values, were adopted. The DBB-MOPSO algorithm was implemented on multi-objective pavement M&R decisions problem. It was found that the optimal M&R plan found by the DBB-MOPSO algorithm was good compared to that found by DMOPSO. The next chapter discusses the model validation of each PMS stage.

Chapter 8

Case Study and Discussion

8.1 Case Study

For simplicity and easy understanding of all stages of developed PMS, a case study is applied. The case study was conducted on selected pavement sections by performing section classification, deterioration prediction, and finally maintenance decision optimisation using the methods developed as part of this research.

The case study consists of five pavement sections selected randomly. For implementing the fuzzy classification model, condition data for five sections at specific times of year were collected from LTPP database, as shown in Table 8-1. It should be noted that the variability of the data has an impact on the section classification and prediction, and ultimately maintenance optimisation. For example, the cracking area in section 2 as in Table 8-3 shows random changes in different years. Similar variations can be seen in cracking length. The pavement sections are evaluated by using FIS; Table 8-2 shows the evaluation results of FIS for five sections compared to Paver system.

Table 8-1: shows distress data for five sections

State code	SHRP ID	Alligator Cracking			Block Cracking			Long & Trans. Cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
23	1026	0	0	0	0	0	0	5.6	5.3	0	0	0	0	0	0	0	0	0	0	0	0	0
25	1002	15.59	0	0	0	0	0	236.4	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0
33	1001	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	1597	0	0	0	0	0	0	47.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	1002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 8-2: Section classification results of FIS

State code	SHRP ID	Fuzzified PCI	Class
23	1026	95	Excellent
25	1002	64	Good
33	1001	95	Excellent
42	1597	75	Very good
50	1002	95	Excellent

The pavement performance prediction models integrate with optimisation of pavement M&R decisions. A deterministic deterioration model, as developed in chapter 6, for arterial highways in the wet freeze climatic zone was applied to predict pavement condition. Table 8-3 shows the required data of deterioration model for the five sections. For optimal M&R actions, the five overlay actions as mentioned in chapter 6 will be scheduled over 10 years for these pavement sections. Furthermore, in order to implement the DBB-MOPSO algorithm, the parameters of the problem are a swarm size of 100, archive size of 100, and the number of iterations of 10.

Table 8-3: Pavement sections details.

Year	Section	Age	Cracking Area	Cracking Length	AADT
1	1	17.16	0	8.2	2175
	2	7.26	15.59	232.9	3674
	3	9.67	0	11.3	9362
	4	9.87	0	378.7	1434
	5	6.02	0	0.8	2949
2	1	18.15	0.3	19.9	2200
	2	8.35	12.12	252.4	5820
	3	10.64	1.15	66.3	9546
	4	10.93	0	386.8	1450
	5	7.09	0	22.7	3000
3	1	19.82	0	11.8	2250
	2	9.31	0.77	323.4	5830
	3	11.75	12.32	35.2	9731
	4	11.71	0	69.6	1469
	5	8.74	0	98.8	3123
4	1	20.89	0	21.9	2275
	2	10.42	28.3	249	6073
	3	13.40	77.5	23.3	10100
	4	12.50	0	51.2	1428
	5	9.81	73.9	64.8	3183
5	1	21.30	0	16.8	2275
	2	12.03	286	370.7	6558
	3	13.62	31.8	41.4	10570
	4	13.76	0.5	202.2	1387
	5	10.74	64.3	94.1	3243
6	1	21.83	0	20.9	2300
	2	13.06	488	138.2	6831
	3	14.41	117.5	25	11270
	4	15.03	0.2	285.3	1346
	5	12.21	33	169.9	3303
7	1	22.84	0	29.2	2325
	2	14.44	144.9	718.4	7104
	3	15.87	66.9	131.5	11800
	4	15.87	0	752.6	1305
	5	13.23	73.2	172.8	3363
8	1	24.31	0	9.6	2020
	2	15.36	92	457.2	7377
	3	16.36	122.4	101.9	12100
	4	17.00	0.2	285.3	1264
	5	13.85	66.6	171.9	3423
9	1	24.94	0	60.2	2020
	2	18.06	306.3	200.4	8298
	3	19.74	268.3	115.6	13000
	4	19.63	3.6	410.8	1141
	5	15.31	181.8	133.9	3483
10	1	28.11	22.6	234.8	2000
	2	19.00	161.1	92.9	8975
	3	20.74	134.4	96.1	14400
	4	20.00	0	688.8	1125
	5	16.00	140.2	157.3	3543

After 10 generations, eleven non-dominated solutions from 100 solutions are found as shown in Figure 8-1. The compromise solution concept is applied to simulate decision makers' preferences. It can be seen that the compromise solution is solution number 4. Table 8-4 shows the optimal maintenance programme found by the developed algorithm. For each section in every year, the number 1 means the specific action of maintenance will be applied. For example, for the section 1, AC overlay 1 in (25 mm) will be applied in year 1. For simple presentation, Figure 8-2 describes optimal M&R actions for each section over 10 years.

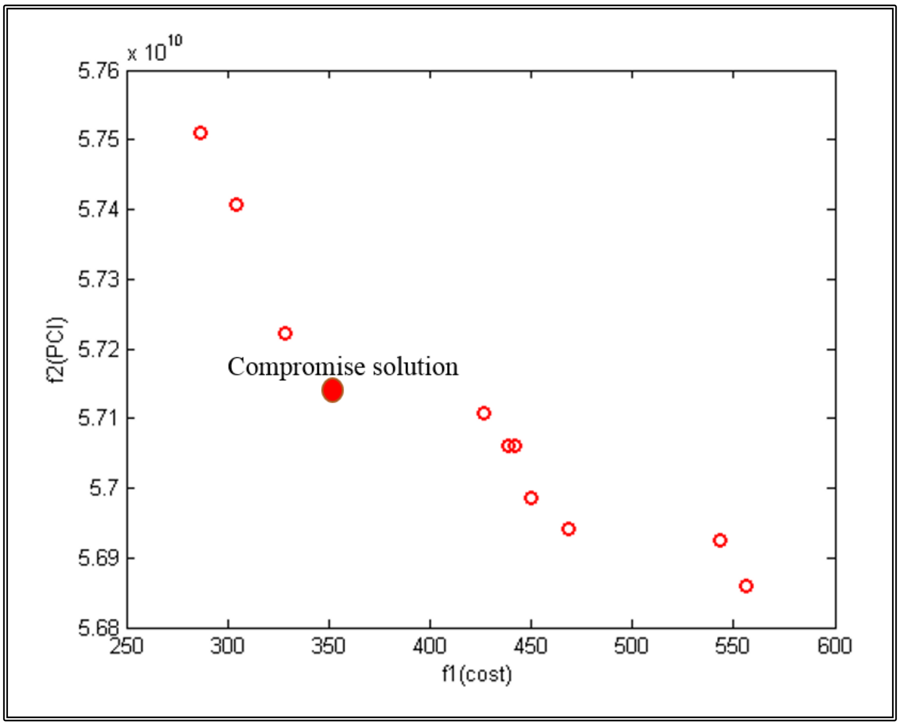

Figure 8-1: Non-dominated solutions and compromise solution after 10 iterations.

Table 8-4: The pavement maintenance plan for five sections over 10 years.

Year 1					Year 2					Year 3					Year 4					Year 5				
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
1	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	0	1	0	0	0	0
0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0

Year 6					Year 7					Year 8					Year 9					Year 10				
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
0	1	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	1	1	0	0	0	1	0
1	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

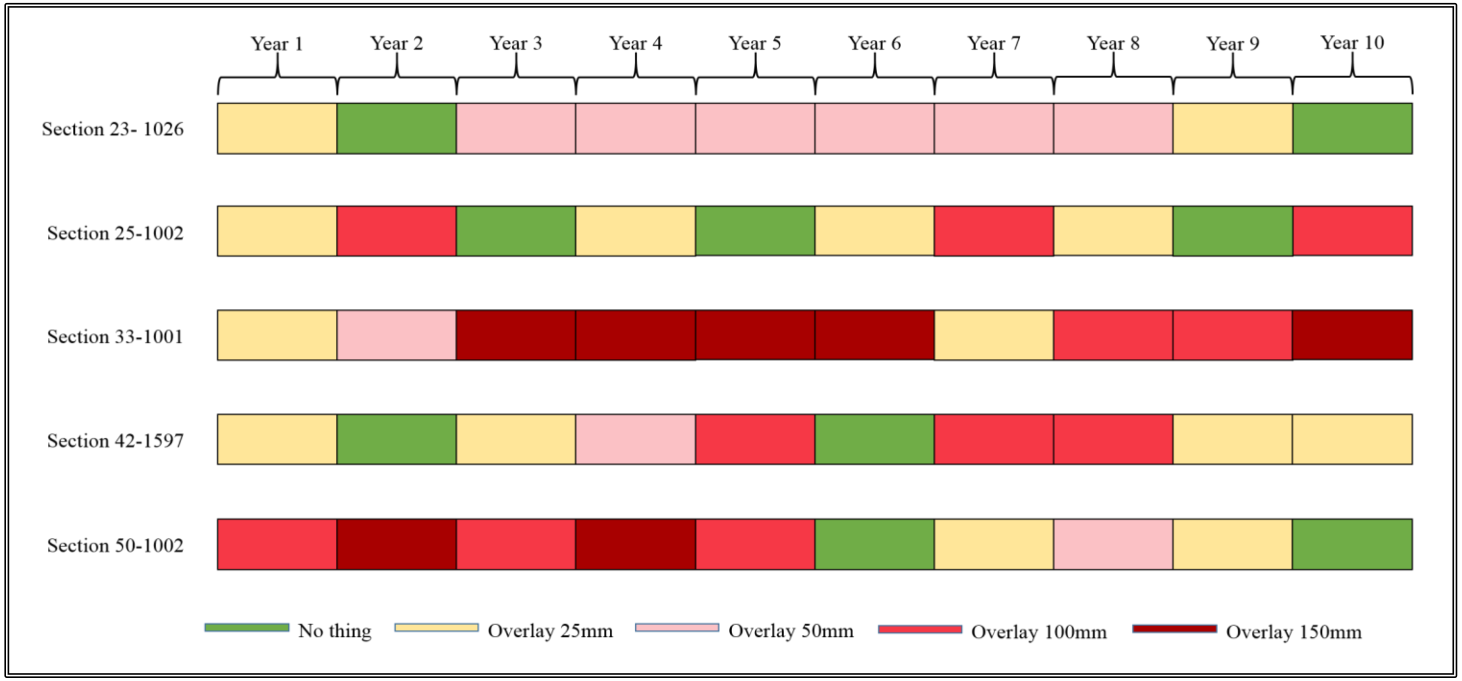

Figure 8-2: Simple presentation of optimal M&R actions plan for five pavement sections.

8.2 Discussion

8.2.1 Pavement Section Classification

The fuzzy inference system has been applied to create new pavement section classification system. The seven types of distresses which are the most frequent distresses are considered as input variables to determine PCI. Although, the results show a good correlation between the fuzzified PCI and the PCI calculated by the commercial MicroPAVER software. There is a need to make extra improvement for fuzzy classification model. For obtaining a strong correlation, since the Micro-Paver system considers many distress types in PCI calculation, other types of distresses could be considered in fuzzy classification model.

For the limitation of data availability and software, the simplest membership function is the triangular membership function. Therefore, three triangular membership functions for each FIS input and the seven triangular membership functions for output are generated. However, Gaussian membership functions provide a better approximation, but they also need more data to train. For future work, with additional data, Gaussian membership functions could be used to improve the performance of the fuzzy classification model.

The fuzzy rules results for 180 and 2nnnnn 91 sections as explained before in Section 5.3.1.2 show that there are significant modifications among fuzzy rules of the both sections groups. The fuzzy rules are generated automatically by learning from data examples, and the 291 sections are the same 180 sections, plus an extra 111 sections: therefore, the new rules are generated from 111 sections. The fuzzy rules of classification model could be improved by using extra pavement section data with a larger spread of poor to excellent sections.

8.2.2 Pavement Performance Prediction

Empirical deterioration models for flexible pavement at network-level were created by using a multiple regression analysis technique. The results indicate that these deterioration models have a good correlation. The advantages of linear regression are its simplicity and widespread availability, but it is based on the assumptions of linearity; some inputs of the deterioration model probably do not correspond to these assumptions. Hence, to address this problem and improve the accuracy of these prediction models, soft computing techniques such as fuzzy logic, Nero-fuzzy could be used if there is sufficient data.

To mitigate the deterioration rate and improve the functional condition of pavement, preventive maintenance such as crack sealing and patching is implemented periodically. This type of treatment has an effect on pavement condition, but it is relatively minor compared to corrective maintenance. The main challenge of preventive maintenance is how to incorporate their effects in deterioration models because the available data of preventive maintenance is not useful for the deterioration model. Therefore, it is required to devise a technique that is able to incorporate the effect of preventive maintenance in deterioration.

8.2.3 Multi-Objective Pavement Maintenance Decision Optimisation

The novel algorithm called discrete barebones multi-objective particle swarm optimisation (DBB-MOPSO) has been developed to programme pavement M&R actions over the analysis period. The results show that this algorithm has found an optimal M&R actions plan. Moreover, the algorithm could be also used for general discrete optimisation problems; there has to be more benchmarking against other competitive algorithms, from the PSO and GA domains. Moreover, standard benchmarking problems from various domains must be tested. Both of these targets are not in the purview of this thesis.

The highway authorities need to estimate the budget requirement to maintain their pavement networks. Therefore, the DBB-MOPSO algorithm was implemented on an unconstrained optimisation pavement M&R problem to assist the highway authorities to estimate required budget for M&R investments. However, if there is an allocated budget and the highway agencies want to schedule M&R actions over specific time period, this algorithm should be applied to a constrained optimisation problem. Therefore, the algorithm can be extended to handle these problems.

The minimum acceptable level of the PCI is dependent on the road type and level of service/threshold needed by the authority. A significant pavement management limitation is that there is no available standard value for the minimum acceptable level of PCI. Therefore, there is a need to study the effects of different acceptable levels of PCI on pavement M&R plans and budget.

Chapter 9

Conclusions and Suggestions

9.1 Conclusions

9.1.1 Pavement Section Classification

A fuzzy inference system (FIS) was used to develop a fuzzified pavement condition index (PCI) for flexible pavement section classification. Unlike the conventional crisp (pass and fail) approach, this system has the potential to deal with uncertain and high-dimensional distress data.

Membership functions were developed for seven commonly used pavement distresses (alligator cracking, block cracking, longitudinal and transverse cracking, patching, potholes, bleeding, and ravelling) extracted from two section data sets (with 180 and 291 sections respectively) in the Long-Term Pavement Performance (LTTP) database. Triangular and semi-triangular shapes were used for the membership function for each distress type. These membership functions were then utilised in a FIS to generate rules for PCI-based section classification.

The results showed a high correlation level of fuzzy classification system. This proves that the FIS-system-based PCI calculation has strong a potential to optimise the influence of borderline values between two categories in pavement section classification, which conventional crisp classification fails to address. The borderline values between two categories have a significant influence on subsequent pavement maintenance and rehabilitation decisions. For example, if two pavement sections have the same category need to maintain and there is no enough maintenance budget for both sections. In the conventional crisp classification, the both sections can be based on subjective judgment while in fuzzy classification system, they can be prioritised based on their membership values.

The model could be improved by considering more sections with different distress types. The sensitivity analysis showed that cracks have a greater influence on the fuzzified classification than the other distress types. Hence, it is possible to say that it is important to identify cracking severity during road condition assessments, as pavement management decisions would be adversely affected by its over- or under-estimation, resulting in erroneous prioritisation and inefficient utilisation of rehabilitation and maintenance funds.

As the proposed method deals with linguistic variables, pavement engineers will be able to easily understand and then realistically classify the sections, avoiding human judgement whilst utilising numerical data of different pavement distresses to generate rules within a short period of time. Overall, this method demonstrated the ability to generate rules within a small amount of time, especially when high-dimensional distress data are needed for section classification.

9.1.2 Pavement Performance Prediction

For flexible pavement, the network-level deterioration prediction model MID-PM has been proposed for different climatic zones and road classes. MID-PM incorporates five input variables: the cumulative Equivalent Single Axle Load (ESAL), the pavement age, maintenance effects (inlay and overlay thickness), and the length and area of pavement cracks which have developed. These results are promising, with 52 to 95%

correlation for two classes of roads in four climatic regions within the LTPP's General Pavement Studies (GPS) sections.

The model's correlations were found to be better for collector roads than for arterial roads. Since, the characteristics of arterial roads are different from collector roads. The deterioration behaviour of arterial roads might tend to be nonlinear compared to collector road. This appears to require further research that looks into the characteristic variations between arterial and collector roads.

The sensitivity analysis shows that distress quantity (cracking), pavement age, and maintenance have the greatest effect, while traffic loading has a minimal influence on the model's performance.

The cross-validation results show that the deterioration models for the arterial road class in all climatic zones have very good accuracy in estimating the future Pavement Condition Index (PCI). The accuracy level for the collector road class is relatively poor due to the shortage of historical testing data. The accuracy of these prediction models can be improved by using soft computing techniques, such as artificial neural networks or fuzzy inference systems, which consider nonlinearity and uncertainty. Further work is under way to improve the accuracy of the model.

9.1.3 Multi-Objective Pavement Maintenance Decision Optimisation

A novel particle swarm algorithm is developed for a discrete multi-objective problem. This novel algorithm is implemented to find the optimal rehabilitation plan considering two objectives: the minimisation of the total pavement maintenance cost and the minimisation of the sum of all residual PCI values.

The novelty of this research is in both pavement management and computer science. In pavement management, this research is the first attempt to use a new algorithm called "barebones particle swarm optimisation" for multi-objective pavement M&R programming. In computer science, the other side of novelty, there is no study that has used this algorithm to solve a discrete (binary) optimisation problem. Therefore, it is the first attempt to develop a barebones particle swarm optimisation algorithm for discrete optimisation problems.

