Department of Civil Engineering

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Predicting Deterioration for the Saudi Arabia Urban Road Network

By

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Dedicated to

My Parents and My Family

بسم الله الرحمن الرحيم

In the Name of Allah the Most Beneficent the Most Merciful

ABSTRACT

Pavements represent an important infrastructure to all countries. In Saudi Arabia, huge investments have been made in constructing a large network. This network requires great care through conducting periodic evaluation and timely maintenance to keep the network operating under acceptable level of service.

Pavement distress prediction and pavement condition prediction models can greatly enhance the capabilities of a pavement management system. These models allow pavement authorities to predict the deterioration of the pavements and consequently determine the maintenance needs and activities, predicting the timing of maintenance or rehabilitation, and estimating the long range funding requirements for preserving the performance of the network.

In this study, historical data of pavement distress and pavement condition on the main and secondary road network of Riyadh, Saudi Arabia were collected. These data were categorized, processed, and analyzed. These data have been employed to generate prediction of pavement distress and condition models for the Saudi Arabia Urban Road Network (SAURN).

Throughout the study, the most common types of pavement distress on SAURN have been identified. The behavior of these distress types has been investigated. A sigmoid function was found to be an excellent representation of the data. Seven for urban main pavement distress models (UMPDM) have been developed. In addition, six urban secondary pavement distress models (USPDM) have been developed. Moreover, two pavement condition models have also been developed, one for urban main pavement condition (UMPCM), and the other for urban secondary pavement condition (USPCM). The developed models provide a reasonable prediction of pavement condition. The models were assessed by standard error and residual analysis. A suitable procedure for the implementation of the models has also been proposed.

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DECLARATION

The described in this thesis was conducted at the University of Nottingham, Department of Civil Engineering between June 2006 and December 2009. I declare that the work is my own and has not been submitted for a degree of another university.

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CHAPTER ONE
INTRODUCTION

1.1 Background

Transportation systems include highway, rail, air, marine and pipelines. Of these, only marine and pipelines do not make use of pavements. The major elements of the highway system are the pavements. For air travel, runways, taxiways, and parking aprons are pavements. The pavements represent one-half of total highway expenditure and moreover expenditure on pavements continues to grow as maintenance and rehabilitation are required (Haas et al. 1994). Transportation infrastructure plays a vital role in the economic, social, and state of all countries and this role cannot be neglected. The impact of growth and prosperity achieved in this sector extends to include other sectors, and therefore, there is a strong relation between growth in the transportation sector and the growth of a country's economy as a whole. All this is reflected in the significant contribution made by this sector to Gross Domestic Product (GDP) and increasing financial returns to the country directly or indirectly. Some studies indicate that costs attributable to transportation are on average almost 20% of the final cost of a product; thus, reducing transportation cost will reduce product cost. For example, reduction of transport cost by 10% leads to lower cost of the final product by almost 2% (SAMA 2004). The contribution of the transportation sector to the GDP of the United States of America for example, represents almost 20% and in Germany, 4.17%, which means that the contribution of this sector in many industrialized countries has significant importance on estimated GDP of these countries. This means that it is necessary to allocate a significant proportion of the budget to the transportation sector, as the sector is considered an important source of government revenue and has a big role in the growth of the country's GDP (SAMA 2004).

Some of the most productive projects are those of roads because of the potential economic savings. Therefore, the amount spent on establishing and expanding the network of paved roads and bridges has a direct and speedy return in reducing transport costs and hence stimulating economic growth.

Transportation in Saudi Arabia has been developed in response to three major needs, notably, social needs, economic and industrial needs, and defence needs. The contribution of the transportation sector to the GDP of the Kingdom represented 3.2% in 2006 while the expenditure was only 1.43% (CDSI 2008). This figure shows that there is a need to allocate more investment to the transportation sector by the Saudi government.

Transportation Infrastructure (roads, rail, airports and seaports) represents important infrastructure to all countries' economies. According to the Federal Highway Administration (FWHA 2008) the United States Department of Transportation (USDOTS) reports transportation (18.9%) accounts for the second largest household expenditure and the expenditure in the highway sector represents the largest amount in transportation. By the late 1980s, the U.S. highway network was near completion. The US network includes more than 50,000 miles of interstate highway, and over 115,000 miles of the national highway system. The total lane mileage length is 4.82 million and the total centreline mileage length is 4.2 million.

The total length of Canada's roads is 521,952 miles of which about 63% is earth and gravel and 37% is paved. The annual expenditure on pavements is more than $4 billion (TAC 1997). The total length of Great Britain's roads is 241,097 miles of which about 100 % is paved (Highways Agency 2005).

The condition of highway pavements on the National Highway System (NHS) in the United States is such that the cost to maintain the system at existing condition levels is nearly $50 billion annually. However, the United States currently spends only about $25 billion per year, and the estimated cost to bring the entire system up from its current level to a good level is $200 billion. Judging from this, it is clear that the system cannot continue to operate with traditional approaches to pavement management at the maintenance level and that the pavement preservation strategies employed at the various levels of Department of Transportation (DOT) (i.e., state, county, and city) need to be restructured (FWHA 2002).

For example, until the mid 1970s, the Arizona Department of Transportation (ADOT) focused on the construction of new roads. But, as the interstate system neared completion, the emphasis shifted to preservation of the present road network to keep track of the condition of its 7400-mile road network and allocate available preservation funds effectively.

In 1974, the ADOT allocated $25 million to pavement preservation and by 1978 the preservation budget had increased to $52 million. The development in ADOT has resulted in enormous cost savings. The $600,000 spent on research, including outside contracts and staff time and expenses, was recovered more than 20 times over during the first year of its implementation (TRB 1983). The state saved more than $200 million in five years by applying the Pavement Management System (PMS) to pavement preservation programming (Mandanat 1997).

A study conducted on 85 developing countries found that 25 % of the paved roads outside urban areas have been lost owing to inadequate maintenance. This loss could have been saved with preventive maintenance costing $12 billion. In addition, 40 % of the paved roads were in need of routine maintenance in five years costing $40 billion. However, if no action is taken, the cost will reach $100 billion. The crisis has reached such dimensions, because the rate of deterioration of roads is not immediately evident. New paved roads deteriorate very slowly and almost imperceptibly in the first ten to fifteen years of their life, and then deteriorate much more rapidly unless timely maintenance is undertaken (The World Bank 1988).

The study pointed out that the costs of routine and periodic maintenance needed to preserve the pavement from further deterioration during the 1986-1999 period was estimated to be around $4.6 billion/year or $46 billion over 13 years. However, if the needs are met on a timely basis, $3 billion would have been saved and the requirements would be about $43 billion. Further to that, as an estimate for the cost of the rehabilitation of the roads, if the maintenance needs for 20% of the roads in fair condition are not met at the proper time, the cost would have been increased by about $20 billion at the point where they require major rehabilitation (The World Bank 1988).

In Saudi Arabia, modern roads appeared in early 1930's in the eastern region due to oil exploration and in the western region to serve pilgrims. Thus the early development was on a need-basis but later, according to a planned scheme. In the first 5 year development plan 1970-75, the objective was to expand the network by building new roads, and now the country is in the eighth development plan 2005-2010. The eighth development plan aims to maintain the network (MOT 2008).

In 1953, the Ministry of Transport (MOT) in Saudi Arabia was established and organized. In this research the roads network constructed by MOT is designated the Rural Road Network (RRN) whenever it is applicable. The total length of the RRN was 148 miles. There were 4,971 miles of paved roads in 1970 and 2,174 miles of unpaved roads (MOT 2008). By the year 2000, the total length for the paved RRN exceeded 27,962 miles and had cost $36 Billion (Al-Naeem 2002). At the end of 2002, the total length, for all types of paved RRN including primary roads, secondary roads, and feeder roads was 32,714 miles and the length of unpaved RRN was 74,544 miles (MOT 2008).

The first organization of municipalities in the Kingdom was founded in 1925, followed by the issuance of the municipal system in 1926 to regulate the management of the municipalities of Makkah. In 1927, the first independent system of municipalities was set up. In late 1962, as a result of the growth of municipal services provided to the citizen, the establishment of municipality affaires was approved to carry out more services. The Ministry of Municipal and Rural Affaires (MOMRA) was established in 1975 and it has been entrusted with the responsibility of providing road infrastructure inside the cities (MOMRA 2008). In this research the roads network constructed by MOMRA is designated the Urban Road Network (URN) whenever it is applicable to separate it from the roads constructed by MOT. However, the roads constructed by MOT and MOMRA in the Kingdom are known as the Saudi Arabia National Roads Network (SANRN) in this thesis whenever it is applicable. Therefore, the SANRN made up of Saudi Arabia Urban Road Network (SAURN) and Saudi Arabia Rural Road Network (SARRN).

By the year 2000, the URN, for 13 administrative regions, which comprise a total of 13 cities, 105 governorates, and 1298 centres, is 26,097 miles and had cost $11.2 Billion. Road construction costs for the major cities and provinces, namely Riyadh city, Jeddah Province, Dammam city, Holy Makkah city, and Madinah Manawarah city, in the kingdom was $5.8 billion over 30 years. The Municipality of Riyadh city has the largest road network among all the cities and provinces and exceeds 5,000 miles at a cost of $2.4 Billion. The estimated cost to maintain the pavements of the Riyadh city road network at existing condition levels is nearly $50 million annually. However, the General Directorate of Operation and Maintenance (GDOM) at Municipality of Riyadh Region spent $21.4 Million in year 2002 to maintain the roads in Riyadh City network (Al-Naeem 2002).

According to Al-Swailmi’s study, the kingdom’s road network had reached over 118,060 miles by 2000. The asphalt paved roads were over 54,059 miles and the agricultural roads 64001 miles. The total costs of constructing the kingdom’s road networks up to 2000 was over $40.44 billion On the other hand, more than $ 0.6 billion were spent on maintenance programs in the last ten years. This indicates that, the total cost of maintenance over ten years is around 5.06 % of the cost of road construction (0.51% per year) while in the United States the maintenance ratio in a year is 2.94 % (Al-Swailmi 2002).

An investment of approximately $50 billion has been made in pavements for the SANRN and billions more will be spent annually on maintenance and upgrading to protect the asset through periodic rehabilitation and maintenance. Considering the above mentioned issues undertaken in the Kingdom of Saudi Arabia, there is a need to develop simple and flexible practical procedures. Also, government officials at the MOT and the MOMRA are very anxious to save the huge budget which has been invested on the Kingdom's roads network and to keep the road network at an acceptable level of service. The emphasis has shifted to preservation of the present SANRN, representing an investment of more than $50 billion. Otherwise, this investment could be lost if pavements are allowed to deteriorate too much. The SANRN consists of flexible pavement types. The study areas in this thesis are taken from the SAURN and therefore the study deals with urban flexible pavements only.

Pavements are complex structures involving many variables, such as materials, construction, loads, environment, performance, maintenance, and economics. Thus, various technical and economic factors must be well understood to design pavements, to build pavements, and to maintain better pavements. Moreover, the problems relating to road maintenance are still more complex due to the dynamic nature of road networks where elements of the network are constantly changing, being added or removed. These elements deteriorate with time and therefore to be maintained in good condition requires substantial expenditure. Also, the preparation and evaluation of the best ways to direct this expenditure is an extremely difficult task due to many factors that affect the deterioration of these elements.

Thus, there is a need to apply a scientific approach to manage the maintenance of the road network effectively. A good system can deal with all these variables and identify priorities for conservation in order to ensure the achievement of the desired goals of maintenance to the fullest. Adapting Pavement Management Systems (PMS) will enable highway agencies to manage and maintain the networks in an effective manner (The World Bank 1988).

Many road maintenance management systems have been developed during the past four decades in the United States of America, Canada, Europe and Australia, but none of these systems fully meets the needs of the SANRN and deals with all the components of the network such as the asphalt paving, bridges, tunnels, safety issues, and road markings. In addition to that, the use of mathematical and scientific means, to achieve the ideal solution for maintaining all elements of the network possible at low cost, is important in any successful PMS.

Recognising its responsibility to protect and maintain the existing network, the MOT has sought to develop a system to manage maintenance work that takes the latest scientific methods in the area of maintenance systems. The MOT aims to establish localized scientific methods to develop plans and programs of road maintenance to optimize the network level in line with policies developed within the financial allocations available.

The road maintenance management system consists of five major systems including PMS, Bridge Management System, Non Pavement Management System, Data Base Management System, and Maintenance Follow-up Management System. The PMS in MOT consists of a number of successive stages and interrelated and complementary to each other. The stages that make up the system of PMS are; survey and evaluation, data processing and choosing the best solution, reporting the optimal solution, and finally monitoring the system and updating the models (Sayaree 2002, and Al-Salloum 1987). Further to that, in 1986, the MOT and the World Bank developed Pavement Condition Rating (PCR) to report pavement condition on the MOT network and to start maintaining the roads network in a scientific manner.

On the other hand, some municipalities at MOMRA have started thinking to develop maintenance manuals to help them upgrading the existing pavement maintenance practices. In 1996 King Abduaziz City of Science and Technology (KACST) funded a project entitled “Development of a Maintenance Management System for Riyadh road Network”. This project aims to have a comprehensive system that includes procedures for pavement evaluation, pavement condition modelling, prioritisation, and budgeting (KACST 1998).

The main objective of the KACST study was to develop a maintenance management system for the Riyadh road network. This objective has been achieved through tasks including, detailed study of existing maintenance practices, development of a maintenance management system with a Geographic Information system (GIS) platform, and improvement of existing maintenance practices using simple and direct techniques which enable evolution of more efficient maintenance programs. After the completion of the above three tasks, the system has then been gradually improved using more complicated techniques and measures to enhance or direct maintenance decisions. The final form of the system was produced taking into consideration the possibility of using the system by other major cities in the Kingdom with minor changes (KACST 1998).

In late 1997, Dammam city officials decided to develop a system that can help maintaining the road network of the city effectively. The system integrates different subsystems including; pavement features coding, visual pavement evaluation, equipment-based pavement evaluation, maintenance and repair strategy selection, maintenance priority ranking, pavement condition prediction, and reporting. These subsystems were all integrated to form the Dammam Municipality Pavement Management System (Al-Abdual Wahhab et al. 2002).

A consultant has already started to develop a PMS for Jeddah Province since 2007. Almadinah Almunwarah Region Municipality is funding a project to develop a PMS for Almadinah holy city road network with the help of a consultant. The development will be in use in early 2010. Makkah holy city Municipality developed a PMS for the city roads and that system has been in use since 2008.

Currently, MOMRA is working on a national project to standardize the practice of PMS. This five year project is a national project and has been contracted with different firms to assist in the development of a standard PMS for URN to be used by 13 regions' municipalities across Saudi Arabia. Consultant Al-Fayez firm is doing the first phase which is an inventory and survey of the existing MRN and collecting geographical data to build an electronic database using GIS to locate all the roads and related information on a map of the Kingdom (MOMRA 2008). In early 2008, MOT contracted with consultant Al-Ayonee to modify the current PMS and to enable the implementation over a three year period across Saudi Arabia (MOT 2008).

1.2 Comparison between Urban and Rural Roads

Rural and urban roads are the same in terms of service function and land service. However, there are significant differences between urban and rural roads. Traffic volumes are higher on urban roads than on rural roads, design speeds on urban roads are lower than on rural roads, and vehicle types are different. Therefore, the design standards, design features, and operational needs are different.

On urban networks, several groups share the roads. City roads commonly have a number of utility lines running parallel to and cross the roads. Utility cuts in the cities include those for electricity, water, storm, sewage, and telephone. Constructing and maintaining these utility lines requires the road pavement be dug. Each utility line is associated with a unique method of construction in terms of backfill, utility protection, separation from adjacent utilities, and depth from the pavement surface. Achievement of an adequate backfill compaction and a smooth finished surface are essential with utility repairs (Al-Swailmi 1994). As a result of this situation, urban roads experience a significant deterioration rate. Patching these trenches results in a noticeable decline in both riding quality and structural integrity of these pavements. Therefore, there is a need for a framework for a maintenance management system (MMS) rather than a PMS; the MMS focuses only on road maintenance to coordinate maintenance works. On the other hand, for the rural networks, it is necessary to consider road construction, tunnels, and bridges in their specific maintenance management needs and this is usually termed a Highway Maintenance management System (HMMS). Some studies suggest a subsystem technique to define and record the information from each subsystem such as water, electricity, and others (Al-Swailmi & Al-Abdl Wahab 2002). The purpose of this system is to help the engineers to deal with the urban network in general and to define the effect of each subsystem in order to coordinate effectively, define responsibilities, increase the efficiency of road works, and reduce the effect of trenches on the network. According to Al-Swailmi (1994), the subsystem technique is a comprehensive system for infrastructure management.

Furthermore, the pavement distress types are different between urban and rural roads. For instance, some studies recommend including all distress types in the PMS; other studies recommend reducing the number of distress types and merging some together. However, all studies agree on the importance of distress definition in a successful PMS. In general the nature of pavement distress types on rural roads is less varied than on urban roads, especially when the environmental factors, construction standards, and traffic volumes are the same; pavement distress types are mainly correlated to traffic volumes. On the other hand, pavement distress types on urban networks are highly varied and they are less correlated with traffic (Al-Swailmi & Al-Abdl Wahab 2002).

In addition, one of the differences is the network size. Rural networks are bigger compared to urban networks and consequently the costs to develop and to implement the PMS will be more. For instance, on rural roads, the sample unit length is generally long to reduce the data volume and consequently to reduce the cost of network evaluation, and according to Al-Swailmi & Al-Abdl Wahab (2002), experience shows that this methodology does not affect the efficiency of road assessment because the road performance relatively similar over significant lengths. On the other hand, urban network engineers use short length pavement sections to represent the urban network because of number of intersections, traffic signals, and trenches.

To conclude, the characteristics of urban and rural networks are not the same. The differences can be grouped into; technical issues such as the types of maintenance work, administrative issues such as sharing of the network by different organizations, the nature of pavement distress types, and the size of the network.

1.3 Problem Statement in Saudi Arabia

Pavement undergoes a process of deterioration directly after opening to traffic. This process under the effects of traffic and environmental conditions begins very slowly so that it may not be noticeable. Over time, the pavement deterioration has different mechanisms and faster rate of deterioration.

Timing of maintenance action is important since it must be carried out at the time of maximum return. Otherwise, the maintenance needs will be higher if the pavement is allowed to experience further deterioration. The pavement starts to deteriorate after opening to traffic. The deterioration starts at a low rate and with time this rate increases. Some studies showed that the highway network deteriorates to an extent that 60% of roads will reach the stage of functional failure in 20 year unless maintenance management systems are implemented. This situation will result in enormous increase in maintenance and reconstruction budget (The world Bank 1987). Many studies showed that the maintenance cost which is a very poor condition is four to five times the cost if a pavement is maintained while it is in a good condition (Haas et al. 1994). Therefore, the implementation of an effective maintenance system will reduce maintenance costs. Preventive maintenance actions taken earlier have a very important role in keeping the pavement in a good condition for longer time, and in reducing the overall costs significantly.

The traditional way of determining maintenance needs in many cities and highway agencies depend upon visual inspection of road condition. In many cases, maintenance activities are performed as a result of user complaints. This type of maintenance practice leads to inefficient and random ways of spending the maintenance budget. Pavement maintenance can be categorized into two main categories (Al-Mansour et al. 1993): corrective maintenance and preventive maintenance. The current practices of most highway authorities concentrate on the first category, with minor attention given to preventive maintenance. The main reason for this is the shortage of available funds, which directs some decision makers toward putting the limited funds on corrective maintenance to satisfy road users, leaving nothing or, at most, a negligible portion for preventive maintenance. However, this strategy is not recommended. For example, Al-Mansour and Sinha (1994) study has shown that the cost saving as a result of performing preventive maintenance is 25%. Techniques based on worst–first or spot repair are not appropriate. In these techniques, errors in pavement evaluation are expected, distress causes are not investigated, maintenance actions may not be suitable, and finally, the allocated funds are not utilized efficiently.

The Kingdom of Saudi Arabia has a huge road network connecting its major cities and neighboring countries. It also has a large municipal and urban road network. Pavements in these roads were designed to a high standard to serve for long periods before any major rehabilitation is required. A pavement network is a capital investment for the nation; funds available for maintaining this infrastructure are ever decreasing while maintenance needs are ever increasing. Moreover, many of these roads have experienced an early deterioration in the form of fatigue cracking and rutting that required enormous funds for maintenance and repair.

Traffic in the cities of Saudi Arabia is high due to the absence of good public transport. Utility trenches cause noticeable deterioration to existing asphalt pavements. Because of utility network expansion and the need to maintain existing lines, utility trenches occur even on newly constructed pavements. Patching these trenches has resulted in a noticeable decline in both riding quality and the structural integrity of these pavements. Utility cuts in the cities include those for electricity, water, storm, sewage, and telephone. Beneath city roads, a tremendous number of these utility lines run parallel to and cross the roads. Trench depths and widths vary within each utility type as well as between the various utility types. Therefore, there is a need for a framework for maintenance management systems (MMS) at each municipality in Saudi Arabia. A MMS in broad terms is part of a PMS (Al-Swailmi 1994).

Therefore, a MMS can be viewed as technique for optimizing the available resources to accomplish a predetermined minimum level of service by coordinating and controlling applications of planning, budgeting, scheduling, and evaluation. On the urban networks at Saudi Arabia, several groups share the roads, and at same time there is a lack of communication among those who share the network. Subsequently, the success of a MMS is significantly affected.

The harsh environment in Saudi Arabia affects almost the whole country. Saudi Arabia has a desert climate. Temperature is one of the most important factors affecting performance of the pavement. Temperature variations within the pavement structure contribute in many different ways to distress and possible failure of that structure. Under loading conditions, the pavement temperature is a major factor affecting the deformation response of bituminous structures (Al-Abdual Wahhab et al. 2001). The harsh environment with high traffic load operating on the Saudi road network makes the pavement more susceptible to a wide range of distress types.

The problem of the Urban Road Networks in Saudi Arabia can be summarized as follows. The impact of the traditional way of determining maintenance needs, absence of reliable deterioration models to define the right timing for maintenance, high traffic loads, climate condition, and utility cuts, is a major concern for the officials in the municipalities. The impacts of all the above issues are a common problem for the city pavements.

The SANRN has a large road network connecting its regions, cities, provinces, towns, villages. Also the network connects neighboring countries. It also has large urban and rural roads. Today, there are over 50000 miles of asphalt paved roads and around 70000 miles of agricultural roads. The total costs of constructing the kingdom's roads network is more than $50,000 billion. Therefore, to preserve this capital infrastructure and maximize its benefits, good systematic maintenance management programs should be followed. And to overcome these challenges, the government officials decided to use a systematic and strategic approach to develop pavement maintenance management systems for the Saudi Arabia National Road Network (SANRN).

The MOMRA manages the Urban Roads Network (URN) and the MOT manages the Rural Roads Network (RRN). Figure 1.1 shows that the SANRN is divided into two main networks, the urban network and rural network.

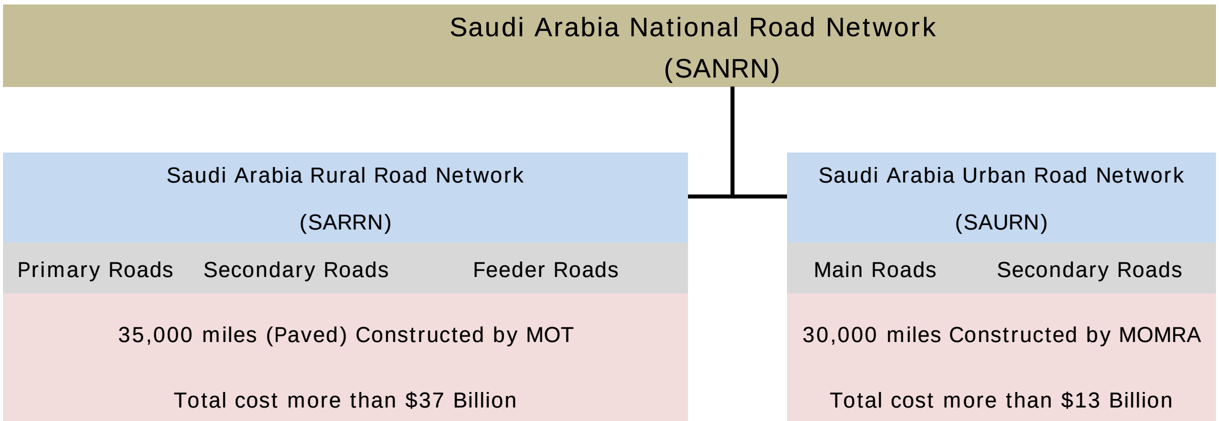

Figure 1.1 SANRN Classification

Furthermore, the Saudi government has requested MOT, MOMRA, Ministry of Hajj (Pilgrims), and (Ministry of Interior- Traffic Department) to set up the national transportation strategy (NTS). The goals of NTS are: supporting social and economic development, providing the needs of national security, increasing the effectiveness of the transportation infrastructure, increasing the safety on the transportation systems, preserving the environment, and increasing the effectiveness of pilgrim's transportation systems (Al-Mogbel 2008).

1.4 Research Objectives

Urban road management is the focus and novelty of this research. Urban roads have their own characteristics as discussed in the previous two sections. In addition to that, pavement distress information is used as quality measure of pavement for urban roads where roughness and deflection measurements are not performed because of a lack of equipment availability, high cost, or do not measure parameters relevant to deterioration on urban roads. It was noticed that road agencies consider PMS as a planning tool for maintaining the network. They used condition indicators in different ways and forms to report on pavement condition on the basis of distress data at network level.

This study will focus only on Saudi Arabia Urban Road Network (SAURN). Therefore, this research will be directed to achieve the following main objectives:

- Reviewing the concept of pavement deterioration models and the factors associated with their performance at network level for urban roads,
- Reviewing and identifying the main pavement condition indicators,
- Reviewing the currently used PMS in Saudi Arabia and some well known PMS around the world,
- Developing two groups of distress models for Urban Roads Network (URN); one group is called Urban Main Pavement Distress Models (UMPDM), and the other is called Urban Secondary Pavement Distress Models (USPDM).
- Developing two pavement condition models for Urban Roads Network. One model is called Urban Main Pavement Condition Model (UMPCM) and the other is called Urban Secondary Pavement Condition Model (USPCM).
- The approach to model individual distress types for urban roads and setting up some applications especially maintenance program because pavement distress types models can be used in detailed manner for developing a demand-based localised maintenance program.

1.5 Research Utilization

Achievement of these objectives will greatly assist in:

- Improving the current PMS and enhancing the calibration for the indices and models used,
- Determining dependency between distress types,
- Proposing maintenance needs by defining the types of distress that most probably will be accrued based on trigger values suggested through the research,
- Proposing the effective timing of maintenance needs based on trigger values suggested through the research,
- Setting up the maintenance priority based on pavement condition and the factors that are affecting the pavement condition,
- Determining the required budget by defining the maintenance needs and the time.

1.6 Thesis Organization

This thesis consists of 8 chapters. Chapter 1 is an introduction chapter where the idea of transportation infrastructure in general and in Saudi Arabia in particular is presented. The novelty of this study on urban road management was presented, where only very little work has been done in the past. The problem statement is discussed. The research objectives and the proposed utilization of the research are also stated.

The pavement management process, the PMS, pavement deterioration, and background and earlier studies are reviewed in chapter 2, while the research methodology is addressed in chapter 3. The description of the research database development is given in chapter 4. Analysis of pavement distress data and the developed models are presented in chapters 5 and 6 respectively. Chapter 7 gives analysis of pavement condition data develops models, and application of the developed models. Chapter 5 through 7 are the main chapters that address the research objectives. Finally, chapter 8 points out and highlights summary, conclusions, limitations, and recommendations resulting from this research. Figure 1.2 shows a flow chart of the thesis.

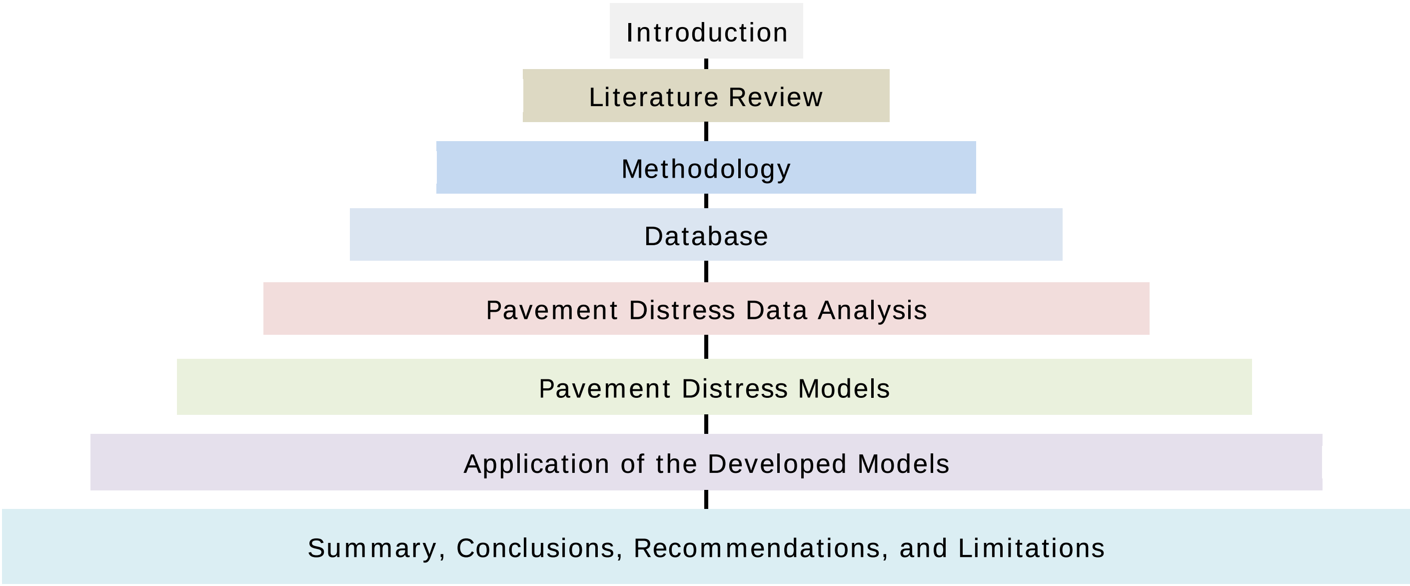

Figure 1.2 Thesis Organization.

1.7 Summary

Chapter one highlights the significance contribution of transportation sector in general and highways in particular to countries' economy. Some history, facts, and statistic figures about transportation in the world in general and Saudi Arabia in details were presented. Some pavement problems related to Saudi Arabia Urban Road Network (SAURN) were discussed. Research objectives, research utilization, and thesis organization were also stated as base for this study. The Next chapter will be the literature review.

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CHAPTER TWO
LITERATURE REVIEW

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CHAPTER TWO
LITERATURE REVIEW

This chapter introduces a general view about pavement management system, pavement evaluation, pavement deterioration, the need for pavement deterioration, predicted parameters, model requirements, method and types of prediction models. Various and different approaches on pavement condition indices, modelling the behaviour of the distress, and pavement deterioration predictions have also been discussed with examples.

2.1 Pavement Management System

A pavement management system consists of a coordinated set of activities, all directed toward achieving the best value possible for the available funds. This is an all inclusive set of activities, which may be characterized in term of major components or subsystems. A pavement management system must serve different management needs or levels and it must interface with the broader highway, airport, and /or transportation management system involved. Figure 2.1 shows a PMS consists of mutually interacting components as planning, programming, design, construction, maintenance, and rehabilitation.

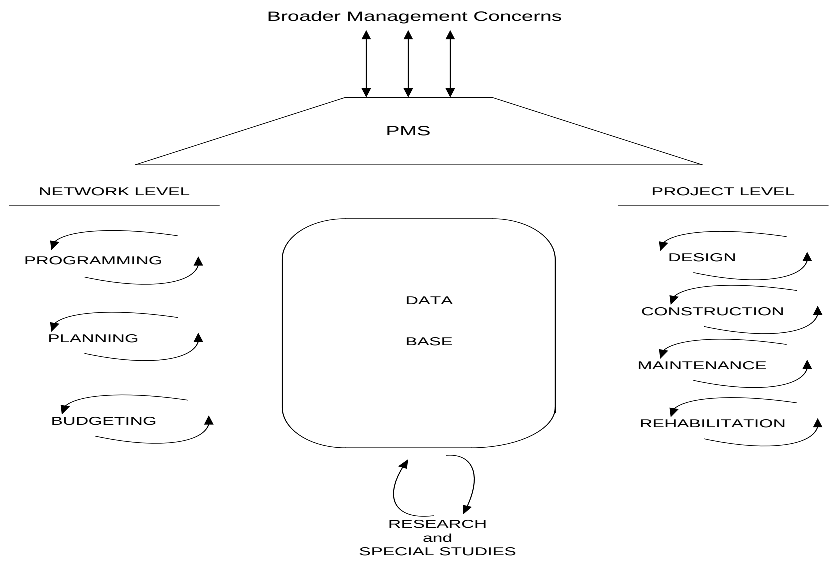

Figure 2.1 Major Component of a Pavement Management System (Hass et al. 1994).

However, the PMS components have important but changing impacts in terms of a level of influence (Barrie and Paulson 1992). The concept shows that the effect on the total life cycle cost of a project decreases as the project evolves as shown in Figure 2.2. The lower portion of the Figure represents the length of time each major component acts over the life of a pavement. The upper portion shows increasing expenditures and decreasing influence over the pavement life. Expenditures during the planning phase are small compared with the total cost. Similarly, the capital costs for construction are a fraction of the operating and maintenance costs associated with a pavement life cycle. However, the decisions made during the early phases of a project have far greater relative influence on later required expenditures than some of the later activities.

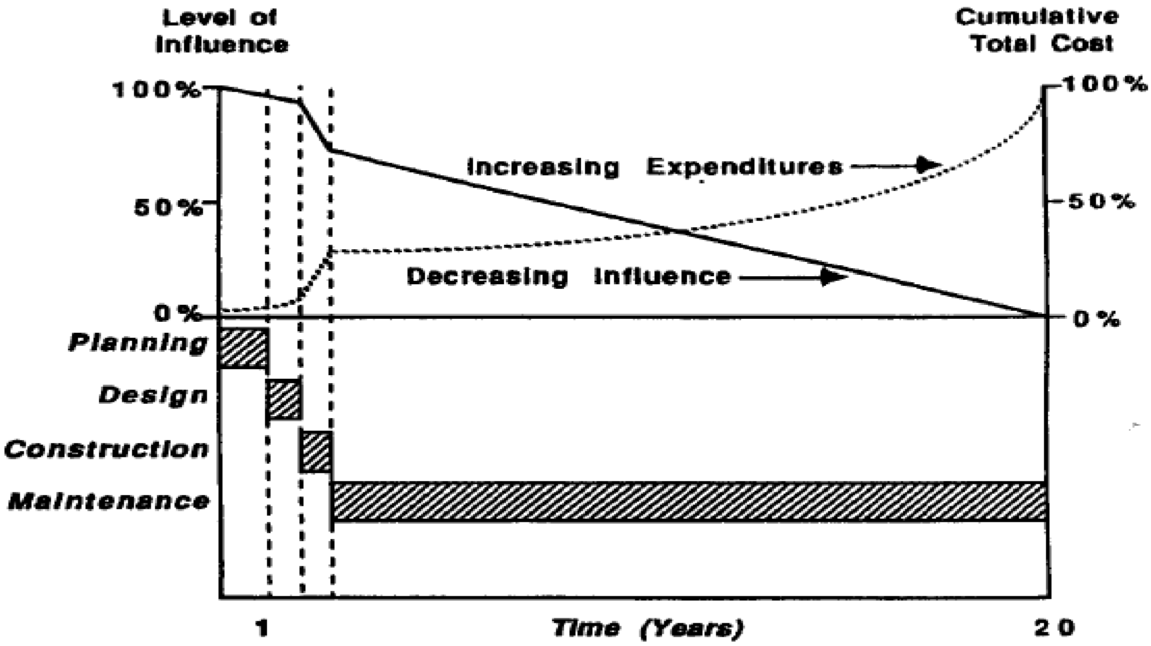

Figure 2.2 Influence Level of PMS Subsystems on the Total Costs (Hass et al. 1994).

Hass, one of the pioneers in PMS, said "Good pavement management is not business as usual, it requires an organized and systematic approach to the way we think and in the way we do day to day business. Pavement management, in its broadest sense, includes all activities involved in the planning and programming, design, construction, maintenance, and rehabilitation of the pavement portion of a public works program." (Hass et al.1994).

There is no solid agreement among most agencies and people who are working in the pavement field. However, there are definitions intended to provide a common and consistent basis for the use of certain fundamental terminology in the pavement field.

Herein, some definitions have been stated by very well known agencies and people. According to the American Association of State Highway and Transportation Officials (AASHTO), "A pavement management system is designed to provide objective information and useful data for analysis so that highway managers can make more consistent, cost-effective and defensible decisions related to the preservation of a pavement network" (AASHTO 2001). The Federal Highway Administration (FHWA) developed a clear definition of PMS "A set of tools or methods that can assist decision makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in serviceable conditions" (FHWA 1989). Haas, Hudson, and Zaniewski define a PMS as "a set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time" (Hass et al. 1994). To conclude, a PMS represents a strategy to manage a road network's needs to serve the users safely, comfortably and efficiently at least total cost and greatest benefit possible.

2.2 Pavement Evaluation

Evaluation is a key part of PMS because it provides the means for seeing how well the PMS components have been satisfied. The major types of pavement evaluation outputs versus time as shown in Figure 2.3 are measure of structural adequacy, measure of ride ability or serviceability, measure of surface distress, and measure of surface friction. In Figure 2.3, the surface distress output has reached a limit of acceptability before any of the other outputs. At this point, some rehabilitation measure has been implemented as shown by vertical discontinuity. The rehabilitation measure has been shown to affect the other outputs, such as improved surface friction, improved serviceability, and increased structural adequacy. The service life of the rehabilitation measures is ended by the serviceability reaching a minimum acceptable value. At this point, another rehabilitation measure has been applied and again the other outputs have been affected. Also, Figure 2.3 demonstrates that all the outputs of a pavement can reach a limit of acceptability one or more times during the life cycle or analysis period. Therefore, it can be concluded that the function of pavement evaluation in a PMS is measuring and assessing the mentioned four measurements in order to provide data for checking the design predictions and updating them if necessary, reschedule rehabilitation measures as indicated by these updated predictions, improve design models, improve maintenance practices, and update network programs (TAC 1997).

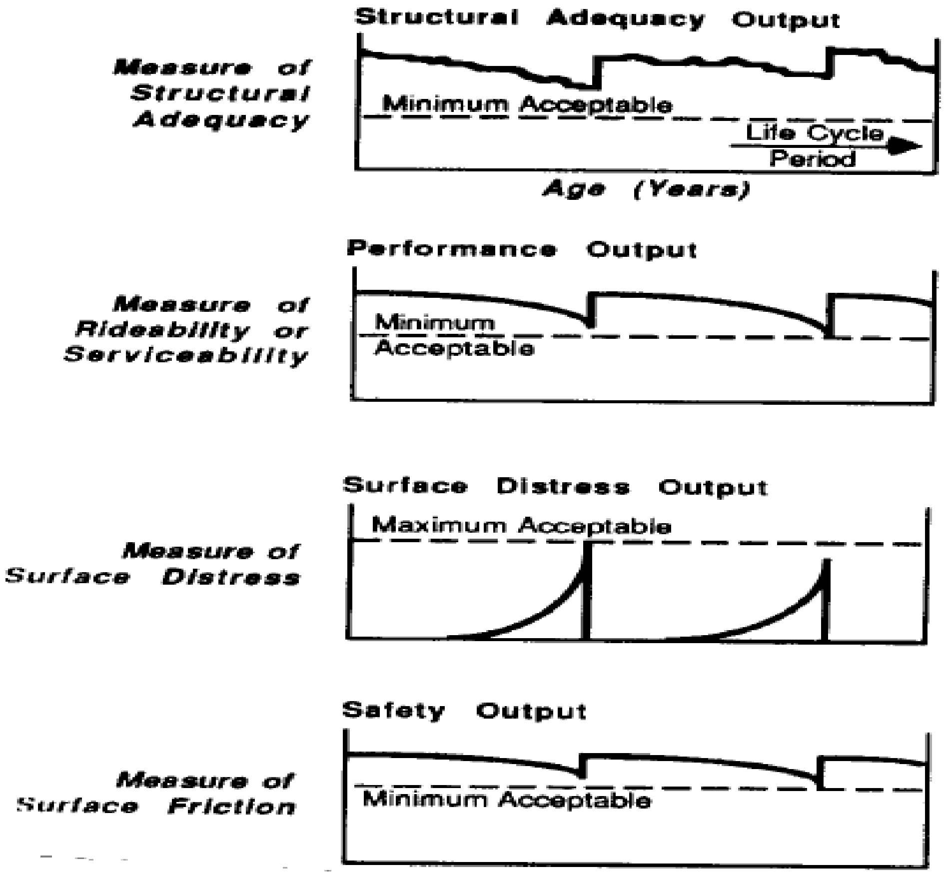

Figure 2.3 Major Types of Pavement Evaluation Outputs (Hass et al. 1994).

The uses of evaluation information are illustrated in Figure 2.4. The input variables include material and can be monitored by physical testing and sampling to provide direct information about layer thicknesses and material properties. Behaviour can be defined as the immediate response of the pavement to load. Thus, deflection tests fall into this category. Distress can be defined as limiting response or damage in the pavement. Thus, the accumulated damage is monitored and evaluated. Performance can be defined as the serviceability history of the pavement, its evaluation accomplished by periodic measurements of the roughness which is directly related to user serviceability. Among the types of pavement evaluation, most agencies consider the following four as most important: serviceability, structural adequacy, surface distress, and safety. Safety is primarily in terms of surface distress and it is a user related measure. The other three considered in terms of functional behaviour using serviceability performance concept.

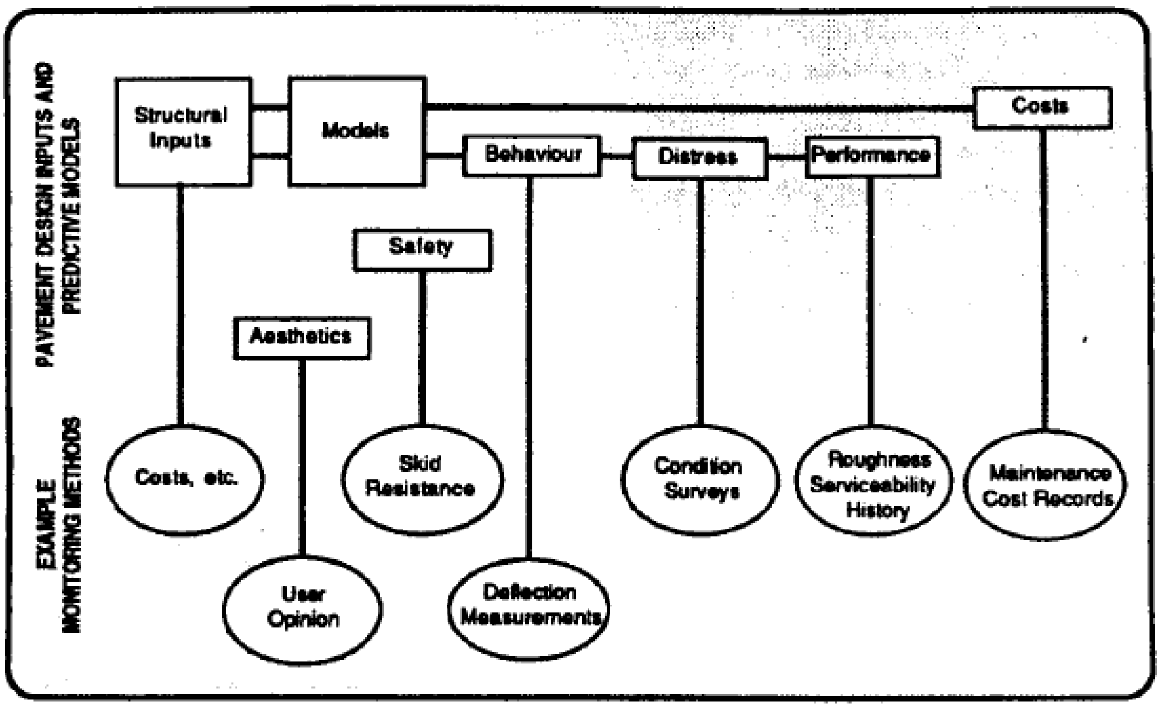

Figure 2.4 Simplified Prediction Portions of Pavement Design and Related Examples of Types of Periodic Evaluation Measurements (Hass et al. 1994).

2.3 Pavement Deterioration

Prediction deterioration is a mathematical description of the expected values that a pavement attribute will take during a specified analysis period (Hudson et al. 1979). An attribute is a property of a pavement section or class of pavements that provides a significant measure of the behavior, performance, adequacy, cost, or value of the pavement. In other words, it is a mathematical description that can be used to predict future pavement deterioration based on the present pavement condition, deterioration factors, and the effect of maintenance (OCED 1987). Deterioration or prediction models express the future state of a pavement as a function of explanatory variables or factors that include pavement structure, age, traffic loads, and environmental variables.

Prediction models can predict a single pavement condition indicator, such as pavement condition index (PCI) based on pavement distress, or an overall pavement condition index (combination of all distresses and ride quality), such as pavement serviceability index (PSI). However, this study recommended that at long term planning that each road agency or municipality to collect sufficient data to model the mechanism of every distress in addition to pavement condition models. Modeling each distress individually will help in estimating the pavement condition and the level of maintenance in the future because these models predict the distress density much better than other overall pavement condition indices. Also prediction models permit increased understanding of pavement behavior so that steps can be taken to reduce the development of distress or extend the service life of pavement.