Although the results showed that the cost obtained via the proposed algorithm is slightly higher than that of the DMOPSO algorithm, the sum of all residual PCI values found by DBB-MOPSO is approximately the same to that obtained by DMOPSO, another existing discrete optimization algorithm. Overall, the optimal maintenance plan found by the novel algorithm is about the same that found by the DMOPSO algorithm.

In addition, the results demonstrated that the novel algorithm (DBB-MOPSO) can converge to the Pareto front with fewer generations, lower diversity, smaller generational distance (GD), and higher maximum spread than the DMOPSO algorithm, although, compared to the DMOPSO algorithm, the DBB-MOPSO algorithm is highly time-consuming. The novel algorithm is still a more effective algorithm because it is a parameter-free technique and converges to the Pareto front with a smaller number of generations.

9.1.4 Overall Conclusion:

Sophisticated, effective and accurate pavement management system was developed for classifying pavement section, predicting pavement condition, and programming pavement M&R strategies. This system is able to deal with huge quantity of condition data for large pavement network with less time and effort compared to commercial system like MicroPAVER. In addition, it is easy for the implementation and the calibration of pavement network anywhere because it has ability to capture and transfer the knowledge and experience easily. Moreover, this system is more understandable for pavement engineers and experts because it deals with linguistic variable. It is effective and useful tool system expert knowledge that provide simple tool for less experience engineer and save the time.

9.2 Contribution to Knowledge

9.2.1 Pavement Section Classification

The key contribution of this part is to develop a simple and effective section classification system that is able to overcome the failure of traditional crisp classification when comparing various pavement distress data against threshold values. In addition, this classification model is able to capture and transfer the knowledge, judgment and experience to evaluate pavement conditions and investment decisions to the less experienced engineers. This system can deal with the uncertainty and subjectivity involved in pavement data and the classification. The fuzzy inference system (FIS) is used to develop this system because it has ability to learn automatically from numerical data, although there is still flexibility to adjust the system manually. This flexibility gives engineers more freedom to optimise the section classifications using one single system. In this sense, an FIS is more transparent than an artificial neural network.

9.2.2 Pavement Deterioration Model

This part of the research has addressed the knowledge gap in the majority of existing deterministic and probabilistic deterioration models at the network level. It is essential to deal with the limitation of the data quantities for training. Therefore, it is sensible to take a holistic approach, and consider the various influential parameters to evaluate the overall performance of the pavement. Deterministic deterioration models for flexible pavement at the network-level are developed. The deterministic deterioration models consider the combined effects of all factors on performance.

9.2.3 Multi Objective Pavement Maintenance Decision Optimisation

The main objective of pavement management systems is to determine the maintenance work quantity and type which should be applied to a particular pavement network. Therefore, a variety of mathematical optimisation techniques have been used in an attempt to schedule pavement maintenance and rehabilitation solutions and allocate resources. To reach the optimal solutions of maintenance decisions, the big challenge is to deal with high-dimensional problems which consider many pavement sections and the associated treatment decision variables covering multiple time periods.

This contribution has addressed the gaps and limitations in knowledge recognised in the existing evolutionary algorithms. These algorithms involving many parameters (such as mutation operator, crossover operator, mutation probability, crossover probability and population size) should be addressed. This research presents an optimisation algorithm that has few parameters to modify that is easy to implement. In addition, this algorithm designated for continuous optimisation problems is developed to address general discrete optimisation problems. The developed algorithm is applied on multi-objective optimisation problem for pavement maintenance management at the network level to optimal maintenance and rehabilitation strategy program.

Chapter 10

Limitations and Suggestions for Future Work

10.1 Introduction

Pavement management systems (PMS) are essential tools in the decision-making procedures to keep the pavement networks at satisfactory levels of service and structural conditions. There are limited researches in the development of intelligent pavement management system by combining the soft computing system. This Chapter presents a summary of the suggestions for future research, and the also shows the research limitations.

10.2 Limitations and Suggestions for Future Work

- An improvement of the fuzzy system could be obtained by using extra pavement section data or changing the shape of membership functions.
- Soft computing techniques could be employed in the model development of pavement deterioration.
- The main challenge of deterioration models is how to mathematically incorporate the benefit of preventive maintenance like crack sealing, patching etc. in their pavement deterioration predictions.

- Different optimisation algorithms could be used to conduct more validation for novel algorithm.
- The current study is focused on an unconstrained optimisation problem; the novel algorithm will be implemented on a constrained problem in future work.
- The sensitivity analysis could be conducted to find the optimal value for the minimum acceptable level of PCI and also to examine budget constraint scenarios.

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Appendices

Appendix A: Distresses data for each section based on severity level.

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
1	1001	10.9	0	0	0	0	0	19.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1011	0	0	0	0	0	0	2.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	4073	10.5	0	0	491.2	0	0	18.4	2.7	0.8	0	1.1	0	0	0	0	0	0	0	0	0	0
1	4126	7.5	0	0	0	0	0	183.1	0	0	0	0	0	0	0	0	0	0	0	18.17	317.8	203.9
1	4127	0	0	0	0	0	0	3.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	4129	22.4	0	213.8	0	0	0	14.3	0	0	0	0	0	0	1	0	0	0	0	0	0	0
2	1001	0	0	0	0	0	0	30.8	16.4	0	1.8	10.2	0	0	0	0	0	0	0	0	0	0
2	1002	0	0	0	0	0	0	309.9	7.4	15.8	0	0	0	0	0	0	0	0	0	0	0	0
2	1004	0	0	0	0	0	0	44.2	51.8	14.8	0	0	0	0	0	0	0	0	0	0	0	0
2	9035	0	0	0	0	0	0	18.1	0	53.6	0	0	0	0	0	0	0	0	0	0	0	0
4	1007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0503	0	0	0	0	0	0	75.2	12.4	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0504	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0505	23	32.3	0	0	0	0	24.4	8.8	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0506	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0508	0	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0509	0	0	0	0	0	0	73.1	41.8	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0559	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0560	216.6	0	0	0	0	0	19.7	0	0	0	0	0	0	0	0	292.8	0	0	0	0	0
6	1253	26.7	7.5	9	0	61.5	0	26.1	176.1	22.1	0	0	0	0	0	0	0	0	0	0	0	0
6	2038	5.4	0	0	0	0	0	246.5	9.6	0	0	0	0	0	0	0	0	0	0	0	0	0
6	7491	27.5	71.7	6	0	0	0	24.8	172.5	19.5	0	0	0	0	0	0	0	82.1	0	0	0	0
6	8149	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	8156	206.1	199.8	41.6	0	0	0	0	106.5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	8534	0	0	0	0	0	0	12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
6	8535	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	1450	0	0	0	0	0	0	49.7	364.3	5.4	0	0	0	0	0	0	420	0	0	0	0	0
12	1030	0	0	0	508.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1060	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1370	29.8	4.1	0	0	0	0	14.7	0	0	1.5	0	0	0	0	0	0	0	0	0	0	0
12	3996	57.4	0	0	0	0	0	58.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	3997	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4096	0	0	0	0	0	0	26.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4097	0	0	0	0	0	0	31.1	31	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4100	4.7	0	0	0	0	0	23.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4103	0	0	0	0	0	0	305.5	0	0	0	0	0	0	0	0	0	0	0	76.3	0	0
12	4106	0	0	0	0	0	0	15.3	0	0	0	0	0	0	0	0	0	0	0	0	411.8	0
12	4107	4.1	34.6	113.7	0	0	0	1.7	1	0	0	0	0	0	0	0	0	0	0	39.62	1.37	0
12	4135	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	4137	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0502	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0503	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0504	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0505	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0506	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0508	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0509	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0561	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0562	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0563	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0564	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
12	0565	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0566	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1001	94.9	0	0	0	0	0	163.1	60	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1004	140.4	0	0	0	0	0	49.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1005	15	0	0	0	0	0	289.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1031	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	4092	1.5	0	0	0	0	0	132.1	83.7	0	0	0	0	0	0	0	0	0	0	0	0	0
13	4093	0	0	0	0	0	0	169.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	4096	0.5	0	0	0	0	0	1.7	3.6	0	0	0	0	0	0	0	0	0	0	0	0	0
13	4112	0	0	0	0	0	0	14.1	0	0	106.8	0	0	0	0	0	0	0	0	0	0	0
13	4113	4.4	0	0	0	0	0	17.3	0	0	52.9	0	0	0	1	0	0	0	0	0	0	0
13	4420	4.7	0	0	0	0	0	45.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0502	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0
13	0503	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0504	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0505	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0506	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0508	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1	0	0
13	0509	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0560	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0561	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0562	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0563	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0564	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0565	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0566	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	1003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
15	1006	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	1008	20.1	0	0	0	0	0	21.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	7080	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	1001	0.3	56.8	0	0	0	0	78	63.9	13.5	0	0	0	0	0	0	0	0	0	0	0	0
16	1005	0	0	0	0	0	0	11.9	57.9	29.3	0	0	0	0	0	0	0	0	0	0	0	0
16	1007	28.3	219.4	0	0	0	0	183.9	12.2	2	0	0	0	0	0	0	0	0	0	0	0	0
16	1009	0.4	0	0.4	0	0	0	4.9	37.5	59.3	0	0	0	0	0	0	0	0	0	0	0	0
16	1010	43.7	0	0	0	0	0	67.1	58	24.3	0	0	0	0	1	0	0	0	0	0	0	0
16	1020	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	1021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	9032	0	0	0	0	0	0	3.7	7.4	12.7	0	0	0	0	0	0	0	0	0	0	0	0
16	9034	2.3	0	0	0	0	0	72.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	1010	25.6	3.6	0	0	0	0	33.4	39.4	0	0	3.2	20.5	0	0	0	0	3.3	0	540.6	0	0
23	1009	2.7	0	0	0	0	0	88.3	3.8	0	0	0	0	0	0	0	0	0	0	0	0	0
23	1026	0	0	0	0	0	0	2.3	3.1	0	0	0	0	0	0	0	0	0	0	0	0	0
24	1632	2	6	0	0	0	0	49.7	26.6	0	0	0	0	0	0	0	0	0	0	0	0	0
24	1634	123	0	0	0	0	0	109.3	14.9	0	0	0	0	0	0	0	0	0	0	0	0	0
24	2401	0	0	0	0	0	0	152.5	0	0	0	0	0	0	0	0	0	0	0	24.3	0	0
24	2805	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	213	0	0
24	0501	43.3	0	26.7	0	0	0	176.2	78.1	3.5	6.7	16.4	0	0	0	0	0	0	0	0	0	0
24	0509	0	0	0	0	0	0	5.8	0	0	0	0	0	0	0	0	0	323.3	0	0	0	0
24	0559	0	0	0	0	0	0	165.2	0	0	0	0	0	0	0	0	14.9	0	0	0	0	0
24	0560	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	323.3	0	0	0	0	0
24	0561	0	0	0	0	0	0	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0562	0	0	0	0	0	0	116.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0563	0	0	0	0	0	0	74.9	0	0	0	0	0	0	0	0	305	0	0	0	0	0
25	1002	8.6	76.2	7.2	0	0	0	166	175.9	56.3	8.8	2.9	0	0	0	0	0	0	0	0	0	0
26	1012	0	12.3	302.6	0	0	0	9.3	58.3	24.2	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
27	1018	0	0	0	0	0	0	234	33.8	0	0	0	0	0	0	0	0	0	0	0	0	0
27	1028	0	0	0	0	0	0	7	57.1	359.9	0	0	0	0	0	0	0	0	0	0	0	0
27	6251	20.5	0.3	0	0	0	0	123.3	72.4	140.6	0	0	0	0	0	0	0.2	0	0	0	0	0
27	0504	0	0	0	0	0	0	55.9	176.1	57.4	0	0	0	0	0	0	0	0	0	0	0	0
27	0506	0	0	0	0	0	0	66.8	256.1	72	0	0	0	0	0	0	0	0	0	0	0	0
27	0507	0	0	0	0	0	0	70.2	128.9	111.4	0	0	0	0	0	0	0	0	0	0	0	0
28	1001	0	305	0	39.5	0	0	41.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	1802	0	0	0	0	0	0	41.5	37.5	45.2	0	0	0	0	0	0	75	0	0	0	0	0
28	3082	20.4	68.7	0	57.8	10.9	0	5.2	0	0	0	0	0	0	0	0	0	0	0	250	0	0
28	3093	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	3094	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0501	13.5	0	0	0	0	0	157	6.4	2	0	0	0	1	0	0	0	0	0	0	0	0
28	0502	20.3	45.5	0	24.3	0	0	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0503	2.2	0	0	80.7	0	0	159.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0504	0.5	0	0	0	0	0	12.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0505	17.7	0	0	0	0	0	56.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0506	25.9	5.6	0	0	0	0	71.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0507	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0508	33.1	0	0	0	0	0	150.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0509	102.4	28.2	0	0	0	0	9.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0560	28.6	1.1	0	69.3	0	0	33.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	1001	0	0	0	0	0	0	93.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	8129	0	0	0	0	0	0	8.5	230.6	7.6	0	0	0	0	0	0	0	0	0	0	0	0
32	1020	62.4	96.9	0	0	0	0	194.4	96.6	16.8	0	0	0	0	0	0	0	0	0	0	0	0
32	1021	47.4	19.9	202.4	0	0	0	13.2	5	123.4	0	1	0	0	0	0	274.3	0	0	0	0	0
32	2027	1.1	0	0	0	0	0	37.2	0	0	2.5	0	0	2	1	0	0	0	0	0	0	0
33	1001	80.9	41.5	0	0	0	0	37.3	4.6	0	0	0	0	0	0	0	0	0	0	0	0	0
34	1011	33	8.5	0	0	0	0	99.2	62.8	152.5	0	0.9	0	0	0	0	0	62.8	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
34	1030	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	1033	0	0	0	0	0	0	454.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	1034	12	7	0	0	0	0	9.9	16.3	116	0	0	0	0	0	0	0	0	0	0	0	0
34	1638	0	0	0	0	0	0	20.2	88.5	62	0	0	0	0	0	0	0	0	0	0	0	0
35	1003	0.1	0	0	0	0	0	51.9	126.6	58.7	0	0	0	0	0	0	0	0	0	0	0	0
35	1005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	213.5	0	0	0	0	0
35	1022	0	0	0	0	0	0	18.3	3.9	248	0	0	0	0	0	0	0	0	0	0	0	0
35	1112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	1028	168.7	0	0	0	0	0	36.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	1030	0	0	0	0	0	0	142.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	1802	2.9	0	0	0	0	0	57.9	0	0	1	0	0	0	0	0	0	0	0	0	0	0
37	2819	0	0	0	0	0	0	40.1	10.2	0	0	0	0	0	0	0	0	0	0	0	0	0
37	2824	0	0	0	0	0	0	15.7	0	0	0	0	0	0	0	0	0.1	0	0	0	0	0
40	1015	6.6	0	0	0	0	0	71.1	22	0	0	0	0	0	0	0	0	0	0	0	0	0
40	4086	0	0	0	0	0	0	8.7	10.1	34.3	0	0	0	0	0	0	0	0	0	0	0	0
40	4087	6.2	19.2	0	0	0	0	3.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	4154	22.1	0	0	0	0	0	32.2	152.5	0	0	0	0	0	0	0	0	0	0	0	0	0
40	4161	56.8	0	0	0	0	0	26.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	4163	0	0	0	0	0	0	52.1	49.3	0	0	0	0	0	0	0	0	0	0	0	0	0
40	4164	0	0	0	0	0	0	239.3	3.7	0	0	0	0	0	0	0	0	0	0	0	0	0
40	4165	3	0	0	0	0	0	22	7.4	0	0	0	0	0	0	0	0	0	0	0	0	0
42	1597	0	0	0	0	0	0	77.5	50	169.3	0.5	0.5	0	0	0	0	0	0	0	0	0	0
45	1011	160.6	3.8	13.9	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
45	1024	2.3	0	0	0	0	0	3.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	1025	36.4	67.1	0	0	0	0	6.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	9187	0	0	0	0	0	0	202.7	11	0	0	0	0	0	0	0	0	0	0	0	0	0
47	1023	0	0	0	0	0	0	23.3	8.5	0	0	0	0	0	0	0	0	0	0	0	0	0
47	1028	16.8	6.1	0	0	0	0	1.2	7.4	0	0	0	0	0	0	0	134.2	0	0	0	381.3	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
47	2001	0	0	0	0	0	0	147	16.1	14.7	0	0	0	0	0	0	0	0	0	0.1	0	0
47	2008	11.8	0	0	0	0	0	189.8	0	0	31.4	0	0	0	0	0	0	0	0	288	0	0
47	3075	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	3101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	3108	0	0	0	0	0	0	51.9	8.6	0	0	0	0	0	0	0	0	0	0	3.3	0	0
47	3110	0	0	0	0	0	0	144.4	0	0	0	0	0	0	0	0	48.1	0	0	0	0	0
47	9024	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	9025	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0001	0	1.7	0	0	0	0	335.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1047	2	0	0	0	0	0	141.4	135	0	0.4	0	0	0	0	0	0	0	0	0	0	0
48	1056	39.7	0	0	0	0	0	27.4	97.2	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1060	1.1	0	0	0	0	0	9.4	0.6	0	0	0	0	0	0	0	0.5	0	0	556	0.76	0
48	1065	0	0	0	0	0	0	118.9	214.6	11	0	0	0	0	0	0	0	0	0	0	0	0
48	1068	58.1	40.3	0	0	0	0	286.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1076	2	17.1	0	0	0	0	43.5	100.3	10.7	2.9	40.3	0	0	0	0	31.3	0	0	0	0	0
48	1077	1.2	0	0	0	0	0	293.6	9.2	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1087	0	0	0	0	0	0	472.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1092	0	0	0	0	0	0	3.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1093	59.4	0	0	0	0	0	73.1	0	0	5.1	0	0	0	0	0	495.6	0	0	0	0	0
48	1094	0.4	0	0	0	0	0	192.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1096	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1109	2.8	0	0	0	0	0	40.5	19.8	2	0	0	0	0	0	0	0	0	0	0	0	0
48	1111	0	0	0	0	0	0	126.8	57.2	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.7	0	0
48	1116	0	0	88.9	0	0	0	5.5	52.5	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1119	9.1	0	0	0	0	0	37.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1122	0	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1122	0	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
48	1130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1169	0	0	0	0	0	0	45.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	1174	45.7	0.6	0	0	0	0	10.3	0	0	0	0	0	0	0	0	457.5	0	0	0	0	0
48	1181	6.8	0	0	0	0	0	505.5	0	0				0	0	0	0	0	0	0	0	0
48	2133	32.6	0	0	0	0	0	35.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	2176	96.4	0	0	0	0	0	126.6	169	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3559	0	0	0	0	0	0	43	76.3	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3579	35.5	0	1.8	0	0	0	72	0	0	0	0	0	0	0	0	101.5	0	0	0	0	0
48	3669	3.7	0	0	0	0	0	208.3	65.3	0	0	1.8	0	0	0	0	0	0	0	0	0	0
48	3679	52.7	3.8	21	0	0	0	73.4	80	390.6	0.1	0	1.1	0	0	0	0	0	0	0	0	0
48	3689	0	0	0	0	338	226	0	0	0	0	0	1.6	0	0	3	0	0	0	0	0	0
48	3729	39.5	0	0	0	0	0	34.3	0	0	0	0	0	0	0	0	0	0	0	3.5	0	0
48	3739	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3749	10.7	31.9	139.7	0	0	0	2.1	4.6	0	0	27.4	45.1	0	0	0	0	0	0	0	0	0
48	3769	5.4	0	0	0	0	0	290.9	4.6	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3835	1	0	0	0	0	0	266.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3855	164.8	0	0	0	0	0	20.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3865	3.6	0	0	0	0	0	45.6	1	0	0	0	0	0	0	0	0	0	0	0	0	0
48	3875	8.7	4.4	0	0	0	0	38.8	4.3	0	0	0	0	0	0	0	152.5	0	0	0	0	0
48	9005	13	0	0	0	0	0	126	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	1001	0	0	0	0	0	0	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	1008	121.7	10.5	0	0	0	0	119.5	101.7	0	0	0	0	0	0	0	0	0	0	0	0	0
49	1017	29.7	53.6	71.9	0	0	297.8	1.4	20.6	18.2	0	0	0	0	0	0	0	0	0	0	0	0
50	1002	11.2	2.9	0	0	0	0	74.7	77.9	0	0	0	0	0	0	0	0	0	0	0	0	0
50	1004	36.3	62.6	0	0	0	0	65	39.9	142.5	0	0	0	0	0	0	0	0	0	0	0	0
51	1023	25.6	0	0	0	0	0	36.5	0	0	0	0	0	0	0	0	0	0	0	335.5	0	0
51	1417	163.7	103.2	23.5	0	0	0	45.3	76.3	27.5	0	0	0	0	0	0	0	0	0	183	0	0
51	1419	11.3	0	0	0	0	0	83.6	30.3	152.5	0	0	0	0	0	0	0	0	0	0	442.2	122

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
51	1464	0	0	0	0	0	0	55.3	125.1	52.5	0	0	0	3	0	0	152.5	0	0	0	427	0
53	1002	2.4	0	0	0	0	0	36.5	0	0	0	0	0	0	0	0	564	0	0	0	0	0
53	1005	0.1	0	0	0	0	0	165.4	31.3	17.9	0	0	0	0	0	0	0	0	0	0	0	0
53	1006	21.2	55.5	52.8	0	0	0	37.6	33.2	16.7	0	0	0	0	0	0	0	0	0	0	0	0
53	1008	0	0	0	0	0	0	16.3	48.7	0	0	0	0	0	0	0	0	0	0	0	305	0
53	1501	52.2	32.5	0	0	0	0	96	182.9	19.7	0	0	0	0	0	0	0	0	0	0	0	0
53	1801	17.4	2.8	0	0	0	0	203	88	273	0	0.4	2.5	0	0	0	0	0	0	0	0	0
56	1007	0	0	0	0	0	0	68.6	33	12.7	0	0	0	0	0	0	0	0	0	0	0	0
56	2015	3.3	0.5	0	0	0	0	197.5	4.6	129.8	0	0	0	0	0	0	0	283.6	36.7	0	0	0
56	2017	0	0	0	297.6	0	0	200.8	193.4	0	0	0	0	0	0	0	0	0	0	0	0	0
56	2019	0	0	0	0	0	0	37	7.6	0	0	0	0	0	0	0	0	0	0	0	0	0
56	2020	0	0	0	0	0	0	1	127.6	65.8	0	0	0	0	0	0	274.5	0	0	0	0	0
56	2037	0	2.1	0	0	0	0	61.8	35.2	107.5	0	0	0	0	0	0	0	0	0	0	0	0
56	7773	0	0	0	0	0	0	2.9	4.7	58.8	0	0	0	0	0	0	0	0	0	0	0	0
72	1003	0	336.1	0	0	0	0	3.4	5.1	0	200.1	0	0	0	0	0	0	0	0	0	564	0
72	4122	0	0	0	0	0	0	120.5	13.5	7.5	0	0	0	0	0	0	0	0	0	457.5	0	0
81	0501	0	1.4	0	0	0	0	23.8	4	4.7	0.1	0.5	4.4	0	5	8	0	0	0	0	0	0
81	0502	141.6	8	0	0	0	0	28.6	170.7	3.2	0	0	0	0	0	0	0	0	0	0	0	0.9
81	0503	153.4	3.1	0	0	0	0	6.9	39.4	116.1	0	0	0	0	0	0	0	0	0	0	0	5.7
81	0504	11.1	0	0	0	0	0	51.9	73.9	77.2	0	0	0	0	0	0	0	0	0	0	0	0
81	0505	14.6	0.8	0	0	0	0	133.4	17.5	0	0	0	0	0	0	0	0	0	0	0	0.4	0
81	0506	79.2	0	0	0	0	0	42.9	13.1	0	0	0	0	0	0	0	0	0	0	0	0	0
81	0507	2.7	0	0	0	0	0	79	100.5	2.5	1.5	0	0	0	0	0	0	0	0	0	0	0
81	0508	13.3	2.7	0	0	0	0	8.8	57.9	111.7	0	0	0	0	0	0	0	0	0	0	0	0
81	0509	96.3	10.2	3.4	0	0	0	15.1	81	57.8	0	0	0	0	1	0	0	0	0	0	0	0
81	1803	0	0	0	0	0	0	3.8	3.8	14.8	0.1	0	0	0	0	0	0	0	0	0	0	0
81	1805	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	2812	0	0	0	0	0	0	138.9	0	26.6	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
81	8529	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	A901	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	A902	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	A903	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	350.5	0	0	0	0	0
82	9017	12.7	18.9	2.8	0	0	0	36.5	65	462.5	0	0	0	0	0	0	0	0	0	563.9	0	0
82	6007	1.7	0	0	0	0	0	30.6	1.7	0	0	0	0	0	0	0	0	0	0	5.3	0	0
82	1005	0	0	0	0	0	0	12.6	23.3	187.1	0	0	0	0	0	0	0	0	0	0	0	0
82	6006	77.5	0	0	0	0	0	13.7	24.8	0	0	0	0	0	0	0	0	0	0	0	0	0
83	1801	0	0	0	0	0	0	172.9	68.1	3.6	7.2	0	0	0	0	0	0	0	0	0	0	0
83	6454	0	1.7	0	0	0	0	11.4	65	40.2	0	0	0	0	0	0	0	0	0	0	0	0
84	1684	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	6802	0.7	4.9	8.7	0	0	0	40.3	60.2	45.7	0.3	9.5	4.5	0	5	2	0	0	0	0	0	0
87	0901	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0902	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0903	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0960	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0961	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0962	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	1620	0	0	0	0	0	0	22.4	30.4	158.1	0	0	0	0	0	0	0	0	0	0	0	0
87	1622	0.5	30.2	0	0	0	0	97.5	197.2	8.4	0	0	0	0	0	0	0	0	0	0	0	0
87	1680	0	0	0	0	0	0	137.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	B310	10.9	0	0	0	0	0	36.6	165.7	0	0	0	0	0	0	0	0	0	0	0	0	0
87	B311	58.8	0	0	0	0	0	32.4	143.2	0	0	0	0	0	0	0	0	0	0	0	0	0
87	B320	1.7	22.1	0	0	0	0	227.7	207.4	45.3	0	0	0	0	0	0	0	0	0	0	0	0
87	B330	4.7	30.4	0	0	0	0	507.4	3.8	0	0	0	0	0	0	0	0	0	0	0	0	0
87	B340	14.2	137.4	0	0	0	0	38.2	44.8	156.1	0.2	0	0	0	0	0	0	0	0	0	0	0
87	B361	0	0	0	0	0	0	241.3	12	0	0	0	0	0	0	0	0	0	0	0	0	0
88	1645	0	0	0	0	0	0	22.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0

State Code	SHRPID	Alligator crack			Block cracking			Long. and Trans. cracking			Patching			Pothole			Bleeding			Ravelling		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
88	1646	44.8	37.6	0	0	0	0	49.4	19	0	0	0	0	0	0	0	273.4	46.6	0	0	0	0
88	1647	62.6	37.2	10.8	0	0	0	5.7	3.1	152.4	0	0	0	0	0	0	0	0	0	28.5	13.7	0
89	0901	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0902	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0903	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	A901	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	A902	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	A903	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0901	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0902	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0903	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0959	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	6405	0	61.8	0.7	0	0	0	125.9	54.3	70.1	0.4	0	0	0	0	0	0	0	0	0	0	0

L is low severity, M is medium severity and H is high severity.

Appendix B: Distress density of each section with pavement condition index PCI.

No.	State Code	SHRP ID	Alligator crack	Block crack	Long. & Trans.	Patching	Pothole	Bleeding	Ravelling	PCI
1	1	1001	1.9	0.0	3.5	0.0	0.0	0.0	0.0	83
2	1	1011	0.0	0.0	0.5	0.0	0.0	0.0	0.0	100
3	1	4073	1.9	87.1	3.9	0.2	0.0	0.0	0.0	64
4	1	4126	1.3	0.0	32.5	0.0	0.0	0.0	95.7	27
5	1	4127	0.0	0.0	0.7	0.0	0.0	0.0	0.0	100
6	1	4129	41.9	0.0	2.5	0.0	0.2	0.0	0.0	29
7	2	1001	0.0	0.0	8.4	2.1	0.0	0.0	0.0	81
8	2	1002	0.0	0.0	59.0	0.0	0.0	0.0	0.0	72
9	2	1004	0.0	0.0	19.6	0.0	0.0	0.0	0.0	79
10	2	9035	0.0	0.0	12.7	0.0	0.0	0.0	0.0	64
11	4	1007	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
12	6	1253	7.7	10.9	39.8	0.0	0.0	0.0	0.0	26
13	6	2038	1.0	0.0	45.4	0.0	0.0	0.0	0.0	77
14	6	7491	18.6	0.0	38.4	0.0	0.0	14.6	0.0	18
15	6	8149	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
16	6	8156	83.8	0.0	20.0	0.0	0.0	0.0	0.0	1
17	6	8534	0.0	0.0	2.3	0.0	0.0	0.0	0.0	98
18	6	8535	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
19	10	1450	0.0	0.0	78.6	0.0	0.0	78.7	0.0	59
20	15	1003	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
21	15	1006	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
22	15	1008	3.6	0.0	3.8	0.0	0.0	0.0	0.0	75
23	15	7080	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
24	20	1010	5.2	0.0	12.9	4.2	0.0	0.6	95.8	41
25	16	1001	10.1	0.0	27.5	0.0	0.0	0.0	0.0	48
26	16	1005	0.0	0.0	17.1	0.0	0.0	0.0	0.0	70
27	16	1007	42.7	0.0	34.2	0.0	0.0	0.0	0.0	32
28	16	1009	0.1	0.0	17.5	0.0	0.0	0.0	0.0	64
29	16	1010	7.5	0.0	25.8	0.0	0.2	0.0	0.0	56
30	16	1020	0.0	0.0	0.1	0.0	0.0	0.0	0.0	100
31	16	1021	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
32	16	9032	0.0	0.0	4.1	0.0	0.0	0.0	0.0	86
33	16	9034	0.4	0.0	12.6	0.0	0.0	0.0	0.0	90
34	23	1009	0.5	0.0	15.9	0.0	0.0	0.0	0.0	88
35	23	1026	0.0	0.0	1.0	0.0	0.0	0.0	0.0	99
36	25	1002	15.9	0.0	68.7	2.0	0.0	0.0	0.0	20
37	26	1012	55.8	0.0	16.3	0.0	0.0	0.0	0.0	17
38	27	1018	0.0	0.0	47.5	0.0	0.0	0.0	0.0	77
39	30	1001	0.0	0.0	16.6	0.0	0.0	0.0	0.0	89
40	30	8129	0.0	0.0	43.7	0.0	0.0	0.0	0.0	67
41	33	1001	22.3	0.0	7.6	0.0	0.0	0.0	0.0	35
42	32	1020	29.0	0.0	56.1	0.0	0.0	0.0	0.0	25
43	32	1021	49.1	0.0	25.8	0.2	0.0	50.0	0.0	3
44	32	2027	0.2	0.0	6.8	0.5	0.5	0.0	0.0	79
45	34	1011	7.6	0.0	57.3	0.2	0.0	11.4	0.0	26
46	34	1030	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
47	34	1033	0.0	0.0	99.3	0.0	0.0	0.0	0.0	69
48	34	1034	4.2	0.0	31.1	0.0	0.0	0.0	0.0	38
49	34	1638	0.0	0.0	30.3	0.0	0.0	0.0	0.0	55

No.	State Code	SHRP ID	Alligator crack	Block crack	Long. & Trans.	Patching	Pothole	Bleeding	Ravelling	PCI
50	35	1003	0.0	0.0	47.1	0.0	0.0	0.0	0.0	53
51	35	1005	0.0	0.0	0.0	0.0	0.0	40.0	0.0	89
52	35	1022	0.0	0.0	47.9	0.0	0.0	0.0	0.0	27
53	35	1112	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
54	37	1028	29.9	0.0	6.4	0.0	0.0	0.0	0.0	48
55	37	1030	0.0	0.0	25.3	0.0	0.0	0.0	0.0	86
56	37	1802	0.5	0.0	10.3	0.2	0.0	0.0	0.0	90
57	37	2819	0.0	0.0	8.9	0.0	0.0	0.0	0.0	92
58	37	2824	0.0	0.0	2.8	0.0	0.0	0.0	0.0	98
59	40	1015	1.2	0.0	16.5	0.0	0.0	0.0	0.0	85
60	40	4086	0.0	0.0	9.4	0.0	0.0	0.0	0.0	75
61	40	4087	4.5	0.0	0.6	0.0	0.0	0.0	0.0	69
62	40	4154	3.9	0.0	32.7	0.0	0.0	0.0	0.0	58
63	40	4161	10.1	0.0	4.6	0.0	0.0	0.0	0.0	62
64	40	4163	0.0	0.0	18.0	0.0	0.0	0.0	0.0	85
65	40	4164	0.0	0.0	43.1	0.0	0.0	0.0	0.0	79
66	40	4165	0.5	0.0	5.2	0.0	0.0	0.0	0.0	89
67	42	1597	0.0	0.0	52.6	0.2	0.0	0.0	0.0	47
68	45	1011	31.6	0.0	0.0	0.0	0.4	0.0	0.0	33
69	45	1024	0.4	0.0	0.7	0.0	0.0	0.0	0.0	94
70	45	1025	17.0	0.0	1.1	0.0	0.0	0.0	0.0	43
71	46	9187	0.0	0.0	36.9	0.0	0.0	0.0	0.0	82
72	47	1023	0.0	0.0	5.6	0.0	0.0	0.0	0.0	90
73	47	1028	4.1	0.0	1.5	0.0	0.0	23.8	67.6	52
74	47	2001	0.0	0.0	31.5	0.0	0.0	0.0	0.0	77
75	47	2008	2.1	0.0	33.6	5.6	0.0	0.0	51.0	69
76	47	3075	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
77	47	3101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
78	47	3108	0.0	0.0	10.7	0.0	0.0	0.0	0.6	90
79	47	3110	0.0	0.0	24.9	0.0	0.0	8.3	0.0	83
80	47	9024	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
81	47	9025	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
82	48	0001	0.3	0.0	57.9	0.0	0.0	0.0	0.0	74
83	48	1047	0.4	0.0	50.3	0.1	0.0	0.0	0.0	70
84	48	1056	7.0	0.0	22.1	0.0	0.0	0.0	0.0	58
85	48	1060	0.2	0.0	1.7	0.0	0.0	0.1	96.1	74
86	48	1065	0.0	0.0	61.1	0.0	0.0	0.0	0.0	62
87	48	1068	17.9	0.0	52.2	0.0	0.0	0.0	0.0	36
88	48	1076	3.4	0.0	27.4	7.7	0.0	5.5	0.0	47
89	48	1077	0.2	0.0	52.3	0.0	0.0	0.0	0.0	76
90	48	1087	0.0	0.0	81.6	0.0	0.0	0.0	0.0	74
91	48	1092	0.0	0.0	0.7	0.0	0.0	0.0	0.0	100
92	48	1093	10.5	0.0	13.0	0.9	0.0	87.8	0.0	58
93	48	1094	0.1	0.0	34.1	0.0	0.0	0.0	0.0	83
94	48	1096	0.0	0.0	0.1	0.0	0.0	0.0	0.0	100
95	48	1109	0.5	0.0	11.0	0.0	0.0	0.0	0.0	86
96	48	1111	0.0	0.0	32.6	0.0	0.0	0.0	0.0	78
97	48	1113	0.0	0.0	0.0	0.0	0.0	0.0	1.0	98
98	48	1116	15.8	0.0	10.3	0.0	0.0	0.0	0.0	39
99	48	1119	1.6	0.0	6.6	0.0	0.0	0.0	0.0	83
100	48	1122	0.0	0.0	0.2	0.0	0.0	0.0	0.0	100