Once the condition of pavement sections has been defined, information about past and estimated future condition is often needed. Curve Models are often fitted through past measures of condition to show past performance. Prediction models are generally used to forecast changes in condition over some future time period. Predicted condition is used in several pavement management activities. Prediction models are some of the most important components of a pavement management system (PMS). Successful PMS are largely depending on these models. Better prediction models make a better pavement management system, which lead to considerable cost savings (Hudson et al. 1997, Mohseni et al. 1991, and Vepa et al. 1996).

The road agencies and municipalities aim to know the needs analysis. In the need analysis, the measures of condition of the pavement sections are combined with other information to determine the time and type of maintenance and rehabilitation treatments needed. The needs analysis is based on a selected time period or until the condition drops to a critical level. Prediction models are used to forecast condition during that analysis period as if no treatment is applied. When the analysis process identifies that a section needs a treatment, other prediction models are used to show the expected impact of that treatment on the condition of the section at the time of treatment. Both of these models together allow needs analysis programs to show the predicted condition through the analysis period with and without the needed treatments. This study deals with developing prediction models when no treatment is applied. The impact of treatment is not included in this study due to lack of data. Chapter three explains this issue in more details.

Since the models that show the impact of recommended maintenance and rehabilitation treatments provide information to calculate the remaining useful life of the section with and without the treatments, the study recommends the municipalities across Saudi Arabia to investigate the issue of the impact of different maintenance programs specially the preventive programs on pavement condition.

Prediction models are essential for many processes of decision – making as they are useful; in establishing answers to the questions of what, where, and when, with respect to maintenance needs. Simply put, the prediction models enable us to determine the type of maintenance treatment to be adopted, the portions of the network requiring treatment, and the timing of the maintenance actions (George 1996).

Some authors differentiate between performance and prediction models based on specific definitions developed for selected measures of condition (Hudson et al. 1997). Other authors discuss (prediction models) and (performance curves) as synonymous and do not differentiate between performance models and prediction models. In this study it was preferable to use the term prediction models to describe predicted condition because the aim of the study was to use historical data to predict the future. The predicted condition can be any one of several measures of condition. It can be distress prediction and/or condition prediction as investigated in chapter six and seven. This study used a condition and distress historical data versus time to develop the predictive models.

2.4 The Need to Predict Deterioration

Models of road deterioration help to improve management, planning techniques, and give economic justification of expenditure and standards in the highways sector. Without adequate data, the road needs can't be quantified or evaluated accurately, and planning decisions tend to become short-term. It is important, therefore, to identify which parameters are essential and relevant for predictive models. Four major applications of predictive models will greatly help in identifying the modeling process and the data needs (Paterson 1987). They are: planning policy and standards; pavement management; pricing and taxation; and verification of design methodologies.

Planning deals with forecasting the needs of the road network to assess the current and future condition and the demands on the network. Such questions as "at what stage should the pavement be resurfaced or strengthened", "what should be the design life", and "which project has priority".

Pavement management systems are being applied at regional or national levels to improve the planning and effectiveness of maintenance works and expenditures. Two basic elements are:

An information system, comprising a database of network inventory, current and historical data, data for traffic volume and loading, maintenance works, and regular monitoring of the network to update; and

A decision – support system, which analyses the data, and identifies current and future needs.

The majority of systems use predictive models to forecast future road condition, the timing, and the consequence of deferring maintenance. Some agencies use extrapolation models based on the historical trend of condition established in past regular condition surveys. Some use basic correlative models from whatever local performance data are available. In either case, the reliability of such models is low until a considerable history of data has been established.

Predictive models which have been derived from a broad empirical base, and which use the current condition and physical parameters to estimate deterioration, are extremely valuable because they are versatile and relatively little effort is required to adapt them to local conditions.

Pricing and taxation amongst various classes of road user involves two primary issues. First, the effects of vehicles and environment on road damage and repair costs are must be investigated. Second, the basis of costs must be determined and allocated.

Verification of design methodologies has different forms and types. Engineering methods for designing road pavement and analyzing the effects of vehicle loading and climate on pavement condition have developed considerably due to the results of major road tests.

2.5 Predicted Parameters

Pavement condition prediction models can be developed to forecast condition in terms of one of the several different measures of condition. Sometimes models are classified based on what types of parameters they predict. Four common groupings include (Lytton 1987):

- Primary response
- Structural performance
- Functional performance
- Damage

In addition, these types of models can predict the impact of treatments on the condition of sections.

2.5.1 Primary Response

Primary response models predict the primary mechanistic response of sections to some imposed load (structural or environmental influences). Deflection, stress, and strain are common responses predicted by primary response models. Mechanistic models are generally used to predict primary responses, and primary responses are normally used only at project or research level. This study has no data set of deflection, stress, and strain. Therefore, the primary response is not the subject of this study.

2.5.2 Structural Performance

Structural information based on construction records, non-destructive testing, or laboratory testing are generally required to use this type of models. Empirical and mechanistic-empirical models are normally used to predict these types of parameters. Structural information or other related information is normally required to use this type of model. Construction records, non-destructive testing, or laboratory testing are not available for this study, therefore, the structure performance is not the subject of this study.

2.5.3 Functional Performance

Functional condition models predict measures of the condition that define how well the pavement section is meeting its basic function. Safety related prediction models normally forecast some characteristics such as the surface friction characteristics of pavement based on skid numbers developed from skid testing. These types of models are often empirical, but they may use material properties as a part of the parameters on which the models are based. Skid resistance data are not available in this study.

2.5.4 Damage

Damage models are derived from either the structural or functional models. Damage is a normalized measure of distress, roughness, surface friction, or other measure of condition. In damage analysis, a damage number of 0 indicates no damage while a damage number of 1 indicates the maximum possible damage. Using damage allows predict the maximum and minimum levels into a single function or formula. In this study, the damage is available in terms of historical condition data such as distress density and pavement condition data.

2.6 Model Requirements

Darter outlined basic requirements for a reliable prediction models as (Darter 1980):

- An adequate database based on in-service sections,
- Consideration of all factors that affect prediction or performance,
- Selection of an appropriate functional form of the model, and
- A method to assess the precision and accuracy of the model.

All the above requirements are fully investigated in the following chapters. The first requirement which is an adequate database has been explained, investigated, and developed in chapter four. The second requirement is about the factor that affect the prediction, this requirement is fully investigated in chapter five. Selections of an appropriate functional form of the models and the accuracy of the models have been detailed in chapter six and seven. However, these requirements must be highlighted in the light of some literature review in the following subsections.

2.6.1 Adequate Database and Factors that Affect Prediction

An adequate database would include a collection of data that would provide information adequate to support the models being developed. In general, this should include the condition measure to be predicted dependent variable and information on the factors that affect prediction that are included in the models. It must include the age and/or loading information that the models will predict the condition as function of independent variable. In many cases the available data from which models can be developed and the resources of an agency to collect future data will control the data used in a model to predict condition. The accuracy of the data on factors that affect performance used in developing models will have a direct impact of the reliability with which the models can predict future pavement condition. In general, more accurate data costs more money to collect and keep current.

2.6.1.1 Construction Dates

Age, loads, or a function of age and loads, are used in many models as the independent variable. These prediction models must have a starting point. That point is generally the date of construction. Construction can sometimes be considered the date of application of the latest major maintenance.

2.6.1.2 Maintenance and Rehabilitation

Another problem with in-service facilities is the maintenance that is applied but not recorded in the database. The purpose of most condition prediction models is to predict the change in condition without treatment and compare that to the change in condition with a treatment. Rehabilitation and reconstruction will have such a major impact on the condition and rate of deterioration, that when they are applied, the date of construction may need to be changed to the date of the rehabilitation or reconstruction. The condition of sections can also be significantly affected by application of preventive and routine maintenance. However, few agencies record the application of routine maintenance with enough detail to allow use of it in condition prediction models. If maintenance, rehabilitation and reconstruction data are not recorded, then models of condition developed as a function of time will not be accurate (Ramaswamy and Ben Akvia 1990).

2.6.1.3 Condition Data

Since most of the models currently used depend on regression analysis, information for the dependent variable or the measure of condition to be predicted is the most obvious information that is needed. The condition data should be available over a range of age be predicted. However, agencies do not generally build roads and allow them to deteriorate to the worst possible condition.

2.6.1.4 Traffic Loading Effect

Traffic loading is considered as the primary factor that affects both pavement design and performance. Traffic loading characteristics include traffic volume, axle load, axle configuration, repletion of axle load, tyre pressure, and vehicle speed. The traffic loading in pavement design is well formulated and investigated whereas the method of using axle loads in PMS as a pavement condition prediction variable is still not well understood (Wijk et al. 1998).

Since loadings are one of the most important factors that affects damages of most pavement section, it is often used as an independent variable in developed condition prediction equations. It is sometimes combined with age as an independent variable. Since in most circumstances, agencies want to know when in years, the pavement will need work, in some models loads are used as a factor that affects the rate of condition change as a function of time which is considered the independent variable.

Few studies have discussed the effect of loading on pavement performance and how it should be used in PMS in an effective manner. For example, a new understanding of the traffic effect was investigated in the light of shake down load limit. If the pavement is subjected to a repeated load greater than the shake down limit, then the pavement will fail as a result of a result of the excessive plastic deformation, this indicates that if the design load is made more than the shakedown load limit, the pavement may gradually fail by the accumulation of plastic strain, resulting in a form of rutting and surface cracking. Excessive stresses and strain in asphalt surfaced pavement due traffic loading will eventually result in deformation and cracking (Shiau and Yh 2000).

According to Huang (1993), the critical tensile and compressive strains under multiple axles are only slight different from those under single axle, for example, the damage caused by the standard 18-kip (80 KN) is almost equal to the damage caused by the 36kip (160 KN)tandem axles or that of 54-kip (240 KN) tridem axles.

According to AASHTO (1993), pavement distress propagation is associated with continuous traffic growth. The formulation of distress types leads to a failure in one the pavement components. AASHTO pavement design procedure requires traffic evaluation for both design and rehabilitation. Therefore, the accuracy of traffic volumes and weight is very important.

Six pavement structures were analysed where three of them are representative of Portuguese pavements, and three are representative of Brazilian pavements. It was performed a linear-elastic mechanistic analysis to determine two structural responses: horizontal tensile strain at the bottom of the asphalt layer and vertical compressive strain at the top of sub grade, associated to the most important pavement distress types in Portugal and Brazil, respectively fatigue cracking and rutting (Fernandes et al. 2005)

A study by Brozze and others (Brozee et al. 2004), the new Mechanistic-Empirical Pavement Design Guide (MEPDG) requires comprehensive traffic inputs to predict pavement performance. Axle load spectra play a critical role in the impact of traffic on pavement performance. Weigh-in-motion (WIM) systems are becoming widely used as an efficient means of collecting traffic load data for mechanistic pavement design. The results of this study not only support but also advance the existing research in this critical area. The findings of this study can be used to estimate pavement life prediction bias when inaccurate WIM data are used. They can also serve as guidelines for state highway agencies for the selection of WIM equipment and the establishment of criteria for equipment calibration.

2.6.1.5 Soil

The natural soil is another important factor which must be considered (AASHTO 1993). Since most loads are eventually transmitted to the natural soil, weaker soils will require thicker and stronger supporting structures. However, this issue is very important in the design process, it is very important in the maintenance when the pavement section show a damage in form of depressions. Since the natural soil, affects the performance. The data on the supporting material should be available for use in developing the models. Generally some type of information about strength is most useful, but information on type of soil would also be helpful. Since many agencies do not have soil information, they develop models ignoring soil properties. This results in supporting materials being an unmeasured that will lead to an increase in prediction error. Some agencies have developed groupings of facilities based on distinctly different soil types and developed separate prediction equations for each. One agency developed separate models for the pavements in the coastal areas and the hill areas because of different soil conditions. Location then becomes a surrogate for soil type.

2.6.1.6 Materials

The thickness, type, and strength of each material would be the best information for use in developing condition prediction models. That data would need to be in the database. However, few agencies have that information for all of their sections. Many agencies group sections together into type groups and develop individual models.

2.6.1.7 Environment

If the model is for a local area and all pavements will be affected the same by environmental conditions, then environment can be neglected. The condition change of the section based on age will basically include the influence of the environment. The older sections will show more influence of the environment because they have been exposed to it for a longer period of time. Many times, the age will act as a surrogate for the influences of environment. Another agency uses a modifier in condition prediction as a function of age that adjusts the prediction model for different environmental zones.

2.6.2 Appropriate Form for Prediction Models

Model building is a creative activity of the human intellect (Hudson et al. 1997). As much knowledge as available on how condition changes should be used in developing the condition prediction models.

Lytton defined the following a priori conditions that must also be met by prediction models which will limit the form to those appropriate for the pavement condition measures being modeled (Lytton 1987):

Initial Value: The initial value of all damage is zero. Similarly the condition of a pavement at the beginning of its service life is excellent.
Initial Slope: Most damage has a slop that is initially zero. However, some damage types such as roughness or rutting have an initial upsurge.
Overall Trend: Most damage is irreversible; the slope must always show a worsening of condition unless a treatment is applied.
Variations in Slope: Damages can be affected by variables such as changes in climatic condition, which can lead to variations in slope.
Final Slope: damage functions such as cracks, area of distress, and serviceability have an upper limit. In all these damage functions, the final slope must be zero, and this type of equation approaches a horizontal asymptotes. By contrast, other types of damages such as roughness or rutting do not have such constrains. Rutting generally starts out developing rapidly and then reduces in rate, until other distress types influence the rate of deterioration, and rutting rate again increases.
Final Value: The maximum value of damage has an upper limit only for those types of distresses for which the final slope is zero.

2.6.3 Method to Assess the Precision and Accuracy of the Model

A valid statistical approach must be used in developing the condition prediction models to provide a basis for determining the precision and accuracy of the model. Since regression analysis is used in most of the model development, statistical methods that show the precision of the regression equations are often used. Probably the most commonly used tests are the standard error of estimate, the coefficient of determination, the residual analysis, correlation coefficient, F-test, and other tests are also used (Draper et al. 1981, and Smith 1986). The specific test must be selected based on the type of regression used.

2.7 Methods of Prediction Models

A prediction model can be developed by one of the following methods (FHWA 1990):

- Empirical Method
- Mechanistic Method
- Mechanistic-Empirical Method

- Probabilistic Method
- Bayesian Method

2.7.1 Empirical Method

The empirical method is generally characterized by the collection of a large amount of data before much speculation as to their significance, or without much idea of what to expect. Empirical method is constructed on the basis of statistical models. This method is the most useful for this study because the study has a large amount of data to do statistical analysis, statistical modeling, and statistical accuracy tests. Chapter 5, 6, 7 investigate these points in details.

2.7.2 Mechanistic Method

Mechanistic method in pavement analysis includes layered elastic and finite element methods. However, these types of methods require detailed structural information which limits the accurate calculation of stresses, strains, and deflections to sections for which the detailed data is available. Mechanistic method depends on the basis of theory of mechanics. So this method is highly dependent on: elastic layer theory, visco-elastic theory, fracture mechanics, and finite element analysis. This method is not appropriate for condition data because the condition data gather only surface data.

2.7.3 Mechanistic – Empirical Method

The analytical – empirical or mechanistic-empirical method has been widely applied in flexible pavement design. This approach consists of two parts: calculating the response of the pavement materials to the applied loading and predicting the pavement performance from these responses. Mixing Mechanistic-Empirical method is a good method in pavement management. However, due to lack of pavement material data, this study cannot be carried out this method.

2.7.4 Probabilistic Method

In this method, pavement condition measures can be treated as a random variable with probabilities associated with its values. The probabilities associated with all the values of random variable can be described by probability distribution. A transition probability matrix is used to define the probability that a pavement in an initial condition state will be in some future condition state. A transition matrix should be developed for each combination of factors that affect pavement performance. This transition probability matrix is basically obtained from expert views (Haas et al. 1994). Probabilistic method is good method when there are not data can be used. This method is not suit here.

2.7.5 Bayesian Method

Bayesian methods depends on combining observed data and expert experience using Bayesian regression techniques which are primarily based on a famous paper published by the Rev. Thomas Bayes (1702-1761). In Bayesian regression analysis, the regression parameters are considered random variables with associated probability distribution. Bayes' theorem can be expressed mathematically as (Thomas 1993):

$$P(p|:x) = \frac{P(x|p).x\ P(p)}{\sum[P(x|p)\ x\ P(p)]}$$

where,

P(x) = distribution of variants over all possible fraction variants

P(p) = prior distribution

P(x|p) = sampling distribution

P(p|x) = posterior distribution

Since this study has enough real data from the field, no need to obtain more data from expert views, and therefore Bayesian method can be avoided.

2.8 Types of Prediction Models

Generally, three major classification models have been developed in pavement management systems so far: Deterministic models, Probabilistic models, and Bayesian models.

However, a classification of prediction models has been suggested by Mahoney (Mahoney 1990) based on earlier work (Lytton 1987). It considers the network and project levels of pavement management and two basic types or classes of models. They are deterministic models and probabilistic models.

Other classifications in use are disaggregate and aggregate models (George 1996). Disaggregate models predicate the evolution of an individual measure of distress. Aggregate models predict composite measures; for example, damage index, condition rating, or serviceability.

Other classification by Hass (1994) pavement models has different forms and types. They can be categorized into the following four basic types

1. Purely mechanistic models based on some primary response (behavior) parameters such as stress, strain, or deflection. The pavement responses are normally due to traffic and /or environmental condition.
2. Regression (empirical) models, where the dependent variable of observed or measured structural functional deterioration is related to one or more independent variables like sub grade strength, axle load reputations, pavement layer thickness and properties, environmental factors, and their interactions.
3. Mechanistic-Empirical models, where a response parameter is related measured structural or functional deterioration, such as distress or roughness through regression equations,
4. Subjective (probabilistic model), where experience is captured in a formalized or structured way, using transition process , for example, to develop deterioration prediction model.

As explained earlier, the available data for this study has a great impact on which method of modeling and which types of model the study will be carried out.

2.9 Empirical Method Examples

The area of road deterioration modeling is very wide and broad area. Different countries all over the world have their own contribution in pavement management system in general and road deterioration in particular. North America has been contributed more in this area and they have more studies compared to European countries, Australia, New Zealand, Asia countries, and South America countries. Furthermore, most of the studies were conducted on highways and rural roads. Only little studies were found on urban roads. In this section of this chapter, various researches from different countries and experience on urban and rural road deterioration modelling were outlined and summarised.

Empirical models relate the change in condition to the age of the facility, loadings applied, or some combination of both (Lytton 1987). Regression analysis is used as a tool to assist in finding the best empirical model which represents the data. However, it must still use a form of equation that is realistic. Prior knowledge of the factors that affect performance is essential to developing reasonable empirical models. This important issue is discussed in chapter five.

Linear and non-linear regression analyses are used in developing empirical models. Microcomputer software has made development of these models much simpler. Least square analyses are used by most regression procedures to relate the selected performance parameter to one or more data variable.

Empirical models are only valid for predicting the condition of sections similar to those on which the models were based. If the conditions change, the models must be changed. An agency adopting an empirical model must ensure that it was developed for the local conditions in which it will be used. Empirical models must be carefully examined to ensure they are realistic. Researchers have developed empirical models in which the parameters have counter-intuitive signs (Butler et al. 1985). Because most empirical models are developed based on performance of in-service sections rather than sections constructed to meet the requirements of an experimental design, unknown and unexplained biases may influence the models. In addition, an agency's routine maintenance policy may significantly affect the predicted condition, and a model developed in one agency with a defined routine maintenance policy may not be appropriate for use by another agency using another maintenance policy (Ramaswamy and Ben Akvia 1990, and Hass et al. 1994).

One of the most important steps in constructing an empirical model is the selection of an appropriate form; although, selection of relevant variables is also very important. There are various forms of regression models, such as, linear, Powers, sigmoid equations, log values, and polynomials are commonly used which are shown in this simple Figure 2.5.

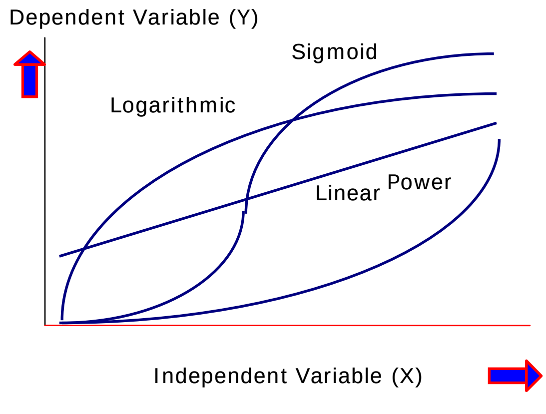

Figure 2.5 Typical Regression Curves.

Regression (empirical) models, is the most popular methods for developing deterministic empirical models. This analysis is used to establish an empirical relationship between two or more of variables. In the regression models, pavement condition is considered as independent variable and a set of factors selected as dependent variables. In most regression analyses the fit of the model is described by the coefficient of determinant (R^2) value (Peter et al. 1995). The R^2 value is based on sample correlation coefficients that indicate the strength of the developed relationship between the response variable and the independent variables when compared to the observed data. R^2 may then be interpreted as the portion of total variability in the dependent variable that can be explained by the independent variables. The R^2 can range from 0 to 100 with the higher number indicating a better fit of the model to the actual data. However, R^2 is not always the right indication especially when nonlinear regression is performed.

Since the study concerns about the behavior of the pavement distress prediction and pavement condition prediction, a brief of discussion and examples will be presented in the following pages on this chapter.

The general process of developing pavement condition indices consists of assigning deduct points to specific types, severity and extent (density) of distress. These deduct points are summed up and subtracted from a constant number (usually 100). This process results in a single value index, which describes the pavement condition. The developed pavement condition indices represent the agency's professional judgment of what combination of distress types and weighted pavement condition factors are important to them.

Distress evaluation is one of the important steps in pavement evaluation, which in turn, is the most critical component of any pavement management system. An indication of the importance of distress data is the fact that distress indexes are used as the common measure of pavement quality in many pavement management systems. Pavement distress types are usually grouped in different classes depending on the viewpoint of the evaluator and the purpose of the survey. These groups might be (Rezqallah 1997):

1. Type-Wise grouping : cracking, surface deformation, surface defect, and others,
2. pavement –type grouping : flexible or rigid pavement distresses,
3. failure type – wise grouping : structural or functional failure distresses,
4. cause-wise grouping : load associated, environmental, built-in cause, and construction practice associated distresses,

5. location-wise grouping : localized or wide-spread distresses, and
6. Performance-wise grouping: riding quality, skid resistance, or structural related distresses.

Pavement distress information can be used in a detailed manner for developing a demand-based localized maintenance program. However, in order to obtain an overall assessment of pavement conditions for a road network, it is often necessary to combine individual distress data to form one composite index which summarizes the condition of each pavement section or segment or project. The composite index will help in deciding whether to repair a section with alligator cracking or rutting. Also density and severity of different distresses will indicate that one pavement section is in a worse state than another pavement with a different set of distresses (Haas et al. 1994). The composite distress index summarizes the pavement condition in terms of individual distress, so that pavement condition may be evaluated, predicted, and improved using effective treatments.

Distress evaluation, or condition survey, includes detailed identification of pavement distress type, severity, extent, and location. To combine these details, an index is assigned to each pavement which is transferred to a general rating. Every highway agency, either develops pavement distress evaluation procedure or select a developed on for its pavement condition survey.

Measure of surface distress data as pavement management data related to the pavement condition has a lot of uses in the network level or the project level. Pavement distress data has long been recognized by pavement engineers as an important parameter for quantifying the quality of a pavement surface. It is important at both the network and project levels of pavement management systems, although the level of detail required for each application is considerably different. In both cases, the pavement distress information is useful in selecting appropriate treatments (Haas et al. 1994).

Pavement evaluation at network level (Christine 1996) deals with summary information related to the entire highway network. As such, it involves policy and programming decisions frequently made by top management. Typical uses of network level pavement evaluation establishing rehabilitation programs, setting policy, and justifying budget requests. The use of surface distress data at this level are (Haas et al. 1994); describing present status, predicting deterioration identifying current and future needs, maintenance priority programming, and to evaluate the effectiveness of alternative treatments. Pavement evaluation at project level (Christine 1996) deals with detailed and technical information related to a specific pavement section, such as, it involves decisions made by middle or lower management. The uses of surface distress data at this level are (Haas et al. 1994); selection of specific maintenance treatments identifies needed spot improvement, develop maintenance quantity estimates, and evaluate the effectiveness of the alternative treatments.

In almost all distress evaluation methodologies, each distress is specified by severity level (low, medium, or high) and an extent level described in measurable units linear or area) or descriptive measure (few, intermittent, frequent, or extensive). Each distress type, severity level, and extent level combination is assigned a deduct value which is an indication of how this combination, when available, affects the perfect pavement.

In 1950, a regression equation (Roberts et al. 1991) known as Present Serviceability Index was developed to evaluate the pavement serviceability based on measurable pavement distresses and a quantifiable measure of the pavement evaluation.

The PSI is determined as follows:

PSI = 5 – 1.91log (1+SV) – 1.38 (RD) ^2 – 0.01 (C+P) ^ 0.5

Where

SV = slope variance

RD = average rut depth

C = pavement cracking in feet/1000 square feet of pavement surface and

P = patching in square feet /1000 square feet of pavement surface

In 1962, AASHTO (Roberts et al. 1991) studied a quantifiable measurement of pavement distress types. The Present Serviceability Index was established by AASHTO during the study. This index is a number which is indicative of the pavement ability to serve traffic and it's based on combination of profile meter readings (roughness) and visual inspection (surface distress types). In this method, each distress included is considered as an independent variable, and all the independent variables combined linearly or nonlinearly to reproduce the user ratings based on pure data fitting. The developed index ranges from 0 to 5 as follows:

4 – 5 very good

3 – 4 good

2 – 3 fair

1 – 2 poor

0 – 1 very poor

Pavement condition was investigated in 1981 by US Army Corps of Engineers (Shahin 2002). The study was resulted in development a single rating number called Pavement Condition Index (PCI) using the PAVER method to represent pavement condition. PAVER is one the most detailed distress evaluation method implemented to data. This method depends on detailed visual inspection of up to 19 different pavements distresses for flexible pavement. The PCI is a numerical index, ranging from 0 for a failed pavement to 100 for a pavement in perfect condition. It measures pavement structural integrity and surface operational condition. The essential concept behinds PCI is to consider each given distress severity and amount as a negative deduct on pavement condition. The PCI index uses only one pavement condition parameter which is distress types in determining the pavement condition index. The PCI is determined as follows:

$$PCI = C - \sum \sum a\,(Ti, Sj, Dij) \times, Dij)\ x\ F$$

Where,

T i = distress type

S j = severity level.

D i j = density of distress.

C = constant (usually 100).

a = weighing factor.

F = adjustment factor for multiple distress.

UK Highway agency PMS (HAPMS) is the HA's version of the UK Pavement Management System (UKPMS). The HAPMS is expected to assist the Agency to deliver better and more cost-effective management of the network of trunk roads and motorways in England. Therefore, the HAPMS was developed to predict pavement condition prediction models to convert pavement condition into an appropriate maintenance treatment and to prioritise maintenance schemes. The prediction modeling approach depends on four criteria: safety, value for money, reduction of disruption and environment. The HAPMS uses software for the Whole-Life Economic Evaluation of Pavement Schemes (SWEEP.S). The SWEEP.S tool is used to demonstrate value for money for their proposed scheme maintenance options. The current pavement condition is assessed and then maintenance options are identified. Based on that, the SWEEP.S analysis evaluates the work's costs and road user's costs for different treatment options (Nicholls et al. 2007).

According to Phillips (1994), the prediction models in HAPMS and UKPMS are to defer treatments where it is cost effective and to give priority instead to preventive maintenance. In addition, HAPMS have the ability to predict future pavement condition and the ability to carry out optimization of multiple options of treatments for all sections of the network. Furthermore, SWEEP.S predicts future treatment on the basis of pavement condition projected forward to next year from the present condition. The prediction modelling approach is using standard shaped curves relating pavement condition to time such as s-shaped curves and other.

The UK's pavement asset management objectives are to update design standards to reflect developments in design and materials to minimise whole life costs and to find survey and maintenance strategies (Warras 2006).

The Performance and Economic Rating System (PERS®) developed by Dynatest international as an analytical tool for life cost analysis and road network maintenance planning system based on budget optimisations. It is a product that is commercially distributed around the world which can be integrated along with various PMS of different highways agencies.

The PERS is based on the mechanistic-empirical method and calculates the future performance using distress models. The PERS may be used as the network PMS to automatically determine the most efficient maintenance strategies for a large number of roadway sections, also, may be used as a project level tool for calculating the effects of different maintenance and rehabilitation strategies on a particular section (PERS 2010).

The main elements of PERS® are (PERS 2010):

- Material dependent Models for predicting the pavement performance based on mechanistic (analytical) principles.
- Models for quantifying the economic effects of pavement conditions.
- Empirical Models, which can be calibrated automatically, and used as an alternative to the mechanistic models.
- Cost/benefit analysis, for optimizing the maintenance strategy for a section.
- Methods for selecting the optimal combination of maintenance and rehabilitation alternatives over a user defined number of budget years (optimisation).

The PERS predicts pavement performance using the incremental-recursive mode by blending all the factors that are essential elements of the pavement deterioration process and enables the user to calibrate the models against historical data (Ullidtz 1999).

The incremental recursive models in PERS estimate pavement performance in relation structural deterioration, rutting, roughness, skid resistance, and surface wear (Lund 2009).

The World Bank's Highway Design and Maintenance Model, HDM-3, includes a deterministic mechanistic-empirical based on roughness progression prediction methodology. In 1993 the World Bank commended updating their software to version HDM-4. Although HDM-4 provides a more refined and flexible program, the majority of the underlying principles have remain unchanged (Bennett 1996).

The modelling concept in HDM can be summarised as; road pavements deteriorate over time under the combined effects of traffic and weather. Traffic axle loading include levels of stress and strain within the pavement layers which are the functions of the stiffness and layer thicknesses of the materials and which under repeated loading cause the initiation of cracking through fatigue in bound materials and the deformation of all materials. Weathering causes bituminous surfacing materials to become brittle. The process of interactive causes and effects, resulting in roughness, is the concept in the approach. Therefore, the pavement strength, the condition, and the age of the pavement at the beginning of the year are given, and the volume of traffic per lane is computed using two damage functions. The ages predicted for the initiation of cracking or ravelling vary with surface and base type, and when the current surfacing age exceeds those, the areas of cracking and ravelling progression are predicted. Potholing begins beyond a threshold of the area and severity of cracking and ravelling, and progresses by volume. So the roughness progression is predicted as the sum of three components: structural deformation, surface condition, and an age-environmental-related roughness term. There are two models namely the incremental roughness model and the aggregate roughness model. These models were found suitable and unsuitable for different countries (The World Bank 1988).

Highway Development and Management Tool (HDM-4) software was developed as part of the international study funded by the World Bank and others. The HDM-4 was developed to provide additional capabilities such as models for traffic congestion, climate effects, safety and environmental effects that are not in HDM-3. The HDM-3 has been used to combine technical and economic appraisals of road projects. Therefore, HDM-4 is not only an economic analysis tool, but also a decision-support tool for road management (HDM-4 Manual 2001).

The road deterioration models in HDM-4 are deterministic in nature and are used for predicting annual conditions of roads as well as part of the inputs into user effects. Eight separate distress models, which can be divided into three categories: surfacing distress types including; cracking, raveling, potholing, deformation distress types including; rutting, and roughness, and surface texture distress types including; texture depth and skid resistance. These models predict the change of distress over a period using either time or traffic as the basis for pavement deterioration using the incremental methods. However, cracking and rutting as the commonest distress models in bituminous pavements, these are the ones whose models in HDM-4 would be examined. This method is the same as the incremental recursive method adopted in PERS. It allows the models in HDM-4 to analyse the various forms of distress types that could arise from pavement deterioration.

The road deterioration models in HDM-4 are structured empirical which provided the theoretical and experimental bases of mechanistic models with the behaviour observed in empirical studies (Paterson and Attoh-Okino 1992).

The Australian Road Research Board (ARRB) has developed two distinctly different roughness progression model types, the network model and the project model. The network model is intended to undertake broad network analysis to arrive at annual maintenance budgets for certain roughness limits and provide maximum life cycle benefits. Once the budget and the roughness limits have been determined for each road type, they can be applied as constraining inputs into the project model analysis (Martin 1996).

The ARRB developed another roughness progression model, rather than simply calibrating HDM-3, because HDM-3 does not directly address the influence maintenance practices has on pavement deterioration (Martin 1996).

According to Picado-Santoes (2004), the city council of Lisbon, Portugal, decided to build a PMS for the vast road network at the beginning of 1999. Implementation of a geographical information system (GIS) –based PMS was designed to a certain structure, including, data acquisition, pavement behavior models, maintenance and rehabilitation costs and actions. Data acquisition is one the most important tasks in the development and implantation of a PMS. In addition to that, the road network database was configured in response to specific needs of the city council in relation to the evaluation of pavement quality and application of the decision-aid tool. The pavement behaviour models are needed to generate information that would serve as input for the decision-aid tool, which is intended to minimize the expected costs of Maintenance and Rehabilitation (M&R) over a given planning time frame while keeping the road network within given performance level.

The Metropolitan Transportation Commission (MTC) of Oakland, California (Wang 2000) presented a modified PCI method in its PMS implementation. MTC consolidated the 19 distress types to only 7 to expedite the pavement condition survey process.

Also, Stan Tech Consulting Ltd. (Wang 2000) has been modified PAVER PCI method. Two major modifications to the original PAVER PCI method were made. The primary one is the way the multiple deduct-values are combined to determine the Corrected Deduct-value (CDV). The other modification is that the individual deduct-value curves are expressed in a standardized log equation form.

Baladi (Wang 2000) proposed a procedure for formulating pavement condition index for individual distress. There are several steps in this process, which starts with the identification and determination of types of distress, severity levels for each type of distress, and the determination of a rating scale, such as 0 to 100. Based on these definitions and the rating scale, a panel of engineers is asked to determine the maximum tolerable density for each type-severity distress before any treatment will be scheduled. This density level is hence designated as the threshold deduct-value, or the so-called engineering criterion for that particular type-severity distress. Finally, deduct-values for other density levels for the same type-severity distress are obtained by linearly scaling up and down according to the designated engineering criterion. This process has been adopted by North Carolina and South Dakota.

13 types of pavement distresses are considered in OHIO method (Harper et al. 1993). Each has three severity levels: low, medium, and high, and three extent levels: occasional, frequent, and extensive. An extent level represents the percentage of section length or area affected by that distress. A weight out of 100 is assigned to each distress. Distress severity and extent are also assigned a fractional weight; a Pavement Condition Rating (PCR) provides an index reflecting the composite effect of various distress type, severity, and extent upon the overall condition. PCR is computed by subtracting the total deduct points from 100. Therefore, $PCR = 100 \sum deduct\ i$

Where deduct i = weight for distress x weight for severity x weight for extent.

The Ministry of Transportation of Ontario (MTO) (MTC 1980) uses two parameters to evaluate the pavement condition. The two parameters are: Distress Manifestation Index

(DMI) and the Ride Comfort Rating (RCR). The DMI is a composite subjective measure (or a multi – attribute) of extent and severity of pavement distress manifestations. 15 distress types that are evaluated for asphalt concrete pavements grouped into three categories: surface defects, surface deformation and cracking. The severity of distress is rated in five categories ranging from very slight to very severe. Extent (or density) is also classified in five categories ranging from few (less than 10 %) to throughout (more than 80 %). The severity and density weighting factors to calculate each distress index which equates to severity on a scale 0.5 to 4 and density on a scale 0.5 to 4.0. The developed formula to calculate the DMI is

$$DMI = \sum wi\,(s\,i + d\,i)$$

Where wi = weighting value representing the relative weight of a distress manifestation

Washington State Department of Transportation (WSDOT) (Washington 1988) has conducted a visual condition survey every two years since 1969 on 100 percent of the state highway system. In the late 1970s and early 1980s WSDOT developed an improved pavement management system that predicate pavement condition for each project based on prior pavement condition data. For flexible pavements, the pavement condition survey is used to evaluate alligator cracking, longitudinal cracking, transverse cracking and patching. The developed Pavement Condition Rating (PCR) is a measure of the observed pavement surface distress and ranges from 100 (no distress) to 0 or below (extensive surface distress). PCR is primarily determined by measures of the extent and severity of pavement surface cracking. The final pavement condition rating (PCR) is a combination of the visual rating and ride rating:

$$PCR = [100 - \sum D]\,[1.0 - 0.3\,\{CPM/5000\}\,\hat{}\,2]$$

Where $\sum D$ is the sum of the detect values, and CPM is the counts per mile

One element of Port Orange Pavement Management System (POPMS) (Michael 1994) is the pavement condition survey done by Center for Urban Transportation Research (CUTR). Pavement distress types were identified by the city as having the most importance in monitoring deterioration. These distress types are; alligator cracking, longitudinal and transverse cracking. Patch deterioration, edge cracking, and rutting, raveling, polished aggregate. The developed index is Defect Rating (DR). DR is computed by subtracting the total defect points from 100. Therefore, DR = [100 - $\sum$ D (defect points)]

One of five indices developed for Pennsylvania models (Chen et al. 1995) was Surface Distress Index (SDI) which relates seven distresses together. These distresses are; Excess Asphalt, Raveling and Weathering, Block Cracking, Transverse and Longitudinal Cracking, Edge Deterioration, Widening Drop-off, and Rutting.

The Surface Distress Index is equal to

(SDI) = 0.1(Excess Asphalt) + 0.13 (Raveling and Weathering) +

0.20 (Block Cracking) + 0.25 (Transverse and Longitudinal Cracking) +

0.05 (Edge Deterioration) + 0.12 (Widening Drop-off) + 0.15 (Rutting).

In China (Wang 2000) Sun and Yao adopted the deduct-value concept in formulating the distress indexes for asphalt pavements. The proposed a different procedure for Pavement Distress Index (PDI) based on a different set of distress definition and measuring method. Three major's steps in this method, namely standardization of distress classification and measurement, formulation of PDI, Finally determination of the weight function.

In 1986, Ministry of Transport (MOT) in the kingdom of Saudi Arabia has selected the Ohio pavement condition system. The method was developed in Ohio State at USA based on the most occurring distresses available in the state pavement network (Rezqallah 1997). The MOT has modified this procedure by changing the segment length of rating and assigned weighting to distress. They added Present Serviceability Rating (PSR) to the pavement rating form and shoulder rating is also added to the rating form. PSR is a simple rating of the pavement from good to bad based on the rater's judgment.

In 1989 pavement condition surveys for the road network of Jubail Industrial City were carried out by KFUPM – Reasserts Institute (Rezqallah 1997) using the pavement distress based rating (PDR) procedure. The pavement distress based rating (PDR) depends on assigning deduct points (DDPs) to each distress type based on its severity and extent levels. The assignment relates to the pavement condition description that is derived from the Pavement Distress Based- Rating (PDR). PDR for a section equals 100 minus the sum of the DDPs for that section. DDPs are assigned on the assumption that only one distress type exists. If there is more than one distress type (two or more), it is recommended that the sum of DDPs is corrected by multiplying by a correction factor (C) of 0.70.

Three rating conditions are specified:

Poor for PDR values of 55 and below,

Fair for PDR values of 56 to 75, and

Good for PDR values of 76 to 100

Riyadh Pavement Maintenance Management System (RRM 2007) developed a combined index of pavement distresses called Urban Distress Index (UDI). UDI is calculated based on pavement distress type, severity and density.

In order to reflect the existing situation in Riyadh Road Network, local professional judgment was utilized for the development of local deducts points for each distress severity. Each distress severity level was assigned a distress weighting value, ranging from zero to five. These weighting values were obtained by careful examination and analysis. Deduct values were developed based on experience and judgment of local pavement managers, engineers and technicians.

UDI is calculated by the following equation:

$UDI = 100 - 20 \sum (Tij\ Di / 100)$ Where,

UDI = Urban Distress Index (pavement condition index),

Tij = Deduct value.

Di = Adjusted density.

Pavement condition is then rated according to UDI value as follows:

0	-	39	Poor
40	-	69	Fair
70	-	89	Good
90	-	100	Excellent

Another study was carried out by Christopher (Robinson et al. 1996). The main objective of the study was to develop models for rigid pavement distresses level versus pavement age. A distress prediction models for Portland cement concrete pavements in Texas was developed for the Pavement Management Information System (PMIS) for the Texas Department of Transportation. The research quantitatively predicts distress level versus pavement age, based on pavement condition data maintained by the Center for Transportation Research (CTR) at the University of Texas at Austin. The following models are available for the following distress types in Continuously Reinforced Concrete Pavement (CRCP): Portland cement concrete patches, asphalt patches, serviceability loss as measured by loss of ride score, transverse crack spacing, and crack spelling. Preliminary models are available for the following distresses in Jointed Concrete Pavement (JCP) and Jointed Reinforced Concrete Pavement (JRCP): patches, comer breaks, faulted joints and cracks, spalled joints and cracks, transverse crack spacing, and slabs with longitudinal cracks. A sigmoid regression equation was used for all distress types. These models are applicable only to non-overlaid Portland cement concrete pavements and are based on an upper limit of fifteen years for CRCP and sixteen years for JCP. The models represent the most accurate regression possible using the sigmoid equation with the available data. The Texas PMIS uses the sigmoid equation for predicting all types of distresses in both rigid and flexible pavements. Most of the distress models for JCP shown considerable scatter, indicating that pavement age is not the only significant factor, and perhaps not the most important one, in predicting distress. However, all the models describe reasonable trends of increasing distress as a function of age. In order to better track pavement behavior over time, they emphasized the need for regular data collection.

In a study performed by Shiyab (2007), for the use of PMS, some models for urban roads were developed. The study showed that the exponential function and polynomial function were found to have good fitness with general data trends with sufficient accuracy to satisfy the general boundary conditions applied to the deterioration of the pavement system which had been stated on the methodology chapter. Some of the developed model as follows:

Local Residential

$$PQI = 100e^{-0.011\,Age}$$

$$PQI = 100 - 0.276Age - 0.030Age^2$$

Where PQI = pavement quality Index

Local Commercial

$$PQI = 100e^{-0.015\,Age}$$

$$PQI = 100 - 0.408Age - 0.035Age^2$$

Where PQI = pavement quality Index

Another study that used sigmoid and power functions for modelling overlaid sections was carried out by Adel et al (1996), as follows.

The power form is

$$DMR = 100 - 5.17(Age)^{0.58}$$

Where DMR = Distress Maintenance Rating

The sigmoid Form is

$$DMR = 100 - 43.96e^{\left(\frac{-2.49}{Age^{-0.56}}\right)}$$

Washington Department of Transportation (WSDOT) used empirical models in the network level PMS (WSDOT 1998).

$$PCR = 100 - 0.76(AGE)^{1.75}$$

Where,

PCR = Pavement condition rating

AGE = Pavement age (years) determined from the time of construction of the overlay to the time of the last condition survey. To ensure better fitted curves, various coefficients was developed for different localities across the state.

Nevada Department of Transportation (NDOT) (Sabaaly et al. 1996) developed a set of performance models for the network level PMS:

$$PSI = -0.83 + 0.23\ DTP + 0.19\ PMF + 0.27\ SN + 0.078\ TMIN + 0.0037\ FT - 7.1\ e^{-7ESAL} - 0.14\ YEAR$$

where,

DTP = Depth of overlay

SN = Structural Number of existing pavement

PMF = Percent mineral filler

TMIN = Average minimum annual air temperature (F)

ESAL = Equivalent single axle loads

YEAR = Year of performance (year of construction is zero)

FT = Number of freeze-thaw cycle per year

Present serviceability index (PSI) defined as:

$$PSI = 5\ e^{-0.0041\ IRI} - 1.38RD^2 - 0.03(C+P)^{0.5}$$

where,

PSI = Present serviceability Index (in 0-5 scale)

IRI = International Roughness Index (mm/km)

RD = Rut depth (mm)

C = Cracking (sqm per 93 sqm)

P = Patching (sqm per 93 sqm)

This is one of the 16 performance models used in NDOT districts.

In Minnesota Department of Transportation (MDOT) (Erlando et al. 1994), the development of the models was centered on the prediction of future distress levels rather than the prediction of a composite index. The prediction models were based on simple two variables modeling relating distress density to age. Additional variables such as surface type, traffic, and structure were handled by grouping the pavements by specific attributes. The project resulted in a set of performance prediction models for about 100 pavement groupings. The distresses models included transverse and longitudinal cracking at two severity levels, multiple cracking, alligator cracking, rutting, raveling, and patching for flexible pavements.

Power and sigmoid models (Adel et al. 1996) were developed by Virginia Department of Transportation's (VDOT) using Distress Maintenance Rating (DMR) score. The power prediction method model represents a more realistic model form than the simple linear model, which meet most of the boundary conditions established for a deterioration model. The model is capable of satisfying the initial boundary condition of no distress at zero, regardless of the values for the other variables. The model fitted by using the non-linear regression techniques. A sigmoid (S-shaped) model is a curve with an inflection point and upper lower asymptotes. The sigmoid model could be appropriate form for predicting pavement indices. Moreover, by having an inflection point, the model is capable of reflecting different deterioration rates throughout the pavement life.

The primary objective of this study (Ping and Yunxia 1998) was to evaluate historical information related to pavement condition survey for determining the best estimate of flexible pavement performance life in Florida. This study explains that the method for developing pavement performance models consists of fitting the selected models to the observed pavement condition data for each pavement section and subsequently establishing equations for predicting the parameters of the model using regression analysis.