No.	State Code	SHRP ID	Alligator crack	Block crack	Long. & Trans.	Patching	Pothole	Bleeding	Ravelling	PCI
101	48	1122	0.0	0.0	0.2	0.0	0.0	0.0	0.0	100
102	48	1130	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
103	48	1169	0.0	0.0	8.2	0.0	0.0	0.0	0.0	94
104	48	1174	8.4	0.0	1.9	0.0	0.0	83.3	0.0	63
105	48	1181	1.2	0.0	92.1	0.0	0.0	0.0	0.0	72
106	48	2133	5.9	0.0	6.5	0.0	0.0	0.0	0.0	67
107	48	2176	17.6	0.0	53.8	0.0	0.0	0.0	0.0	45
108	48	3559	0.0	0.0	21.7	0.0	0.0	0.0	0.0	82
109	48	3579	6.8	0.0	13.1	0.0	0.0	18.5	0.0	64
110	48	3669	0.7	0.0	48.5	0.3	0.0	0.0	0.0	74
111	48	3679	13.7	0.0	96.4	0.2	0.0	0.0	0.0	20
112	48	3689	0.0	100.0	0.0	0.3	0.5	0.0	0.0	21
113	48	3729	7.0	0.0	6.1	0.0	0.0	0.0	0.6	64
114	48	3739	0.4	0.0	0.0	0.0	0.0	0.0	0.0	94
115	48	3749	32.3	0.0	1.2	12.8	0.0	0.0	0.0	7
116	48	3769	1.0	0.0	52.4	0.0	0.0	0.0	0.0	75
117	48	3835	0.2	0.0	47.2	0.0	0.0	0.0	0.0	75
118	48	3855	29.2	0.0	3.7	0.0	0.0	0.0	0.0	51
119	48	3865	0.6	0.0	8.3	0.0	0.0	0.0	0.0	91
120	48	3875	2.3	0.0	7.6	0.0	0.0	27.0	0.0	71
121	48	9005	2.3	0.0	22.3	0.0	0.0	0.0	0.0	78
122	49	1001	0.0	0.0	9.0	0.0	0.0	0.0	0.0	94
123	49	1008	23.4	0.0	39.2	0.0	0.0	0.0	0.0	39
124	49	1017	27.5	52.8	7.1	0.0	0.0	0.0	0.0	3
125	50	1002	2.6	0.0	27.8	0.0	0.0	0.0	0.0	65
126	50	1004	17.5	0.0	43.8	0.0	0.0	0.0	0.0	23
127	51	1023	4.8	0.0	6.8	0.0	0.0	0.0	62.9	67
128	51	1417	51.5	0.0	26.4	0.0	0.0	0.0	32.4	19
129	51	1419	2.0	0.0	47.2	0.0	0.0	0.0	100.0	13
130	51	1464	0.0	0.0	41.3	0.0	0.5	27.0	75.7	38
131	53	1002	0.4	0.0	6.5	0.0	0.0	100.0	0.0	78
132	53	1005	0.0	0.0	38.0	0.0	0.0	0.0	0.0	72
133	53	1006	23.0	0.0	15.5	0.0	0.0	0.0	0.0	19
134	53	1008	0.0	0.0	11.5	0.0	0.0	0.0	54.1	62
135	53	1501	15.0	0.0	52.9	0.0	0.0	0.0	0.0	31
136	53	1801	3.6	0.0	100.0	0.5	0.0	0.0	0.0	23
137	56	1007	0.0	0.0	20.3	0.0	0.0	0.0	0.0	80
138	56	2015	0.7	0.0	60.5	0.0	0.0	58.3	0.0	35
139	56	2017	0.0	54.2	71.8	0.0	0.0	0.0	0.0	53
140	56	2019	0.0	0.0	8.6	0.0	0.0	0.0	0.0	92
141	56	2020	0.0	0.0	34.5	0.0	0.0	48.6	0.0	51
142	56	2037	0.4	0.0	36.2	0.0	0.0	0.0	0.0	53
143	56	7773	0.0	0.0	11.8	0.0	0.0	0.0	0.0	63
144	72	1003	59.6	0.0	1.5	35.5	0.0	0.0	100.0	14
145	72	4122	0.0	0.0	25.1	0.0	0.0	0.0	81.1	76
146	12	1030	0.0	90.2	0.0	0.0	0.0	0.0	0.0	72
147	12	1060	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
148	12	1370	6.4	0.0	2.8	0.3	0.0	0.0	0.0	63
149	12	3996	10.2	0.0	10.4	0.0	0.0	0.0	0.0	69
150	12	3997	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
151	12	4096	0.0	0.0	4.7	0.0	0.0	0.0	0.0	97

No.	State Code	SHRP ID	Alligator crack	Block crack	Long. & Trans.	Patching	Pothole	Bleeding	Ravelling	PCI
152	12	4097	0.0	0.0	11.0	0.0	0.0	0.0	0.0	84
153	12	4100	0.8	0.0	4.2	0.0	0.0	0.0	0.0	87
154	12	4103	0.0	0.0	54.1	0.0	0.0	0.0	13.5	80
155	12	4106	0.0	0.0	2.7	0.0	0.0	0.0	73.0	60
156	12	4107	27.0	0.0	0.5	0.0	0.0	0.0	7.3	27
157	12	4135	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
158	12	4136	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
159	12	4137	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
160	13	1001	17.3	0.0	40.6	0.0	0.0	0.0	0.0	52
161	13	1004	24.9	0.0	8.8	0.0	0.0	0.0	0.0	62
162	13	1005	2.7	0.0	51.3	0.0	0.0	0.0	0.0	70
163	13	1031	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
164	13	4092	0.3	0.0	38.2	0.0	0.0	0.0	0.0	71
165	13	4093	0.0	0.0	30.0	0.0	0.0	0.0	0.0	84
166	13	4096	0.1	0.0	0.9	0.0	0.0	0.0	0.0	99
167	13	4112	0.0	0.0	2.5	18.9	0.0	0.0	0.0	75
168	13	4113	0.8	0.0	3.1	9.4	0.2	0.0	0.0	79
169	13	4420	0.8	0.0	8.1	0.0	0.0	0.0	0.0	90
170	24	1632	1.4	0.0	13.2	0.0	0.0	0.0	0.0	80
171	24	1634	21.2	0.0	21.4	0.0	0.0	0.0	0.0	59
172	24	2401	0.0	0.0	26.3	0.0	0.0	0.0	4.2	83
173	24	2805	0.0	0.0	0.0	0.0	0.0	0.0	36.8	89
174	27	1028	0.0	0.0	75.1	0.0	0.0	0.0	0.0	32
175	27	6251	3.7	0.0	59.6	0.0	0.0	0.0	0.0	38
176	28	1001	54.1	7.0	7.4	0.0	0.0	0.0	0.0	48
177	28	1802	0.0	0.0	22.0	0.0	0.0	13.3	0.0	66
178	28	3082	15.8	12.2	0.9	0.0	0.0	0.0	44.3	47
179	28	3093	0.0	0.0	0.2	0.0	0.0	0.0	0.0	100
180	28	3094	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
181	12	0502	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
182	12	0503	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
183	12	0504	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
184	12	0505	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
185	12	0506	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
186	12	0507	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
187	12	0508	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
188	12	0509	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
189	12	0561	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
190	12	0562	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
191	12	0563	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
192	12	0564	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
193	12	0565	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
194	12	0566	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
195	13	0502	0.0	0.0	0.0	0.0	0.0	0.0	0.2	99
196	13	0503	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
197	13	0504	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
198	13	0505	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
199	13	0506	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
200	13	0507	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
201	13	0508	0.0	0.0	0.0	0.0	0.0	0.0	0.7	98
202	13	0509	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100

No.	State Code	SHRP ID	Alligator crack	Block crack	Long. & Trans.	Patching	Pothole	Bleeding	Ravelling	PCI
203	13	0560	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
204	13	0561	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
205	24	0501	12.4	0.0	45.7	4.1	0.0	0.0	0.0	29
206	24	0509	0.0	0.0	1.0	0.0	0.0	57.3	0.0	68
207	24	0559	0.0	0.0	29.3	0.0	0.0	2.6	0.0	83
208	24	0560	0.0	0.0	1.6	0.0	0.0	55.8	0.0	85
209	24	0561	0.0	0.0	8.5	0.0	0.0	0.0	0.0	94
210	27	0504	0.0	0.0	51.3	0.0	0.0	0.0	0.0	53
211	27	0506	0.0	0.0	70.0	0.0	0.0	0.0	0.0	47
212	27	0507	0.0	0.0	55.0	0.0	0.0	0.0	0.0	47
213	28	0501	2.4	0.0	29.3	0.0	0.2	0.0	0.0	67
214	28	0502	11.7	4.3	6.6	0.0	0.0	0.0	0.0	45
215	28	0503	0.4	14.3	28.3	0.0	0.0	0.0	0.0	82
216	28	0504	0.1	0.0	2.2	0.0	0.0	0.0	0.0	98
217	28	0505	3.1	0.0	10.0	0.0	0.0	0.0	0.0	80
218	28	0506	5.6	0.0	12.6	0.0	0.0	0.0	0.0	65
219	81	0501	0.2	0.0	5.3	0.8	2.1	0.0	0.0	36
220	88	1645	0.0	0.0	4.1	0.0	0.0	0.0	0.0	97
221	82	9017	6.1	0.0	100.0	0.0	0.0	0.0	99.9	11
222	88	1646	14.6	0.0	12.1	0.0	0.0	56.7	0.0	44
223	81	0502	25.2	0.0	34.0	0.0	0.0	0.0	0.2	41
224	82	6007	0.3	0.0	5.6	0.0	0.0	0.0	0.9	90
225	81	0503	26.3	0.0	27.3	0.0	0.0	0.0	1.0	29
226	81	0504	1.9	0.0	34.1	0.0	0.0	0.0	0.0	55
227	81	0505	2.6	0.0	25.4	0.0	0.0	0.0	0.1	75
228	81	0506	13.3	0.0	9.4	0.0	0.0	0.0	0.0	68
229	81	0507	0.5	0.0	30.6	0.3	0.0	0.0	0.0	73
230	81	0508	2.7	0.0	30.0	0.0	0.0	0.0	0.0	44
231	81	0509	18.5	0.0	25.9	0.0	0.2	0.0	0.0	26
232	81	1803	0.0	0.0	3.9	0.0	0.0	0.0	0.0	84
233	81	1805	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
234	81	2812	0.0	0.0	28.6	0.0	0.0	0.0	0.0	74
235	81	8529	0.4	0.0	0.0	0.0	0.0	0.0	0.0	94
236	81	A901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
237	82	1005	0.0	0.0	38.5	0.0	0.0	0.0	0.0	45
238	82	6006	13.4	0.0	6.6	0.0	0.0	0.0	0.0	63
239	83	1801	0.0	0.0	44.6	1.3	0.0	0.0	0.0	72
240	84	1684	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
241	86	6802	2.4	0.0	24.6	2.4	1.2	0.0	0.0	19
242	87	0901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
243	87	0902	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
244	87	0903	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
245	87	0960	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
246	87	0961	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
247	87	0962	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
248	87	1620	0.0	0.0	35.5	0.0	0.0	0.0	0.0	50
249	87	1622	5.4	0.0	53.7	0.0	0.0	0.0	0.0	45
250	87	1680	0.0	0.0	24.4	0.0	0.0	0.0	0.0	86
251	87	B310	2.0	0.0	36.8	0.0	0.0	0.0	0.0	62
252	87	B311	10.7	0.0	32.0	0.0	0.0	0.0	0.0	50
253	87	B320	4.3	0.0	87.5	0.0	0.0	0.0	0.0	35

No.	State Code	SHRP ID	Alligator crack	Block crack	Long. & Trans.	Patching	Pothole	Bleeding	Ravelling	PCI
254	87	B330	6.2	0.0	90.6	0.0	0.0	0.0	0.0	49
255	88	1647	19.6	0.0	28.6	0.0	0.0	0.0	7.5	11
256	89	0901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
257	89	0902	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
258	89	0903	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
259	89	A901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
260	89	A902	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
261	89	A903	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
262	90	0901	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
263	90	0902	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
264	90	0903	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
265	90	0959	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
266	90	6405	11.1	0.0	44.4	0.1	0.0	0.0	0.0	33
267	81	A902	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
268	81	A903	0.0	0.0	0.0	0.0	0.0	63.8	0.0	84
269	83	6454	0.3	0.0	20.7	0.0	0.0	0.0	0.0	61
270	87	B340	26.9	0.0	42.4	0.0	0.0	0.0	0.0	17
271	87	B361	0.0	0.0	46.1	0.0	0.0	0.0	0.0	80
272	4	0503	0.0	0.0	15.5	0.0	0.0	0.0	0.0	88
273	4	0504	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
274	4	0505	9.8	0.0	5.9	0.0	0.0	0.0	0.0	52
275	4	0506	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
276	4	0507	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
277	4	0508	0.0	0.0	0.2	0.0	0.0	0.0	0.0	100
278	4	0509	0.0	0.0	20.4	0.0	0.0	0.0	0.0	84
279	4	0559	0.0	0.0	1.2	0.0	0.0	0.0	0.0	99
280	4	0560	38.4	0.0	3.5	0.0	0.0	51.9	0.0	51
281	13	0562	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
282	13	0563	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
283	13	0564	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
284	13	0565	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
285	13	0566	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
286	24	0562	0.0	0.0	20.7	0.0	0.0	0.0	0.0	87
287	24	0563	0.0	0.0	13.3	0.0	0.0	54.1	0.0	84
288	28	0507	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100
289	28	0508	5.9	0.0	26.6	0.0	0.0	0.0	0.0	68
290	28	0509	23.1	0.0	1.6	0.0	0.0	0.0	0.0	41
291	28	0560	5.3	12.3	6.0	0.0	0.0	0.0	0.0	69

Appendix C: The parameters data of deterioration model for wet freeze – arterial.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
23	1001	01/11/1972	131	0.00	0	0	0	100
23	1001	11/08/1989	334	16.77	0	0	161.5	75
23	1001	29/08/1990	558	17.82	0	0	210.6	74
23	1001	26/08/1991	778	18.81	0	4.31	181.7	71
23	1001	28/04/1993	1007	20.49	0	0	135.1	79
23	1001	21/04/1995	1248	22.47	0	0	7	27
23	1001	05/10/1995	1489	22.92	3.1	0	0	93
23	1001	25/10/1995	1730	22.98	0	0	0	100
23	1001	23/09/1999	1960	26.89	0	0	0	86
23	1001	27/06/2000	2081	27.65	0	0	33.5	98
23	1001	27/06/2002	2239	29.65	0	0	42.2	47
23	1009	10/08/1989	186	18.94	0	8.85	160.3	77
23	1009	30/08/1990	269	19.99	0	0	194.2	80
23	1009	26/08/1991	352	20.98	0	7.3	213.8	63
23	1009	28/04/1993	438	22.66	0	41.13	221.3	55
23	1009	13/05/1993	524	22.70	0	156.8	13	53
23	1009	26/10/1995	616	25.15	2	0	32.9	94
23	1009	18/08/1997	710	26.96	0	2.7	99.1	85
23	1009	17/09/1998	805	28.04	0	0	173.3	71
23	1009	25/07/2001	877	30.90	0	5.5	281.3	74
23	1009	29/04/2004	989	33.66	0	68.7	387.3	23
23	1012	01/08/1985	531	0.00	0	0	0	100
23	1012	10/08/1989	1234	4.02	0	0	0	100
23	1012	30/08/1990	1714	5.08	0	0	2.2	100
23	1012	25/08/1991	2201	6.06	0	0	27.3	99
23	1012	28/04/1993	2731	7.74	0	0	11.1	100
23	1012	11/07/1994	3266	8.94	0	0	10	92
23	1012	26/10/1995	3816	10.23	0	0	24	96
23	1012	21/09/1998	4458	13.14	0	0	29.3	85
23	1012	28/06/2000	5207	14.91	0	0	4.6	100
23	1026	01/07/1973	52	0.00	0	0	0	100
23	1026	18/08/1989	157	16.13	0	0	7.9	99
23	1026	30/08/1990	323	17.16	0	0	8.2	99
23	1026	25/08/1991	490	18.15	0	0.3	19.9	94
23	1026	28/04/1993	661	19.82	0	0	11.8	98
23	1026	23/05/1994	834	20.89	0	0	21.9	90
23	1026	17/10/1994	1007	21.30	0	0	16.8	91
23	1026	01/05/1995	1182	21.83	0	0	20.9	89
23	1026	26/10/1995	1357	22.32	0	0	15.8	92
23	1026	02/05/1996	1534	22.84	0	0	29.2	84
23	1026	15/10/1996	1711	23.29	1.7	0	0	100
23	1026	13/05/1997	1902	23.87	0	0	10.4	99
23	1026	21/10/1997	2093	24.31	0	0	9.6	99
23	1026	11/06/1998	2284	24.94	0	0	60.2	91
23	1026	09/08/2001	2523	28.11	0	22.6	234.8	56
23	1028	01/11/1972	92	0.00	0	0	0	100
23	1028	18/08/1989	275	16.79	0	0	272.3	73
23	1028	30/08/1990	440	17.83	0	0	324.4	77