The regression equations were a function of pavement performance age. The variable age is the most significant factor for predicting PCR (Pavement Condition Rating), because it is a common factor in the estimation of both cumulative traffic loads and environmental loads over the life-cycle period. In developing the performance prediction models, it is important to choose a function that obeys the prescribed boundary conditions for the variable being predicted PCR. For this study, the models developed should predict the trend in PCR with time. These boundary conditions suggest the use of a non-linear, polynomial curve for modelling pavement performance.

A total of 279 pavement sections from the surveyed pavement network were selected for curve fitting. A best-fit curve applies to each data set of the 279 selected pavement sections using a constrained least squares method. Accuracy analysis indicated that polynomial curve fitted the observed PCR trends quite well.

The North Dakota study (Johnson and Cation 1992) developed overall distress, structural and roughness, performance curves for 42 different performance class pavements. The original pavement data was categorised into groups based on similar characteristics such as surface type, traffic and structure. These groups (or families) were then analysed to develop performance curves. This approach assumes that pavements with the same grouping will perform similarly throughout their lives. This method is easy to understand and modify in the future. The research investigated the use of linear regression analysis, the AASHTO power function, and non-linear analysis. It was found that non-linear analysis in the form of a fourth degree polynomial, gave the best results for distress and structural indices. For example, the average distress index R^2 for 42 classes of pavements was 0.77.

Colorado department of transportation developed various performance curves for each distress type. Three levels of performance curve are used, which are site-specific, pavement family, default curve. The most desirable is site-specific curve. If it is not available due to lack of data, family curves are used. Default curves are applied.

It is recognized that pure empirical models are demanding massive data support. In case of where data are deficient, experts can supplement knowledge. Experts' models are developed based on the opinions of experienced engineers who are familiar with deterioration patterns. South Dakota Department of Transportation used this approach to develop their deterioration models. Experienced engineers were asked to provide estimates of ages of pavements to reach particular conditions in terms of severity and extent for different distress types. With these data, a regression analysis was performed to determine the coefficients for the specified model (Jackson et al. 1996).

The modelling pavement deterioration behavior was developed specifically for use in PAVER (Shahin et al. 1987). Three mathematical curve – fitting techniques were used to build pavement deterioration models. These mathematical models are: stepwise regression, B-spline approximation, and constrained least squares estimation.

Prediction models were developed for different modes of distress in India (Sood et al. 1994). A total of 113 test sections were selected for collecting data over a period of 3 to 5 years. The large amount of data collected was subjected to the following forms of analysis. Separate models were developed of crack progression and roughness over time.

Prediction models were developed for Norwegian Public Roads based on rutting and roughness diagnosed by expert system (Haugodegard et al. 1994). These curves were partly empirical and partly mechanistic.

The Ministry of Transportation in Ontario Canada compared the prediction capabilities of 5 different model types (Hajek 1985) include:

- OPAC model (mechanistically derived)
- PARS model (empirical, pavement classes)
- Power curve (empirical, site-specific)
- Sigmoid curve (empirical site-specific)
- Factored PARS model (Bayesian approach, site-specific)

It was noted that, the prediction accuracy of the empirical site-specific models for sigmoid curve was far better than other types.

The Texas Transport Institute in cooperation with the Texas State Department of Highways and Public Transportation also investigated appropriate curve fitting of actual pavement performance data, for use in serviceability prediction (Garcia-Diaz 1985). The proposed model represents an improvement over the form of the original AASHO Road Test performance equation in that it predicts more realistic long term behaviour. This is achieved through the use of a sigmoid or S-shaped curve that recognises the ability of a pavement to reduce its rate of deterioration as the traffic level approaches the service life of the pavement.

The shape that a functional performance curve should take can be deduced from the boundary conditions placed on the serviceability index scale as well as the long term observations of field data. A statistical procedure used for estimating the parameters of the performance relationship guarantees that the goodness of fit between predicted and observed data is maximised. The S-shaped performance curve was found to adequately describe the performance of a flexible pavement in Texas.

Cardosa and Marcon (1998) studied three model types and conclude that curve fitting of actual performance data using regression was more accurate when compared to the models developed by HDM models. Regression analyses were carried out relating pavement condition, represented by five dependent criterion variables to the predictor independent variables (age or traffic loading). Five types of models (linear, logarithmic, polynomial, power and exponential) were considered in the analysis.

The main objective of this research (Al-Suleiman et al. 1992) was to develop pavement performance models for Jordanian rural roads where pavement evaluation equipment and funds are limited. The analysis showed that the power function was suitable to model the relationship.

An extensive research was done by Phang and Stott (1981) on Brampton road test in Canada to study the progress of distresses prior to maintenance work over the passage of time and traffic. The distress Manifestation, (DM), assigned to a pavement at any time is the summation of the weighted values for condition (severity and extent) of each type and class of pavement distress present. If the component weighted values for each type of distress is examined over a period of time, one can trace the progression of that specific distress and perhaps determine whether certain types of distress lead to rapid failure, and as well, perhaps note those distresses which are not critical. The weighting for each distress type and class derived through iterative correlation with the performance of many thousands of kilometers of highway, do in fact, indicate a relative deterioration gradient applicable to the specific distress. Many points have been concluded, but herein a summary of important conclusions of this study.

Rut formation in the wheel track is the first distress type which generally appears. Rutting in full depth asphalt sections is marginally deeper in the thinner sections than in the thicker sections.

Longitudinal cracking in the wheel track appears to be the next most significant distress. The appearance of longitudinal cracking in the wheel tracks was earliest for the thin section and latest for the thick section. This crack type progressed rapidly to alligator in the thin section, but remained as a single crack in all other sections.

Transverse cracking did not appear until 10 years of service. Pavement edge cracking was significant only with thinnest of the fill depth asphalt concrete sections.

Alligator cracking in or near the wheel tracks generally precedes resurface.

2.10 Different Method Examples

A good example of mechanistic –empirical models is provided by Queiroz (Haas et al. 1994) where linear elasticity was used as the basic constitutive relationship for pavement material. Calculated responses included surface deflection, horizontal tensile stress, strain and strain energy at the bottom of the asphalt layer, and vertical compressive stress and strain energy at the top of the subgrade. The observed roughness and cracking are related to calculated response.

Probabilistic model is an excellent way to create individual distress prediction but it needs a good knowledge of distribution law for the variable being predicted (Helali et al. 1996, Abbas et al. 1994). A transition matrix should be developed for each combination of factors that affect pavement performance. This transition probability matrix is basically obtained from expert views (Haas et al. 1994). The good advantage of probabilistic model is that the probabilistic models capture the uncertainty of the rate of deterioration (Abbas et al. 1994).

For pavement prediction modeling, the transition probability matrix defines the probability that a pavement in an initial condition state will be in some future state. This matrix is usually obtained by using a formal interview method. The experts are asked to determine to the best of their ability, the probability a pavement in one condition sate to go each of the future condition states in one time period (Haas et al. 1994). Because the Markov process estimates the future condition state solely from the current condition state, other factors that affect the pavement behavior are handled by defining a transition matrix for each combination of factors such as pavement type, pavement thickness, traffic volume or load, and environmental conditions.

An example of probabilistic model is Markov process or Markov chain. Markov chain is a probabilistic model that accounts for the uncertainties present with respect to both the existing pavement condition and future pavement deterioration. Arizona Department of Transportation (AzDOT) has used transition probability matrices for network optimization system (Wang at al 1994).

An incremental discrete deterioration model was constructed using an ordered probit model for estimating infrastructure transition probabilities from infrastructure data (Madanet et al. 1995).

A number of studies have involved the application of Artificial Neural Networks (ANN) to develop a pavement prediction models. For examples, Mississippi Department of Transportation developed ANN models to predict pavement conditions for five families of pavements: original flexible, overlaid flexible, composite, jointed, and continuously reinforced concrete (Shekharan 2000).

Owusu-Ababio (1998) applied ANN to model performance of thick asphalt pavement. It was concluded that the ANN model outperform the multiple linear regression model in terms of standard error and R square value.

As result of a research used ANN to develop model to forecast pavement crack condition in university of South Florida, the research concluded that the ANN can be effective tool for pavement maintenance planning (Lou et al. 2001).

An application of the Canadian Strategic Highway Research Program (C-SHRP) Bayesian statistical analysis methodology for pavement deterioration modeling by the Ministry of Transportation, Ontario, Canada is described by Hajek and Bradbury in reference (Hajek et al. 1996). In this application, several distress prediction models were constructed initially based on the data alone using linear regression technique as required for the C-SHRP Bayesian analysis. After evaluation, the best one was selected for further analysis. Subsequently, five experts with 10 to 30 years of relevant experience and knowledge of past failures of pavement surface containing steel slag aggregate were requested to rate the level of distress at different age with different traffic and asphalt binder content using a scale from 0 (no distress) to 10 (sufficient distress that unmistakably requires a rehabilitation treatment).

Separate matrices for cracking and ravelling were used since the distress index was considered as a linear function of cracking and ravelling. The distress index (DI) matrices were then obtained by adding two matrices (each having 18 cells) coded by each expert.

Five different prior models (experience based) were developed using the C-SHRP Bayesian statistical analysis software, XLBays keeping the same format as that was used for the data based model. Finally, posterior models were developed from the prior models and field data using "N-prior" analysis option available in the said software.

After carrying out sensitivity analysis of these models, the final distress prediction model was selected. As indicated in the paper, "the C-SHRP Bayesian statistical analysis software provides a unique feature that enables the user to obtain a probability density function for regression coefficients (for the data-based, expert-based and combined models) and plot them in one composite Figure for easy comparison".

The data based model, prior models, posterior models and recommended model are given below (also shown in the Figure) (Hajek et al. 1996):

Data based Model:

$$DI = 127 + 5.64AGE - 18.6AC - 5.88\log TRAFFIC$$

where,

DI = Distress Index

AGE = Age of the pavement surface course

AC = Percentage by mass of asphalt cement in the surface course

TRAFFIC = AADT volume per lane

The form of the model is, $DI = B_o + B_1AGE + B_2AC + B_3\log TRAFFIC$

P = probability that the mean of the regression coefficients or constants is equal to zero.

Recommended Model: $DI = 94.8 + 6.29AGE - 15.4AC - 2.57\log TRAFFIC$

2.11 Summary

The literature review shows a series of researches that attempted to different techniques in developing condition indices and in modeling pavement prediction and performance. However, the following points summarize the literature review:

- Surface distress evaluation is important in a Pavement Management System (PMS).

- Modeling pavement is an essential activity of PMS. The models play a crucial role in several aspects (George et al. 1989). First, they are used to predict when maintenance will be required for individual road sections and how to prioritize competing maintenance requirement. Second, the model enables the agency to estimate long-range funding requirement of the pavement preservation and to analyze the consequences of different budgets on condition of pavement network. Third, models can be used for design as well as the life – cycle economic evaluation.

- Pavement Prediction model is the most technologically difficult portion of pavement management (Johnson and Cation 1992) due to the uncertainties of pavements behavior under changeable traffic load, environment, and the difficulty of quantifying many factors affecting pavements.

- Darter noted four criteria to use in developing reliable pavement models. These criteria include:

  - an adequate database built from in service pavements,
  - the inclusion of all variables that significantly affect pavement performance,
  - an adequate functional form of the model, and
  - a model that meets the proper statistical criteria for precision and accuracy.

- The following Table summarizes the advantage and disadvantage of different types of model (FHWA 1990).

Table 2.1 Models Comparison

Models	Advantage	Disadvantage
Regression	• Microcomputer software packages are now widely available for analysis which makes modelling easy and less time consuming. • These models can be easily installed in a PMS. • Models take less time and storage to run.	• Needs large database for a better model. • Works only within the range of input data. • Faulty data sometimes get mixed up and induces poor prediction. Needs data censorship. • Selection of proper form is difficult and time taking.
Survivor Curve	• Comparatively easy to develop. • It is simpler as it gives only the probability of failure corresponding to pavement age.	• Considerable error may be expected if small group of units are used.
Markov	• Provides a convenient way to incorporate data feedback. • reflects performance trends regardless of non-linear trends	• No ready made software is available. • Past performance has no influence • It does not provide guidance on physical factors which contribute to change. • Needs large computer storage and time.
Semi-Markov	• Can be developed solely on subjective inputs. • Needs much less field data. • Provides a convenient way to incorporate data feedback. • Past performance can be used	• No ready made software is available. • Needs large computer storage and time.
Mechanistic	• Prediction is based on cause-and-effect relationship, hence gives the best result.	• Needs maximum computer power, storage and time. • Uses large number of variables (e.g. material properties, environment conditions, geometric elements, loading characteristics etc.). • Predicts only basic material responses
Mechanistic-empirical	• Primarily based on cause-and-effect relationship, hence its prediction is better. • Easy to work with the final empirical model. • Needs less computer power and time.	• Depends on field data for the development of empirical model. • Does not lend itself to subjective inputs. • Works within a fixed domain of independent variable. • Generally works with large number of input variables (material properties, environment conditions, geometric elements, etc.) which are often not available in a PMS.
Bayesian	• Can be developed from past experience and limited field data. • Simpler than Markov and Semi-Markov models. • Can be suitably enhanced using feedback data.	• May not consider mechanistic behaviour. • Improper judgement can lead to erroneous model.

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CHAPTER THREE
METHODOLOGY

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CHAPTER THREE
METHODOLOGY

To achieve the objectives of the research which were written in chapter one, a research methodology should be stated clearly and specifically. The proposed methodology written in this chapter defines the research scope, research methodology, and experimental design of the study. A brief discussion on database development, model parameters, and model formulation has been highlighted.

3.1 Research Scope

This research aims to develop two major targets for Saudi Arabia Urban Road Network (SAURN); firstly, developing pavement distress models, and secondly developing pavement condition models. The first target is divided into two groups; Urban Main Pavement Distress Models (UMPDM), and Urban Secondary Pavement Distress Models (USPDM). The second target is also divided into two models; Urban Main Pavement Condition Model (UMPCM), and Urban Secondary Pavement Condition Model (USPCM).

In order to achieve these two major targets, the following points were made to clarify the proposed methodology for this research:

- The study focuses on SAURN only. Saudi Arabia Rural Road Network (SARRN) is not included.

- The research investigates two classes of road; main and secondary pavement roads.

- In general there is one standard policy for constructing the main roads. The contractors must follow the standard. For secondary roads, there is a different standard. The reason behind this is the different functions of the roads. The typical cross section for the main sections is shown in Figure 3.1 whereas the typical cross section for the secondary sections is shown in Figure 3.2 (KACST 1998, and RRM 1998b).

- Since the construction policy is similar across Saudi Arabia, the selected URN data are data for main and secondary pavement sections which have homogenous pavement characteristics in terms of structure.

Figure 3.1 Cross Section of Main Pavement Section (RRM 1998b).

Figure 3.2 Cross Section of Secondary Pavement Section (RRM 1998b).

- These roads were constructed by the Ministry of Municipal and Rural Affairs (MOMRA). Here they will be referred to as the Urban Roads Network (URN).

- Since MOMRA has constructed the URN throughout the municipalities across Saudi Arabia, the general procedure for construction is similar everywhere. A different design is used for severe conditions where necessary. These severe condition cases are very few and they represent a very small percentage of the SAURN.

- Maintenance activities are almost the same across the SAURN because the funds come from a single body, namely MOMRA. However, the budgets are different from municipality to municipality. Across Saudi Arabia the main activity is an overlay.

- The source of the URN data is the Pavement Management System (PMS) unit in the General Directorate of Operation and Maintenance (GDOM) at Riyadh Region Municipality (RRM).

- Although the source of the URN data is RRM-GDOM, the objectives of the study are to develop deterioration models for urban roads across Saudi Arabia. Therefore, to some extent the data can be generalized to develop pavement distress models and pavement condition models.

- The URN data information contains; municipal branch name, municipal branch number, highway class, section number, sample number, survey date, maintenance data, Annual Average Daily Traffic (AADT), drainage, UDI Value, UDI rate as discussed in chapter 2, distress density, and distress severity. The distress types include Fatigue Cracks, Block Cracks, Longitudinal & Transverse Cracks, Patching, Potholes, Depressions, Rutting, Shoving, Bleeding, Polishing, Weathering & Raveling, Patching Cracking, Patching Depressions, Patching Potholes, Patching Weathering & Raveling (RRM 1998b).

- Riyadh region Municipality has done five surveys for main sections and three surveys for secondary sections so far. The available surveys for main sections were carried out in 1998, 2000, 2002, 2005, and 2007. The available surveys for secondary roads are from 1999 to 2005 (RRM 2007).

- Only three types of maintenance have been applied on URN, namely deep patching, shallow patching, and thin overlay. However, most of the maintenance is overlay work. In this research, only data for overlaid main sections and overlaid secondary sections have been used.

- In this research only overlays are considered since an overlay increases the pavement performance to its maximum. This ensures consistency with the assumption that the pavement condition is at its highest value of 100 immediately after the maintenance and before opening the road to the traffic.

- The pavement age is determined from the last major maintenance date, which is an overlay date.

- The factors in the study are the ones commonly available and reliable. They are; percent of distress density, pavement condition, pavement age, traffic, and drainage (RRM 1998b).

- The URN data can be classified into two major types.

- The two major types are pavement distress data, and pavement condition data.

- The pavement distress data are percent of distress density in the surveys for each distress, pavement age, traffic, and drainage.

- The pavement condition data are pavement condition index value in the surveys, pavement age, traffic, and drainage.

- The pavement distress and condition data sets are each divided into two databases, one for urban main sections, the other for urban secondary sections, giving four databases in total.

- After building the required databases, they will be subjected individually to two major steps.

- The first major step is that each database will be analyzed in terms of normality, and then a model factors significance test. The second major step is to build the models.

- Chapters 5, 6, and 7 deal with analyzing the data and modeling for the four databases.

- Modeling diagnostics and model accuracy will be investigated after modeling. Chapter 6 and 7 discuss this important issue.

- The developed models will be named as follows:
    - Urban Main Pavement Distress Models (UMPDM)
    - Urban Secondary Pavement Distress Models (USPDM)
    - Urban Main Pavement Condition Model (UMPCM)
    - Urban Secondary Pavement Condition Model (USPCM)

- The developed models will be assessed against standard error.

- Adequacy measures of the developed models will be analyzed in terms of a residual analysis.

- 95% confidence limits for the data will be produced for each model.

- 95% confidence limits for the models will be also produced.

- The flow chart in Figure 3.3 shows the breakdown of the SAURN into two main classes; main roads and secondary roads.

- The flow chart explains the major components of this study, namely developing the database after checking the data, developing the required models, and the validation process on the models, and finally the implementation of the models in the PMS of SAURN.

3.2 Dataset Development

To obtain generic models for URN that can be utilized with a significant level of confidence, this study has covered all possible and accessible pavement sections that satisfy the research scope discussed in section 3.1. The PMS unit in the General Directorate of Operation and Maintenance (GDOM) at Riyadh region municipality (RRM) is the only source for URN data. In this study, the GDOM data have been checked for outlier cases.

- For this study, the dataset was developed though different steps as follows:
- Some apparent outliers exist within the data but all data was analysed so that extreme values could be identified as part of modelling process.
- Only overlaid sections were included in the study to ensure that the initial pavement condition is close to 100.
- Section boundary modifications were as checked. Any section that had been merged with another due to any reason was removed to ensure accuracy for the selected sections used in building the research dataset.
- Maintenance ratio was also checked to ensure that most of the section had been maintained by overlay. Any section with less than 90 % was removed. The maintenance ratio is calculated based on maintenance area and the survey area for a given section.
- Any section was exposed to maintenance activities after the overlay date were removed.

- Any section satisfies the above four conditions was used to build the research work or the dataset for the research and can be considered as the original work in this study.
- Each section contains different number of sample unit depends on the geometry of the section.
- Each sample unit contains one or more than pavement distress type's record (type, severity, density) and only one UDI value (these values from the GDOM database).
- For the UDI dataset, the original work used the UDI of pavement section at given survey date by averaging the sample UDI values.
- This value has been used as one reading in the dataset.
- The other reading point for same pavement section was taken by same process but at different survey time.
- The dataset of the UDI models was built based on the above steps.
- This process is same for both main and secondary roads.
- For the pavement distress type's dataset, weighting values were used for each distress type and severity. These weighting values were developed for Riyadh pavement management system 1998.
- The original work used the average for each distress types for severity level. For instance, a sample unit has only one pothole, three times block crack with two different severity levels (2 medium and one high), and five times longitudinal cracking with three different severity levels (two low, two medium, and one high). In this case, for potholes the average distress density is that of the one pothole. For block cracking, the average distress density is calculated for the two values of medium severity level, the weighting is applied and the total distress is the sum of the medium and single high severity weighted values. For longitudinal cracking, the average distress density is calculated for the tow values of low and medium severity level, the weighting is applied and the total distress is the sum of the low, medium and single high severity weighted values.

The checked collected data have been summarized and tabulated to develop individual distress models for URN or to develop the pavement condition models. The collected data are detailed in chapter four. A brief description for database development in this research will be presented. However, the details will be given in chapter four. The Riyadh city road network is large. The number of pavement sections in the network is more than 7500 (Al-Swailmi 2002). In this stage the data needs to be filtered and stored to remove irrelevant data. The data is then classified according to the mentioned parameters. The classification will be formatted to cover all possible cases. The possible cases depend on parameters that are under investigation in this study. In general, the parameters are; road class, traffic count, drainage condition, pavement condition values, distress types, and distress density.

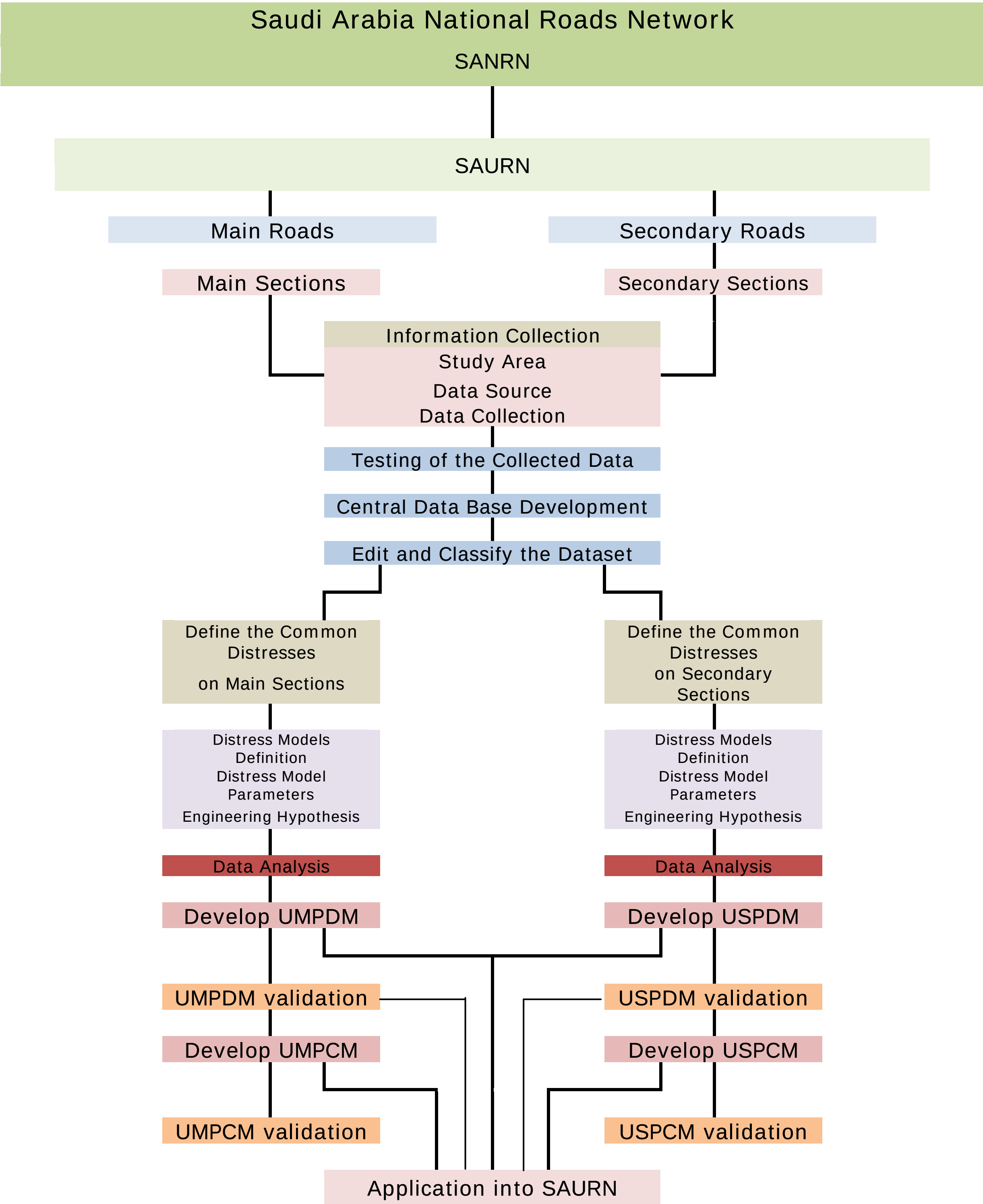

Figure 3.3 Flow Chart of the Research Methodology.

3.3 Model Parameters Definition

The model parameters depend on; the features of the study, the nature of the collected data, the requirements of the study, and the parameters that affect the behavior of the pavement. It was hypothesized that these parameters should include: distress type, distress severity, distress density, pavement condition, maintenance type, pavement age, highway class, traffic volume, drainage, and climate condition. However, not all parameters will be included in the process of modeling and chapter five covers this point thoroughly. The following is a brief discussion of these parameters (KACST 1998, RRM 1998a, RRM 1998b, and RRM 2007):

Distress Type:

Development and implementation of a pavement distress survey procedure requires a clear definition of the distress type. During the research of RPMS, the research considers 15 distress types which are commonly observed on the Riyadh road network and they are, Fatigue Cracks, Block Cracks, Longitudinal & transverse Cracks, Patching, Potholes, Depression, Rutting, Shoving, Bleeding, Polished Aggregate, Weathering & Raveling, Patching Cracks, Patching Depressions, Patching Potholes, and Patching Weathering & Raveling. This study will consider only the most common distress types on Riyadh road network. The Dammam Pavement Management System (DPMS) includes 19 pavement distress types on their city network. Makkah holy city Municipality and Al-Madinah Al-Munawarah region Municipality utilize 15 types of pavement distress.

Distress Severity:

Distress types can take on a variety of severity conditions. These are divided into three levels: low, medium and high. Although these levels are subjective descriptions, they describe distinct categories of the progression of the distress type that relate well to rehabilitation needs. In general, the three levels of distress severity are; low, medium, and high. This study will consider these severity levels.

Distress Density:

The quantity of each type and severity level measured and expressed in convenient units. Density for distress types measured by the square meter is calculated as follows;

Density = (distress amount in square meters/sample unit area in square meters) * 100

Density for distress types measured by the linear meter is calculated as follows;

Density = (distress amount in linear meters /sample unit area in square meters) * 100

Density for distress types measured by number (potholes) is calculated as follows;

Density = (distress amount in square meters /sample unit area in square meters) * 100

Pavement Condition:

Any pavement condition assessment procedure establishes a standard critical threshold level below which the pavement is considered unacceptable and in need of major maintenance, and/or routine maintenance. In addition, a pavement condition assessment procedure permits ranking of roads according to their maintenance/rehabilitation needs. Pavement condition surveys collected over several years allows determination of the rate of deterioration of different pavement sections of the network. Furthermore, this helps the organization to modify or calibrate their prediction models.

Riyadh region Municipality uses Urban Distress Index (UDI) to report the pavement condition. DPMS uses Pavement Condition (PCI); the MOT uses pavement Condition Rating (PCR). The UDI or other measures is based on visual distress data. The distress data basically consists of types, densities, and severities. The UDI is a composite distress measure derived from the 15 individual pavement distress types. Theoretically, the UDI ranges from 0 to 100 where 100 represent the highest performance point (Excellent). This index is calculated using the type, severity and quantity of each distress in a specific sample. The pavement section can be evaluated based on UDI using the following rating:

0 - 39	Poor
40 - 69	Fair
70 - 89	Good
90 - 100	Excellent

Maintenance Types:

The options or the maintenance decisions which have been applied on the SAURN in general and Riyadh city network in particular are; overlay, patching, crack sealing, potholes treatment and others. However, due to lack of information about the exact date of road network construction, the focus was only on overlaid road network as the overlay is a major maintenance and it will bring the pavement condition to the highest performance point. The researcher presumes that the pavement condition is 100 after applying the overlay and before opening the overlaid road to the traffic. Therefore, the pavement age can be defined.

Pavement Age (Last major maintenance date):

It is presumed that the overlay date is the starting point. Therefore, the pavement age, for pavements on URN start at the most recent overlay date.

Road Class:

In RPMS, two classes are defined: main and secondary roads. A main road is more than 30 meters in width in both directions with an island in the middle. Each main road contains one or more pavement sections. Main roads represent about 35 % of the total network area in Riyadh city. On the other hand, secondary roads are found inside defined regions surrounded by four main roads. Secondary roads represent approximately to 65 % of the Riyadh city network.

Traffic:

Pavement deterioration is highly affected by traffic volume and vehicle types. Average Annual Daily Traffic (AADT) data is available for main roads. The traffic volume on secondary roads is low. Therefore, traffic influences will not be included in this research for secondary roads.

Drainage:

This factor has been adopted on the grounds that the method of drainage could be important and have a significant impact on the pavement condition on the urban network. The availability of a drainage system can affect the condition of a pavement. Therefore, pavement sections are grouped into two groups: sections with a drainage system and sections without a drainage system. It is expected that pavement sections with a drainage system will have a better condition than pavement sections without a drainage system. Therefore, the study will consider the two conditions.

Climatic Condition:

The climate condition across Saudi Arabia is almost uniform in terms of temperature and rainfall.

Survey Date:

The inspector has to write the date of survey for each section surveyed to be recorded for future planning. The GDOM, at Riyadh region municipality, surveys the network every two years. Five surveys were completed for the main roads. The first survey was in 1998, the second one was in 2000, the third survey was in 2002, the fourth survey was in 2005, and the fifth one was 2007. Three surveys were completed for the secondary roads. The first survey was in 1999/2000, the second was in 2001/2002, and the third was on 2003-2005. This data is very important to study the progression of the deterioration.

Branch:

A branch is any identifiable part of the pavement network which is a single entity and has a distinct function. The branch number is a unique code that is used to help store and retrieve data from the data base. The city of Riyadh is divided into 15 branches. Each branch was given a name and number.

Section Number:

A section is a division of a branch; it has certain consistent characteristics throughout its area or length. The reference number is given by RPMS to each section, starting from the beginning of the road under consideration. Section number depends on the branch number, district code, and region code.

Sample Number:

A sample unit (number) is any identifiable area of the pavement section; it is the smallest component of the pavement network. Each pavement section is divided into sample units for pavement inspection.

3.4 Model formulation

The main objective of distress models is to predict the distress density at any time and to determine the extrapolated quantities for a given pavement section. The main objective of the pavement condition model is to predict the pavement condition at any time and how to implement these models into a PMS. Such modelling will help greatly in determining the effective timing of applying maintenance. There are different categories of modelling techniques as described in chapter two. The mechanistic approach requires a huge detailed data base of structural, field, and laboratory testing, in addition to pavement characterization parameters, which generates difficult task. On the other hand, probabilistic modelling, such as the Markovian approach, depends primarily on very skilled and expert pavement engineers to develop transition probability matrices for different combinations of pavement condition. The empirical approach (regression modelling) is simple and easy compared to the previous techniques and does not require elaborate involvement of any mechanistic structural testing for the fundamental pavement responses, or engineering judgement, and it captures as many factors as available that affect the distress behaviour (Hass et al. 1994).

3.5 Design of Experiment

Various factors can affect pavement performance. These factors include distress type, distress density, pavement condition (UDI, PCR), time, road class, traffic loading, and drainage. The design of the experiment will cover these factors. Figure 3.4 shows the flow of experimental design for this study.

3.6 Model Validation

In fitting a model to a given data set, regardless of the method which has been used to produce the fit, and regardless of the types of model linear or nonlinear, it is recommended to assess how well the model fits the data. Therefore, the model must be subjected to some tests to determine whether it should be employed. The proposed model and its formula must be tested against standard error of estimate, coefficient of determination, and residual analysis.

3.7 Summary

Research scope, model formulation, design of experiment, and model validation are the base for building the required database for this study. In a practical application, building a good database is an essential requirement to develop reliable models. Therefore, the next chapter is the database development of this research.

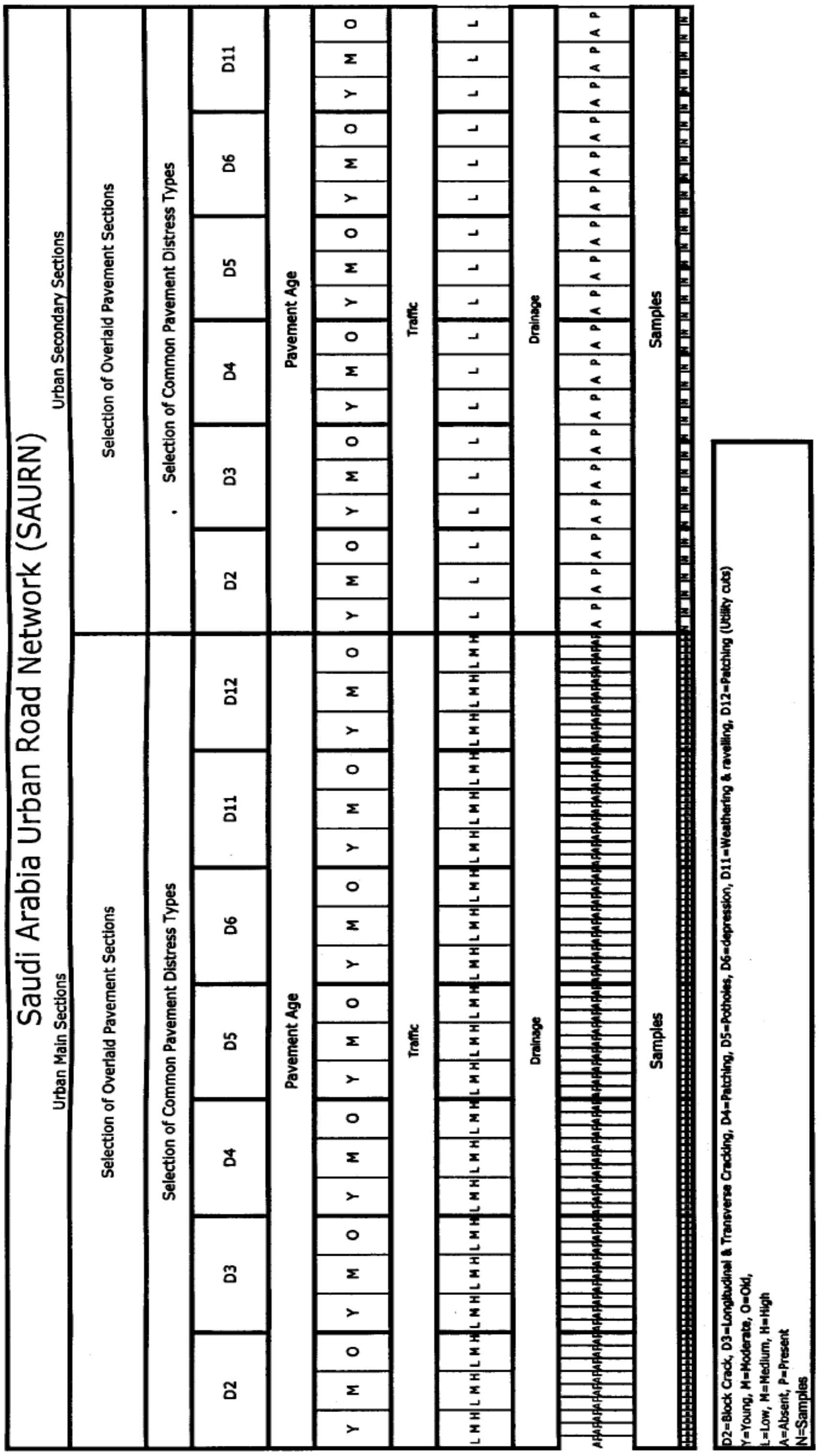

Figure 3.4 Experimental Design of the Study.

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CHAPTER FOUR

DATASET

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CHAPTER FOUR
DATASET

This chapter contains background about the role of the database in a pavement management system (PMS). In addition, it contains an introduction to the research dataset, the study area, and data source. Furthermore, the development process including the network and sampling, study criteria, raw data of pavement condition surveys, pavement distress surveys, distress density and UDI calculation, and approach of development of the data base will be presented. Finally, samples of developed dataset will be given.

4.1 Introduction

A good database is the foundation from which all pavement management and decision support is derived. The accuracy and completeness of required data is paramount to the PMS (FHWA 2002). The database function in a PMS can be centralized so that all the concerned divisions have access to the needed data which will reduce the duplication. Therefore, the data must be integrated and accessible for a successful analysis for network and project level. Organizing, acquiring, and recording the data in a systematic and accessible manner is necessary in PMS (Haas et al. 1994). Although, the focus of many existing PMS is on condition and performance of the surface and structure of the pavement, a comprehensive PMS uses data from a variety of sources. According to Hass (1991) the classes of data needed include; section description, performance related data, historic related data, policy related data, geometry related data, environmental related data, and cost related data. All, but the policy and cost related data, provide background information required for the analysis and modeling of pavement performance.

There are four measures for pavement evaluation namely; roughness, surface distress, deflection, and surface friction. These four measures in addition to maintenance cost, and user cost are the output variables of the pavement. That can be measured to determine whether or not the pavement is behaving satisfactorily. All these measures can be predicted at the design stage and then periodically evaluated while the pavement is in service (Hass 1991, and FHWA 1990).

There are several major classes of inventory data to be considered in pavement management. According to Hass (1991) these classes include:

- Section reference and description,
- Geometry,
- Pavement structure,
- Costs,
- Environment,
- Drainage, and
- Traffic.

Due to wide variety of data required to effective PM, many agencies maintain the data in separate. Separate data files are maintained for; construction history, traffic, maintenance, pavement quality measures. Regardless of the types of data that are stored in the dataset, it must have integrity, accuracy, validity, security, and documentation (FHWA 1990).

A good database contains the following files:

- Condition rating file,
- Distress measures file,
- Traffic level contains ADT,
- Roads and roads history file contains the construction history of all pavement, and
- Maintenance history files containing types of maintenance activities and cost.

A good example of a comprehensive database is Arizona department of transport database (ADOT 2006). ADOT maintains three data bases; the pavement management data, the construction history, and the deflection data. The pavement management data contains information on the route identification, traffic level, growth rate, maintenance cost, and pavement condition data. The pavement condition data include cracking, roughness, and skid measurements. These condition measures are maintained for each year of an observation. The pavement construction data base contains a record for each project that has been performed by the department. These records are the location, the type of material and the thickness of each pavement layer for each construction project. The deflection data base contains records of all the data collected with the dynaflect and dynatest. The ADOT database is a good example of a dataset that is centrally managed and commonly accessed and analyzed. Historical pavement condition measures maintained on the system permit periodic evaluation of the overall condition of the network and the development of prediction models.

4.2 Research Dataset

4.2.1 Background

This research investigates important measures of pavement evaluation which are the surface distress and the rating condition. Modeling the distress types individually is dependent upon the accuracy and reliability of the dataset. A major concern in this research is to develop a consistent dataset for achieving reliable results for Saudi Arabia Urban Road Network (SAURN).

There are 13 regions in Saudi Arabia. The Ministry of Municipal and Rural Affaires (MOMRA) is aiming to standardize the practice of pavement management system for all the municipalities in the 13 regions. MOMRA has started this project on 2008 by phase one which is a comprehensive inventory for the urban road network information. Phase one takes three years to finish, the total length of the urban road network across Saudi Arabia is more than 30,000 miles costs more than $ 15 Billion (MOMRA 2008).

4.2.2 Study Area

The largest regions in Saudi Arabia were visited including Riyadh region, Makkah region, and Eastern region. The largest city in Riyadh region is Riyadh city, the largest city in Makah region is Jeddah, and the largest city in Eastern Region is Dammam. Therefore, officials in the three municipalities were contributed for collection the data because all three municipalities have their own PMS. The most reliable and the comprehensive data set were found to be from the Riyadh road network. Thus, it was decided to use Riyadh pavement distress data and condition rating data only for this research.

4.2.3 Data Source

The General Directorate of Operation and Maintenance (GDOM) at Riyadh Region Municipality is fully responsible for the Riyadh Pavement Management System (RPMS). Therefore, the main source for the study was GDOM. The Pavement Management System unit at the GDOM collects pavement condition and related information of the network periodically (RRM 2007). The Riyadh municipality condition rating method called Urban Distress Index (UDI) was used in generating a huge distress survey dataset. This method was explained in chapter two.

4.3 Dataset Features

4.3.1 The Network and the Sampling

To obtain pavement distress models and pavement condition models, for SAURN, that can be utilized with a significant level of confidence, the study covered all accessible pavement ranges of Riyadh road network. Riyadh roads are divided into two main categories; main sections and secondary sections. Main sections defined as the roads with Middle Island or with total width of more than 30 meters without Middle Island. The section for a main road is a defined distance between two intersections in the main road. Secondary roads defined region surrounded by four main roads. The section for a secondary road is defined as the area surrounded by four main roads. The sections for both main and secondary roads are divided into a number of sample units. A sample unit for the main road is 100 meter length per lane from the section. The sample unit of the secondary section is the distance between two intersections (RRM 1998a).

The data was collected based on pavement sections which were surveyed several times. The developed dataset includes information extracted from different surveys. Only information that are required or needed in the research were summarized and tabulated. The General Directorate of Operation and Maintenance (GDOM)-Riyadh Region Municipality was the main source contacted to collect the data for Urban Road Network (URN). The data was collected through the Riyadh PMS (RPMS) unit. The GDOM updates surveying the network from time to time. Five surveys were completed for main roads while three surveys were completed for secondary roads. The research included all accessible data regarding the distress survey and condition rating for URN. Therefore, information regarding the network and the sampling was presented before describing the collected data and developed dataset.

Riyadh Municipality divided Riyadh city into 15 sub-municipalities. Each branch municipality is covering a number of districts. A district is an area surrounded by four main roads. Each district is divided into a number of regions. A region is an area that contains a number of secondary sections surrounded by four main sections within a district. Every category from the two road categories is divided into branches. These branches are divided into sections.

The study included both main and secondary roads from the entire network. The main sections on the network represent 35% of the total network and the secondary sections represent 65% of the total network. The total network makes up more than 7500 main pavement sections and more than 1600 secondary sections (RRM 2007). Figure 4.1 shows the percentage of the main and secondary sections.

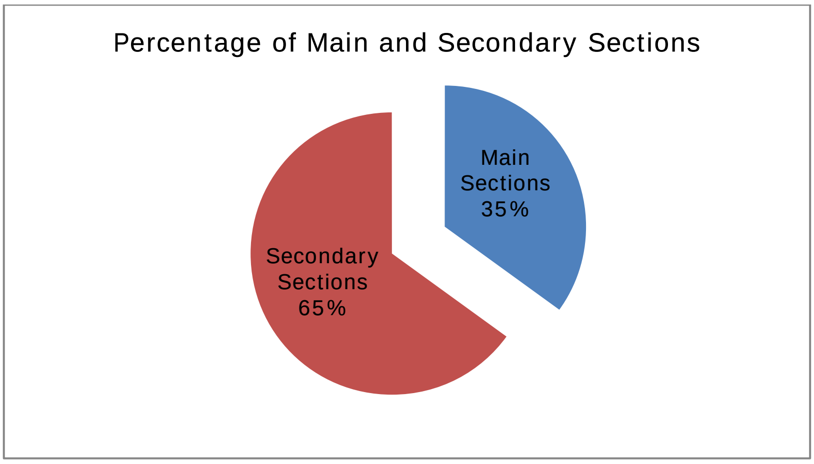

Figure 4.1 Percentages of Main and Secondary Sections

However, the study covers sections that meet the study criteria to develop the required dataset.

4.3.2 Study Criteria

Accuracy and reliability of the data is paramount for achieving the objective of the study, and for the accuracy of the proposed models. Therefore, some boundary conditions have been applied to the data to ensure accuracy and reliability for the research dataset as far as possible. The boundary conditions include:

- Only overlaid sections were included in the study to ensure that the initial pavement condition is 100.
- Section boundary modifications were as checked. Any section that had been merged with another due to any reason was excluded to ensure accuracy for the selected sections used in building the research dataset.
- Maintenance ratio was also checked to ensure that most of the section had been maintained by overlay. Any section with less than 90 % was excluded. The maintenance ratio is calculated based on maintenance area and the survey area for a given section.

Based on the above criteria and the availability of data, 701 main sections and 228 secondary sections were found to be applicable to develop the dataset.

4.3.3 Raw Data of Pavement condition Surveys

The obtained distress survey raw data contain much information. The URN raw data information contains section number, region number, sample number, road section name (from/to), branch number branch name, district number, district name, sample date, sample length, sample width, sample area, service lane area, number of service lane, number of lane, total number of lanes, district code, distress area, distress severity level, distress density, UDI value, and UDI rate.