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
23	1028	25/08/1991	615	18.81	0	0	181.1	81
23	1028	27/04/1993	803	20.48	0	0.63	430.2	65
23	1028	03/05/1994	1003	21.50	0	33.3	432.9	37
23	1028	14/10/1994	1203	21.95	1.8	0	0	100
23	1028	26/10/1995	1413	22.98	0	0	9.5	100
23	1028	10/06/1998	1652	25.60	0	0	49.6	90
23	1028	08/08/2001	1832	28.77	0	0	108.3	87
23	1028	19/05/2004	2040	31.55	0	0	258.7	60
23	1028	26/08/2009	2287	36.82	0	0	319.7	38
23	1028	08/06/2011	2530	38.60	0	0.5	350.7	36
25	1002	01/05/1982	159	0.00	0	0	0	100
25	1002	02/08/1989	319	7.26	0	15.59	232.9	86
25	1002	06/09/1990	429	8.35	0	12.12	252.4	87
25	1002	21/08/1991	539	9.31	0	0.77	323.4	86
25	1002	01/10/1992	674	10.42	0	28.3	249	82
25	1002	11/05/1994	798	12.03	0	286	370.7	50
25	1002	24/08/1994	922	12.31	0	335.5	25.6	37
25	1002	24/05/1995	1051	13.06	0	488	138.2	39
25	1002	09/10/1996	1185	14.44	0	144.9	718.4	30
25	1002	07/05/1997	1324	15.02	0	175.8	335.7	26
25	1002	10/09/1997	1463	15.36	0	92	457.2	33
25	1002	24/05/2000	1620	18.06	0	306.3	200.4	40
25	1002	25/04/2002	1789	19.98	0	161.1	92.9	19
25	1002	10/06/2003	1965	21.11	0	329.4	240.8	17
25	1002	20/04/2004	2148	21.97	0	203.4	241.4	14
25	1003	01/09/1974	36	0.00	0	0	0	100
25	1003	04/08/1989	83	14.92	0	0	586.9	72
25	1003	06/09/1990	105	16.01	0	1.57	589.5	70
25	1003	23/08/1991	128	16.97	0	2.62	585.7	70
25	1003	30/09/1992	159	18.08	0	13.8	579.1	60
25	1003	27/10/1995	235	21.15	0	11.16	608.5	61
25	1003	23/10/1996	329	22.14	0	122.1	159.1	55
25	1003	16/06/1998	405	23.79	0	108.7	261.4	42
25	1004	01/07/1974	88	0.00	0	0	0	100
25	1004	04/08/1989	409	15.09	0	0	15.6	100
25	1004	05/09/1990	581	16.18	0	0	28.6	99
25	1004	22/08/1991	719	17.14	0	0	26.7	99
25	1004	30/09/1992	873	18.25	0	0	30.5	99
25	1004	29/10/1995	1055	21.33	0	0	36.9	98
25	1004	05/06/1997	1252	22.93	0	5.2	114.2	87
25	1004	15/06/1998	1626	23.96	0	0	102.8	79
25	1004	31/05/2000	1835	25.92	0	1.6	114.4	80
25	1004	23/04/2002	2052	27.81	1.8	0	0	100
25	1004	01/10/2002	2269	28.25	2	0	0	100
25	1004	29/09/2009	2514	35.25	0	5.4	309.2	77
33	1001	01/01/1981	26	0.00	0	0	0	100
33	1001	10/08/1989	229	8.61	0	0	1.4	100
33	1001	04/09/1990	384	9.67	0	0	11.3	100
33	1001	23/08/1991	419	10.64	0	1.15	66.3	94
33	1001	01/10/1992	480	11.75	0	12.32	35.2	86

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
33	1001	26/05/1994	660	13.40	0	77.5	23.3	71
33	1001	16/08/1994	840	13.62	0	31.8	41.4	78
33	1001	01/06/1995	1020	14.41	0	117.5	25	60
33	1001	13/11/1996	1211	15.87	0	66.9	131.5	72
33	1001	14/05/1997	1427	16.36	0	122.4	101.9	51
33	1001	22/10/1997	1643	16.80	0	117.2	108.2	51
33	1001	28/06/2000	1879	19.49	0	0	117.7	93
33	1001	28/09/2000	2115	19.74	0	268.3	115.6	40
33	1001	27/09/2001	2385	20.74	0	134.4	96.1	44
33	1001	08/04/2002	2682	21.26	0	154.9	110	41
33	1001	25/11/2003	2993	22.90	3.5	0	0	100
33	1001	16/04/2009	3374	28.29	0	19.7	256	78
34	1011	05/10/1989	176	19.60	0	0	211.8	85
34	1011	12/09/1990	358	20.53	0	0	233	87
34	1011	05/04/1992	573	22.10	0	0	208.8	70
34	1011	24/02/1993	937	22.99	0	0	223.4	82
34	1011	03/11/1995	1243	25.68	0	0.18	486.7	65
34	1011	29/07/1997	1622	27.41	0	41.5	451.5	43
34	1011	14/10/1999	2106	29.62	4.5	0	0	100
34	1011	17/07/2000	2534	30.38	0	0	15.6	100
34	1011	29/09/2002	2951	32.58	0	0	0	100
34	1011	10/10/2007	3411	37.61	0	410.4	97	19
34	1011	09/05/2009	4551	39.19	0	473	139.3	17
34	1030	28/07/1989	59	20.07	0	516.4	96.3	58
34	1030	11/09/1990	121	21.20	0	287.3	205.1	51
34	1030	15/08/1991	183	22.12	0	132.5	427.4	54
34	1030	28/09/1992	251	23.24	0	104.97	314.5	58
34	1030	30/10/1995	436	26.33	0	90.45	436.4	37
34	1030	22/07/1997	537	28.06	4	0	0	100
34	1030	11/05/1999	744	29.86	0	0	0	100
34	1030	18/07/2000	806	31.05	0	0	25.5	99
34	1030	26/09/2001	880	32.24	0	21.7	150.8	76
34	1030	10/11/2005	957	36.36	0	189.6	331.3	13
34	1030	26/06/2007	1013	37.98	0	233.7	263.9	15
36	1011	08/08/1989	296	5.19	0	0	277.4	78
36	1011	10/09/1990	646	6.28	0	37.61	262.5	63
36	1011	18/08/1991	758	7.21	0	0.26	380.5	72
36	1011	23/04/1993	867	8.89	0	486.11	40.4	72
36	1011	17/08/1993	976	9.21	0	342.1	176.1	43
36	1011	09/10/1995	1106	11.35	4	0	67.7	96
36	1011	05/08/1998	1461	14.18	0	0	270.5	86
36	1011	22/06/1999	1826	15.06	0	8.5	305.5	69
36	1011	25/05/2004	2245	19.98	0	21.8	305	50
42	1597	01/09/1980	16	0.00	0	0	0	100
42	1597	25/08/1989	35	8.98	0	0	37.8	95
42	1597	16/07/1990	56	9.87	0	0	378.7	76
42	1597	07/08/1991	75	10.93	0	0	386.8	76
42	1597	18/05/1992	96	11.71	0	0	69.6	85
42	1597	01/03/1993	116	12.50	0	0	51.2	78
42	1597	07/06/1994	132	13.76	0	0.5	202.2	66

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
42	1597	13/09/1995	152	15.03	0	0.2	285.3	61
42	1597	17/07/1996	175	15.87	0	0	752.6	63
42	1597	02/09/1997	196	17.00	0	0.2	285.3	33
42	1597	20/04/2000	215	19.63	0	3.6	410.8	27
42	1597	18/06/2000	234	19.79	0	0	688.8	58
42	1597	08/11/2000	253	20.19	6	0	0	100
42	1597	17/07/2003	263	22.87	0	0	12.7	99
42	1597	16/08/2007	296	26.95	0	49.5	95.1	64
42	1597	09/06/2009	332	28.77	0	98.9	240.8	42
42	1597	17/08/2011	367	30.96	0	289.8	408.9	0
42	1599	01/08/1987	40	0.00	0	0	0	100
42	1599	29/08/1989	81	2.08	0	0	0	100
42	1599	27/09/1990	163	3.16	0	0	0	100
42	1599	07/08/1991	242	4.02	0	0	13.8	99
42	1599	01/03/1993	323	5.58	0	0	0	100
42	1599	01/09/1994	402	7.09	0	0	1	100
42	1599	21/06/1995	536	7.89	0	0	3.5	100
42	1599	19/07/1996	610	8.97	0	0	16.7	98
42	1599	26/03/1998	779	10.65	0	0.8	27.9	95
42	1599	17/08/2000	970	13.05	0	0.2	91	79
42	1599	12/06/2002	1110	14.86	0	0	58.5	93
42	1599	24/04/2003	1238	15.73	0	0.3	57	77
42	1599	10/08/2005	1403	18.03	0	1.1	72.8	74
42	1599	01/09/2009	1538	22.09	0	44.3	91.4	46
42	1599	16/08/2011	1712	24.04	2.5	0	0	100
42	1605	01/09/1971	152	0.00	0	0	0	100
42	1605	29/08/1989	371	17.99	0	0	173.7	85
42	1605	26/09/1990	718	19.07	0	0	23.1	98
42	1605	08/08/1991	1206	19.93	0	0	22	96
42	1605	20/05/1992	1399	20.72	0	5.9	19.1	77
42	1605	25/05/1993	1625	21.73	0	1.33	50.4	91
42	1605	22/11/1993	1851	22.23	0	3.3	31	84
42	1605	26/04/1994	2274	22.65	0	16.5	47.5	79
42	1605	19/04/1995	2858	23.63	0	0	128	62
42	1605	25/10/1995	3442	24.15	2	0	0	100
42	1605	04/06/1998	3799	26.76	0	0	71.6	90
42	1605	07/06/2000	4149	28.77	0	0	157.1	79
42	1605	10/05/2002	4595	30.69	0	0	425.8	74
50	1002	01/08/1984	43	0.00	0	0	0	100
50	1002	09/08/1989	139	5.02	0	0	0	100
50	1002	08/08/1990	224	6.02	0	0	0.8	100
50	1002	04/09/1991	311	7.09	0	0	22.7	97
50	1002	27/04/1993	322	8.74	0	0	98.8	88
50	1002	25/05/1994	355	9.81	0	73.9	64.8	62
50	1002	17/08/1994	388	10.04	0	28.4	57	73
50	1002	27/04/1995	463	10.74	0	64.3	94.1	62
50	1002	12/10/1995	538	11.20	0	0	76.5	90
50	1002	17/10/1996	617	12.21	0	33	169.9	54
50	1002	15/05/1997	693	12.79	0	14.1	253.6	61
50	1002	23/10/1997	769	13.23	0	73.2	172.8	47

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
50	1002	09/06/1998	830	13.85	0	66.6	171.9	44
50	1002	29/09/1999	877	15.16	0	100.3	119.5	42
50	1002	23/11/1999	924	15.31	0	181.8	133.9	33
50	1002	08/03/2000	982	15.60	0	140.2	157.3	36
50	1002	29/06/2000	1040	15.91	0	2.3	322.4	69
50	1002	06/09/2000	1098	16.10	0	77.4	209.9	36
50	1002	05/06/2001	1179	16.84	0	62.1	250.7	38
50	1002	13/09/2001	1260	17.12	0	114	164.4	32
50	1002	23/10/2002	1323	18.23	0	130.3	167.1	28
50	1002	29/04/2003	1375	18.74	0	162.1	172.5	22
50	1002	26/11/2003	1427	19.32	0	163.9	197.7	22
50	1004	09/08/1989	60	4.94	0	0	101.8	89
50	1004	07/08/1990	109	5.93	0	0.57	114.1	87
50	1004	20/09/1991	161	7.05	0	22.86	139.6	73
50	1004	27/04/1993	205	8.65	0	4.35	209.3	75
50	1004	12/10/1995	255	11.11	0	3.22	237.3	73
50	1004	04/11/1997	295	13.17	0	98.9	412.4	17
50	1004	14/07/1999	305	14.86	0	176.4	197.2	34
50	1004	25/05/2000	343	15.73	0	139.7	604.8	23
50	1004	28/06/2000	381	15.82	0	1.65	874.6	67
50	1004	17/05/2001	478	16.71	0	0	29.6	75
50	1004	15/08/2001	575	16.95	2.5	0	0	100
50	1004	18/05/2004	634	19.71	0	0	54.2	93
50	1004	22/08/2007	657	22.97	0	0	128.5	74
50	1004	16/06/2009	680	24.79	0	0	169	72
50	1004	07/06/2011	727	26.76	0	0	143.6	73

Appendix D: The parameters data of deterioration model for wet freeze – collector.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
9	1803	01/07/1985	21	0.00	0	0	0	100
9	1803	31/07/1989	50	4.08	0	0	6.3	96
9	1803	05/09/1990	91	5.18	0	0	165.4	85
9	1803	22/08/1991	158	6.14	0	0	19.1	94
9	1803	30/09/1992	225	7.25	0	0.67	111.4	87
9	1803	12-May-94	250	8.86	0	19.6	126.8	73
9	1803	25-Aug-94	275	9.15	0	1.1	78.4	89
9	1803	25-May-95	311	9.90	0	22.3	237.4	64
9	1803	08-Oct-96	380	11.27	0	15.4	694.6	57
9	1803	08-May-97	449	11.85	0	28	910.2	59
9	1803	11-Sep-97	518	12.20	0	31.6	493.9	49
9	1803	17-Jun-98	587	12.96	0	18.1	766	61
9	1803	02-May-00	648	14.84	0	27.7	761.5	55
9	1803	23-Jun-00	709	14.98	2	0	0	100
9	1803	19/07/2000	770	15.05	0	0	0	100
9	1803	11-Jun-03	801	17.94	0	8.8	91.7	79
9	1803	22-Apr-04	825	18.81	0	11.7	98	73
9	1803	13-Jun-07	849	21.95	0	25.8	138.2	66
42	1618	23-Jun-89	18	0.56	0	0	78.5	85
42	1618	17/07/1989	34	0.62	0	0	0	74
42	1618	25/09/1990	52	1.82	6	0	0	100
42	1618	05/08/1991	69	2.67	0	0	0	100
42	1618	29/09/1992	87	3.83	0	0	8.4	100
42	1618	18/08/1996	116	7.71	0	0	395.2	81
42	1618	11-Aug-98	139	9.69	0	5.2	482.4	41
42	1618	25/07/2000	155	11.65	0	0	335.9	76
42	1618	24-Apr-02	178	13.39	0	5.2	456.4	43
29	1002	01/04/1986	9	0.00	0	0	0	100
29	1002	21/06/1989	20	3.22	0	0.41	164.3	83
29	1002	20-Jun-90	30	4.22	0	0.47	179.3	81
29	1002	10-Dec-91	41	5.69	0	1.59	198.2	71
29	1002	06/05/1992	53	6.10	0	5.2	254	67
29	1002	01/04/1993	65	7.00	0	1.2	272.5	63
29	1002	04/05/1993	77	7.09	0	8.1	273.9	44
29	1002	11-Jul-95	91	9.28	0	8.1	322.2	51
29	1002	17-Apr-96	106	10.05	0	0.57	333.2	45
29	1002	17-Mar-00	120	13.96	0	215	352.8	4
29	1002	13/02/2003	142	16.87	0	200.4	377.2	11

Appendix E: The parameters data of deterioration model for wet non freeze – arterial.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
18	1028	01/01/1975	685	0.00	0	0	0	100
18	1028	05/11/1989	3631	14.84	0	0.51	391.8	81
18	1028	28/06/1990	5698	15.49	0	0.37	275.2	84
18	1028	09/05/1991	7789	16.35	0	1.79	372.4	80
18	1028	11-Jul-91	9880	16.52	0	41.7	46.9	76
18	1028	19-Dec-91	11971	16.96	0	61.5	55.8	72
18	1028	01-May-92	14133	17.33	0	59.9	49.6	73
18	1028	18-Mar-93	16366	18.21	0	71.4	187.6	69
18	1028	27/05/1994	16771	19.40	0	1.31	345.5	74
18	1028	05-Apr-95	19146	20.26	0	84.1	235.9	68
18	1028	09-Nov-05	22293	30.86	6	0	161.3	90
18	1028	12/06/2012	22672	37.45	0	0	344.7	84
18	1037	01/01/1983	75	0.00	0	0	0	100
18	1037	01/01/1987	159	4.00	0	0	0	100
18	1037	06/11/1989	251	6.85	0	226.46	487.1	76
18	1037	09/05/1991	352	8.35	0	319.4	359.1	74
18	1037	06/10/1992	561	9.76	0	213.9	604.8	74
18	1037	23/03/1993	672	10.22	0	557.8	0	67
18	1037	11/05/1994	790	11.36	0	255.4	307.7	68
18	1037	27/05/1994	933	11.40	0	476.83	91.4	73
18	1037	13/10/1994	1051	11.78	1	0	0	100
18	1037	23/03/1996	1215	13.22	0	0	252.7	86
18	1037	10/02/1999	1366	16.11	0	0	183.8	88
18	1037	25/08/2005	1546	22.65	1	0	4.3	100
18	1037	13/10/2011	1599	28.78	0	6.6	368.5	75
20	1009	01/01/1985	61	0.00	0	0	0	100
20	1009	01-Jan-87	119	2.00	0	0	0	100
20	1009	02/05/1989	186	4.33	0	0.41	27.4	95
20	1009	10/12/1990	244	5.94	0	0.69	108.4	85
20	1009	26/10/1991	312	6.81	0	1.35	114	78
20	1009	08/04/1993	385	8.27	0	3.8	152.4	66
20	1009	14-Apr-95	464	10.28	0	5.2	216.3	59
20	1009	26-Apr-96	546	11.32	14	0	0	100
20	1009	26/04/1996	628	11.32	0	0	0	100
20	1009	13-Jan-99	720	14.03	0	152.6	0	40
20	1009	06-Oct-03	828	18.76	0	132.3	169.3	53
21	1014	01/06/1985	292	0.00	0	0	0	100
21	1014	17/10/1989	923	4.38	0	0	201.6	88
21	1014	02/05/1991	1344	5.92	0	0	190.7	86
21	1014	30/09/1992	1475	7.33	0	0	118.5	90
21	1014	15-Dec-94	1963	9.54	0	0	33.5	90
21	1014	30/11/1995	2170	10.50	0	0.76	212.6	78
21	1014	18-Mar-99	2792	13.79	0	3.9	66.5	70
21	1014	25-May-00	3445	14.98	0	10.6	75.3	65
21	1034	01/02/1973	8	0.00	0	0	0	100
21	1034	05/11/1989	56	16.76	0	0	128.3	92
21	1034	29/06/1990	177	17.40	0	0.3	84	91