There are many manuals identifying and describing the types of flexible pavement distress. For example, the federal highway administration (FHWA) identified 15 types (FHWA 2003), American Association of State Highway and Transportation Officials (AASHTO) identified 15 types (AASHTO 2007), the PAVER system identified 19 types (Shain 2002), and Washington department of transportation identified 17 types (WSDT 1998), Ontario Ministry of Transport identified 23 types (MTCO 1989), and British Columbia Ministry of Transport identified 12 types (BC 2009). However, on Riyadh road network, According to KACST (1998), there are 15 types were most frequent and they affect the performance of the network. Table 4.1 shows the classification groups of the distress, distress names, and the distress codes. For main Roads, the GDOM focuses on all 15 types except D13, D14, and D15. For secondary roads, the GDOM measures only D2, D3, D4, D5, D6, and D11.

Table 4.1 Distress on Urban Roads Network (URN)

Distress Classifications				
Groups Names	Distress Names	Code	Main Sections Frequency	Secondary Sections Frequency
Cracking	Fatigue Cracking	D1	13	0
	Block Cracks	D2	1061	225
	Longitudinal & Transverse Cracking	D3	906	333
Patching and Potholes	Patching	D4	1065	354
	Potholes	D5	728	171
Surface Deformation	Depression	D6	818	224
	Rutting	D7	19	0
	Shoving	D8	10	0
Surface Defects	Bleeding	D9	6	0
	Polishing	D10	10	0
	Weathering and Ravelling	D11	1065	323
Utility Cuts Distress	Cracking	D12	1034	0
	Depression	D13	0	0
	Potholes	D14	0	0
	Weathering and Ravelling	D15	0	0

Since the study aims to develop pavement distress and pavement condition models, it is important to see which of the above distress types are more frequent. The most frequent distress types that have been detected in the study area for the selected main sections are shown in Table 4.2 and Figure 4.2. They are Block Cracks, Longitudinal & Transverse Cracking, Patching (should be distinguished from deep or shallow patching which is a treatment types as will be discussed in chapter seven), Potholes, Depressions, Weathering & Raveling, and Cracking (utility cuts), whereas for the secondary sections, the RPMS only looks for 6 out the 15 distress types. Therefore, the researcher decided to study all the 6 distress types as shown in Table 4.3 and Figure 4.3. They are Block Crack, Longitudinal & Transverse Cracking, Patching, Potholes, Depressions, and Weathering & Raveling.

4.3.4 Pavement Distress Surveys

The PMS unit has conducted visual inspections of the network. 15 distress types were monitored and inspected. The Degree of pavement deterioration is a function of distress type, distress severity, and distress density. The data collected for distress evaluation included the following (RRM 1998b):

- Distress Type.
- Distress Density, and
- Distress Severity.

Table 4.2 Common Distress on Main Sections

Common Distress Types on Main Sections		
Distress Names	Code	Frequency (2330 samples)
Block Cracks	D2	1061
Longitudinal & Transverse Cracking	D3	906
Patching	D4	1065
Potholes	D5	728
Depression	D6	818
Weathering and Ravelling	D11	1065
Cracking (Utility Cuts)	D12	1034

Table 4.3 Common Distress on Secondary Sections

Common Distress Types on Secondary Sections		
Distress Names	Code	Frequency (641 Samples)
Block Cracks	D2	225
Longitudinal & Transverse Cracking	D3	333
Patching	D4	354
Potholes	D5	171
Depression	D6	224
Weathering and Ravelling	D11	323

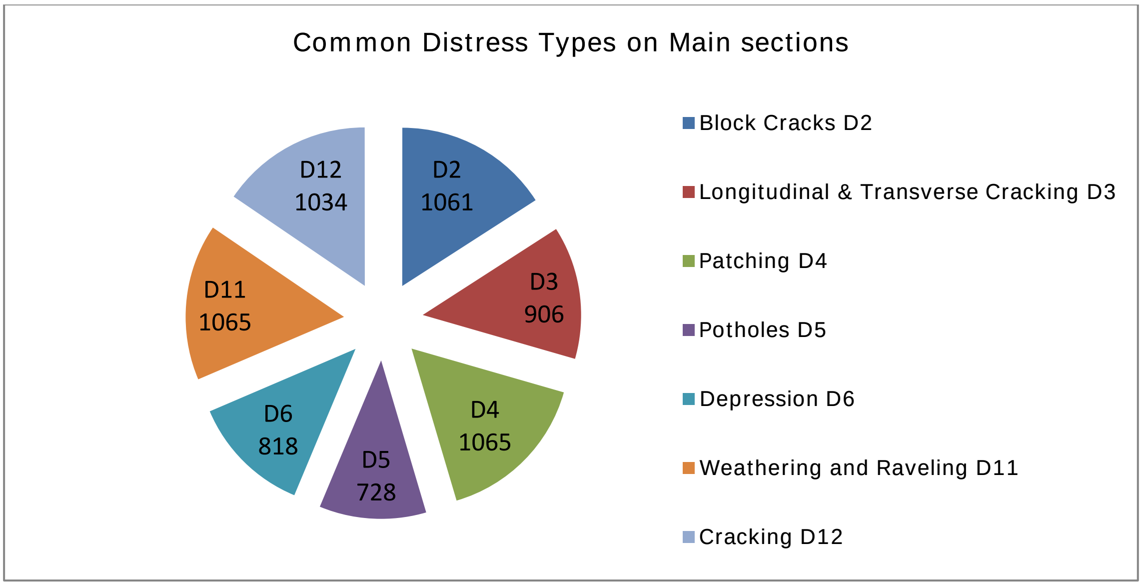

Figure 4.2 Frequency of the common Distress Types on Main Sections.

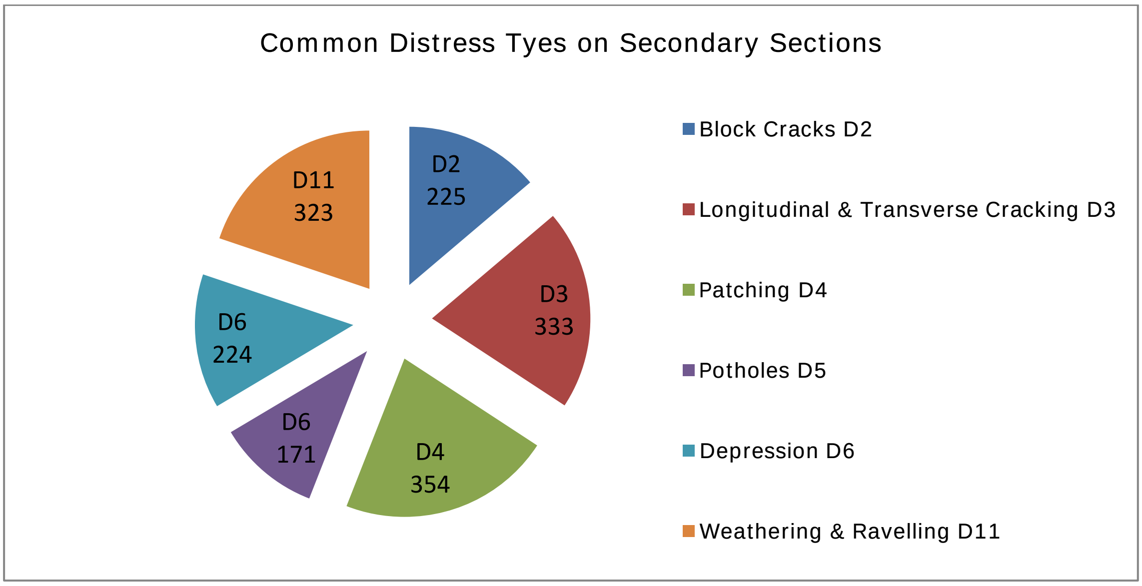

Figure 4.3 Frequency of the common Distress Types on Secondary Sections.

To enable collection of appropriate road distress data, a special manual was developed for Urban Distress Index methodology, procedure and calculations. Moreover, a team of inspectors from the GDOM was given an extensive short course on the UDI System. Each inspector was then sent to a particular section of the network to record the existing distress types, quantities, and severity for each sample unit within that section. Collection of this information was performed by the inspector walking through the selected section and recording the distress types, quantities and severity. A distress evaluation form was designed, through RPMS, for each sample unit in the main sections, and secondary sections.

Since each calculated distress density corresponded to a certain distress severity level, a combined value was calculated based on a weight factor for each severity level. These weight factors are listed in the following Tables, Table 4.4 for main sections and Table 4.5 for secondary sections. These weight factors have been used based on the idea of deducting points used by RPMS and the PAVER system (RRM 1998b, USACERL 1990, and Shahin 2002). Since patching has assigned only low severity level, the weight factor is 1.

Table 4.4 Severity Levels' Deduct points for Main Sections

Deduct Points for Severity Levels on Main Sections				
Distress Names	Code	Low severity	Medium Severity	High Severity
Block Cracks	D2	2.00	2.50	4.00
Longitudinal & Transverse Cracking	D3	2.00	2.50	4.00
Patching	D4	1.00	-	-
Potholes	D5	4.00	4.50	5.00
Depression	D6	2.00	3.00	4.00
Weathering and Ravelling	D11	2.00	2.50	4.00
Cracking (Utility Cuts)	D12	2.00	3.00	4.00

Table 4.5 Severity Levels' Deduct points for Secondary Sections

Deduct Points for Severity Levels on Secondary Sections				
Distress Names	Code	Low severity	Medium Severity	High Severity
Block Cracks	D2	2.00	2.50	4.00
Longitudinal & Transverse Cracking	D3	2.00	2.50	4.00
Patching	D4	1.50	-	-
Potholes	D5	4.00	4.50	5.00
Depression	D6	2.00	3.00	4.00
Weathering and Ravelling	D11	2.50	3.00	4.00

4.3.5 The Impact of Weighting Factors

The previous Tables 4.4 and 4.5 suggest weighting factors for each severity level. Distress is one of the primary measurements of pavement condition. Thus, in a pavement evaluation program, distress type, severity, and extent should be properly identified. The Urban distress index (UDI) calculated mathematically combining the effects of distress types on pavement conditions. Before the calculation of UDI, each distress attribute must be assigned a weight factor and a severity factor. Riyadh PMS used subjective rating values of distress attributes to a rational weighting scale that provides quantified measurements of the effects of each distress on pavement damage. These weighting factors were based on Micro Paver, and experience of engineers.

Through the analysis and calculation of a UDI value, it was found that pothole has the largest weight factor (5) and patching has the lowest (1 and 1.5) for main and secondary roads. The severity factors vary from 1 to 5, depending on the distress type and severity level. For instance, a sample unit in a pavement section has one high severity of potholes could drop the quality of a pavement section 5 times a pavement section has distress of patching.

4.3.6 Distress Density and UDI Calculation

The following example shows how the distress density and the UDI are calculated. A pavement section has the following information: asphalt concrete, main road, area of 3000 square meters, 10 number of sample units in the section, and a team surveyed five sample units as follows:

- Two types of distress in sample number 2 included Block Cracking (D2), and Longitudinal and Transverse Cracking (D3). Densities are low 25%, and Medium 55% respectively,
- 85 % Medium Longitudinal and Transverse Cracking (D3) in sample number 4,
- 25% Low Block Cracking (D2) and 25% Medium Longitudinal and Transverse Cracking (D3) in sample number 6,
- 25% Medium Longitudinal and Transverse Cracking (D3) in sample number 6,
- 30% Low Potholes (D5) in sample number 8 (the last sample surveyed).

All the details are presented in Table 4.6

The distress density calculation was discussed in chapter three as follows (RRM 1998b):

Density for distress D2 is measured by the following formula

$$Density(\%) = \frac{Distress\ amount\ in\ square\ meters}{Sample\ unit\ area\ in\ square\ meters} x100$$

Density for distresses D3 measured by the following formula

$$Density(\%) = \frac{Distress\ amount\ in\ linear\ meters}{Sample\ unit\ area\ in\ square\ meters} x100$$

The formula for D5 measured by the following formula

$$Density(\%) = \frac{Distress\ amount\ in\ square\ meters}{Sample\ unit\ area\ in\ square\ meters} x100$$

There are three major steps to UDI (RRM 1998b). They are:

- The first step is to find the deduct value (DV) for severity levels of different types of distress which were found in the survey.
- The second step is to multiply the deduct value by distress density dividing the result by 100, and then sum all the values together,
- The third step is to find UDI (sample) according to the following formula

  UDI=100-20(Result found in step two),
- The UDI for the section is the average of UDI (sample).

Table 4.6 Calculation Example for Distress Density and UDI

		Urban Distress Index (Pavement Section)	UDI	Rating
Section Name	ALolya Road			
Section Code	4411112			
Class Road	Main Section			
Section Area (m2)	3000			
Number of Samples	10	100-20 [∑ (D x DV) /100]	63.7	Good
Area of Sample (m2)	300			
Samples Surveyed	5			

Sample	UDI Calculation Steps		D2 Low	D2 Medium	D3 Low	D3 Medium	D5 Low
Sample 2	S1	Density (D)	25.00	55.00	75.00	25.00	
	S2	DV	2.00	2.50	2.00	2.50	
	S3	(D X DV)/100			4.00		
	S4	UDI (Sample)			20		
Sample 4	S1	Density (D)				85.00	
	S2	DV				2.50	
	S3	(D X DV)/100			2.13		
	S4	UDI (Sample)			57.5		
Sample 6	S1	Density (D)	25.00			25.00	
	S2	DV	2.00			2.50	
	S3	(D X DV)/100			1.13		
	S4	UDI (Sample)			77.5		
Sample 8	S1	Density (D)				25.00	
	S2	DV				2.50	
	S3	(D X DV)/100			0.63		
	S4	UDI (Sample)			87.5		
Sample 10	S1	Density (D)					30.00
	S2	DV					4.00
	S3	(D X DV)/100			1.20		
	S4	UDI (Sample)			76		

4.3.7 Development Approach

As stated earlier, Riyadh city network is large. Now the total area of the city is 4419 km2 (RRM 2009). After defining the research scope, and the study criteria of the data, the raw data has been drastically reduced. After that, the data was filtered to remove irrelevant data and stored. The data has been classified according to the previously mentioned parameters. The classification will be formatted to cover all possible cases. The possible cases depend on parameters that are under investigation in this study. In general, the parameters are road types and class (main pavement sections and secondary pavement sections), traffic account, drainage condition (absent/present), pavement condition, distress types, distress density, maintenance type, and pavement age.

The collected data were checked for any irrational, irregular, or illogical behavior like unexpected rate of deterioration. Each survey was subjected to checking, filtering individually and general observations to ensure the consistency and repeatability of the data. The checked collected data were summarized and tabulated to include only the required data under investigation either the investigation of distress behavior or developing models. These data or factors were explained in chapter three.

To overcome the complexity of the network data due to the many parameters that affect the study, an approach for the study should be followed in order to build the required dataset. However, building dataset will be achieved in stages.

The first stage of the suggested approach identified the types of distress in general across the entire network, and then the types of distress were also classified into the selected specific pavement sections for both main and secondary roads. As a result of this stage, common distress types on main sections and secondary sections could be identified. Figure 4.2 and Figure 4.3 showed the results.

The second stage considered the rest of parameters that affect the two main categories of the study. However, only the significant factors were studied only. Considering the research scope and model formulation which were presented in chapter three, the information that has potential significance on the URN are**;** the Urban Distress Index (UDI) for main and secondary pavement sections, pavement age for main and secondary pavement sections, maintenance type (overlay) for main and secondary pavement sections, AADT for main pavement sections only because the traffic on the secondary sections is low, drainage for main and secondary pavement sections, distress type for main and secondary pavement sections, distress density for both main and secondary pavement sections. Information on these factors was tabulated accordingly with the classification resulting from stage one. However, analysis of variance will be conducted in the following chapters to check if all mentioned parameters have an effect on the pavement deterioration or not.

The third stage considered distress parameters, namely distress type, and distress density. In addition a new classification was based on each distress individually where possible. The fourth stage was to tabulate the data into proper format. Then the tabulated data will be subjected to checking, filtering and storing to remove irrelevant data.

The fifth stage was to tabulate the dataset into four main types as follows:

- Pavement distress datasets for main sections,
- Pavement distress datasets for secondary sections,
- Pavement condition datasets for main sections,
- Pavement condition datasets for secondary sections,

The data was tabulated into proper format. The tabulated and summarized data became the developed dataset for this study. Four samples of developed dataset are presented in the following section.

4.4 Samples of Developed Dataset

According to the research objectives, four datasets have been developed. They will be used to build models for pavement distress and models for pavement condition. Table 4.7 summarizes the four datasets. Sample of distress density values on main and secondary sections are presented in Tables 8 and 9 respectively. Tables 4.10 and 4.11 show samples of UDI value on main and secondary sections.

4.5 Summary

The developed datasets will be used to achieve the research objectives, including Urban Main Pavement Distress Models (UMPDM), Urban Secondary Pavement Distress Models (USPDM), Urban Main Pavement Condition Model (UMPCM), and Urban Secondary Pavement Condition Model. The following two chapters deal with objectives of the study and how the objectives were achieved. Chapter five deals with pavement distress models and chapter six deals with pavement condition models and implementation of these models into PMS for SAURN.

Table 4.7 Summary for Developed Datasets

Dataset Name and Source	Dataset Content	Output
Main Roads Distresses MOMRA-RRM-GDOM Sample (Table 8)	Distresses Information Pavement Age AADT Last Major Maintenance Drainage	Develop UMPDM
Dataset Name and Source	Dataset Content	Output
Secondary Roads Distresses MOMRA-RRM-GDOM Sample (Table 9)	Distresses Information Pavement Age Last Major Maintenance Drainage	Develop USPDM
Dataset Name and Source	Dataset Content	Output
Main Roads UDI MOMRA-RRM-GDOM Sample (Table 10)	UDI Pavement Age AADT Last Major Maintenance Drainage	Develop UMPCM
Dataset Name and Source	Dataset Content	Output
Secondary Roads UDI MOMRA-RRM-GDOM Sample (Table 11)	UDI Pavement Age Last Major Maintenance Drainage	Develop USPCM

Table 4.8 Sample of Distress Density Values on Overlaid Main Sections

Section No	Age	Traffic	DCODE	D2	D3	D4	D5	D6	D11	D12
340405641M	1.66	6,323	Not Drained	6.49	1.89	2.50	1.22	0.50	3.27	0.00
340405641M	3.83	7,066	Not Drained	16.36	3.26	2.75	1.78	3.06	6.84	14.74
340405641M	6.80	8,230	Not Drained	34.56	8.32	19.00	20.07	14.49	33.95	18.81
340405641M	0.00	5,806	Not drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
340408642M	0.00	5,655	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
340408642M	1.52	6,115	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
340408642M	3.82	6,880	Not Drained	0.63	2.45	23.07	0.00	6.88	5.11	13.93
340408642M	6.84	8,033	Not Drained	15.25	2.61	37.67	9.94	42.95	46.31	25.43
340409642M	0.00	7,803	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
340428622M	0.00	6,140	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
340428622M	0.56	6,321	Drained	0.00	0.00	4.25	0.00	0.00	1.85	2.25
340428622M	2.33	6,920	Drained	5.79	4.67	4.48	0.81	5.06	3.26	9.74
340428622M	7.25	8,907	Drained	9.69	4.67	34.53	19.56	6.76	10.74	18.35
340428622M	9.95	10,228	Drained	19.86	6.95	49.54	26.30	12.88	26.11	18.82
351124190M	0.00	8,682	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
351124190M	1.98	9,611	Drained	5.55	6.02	18.48	0.00	1.35	5.50	2.75
351124190M	5.10	11,276	Drained	20.17	16.57	29.09	10.63	19.68	27.21	16.83
351527335M	0.00	1,384	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
351527335M	1.68	1,508	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
351527335M	4.00	1,699	Not Drained	5.90	0.00	9.00	0.00	3.38	7.78	10.12
351527335M	7.15	1,997	Not Drained	12.62	12.79	24.53	0.00	3.65	11.88	15.91
351527335M	###	2,596	Not Drained	22.00	39.14	35.34	15.54	23.63	23.43	40.13
360303246M	0.00	4,583	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360303246M	2.25	5,143	Drained	2.03	0.00	4.00	0.00	1.39	6.03	1.53
360303246M	5.62	6,114	Drained	9.82	7.78	17.92	13.55	1.52	14.34	5.98
360303246M	8.22	7,948	Drained	21.84	55.88	20.68	23.83	10.75	32.13	6.33
360304246M	0.00	4,594	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360304246M	2.20	5,143	Not Drained	7.92	8.00	21.48	3.78	8.25	9.59	6.93
360401091M	0.00	7,877	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360401091M	0.44	8,055	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360402013M	0.00	20,194	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360402013M	0.65	20,884	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360402013M	1.66	21,986	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360402013M	2.66	23,144	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
360402013M	3.93	24,706	Drained	18.59	8.91	20.41	1.06	12.84	16.56	25.95
370103490M	0.00	3,066	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
370103490M	0.60	3,162	Not Drained	1.01	0.00	2.50	0.00	0.69	2.09	1.00
370103490M	3.90	3,745	Not Drained	13.67	5.50	9.01	0.00	2.84	5.75	8.29
370103490M	6.84	4,869	Not Drained	21.91	10.67	37.18	10.80	30.44	24.01	24.24
441015532M	0.00	10,813	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
441015532M	0.67	11,191	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
441015532M	3.03	12,631	Not Drained	18.00	0.00	17.14	0.21	0.00	7.77	10.53
441015532M	6.02	14,726	Not Drained	28.93	3.61	38.99	8.56	0.00	29.94	13.17
441015532M	9.02	17,178	Not Drained	31.62	22.61	52.79	23.02	16.44	46.81	28.08
481513004M	0.00	13,907	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
481513004M	1.43	14,968	Drained	0.00	0.00	0.00	0.00	0.00	0.00	0.00
481513004M	3.79	16,893	Drained	4.73	0.00	18.04	0.00	0.70	6.93	7.94
481513004M	6.67	19,579	Drained	14.87	8.02	34.89	16.18	1.66	39.70	15.27
481513004M	9.34	22,454	Drained	38.83	14.25	83.42	25.53	14.55	47.47	16.62

Table 4.9 Sample of Distress Density Values on Overlaid Secondary Sections

Region	Time	Drainage	D2	D3	D4	D5	D6	D11
340402	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
340402	0.39	Drained	1.51	1.27	2.80	0.00	0.17	2.03
350902	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
350902	0.71	Drained	1.91	4.55	7.20	2.88	1.22	10.20
351128	0.00	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
351128	0.18	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
351202	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
351202	0.34	Drained	0.17	0.00	8.79	0.00	2.20	7.32
361001	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
361001	1.56	Drained	3.00	9.00	10.00	2.50	1.10	3.35
361001	4.57	Drained	9.31	14.26	16.10	5.86	1.93	9.90
370101	0.00	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
370101	2.68	Not Drained	0.00	1.20	5.00	0.00	0.00	3.50
370101	5.57	Not Drained	3.00	4.87	15.72	9.24	0.35	9.29
370105	0.00	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
370105	0.77	Not Drained	9.20	2.50	3.30	0.00	0.00	2.50
370105	3.83	Not Drained	14.22	6.63	9.20	9.50	0.26	8.12
380109	0.00	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
380109	2.15	Not Drained	0.00	2.15	20.00	0.00	0.00	0.00
380109	4.62	Not Drained	0.00	9.87	38.16	0.00	0.75	0.00
390201	0.00	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
390201	2.20	Not Drained	0.00	2.20	4.00	0.00	0.00	9.00
390201	4.94	Not Drained	0.00	4.10	27.88	2.34	0.63	26.91
411001	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
411001	1.54	Drained	0.07	4.71	19.11	0.00	0.47	7.12
421002	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
421002	0.46	Drained	0.00	0.00	0.00	0.00	0.00	0.00
421002	3.02	Drained	2.00	3.02	3.00	0.00	1.00	5.00
421002	7.10	Drained	10.49	11.59	15.32	12.34	6.41	19.45
431306	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
431306	2.78	Drained	0.00	2.78	21.00	0.00	0.00	0.00
431306	5.90	Drained	0.00	6.90	46.38	0.00	1.01	3.32
440409	0.00	Not Drained	0.00	0.00	0.00	0	0.00	0.00
440409	2.75	Not Drained	2.75	2.75	2.75	1.31	2.75	2.75
440409	5.73	Not Drained	3.25	12.79	45.74	2.75	1.43	8.57
450517	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
450517	0.52	Drained	0.00	0.00	5.00	0.00	0.00	1.50
450517	3.31	Drained	1.00	2.00	1.00	0.00	2.00	3.55
450517	5.60	Drained	4.04	13.25	11.51	10.00	5.79	14.58
470801	0.00	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
470801	0.70	Not Drained	0.00	0.00	0.00	0.00	0.00	0.00
470801	3.53	Not Drained	5.20	17.95	8.30	0.66	0.43	2.12
480302	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
480302	1.82	Drained	6.48	5.60	16.10	0.51	7.92	5.71
481506	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
481506	2.23	Drained	1.00	2.23	12.00	0.00	2.23	1.00
481506	5.79	Drained	12.03	7.76	36.76	10.75	7.68	4.10
490206	0.00	Drained	0.00	0.00	0.00	0.00	0.00	0.00
490206	1.98	Drained	3.41	2.32	12.22	4.21	2.66	6.08

Table 4.10 Sample of UDI values on Overlaid Main Sections

Section No	Age	Traffic	DCODE	UDI
340408642M	0.00	5,655	Not Drained	100
340408642M	1.52	6,115	Not Drained	100
340408642M	3.82	6,880	Not Drained	99
340408642M	6.84	8,033	Not Drained	91
340409642M	0.00	7,803	Not Drained	100
370103490M	0.00	3,066	Not Drained	100
370103490M	0.60	3,162	Not Drained	98
370103490M	3.90	3,745	Not Drained	94
370103490M	6.84	4,869	Not Drained	75
380201962M	0.00	902	Drained	100
380201962M	1.31	964	Drained	99
380201962M	4.18	1,117	Drained	94
390164698M	0.00	14,848	Not Drained	100
390164698M	0.06	14,896	Not Drained	100
390177233M	0.00	539	Not Drained	100
390177233M	0.54	554	Not Drained	100
390177233M	7.89	758	Not Drained	69
410107064M	0.00	6,073	Drained	100
410107064M	0.33	6,178	Drained	100
410107064M	3.25	7,175	Drained	85
410107064M	6.90	8,421	Drained	70
410108064M	0.00	4,581	Drained	100
410108064M	0.32	4,657	Drained	100
410108064M	3.24	5,408	Drained	88
420901079M	0.00	3,194	Drained	100
420901079M	8.61	4,968	Drained	82
420901079M	10.8	5,419	Drained	63
420902079M	0.00	4,970	Not Drained	100
420902079M	0.03	4,979	Not Drained	100
431303140M	0.00	683	Not Drained	100
431303140M	0.09	687	Not Drained	100
431303140M	2.58	780	Not Drained	80
440405546M	0.00	1,321	Not Drained	100
440405546M	0.45	1,352	Not Drained	100
440405546M	2.47	1,500	Not Drained	95
440405546M	4.81	1,690	Not Drained	82
440405546M	7.96	1,988	Not Drained	82
440405546M	10.77	2,295	Not Drained	44
470704837M	2.68	1,219	Not Drained	88
470704837M	5.02	1,375	Not Drained	80
470704837M	7.55	1,565	Not Drained	61
470708838M	0.00	331	Not Drained	100
470708838M	0.07	333	Not Drained	100
470715832M	0.00	651	Not Drained	100
470715832M	0.96	684	Not Drained	100
470715832M	3.78	791	Not Drained	100
481125001M	0.00	14,281	Drained	100
481125001M	0.52	14,665	Drained	100
481125001M	2.88	16,132	Drained	91

Table 4.11 Sample of UDI values on Overlaid Secondary Sections

Section No	Time	Drainage	UDI
340402	0.00	Drained	100
340402	0.39	Drained	99
370118	0.00	Not Drained	100
370118	0.65	Not Drained	98
370118	3.97	Not Drained	84
380109	0.00	Not Drained	100
380109	2.15	Not Drained	97
380109	4.62	Not Drained	88
390814	0.33	Not Drained	100
390814	1.66	Not Drained	94
390814	4.44	Not Drained	82
410106	0.00	Drained	100
410106	1.77	Drained	97
410106	3.31	Drained	92
410106	6.40	Drained	82
411432	0.00	Drained	100
411432	0.96	Drained	95
411432	4.42	Drained	75
440406	0.00	Not Drained	100
440406	0.13	Not Drained	100
440406	2.10	Not Drained	92
440406	5.09	Not Drained	64
450201	0.00	Not Drained	100
450201	1.20	Not Drained	93
450203	0.00	Drained	100
450203	1.04	Drained	93
450204	0.00	Drained	100
450204	1.73	Drained	91
470502	0.00	Not Drained	100
470502	0.58	Not Drained	99
470502	3.16	Not Drained	92
470502	5.85	Not Drained	70
481523	0.00	Not Drained	100
481523	1.55	Not Drained	98
490206	0.00	Drained	100
490206	1.98	Drained	94
490209	0.00	Not Drained	100
490209	1.71	Not Drained	95
490210	0.00	Drained	100
490210	1.85	Drained	95
490311	0.00	Drained	100
490311	1.50	Drained	97
490601	0.00	Not Drained	100
490601	0.10	Not Drained	98

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CHAPTER FIVE
PAVEMENT DISTRESS DATA ANALYSIS

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CHAPTER FIVE
PAVEMENT DISTRESS DATA ANALYSIS

This chapter contains descriptive statistics and inductive statistics for pavement distress data for the urban main roads database and urban secondary roads database. The descriptive analysis highlights the numerical summaries and scatter plots. The inductive analysis discusses the significant factors affecting pavement deterioration including experimental design, and tests of significance for both parametric test and nonparametric test.

5.1 Urban Main Roads

In Riyadh city, the Urban Main Roads are more than 30 meters in width in both directions with an island in the middle. They represent 35 % of the total network (RRM 2007). A total of 701 overlaid main pavement sections were found to be applicable for the study constraints as explained in the chapter on methodology.

5.2 Descriptive Statistics for Urban Main Roads

Descriptive statistics (Keller 2009) deals with methods of organizing, summarizing, and presenting data in a convenient and informative way. Inductive statistics (Keller 2009) deals with conclusions or inferences about characteristics of populations based on sample data. Descriptive statistics is used to describe the main features of a collection of data in quantitative terms. One form of descriptive statistics (Moore 2003, and William et al. 1983) uses graphical techniques to present data in ways that make it easy to extract useful information. Another form of descriptive statistics (Keller 2009, Moore 2003, Neufeld 1997) uses numerical techniques to summarise data. In descriptive statistics the aim is to quantitatively summarize a data set, rather than to support inductive statements about the population that the data are thought to represent. Even when a data analysis draws its main conclusions using inductive statistical analysis, descriptive statistics are generally presented along with more formal analyses, to give an overall sense of the data being analyzed. Examples of descriptive statistics are measures of central tendency, dispersion, scatter plots and association (Walpole et al. 2001).

5.2.1 Background

The pavement management system unit in Riyadh Region Municipality has a huge data base containing data for main roads. As discussed in the chapter on database, a specific database was developed for this study in a systematic and coherent way that included information (KACST 1998, RRM 2007, RRM 1998a, RRM 1998b, RRM 1998c, and RRM 1998d) on pavement characteristics, pavement distress data, and pavement maintenance data. Pavement characteristics data included information on pavement class, pavement type, pavement age, traffic volume, and availability of a drainage system. Pavement distress data included information on distress type, severity, extent and location. Seven common distress types (Mubaraki and Thom 2008) were considered as they occurred most frequently, namely; block cracks, longitudinal and transverse cracking, patching, potholes, depressions, weathering and ravelling, and cracking (due to patching). Pavement maintenance data included information about what type of maintenance strategy has been applied on the pavements and the maintenance date. Numerical summaries and graphs are presented in 5.2.2 and 5.2.3 to describe the content of the database.

Preliminary exploratory data analysis performed by using numerical summaries and graphs to describe the variables in a data set and the relation among them (Keller 2008 and Bogdanoff 1970). Any set of data contains information about a group of individuals. These individuals are described by variables. Some variables are categorical and others are quantitative. A categorical variable places each individual into a category, for example the pavement age factor has three levels; young, moderate, and old. Traffic factor has three levels; low, medium, and high. Drainage factor has two levels; with and without. A quantitative variable has numerical values that measure some characteristics of each individual, like pavement distress density for different types of pavement distress. Preliminary exploratory data analysis will be shown by using numerical summaries and scatter plots to describe the variables in a data set and the relation among them. Therefore, the distribution of a variable tells what values it takes and how often it takes these values. The overall pattern and the deviations from the pattern will be examined. Shape, centre, outliers, and spread describe the overall pattern of a distribution and the scatter plots can reveal trends or other changes over time.

5.2.2 Numerical Summaries

5.2.2.1 Background

It can be seen in the chapter on database and in the section 5.1 from this chapter, the summary data base for main roads data has a sample size of 2330 reading points, representing the distress density values, for each of the seven different types of pavement distress. The pavement distress density value is the response variable. Pavement age, traffic, and drainage are explanatory variables that explain or influence changes in the response variable. They are incorporated as records into the data base with pavement distress density values. Therefore, the descriptive statistics summaries of the response variables under the explanatory variables are described in the following Tables. Inspecting the scores of the response variable, it can be seen that the variation is everywhere. But it is impossible to tell much more than this from the raw data alone. To analyse the data further, it is needed to have a single number that summarizes a set of other numbers (Walpole et al. 2001).

Fundamental tasks in exploratory data analysis are to estimate a parameter for the distribution, to characterize the spread, or variability, of a data set, and to characterize the location and variability of a data set.

One of the fundamental tasks (Brown and Saunders 2008) is to estimate a location parameter for a distribution, for example, to find a typical or central value that best describes the data. The most common measure of the central tendency of a distribution of scores is the mean. However, the mean is sensitive to the influence of a few extreme observations. The median is the midpoint of a distribution, the number such that half the observations are smaller and the other half are larger. Therefore the median score accounts for the extreme observations.

However, a measure of centre alone can be misleading. Therefore, another fundamental task, to characterize the spread, or variability, of a data set is important. One way to measure spread is to give the smallest and the largest observations. A good way to improve the description of spread is by looking at the first and third quartiles. The first quartile lies one quarter of the way up the ordered list. The third quartile lies three quarters of the way up the ordered list. However, the most common measure of the variability of a distribution is the standard deviation. It measures spread by looking at how far the observations are from their mean. Strong skweness or few outliers can greatly increase the standard deviation. Therefore, to characterize the location and variability of a data set is important (Moore 2003).

A further characterization of the data includes Skewness and kurtosis. Skewness is a measure the lack of symmetry. A distribution, or data set, is symmetric if it looks the same to the left and right of the centre point. Kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution. Thus, data sets with high kurtosis tend to have a distinct peak near the mean, decline rather rapidly, and have heavy tails. Data sets with low kurtosis tend to have a flat top near the mean rather than a sharp peak (Moore 2003).

5.2.2.2 Pavement Age

Pavement age was defined as the number of years since construction or the last major maintenance. The pavement section ages were grouped into three categories or three levels. These categories or levels were young (1 to 4 years), moderate sections (4 to 8 years), and old sections (greater than 8 years). The sample size, the minimum and maximum, the mean, the standard deviation, the variance, the kurtosis, and the skewness are reported for the three groups as shown in Table 5.1 for Urban Main Sections (UMS). General observations from the Table can show that the pavement distress density varies between distress types. The data are skewed to the right for all types of distress. Therefore we can say that the variation is present and the data are not normally distributed for each level under study.

Table 5.1 Descriptive Statistic Results for Pavement Age at Different Levels-UMS

Factor								
Pavement Age								
Levels	Statistic	Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
Young Sections	Sample size	1733	1733	1733	1733	1733	1733	1733
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	41.50	20.90	57.10	16.93	64.67	29.36	31.35
	Mean	2.77	1.50	5.27	0.36	1.66	2.42	1.75
	Std. Deviation	5.80	3.30	10.15	1.33	5.09	4.93	3.75
	Variance	33.58	10.87	103.02	1.76	25.92	24.28	14.08
	Kurtosis	5.70	5.83	3.12	40.09	32.98	4.55	8.96
	Skewness	2.37	2.43	1.97	5.53	4.93	2.23	2.69
Moderate Sections	Sample size	450	450	450	450	450	450	450
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	85.00	34.36	92.94	45.12	62.77	81.71	57.75
	Mean	18.99	8.11	34.35	10.04	9.16	26.56	15.65
	Std. Deviation	10.61	6.60	13.95	9.08	10.53	15.93	10.03
	Variance	112.48	43.62	194.73	82.38	110.89	253.84	100.58
	Kurtosis	3.89	0.95	1.04	-0.51	4.03	0.03	1.93
	Skewness	0.83	0.97	-0.29	0.50	1.79	0.55	1.14
Old Sections	Sample size	147	147	147	147	147	147	147
	Minimum	1.88	0.00	20.39	1.04	0.00	19.90	5.00
	Maximum	77.95	61.93	91.69	42.20	54.55	95.50	62.35
	Mean	29.21	31.33	50.81	21.94	17.41	52.90	27.22
	Std. Deviation	8.38	14.40	12.13	6.35	11.42	17.22	11.19
	Variance	70.28	207.31	147.25	40.36	130.47	296.43	125.20
	Kurtosis	8.42	-0.77	1.50	2.73	0.10	-0.63	-0.02
	Skewness	1.06	0.07	0.55	-0.56	0.61	0.23	0.61

5.2.2.3 Traffic

Traffic factor was defined as the average daily traffic (ADT). The traffic sections were grouped into three categories or three levels. These categories or levels were low (0 to 1500 ADT), Medium (1500 to 10000 ADT), and high (greater than 10000 ADT). General observations from Table 5.2 show that the variation is present and the data are not normally distributed for each traffic level under study on UMS.

Table 5.2 Descriptive Statistics Results for Traffic at Different Levels-UMS

		Factor						
		Traffic						
Levels	Statistic	Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
Low traffic Sections	Sample size	849	849	849	849	849	849	849
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	77.95	61.93	91.69	40.59	64.67	89.23	53.60
	Mean	6.31	4.09	12.10	3.05	3.16	8.73	4.81
	Std. Deviation	10.59	9.20	18.06	7.23	7.49	16.84	9.07
	Variance	112.19	84.58	326.22	52.30	56.12	283.71	82.20
	Kurtosis	4.21	12.05	0.64	5.70	13.65	5.14	6.70
	Skewness	1.91	3.28	1.29	2.54	3.36	2.35	2.48
Medium traffic Sections	Sample size	1018	1018	1018	1018	1018	1018	1018
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	85.00	61.58	92.94	45.12	62.77	95.50	57.75
	Mean	8.17	4.95	14.26	3.71	4.34	10.73	6.60
	Std. Deviation	11.42	9.28	18.61	7.52	8.52	17.26	10.28
	Variance	130.43	86.15	346.32	56.51	72.53	297.82	105.63
	Kurtosis	2.69	10.81	0.27	3.37	9.58	3.79	4.08
	Skewness	1.50	3.04	1.10	2.07	2.78	2.00	1.97
High traffic Sections	Sample size	463	463	463	463	463	463	463
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	46.03	57.29	83.42	42.20	50.80	83.85	62.35
	Mean	8.57	5.05	15.69	4.32	5.32	12.08	7.07
	Std. Deviation	11.05	8.84	19.29	8.04	9.16	17.74	10.19
	Variance	122.06	78.23	372.13	64.69	83.87	314.67	103.86
	Kurtosis	-0.20	9.34	-0.19	2.09	4.60	2.22	3.63
	Skewness	1.02	2.76	0.96	1.80	2.16	1.65	1.82

5.2.2.4 Drainage

Drainage factor was defined as whether the section has a drainage system or not. The drainage sections were grouped into two categories or two levels. These categories or levels were drained sections and not drained sections. General observations from Table

5.3 can show that the pavement distress density varies between distress types on UMS. Table 4 shows a summary for all three factors.

Table 5.3 Descriptive Statistics Results for Drainage at Different Levels-UMS

Factor								
Drainage								
Levels	Statistic	Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
Drained Sections	Sample size	602	602	602	602	602	602	602
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	77.95	61.58	92.94	42.20	51.28	87.37	62.35
	Mean	6.82	4.00	12.47	3.33	4.46	8.91	5.67
	Std. Deviation	10.22	8.01	17.47	7.34	8.49	15.34	9.67
	Variance	104.36	64.10	305.36	53.94	72.05	235.21	93.44
	Kurtosis	4.08	16.69	1.03	5.40	6.30	4.91	7.77
	Skewness	1.72	3.59	1.31	2.42	2.43	2.20	2.52
Not Drained Sections	Sample size	1728	1728	1728	1728	1728	1728	1728
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	85.00	61.93	91.69	45.12	64.67	95.50	53.60
	Mean	7.83	4.89	14.21	3.69	3.98	10.74	6.17
	Std. Deviation	11.37	9.54	18.95	7.60	8.27	17.84	9.95
	Variance	129.22	90.92	359.13	57.76	68.44	318.33	98.99
	Kurtosis	2.10	9.58	0.06	3.26	10.44	3.44	3.76
	Skewness	1.47	2.92	1.08	2.08	2.93	1.97	1.96

Table 5.4 Descriptive Statistics Summary Results for all the Data-UMS

Factors								
Pavement age, Traffic, Drainage								
Levels	Statistic	Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
All Mixed	Sample size	2330	2330	2330	2330	2330	2330	2330
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	85.00	61.93	92.94	45.12	64.67	95.50	62.35
	Mean	7.57	4.66	13.76	3.59	4.11	10.27	6.04
	Std. Deviation	11.09	9.17	18.59	7.53	8.33	17.24	9.88
	Variance	122.95	84.11	345.68	56.77	69.38	297.38	97.56
	Kurtosis	2.51	10.90	0.27	3.74	9.25	3.80	4.68
	Skewness	1.53	3.07	1.13	2.16	2.79	2.03	2.09

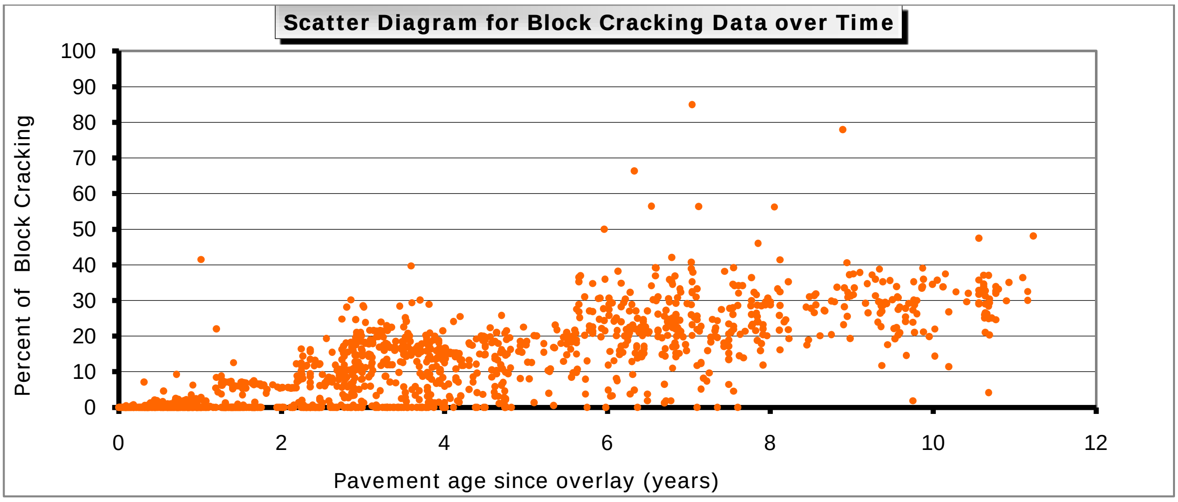
5.2.3 Scatter Plots

Once a data file has been created in the desired format, the data integrity has been checked, and the summary statistics on the response variables estimated, the next step is to start exploring the data to understand the fundamental structure. One of the most useful tools is the basic scatter plot (Keller 2008, and William et al. 1983). This technique allows explorations for examining relationships between response variables, and explanatory variables.

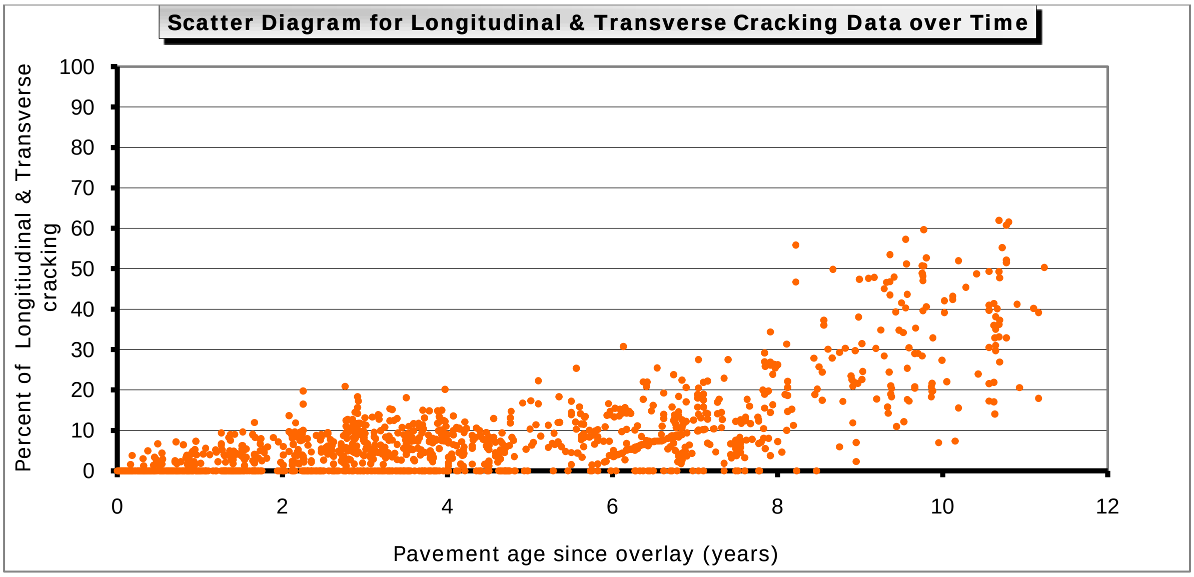
In this exploratory phase, the key is to graph everything that makes sense to graph. These pictures will reveal influential data points and will guide the subsequent modelling activities. Since the research has only one response variable which is the measurement of pavement distress density, the graph expresses the response against the explanatory variables in general and at different levels. This will give an indication of the main factors that have an effect on response variables. The graphs show response variable conditioned on the levels of explanatory factors. The most important characteristics of the scatter plots are the strength and direction of the relationship (Keller 2008).