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
21	1034	07/05/1991	304	18.26	0	0	128.8	92
21	1034	10-Jul-91	431	18.43	0	0	19.6	99
21	1034	17-Aug-92	564	19.54	0	0	19.6	99
21	1034	06/10/1992	697	19.68	0	0	54.4	95
21	1034	10-Mar-93	837	20.10	0	0	21.8	98
21	1034	30/05/1994	984	21.32	1	0	0	100
21	1034	09-Dec-94	1131	21.85	0	0	0	100
21	1034	22/03/1996	1293	23.13	0	0	159	91
21	1034	03-Feb-98	1472	25.00	0	0	163.8	90
21	1034	16/11/2000	1605	27.79	0	0	0	100
21	1034	02-Nov-05	1857	32.75	0	0	304.5	72
29	1005	01/05/1974	53	0.00	0	0	0	100
29	1005	20/06/1990	207	16.14	0	0.57	1012.5	71
29	1005	10/12/1991	366	17.61	0	0.92	776	72
29	1005	05-May-92	563	18.01	0	0.9	983.2	71
29	1005	01/04/1993	710	18.92	0	0.76	526.1	78
29	1005	05-May-93	857	19.01	0	63.8	596	63
29	1005	12-Jul-95	1032	21.20	0	63.8	598	63
29	1005	17/04/1996	1220	21.96	0	1.58	789.2	73
29	1005	14-Mar-00	1433	25.87	0	218.7	383.2	34
29	1005	20/11/2000	1646	26.56	0	2.06	961.7	70
29	1005	13-Feb-03	1880	28.79	0	199.7	575.4	17
29	1005	26-Apr-05	2101	30.99	0	218	638.2	40
29	1008	01/04/1986	141	0.00	0	0	0	100
29	1008	13/03/1989	304	2.95	0	0.388	224.9	80
29	1008	30/10/1990	345	4.58	0	0.63	186.7	82
29	1008	03/11/1991	396	5.59	0	2.16	232.2	79
29	1008	16-Feb-92	449	5.88	0	3.8	245	79
29	1008	05/03/1993	504	6.93	0	15.05	259.1	68
29	1008	29-Mar-93	559	6.99	0	0	268.7	78
29	1008	17/04/1996	611	10.05	0	0	328.1	68
29	1008	01-Feb-00	665	13.84	0	100.3	243.8	39
29	1008	17/12/2000	719	14.71	0	4.15	878.8	69
29	1008	19-Feb-03	779	16.89	0	507.3	19	28
29	1010	01/08/1980	931	0.00	0	0	0	100
29	1010	01-Jan-87	2042	6.42	0	0	0	100
29	1010	10/06/1989	3264	8.86	0	0	499	71
29	1010	16/12/1991	4016	11.37	0	0	508.7	66
29	1010	26-Mar-93	4877	12.65	0	0	216.6	76
29	1010	01/04/1993	5738	12.67	0	0	492.5	50
29	1010	17/04/1996	6598	15.71	0	0	525.2	40
29	1010	13-Mar-00	7784	19.61	5.7	0	0	100
29	1010	20/11/2000	8970	20.30	0	0	0	100
29	1010	13-Feb-03	10240	22.54	0	0	305	86

Appendix F: The parameters data of deterioration model for wet non freeze - collector.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
21	1010	01/05/1985	16	0.00	0	0	0	100
21	1010	27/10/1989	35	4.49	0	0	0	100
21	1010	28-Jun-90	48	5.16	0	0	10.9	99
21	1010	08/05/1991	61	6.02	0	0	11	99
21	1010	09/07/1991	74	6.19	0	0	0	100
21	1010	18/08/1992	87	7.30	0	0.4	0	97
21	1010	30/09/1992	100	7.42	0	1.06	4.8	97
21	1010	09/03/1993	114	7.85	0	0	19	98
37	1802	01/10/1985	45	0.00	0	0	0	100
37	1802	19/03/1991	110	5.46	0	1.3	1	90
37	1802	10-Oct-92	157	7.03	0	7.94	11.8	81
37	1802	15/04/1994	204	8.54	0	247.1	2.3	51
37	1802	18-Jul-95	254	9.79	0	168.1	93.5	43
37	1802	09/02/1996	288	10.36	0	56.1	281.5	39
37	1802	02/04/1996	322	10.50	0	261.4	43.8	32
37	1802	11/12/1996	356	11.20	1.2	46.9	40.6	68
37	1802	10-Oct-97	400	12.02	0	2.9	57.9	84
37	1802	15/01/2002	460	16.29	0	582.2	0	9
45	1024	01/08/1985	1	0.00	0	0	0	100
45	1024	09-Jan-90	2	4.44	0	0	49.1	95
45	1024	05-Mar-91	4	5.59	0	0	73.4	92
45	1024	16-Mar-92	6	6.62	0	0	0	100
45	1024	16-Jul-92	8	6.96	0	0	0	100
45	1024	07-Jun-93	10	7.85	0	0	6.5	100
45	1024	27-Jan-96	12	10.49	0	0	1.6	100
45	1024	23-Jun-97	14	11.89	0	2.3	4.7	93
45	1024	09-Feb-99	16	13.52	0	2.6	6.9	87
45	1024	10-Mar-01	18	15.61	0	2.44	33.9	91
45	1024	28-Feb-02	20	16.58	0	7.3	11.7	76
45	1024	23-Apr-04	23	18.73	0	7.3	12.3	76
45	1024	24-Jul-06	26	20.98	0	8.4	9	73
45	1024	18-May-12	29	26.80	0	11.4	10.9	72

Appendix G: The parameters data of deterioration model for dry freeze – arterial.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
2	1004	01/08/1977	43	0.00	0	0	0	100
2	1004	08-Jul-88	172	10.93	0	0	0	100
2	1004	04-Jun-90	272	12.84	0	0	106.8	76
2	1004	19-Aug-91	372	14.05	1.8	0	0	100
2	1004	27-Aug-93	480	16.07	0	0	110.2	88
2	1004	13-Jun-95	550	17.86	0	0	121.3	77
2	1004	19-Aug-97	624	20.05	0	0	137.8	80
2	1004	22/06/1999	698	21.89	0	0.5	326.9	83
2	1004	10/07/2001	773	23.94	0	0	202.3	82
2	1004	12/06/2003	843	25.86	0	0.3	157	77
2	1004	03-May-05	914	27.75	0	2	167.6	55
8	1029	01/06/1972	15	0.00	0	0	0	100
8	1029	28-Jul-88	33	16.16	0	0	0	100
8	1029	20-Oct-89	50	17.39	0	0	489.6	67
8	1029	25-Aug-91	77	19.23	0	0	415	63
8	1029	21-Oct-91	104	19.39	0	13.8	178.9	63
8	1029	15/07/1994	118	22.12	0	0	524.7	71
8	1029	08-Sep-95	123	23.27	0	19.7	227	53
8	1029	09-May-96	133	23.94	0	0	117.2	15
8	1029	13-Oct-98	149	26.37	0	19.2	107.7	50
8	1029	19/10/2000	177	28.38	0	15.03	109.1	33
8	1029	21-Aug-01	205	29.22	0	18.6	202.9	40
8	1029	29-Apr-03	236	30.91	0	61.5	246.8	14
8	1029	23-Oct-03	267	31.39	4	0	0	100
8	1029	15-Aug-07	352	35.20	0	0.4	72.8	83
8	1029	26-Oct-10	466	38.40	0	1.4	113.7	80
8	1029	26/10/2010	580	38.40	0	1.4	89.7	83
8	1029	19/09/2011	694	39.30	0	0.5	61.6	61
8	1053	01/02/1984	61	0.00	0	0	0	100
8	1053	27-Jul-88	118	4.48	0	0	0	100
8	1053	19/10/1989	179	5.71	0	0	0	93
8	1053	07/07/1990	216	6.43	0	0	78.2	88
8	1053	13-Apr-93	276	9.20	0	8.7	22.2	71
8	1053	04/11/1993	336	9.76	0	0	85.7	89
8	1053	06-Dec-93	396	9.85	0	4.1	63.5	73
8	1053	14/03/1994	471	10.11	0	0.7	54.6	68
8	1053	21/10/1994	546	10.72	0	9.9	19.5	54
8	1053	13-Feb-95	636	11.03	0	24.8	26.2	53
8	1053	08-May-95	726	11.26	0	24.5	97.1	55
8	1053	10/05/1996	821	12.27	0	0	49.9	90
8	1053	21/10/1996	916	12.72	0	28.8	17.2	69
8	1053	14/11/1996	1011	12.79	0	26.6	19.9	79
8	1053	07/03/1997	1045	13.10	0	31	23.4	56
8	1053	20/03/1997	1079	13.13	0	44.8	28.8	66
8	1053	05/08/1997	1113	13.51	0	32.4	23.9	77
8	1053	24/08/1998	1143	14.56	0	30	28.6	75
8	1053	12-May-00	1265	16.28	0	23.3	50.7	65
8	1053	19/10/2000	1387	16.71	0	0	47.7	96

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
8	1053	13-Apr-01	1511	17.20	0	18.3	58.4	65
8	1053	30-Oct-01	1635	17.74	4.1	0	0	100
8	1053	21-Oct-03	1952	19.72	0	0	66.5	96
8	1053	20-Aug-07	2281	23.55	0	23.3	309	70
8	1053	29-Sep-09	2508	25.66	0	38.1	334.4	66
8	1053	27-Oct-10	2735	26.74	0	41.2	360.2	51
8	1057	01/05/1985	30	0.00	0	0	0	100
8	1057	27-Jul-88	65	3.24	0	0	0	100
8	1057	19/10/1989	100	4.47	0	0	13.1	100
8	1057	07/07/1990	149	5.18	0	0	119.5	93
8	1057	24/10/1991	237	6.48	0	0	103.1	94
8	1057	04/11/1993	406	8.51	0	0	8	100
8	1057	18-Jul-94	447	9.21	0	0	69	95
8	1057	10/05/1996	504	11.03	0	3.74	274.4	83
16	1007	01/06/1972	35	0.00	0	0	0	100
16	1007	22-Jul-88	66	16.14	0	0	0	100
16	1007	20/09/1989	98	17.30	0	0	506.8	74
16	1007	19/07/1990	155	18.13	0	0.98	604.1	69
16	1007	26/07/1991	185	19.15	0	3.18	509.3	73
16	1007	12/08/1993	233	21.20	0	26.51	415.6	59
16	1007	04/06/1996	250	24.01	0	135.67	334.6	61
16	1007	01-May-97	306	24.91	0	247.7	227.1	29
16	1007	05-May-98	372	25.92	3.5	0	0	100
16	1007	08/05/2001	399	28.93	0	0	0	47
16	1007	01/05/2003	456	30.91	0	0	0	100
16	1007	18/10/2007	513	35.38	0	0	1.4	100
16	1007	08/07/2009	618	37.10	0	0	4.8	100
16	1007	23/08/2010	723	38.23	0	0	13.4	99
16	1007	22/06/2011	828	39.06	0	0	19.3	94
16	1009	01/10/1974	48	0.00	0	0	0	100
16	1009	21-Jul-88	242	13.80	0	0	0	100
16	1009	20/09/1989	453	14.97	0	0	79.1	77
16	1009	19/07/1990	845	15.80	0	0	65.1	93
16	1009	26/07/1991	1243	16.82	0	0	80.9	92
16	1009	08-Jul-92	1736	17.77	0	2.1	75.4	90
16	1009	16/10/1993	2376	19.04	0	0	143.7	81
16	1009	05/06/1996	2811	21.68	0	0	302.6	69
16	1009	25-Jul-97	3557	22.81	0	0.8	125.7	68
16	1009	10-Aug-99	4404	24.86	0	1.3	131.2	72
16	1009	14/10/2000	4905	26.04	0	0	121.6	86
16	1010	01/10/1969	30	0.00	0	0	0	100
16	1010	19-Jul-88	165	18.80	0	0	0	100
16	1010	21/09/1989	312	19.97	0	0	263.7	89
16	1010	21/07/1990	476	20.80	0	0	275.7	88
16	1010	24-Oct-90	640	21.06	0	0	161.4	92
16	1010	28/07/1991	757	21.82	0	0	267.3	89
16	1010	12/08/1991	874	21.86	0	0	138.7	93
16	1010	17/08/1993	1282	23.88	0	0	116.1	93
16	1010	16/12/1993	1690	24.21	0	9.4	117.2	76
16	1010	21/03/1994	1925	24.47	0	11.2	116.2	76

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
16	1010	25/08/1994	2160	24.90	0	11.4	117.1	75
16	1010	02/11/1994	2395	25.09	0	8.5	146.5	88
16	1010	21-Feb-95	2642	25.39	0	10.9	183.8	86
16	1010	22-May-95	2889	25.64	0	15.7	174.2	84
16	1010	11-Sep-95	3136	25.94	0	22.6	154.2	72
16	1010	06/06/1996	3320	26.68	0	0	204.8	91
16	1010	31-Oct-96	3504	27.08	0	29.1	154	65
16	1010	25-Nov-96	3688	27.15	0	29.1	155.9	65
16	1010	14-Mar-97	3964	27.45	0	74.4	108.1	70
16	1010	16-Apr-97	4240	27.54	0	61.2	153.6	61
16	1010	26-Jun-97	4516	27.73	0	43.7	174.4	68
16	1020	01/09/1986	36	0.00	0	0	0	100
16	1020	22-Jul-88	75	1.89	0	0	0	100
16	1020	20/09/1989	116	3.05	0	0	0.6	100
16	1020	19/07/1990	155	3.88	0	0	8.5	100
16	1020	25/10/1990	194	4.15	0	0	0	100
16	1020	26/07/1991	220	4.90	0	0	0	100
16	1020	12/08/1993	235	6.95	0	0	1.6	100
16	1020	13-Sep-95	291	9.03	0	0	0	100
16	1020	05/06/1996	332	9.76	0	0	68.6	80
16	1020	24/07/1997	358	10.89	0	0	0.8	100
16	1020	22-Jun-99	424	12.80	0	0	0	100
16	1020	10/10/2002	457	16.11	0	1.6	0	87
16	1020	16-Jul-04	535	17.87	0	2	0	86
16	1020	18/10/2007	574	21.13	0	3.6	2.6	75
16	1020	21/04/2009	580	22.64	0	5.3	9.7	74
16	1020	20/08/2010	586	23.97	0	4.6	12.2	81
16	1020	28/04/2011	592	24.65	0	7	32.3	72
16	1020	03/10/2011	598	25.09	0	0	0	100
16	1021	01/10/1985	166	0.00	0	0	0	100
16	1021	19-Jul-88	383	2.80	0	0	0	100
16	1021	21/09/1989	614	3.97	0	0	0	100
16	1021	21/07/1990	845	4.80	0	0	0	100
16	1021	24-Oct-90	1042	5.06	0	0	0	100
16	1021	28/07/1991	1371	5.82	0	0	0	93
16	1021	03/08/1991	1700	5.84	0	0	0	95
16	1021	17/08/1993	1959	7.88	0	0	1.4	100
16	1021	12-Sep-95	2567	9.95	0	0	0	100
16	1021	05/06/1996	2665	10.68	0	0	73.6	96
16	1021	29/07/1997	2783	11.82	0	0	0	93
16	1021	13/08/1999	2926	13.86	0	0	0	100
16	1021	14/10/2000	3066	15.04	0	0	0	100
16	1021	17/10/2002	3222	17.04	0	0	0	100
16	1021	22/07/2004	3558	18.81	0	0	0	100
30	7066	01/09/1982	277	0.00	0	0	0	100
30	7066	02-Nov-88	527	6.17	0	0	0	100
30	7066	27/09/1989	748	7.07	0	0.91	69.7	89
30	7066	16-May-91	1047	8.70	0	21.3	79.3	69
30	7066	29/07/1991	1346	8.91	0	6.3	59.5	81
30	7066	18/08/1993	1800	10.96	4.8	0	4.1	100

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
30	7066	08/06/1996	2291	13.77	0	0	15.3	100
30	7066	31-Jul-96	2782	13.91	0	0	11.8	99
30	7066	19-May-98	3299	15.71	0	0	11.6	100
30	7066	04-Jun-99	3829	16.76	0	0	11.8	98
30	7066	20/07/2000	4359	17.88	0	0	7.7	100
30	7066	30-Jul-01	4915	18.91	2.4	0	0	100
30	7066	10/05/2004	5264	21.69	0	0	24.5	99
30	7066	21/06/2007	5701	24.80	0	0	48.6	97
30	7066	20/07/2009	6091	26.88	0	2.7	136.5	50
30	7088	01/06/1981	219	0.00	0	0	0	100
30	7088	02-Nov-88	506	7.42	0	0	0	100
30	7088	27/09/1989	775	8.32	0	13.93	156.1	69
30	7088	20-May-91	1074	9.97	0	25.9	111.3	71
30	7088	29/07/1991	1373	10.16	0	40.33	95.6	59
30	7088	10-Oct-91	1672	10.36	4.8	0	0	100
30	7088	18/08/1993	2110	12.21	0	0	0	100
30	7088	08/06/1996	2583	15.02	0	0	19.8	99
30	7088	02-Aug-96	3056	15.17	0	0	17	98
30	7088	18-Jun-98	3554	17.05	0	0	18.8	96
30	7088	26/07/2000	3934	19.15	0	0.6	14.8	95
30	7088	08-Aug-01	4471	20.19	2.4	0	0	100
30	7088	18/05/2004	4953	22.96	0	0	61.3	95
30	7088	27/06/2007	5419	26.07	0	0	134.4	91
30	7088	21/07/2009	5891	28.14	0	1.4	162	65
30	8129	31-May-88	22	0.00	0	0	0	100
30	8129	01/06/1988	44	0.00	0	0	0	100
30	8129	03/10/1989	89	1.34	0	0	78.5	92
30	8129	29/07/1991	118	3.16	0	0	129.8	87
30	8129	06/07/1992	148	4.10	0	0	273.5	27
30	8129	18/08/1993	175	5.21	0	0	277.2	79
30	8129	14-Dec-93	202	5.54	0	0	180.8	84
30	8129	17-Mar-94	234	5.79	0	0	180.3	84
30	8129	31-Oct-94	266	6.41	0	0	243.3	64
30	8129	17-Feb-95	301	6.71	0	0	300.2	61
30	8129	18-May-95	336	6.96	0	0	218.2	66
30	8129	10/06/1996	371	8.02	0	0	452.1	62
30	8129	28-Oct-96	406	8.41	0	0	274.9	64
30	8129	23-Jan-97	485	8.65	0	0	320.4	64
30	8129	12-Mar-97	564	8.78	0	0	323.5	67
30	8129	25-Mar-97	643	8.81	0	0	266.7	63
30	8129	11-Aug-97	722	9.19	0	0	300.7	68
30	8129	01-Oct-97	801	9.33	0	0	318.4	67
30	8129	23-Jun-99	880	11.06	0	0	292.1	64
30	8129	25/08/1999	959	11.23	0	0	334.9	75
30	8129	17/05/2002	1001	13.96	0	4.7	188.8	46
30	8129	28-Jul-03	1080	15.15	3.8	0	0	100
30	8129	23/04/2007	1150	18.89	0	0	0	100
30	8129	03/08/2010	1198	22.17	0	0	22.4	95
30	8129	17/07/2012	1311	24.13	0	0	32.2	93
49	1001	01/11/1980	65	0.00	0	0	0	100

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
49	1001	04-Apr-89	147	8.42	0	0	0	100
49	1001	30/10/1989	229	8.99	0	0	6.6	100
49	1001	22/08/1991	278	10.80	0	0	98.8	89
49	1001	15-Apr-93	329	12.45	0	0	274.4	63
49	1001	02-Dec-93	380	13.08	0	0	163.6	81
49	1001	11-Mar-94	433	13.36	0	0	358.1	73
49	1001	05-Aug-94	486	13.76	0	0	311.7	77
49	1001	20-Oct-94	539	13.97	0	0	295.6	77
49	1001	28-Feb-95	587	14.32	0	0	169.9	84
49	1001	04-May-95	635	14.50	0	0	254.4	80
49	1001	17-Oct-96	686	15.96	0	0	0	100
49	1001	12-Nov-96	737	16.03	0	0	37.4	95
49	1001	06-Mar-97	788	16.34	0	0	65	92
49	1001	07-Apr-97	839	16.43	0	0	81.1	91
49	1001	22-Oct-99	929	18.97	0	0	118.8	86
49	1001	06-Oct-04	978	23.93	0	1.5	218	63
49	1001	15/10/2012	1024	31.95	0	16.5	289.1	50
49	1008	01/08/1976	155	0.00	0	0	0	100
49	1008	17-Aug-88	372	12.04	0	0	0	100
49	1008	27/10/1989	599	13.24	0	85.14	269.5	69
49	1008	04-May-90	734	13.75	0	11.8	280.5	65
49	1008	08/01/1991	873	14.44	1	0	44.5	95
49	1008	17-Jul-91	1012	14.96	0	0	110	88
49	1008	28/08/1991	1151	15.07	0	0	82.5	86
49	1008	02/11/1993	1297	17.25	0	0	306	79
49	1008	14/05/1996	1523	19.78	0	0.6	717.1	64
49	1008	07-Oct-97	1741	21.18	0	132.2	279.2	38
49	1008	13-Oct-99	1981	23.20	0	137	314.6	21
49	1017	01/08/1966	57	0.00	0	0	0	100
49	1017	17-Aug-88	106	22.05	0	0	0	100
49	1017	27/10/1989	155	23.24	0	0	79.1	89
49	1017	04/07/1990	191	23.92	0	0	120.6	83
49	1017	18-Jul-91	228	24.96	0	0	291	70
49	1017	29/08/1991	265	25.08	0	0	217.3	69
49	1017	03/11/1993	304	27.26	0	60.58	279.4	76
49	1017	22-Sep-95	361	29.14	0	290.6	203.2	20
49	1017	15/05/1996	428	29.79	0	150.37	344.6	51
49	1017	30-Sep-97	506	31.16	0	453	58.2	3
49	1017	15-Oct-99	577	33.20	0	449.8	60.7	2
49	1017	18-Apr-01	614	34.71	0	330.6	206.2	13
53	1005	01/07/1973	168	0.00	0	0	0	100
53	1005	05-Sep-88	454	15.18	0	0	0	100
53	1005	08-Jun-89	616	15.94	0	11.3	354.7	59
53	1005	13/09/1989	923	16.20	2	0	158.8	90
53	1005	03/07/1991	1074	18.00	0	1.28	41.8	95
53	1005	28/06/1993	1286	19.99	0	0	46	98
53	1005	29-Aug-94	1526	21.16	0	1.2	145.7	88
53	1005	17/05/1995	1779	21.88	0	0	9.4	100
53	1005	08-Jul-97	2076	24.02	0	0.1	230.6	79
53	1005	08/10/1998	2373	25.27	0	6	202.2	63

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
53	1005	06/06/2001	2486	27.93	0	56.7	129.4	60
53	1005	19-Nov-01	2925	28.39	2.5	0	152.4	91
53	1005	24/05/2004	3321	30.90	0	0	189.9	88
53	1005	18/07/2007	3642	34.05	0	0.3	216.7	74
53	1006	01/10/1983	3735	0.00	0	0	0	100
53	1006	01-Sep-89	105	5.92	0	0	0	100
53	1006	13/09/1989	210	5.95	0	0	8.5	100
53	1006	30-May-91	267	7.66	0	3.4	167	78
53	1006	03/07/1991	324	7.75	0	0.29	95.6	86
53	1006	27/06/1993	414	9.74	0	2.5	164	80
53	1006	18/05/1995	517	11.63	0	17.75	362.8	62
53	1006	06-May-97	596	13.60	0	129.5	133.5	17
53	1006	12-May-99	676	15.61	0	111.9	155.9	39
53	1006	24-Apr-00	754	16.56	0	143.1	169.6	32
53	1006	16/04/2003	777	19.54	0	123.2	222	24
53	1006	29/06/2005	803	21.74	0	147.9	213.9	22
53	1008	01/11/1978	93	0.00	0	0	0	100
53	1008	15-Jul-89	215	10.70	0	0	0	100
53	1008	17/07/1989	337	10.71	0	0	218.5	83
53	1008	02/08/1990	405	11.75	0	1.6	229.9	68
53	1008	28-May-91	475	12.57	0	0	383.9	51
53	1008	04/07/1991	545	12.67	0	3	281.9	65
53	1008	28/06/1993	624	14.66	0	5.2	338.1	64
53	1008	16-Jun-94	706	15.62	0	91.8	352	15
53	1008	31-Aug-94	788	15.83	2	0	0	100
53	1008	16/05/1995	873	16.54	0	0	3.8	100
53	1008	28-Apr-97	958	18.49	0	0	96	68
53	1008	21/04/1999	1007	20.47	0	7.3	225.2	34
53	1008	29/04/2002	1046	23.49	0	18.6	298.4	31
53	1008	25/05/2004	1100	25.56	0	41.6	305.4	8
53	1501	01/07/1982	12	0.00	0	0	0	100
53	1501	10-May-89	29	6.86	0	0	0	100
53	1501	13/09/1989	46	7.20	0	0	235.9	78
53	1501	08/08/1990	64	8.10	0	0	213.5	75
53	1501	29-May-91	97	8.91	0	0	274.5	63
53	1501	03/07/1991	130	9.00	0	0	219.8	75
53	1501	28/06/1993	155	10.99	0	0	269.3	66
53	1501	17/05/1995	164	12.88	0	0	398.1	66
53	1501	21-Aug-95	173	13.14	0	7.6	408.8	59
53	1501	29-Apr-97	184	14.83	0	84.7	332.6	27
53	1501	10-May-99	202	16.86	0	98.9	265.3	30
53	1501	18-Apr-00	216	17.80	0	170	251.4	24
56	1007	01/07/1980	21	0.00	0	0	0	100
56	1007	17-Aug-88	48	8.13	0	0	0	100
56	1007	26/09/1989	75	9.24	0	0	103.8	89
56	1007	21/07/1990	103	10.05	0	0	152.5	87
56	1007	13-May-91	131	10.86	0	0	94.8	90
56	1007	08/08/1991	159	11.10	0	1.35	256.2	78
56	1007	12-Aug-93	185	13.11	0	0	111	87
56	1007	09-Dec-93	211	13.44	0	0.5	106.3	86

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
56	1007	16-Mar-94	235	13.71	0	0.7	109.3	85
56	1007	19-Apr-94	259	13.80	0	0	101.8	86
56	1007	19-Aug-94	283	14.13	0	0.6	114	77
56	1007	16/02/1995	288	14.63	0	0	88.2	81
56	1007	17/05/1995	293	14.87	0	0	86.9	85
56	1007	08/09/1995	298	15.19	0	0	89	89
56	1007	11/06/1996	305	15.95	0	1.11	176.1	82
56	1007	24/10/1996	312	16.31	0	0	109	85
56	1007	17/11/1996	319	16.38	0	0	110.2	85
56	1007	10/03/1997	324	16.69	0	0	95	88
56	1007	08/07/1997	329	17.02	0	0	98.1	86
56	1007	30/09/1997	334	17.25	0	0	154.8	85
56	1007	12/05/1998	339	17.86	0	0	103.4	84
56	1007	19/10/1999	344	19.30	0	0	82.5	91
56	1007	30/07/2002	365	22.08	0	0	118.2	73
56	1007	21-Sep-04	371	24.22	0	0.8	137.7	64

Appendix H: The parameters data of deterioration model for dry freeze – collector.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
8	1047	01/10/1983	44	0.00	0	0	0	100
8	1047	20/10/1989	64	6.05	0	0.15	383.9	71
8	1047	25/08/1991	161	7.90	0	201.2	376	60
8	1047	22-Oct-91	258	8.06	0	0	3.23	57
8	1047	15/07/1994	318	10.79	2.8	0	21.1	98
8	1047	07-Sep-95	417	11.93	0	101	7.11	88
8	1047	09/05/1996	440	12.61	0	0	142.9	84
56	7775	01/10/1986	70	0.00	0	0	0	100
56	7775	21/10/1989	157	3.06	0	0	226.3	79
56	7775	16/07/1990	209	3.79	0	0	239.5	77
56	7775	04/08/1991	261	4.84	0	0	120.6	81
56	7775	21/10/1993	310	7.06	0	0	220.5	70
56	7775	15/09/1995	374	8.96	0	0	177	69
56	7775	09/05/1996	421	9.60	0	0	236	70
56	7775	14/08/1996	468	9.87	0	0	204.8	70
56	7775	31/07/1997	506	10.83	0	0	204.3	67
56	7775	17-May-99	540	12.62	0	0	221.3	66
56	7775	17/04/2002	565	15.54	0	1.1	203.6	64
56	7775	27-Sep-02	587	15.99	1	0	0	100
56	7775	09/06/2005	619	18.69	0	0	209.1	64
56	7775	11/04/2007	649	20.53	0	0	215	57
56	7775	10/08/2009	679	22.86	0	0	468.7	34
56	7775	26/08/2010	709	23.90	0	0.6	363.9	19
56	7775	30/09/2011	739	25.00	0	0	209.7	74
56	7775	15/08/2012	769	25.87	0	0	0	100

Appendix I: The parameters data of deterioration model for dry non freeze – arterial.

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
35	1003	01/06/1982	30	0.00	0	0	0	100
35	1003	05/12/1989	54	7.51	0	1.37	152.8	87
35	1003	22/01/1991	128	8.64	0	0.95	202.6	83
35	1003	28-Mar-91	202	8.82	0	0	50.6	97
35	1003	27-Sep-91	276	9.32	0	2.51	157.7	81
35	1003	22-Jan-93	333	10.64	0	0.89	201.4	77
35	1003	17-Feb-94	395	11.72	0	0	103.4	73
35	1003	17/03/1995	478	12.79	0	0.65	201.3	74
35	1003	26-Apr-95	561	12.90	0	10.4	111.8	72
35	1003	28-Apr-97	696	14.91	0	0.1	263.2	65
35	1003	15-Mar-99	782	16.79	0	0	275.7	59
35	1005	01/10/1983	128	0.00	0	0	0	100
35	1005	31/10/1989	380	6.08	0	0	0	100
35	1005	26-Mar-91	632	7.48	0	0	0	100
35	1005	21/08/1991	884	7.89	0	0	0	100
35	1005	24/10/1992	1143	9.07	0	0	0.5	99
35	1005	15-Feb-94	1381	10.38	0	0	0	100
35	1005	18/03/1995	1651	11.46	0	0	13.1	99
35	1005	29-Apr-97	1961	13.58	0	0	0	96
35	1005	16-Mar-99	2257	15.46	0	0	0	96
35	1005	08-May-02	2580	18.60	0	0	0	96
35	1005	04-Apr-05	2933	21.51	0	0	305	87
35	1005	28-Sep-09	3319	25.99	0	0	292.7	86
35	1005	20/08/2012	4378	28.89	0	0	0	100
35	1005	02-Apr-13	5437	29.50	0	0	0	100
35	1112	01/06/1984	36	0.00	0	0	0	100
35	1112	01-Jan-87	43	2.58	0	0	0	100
35	1112	05-Dec-89	69	5.51	0	0	0	100
35	1112	22-Jan-91	129	6.64	0	0	8.9	100
35	1112	27-Mar-91	189	6.82	0	0	0	100
35	1112	27/09/1991	249	7.32	0	0	3.8	100
35	1112	18-Mar-92	297	7.79	0	318.9	8.6	37
35	1112	27/01/1993	350	8.66	0	0	0.6	100
35	1112	09-Jun-93	396	9.02	0	364.3	4.7	12
35	1112	16-Feb-94	450	9.71	0	0	0	100
35	1112	26-Oct-94	504	10.40	0	0	0	100
35	1112	15/03/1995	523	10.78	0	0.85	37.8	95
35	1112	25/04/1995	542	10.90	0	0	0	100
35	1112	27-Jun-95	561	11.07	0	0	0	100
35	1112	25-Nov-96	618	12.48	0	0	0	100
35	1112	20-Mar-97	645	12.80	0	103.5	25.7	59
35	1112	28-Apr-97	702	12.91	2.3	0	0	100
35	1112	09-Sep-97	759	13.27	0	0	0	100
35	1112	08-Feb-99	788	14.69	0	144.6	33.6	42
35	1112	15-Mar-99	864	14.78	0	0	2	100
35	1112	02-Feb-00	942	15.67	0	0	12.3	96
35	1112	21/01/2001	1022	16.64	0	0	57.1	95
35	1112	10-May-02	1105	17.94	0	0	32.1	94

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
35	1112	04-Nov-02	1188	18.43	0	0	25.1	95
35	1112	22-Jul-03	1199	19.14	0	0	28.4	95
35	1112	12-Nov-04	1250	20.45	0	0	29.6	94
48	1065	01/09/1969	106	0.00	0	0	0	100
48	1065	24-Jan-90	142	20.40	0	0	134.2	83
48	1065	10-Jun-91	190	21.77	0	0	250.6	76
48	1065	09-Oct-91	238	22.10	0	0	117.3	85
48	1065	26-Jan-93	304	23.40	0	0	243.9	69
48	1065	15-Apr-93	370	23.62	0	1.5	296	63
48	1065	14-Mar-95	506	25.53	0	0.32	288	54
48	1065	08-Aug-95	642	25.93	0	1.5	337.2	60
48	1065	12-May-97	840	27.69	0	0	384.5	60
48	1076	01/11/1977	141	0.00	0	0	0	100
48	1076	06-Dec-89	224	12.10	0	0	45.6	87
48	1076	23/01/1991	280	13.23	0	13.47	1111.5	32
48	1076	02/10/1991	336	13.92	0	2.71	74.1	85
48	1076	14/03/1995	417	17.36	0	18.39	169.5	56
48	1076	15-Mar-12	541	34.37	0	55.5	362.3	44
48	1076	14/02/2013	665	35.29	0	65.3	367.5	14
48	1111	01/09/1972	58	0.00	0	0	0	100
48	1111	06-Dec-89	126	17.26	0	0	45.7	93
48	1111	06-Dec-90	193	18.26	0	0	45.7	93
48	1111	23-Jan-91	270	18.39	0	0	56.2	90
48	1111	02/10/1991	347	19.08	0	0	52.1	96
48	1111	06-Nov-91	424	19.18	0	0	64.5	91
48	1111	26-Jan-93	493	20.40	0	0	67.3	93
48	1111	07-Jul-93	562	20.85	0	0	72.6	90
48	1111	14-Mar-95	745	22.53	0	0	64.8	91
48	1111	28-Jul-95	928	22.90	0	0	110.9	87
48	1111	09-Jun-97	1128	24.77	0	0	207	83
48	1111	25-Mar-98	1255	25.56	0	1.1	206.9	80
48	1111	07-Jun-99	1378	26.76	0	1.3	180.9	77
48	1111	01-Mar-01	1509	28.50	1.6	0	0	100
48	1111	28-May-03	1648	30.74	0	0	0	100
48	1111	05-Nov-07	1804	35.18	0	0.2	305	84
48	1111	30-Sep-09	1965	37.08	0	2.5	333.8	82
48	1111	14-Mar-12	2126	39.53	0	0.9	1	96
48	3769	01/06/1976	56	0.00	0	0	0	100
48	3769	01-Dec-89	147	13.50	0	0	47.3	97
48	3769	11-Sep-90	172	14.28	0	0	49.5	97
48	3769	13-Dec-90	197	14.53	0	0	84.6	95
48	3769	13-Jun-91	246	15.03	0	0	89	94
48	3769	26-Sep-91	295	15.32	0	0	78.2	95
48	3769	21-Oct-92	319	16.39	0	0	129.1	92
48	3769	09-Jul-93	354	17.10	0	0	218.7	88
48	3769	20/03/1995	476	18.80	0	14.86	223.6	80
48	3769	07-Nov-95	598	19.43	0	2	286.3	84
48	3769	12-Jun-97	736	21.03	0	5.4	329.5	83
48	3769	08-Jul-99	861	23.10	0	26	316	53
48	3769	10-Oct-01	1006	25.36	0	32.7	375.3	49