5.2.3.1 Scatter Plots for Pavement Age

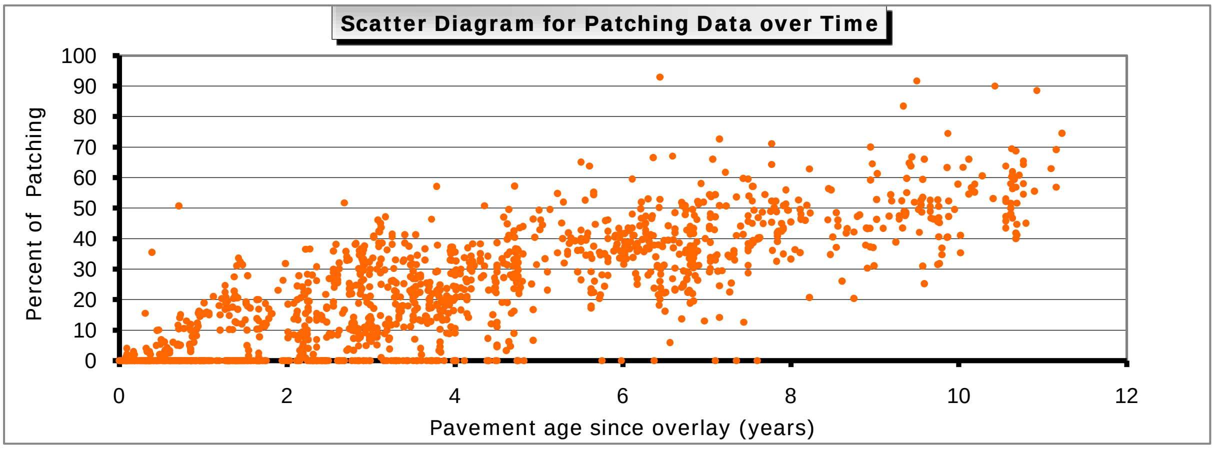
Most of the points appear to be scattered randomly and the variation increases with time for all types of pavement distress on UMS as shown in Figure 5.1 (a-g). Therefore the relation is a weak linear relationship and positive linear relationship between the pavement distress density and pavement age. To conclude, the scatter diagrams depict nonlinearity.



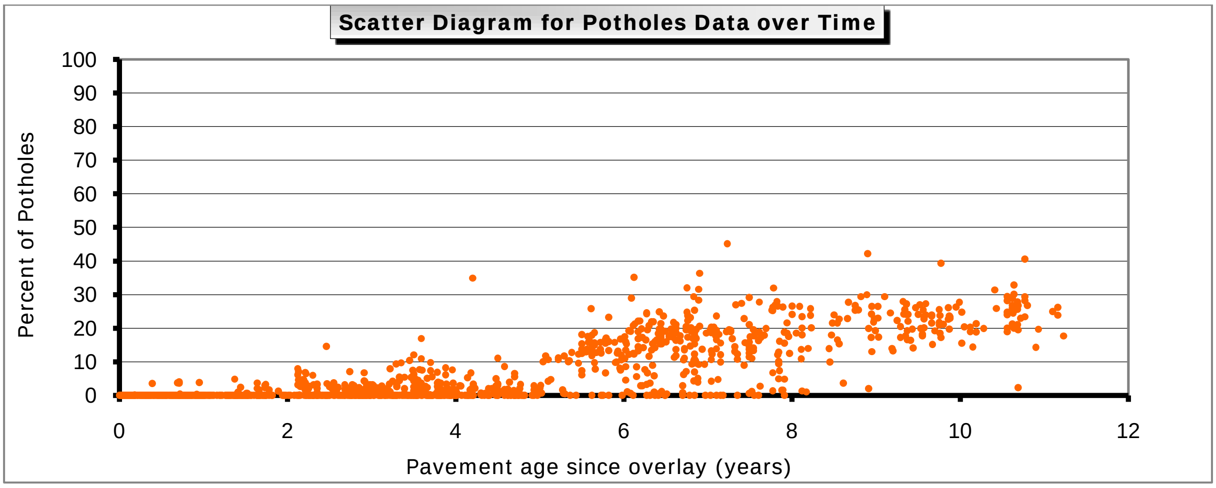
(a)


Scatter Diagram for Longitudinal & Transverse Cracking Data over Time
Percent of Longitiudinal & Transverse cracking
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)

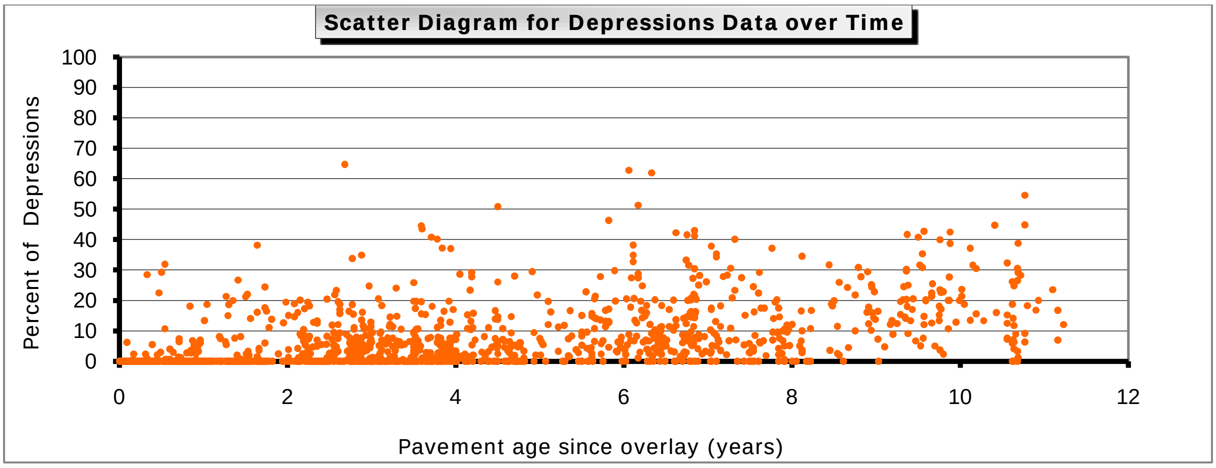
(b)


Scatter Diagram for Patching Data over Time
Percent of Patching
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)

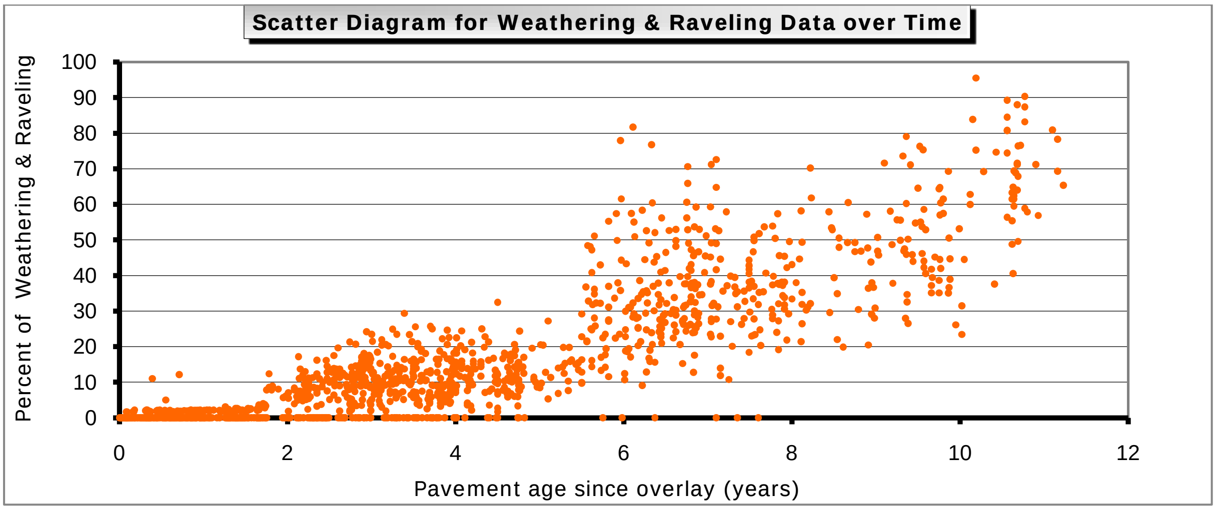
(c)


Scatter Diagram for Potholes Data over Time
Percent of Potholes
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)

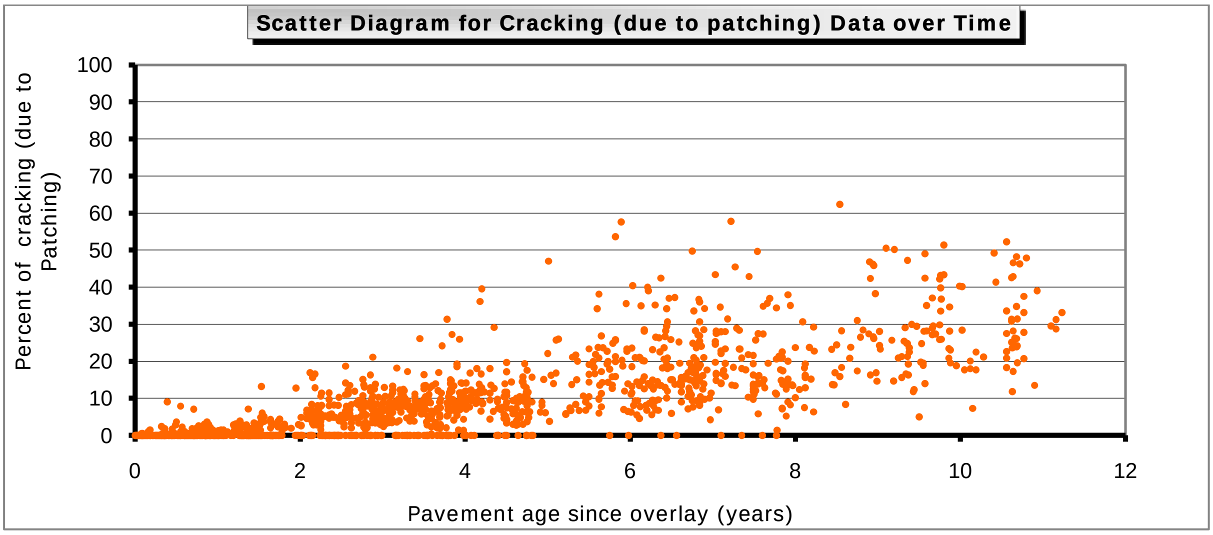
(d)



(e)



(f)

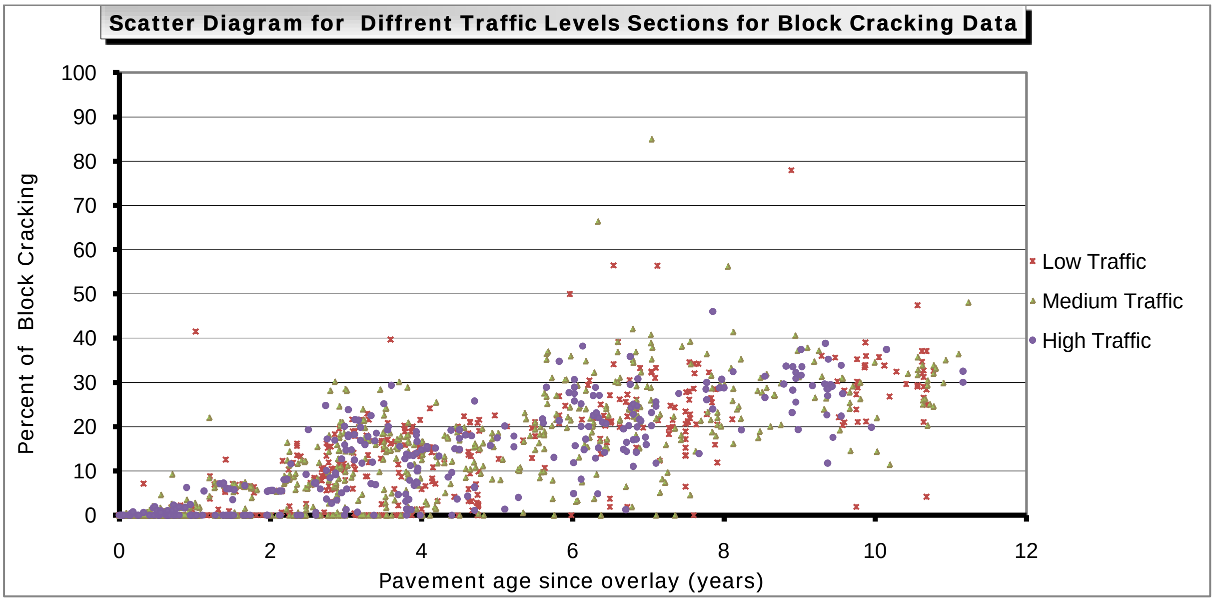


(g)

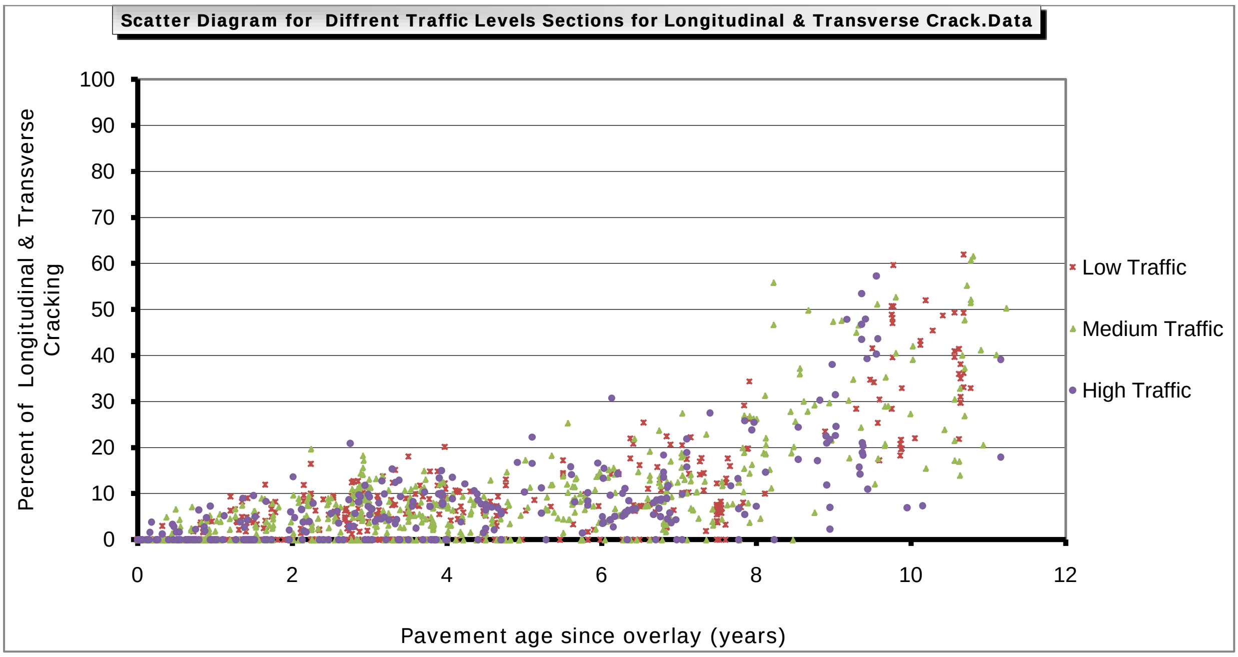
Figure 5.1 Scatter Plots for Pavement Age (UMS) for (a) Block Cracks, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

5.2.3.2 Scatter Plots for Traffic

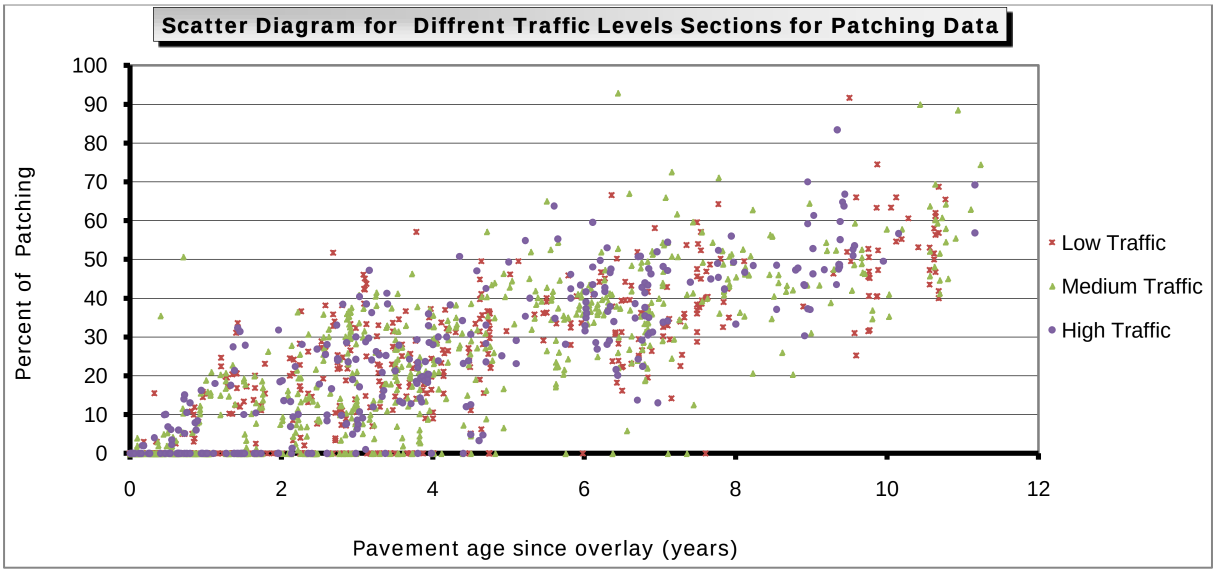
Most of the points are mixed together for all types of pavement distress on UMS as shown in Figure 5.2 (a-g). Therefore, difference in traffic level may not significantly affect pavement deterioration rate more. However, the inductive or the inferential analysis will support these observations.



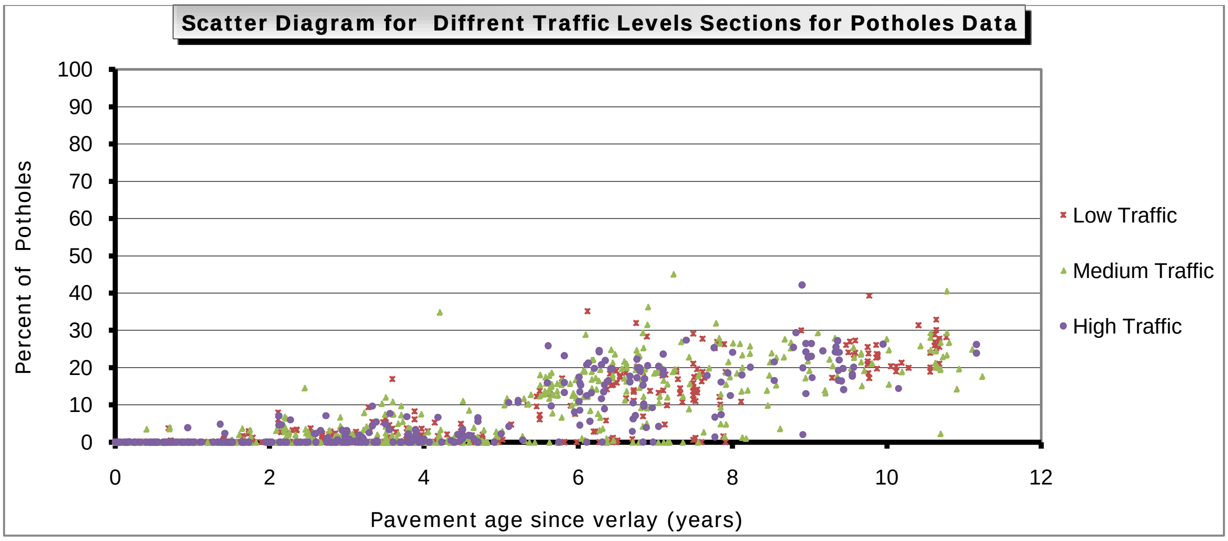
(a)



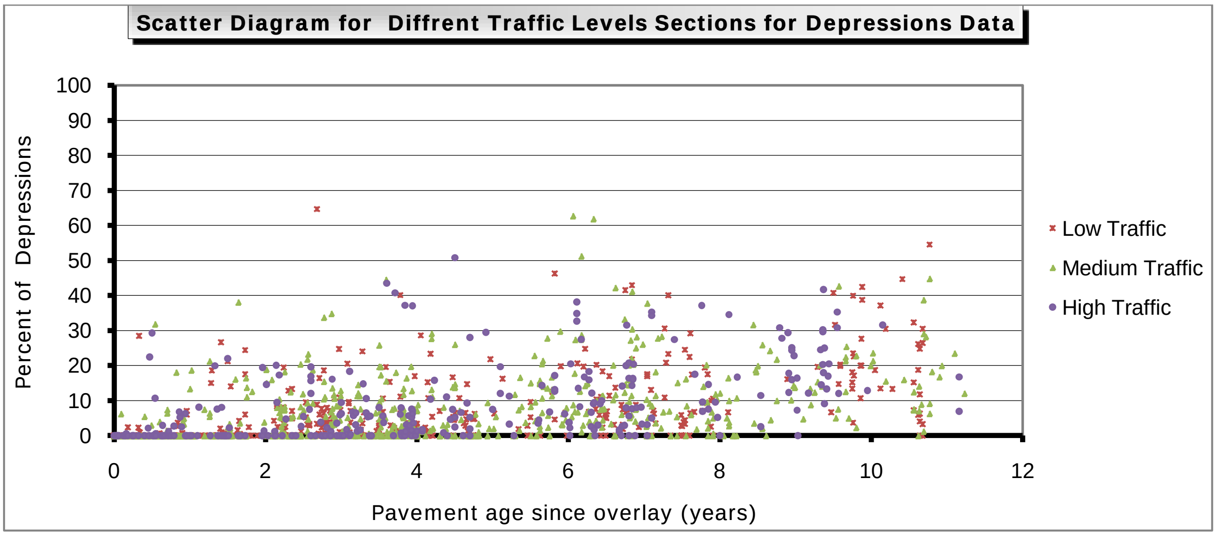
(b)


Scatter Diagram for Diffrent Traffic Levels Sections for Patching Data
Percent of Patching
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Low Traffic
Medium Traffic
High Traffic

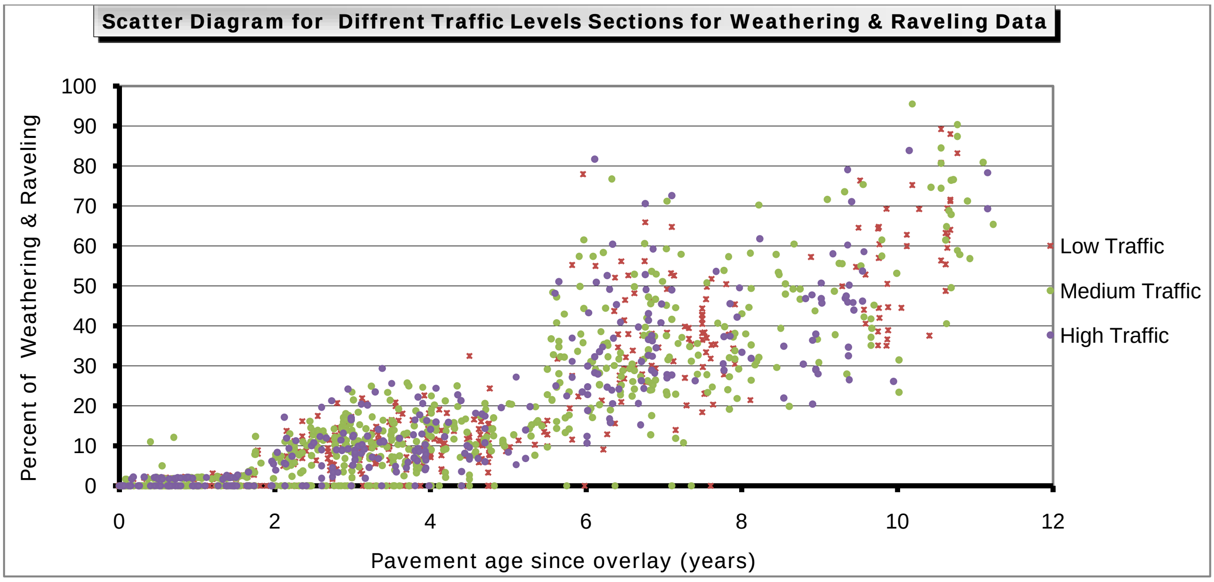
(c)


Scatter Diagram for Diffrent Traffic Levels Sections for Potholes Data
Percent of Potholes
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since verlay (years)
Low Traffic
Medium Traffic
High Traffic

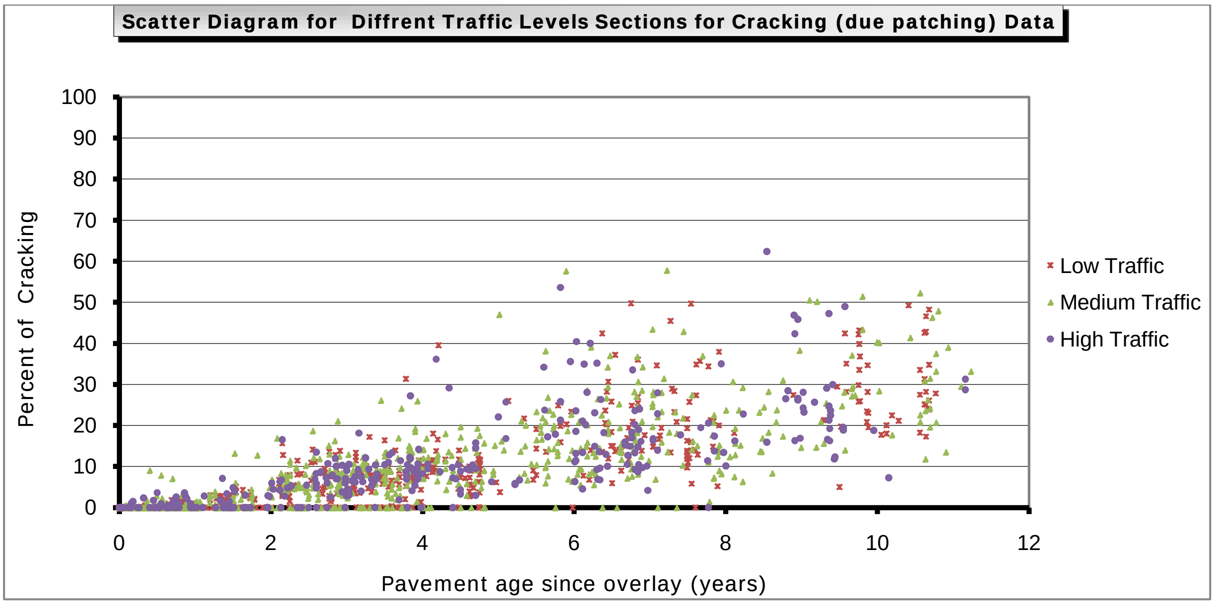
(d)


Scatter Diagram for Diffrent Traffic Levels Sections for Depressions Data
Percent of Depressions
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Low Traffic
Medium Traffic
High Traffic

(e)



(f)

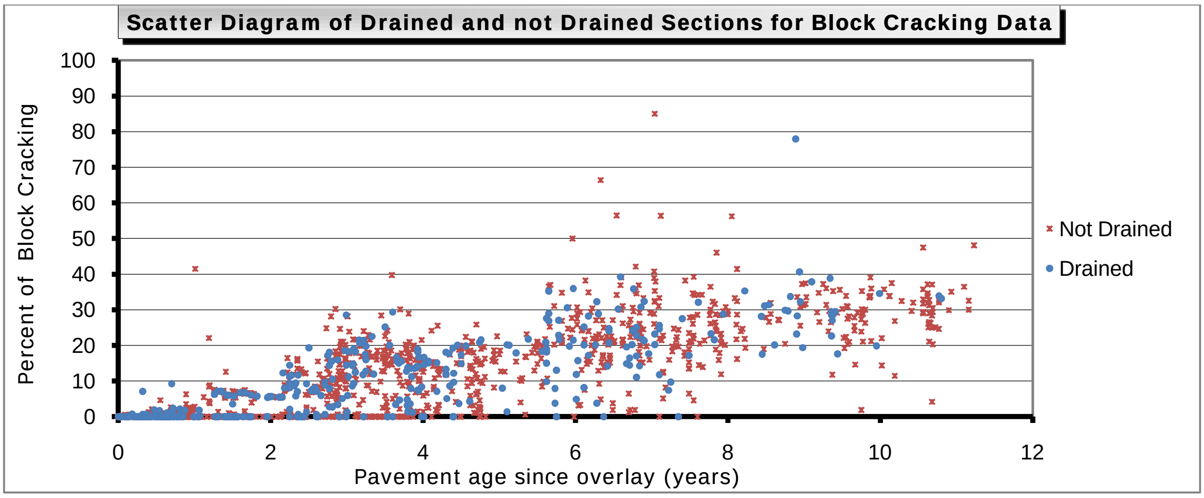


(g)

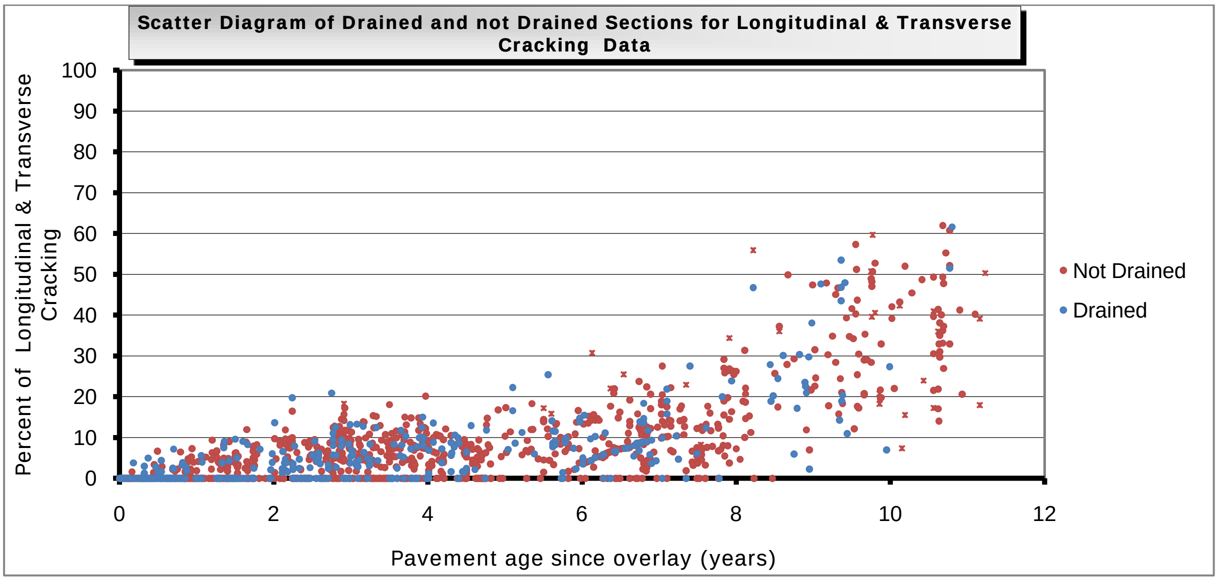
Figure 5.2 Scatter Plots for Traffic (UMS) for a) Block Cracks, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

5.2.3.3 Scatter Plots for Drainage

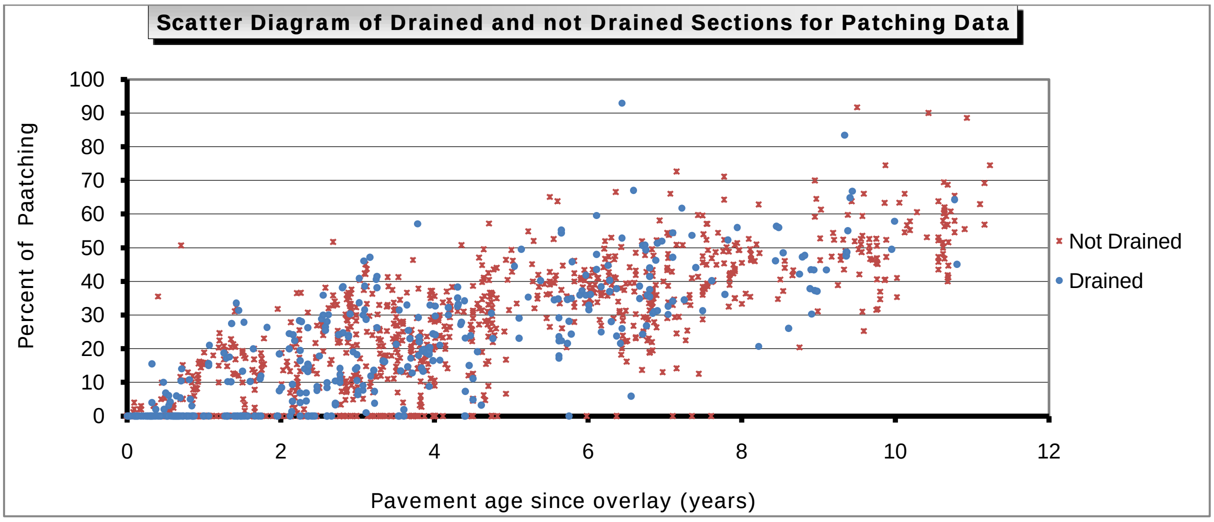
Most of the points are mixed together for all types of pavement distress on UMS as shown in Figure 5.3 (a-g). Therefore, different drainage levels may not affect pavement deteriorates more. However, the inductive analysis will support these observations.


Scatter Diagram of Drained and not Drained Sections for Block Cracking Data
Percent of Block Cracking
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Not Drained
Drained

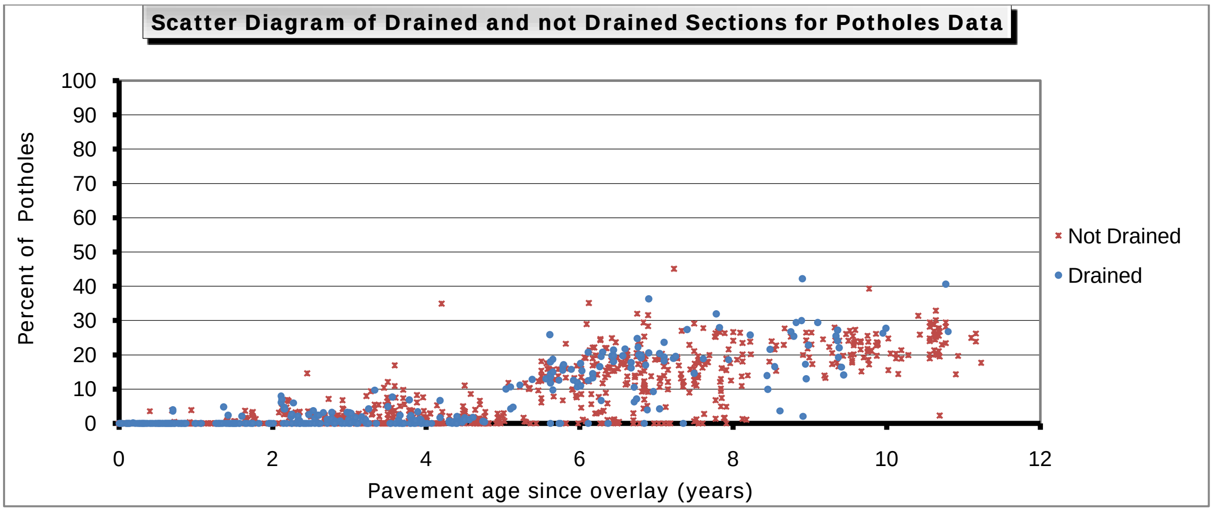
(a)


Scatter Diagram of Drained and not Drained Sections for Longitudinal & Transverse Cracking Data
Percent of Longitudinal & Transverse Cracking
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Not Drained
Drained

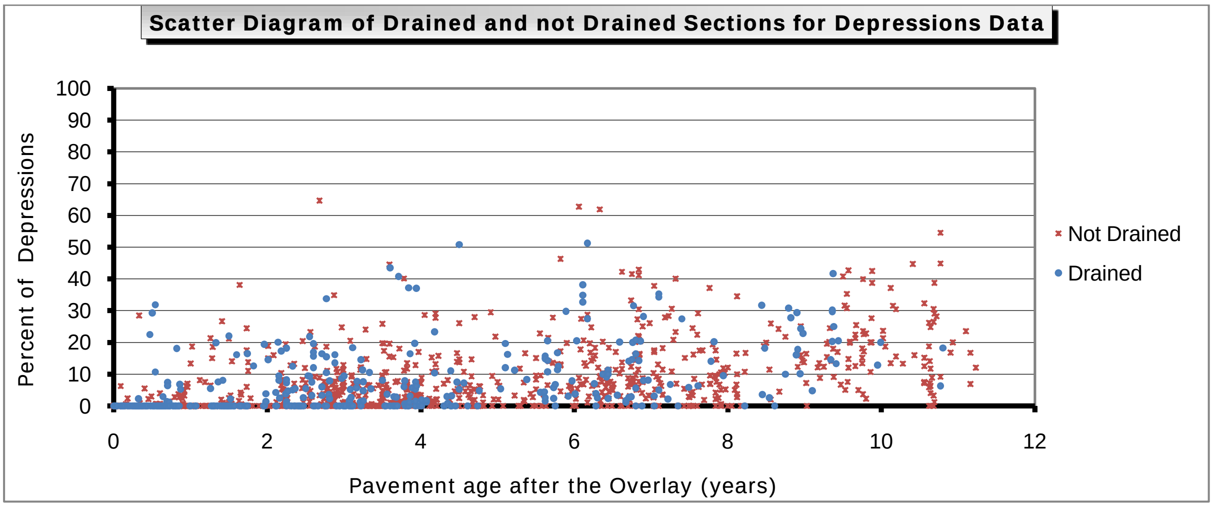
(b)


Scatter Diagram of Drained and not Drained Sections for Patching Data
Percent of Paatching
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Not Drained
Drained

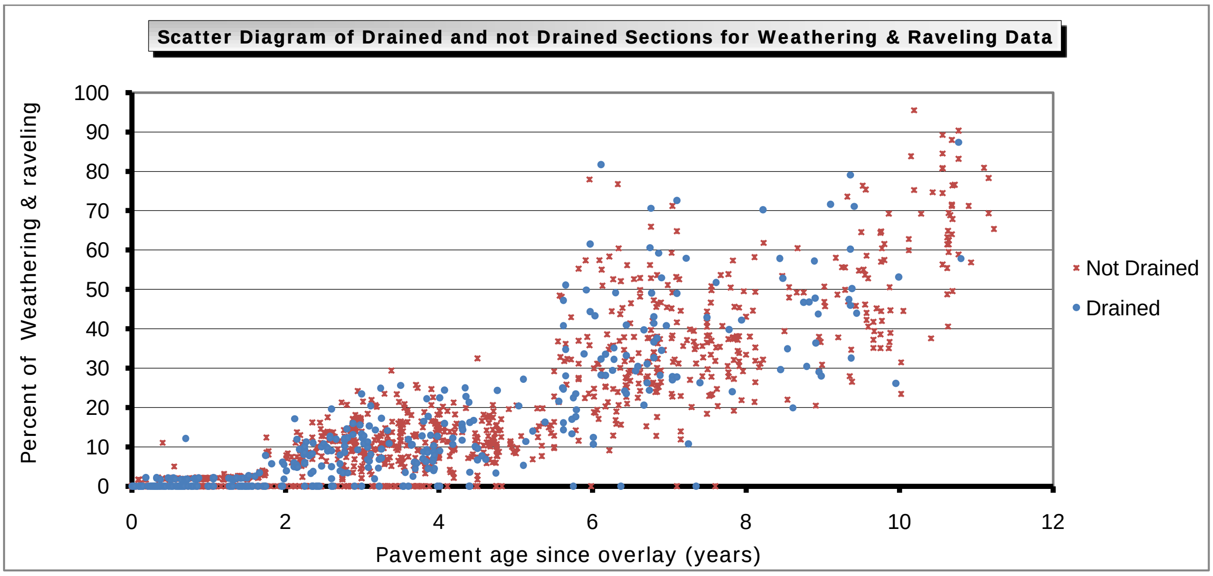
(c)


Scatter Diagram of Drained and not Drained Sections for Potholes Data
Percent of Potholes
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Not Drained
Drained

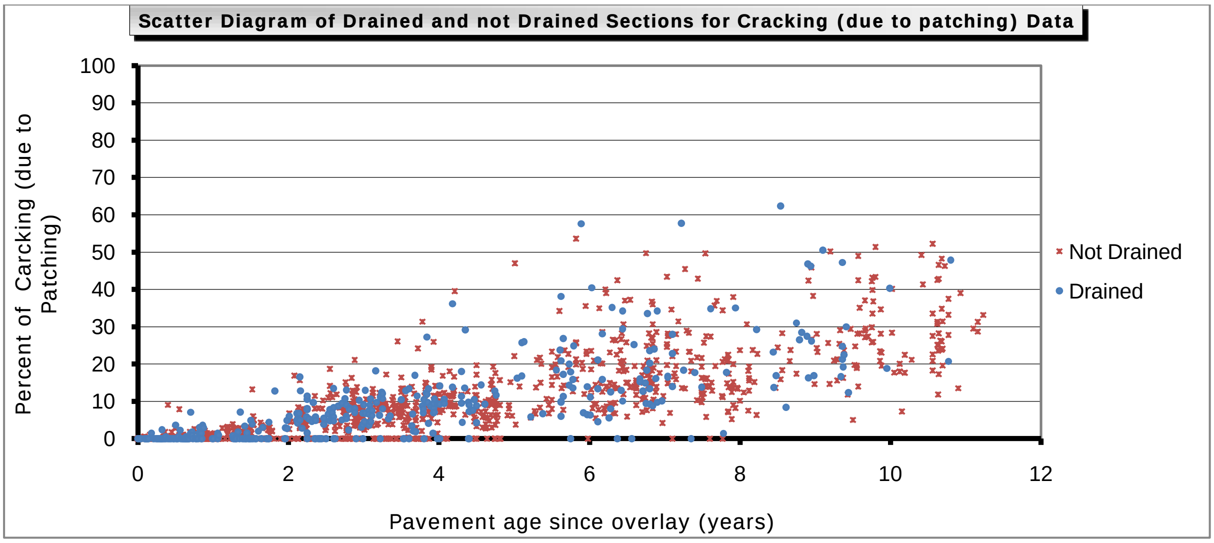
(d)


Scatter Diagram of Drained and not Drained Sections for Depressions Data
Percent of Depressions
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age after the Overlay (years)
Not Drained
Drained

(e)


Scatter Diagram of Drained and not Drained Sections for Weathering & Raveling Data
Percent of Weathering & raveling
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
Pavement age since overlay (years)
Not Drained
Drained

(f)



(g)

Figure 5.3 Scatter Plots for Darainage (UMS) for (a) Block Cracks, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to Patching).

5.2.4 Descriptive Statistics Conclusions for Urban Main Roads

The numerical summaries reveal that the pavement distress density values for all types of distress under study show variation in distribution. Traffic and drainage show more variation and dispersion. The data are not normal. The scatter diagrams reveal that most points of different levels for different factors are mixed together randomly and nonlinearity is present.

5.3 Inductive Statistics for Urban Main Roads

Inductive statistics deals (Keller 2009) with conclusions or inferences about characteristics of populations based on sample data. The inductive statistics depends on probability and it includes statistical assumptions, statistical decision theory, estimation theory, statistical hypotheses testing, design of experiments, analysis of variance, and others (Walpole et al. 2001, and Winkler 1975).

5.3.1 Significant Factors Affecting Pavement Deterioration

The selection of independent variables for the prediction equation is based on experience suggesting that the prediction of pavement condition depends on the following factors: pavement age, traffic volume, and availability of a drainage system. Therefore, in this study, pavement deterioration recognizes three factors in defining distress propagation.

However, the three factors will be subjected to tests of significance to determine the significant factors for distress models. As a basic principle, the form of the model is selected based on the boundary conditions and/or other variables that govern the deterioration of the pavements (Chen et al. 1995, Hajek and Hass 1987, Prozni and Madanat 2004, and Vepa et al. 1996).

5.3.2 Experimental Design of the Study

Experimental design is widely used in scientific research. The primary goal in scientific research is usually to show the statistical significance of an effect that a particular factor exerts on the dependent variable of interest (Casella 2008, Montgomery and Peck 1982, and Fisher 1971). However, experiment design is a discipline that has very broad application across all the sciences.

A total of 701 overlaid pavement sections were found to be applicable for the study constraints. 2330 observations on all selected pavement sections for each distress type were used to study the significant factors.

Therefore, the researcher is interested in the effect of different factors or the intervention of the pavement age, traffic, and drainage on distress density progression. Thus it can be concluded that the factors are the treatment and the distress density is the experiment unit (Montgomery and Peck 1982).

The layout of the experimental design along with data included in the study is presented in Table 5.5. Experimental design of the study shows that the study is a multifactor experimental design. The independent variables are pavement age, traffic levels, and availability of a drainage system. These independent variables are called factors. Each single factor has different categories. All the factors will be investigated separately in the following subsections.

The 2330 observations were distributed according to the design in the Table, for example 1733 observations were found on the network that has young pavement sections. 602 observations were found on the network that the roads were drained. 463 observations were found on the network that the roads were accommodating high traffic. Table 5.6 shows a summary of the factors and the levels.

Table 5.5 Experimental Design-UMS

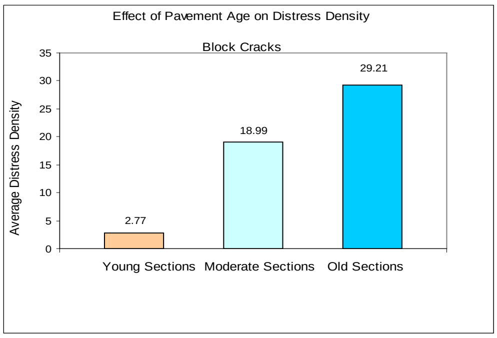
Maintenance Type	Pavement Age		Number of observations on the selected sections for each distress								
				With Drainage System				Without Drainage System			
					Low Traffic	Medium Traffic	High Traffic		Low Traffic	Medium Traffic	High Traffic
Overlay	Young Sections	1733		468	102	216	150	1265	559	527	179
Overlay	Moderate Sections	450		106	12	47	47	344	131	162	51
Overlay	Old Sections	147		28	2	10	16	119	43	56	20
Overlay	Total		2330	602	116	273	213	1728	733	745	250

Table 5.6 Factors and Levels-UMS

Classification of Variables	
Factors	Levels
Pavement Age	Young
	Moderate
	Old
Traffic	Low
	Medium
	High
Drainage	With drainage
	Without drainage

5.3.2.1 Pavement Age

It is known that pavement age is one of the most important variables that affect distress propagation. Pavement age is measured from the date of construction or from the date of the last major maintenance. However, only last major maintenance sections were considered in this study due to lack of construction date data. Urban main road sections were grouped into three categories as follows: young (0 to 4 years), moderate (4.1 to 8 years), and old (>8 years). The average distress density values of each distress within each group are shown in Figure 5.4 (a-g). As expected, all distress types tend to increase with time. However, this increase is relatively varied from distress to distress. More details will be presented using suitable statistical tests.



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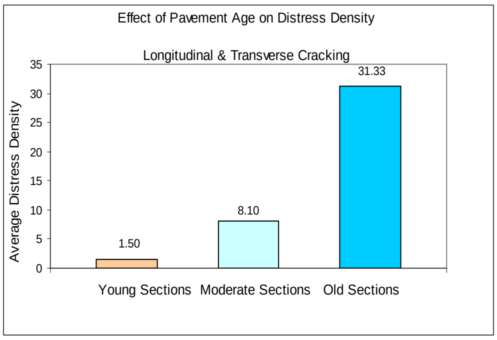

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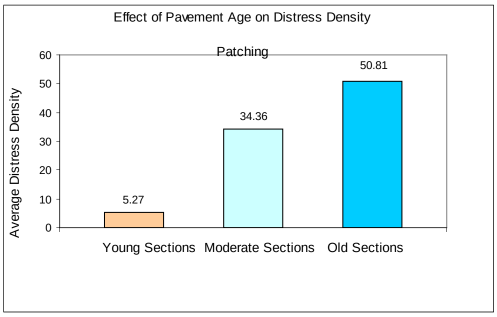

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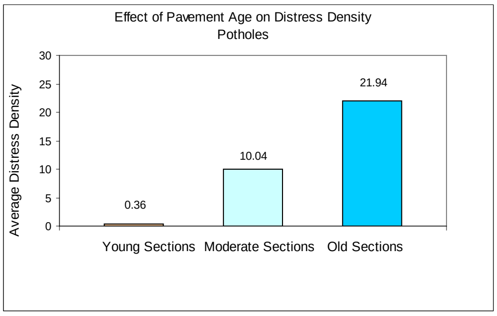

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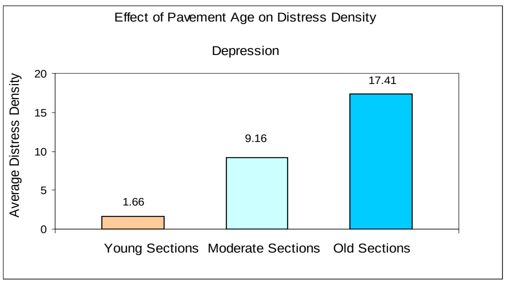

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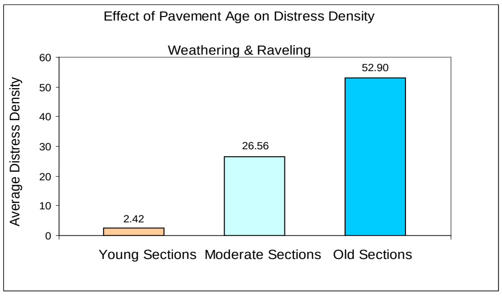

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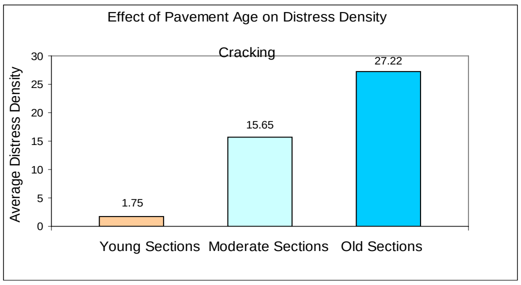
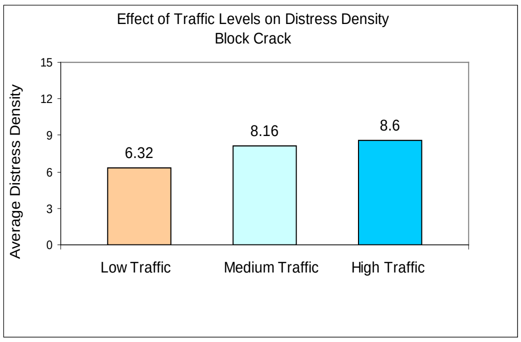


(g)

Figure 5.4 Effect of Pavement Age (UMS) on (a) Block Cracking, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

5.3.2.2 Traffic

The ADT was used to classify the traffic into three levels, low, medium, high. Low traffic level ranged from 0 to 1500 ADT, medium traffic level ranged from 1500 to 10000 ADT, and high traffic level is more than 10000 ADT. The average distress density values for different traffic levels of each distress type are shown in Figure 5.5 (a-g). In general, the difference in mean values is not clear. There appears to be little difference between the different levels of traffic on distress propagation. However, this small difference will be examined by suitable statistical tests.



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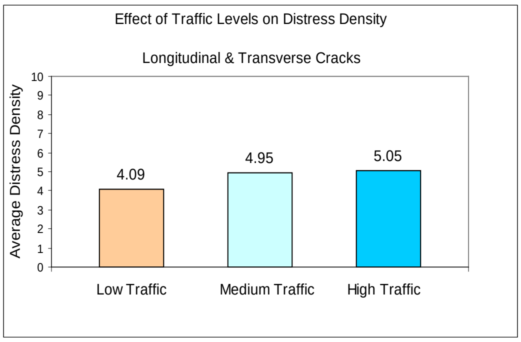

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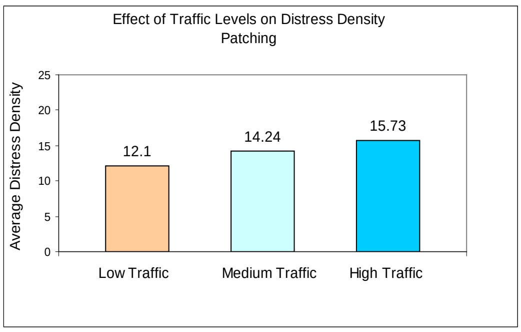

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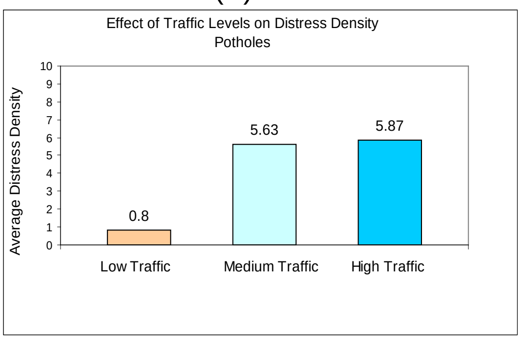

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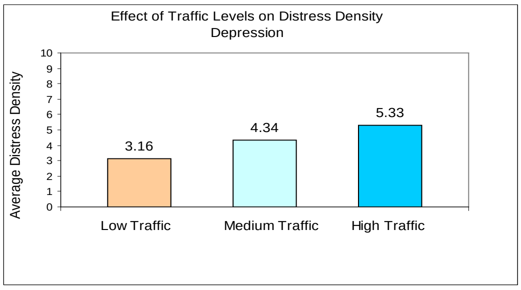

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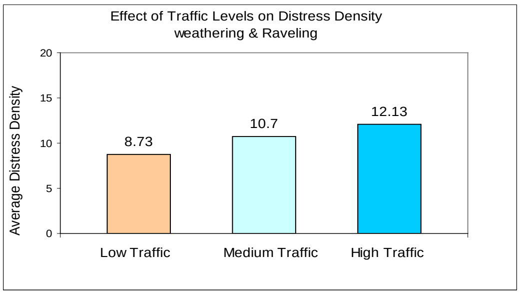

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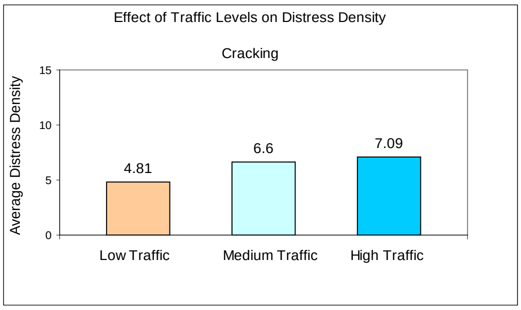
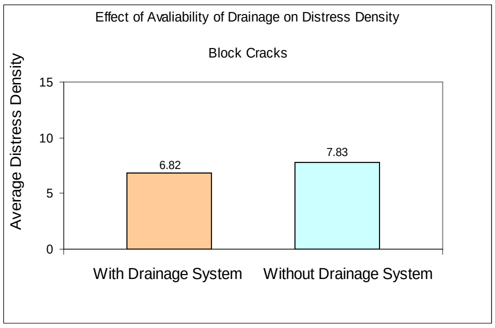


(g)

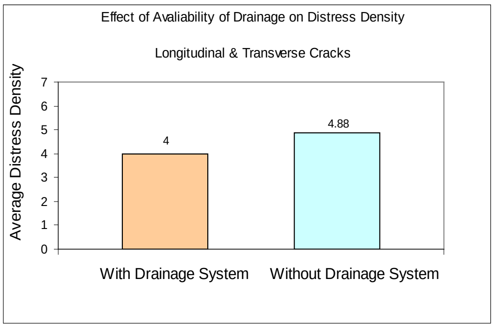
Figure 5.5 Effect of Traffic (UMS) on (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Revelling, and (g) Cracking (due to patching).

5.3.2.3 Drainage

The availability of a drainage system can affect distress propagation. Therefore, pavement sections were grouped into those sections with a drainage system and those sections without a drainage system. It was expected that distress on drained sections would propagate less than distress on not drained sections. However, Figure 5.6 (a-g) shows small differences in average values of distress density.



(a)



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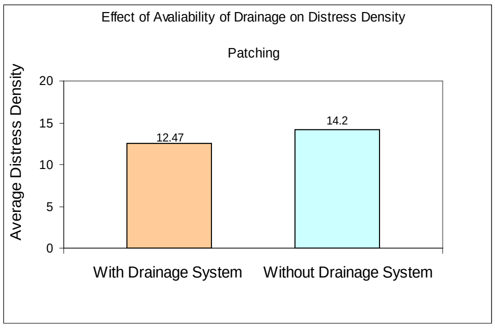

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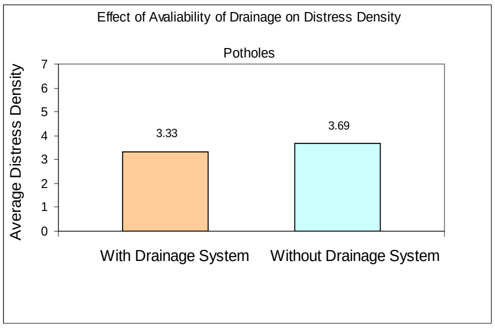

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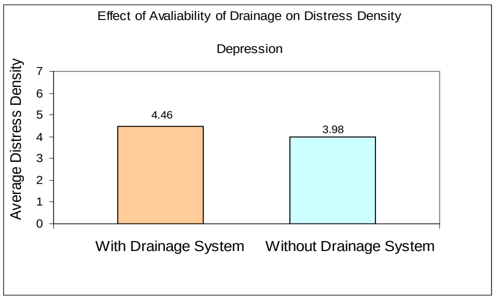

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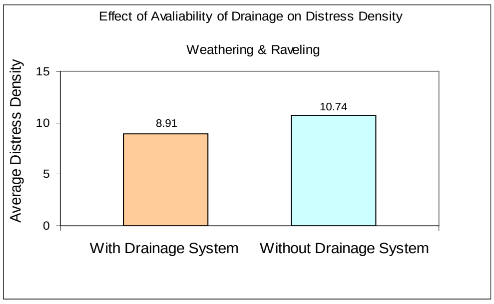

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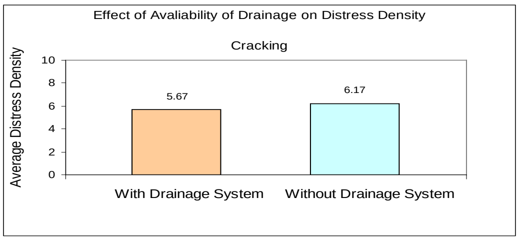


(g)

Figure 5.6 Effect of Drainage (UMS) on (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

5.3.2.4 Normality Test

The normality test aims to check the distribution of the data. Before analysing the data, it is important to know whether the data are following a normal distribution. There are many tests to check normality (Siegel and Castellen 1988). However, the most popular methods are the Kolmogorov-Smirnov test (K–S test) and the Shapiro-Wilk test (W-S test). These tests compare the set of scores in the sample to a normally distributed set of scores with the same mean and standard deviation.

The output of these two tests gives K-S values, S-W values, and p-values. The P value is a probability, with a value ranging from zero to one. It is a measure of how much evidence against the null hypothesis. The null hypothesis, traditionally represented by the symbol Ho, represents the hypothesis of no change or no effect.

For example, if the P-value is 0.05, that means that there is a 5% chance of observing a difference as large as observed even if the two population means are identical. It is tempting to conclude that there is a 95% chance that the observed difference reflects a real difference between populations and a 5% chance that the difference is due to chance. Popular P-values are 5% (0.05), 1% (0.01) and 0.1% (0.001). The chosen alpha is 0.05. If the P-value is less than the chosen alpha this would indicate that the null hypothesis (Ho) is rejected.

There is nothing special about choosing P-value 0.05 or 95% confidence. It is just convention that confidence intervals are usually calculated for 95% confidence. In theory, confidence intervals can be computed for any degree of confidence. If the researcher wants more confidence, the intervals will be wider. If the researcher is willing to accept less confidence, the intervals will be narrower (Walpole et al. 2001).

The null hypothesis (Ho) and the alternative hypothesis (Ha) must be stated in order to perform a statistical hypothesis test (Walpole et al. 2001). A statistical hypothesis is a method of making statistical decisions using the output data. If the P-value is less than the chosen alpha level, then the null hypothesis is rejected. The null hypothesis, therefore, would be that there is no difference between the distribution of the data for each distress and a normal distribution.

When the data are classified into groups, it is the distribution within groups that is important rather than the overall distribution (SPSS Manual version 16). Therefore, normality tests were done for the data in each factor by testing the raw scores and residual values as well (Keller 2009).

In analysis of variance, the residual is the difference between an actual value and the mean score for the group from which the value was taken. Tables 5.7, 5.8, and 5.9 indicate that the null hypothesis for each distress is rejected under the three factors. Therefore, the data for each distress in the entire database are not following a normal distribution.

Normality tests shows that all seven distress types' data are not normally distributed. The data violate the required conditions to use parametric tests like the two sample test and analysis of variance. This means that to do statistical tests on the factors, tests that are designed for data with a non normal (non parametric) distribution would be used. Therefore, non parametric tests were performed to determine which variables are significant in the prediction of each distress type.

Table 5.7 shows that for p-values are less than 0.05 at different K-S values. Therefore, the null hypothesis (Ho) is rejected and subsequently the data are not normal for each pavement distress types for factor of pavement age.

Table 5.8 shows that the null hypothesis the data are not normal for each pavement distress types for factor of traffic. Table 9 shows that the null hypothesis (Ho) the data are not normal for each pavement distress types for factor of drainage.

Table 5.7 Results of Normality Test for Pavement Age-UMS

Factor								
Pavement Age								
Levels	Statistic	Types of Distress						
		Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
Young Sections	K-S	0.405	0.450	0.416	0.478	0.431	0.407	0.413
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Moderate Sections	K-S	0.061	0.110	0.061	0.161	0.192	0.064	0.108
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Old Sections	K-S	0.101	0.088	0.078	0.085	0.067	0.084	0.106
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Table 5.8 Results of Normality Test for Traffic-UMS

Factor								
Traffic								
Levels	Statistic	Types of Distress						
		Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
Low traffic Sections	K-S	0.336	0.345	0.357	0.402	0.367	0.307	0.325
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Medium traffic Sections	K-S	0.283	0.299	0.296	0.356	0.333	0.268	0.276
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
High traffic Sections	K-S	0.258	0.284	0.270	0.348	0.293	0.251	0.248
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Table 5.9 Results of Normality Test for Drainage-UMS

Factor								
Drainage								
Levels	Statistic	Types of Distress						
		Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.	Cracking
Drained Sections	K-S	0.297	0.303	0.417	0.368	0.337	0.272	0.286
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Not Drained Sections	K-S	0.298	0.314	0.046	0.377	0.340	0.286	0.284
	P-value	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

5.3.3 Test of Significance

5.3.3.1 Nonparametric Test

5.3.3.1.1 Background and selecting the appropriate tests

Classification of variables into factors and levels as was mentioned earlier in Table 5.6 shows that the factors have to be tested in two different tests. Tests for several independent samples were performed for pavement age and traffic, where there were three levels, whereas two independent tests were performed for drainage where two levels were used. Therefore, the *Kruskal-Wallis H-test* would be appropriate for pavement age and traffic factors three levels in each factor under investigation, and the *Mann-Whitney U test* would be appropriate for drainage factors where only two levels were investigated (Moor 2003 and Williams 2004).

However, tests for pavement age and traffic factors must only be performed into two steps if the first step is significant. The first step is the *Kruskal-Wallis H-test.* If this test is significant, the second step is to do the *Mann-Whitney U* only for pavement age and traffic factors. And then finally based on both steps, a conclusion could be drawn. The null hypothesis (Ho) would be that there is no difference between the means of levels of factor, whereas the alternative hypothesis (Ha) is that there is a difference in at least one of the means. Tables 5.10, 5.11, and 5.12 show the results of significance factors using nonparametric tests.

5.3.3.1.2 Pavement Age

Pavement age factor for each distress is significant as Ho is rejected. Rejecting Ho means accepting Ha which says there is a difference where at least one of the means is different. Consequently this indicates that pavement age factor does affect the pavement deterioration and hence the pavement distress propagation.

Table 5.10 results showed that the *Kruskal-Wallis H-test* was significant for each pavement distress. Consequently the *Mann-Whitney U test* can be performed for each level. The results showed that for each distress Ho is rejected for young-moderate level and for medium-old level. Based on these two results, Ho is rejected for pavement age factor, therefore the alternative hypothesis is accepted. So pavement age plays an important role in pavement deterioration.

Table 5.10 Kruskal-Wallis H-test and Mann-Whitney U Test Results for Pavement Age-UMS

_Factor							
Pavement age							
	First Step		Second Step				Final Step
Categories	Overall (Young to old)		Young-Moderate		Moderate-Old		
Output of the Test	K-W		M-W		M-W		
Distress	P-value	Test Result	P-value	Test Result	P-value	Test Result	Decision
Block Cracks	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Longitudinal & Transverse Cracking	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Patching	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Potholes	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Depressions	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Weathering & Ravelling	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Cracking (due to patching)	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho

5.3.3.1.3 Traffic

The traffic factor for each distress is not significant as Ho is accepted. Table 5.11 results show that the *Kruskal-Wallis H-test* was significant for each distress. Consequently the *Mann-Whitney U test can* be performed for each level. The results showed that for each distress Ho is rejected for low and medium level and accepted for medium and high level. Based on these two results, Ho for traffic is accepted. Therefore the alternative hypothesis is rejected. So traffic factor does not play an important role in pavement deterioration like the role of pavement age in pavement deterioration.

Table 5.11 Kruskal-Wallis H-test and Mann-Whitney U Test Results for Traffic-UMS

Factor							
Traffic							
	First Step		Second Step				Final Step
Categories	Overall (Low to High)		Low-Medium		Medium-High		
Output of the Test	K-W		M-W		M-W		
Distress	P-value	Test Result	P-value	Test Result	P-value	Test Result	Decision
Block Cracks	0.000	Significant	0.000	Reject Ho	0.317	Accept Ho	Accept Ho
Longitudinal & Transverse Cracking	0.000	Significant	0.000	Reject Ho	0.630	Accept Ho	Accept Ho
Patching	0.000	Significant	0.000	Reject Ho	0.218	Accept Ho	Accept Ho
Potholes	0.001	Significant	0.002	Reject Ho	0.200	Accept Ho	Accept Ho
Depressions	0.000	Significant	0.000	Reject Ho	0.031	Accept Ho	Accept Ho
Weathering & Ravelling	0.000	Significant	0.000	Reject Ho	0.138	Accept Ho	Accept Ho
Cracking (due to patching)	0.000	Significant	0.000	Reject Ho	0.240	Accept Ho	Accept Ho

5.3.3.1.4 Drainage

Drainage factor for each distress is not significant as Ho is accepted. Accepting Ho means rejecting Ha which says there is a difference where at least one of the means is different. Consequently this indicates that drainage factor does not affect the pavement deterioration and hence the pavement distress propagation. Table 5.12 results show that for each distress Ho is accepted, therefore the alternative hypothesis is rejected. So availability of drainage traffic does not play an important role in pavement deterioration like the role of pavement age in pavement deterioration.

Table 12 Mann-Whitney U Test Results for Drainage-UMS

Factor			
Drainage			
Categories	Drained - Not Drained		
Output of the Test	M-W		
Distress	P-value	Test Result	Decision
Block Cracks	0.295	Not Significant	Accept Ho
Longitudinal & Transverse Cracking	0.513	Not Significant	Accept Ho
Patching	0.196	Not Significant	Accept Ho
Potholes	0.335	Not Significant	Accept Ho
Depressions	0.197	Not Significant	Accept Ho
Weathering & Ravelling	0.308	Not Significant	Accept Ho
Cracking (due to patching)	0.557	Not Significant	Accept Ho

5.3.3.1.5 Nonparametric Test conclusions

In the light of the results of nonparametric tests, it can be concluded that pavement age is the only factor that has significance in the prediction of pavement deterioration and distress behaviour. However, the effect of the other two factors, traffic and drainage, will be tested again in the modelling process.

Nonparametric tests in general have disadvantages (Siegel and Castellen 1988). One of the main disadvantages of non parametric tests is no confidence intervals are given as part of the output, so whether there is a significant difference or not on the factors, no idea how large this difference may be.

Non parametric tests are less powerful than parametric tests, and may not detect small differences. Therefore, when the assumptions for a parametric test are met, it is generally (but not necessarily always) preferable to use the parametric test rather than a nonparametric (Siegel and Castellen 1988).

5.3.3.2 Parametric Test

5.3.3.2.1 Background and selecting the appropriate tests

In reality, a random sample of a population has been taken to obtain the necessary data. For instance, to estimate a population mean, we compute the sample mean. Although there is very little chance that the sample mean and the population mean are identical, they might be quite close. However, for purpose of statistical inferences, how close, they are, is recommended (Walpole et al. 2001). Therefore, the data can be considered as a random sample of a population and hence for each value of (*n*), the mean of the sampling distribution is the mean of the population from the sampling. The variance of the sampling distribution is the variance of the population divided by the sample size (*n*). The standard deviation of the sampling distribution is called the standard error of the mean (Keller 2009).

One important phenomenon in the sampling distribution is the sample size. As (*n*) gets larger the sampling distribution becomes increasingly bell shaped. This phenomenon is summarized in a remarkable mathematical proposition called the Central Limit Theorem (Keller 2009, Moore 2003, Walpole et al. 2001, and Williams 2004).

The Central Limit Theorem (CLT) says "The sampling distribution of the mean of a random sample from any population is approximately normal for a sufficiently large sample size. The larger the sample size, the more closely the sampling distribution will resemble a normal distribution".

The accuracy of the approximation alluded to in the CLT depends on the probability distribution and on the sample size. If the population is normal, then the data is normally distributed for all values of *n*. If the population is non-normal, then the data is approximately normal only for large values of *n*.

In many practical situations, a sample size of 30 may be sufficiently large to allow the researcher to use the normal distribution as an approximation for the sampling distribution (Keller 2009).

To conclude based on the CLT, the data is considered to be normal as each individual in the data set has a sample size of 2330 points.

It can be seen from the Table 5.6 the pavement age and traffic factors have three levels, whereas drainage factor has only two levels. Therefore the test of significance for the factors could be examined by different approaches. The test statistic value will be used to evaluate the hypotheses. Test statistics take into account the amount of variability inherent in the averages and the size of the samples (Moore 2003, and Keller 2009).

The *t statistic* will be used because the sample standard deviation (s) will be considered in the experimental design study. Therefore, hypothesis testing with t statistics will be compared to t distributions. However, because of the large sample in the comparison, the t distribution should look almost identical to the normal distribution, and this is stated clearly in the Central Limit Theorem (CLT) as it mentioned before.

Table 5.6 shows that all the three factors have more than one level. Therefore, the study involved two or more independent samples. Consequently hypothesis testing for single samples with *t statistic* will not be appropriate in this study. So, hypothesis testing *two samples t statistic* will be appropriate for drainage factor because this factor has two levels (with drainage and without drainage) provided that the samples meet its condition. To perform the *two samples t statistic* test (Moore 2003), there are two main conditions. First, the sampling distribution must be approximately normal. Second, both sample variances are not too far from each other.

Both conditions are met, the first condition can be counted by the (CLT) because the sample size is large, so normality is guaranteed, and the test for equality of variances will be conducted by *Levene's test* (SPSS Manual version 16). This test is shown in the output of *t*-test. Therefore, hypothesis testing *independent samples t statistic* will be conducted on availability of drainage factor to test its significance on distress behavior. The null hypothesis *Ho* and the alternative hypothesis *Ha* can be stated in statistical terminology as;

Ho: μ1=μ2 versus Ha: μ1≠μ2

The confidence level used was 95 percent. The *two samples t statistic* hypothesis was calculated by the following formula (Walpole et al. 2001).

$$t = \frac{\mu_1 - \mu_2}{\left[\left(S^2/n_2\right)+\left(S_2{}^2/n_2\right)\right]^{0.5}}$$

Where

μ1=mean of first sample,

μ2=mean of second sample,

S^2 = first sample variance,

and $S_2{}^2$ =second sample variance.

However, before interpreting the t test result, the variance has to be checked to insure that the variance within the two groups is equal. Therefore, the Levene's test result must be read before interpreting the two *samples t statistic* (SPSS Manual version 16). The null hypothesis for Levene's test is that there is no difference between the variance of the two levels in drainage factor. If the significance value is greater than 0.05, equal variances are assumed, if the significance value is less than 0.05, equal variances are not assumed. Then, the mean difference between the two levels must be checked; if the mean difference is high, there is significance, otherwise not (SPSS Manual version 16).

Although the other two factors (pavement age and traffic) have three levels, *two samples t statistic* can be conducted on each level of the experimental conditions. However, this strategy would require 3 separate hypotheses tests. This would cause serious problem. This problem with analyzing a single experiment using 3 *t tests* has to do with the chances of incorrectly rejecting a true null hypothesis.

The analysis of variance (ANOVA) (Walpole et al. 2001) analyzes whether or not there are significant differences between three condition means considering the total amount of variability in distress values. This variability is caused by differences between conditions and within condition. Therefore, the ANOVA will account for independent samples and then ANOVA F can be calculated and then p-value can be found to check the significance of the independent variables together. Although this test can give an answer whether the pavement age and the traffic factors are significant or not, it does not reveal which conditions are significantly different from which. In other words, there are significant differences between the levels but which levels differ significantly from each other. For instance which levels among the three levels of pavement age differ most significantly, young sections, moderate sections, or old sections for each distress behavior.

To consider the interaction between all combinations, analysis of multi-condition must be performed (Moor 2003, and SPSS Manual version 16). A good statistical test to tackle such a situation is to use post hoc tests. The post hoc tests are tests to check the difference in means when there are more than two factors in the study. They are only valid when done after obtaining a significant result with the ANOVA F test. Therefore, the analysis of variance (ANOVA) will be performed for the pavement age and traffic volume factors in order to do the post hoc tests if the ANOVA F test is significant (Moor 2004).

Similarly to perform the ANOVA F test (Walpole et al. 2001), two main conditions must be met. First, the sampling distribution must be approximately normal. Second, both sample standard deviation variances are not too far from each other. Both conditions are met. Therefore, Hypothesis testing *ANOVA F test* will be conducted on pavement age and traffic volume to check their significance on distress behavior.

The null hypothesis *Ho* and the alternative hypothesis *Ha* can be stated in statistical terminology as:

Ho: $\mu 1=\mu 2=\mu 3$

versus Ha: $\mu 1\neq\mu 2\neq\mu 3$

The confidence level used was 95 percent. The Hypothesis testing *ANOVA F test* was calculated by the following formula.

$F=MSG/MSE$

Where

MSG= *the mean square for the groups*

MSE= *the mean square for error*

After finding out the ANOVA F value, the Post hoc test can be investigated. Post hoc tests are two of the ways to infer and assess the significance of the difference between one of conditions. However, there is no one standard way to do a post hoc test. There are, for examples, 18 different types of post hoc tests. There is evidence from old studies to support use of the Tukey HSD procedure. The HSD is based on the mean square for error (MSE), the total number of conditions in the study, the sample size, and a modified distribution of t statistics. Any pair of means whose difference is greater than the HSD is declared significant (Williams 2004).

5.3.3.2.2 Pavement Age

The results of the ANOVA F test indicated that there is significance in the overall test for each pavement distress as shown in Table 5.13. Consequently, Post hoc tests can be performed for each level in the pavement age factor. The results showed that for each distress Ho is rejected for young-moderate level and moderate-old level. Based on previous results, Ho is rejected for pavement age factor. Therefore the alternative hypothesis is accepted. So pavement age plays important role in pavement deterioration.

Table 5.13 ANOVA F test and Post Hoc test Results for Pavement Age-UMS

Factor									
Pavement Age									
	First Step		Second Step						Final Step
Categories	Overall (Low to High)		Young-Moderate		Moderate-Old		Young-Moderate		
Output of the Test	F-TEST		Post Hoc (Tukey HSD)		Post Hoc(Tukey HSD)		Post Hoc(Tukey HSD)		
Distress	P-value	Test Result	P-value	Test Result	P-value	Test Result	P-value	Test Result	Decision
Block Cracks	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Longitudinal & Transverse Cracking	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Patching	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Potholes	0.000	Significant	0.000	Reject Ho	0.000	Accept Ho	0.000	Reject Ho	Reject Ho
Depressionss	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Weathering & Ravelling	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Cracking (due to patching)	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho

5.3.3.2.3 Traffic

The results of the ANOVA F test as shown in Table 5.14 indicate that there is no significance in the overall test for longitudinal & transverse cracking, and for potholes. Therefore the post hoc test cannot be performed for these two pavement distress types. The post hoc test for other distress types showed mixed results, some rejecting Ho and others accepting Ho. Based on all the results, Ho is accepted for traffic factor. Therefore the alternative hypothesis is rejected**.** So traffic plays a statistically less important role in pavement deterioration according to this data set.

Table 5.14 ANOVA F test and Post Hoc test Results for Traffic-UMS

Factor									
Traffic									
	First Step		Second Step						Final Step
Categories	Overall (Low to High)		Low-Medium		Low-High		Medium-High		
Output of the Test	F-TEST		Post Hoc(Tukey HSD)		Post Hoc(Tukey HSD)		Post Hoc(Tukey HSD)		
Distress	P-value	Test Result	P-value	Test Result	P-value	Test Result	P-value	Test Result	Decision
Block Cracks	0.000	Significant	0.001	Reject Ho	0.001	Reject Ho	0.799	Accept Ho	Accept Ho
Longitudinal & Transverse Cracking	0.078	Not Significant	-	-	-	-	-	-	Accept Ho
Patching	0.002	Significant	0.033	Accept Ho	0.002	Reject Ho	0.354	Accept Ho	Accept Ho
Potholes	0.011	Not Significant	-	-	-	-	-	-	Accept Ho
Depressions	0.000	Significant	0.006	Accept Ho	0.000	Reject Ho	0.089	Accept Ho	Accept Ho
Weathering & Ravelling	0.002	Significant	0.033	Accept Ho	0.002	Reject Ho	0.341	Accept Ho	Accept Ho
Cracking (due to patching)	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.672	Accept Ho	Accept Ho

5.3.3.2.4 Drainage

Drainage factor for each distress is not significant as Ho is accepted. Accepting Ho means rejecting Ha which says there is a difference in at least one of the means. However, the results of the test indicate that there is a mean difference but the mean difference is quite low for each distress as shown in Table 5.15. Consequently this indicates drainage factor does not affect the pavement deterioration and hence the pavement distress propagation. So availability of drainage plays a statistically less important role in pavement deterioration according to this data set.

Table 5.15 Two Samples t- test Results for Drainage-UMS

Factor			
Drainage			
Categories	Drained - Not Drained		
Output of the Test	Two samples t test		
Distress	Mean Difference (%)	Test Result	Decision
Block Cracks	1.012	Not Significant	Accept Ho
Longitudinal & Transverse Cracking	0.889	Not Significant	Accept Ho
Patching	1.735	Not Significant	Accept Ho
Potholes	0.359	Not Significant	Accept Ho
Depressions	-0.480	Not Significant	Accept Ho
Weathering & Ravelling	1.823	Not Significant	Accept Ho
Cracking (due to patching)	0.493	Not Significant	Accept Ho

5.3.3.2.5 Parametric Test Conclusions

Parametric tests are more powerful than nonparametric tests provided they meet the condition which is basically normality of the data and equality in the variances. Assuming both conditions were met, pavement age is the only factor that has significance in the prediction of pavement deterioration and distress behaviour in this study. Both parametric and nonparametric tests showed the same result which is basically that the pavement age factor is significant, traffic and drainage factors are not.

5.3.4 Inductive Statistics Conclusions

Inferences from normality tests, parametric tests, and nonparametric tests showed that the data are not normally distributed and the pavement age factor is the only factor that shows significance.

5.4 Urban Main Roads Database Analysis Conclusions

First part in this chapter is the urban main roads database. Based on numerical summaries, scatter plots, normality tests, descriptive tests, and inductive tests, the following points can be concluded:

- The variation in the data is noticeable,
- Data are not normal,
- Nonlinearity is clear more than linearity
- Among the three factors pavement age, traffic, and drainage, only pavement age affects the prediction models. However, in the modelling process this point will be investigated further.

5.5 Urban Secondary Roads

In Riyadh city, the secondary roads are less than 30 meters in width in both directions with an island in the middle (RRM 2007). They represent 65 % of the total network. A total of 228 regions (secondary overlaid pavement sections) were found to be applicable for the study constraints as explained in the chapter of methodology.

5.6 Descriptive Statistics for Urban Secondary Roads

As discussed in section 5.2, descriptive statistics (Keller 2009) deals with methods of organizing, summarizing, and presenting data in a convenient and informative way. Inductive statistics (Keller 2009) deals with conclusions or inferences about characteristics of populations based on sample data. Examples of descriptive statistics are measures of central tendency, dispersion, scatter plots and association

5.6.1 Background

The pavement management system unit in Riyadh Municipality has a huge data base containing the data for secondary roads. As discussed in the chapter on database, a specific database was developed for this study in a systematic and coherent way that included information (KACST 1998, RRM 2007, RRM 1998a, RRM 1998b, RRM 1998c, and RRM 1998d) on pavement characteristics, pavement distress data, and pavement maintenance data. Pavement characteristics data included information on pavement class, pavement type, pavement age, and availability of a drainage system. Pavement distress data included information on distress type, severity, extent and location.

Six common distress types (Mubaraki and Thom 2008) were considered as they are occurring most frequently, namely; block cracks, longitudinal and transverse cracking, patching, potholes, depressionss, and weathering and ravelling. Pavement maintenance data included information about what type of maintenance strategy has been applied on the pavements and the maintenance date. Numerical summaries and graphs are presented to describe the content of the database.

5.6.2 Numerical Summaries

5.6.2.1 Background

It can be seen in the chapter on database and in section 5.5 from this chapter; the summary data base for main roads data has a sample size of 641 reading points, representing the distress density values for each of the six different types of pavement distress. The pavement distress density value is the response variable. Pavement age and drainage are explanatory variables that explain or influence changes in the response variable.

They are incorporated as records into the data base with pavement distress density values. Therefore, the descriptive statistics summaries of the response variable under the explanatory variables are described in the following Tables.

5.6.2.2 Pavement Age

Pavement age was defined as the number of years since construction or the last major maintenance. The pavement section ages were grouped into three categories or three levels. These categories or levels were young (1 to 2 years), moderate sections (2 to 5 years), and old sections (greater than 5 years). As discussed in 5.2.2.2 from this chapter, the sample size, the minimum and maximum, the mean, the standard deviation, the variance, the kurtosis, and the skewness are reported for the three groups as shown in Table 5.16 for Urban Secondary Sections (USS).

General observations from the Table can show that the pavement distress density varies between distress types. The data are skewed to the right for all types of distress. Therefore we can say that the variation is present and the data are not normally distributed for each level under study.

Table 5.16 Descriptive Statistic Results for Pavement Age at Different Levels-USS

Factor							
Pavement Age							
Levels	Statistic	Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.
Young Sections	Sample size	420	420	420	420	420	420
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	25.00	20.00	41.00	16.00	15.00	51.00
	Mean	0.63	0.90	3.19	0.30	0.38	2.03
	Std. Deviation	2.29	2.25	6.19	1.27	1.44	6.00
	Variance	5.25	5.05	38.29	1.61	2.07	36
	Kurtosis	49.62	22.07	8.25	70.94	53.51	25.48
	Skewness	6.27	4.08	2.61	7.25	6.67	4.68
Moderate Sections	Sample size	143	143	143	143	143	143
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	29.00	20.00	58.00	14.00	10.00	45.00
	Mean	3.14	4.69	13.93	1.95	1.07	8.02
	Std. Deviation	5.29	4.40	11.94	3.47	1.75	8.28
	Variance	27.94	19.36	142.64	12.00	3.05	68.61
	Kurtosis	8.73	2.05	1.93	2.36	9.05	3.74
	Skewness	0.83	0.97	-0.29	0.50	1.79	0.55
Old Sections	Sample size	78	78	78	78	78	78
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	27.00	33.00	63.00	16.00	21.00	51.00
	Mean	8.25	10.64	26.16	5.98	3.60	14.84
	Std. Deviation	6.17	6.17	14.16	5.07	4.40	11.93
	Variance	38.12	38.10	200.70	25.65	19.34	142.26
	Kurtosis	0.11	1.61	-0.59	-1.53	2.96	1.42
	Skewness	.72	1.01	0.479	0.059	1.69	1.34

5.6.2.3 Drainage

Drainage factor was defined as whether the section has a drainage system or not. The drainage sections were grouped into categories or two levels. These categories or levels drained sections and not drained sections. General observations from Table 5.17 can chow that the pavement distress density varies between distress types on USS. Table 5.18 shows a summary for all the three factors on USS.

Table 5.17 Descriptive Statistics Results for Drainage at Different Levels-USS

Factor							
Drainage							
Levels	Statistic	Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.
Drained Sections	Sample size	602	602	602	602	602	602
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	77.95	61.58	92.94	42.20	51.28	87.37
	Mean	6.82	4.00	12.47	3.33	4.46	8.91
	Std. Deviation	10.22	8.01	17.47	7.34	8.49	15.34
	Variance	104.36	64.10	305.36	53.94	72.05	235.21
	Kurtosis	4.08	16.69	1.03	5.40	6.30	4.91
	Skewness	1.72	3.59	1.31	2.42	2.43	2.20
Not Drained Sections	Sample size	439	439	439	439	439	439
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	29.00	33.00	63.00	16.00	21.00	51.00
	Mean	2.12	2.93	8.38	1.36	0.92	4.93
	Std. Deviation	4.73	4.86	12.62	3.40	2.43	8.94
	Variance	22.34	23.64	159.31	11.59	5.94	79.88
	Kurtosis	9.35	5.98	2.70	4.71	22.73	6.81
	Skewness	2.92	2.43	1.73	2.42	4.31	2.44

Table 5.18 Descriptive Statistics Summary Results for all the Data-USS

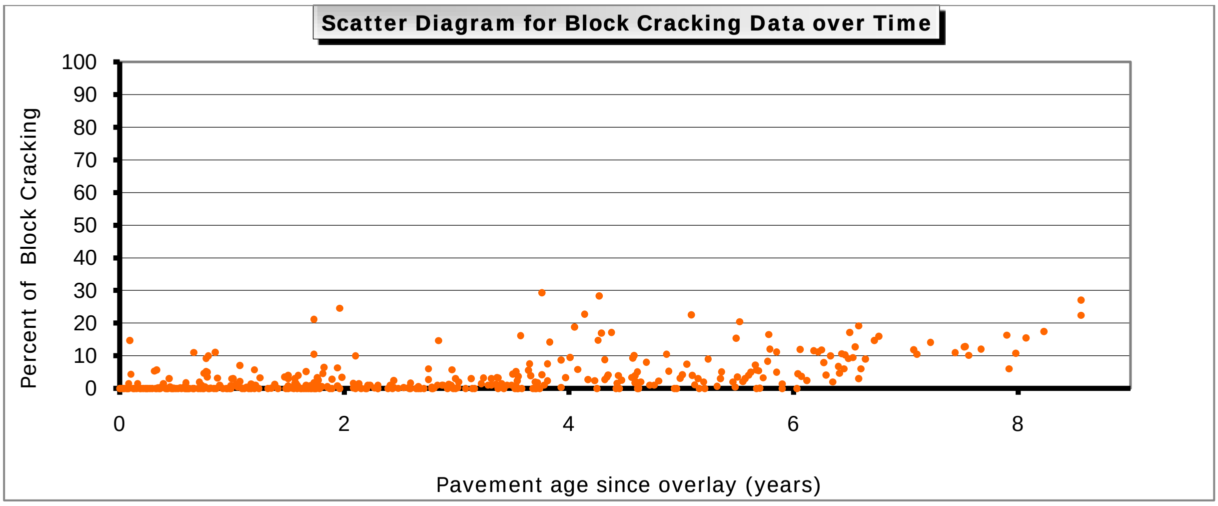
Factors							
Pavement age, Traffic, Drainage							
Levels	Statistic	Block Cracks	Long. & Trans.	Patching	Potholes	Depressions	Weat. & Rave.
All Mixed	Sample size	641	641	641	641	641	641
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00
	Maximum	29.00	33.00	63.00	16.00	21.00	51.00
	Mean	2.12	2.93	8.38	1.36	0.92	4.93
	Std. Deviation	4.53	4.78	12.00	3.20	2.33	8.70
	Variance	20.53	22.82	143.99	10.25	5.44	75.53
	Kurtosis	9.67	5.97	3.16	5.57	20.78	7.65
	Skewness	2.96	2.27	1.82	2.56	4.12	2.60

5.6.3 Scatter Plots

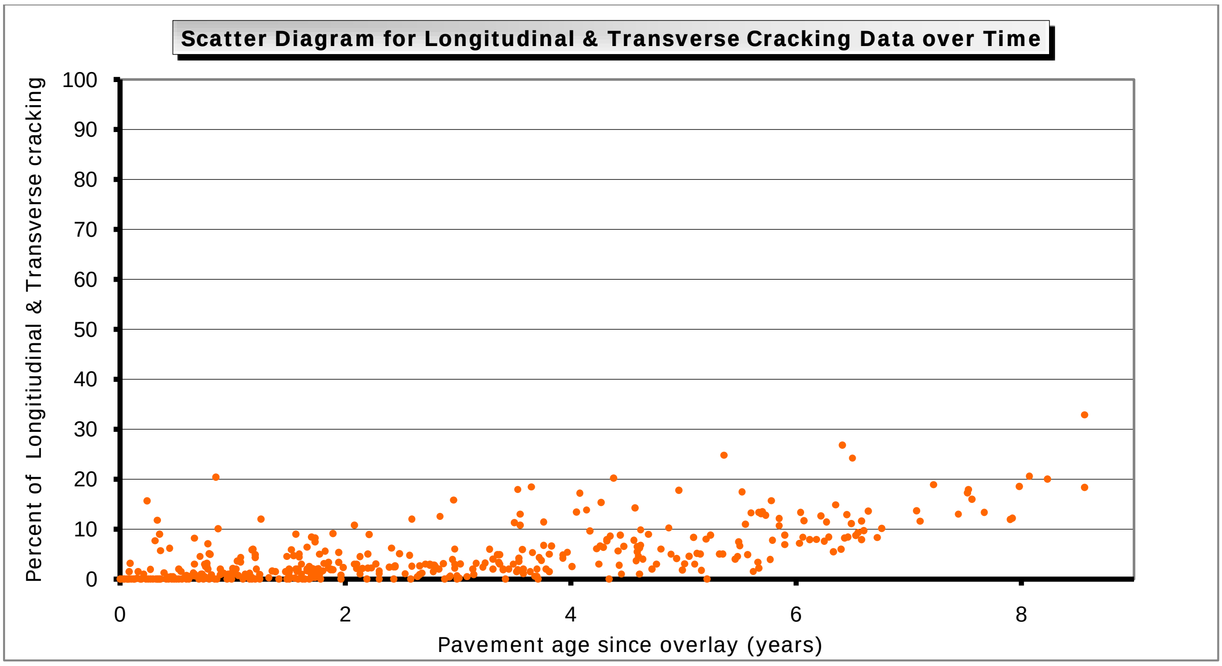
As discussed in 5.2.3 from this chapter, the scatter diagrams for distress types will be presented in the following two subsections. The first scatter diagrams for pavement age factor. The second scatter diagrams for drainage factor.