State Code	SHRP ID	Survey Date	Cum. ESAL	Age	M&R	Crack Area	Crack Length	PCI
48	3769	22-Jul-04	1165	28.14	2	0	0	100
48	3769	21-Sep-07	1339	31.30	0	93	927.7	30
48	3875	01/11/1985	194	0.00	0	0	0	100
48	3875	12-Jun-91	291	5.61	0	0	0	92
48	3875	13/10/1991	388	5.95	1	0	0	100
48	3875	10-Jun-92	471	6.61	0	0	0	100
48	3875	13-Oct-92	554	6.95	0	0	1	100
48	3875	18-May-93	625	7.54	0	0.2	7.3	97
48	3875	13/03/1995	856	9.36	0	0	24.7	99
48	3875	09-Aug-95	1087	9.77	0	4.5	13	91
48	3875	13-May-97	1501	11.53	0	13.1	52.1	79
48	3875	25-Aug-99	1726	13.81	0	25.5	53	49
48	3875	05-Jun-00	1957	14.59	0	23.2	62.8	49

Appendix J: The Matlab code of the main function of discrete barebones particle swarm optimisation algorithm (DBB-MOPSO).

```
% Main code of DBB-MOPSO algorithm
Algorithm
  %find the optimal maintenance programming for pavement sections by
% using multi objective particle swarm optimisation
%-------------------------------------------------------------------%
% No_par = number of particles(swarm size)
% par_dim = particle Dimension
% No_Maint = number of maintenance and rehabilitation actions
% arch_cap = maximum capacity of the archive
% Tmax = maximum number of iterations
% T_current = current iteration
% t = initialise the swarm S0
% Vmax = maximum velocity
% Y_prev = fitness archive for best local positions
% A_cur = fitness current for two objective function
% x = matrix for particle position
% v = matrix for velocity
% Pb = Best local position matrix
% X_prev= position Archive
% r3 and r4 random parameters [0,1]
% mutation_p = mutation parameter
% Pg = Global Leader
% copy right Maher Mahmood
% Civil Engineering Group, School of architecture, Design and Built Environment
% Nottingham Trent University
% Email: maher.mahmood2010@my.ntu.ac.uk or maher78_2004@yahoo.com
% supervisors: Dr. S. Mathavan and Dr. M. Rahman
%-------------------------------------------------------------------%
% Initialisation variables
%-------------------------------------------------------------------%
clear all
close all
tic;
No_par=100;
par_dim=50;
No_Maint=5;
arch_cap=100;
Tmax=100;
T_current = 1;
t=0;
mkdir 'MOPSOoutput'  %create new file directory to save solutions
% create matrices for positions, velocities and fitness values
x=zeros(No_Maint, par_dim, No_par);
v=zeros(No_Maint, par_dim, No_par);
x_tmp=zeros(No_Maint, par_dim, No_par);
Y_prev=zeros(No_par,2);
A_cur=zeros(No_par,2);
% Initialisation positions and velocities
x=zeros(No_Maint, par_dim, No_par);
x_cont=randi(5, No_par, par_dim);
h = waitbar(0,'Initializing waitbar...');
for i=1:No_par
        for j=1:par_dim
```

```
                for k=1:No_Maint
                    perc = i;
                    waitbar(perc/100,h,sprintf('%d%% initialization...',perc))
                        if k==x_cont(i,j)
                            x(k,j,i)=1;
                        end
                end
        end
end
close(h)
Pb=x;% assume the best local positions (Pb)are the same first positions (x)
h = waitbar(0,'Initializing waitbar...');
for i=1:No_par
        perc = i;
        waitbar(perc/100,h,sprintf('%d%% fitness...',perc))
        Y_prev(i,1)=cost_Dfunction(x(1:No_Maint,1:par_dim,i));
        Y_prev(i,2)=condition_Dfunction(x(1:No_Maint,1:par_dim,i));
        A_cur(i,1)= Y_prev(i,1);
        A_cur(i,2)= Y_prev(i,2);
end
close(h)
X_prev=x; % save the positions in Archive X_prev or previous positions
% Pareto optimal
[C,Xc]=Pareto_PSO(A_cur,X_prev);
 % Archive
%Ar0 = [C,Xc];% size will be 100 x 52; Ar0 = cat(C,Xc,2);
if size(C,1) > arch_cap
    [C_pruned, Xc_pruned] = prune_archive(C,Xc,arch_cap);% follow Section 4.6 of the
paper
end
% Particle Leader
D=C; Xd=Xc;
Pg=global_leader(A_cur,D,Xd);% Pg Leader
n_integer=5;       %random integer
mut_rand=[];
gauss_norm=[];     % gauss_norm = Gaussian Distribution
unif_dist=[];      %  unif_dist = uniform distribution U(0,1)
Mu=[];             % Mu = mean
Sd=[];             % Sd = standard deviation
Data1 = [];
Data2 = [];
h = waitbar(0,'Initializing waitbar...');
for t= 1:Tmax
     perc = t;
     waitbar(perc/100,h,sprintf('%d%% iteration...',perc))
     for i=1:No_par
         for k=1:No_Maint
              for j=1:par_dim
                   Mu(k,j,i)= 0.5*(Pb(k,j,i)+Pg);
                   Sd(k,j,i)= abs(Pb(k,j,i)-Pg);
                       if Sd(k,j,i)~=0
                          % Gaussian Distribution formula
                          gauss_norm(k,j,i) =(1/(Sd(k,j,i)*sqrt(2*pi)))*(exp((-
1/2)*(((x(k,j,i)- Mu(k,j,i))/Sd(k,j,i))^2)));
                          % uniform distribution
                          unif_dist(k,j,i)= rand(1,1);
                                  if  unif_dist(k,j,i) <0.5
                                      x_tmp(k,j,i)=gauss_norm(k,j,i);
```

```
                                   else
                                       x_tmp(k,j,i)=Pg;
                                   end
                        else
                          x_tmp(k,j,i)=Pg;
                        end
                    % velocity the difference
                    % between the new position x(i,j) and previous position
X_prev(i,j)
                    v(k,j,i)= x_tmp(k,j,i)- X_prev(k,j,i);
               end
          end
      end
% update discrete particle positions based on maximum velocity
 for i=1:No_par
             for j=1:par_dim
                 max_velocity=max(v(:,j,i));
                 countmax=0;
                        for k=1:No_Maint
                                    if v(k,j,i)==max_velocity
                                       countmax=countmax+1;
                                       v_tmp(countmax,j,i)=k;
                                    end
                            x(k,j,i)=0;
                        end
                 randnum=randi(countmax);
                 indx=v_tmp(randnum,j,i);
                 x(indx,j,i)=1;
             end
 end
% find fitness function and position
for i=1:No_par
        A_cur(i,1)=cost_Dfunction(x(1:No_Maint,1:par_dim,i));
        A_cur(i,2)=condition_Dfunction(x(1:No_Maint,1:par_dim,i));
        %A_cur(i,1)= cost_Dfunction(x(:,:,i),T_current);
        %A_cur(i,2)= condition_Dfunction(x(:,:,i),T_current);
        X_prev=x;
        % find local best position
                if
(((A_cur(i,1)<=Y_prev(i,1))&&(A_cur(i,2)<Y_prev(i,2)))||((A_cur(i,1)<Y_prev(i,1))&&(A
_cur(i,2)<=Y_prev(i,2))))
                        Y_prev(i,1)=A_cur(i,1); Y_prev(i,2)=A_cur(i,2);
                        Pb(:,:,i)=x(:,:,i);
                else
                        Y_prev(i,1)=Y_prev(i,1); Y_prev(i,2)=Y_prev(i,2);
                        Pb(:,:,i)=Pb(:,:,i);
                end
end
% Pareto optimal
[C,Xc] = Pareto_PSO(A_cur,X_prev);
% check the capacity of Archive
%Ar0 = [C,Xc];   % size will be 100 x 52; Ar0 = cat(C,Xc,2);
        if size(C,1) > arch_cap
            [C_pruned, Xc_pruned] = prune_archive(C,Xc,arch_cap);
        end
% Particle Leader
D=C; Xd=Xc;
Pg=global_leader(A_cur,D,Xd);% Pg Leader
```

```
mode=mod(t,5);
        if mode==0
            H=figure(t);
            plot(D(:,1),D(:,2),'ro','linewidth',1.5);
            xlabel('f1(cost)');
            ylabel('f2(PCI)');
            saveas(H,'FIGURE');
        end
% MUTATION OPERATOR
for i=1:No_par
        for j=1:par_dim
            mut_rand=rand(1,1);% Random number between 1 and dimension of decision
variable
            mutation_rate=exp((-8*t)/Tmax);
                if mut_rand < mutation_rate
                   maint_rand=randi(4);
                       for k=1:No_Maint
                               if x(k,j,i)==1
                                  x(k,j,i)=0;
                                  indx_one=k;
                               end
                       end
                       for k=1:No_Maint
                               if maint_rand < indx_one
                                  x(maint_rand,j,i)=1;
                               else
                                  x(maint_rand+1,j,i)=1;
                               end

                end

end
% evaluate the fitness of each particle
for i=1:No_par
        A_cur(i,1)= cost_Dfunction(x(1:No_Maint,1:par_dim,i));
        A_cur(i,2)= condition_Dfunction(x(1:No_Maint,1:par_dim,i));
        X_prev=x;
            if
(((A_cur(i,1)<=Y_prev(i,1))&&(A_cur(i,2)<Y_prev(i,2)))||((A_cur(i,1)<Y_prev(i,1))&&(A
_cur(i,2)<=Y_prev(i,2))))
                Y_prev(i,1)=A_cur(i,1); Y_prev(i,2)=A_cur(i,2);
                Pb(:,:,i)=x(:,:,i);
            else
                Y_prev(i,1)=Y_prev(i,1); Y_prev(i,2)=Y_prev(i,2);
                Pb(:,:,i)=Pb(:,:,i);
            end
end
% Prune the external archive
[C,Xc] = Pareto_PSO(A_cur,X_prev);
% check the capacity of Archive
%Ar0 = [C,Xc];   % size will be 100 x 52; Ar0 = cat(C,Xc,2);
    if size(C,1) > arch_cap
       [C_pruned, Xc_pruned] = prune_archive(C,Xc,arch_cap);
    end
% Particle Leader
D=C; Xd=Xc;
Pg=global_leader(A_cur,D,Xd);% Pg Leader
D_prev=D;
```

```
mode=mod(t,5);
    if mode==0
       F=figure(t);
       plot(D(:,1),D(:,2),'ro','linewidth',1.5);
       xlabel('f1(cost)');
       ylabel('f2(PCI)');
       saveas(F,'FIG');
       % save and move the non-dominated solutions of each 5 iterations into file
directory
       fn = num2str(t);
       dlmwrite(fn,D,'delimiter', '\t');
       movefile(fn,'MOPSOoutput');
    end

close(h)
toc;
```

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Appendix K: The Matlab code of the pavement cost minimisation function of discrete barebones particle swarm optimisation algorithm (DBB-MOPSO).

```
% objective function-minimisation of treatment cost
% R = discount rate
% C_m = Maintenance cost
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% Email: maher.mahmood2010@my.ntu.ac.uk or maher78_2004@yahoo.com
% supervisors: Dr. S. Mathavan and Dr. M. Rahman
function total_cost = cost_Dfunction(x)
% L = 152.5; % pavement section length
disc_rate = 0.04; % discount rate
% z= Number of treatment action
% C=xlsread(filename1);% read treatment from filename1
% w=xlsread(filename2);% read pavement section width from filename2
maint_cost=[0,10,33,41,78];
par_dim=50;
No_Maint=5;
total_cost = 0;
year=0;
for j=1:par_dim
        for k=1:No_Maint
            total_cost = total_cost + (maint_cost(k)*x(k,j,:));
        end
        m = mod(j,5);
        if m == 0
           year=year+1;
           total_cost = total_cost*(1+disc_rate)^(-1*year);
        end

end
end
```

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Appendix L: The Matlab code of pavement condition function of discrete barebones particle swarm optimisation algorithm (DBB-MOPSO).

```
% objective function-minimisation of the sum of all residual PCI values%%-
-%---------------------------------------------------------------------%
% L = pavement section length
% w = pavement section width
% PCI_min = Minimum acceptable pavement condition index
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% supervisors: Dr. S. Mathavan and Dr. M. Rahman
function condition_index = condition_Dfunction(x)
L = 152.5;
w = 3.6;
par_dim=50;
No_Maint=5;
PCI_max=100;
Maint_thick=[0,1,2,4,6];% maintenance (overlay) thickness
traffic=xlsread('AADT.xlsx');% read traffic data from filename1
crack_area=xlsread('area.xlsx');% read cracking area for each section at each year
from filename2
crack_length=xlsread('Length.xlsx');% read cracking length for each section at each
year from filename3
age=xlsread('Age.xlsx');% read pavement section age from filename4
%if T_current ==1
condition_index = 0;
%else
for j=1:par_dim
        for k=1:No_Maint
                    if x(k,j,:)==1
                       % prediction model for wet freeze-arterial road
                       PCI(k,j)=97.744-(0.15*crack_area(j))-(0.064*crack_length(j))-
(0.515*age(j))+(3.748*Maint_thick(k));
                    else
                       PCI(k,j)=0;
                    end
             condition_index = condition_index + (PCI_max - PCI(k,j))*L*w*traffic(j);
        end
end
end
```

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Appendix M: The Matlab code of Pareto optimal Algorithm.

```
% Pareto Optimality Algorithm
        %-----------------------------------------------------------------%
% Q = another archive of fitness values of non-dominated solutions
% Xq = another archive of positions of non-dominated solutions
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% supervisors: Dr. S. Mathavan and Dr. M. Rahman
function [C,Xc]=Pareto_PSO(A_cur,X_prev)
C=[];
Xc=[];
Q=[];
Xq=[];
Z=size(A_cur,1); % equal size of swarm
if Z > 1   %100
       for n=1:Z
               for m=n+1:Z
                       if ((A_cur(n,1)<A_cur(m,1))&&(A_cur(n,2)<=A_cur(m,2)))
                           Q=[Q;A_cur(m,:)];Xq=[Xq;X_prev(:,:,m)];
                       elseif ((A_cur(n,1)<=A_cur(m,1))&&(A_cur(n,2)<A_cur(m,2)))
                               Q=[Q;A_cur(m,:)];Xq=[Xq;X_prev(:,:,m)];
                       elseif ((A_cur(m,1)<A_cur(n,1))&&(A_cur(m,2)<=A_cur(n,2)))
                               Q=[Q;A_cur(n,:)];Xq=[Xq;X_prev(:,:,n)];
                       elseif ((A_cur(m,1)<=A_cur(n,1))&&(A_cur(m,2)<A_cur(n,2)))
                               Q=[Q;A_cur(n,:)];Xq=[Xq;X_prev(:,:,n)];
                       end
               end
       end
           if size(Q,1)>1
          [C inx] = setdiff(A_cur,Q,'rows');
          Xc = X_prev(:,:,inx);
       else
           C=A_cur;
           Xc=X_prev;
       end
else
       C=A_cur;
       Xc=X_prev;
end
end
```

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Appendix N: The Matlab code of pruning the external archive.

```
% Pruning the external archive based on crowding distance method

% C = fitness values of non-dominated solutions
% Xc = positions of non-dominated solutions
% Na = maximum capacity of the archive
% f = total number of non-dominated solutions to be pruned to Na
% m = two objective functions
% CDA = crowding distances matrix for archive
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function [C_pruned, Xc_pruned] = prune_archive(C,Xc,arch_cap)
f=size(C,1); % find the size of non-dominated solutions
arch_size = size(Xc,1); % size of particles in archive
m=2; % number of objective functions
CDA_obj_j=zeros(arch_size,m);
    for j=1:m
        C_j = C(:,j);
        [C_j_sort, I] = sort(C_j,1); % sort the non-dominated solutions based on
their fitness values for each objective
        F_value=C(I,j); %fitness value
        particle_extreme_1 = I(1); % the first non-dominated solution
        particle_extreme_2 = I(end);% the last non-dominated solution
        CDA(particle_extreme_1,j) = 10000;
        CDA(particle_extreme_2,j) = 10000;
                for k=2:f-1
                    particle_idx = I(k);
                    % calculate the crowding distance
                    CDA_obj_j(particle_idx,j)=(F_value(k+1)-F_value(k-
1))/(F_value(end)-F_value(1));
                end
    end
% FIND (arch_cap) particles have MAX. CROWDING DISTANCE
CDA = sum(CDA_obj_j,2);
[CDA_sorted,indx]=sort(CDA,'descend');
indx_pruned = indx(1:arch_cap);
C=C(indx_pruned,:);
Xc=Xc(:,:,indx_pruned);
C_pruned = C;
Xc_pruned = Xc;
end
```

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Appendix O: The Matlab code of global best position (leader) selection.

```
% Global best position using Sigma Method
% n = Archive size
% sig_A = sigma value matrix for Archive
% sig_S = sigma value matrix for swarm
% dist = distance archive
% copy right Maher Mahmood
% sum = summation matrix
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% supervisors: Dr. S. Mathavan and Dr. M. Rahman
function Pg=global_leader(A_cur,D,Xd)
n=size(D,1);
sig_A=[];
sig_S=[];
dist=[];
sum=[];
g=0;
% Sigma calculation for Archive
        for f=1:n
        sig_A(f)=((D(f,1))^2-(D(f,2))^2)/((D(f,1))^2+(D(f,2))^2);
        sum(f)=0;
        end
% Sigma calculation for swarm
        for i=1:(size(A_cur,1))
        sig_S(i)=((A_cur(i,1))^2-(A_cur(i,2))^2)/((A_cur(i,1))^2+(A_cur(i,2))^2);
        end
% the first non-dominated solution
sum(1)=0;
        for i=1:(size(A_cur,1))
        sum(1)=sum(1)+((sig_A(1)- sig_S(i))^2);
        end
dist(1)=sqrt(sum(1));
for f=2:n
         for i=1:(size(A_cur,1))
         sum(f)=sum(f)+(sig_A(f)- sig_S(i))^2;
         end
    dist(f)=sqrt(sum(f));
        if dist(f)<=dist(1)
           dist(f)=dist(1);
           g=f;
        end
    Pg=Xd(g);
end
end
```

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