5.6.3.1 Scatter Plots for Pavement Age

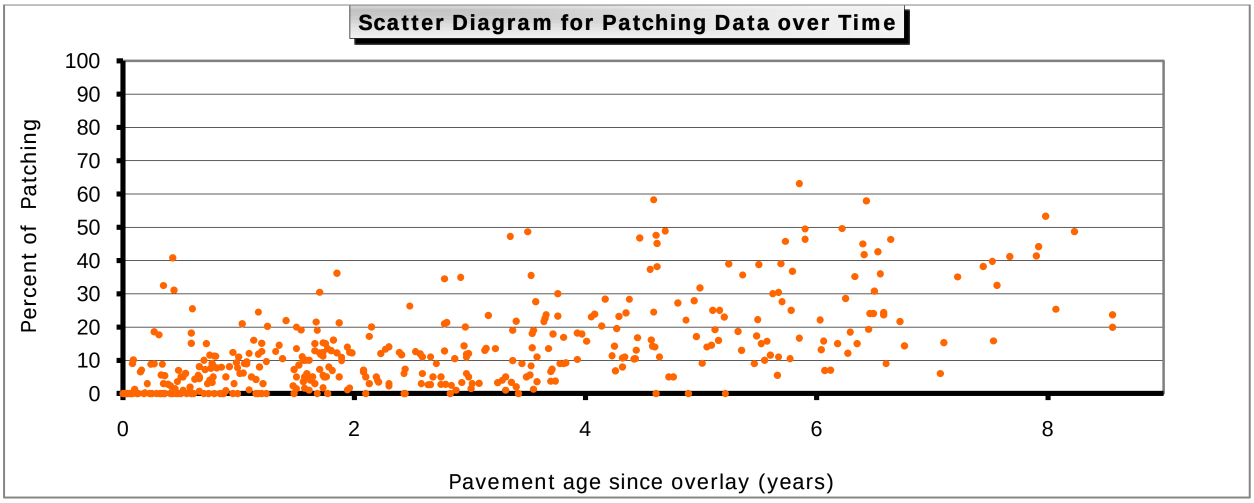
Most of the points appear to be scattered randomly and the variation increases with time for all types of pavement distress on USS as shown in Figure 5.7 (a-f). Therefore the relation is a weak linear relationship and positive linear relationship between the pavement distress density and pavement age. To conclude, the scatter diagrams depict nonlinearity.



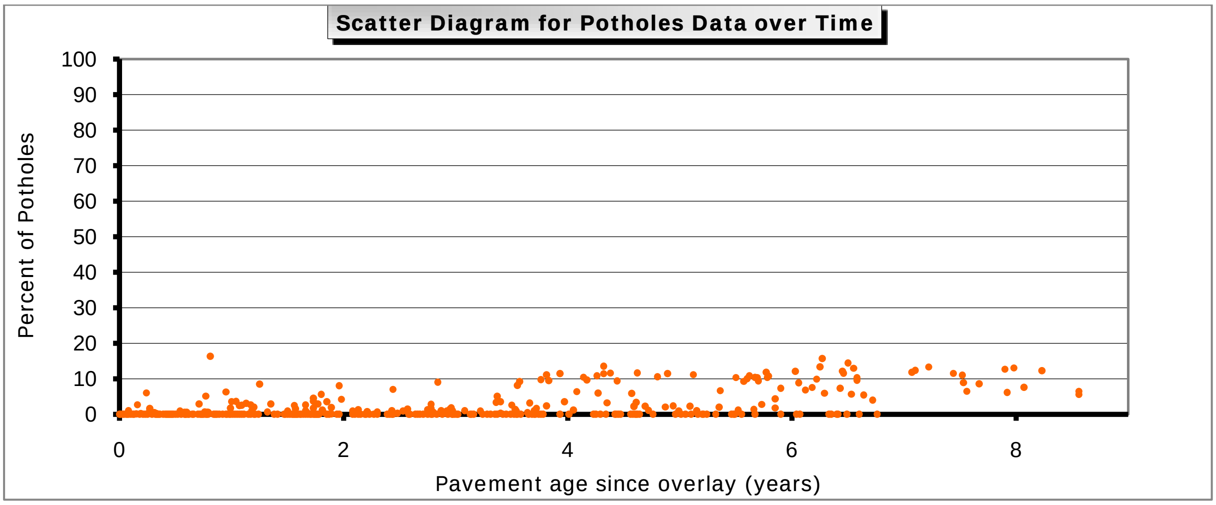
(a)



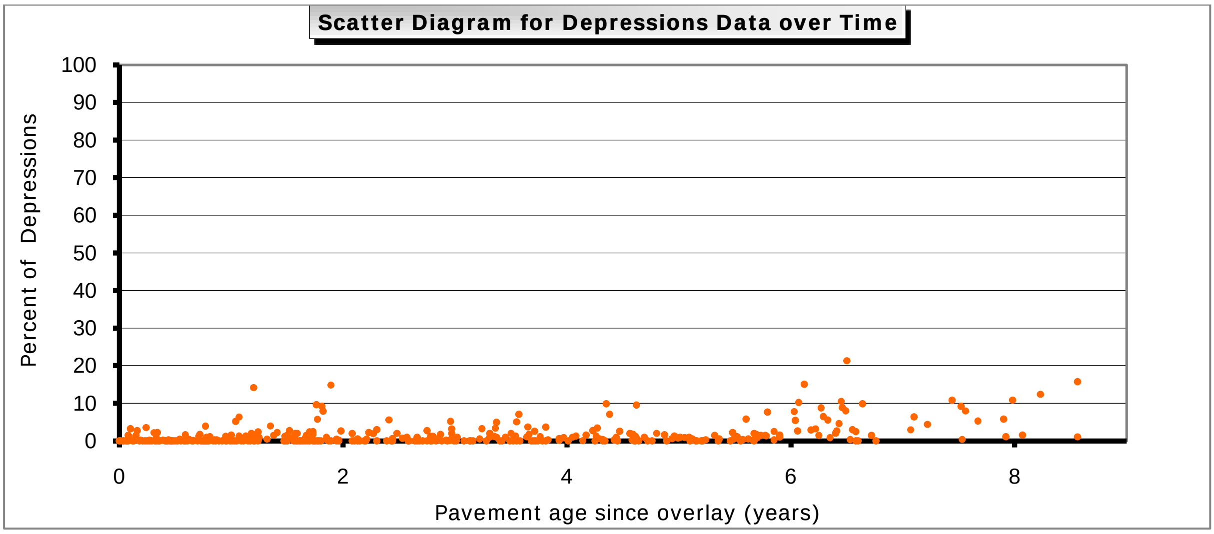
(b)


Scatter Diagram for Patching Data over Time
Percent of Patching
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
Pavement age since overlay (years)

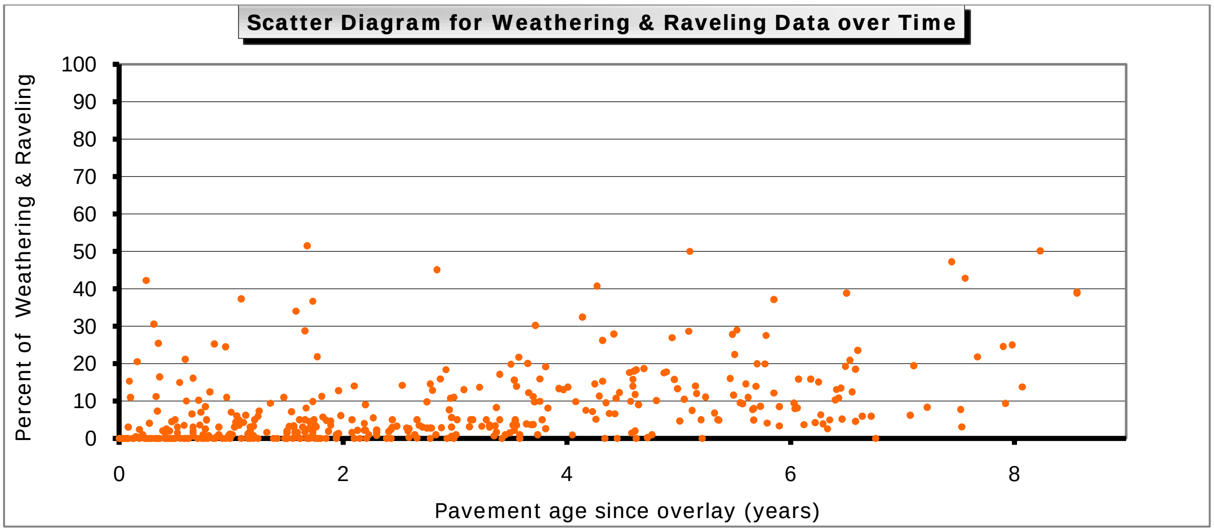
(c)


Scatter Diagram for Potholes Data over Time
Percent of Potholes
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
Pavement age since overlay (years)

(d)


Scatter Diagram for Depressions Data over Time
Percent of Depressions
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
Pavement age since overlay (years)

(e)

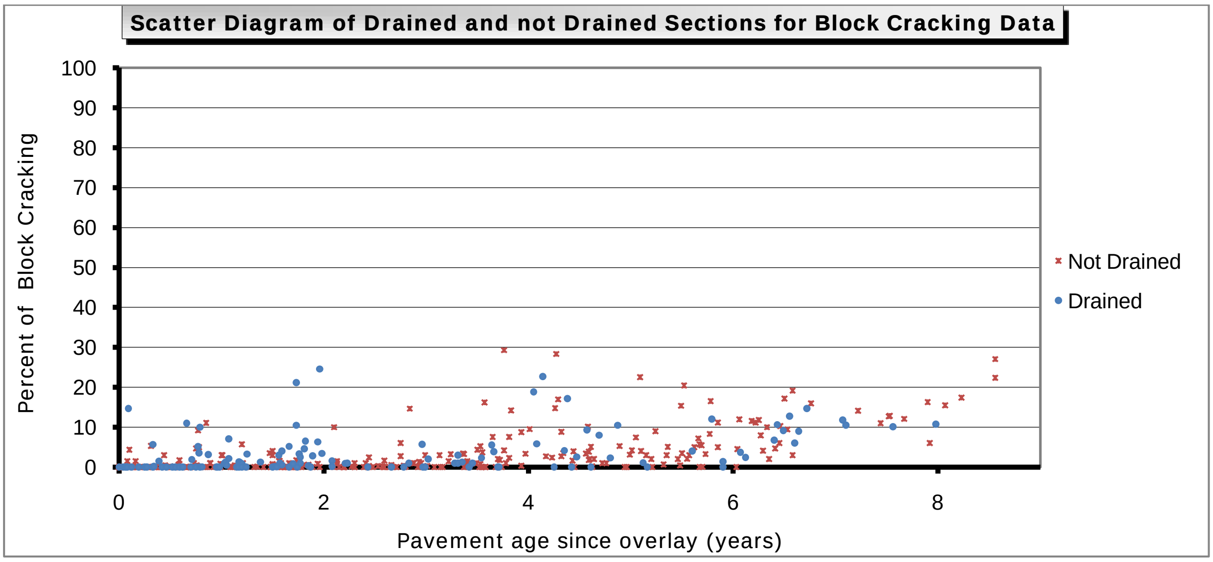


(f)

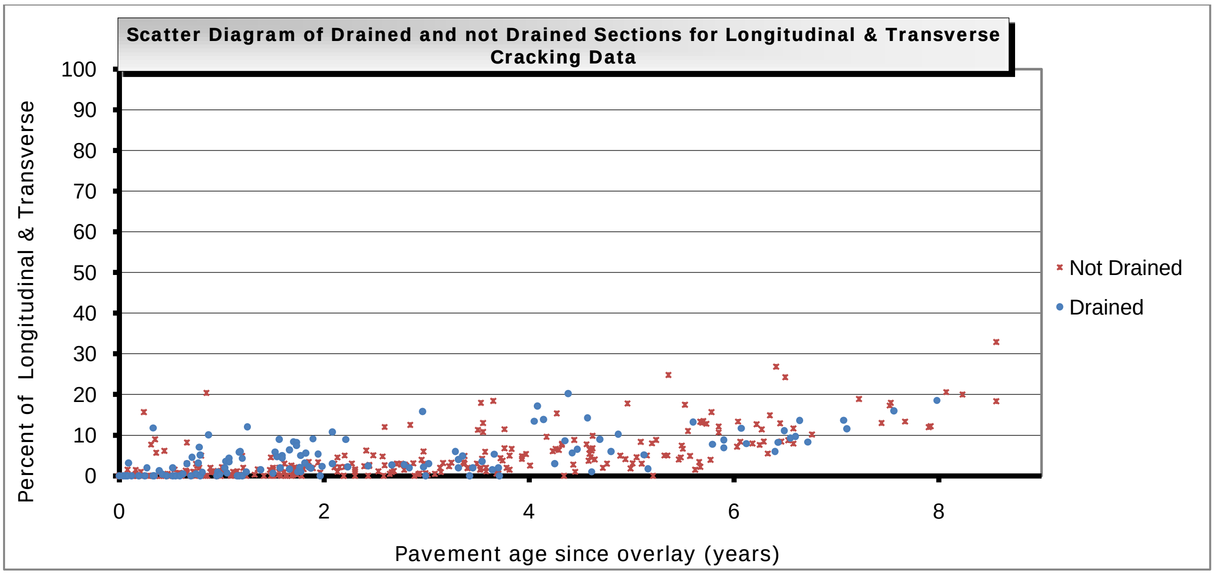
Figure 5.7 Scatter Plots for Pavement Age (USS) for (a) Block cracks, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Ravelling.

5.6.3.2 Scatter Plots for Drainage

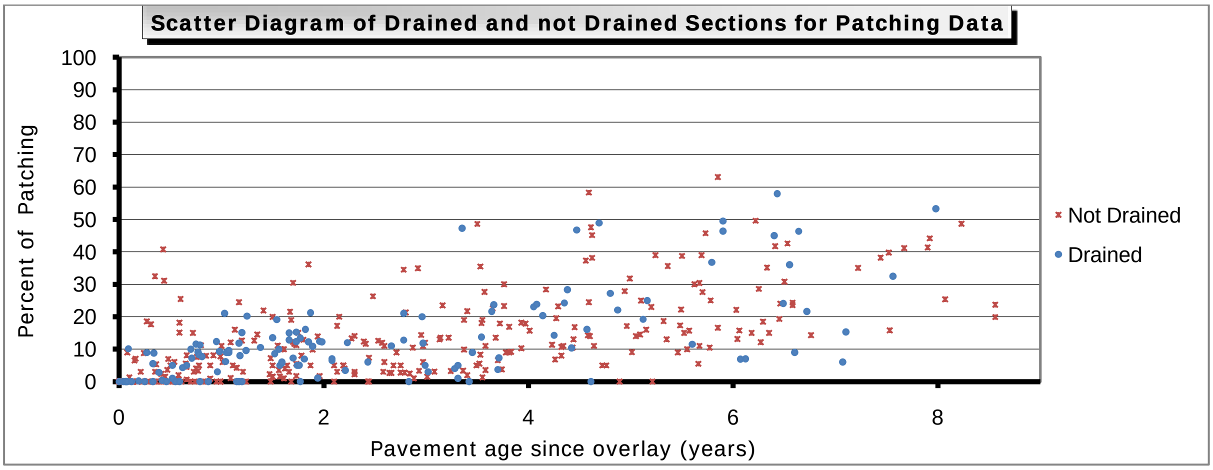
Most of the points are mixed together for all types of pavement distress on USS as shown in Figure 5.8 (a-f). Therefore, different drainage levels may not affect pavement deterioration rate. However, the inductive analysis will support these observations.



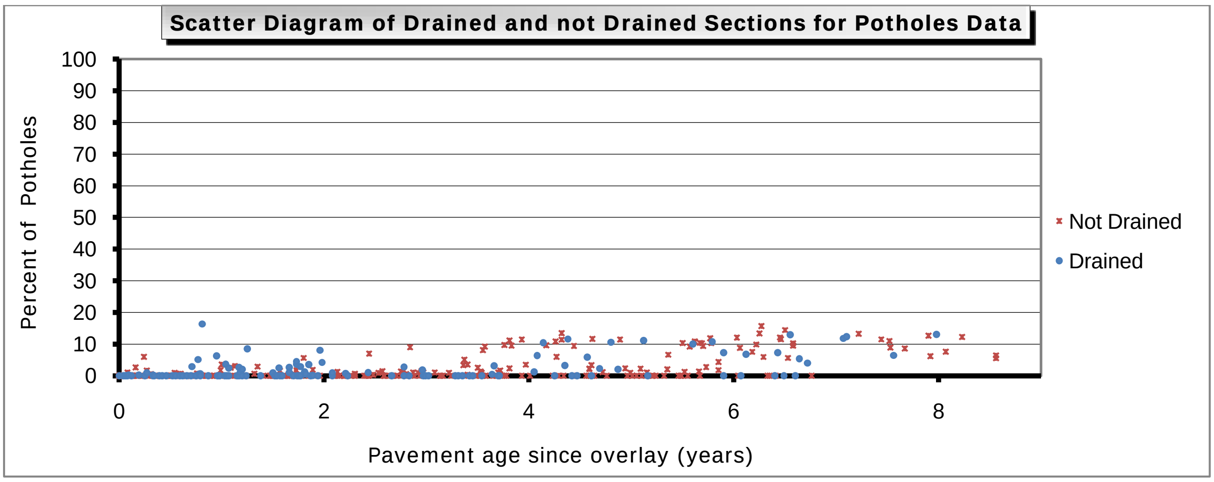
(a)


Scatter Diagram of Drained and not Drained Sections for Longitudinal & Transverse Cracking Data
Percent of Longitudinal & Transverse
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
Pavement age since overlay (years)
Not Drained
Drained

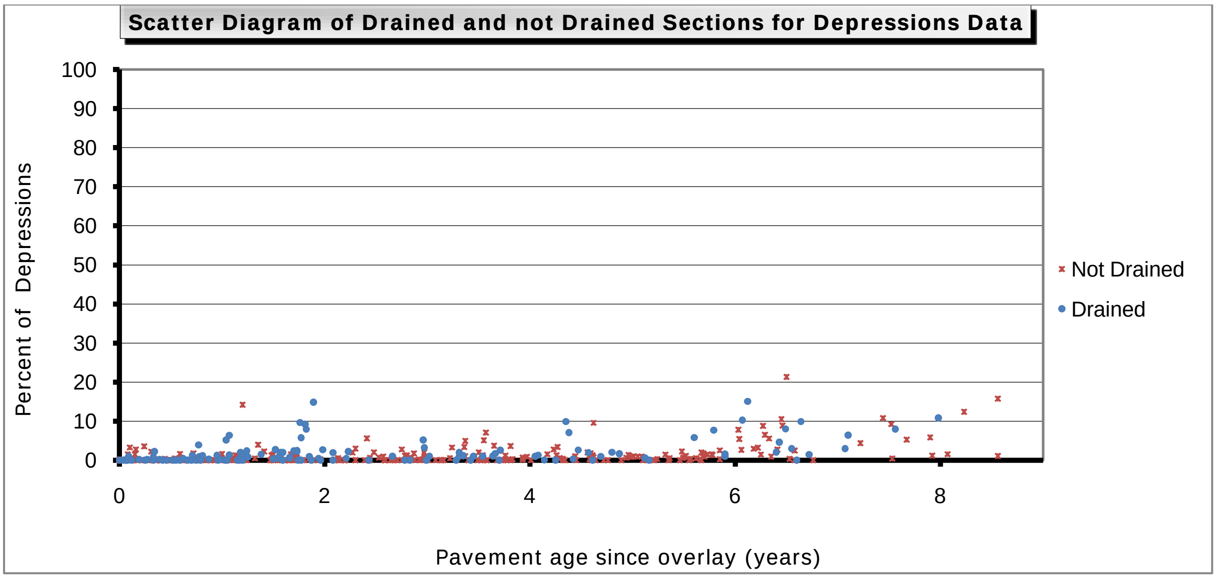
(b)


Scatter Diagram of Drained and not Drained Sections for Patching Data
Percent of Patching
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
Pavement age since overlay (years)
Not Drained
Drained

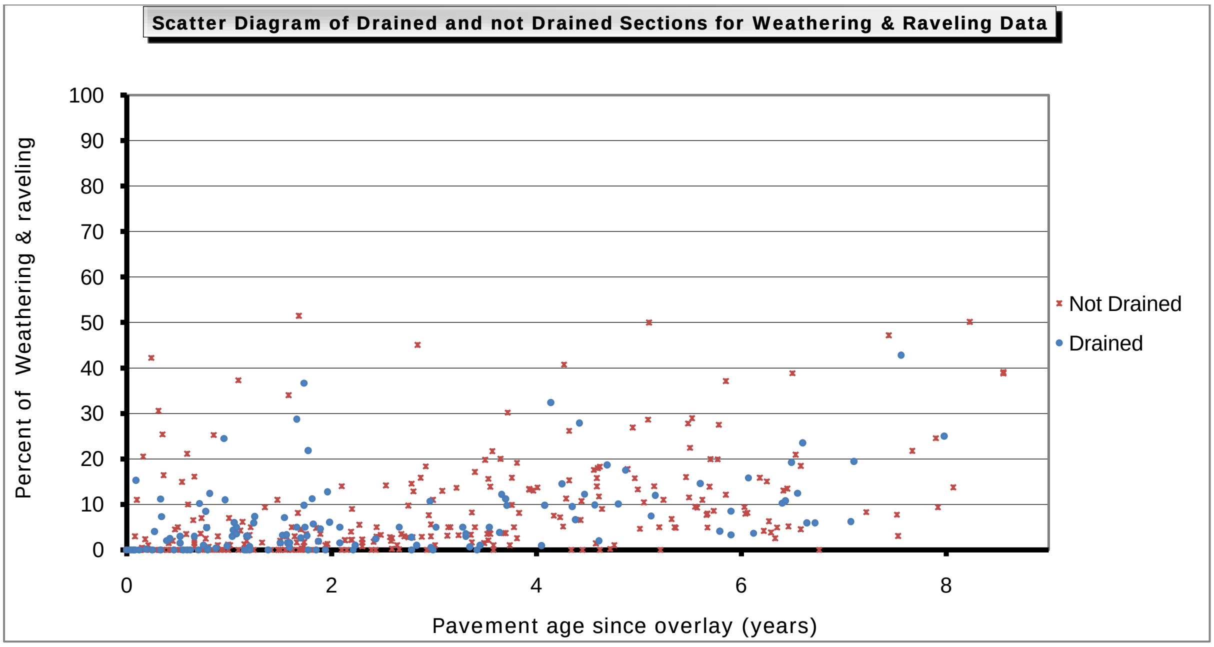
(c)


Scatter Diagram of Drained and not Drained Sections for Potholes Data
Percent of Potholes
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
Pavement age since overlay (years)
Not Drained
Drained

(d)



(e)



(f)

Figure 5.8 Scatter Plots for Darainage (USS) for (a) Block cracks, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Revelling.

5.6.4 Descriptive Statistics Conclusions for Secondary Roads

The numerical summaries reveal that the pavement distress density values for all types of distress under study show variation in distribution. Drainage shows more variation and dispersion. The data are not normal. The scatter diagrams revel that most points of different levels for different factors are mixed together randomly and nonlinearity is present.

5.7 Inductive Statistics for Urban Secondary Roads

As mentioned before, inductive statistics deals (Keller 2009) with conclusions or inferences about characteristics of populations based on sample data. The inductive statistics depends (Walpole et al. 2001) on probability and they include statistical assumptions, statistical decision theory, estimation theory, statistical hypotheses testing, design of experiments, analysis of variance, and others.

5.7.1 Significant Factors Affecting Pavement Deterioration

The selection of independent variables for the prediction equation is based on experience suggesting that the prediction of pavement condition depends on the following factors: pavement age, and availability of a drainage system. Therefore, in this study, pavement deterioration recognizes two factors in defining distress propagation. However, the two factors will be subjected to tests of significance to determine the significant factors for distress models.

As a basic principle, the form of the model is selected based on the boundary conditions and/or other variables that govern the deterioration of the pavements.

5.7.2 Experimental Design-USS

As discussed before, a total of 228 regions (secondary overlaid pavement sections) were found to be applicable for the study constraints. 641 observations on all selected pavement sections for each distress type were used to study the significant factors.

The layout of the experimental design along for USS with data included in the study is presented in Table 5.19. Experimental design of the study shows that the study is a multifactor experimental design. The independent variables are pavement age, traffic levels, and availability of drainage system. These independent variables are called factors. Each single factor has different categories. Table 5.2 shows a summary of the factors and the levels for USS.

Table 5.19 Experimental Design-USS

						Number of observations on the selected sections for each distress	
						With Drainage System	Without Drainage System
Maintenance Type	**Overlay**	Pavement Age	**Young Sections**	420	641	202	439
			Moderate Sections	143			
			Old Sections	78			

Table 5.20 Factors and Levels-USS

Classification of Variables	
Factors	Levels
Pavement Age	Young Moderate Old
Drainage	With drainage Without drainage

5.7.2.1 Pavement Age

It is known that pavement age is one of the most important variables that affect distress propagation. Pavement age is measured from the date of construction or from the date of the last major maintenance. However, only last major maintenance sections were considered in this study due to lack of construction date data. Urban secondary roads sections were grouped into three categories as follows: young (0 to 2 years), moderate (2 to 5 years), and old (>5 years). The average distress density values of each distress within each group for USS are shown in Figures 5.9 (a-g). As expected, all distress types tend to increase with time. However, this increase is relatively varied between distress types. More details will be presented using suitable statistical tests.

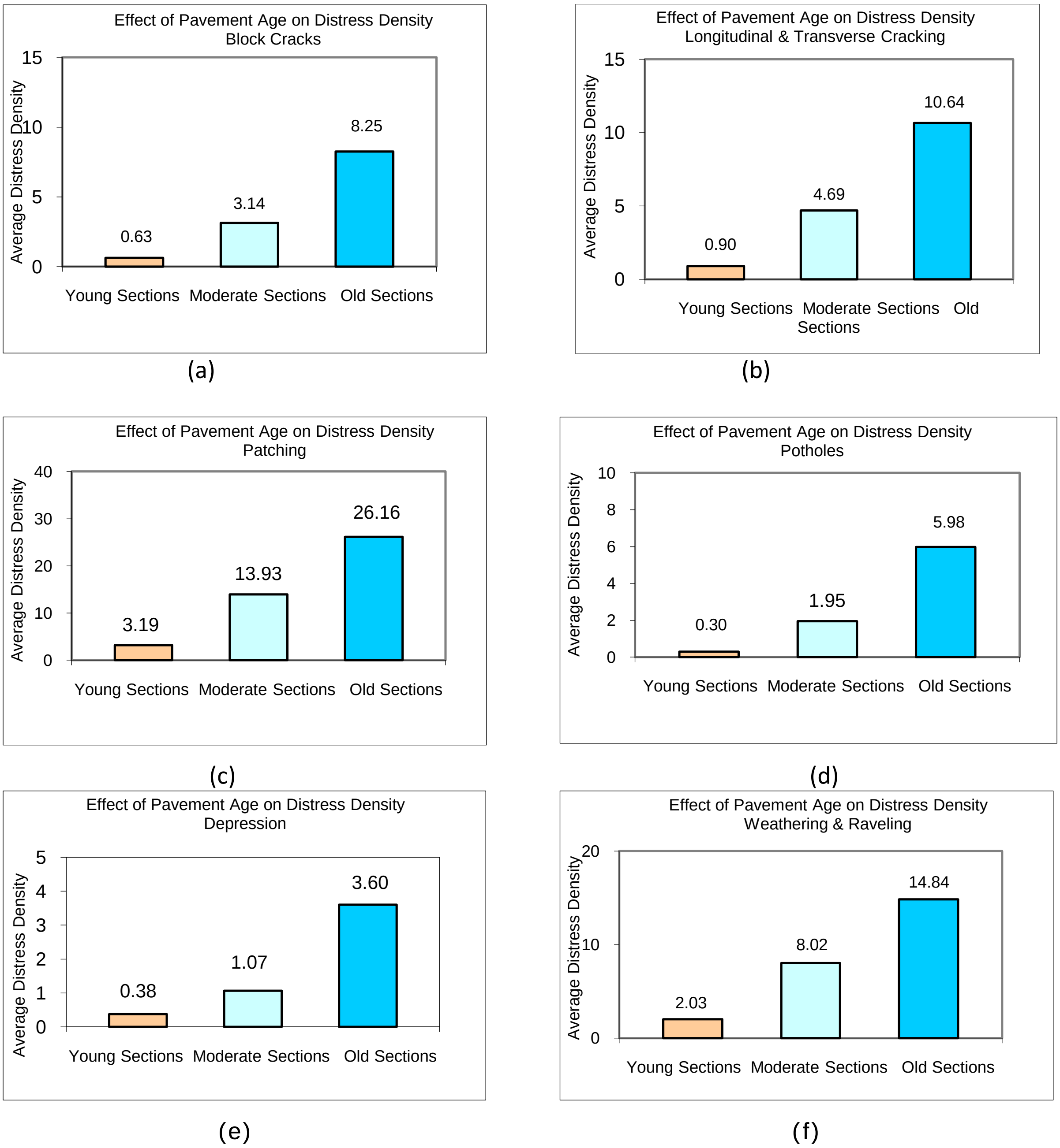


Figure 5.9 Effect of Pavement Age (USS) on (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Ravelling.

5.7.2.2 Drainage

The availability of a drainage system can affect distress propagation. Therefore, pavement sections were grouped into those sections with a drainage system and those sections without a drainage system. It was expected that distress on drained sections would propagate less than distress on not drained sections. However, Figure 5.10(a-f) shows very small differences in average values of distress density between drained and not drained sections.

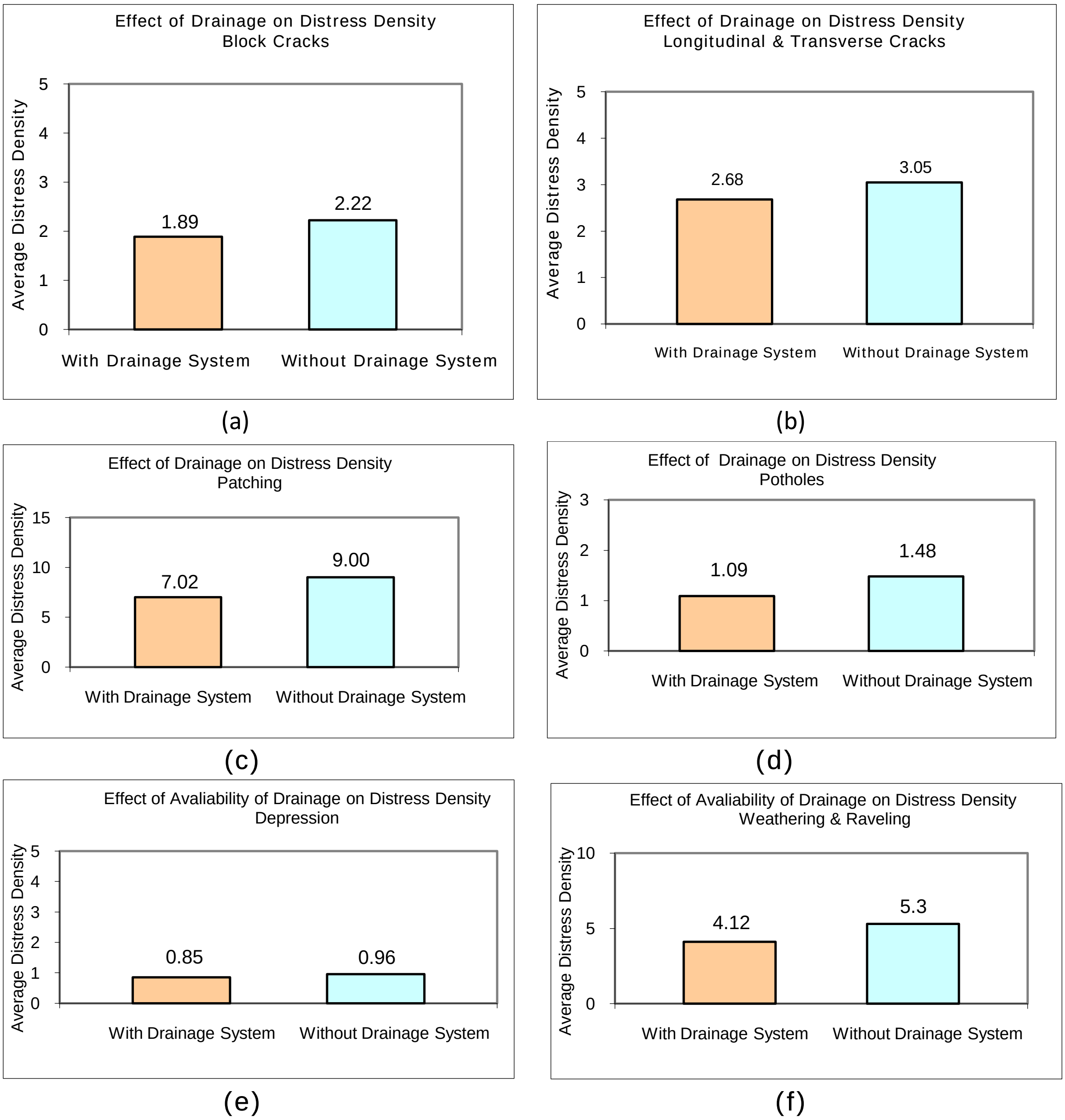


Figure 5.10 Effect of Drainage (USS) on (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Revelling.

5.7.2.3 Normality Test

As discussed in 5.3.2.4, the following Tables 5.21 and 5.22 show the result of normality test for pavement age and drainage factors on USS respectively. Normality tests show that all six distress types are skewed to the right and the sample variances are not equal. The data violate the required conditions to use parametric test like the two sample test and analysis of variance. Therefore, non parametric tests were performed to determine which variables are significant in the prediction of each distress type.

Table 5.21 Results of Normality Test for Pavement Age-USS

Factor							
Pavement Age							
Levels	Statistic	Types of Distress					
		Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.
Young Sections	K-S	0.408	0.363	0.361	0.470	0.418	0.368
	P-value	0.000	0.000	0.000	0.000	0.000	0.000
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Moderate Sections	K-S	0.276	0.143	0.143	0.286	0.270	0.182
	P-value	0.000	0.000	0.000	0.001	0.000	0.000
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Old Sections	K-S	0.116	0.112	0.112	0.176	0.224	0.169
	P-value	0.011	0.008	0.016	0.001	0.000	0.000
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

Table 5.22 Results of Normality Test for Drainage-USS

Factor							
Drainage							
Levels	Statistic	Types of Distress					
		Block Cracks	Long.& Trans.	Patching	Potholes	Depressions	Weat.& Rave.
Drained Sections	K-S	0.320	0.265	0.280	0.398	0.347	0.277
	P-value	0.000	0.000	0.000	0.000	0.000	0.000
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho
Not Drained Sections	K-S	0.320	0.280	0.238	0.401	0.351	0.305
	P-value	0.000	0.000	0.000	0.000	0.000	0.000
	Decision	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho	Reject Ho

5.7.3 Test of Significance

5.7.3.1 Nonparametric Tests

5.7.3.1.1 Pavement Age

As discussed in 5.3.3.1.2 from this chapter, pavement age plays important role in pavement deterioration for secondary roads. Table 5.23 shows the result for USS.

Table 5.23 Kruskal-Wallis H-test and Mann-Whitney U test Results for Pavement Age -USS

_Factor							
Pavement age							
	First Step		Second Step				Final Step
Categories	Overall (Young to old)		Young-Moderate		Moderate-Old		
Output of the Test	K-W		M-W		M-W		
Distress	P-value	Test Result	P-value	Test Result	P-value	Test Result	Decision
Block Cracks	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Longitudinal & Transverse Cracking	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Patching	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Potholes	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Depressions	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Weathering & Ravelling	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Cracking (due to patching)	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	Reject Ho

5.7.3.1.2 Drainage

As discussed in 5.3.3.1.4 from this chapter, drainage plays statistically less important role in pavement deterioration for secondary roads. Table 5.24 shows the result.

Table 5.24 Mann-Whitney U test results for Drainage-USS

Factor			
Drainage			
Categories	Drained - Not Drained		
Output of the Test	M-W		
Distress	P-value	Test Result	Decision
Block Cracks	0.636	Not Significant	Accept Ho
Longitudinal & Transverse Cracking	0.236	Not Significant	Accept Ho
Patching	0.125	Not Significant	Accept Ho
Potholes	0.565	Not Significant	Accept Ho
Depressions	0.208	Not Significant	Accept Ho
Weathering & Ravelling	0.100	Not Significant	Accept Ho

5.7.3.1.3 Nonparametric Test conclusions

It can be concluded that pavement age is the only factor that has significance in the prediction of pavement deterioration and distress behaviour. However, the effect of the other factor, drainage, will be tested again in the modelling process.

5.7.3.2 Parametric Tests

5.7.3.2.1 Pavement Age

As discussed in 5.3.3.2.2 from this chapter, the results of the ANOVA F test indicated that there is significance in the overall test for each pavement distress as shown in Table 5.25. Consequently, Post hoc test can be performed for each level in the pavement age factor. The results showed that for each distress Ho is rejected for young-moderate level and moderate-old level. Based on previous results, Ho is rejected for pavement age factor. Therefore the alternative hypothesis is accepted. So pavement age plays an important role in pavement deterioration.

Table 5.25 ANOVA F test and Post Hoc test Results for Pavement Age-USS

Factor									
Pavement Age									
	First Step		Second Step						Final Step
Categories	Overall (Low to High)		Young-Moderate		Moderate-Old		Young-Moderate		
Output of the Test	F-TEST		Post Hoc (Tukey HSD)		Post Hoc(Tukey HSD)		Post Hoc(Tukey HSD)		
Distress	P-value	Test Result	P-value	Test Result	P-value	Test Result	P-value	Test Result	Decision
Block Cracks	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Longitudinal & Transverse Cracking	0.000	Significant	0.000	Reject Ho	0.000	Accept Ho	0.000	Reject Ho	Reject Ho
Patching	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Potholes	0.000	Significant	0.000	Reject Ho	0.000	Accept Ho	0.000	Reject Ho	Reject Ho
Depressions	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho
Weathering & Ravelling	0.000	Significant	0.000	Reject Ho	0.000	Reject Ho	0.000	Reject Ho	Reject Ho

5.7.3.2.2 Drainage

As discussed in 5.3.3.2.4 from this chapter, drainage factor for each distress is not significant as Ho is accepted. Accepting Ho means rejecting Ha which says there is a difference at least one of the means is different. However, the results of the test indicate that there is mean difference but the mean difference is quite low for each distress as shown in Table 5.26. Consequently this indicates that drainage factor does not affect the pavement deterioration and hence the pavement distress propagation. So availability of drainage does not play an important role in pavement deterioration like the role of pavements age in pavement deterioration.

Table 5.26 Two Samples t- test Results for Drainage-USS

Factor			
Drainage			
Categories	Drained - Not Drained		
Output of the Test	Two samples t test		
Distress	Mean Difference (%)	Test Result	Decision
Block Cracks	0.322	Not Significant	Accept Ho
Longitudinal & Transverse Cracking	0.372	Not Significant	Accept Ho
Patching	1.977	Not Significant	Accept Ho
Potholes	0.272	Not Significant	Accept Ho
Depressions	0.198	Not Significant	Accept Ho
Weathering & Ravelling	0.738	Not Significant	Accept Ho

5.7.3.2.3 Parametric Test Conclusions

Parametric tests are more powerful than nonparametric tests provided they meet the condition which is basically normality of the data and equal in the variances. Assuming both conditions were met, pavement age is the only factor that has significance in the prediction of pavement deterioration and distress behavior. Both parametric and nonparametric tests showed same result which is basically the pavement age factor is significant, and drainage factor is not.

5.7.3.2.4 Inductive Statistics Conclusions

Inferences from normality tests, parametric tests, and nonparametric tests showed that the data are not normally distributed and the pavement age factor is the only factor that shows significance.

5.8 Urban Secondary Roads Database Analysis Conclusions

The Second part in this chapter is the urban secondary roads database. Based on numerical summaries, scatter plots, normality tests, descriptive tests, and inductive tests, the following points can be concluded:

- The variation in the data is noticeable,
- Data are not normal,
- Nonlinearity is clear more than linearity

- Two factors, pavement age and drainage are available. However, only pavement age has major affects on the prediction models. However, in the modelling process this point will investigated more.

5.9 Summary

The analysis of urban main and secondary roads database shows that the variation in the data is noticeable, data are not normal, and nonlinearity is clear more than linearity. The pavement age has major affects on the prediction models while the traffic and drainage play statistically less important role in pavement deterioration.

The main objective of this study will be investigated in details in the next chapter. The main objective of this study is to model the pavement distress types, taking in consideration the results of this chapter, for Saudi Arabia Urban Roads Network (SAURN).

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CHAPTER SIX
PAVEMENT DISTRESS MODELS

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CHAPTER SIX
PAVEMENT DISTRESS MODELS

This chapter contains introduction about statistical modelling, the major stages in statistical modelling, and sources of uncertainty in modelling. Also this chapter highlights the boundary conditions, nonlinear regression modelling, and modelling process for urban main roads, and urban secondary roads.

6.1 Statistical Modelling

Statistical modelling is a description of the total variation in one quantity y given by a mathematical function of one or more other quantities x and a random error that follows a particular probability distribution (Gilchrist 1984). There are three main parts to every statistical model; the response variable, usually denoted by y, the mathematical function, usually denoted as f (x), and random errors, usually denoted by e. This error makes the relationship between the response variable and the predictor variables a "statistical" one, rather than a perfect deterministic one. This is because the functional relationship between the response and predictors holds only on average, not for each data point (Lee et al. 1993, and Tarter 2000).

If we consider the general form for modelling, it can be expressed in the following form $y=f(x;\beta) + e$, where the response variable, y, is a quantity that varies in a way that it can be calculated in order to summarise and exploit via the modelling process. The predictor variables (x), and the parameters (β) are combined in different forms to give the function. The random errors are unknown. They are simply the difference between the data and the mathematical function. They are assumed to follow a particular probability distribution.

Process models are used for four main purposes; estimation, prediction, calibration, and optimization. The goal of estimation is to determine the values of the function. The goal of prediction is to determine the value of a new observation of the response variable. The goal of calibration is to quantitatively relate measurements made using one measurement system to those of another measurement system. The goal of Optimization is to determine the values of process inputs that should be used to obtain the desired process output (Gilchrist 1984, and Peter et al. 1995).

One of the powerful methods in modelling is regression methods. Regression methods have become an integral component of any data analysis associated or concerned with describing the relationship between a response variable and one or more explanatory variables (Hosmer and Lemeshow 1989). In fact regression analysis may be the most widely used statistical technique (Montgomery and Peck 1982).

Generally regression analysis estimates the dependent variable given the independent variables. The estimation target is a function of the independent variables called the regression function. More specifically, regression analysis helps to understand how the typical value of the dependent variable changes when any one of the independent variables is varied. Important objectives of regression analysis are to fit the model to the data and model adequacy checking. The quality of the fit is investigated, leading either to modification of the model or the fit or to adoption of the model (Montgomery and Peck 1982).

Regression models are used for several purposes, including data description, parameter estimation, prediction and estimation, control, to understand which among the independent variables are related to the dependent variable, to infer in some causes causal relationship between the independent and dependent variables, and to explore the forms of these relationships (Tarter 2000).

Regression analysis depends to some extent on making assumptions about this process (Arther 1968, Erlando and Chunhua 1994, and Gilchrist 1984). The classical assumptions for regression usage include: the sample must be representative of the population for the inference prediction, and the error is assumed to be a random variable with a mean of zero conditional on the explanatory variables.

The most popular and well-established statistical techniques that are useful for different model building situations are; linear least square regression, nonlinear least square regression, weighted least square regression, and LOESS (Ryan 1997). However, a brief discussing for linear and nonlinear regression is presented.

Linear regression models are one in which the parameters appear linearly, whereas nonlinear regression models have at least one parameter appearing nonlinearity. Nonlinear regression models differ greatly in their estimation properties from linear regression models. Linear models give rise to unbiased, normally distributed, minimum variance estimators. Nonlinear models tend to do so when the sample size becomes large.

In nonlinear regression models the predicted values of y will be biased, the extent of the bias depending upon a quantity known as the intrinsic nonlinearity of the model and data set combination. Furthermore, interpretation of parameter estimates involves an additional quantity known as the parameter effects nonlinearity (George et al. 1989, and Ratkowsky 1983). Therefore, for a nonlinear model to work, low intrinsic nonlinearity and parameter effects nonlinearity are desired.

The main advantage of using linear least squares regression is that very efficient use of the data. The main disadvantage of linear least squares are limitations in the shapes that linear models can assume over long ranges, possibly poor extrapolation properties, and sensitivity to outliers (Montgomery and Peck 1982, and Gilchrist 1984).

On other hand, the biggest advantage of nonlinear least squares regression over many other techniques is the broad range of functions that can be fit. The big disadvantage is the need to use iterative optimization procedures to compute the parameter estimates. (Fishburn 1988, and Tung 2007).

Engineering models are in general nonlinear models where the response of some appropriate engineering variable depends in a nonlinear manner on the application of some independent parameters (Hauser 2009).

6.2 The Major Stages in Statistical Modelling

Generally there are five major stages in the process of statistical modelling. They are identification, estimation and fitting, validation, application, and iteration (Gilchrist 1984).

6.2.1 Identification

The modeller begins with ideas, experience, and relevant literature and data. So the first task is to identify the model appropriate to the problem in hand. Therefore, the identification stage is the process of finding or choosing an appropriate model for a given situation. An essential component of all modelling is the study of what is already known relating to the problem. What information, what knowledge prior to any gathering of data. So the modeller needs information about variables. The choice of which variables to use in a model is crucial. The neglect of an important variable can have some strange effects on the model. Some variables are essential to a model but many others may not useful. Information about data is also something very important in terms of availability and reliability. Therefore, an important component of the prior information needs to be information about the quality of the data available. Also, thought must be given to the sources of error and random variation that have to be modelled, and finally information about the models. This process called the conceptual identification. After gathering information about the data in terms of conceptual approach, we have to collect the data of the problem in hand and present it in a clear and useful way and this process is called empirical identification. To complete the identification stage, we weld together the both knowledge and data to start building a model.

The conceptual identification and the empirical identification give a good start for building a model. Therefore, the modeller can in practice combine both approaches in order to start building a good model.

6.2.2 Estimation

Once the proposed model has been found, the modeller considers how a proposed model may be fitted to a set of data. There are many techniques to fit data to a model. The most popular one is the least square method.

6.2.3 Validation

The validation stage takes place in the development stage of the model, in the testing step when new data is gathered to provide a further validation of the model, and in the application stage when monitoring procedures are introduced to check whether an initially satisfactory model remains valid in use. Generally, the process of comparison of the models with reality is called validation. Comparing of the model with a knowledge base with prior information is called conceptual validation. Comparing with the data base is called empirical validation. So validation data is data collected for the validation process. Therefore validation stage is to examine whether the model is a good description in terms of its behaviour and of the application proposed.

6.2.4 Application

The application means, the interaction between model identification, fitting, Validation and the intended application of the model.

6.2.5 Iteration

The iteration is a process of continuous development till the model does the job.

6.3 Sources of Uncertainty in Modelling

"All models are wrong, but some are useful" (Box and Draper 1987). All models are "wrong" in the sense of being a simplified representation of some reality. Therefore uncertainty is there.

The most difficult source of the uncertainty to deal with is that due to the possibility of error in the identification process, so possibility of unknown factors that might affect the model and this problem called lurking variable (Moore 2003). So the effect of lurking variable will be contained in the error term.

The other major source of uncertainty is the data. Even sometimes the data are enough but the quality is far from perfect due to natural variability of the quantities being measured and due to unnatural variability such as mistakes measurement, and misunderstanding.

6.4 Boundary Conditions

From an engineering point of view, the pavement deteriorates in a particular pattern. Put simply, a priori conditions that must be met by prediction models which will limit the form to those appropriate for the modelling process may be summarized as follows:

- The initial value of all damage is zero.
- Most damage has a slope that is initially zero. However, some damage types such as roughness or rutting have an initial upsurge.
- Most damage is irreversible; the slope must always show a worsening of condition unless a treatment is applied.
- Damage functions such as the distresses under study have final slope zero, damage reaches the horizontal line at 100%. By contrast, other types of damage such as roughness or rutting don't have this constraint.
- The minimum value for damage should not be negative at any value of the pavement age.
- The maximum value of damage has an upper limit only for those types of distresses for which the final slope is zero.

6.5 Nonlinear Regression Modelling

6.5.1 Regression technique

In the light of the literature review chapter and different types of modelling techniques, it is clear that the pure mechanistic models, the mechanistic–empirical models, and the subjective probabilistic models are not relevant to the Riyadh pavement management system, which depends on a surface distress survey only (Barent and Freddy 1979, Darter 1980, Darter 1979, Gearge et al. 1989, Hass et al. 1994, Hass and Hudson 1978, Lee et al. 1993). The empirical technique (regression Models) is very suitable for the situation in the Riyadh network. It is practical, simple, and easy to develop provided that adequate data are available (Al-Mansour et al. 1999).

6.5.2 Distress Prediction Equations

6.5.2.1 Background

Nonlinear regression models, divided into families according to their typical behaviour, were tested and evaluated. These were exponential models, power models, yield density models, growth models, sigmoid models, and miscellaneous models. The evaluation was based on the boundary conditions and the form of equations that provide the best fit to the actual data. The sigmoid model family was selected to fit the data because it is the one which can suit the research methodology and fits the boundary conditions (Ratkowsky 1983, Shahin et al. 1987). Various scientists and researchers discovered, reinvented, and adapted the curves of nonlinear S-shape many times for different domains of knowledge. Therefore, S-shaped curves possess a lot of different names: Logistic curve, Verhulst-Pearl equation, Pearl curve, Richard's curve (Generalized Logistic), Growth curve, Gompertz curve, S-curve, S-shaped pattern, Saturation curve, Sigmoid curve, Foster's curve, Bass model, and many others (Dmitry and Roland 2007, Hosmer and Loeshow 1989, and Rowe et al. 2008,).

Researchers all around the world have produced S-shaped curves for projecting the performance of technologies, to foresee population changes, for market penetration analyses, for micro-economic and macro-economic studies, for diffusion mechanisms of technological and social inventions, for ecological modelling, for biology, for agricultural, for engineering, and for many other purposes. This indicates the suitability of S curves in modelling.

These curves start at a fixed point and increase their rate to reach an inflection point and then the rate decreases to approach asymptotically to a final value. Many natural processes and complex systems display a history dependent progression from small beginnings that accelerate and approach a climax over time. For lack of complex descriptions a sigmoid function is often used (Adel et al. 1996, Ratkowsky 1983, and Zwietering et al. 1990).

Several equations of sigmoid form appear to fit the data with more or less the same coefficients. The criterion that dictated the selection of a particular function for each distress was its ability to satisfy the initial and possibly the end of life boundary conditions. The evidence from the literature has indicated the suitability of sigmoid functions to represent distress predictions (George et al. 1989, Robinson et al. 1996, Sadek et al. 1996, and Saraf and Majidzaadeh 1992). As result of that, the researcher prefers one form for each distress model for uniformity and general flexibility and also for calibration.

6.5.2.2 The Applicable Sigmoid Function Options

Numerous mathematical functions have been proposed for modelling sigmoid curves, many of which are claimed to have some underlying theoretical basis. In the literature, there are many equations having the S-curve shape, from simple equations to those with complex structure, from equations having two parameters to equations having more than four parameters.

Among these are the simple rational forms, the simple logistics form, the logistic distribution form (cumulative form), the generalized logistic form (Richard), the standard logistic form, the Gompertz, the Weilbull equation, a form derived from Weilbull equation, Stannard equation, Shuute equation, and the Morgan Mercer Flodin (MFF) form.

A simple S-curve can be defined in simple form such as;

$$y = a*[\frac{t^b}{c+t^b}] \qquad (1)$$

Where a, b, and c are constant values that define the shape of the sigmoid.

The logistic function or logistic curve is the most common sigmoid. This function finds application in a range of fields including engineering, and others. However, it is sufficient to compute t over a small range of real numbers. The simple logistic function can be defined by the formula.

$$y = \frac{1}{1+e^{-t}} \quad (2)$$

The logistic distribution is a continuous probability distribution. Its cumulative distribution function is the logistic function. This formula can be defined in such format as follows

$$y = \frac{a}{1+e^{-(t-m)/s}} + d \quad (3)$$

Where

The (a) parameter controls the upper asymptote,
The (m) parameter controls the time of maximum growth,
The (s) parameter controls the growth rate,
The (d) parameter is allows the representation of a lower asymptote in a similar manner in the generalised form,
The (t) parameter is the time.

The generalized logistic curve or function, also known as the Richard curve is a widely – used and flexible sigmoid function for growth modelling, extending the well-known logistic curve as following:

$$y(t) = a + \frac{b-a}{1+\lambda e^{-\beta+3(x-m)^{1/\omega}}} \quad (4)$$

Where
a= the lower asymptote,
b= the upper asymptote, if a=0 then b is called the carrying capacity,
β = the growth factor,
ω >0: affects near which asymptote maximum growth occurs.
λ = depends on the value y (t)
t= time,
m= the time of maximum growth if $\lambda = \omega$,

However, the standard equation of the generalized curve is symmetric in shape around a mid-point. This equation has been used in predictive relationships for pavement design since the early 1980s' (The Asphalt Institute 1982). The standard one has this formula

$$y(t) = a + \frac{b}{1+e^{-\beta+\delta(x-m)}} \quad (5)$$

However, this can be modified to this form

$$y = a + \frac{b}{1 + \lambda e^{-\beta(x-m)^{1/\lambda}}} \tag{6}$$

Where

The (a) parameter controls the lower asymptote,

The (b) parameter controls the upper asymptote,

The (β) parameter controls the growth rate,

The (m) parameter controls the time of maximum growth,

The (λ) parameter controls where maximum growth occurs,

The (x) parameter is the time

Another example of a sigmoid curve that reaches at large values is the Gompertz curve. It is a type of mathematical model for a time series, where the growth is slowest at the start and end of a time period. The curve has the following form:

$$y = ae^{be^{ct}} \tag{7}$$

Where

a= the upper asymptote,

c = the growth rate,

b,c are negative numbers

Weilbull equations haven been used in the representation of sigmoid functions. For example the cumulative distribution function for Weilbull is in the form of

$$y(t) = 1 - \exp(-(t/\beta)^{\omega}) \tag{8}$$

The modification of the above equation leads to an equation in this form:

$$y(t) = \frac{a}{e^{(\beta/t)^{\omega}}} \tag{9}$$

Where

α = an asymptote that controls upper limit= 100,
β = the position of the first inflection point on the curve,
ω = a coefficient that controls the shape on the curve.

A similar equation with more parameters has been used by Texas Department of Transportation (Robinson et al. 1996, and Dossey and Hudson 1994).

The Stannard and Shuute equations (Zwietering et al. 1990) are sigmoid functions that measure the growth rate. They have a complex structure and more than 3 parameters in the form. They are written respectively as the follows:

$$y(t) = a\{1+\exp[-\frac{l+kt1b}{p}]\}^{-p} \tag{10}$$

$$y(t) = \{y1\wedge b + (y2\wedge 2 - y1\wedge b)\frac{1-\exp[-a(t-\lambda)]}{1-\exp[-a(\lambda 2-\lambda 1]}\}^{1/b} \tag{11}$$

The Morgan-Mercer-Flodin model has the following formula (Rowe et al. 2008)

$$y = a - \frac{a-\beta}{1+\lambda t^{\alpha}} \tag{12}$$

The (a) parameter controls the upper asymptote

The (β) parameter at t=0,

The (λ) parameter controls the growth rate

The (α) parameter controls the point of inflection

6.5.2.3 The Choice of Sigmoid Function

The choice of function among a number of useful and applicable functions can be considered in terms of qualitative considerations like the appearance of forecast plots, intuitive reasonableness of the model, simplicity of the form model, and ease of use. The idea of qualitative considerations is to minimize the number of functions to a reasonable number for further comparisons. At first, therefore, these models were compared with respect to their ease of use. It is very obvious that equations 4, 5, 6, 10, 11, and 12 have complex structure and more than three parameters. Therefore, these six equations will be excluded from the final comparison.

The simple logistic function, equation 2, is sufficient to compute t over only a small range of real numbers and it does not start at zero. The Gompertz curve, equation 7, reaches at large values but it does not start at zero. Therefore, equations 2 and 7 will also be discarded because they violate one of the boundary conditions which is the initial value of all damage is zero. Weilbull curve, equation 8, is going to be neglected.

After careful consideration and for ease of use and ability to fit the data, 3 equations out of the 12 options were selected to do the modelling and to explore the difference between them in order to select the best one.

The equations are

$$y(t) = a * [\frac{t^b}{c + t^b}] \qquad (1)$$

Where a, b, and c are constant values that define the shape of the sigmoid.

$$y(t) = \frac{a}{1 + e^{-(t-m)/s}} + d \qquad (3)$$

Where

The (a) parameter controls the upper asymptote,
The (m) parameter controls the time of maximum growth,
The (s) parameter controls the growth rate,
The (d) parameter is allows the representation of a lower asymptote in a similar manner in the generalised form,
The (t) parameter is the time.

$$y(t) = \frac{a}{e^{(\beta / t)^{\omega}}} \qquad (9)$$

Where
α = an asymptote that controls the upper limit= 100,
β = the position of the first inflection point on the curve,
ω = a coefficient that controls the shape of the curve.

However, a single form in the modelling process must be used as will be discussed in the rest of this chapter.

6.6 Modelling Process for Urban Main Roads

6.6.1 Selecting the Best Form

All the three equations are good and useful in modelling pavement prediction based on research methodology, boundary condition, available data, and the engineering principle for this research and achieving the objectives. However, a single form must be selected to implement it for pavement management at the Saudi Arabia Urban Road Network (SAURN).

The most popular criteria for comparing different models are standard error of the model Mean square of Error (MSE) and coefficient of determination of the model R^2. Basically, MSE is one of many ways to quantify the difference between an estimator and the true value of the quantity being estimated. R^2 measures the proportion of the variation in y that can explained by the variation in x, in other word R^2 is defined as the covariance divided by the standard deviations of the variables. R^2 statistics is not always giving a good conclusion in comparing between/among models because R^2 statistics is not directly comparable (Montgomery and Peck 1982). Moreover, for nonlinear analysis, R^2 is not always reliable a parameter to measure the goodness of fit as for linear regression analysis (Tran and Hall 2005). For instance, for one set of data, three models have different MSE values and the highest R is for the highest MSE among the three. Therefore at this stage only MSE would be calculated to judge which one is the best among the three and consequently it would be selected to be the proposed model form for the urban main roads data as shown in Table 6.1.

Table 6.1 The Results of standard Error of Estimate for comparing Three Selected Models-UMS

Distress Code	Comparison Between Selected Models		
	Standard Error of Estimate		
	Equitation (1)	Equitation (3)	Equitation (9)
Block Cracks	5.97	6.15	5.88
Longitudinal & Transverse Cracking	5.74	5.27	5.56
Patching	8.95	9.33	9.02
Potholes	3.91	4.29	3.88
Depressions	6.95	6.91	6.88
Weathering & Ravelling	7.49	8.12	7.53
Cracking	5.69	5.53	5.62

It can be concluded that equation 9 records the lowest values of standard error in most cases. Therefore, the proposed distress equation of the model will be:

$$y(t) = \frac{a}{e^{(\beta/t)^{\omega}}}$$

Where

α = an asymptote that controls the upper limit= 100,

β = the position of the first inflection point on the curve,

ω = a coefficient that controls the shape of the curve.

The form has only one predictor variable which is the pavement age time t. The form has one known parameter α to control the upper limit to not exceed 100 and it has zero intercept because damage has a slope that is initially zero as discussed in the boundary conditions. The form has two unknown parameters β and ω to build the shape characteristics of a prediction model for each pavement distress type.

The other two predictor's variables, traffic and drainage, are not included in the proposed equation due to their minor importance in the prediction model as was discussed and proved in the chapter on pavement distress data analysis. However, this issue will be discussed further later in the following subsection.

6.6.2 Method of Calculating Shape Coefficients

The nonlinear regression procedure in the SPSS software package (SPSS Manual version 16) was used to calculate coefficients for the proposed sigmoid function for each distress type. The nonlinear regression procedure allows for the specification of any equation form, any number of dependant variables and the ranges in which the dependant variables are expected to fall. Table 6.2 summarises the calculated shape coefficients for the Urban Main sections (UMS) distress prediction models. The proposed form has one predictor variable which is the pavement age.

Table 6.2 Shape Coefficients for Prediction Models for the Proposed Distress Equation-UMS

Distress Name	Model Shape Coefficients	
	β	ω
Block Cracks	13.752	0.588
Longitudinal & Transverse Cracking	10.846	1.640
Patching	6.317	0.789
Potholes	14.388	0.968
Depressions	36.896	0.455
Weathering & Ravelling	7.116	1.291
Cracking	14.665	0.671

6.6.3 Calibration Methodology

As discussed and concluded in the chapter on pavement distress data analysis, the pavement age is the only factor that shows significance in the prediction modelling. If we consider the other two predictor variables, which are the traffic and the drainage, the proposed distress equation would have been in the following form:

$$y(t) = \frac{a}{e^{(\chi * \delta * \beta / t)^{\omega}}}$$

Where

α = an asymptote that controls the upper limit= 100,

β = the position of the first inflection point on the curve,

ω = a coefficient that controls the shape on the curve,

χ = a modifying coefficient for traffic,

δ = a modifying coefficient for drainage.

The purpose of the traffic and drainage coefficients specified in the proposed distress model is to modify the distress equation to be as accurate as possible provided the data are available. The proposed distress equation makes use only of the variables β and ω, which have numerical values calibrated to all observed data for a particular distress type. From an engineering point of view, the development of pavement distress is affected by a variety of variables other than age, such as traffic, and drainage. The availability of data for these variables allows the calibration of the modifying coefficients in the sigmoid models. Table 6.3 shows a classification for the modifying coefficients. As indicated earlier, the data has one predictor variable which is the pavement age time *t* and the data has another two factors. They have been designated as modifying coefficients.

Table 6.3 Modifying Coefficients-UMS

Classification of Modifying Factors			
Modifying Factors	Coefficients symbol	Modifying Variables	Categories of variable
Traffic Loading factor	χ	ADT	Low Medium High
Availability of Drainage System	δ	Drainage	Absence Presence

6.6.3.1 Numerical Values and the 95% Confidence Interval.

Each modifying coefficient was calculated by the nonlinear regression technique in SPSS. For this analysis, the model coefficients were held as constant, and the only variables under consideration were the traffic and the drainage. The best fit value of each coefficient to its relevant data set was calculated. The 95% confidence interval in the parameter estimates, using the nonlinear regression procedure in SPSS, was performed on the UMS database to determine which variables were significant in the prediction of each distress type. Traffic and drainage were examined. Table 6.4 shows 0 within the upper and lower bounds. This means the two predictors traffic and drainage cannot be assumed to be different than 0. Therefore, the traffic and drainage are not significant and consequently will be not included in the modelling process. This result strongly supports the inductive and descriptive analysis results. Therefore neither the traffic nor the drainage has influence on the distress equation.

Table 6.4 Modifying Coefficients and 95% Confidence Interval-UMS

Distress Code	Numerical Values for Modifying Coefficients		
	χ	δ	Upper and Lower 95% CI
Block Cracks	2.861	3.501	0 within the bounds for traffic and drainage
Longitudinal & Transverse Cracking	2.215	5.948	0 within the bounds for traffic and drainage
Patching	1.511	4.023	0 within the bounds for traffic and drainage
Potholes	4.093	3.440	0 within the bounds for traffic and drainage
Depressions	24.947	0.616	0 within the bounds for traffic and drainage
Weathering & Ravelling	2.120	2.388	0 within the bounds for traffic and drainage
Cracking	14.665	0.671	0 within the bounds for traffic and drainage

6.6.3.2 T-test for All the Parameters

Table 6.5 summarises the calculated shape coefficients for the Urban Main Roads distress prediction models and corresponding t ratio value. The t ratio is calculated by dividing the parameter estimate by the standard error for the parameter (Montgomery and Peck 1982).

This result indicates that the modifying coefficients are not important in the prediction equation. Again this result support supports the inductive and descriptive analysis result.

Table 6.5 Shape Coefficients for Prediction Models with Modifying Coefficient and t test -UMS

Distress Code	Model Shape Coefficients				t-ratio
	χ	δ	β	ω	
Block Cracks	1.384	0.819	12.137	0.588	Not Significant for the 4-parameter
Long.& Trans. Cracking	4.469	0.283	8.573	1.640	Not Significant for the 4-parameter
Patching	0.678	0.466	20.009	0.789	Not Significant for the 4-parameter
Potholes	1.276	0.946	11.927	0.968	Not Significant for the 4-parameter
Depressions	1.473	1.885	13.285	0.455	Not Significant for the 4-parameter
Weathering & Ravelling	0.913	1.140	6.843	1.291	Not Significant for the 4-parameter
Cracking	5.012	0.281	10.416	0.671	Not Significant for the 4-parameter

6.6.4 Test of Error Distribution

The modifying coefficients may intend to make the distress prediction models more accurate as additional data on the traffic, and drainage were available. After calculating the best values of the modifying coefficients, their accuracies when they were used in combination were tested against the general equation. The purpose of this test was to determine whether the prediction accuracy of the distress models was significantly improved by using the modifying coefficients.

Two estimates were made of each distress, one each with and without modifying coefficients. And then an absolute error was then calculated for each value as follows:

Error (with Coefficients) =observed-predicted (with Coefficients)
Error (without Coefficients) =observed-predicted (without Coefficients)

If the coefficients are helpful in prediction, then the error distribution with the coefficients should have a smaller variance than the error distribution without the coefficients.

The null hypothesis *Ho* and the alternative hypothesis *Ha* can be stated in statistical terminology as:

Ha: σ (Without Coefficients) = σ (With)
Ha: σ (Without Coefficients) > σ (With)
The test static for this hypothesis was calculated by the following formula
F=S (without)/S (with)

For 120 degree of freedom (the limit for most statistical Tables), the hypothesis is rejected for values of F>=1, with 95% Confidence limit. The modifying coefficients interact with the other in the distress equation; therefore, the error term for all significant variables for each distress type were grouped into one population for conducting the F-test for that distress model.

The test F-test statistics calculated for the various distress types are given in Table 6.6. The results of the test indicate that no significant improvement in prediction accuracy is made for all distress types. This result supports the result in the previous chapter which says the traffic and drainage should not be in the sigmoid distress prediction or should be set equal to 1.0 in the sigmoid distress prediction at this stage of the PMS implementation.

Table 6.6 Results of F-Test-UMS

Test				
F-test Results				
Output of the Test	F-test		Significance	
Distress	F-Calculated	F-Tabulated	P-value	Test Result
Block Cracks	0.928	1.000	0.000	Accept Ho
Longitudinal & Transverse Cracking	0.959	1.000	0.000	Accept Ho
Patching	0.900	1.000	0.000	Accept Ho
Potholes	0.900	1.000	0.000	Accept Ho
Depressions	0.980	1.000	0.000	Accept Ho
Weathering & Ravelling	0.990	1.000	0.000	Accept Ho
Cracking	0.900	1.000	0.000	Accept Ho

6.6.5 Importance of Pavement Age

The question now arises of why pavement age is so significant in the predicting pavement deterioration. As indicated earlier the prediction equation recognizes three causal factors in defining pavement deterioration. They are age in years since last overlay, traffic, and drainage, with being pavement age the most significant factor. The traffic and drainage are of only minor importance can clearly be seen from different results including descriptive analysis, inductive analysis, modelling analysis. This was clear through numerical values and scatter plots in chapter 5, and sections 6.6.3.1, 6.6.3.2, and 6.6.4 of this chapter.

The answer for this question can be expressed from three standpoints. The first is the data, the second is the designed traffic level, and the third comes through the literature and the possible causes of pavement distresses under study. The data show that the age alone can account for a substantial portion of the decline in serviceability. Age is significant because it is a common factor in the estimation of both traffic and effect of drainage over the life cycle period. Therefore, age can be a surrogate for the effect of traffic and drainage in prediction model. So it can be concluded that age plays a pivotal role in predicting pavement deterioration.

The second possible reason behind this is the fact that the pavements were designed to perform for the expected traffic level.

The third standpoint concerns the possible causes of flexible pavement distress from the literature (Al-Swailmi and Al-Abdal Whab 2001, FHWA 1990, FHWA 2002, RRM 1998b, Shain 2002, USCERL 1990, USCERL 1981, and WSDT 1988). As mentioned before, the common pavement distress types on the network are; block cracking, longitudinal and transverse cracks, patching, potholes, depressions, and cracking due to patching. The block cracking takes the form of interconnected cracks that divide the pavement up into rectangular pieces. A possible cause is an inability of asphalt binder to expand and contract with temperature cycles because of asphalt binder aging or poor choice of asphalt binder. Longitudinal cracks are parallel to the pavement's centreline or laying direction. The possible causes are poor joint construction. Transverse cracks are perpendicular cracks to the pavement's centreline or laying direction. The possible causes are shrinkage of the asphalt surface due to low temperatures or asphalt binder hardening, reflective crack caused by cracks beneath the surface asphalt layer, and top down cracking.

Depressions are localized pavement surface areas with slightly lower elevations than the surrounding pavement. The possible cause is subgrade settlement resulting from inadequate compaction during construction. Potholes are small, bowl-shaped depressions in the pavement surface that penetrate all the way through the HMA layer down to the base course. A possible cause is determination of alligator cracking. As alligator cracking becomes severe, the interconnected cracks create small elements of pavement, which can be dislodged as vehicles drive over them, and the remaining hole is called a pothole.

Patching is an area of pavement that has been replaced with new material to repair the existing pavement. The possible causes are previous localized pavement deterioration that has been removed and patched, and utility cuts. Ravelling is the progressive disintegration of an asphalt layer from the surface downward as a result of the dislodgement of aggregate particles. The possible cause is loss of bond between aggregate particles and the asphalt binder.

Therefore, distress propagation on SAURN due to climatic problems, material problems, construction problems, and utility cuts. Urban roads are not rural roads. Beneath the city roads a large number of utility lines run parallel to and across the roads. Therefore, all utility agencies share the network with the municipalities (Al-Mansour and Al-Swilim 1997, Al-Swailmi 1994, Al-Swailmi and Al-Abd Whab 2001). So distress propagation comes from different factors, it is not only traffic problem and/or drainage.

To conclude, the traffic and drainage have minor affect compared to pavement age, in this study, because age surrogates for the effect of traffic and drainage in the prediction model. The pavements were designed to accommodate the expected traffic level, the effect of climate, the effect of material problem, the effect of construction problem, and the effect of utility cuts.

6.6.6 Assessing the Selected Models

Measures of adequacy are very important before adopting a model and implementing it in a pavement management system (Keller 2009, and Fwa 1990). In any nonlinear analysis, it is necessary to assess the fit of the model to the data and to assess the appropriateness of the assumptions about the regression analysis (Hauser 2009, and Box and Draper 1987), namely sensibleness of parameter values, comparison of mean squares and extra sums of squares, and plots of residuals. If there are any inadequacies in the model, or if any of the assumptions do not seem to be appropriate, then the model must be modified and the analysis continued till a satisfactory result is obtained. However, in nonlinear estimation, it is possible to converge to parameter values which are obviously wrong. This is because they may have converged to a local minimum, or got stalled because of awkward behaviour of the function (Montgomery and Peck 1982). Assessment of any fitted model should be therefore begin with a careful consideration of the parameter estimates and whether they make sense scientifically.

If the parameters do not make sense, it is recommended to check the starting values were used. If the program has proceeded smoothly to an apparently legitimate convergence point, but the parameters are not reasonable, check the function and its coding, the derivatives and their coding, the starting values, the data, and the observations. Furthermore, check if the response variable correctly specified, and if the residuals well behaved.

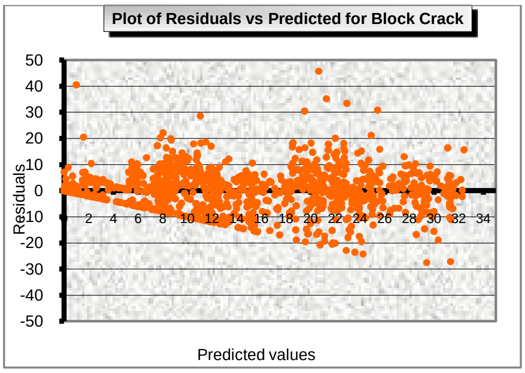
If these checks are satisfactory but the parameter vector is not good, change parameter vector. If the parameters are not appropriate again, the function is not appropriate. When the parameters converge to reasonable values, residual analysis must be checked to measure the model adequacy (Montgomery and Peck 1982, Arthur 1968, and Ryan 1997).

6.6.6.1 Residual Analysis

Analysis of residuals is an effective method for discovering several types of model deficiencies (Bates and Watts 1988). Since a residual may be viewed as the deviation between the data and the fit, it is a measure of the variability not explained by the regression model. The residuals have several important properties. They have zero mean and constant variance, and they are not independent (Montgomery and Peck 1982, Arthur 1968, Bates and Watts 1988, Ryan 1997, and Ratkowsky 1989). An analysis of the residuals will allow us to determine these properties, whether the error variable is normal, whether the error variance is constant, and whether the errors are independent.

6.6.6.1.1 Non-Variance Constant

The variance of the error variable is required to be constant. When this requirement is violated, the condition is called “heteroscedasticity” (Keller 2009, and Chatterjee 1991). Particular attention should be paid to whether the residuals have a uniform spread to insure constant variance. One method of diagnosing is to plot the residuals against the predicted values of the response variable because the error and the predicted variable are uncorrelated while the error and observed values are usually correlated (Draper and Smith 1981, and Ryan 1997). Figure 6.1 (a-g), for UMS, illustrates a case in which in the variance of the error is appropriately independent of the value of a parameter. A plot of the residuals against the predicted variable may also reveal one or more unusually large residuals. These points are of course potential outliers. Large residuals that occur at the extreme predicted variables could also indicate that the true relationship between response and predictor is a nonlinear relationship (Bates and Watts 1988). As a result, there is no big appearance change in the variation of the residuals for each distress type. Therefore, there are no obvious model defects in each distress model. It can be seen that there is a straight line in the Figure, that due to zero values of distress density at pavement age more than zero.



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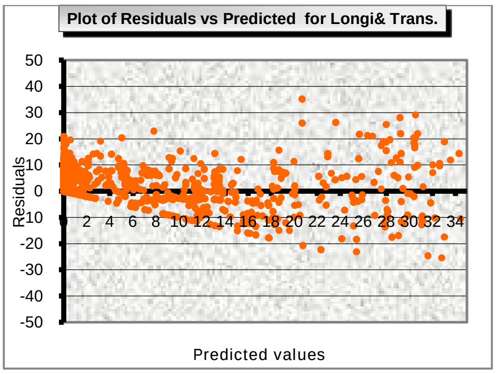

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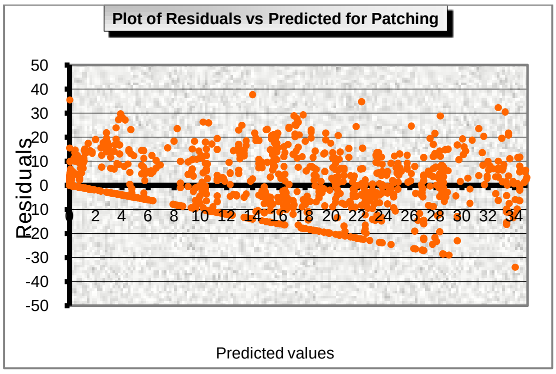

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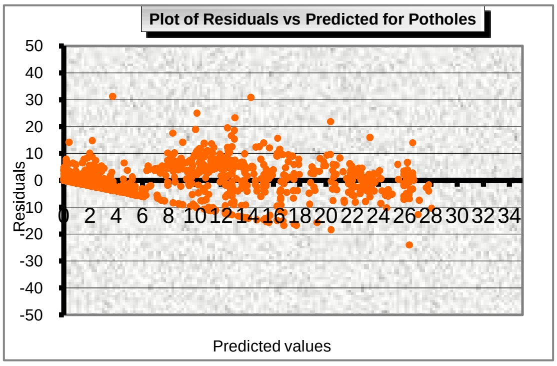

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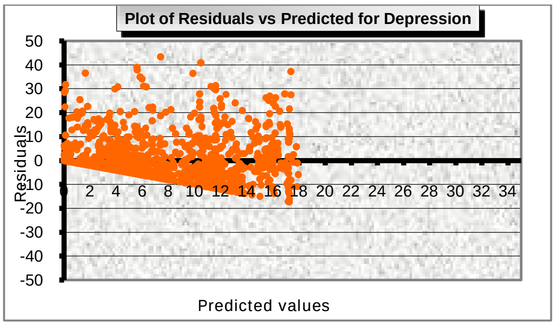

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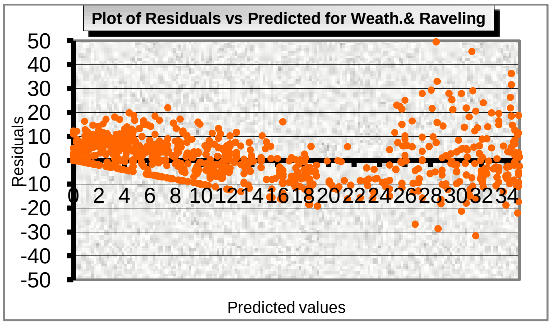

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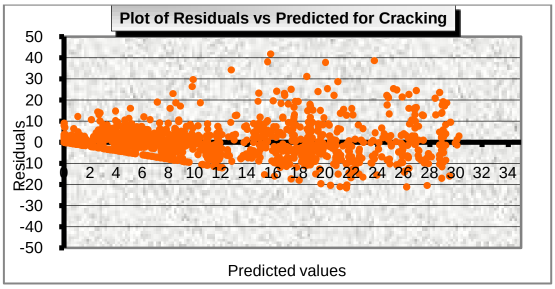
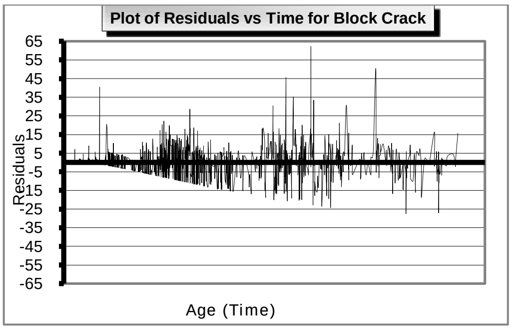


(G)

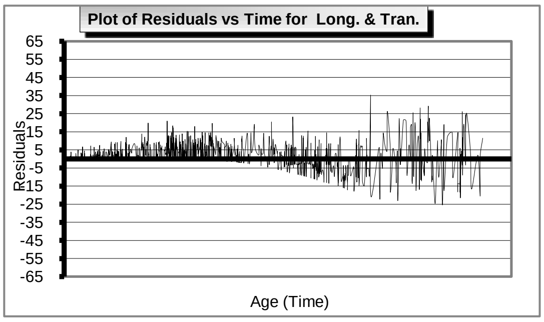
Figure 6.1 Plot of Predicted values versus Residuals (UMS) for (a) Block Cracking, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

6.6.6.1.2 Non-Independence of the Error Variable

Non random behaviour of the residuals tends to indicate lack of adequacy of the model. Since time is the only variable in the data, the only plot is that of the residuals against time. The values of the error variable are independent. When the data are time series, the errors often are correlated. Error terms that are correlated over time are said to be "autocorrelated" (Keller 2009). Therefore, if the residuals are related, it is likely that autocorrelation exists. If there is no relation among the residuals, time indicates independence and the residuals show random behaviour; therefore, the model shows good adequacy. Figure 6.2 (a-g) shows that the residuals appear to be randomly distributed over time periods for each distress on UMS.



(a)



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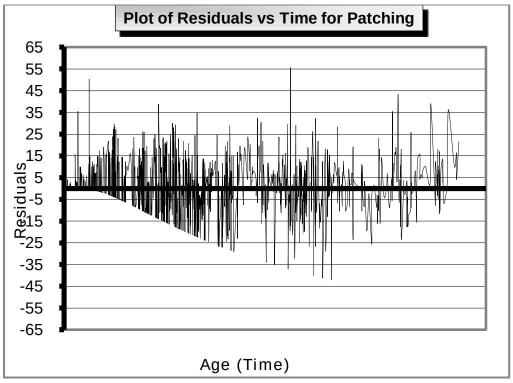

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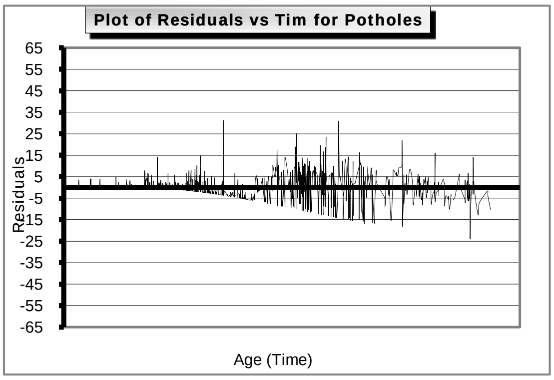

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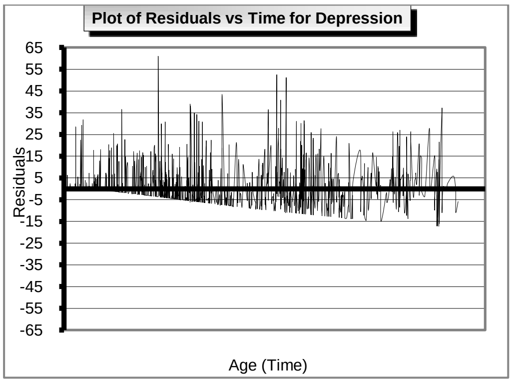

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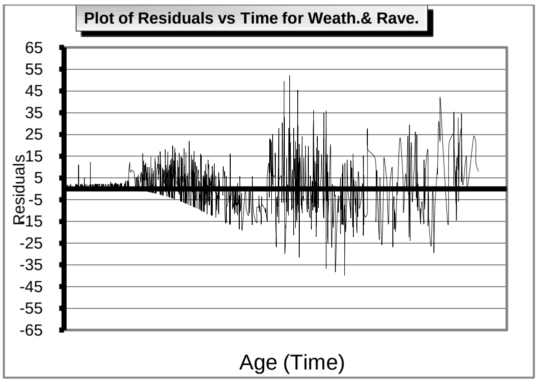

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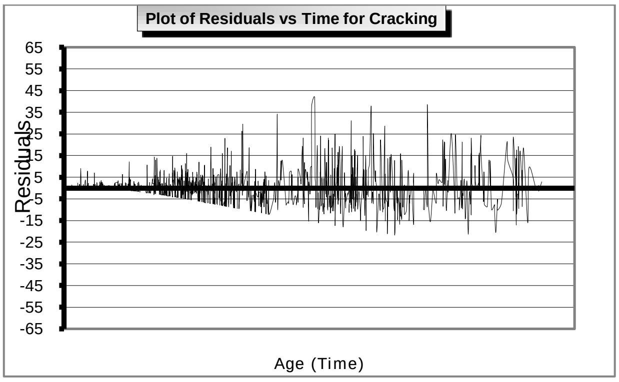
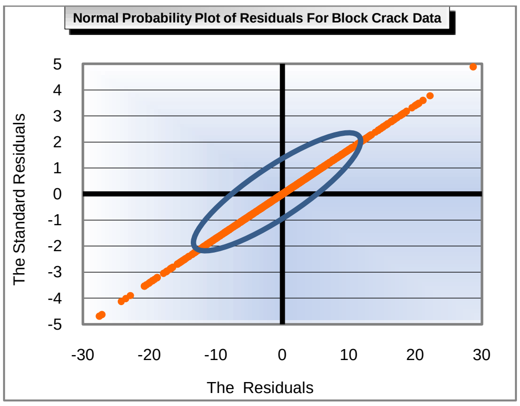


(g)

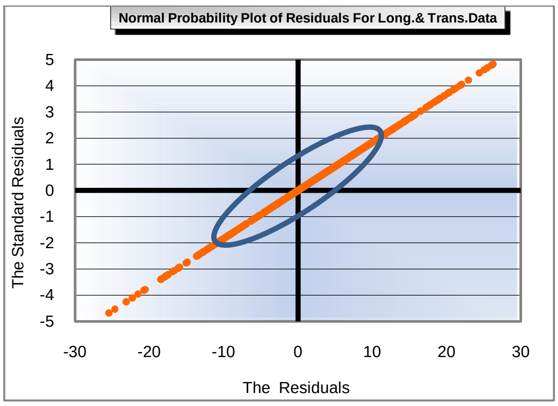
Figure 6.2 Plot of Residuals versus Time (UMS) for (a) Block Cracking, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

6.6.6.1.3 Non-Normality

A normal probability plot of the standardized residuals is frequently used for checking the normality assumption of the error. It is useful to work with the standardised residuals. The standardised residuals have zero mean and approximately unit variance. It as calculated by dividing the residual values by the MSE. When a normal probability plot is used, the standardized residuals must be used (Ryan 1997). One method to check normality is to plot the standardized residuals against their expected values. Some analysts prefer to construct normal probability plot using the standardized residuals. The standardized residuals are useful in detecting departures from normality. If the errors are normally distributed, then approximately 95 percent of the standardised residuals should fall between -2 and +2 (Montgomery and Peck 1982). Figure 6.3 (a-g) uses this method and it is shows that the points lie along a straight line. For all distress types, most values fall between -2 and +2. This Figure, therefore, shows that the normality assumption is satisfied and as result the model shows an acceptable accuracy.



(a)



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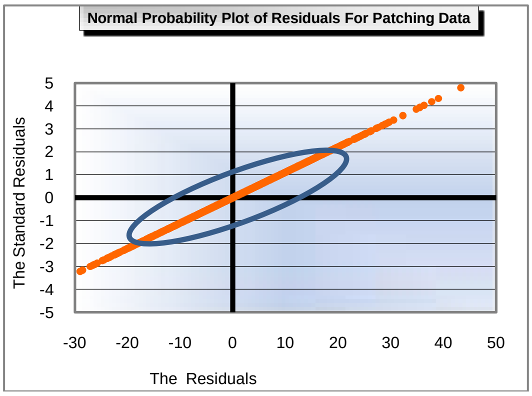
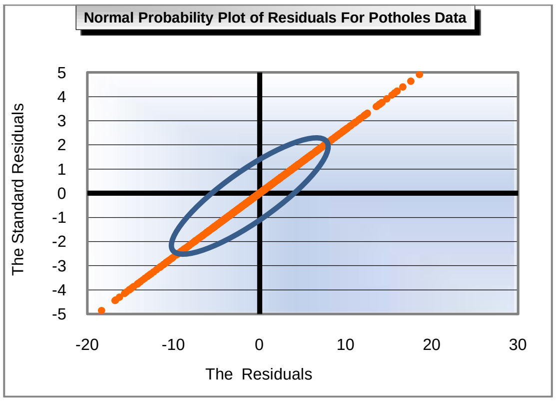
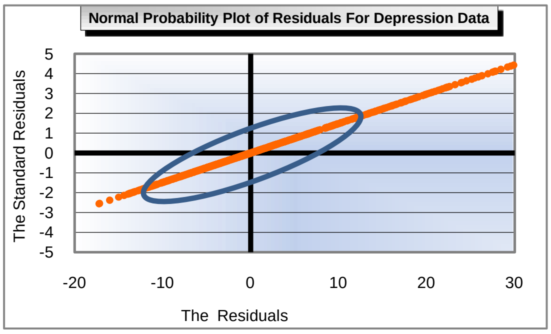
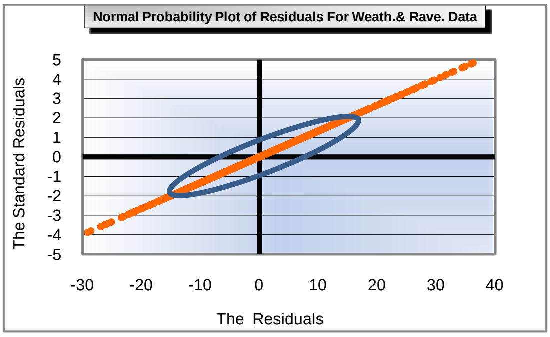


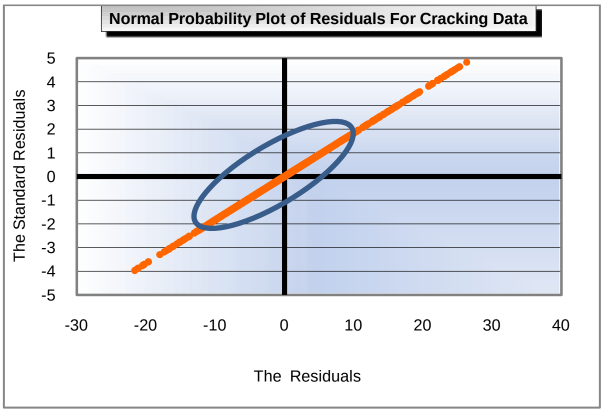


(c) (d)





(e) (f)



(g)

Figure 6.3 Normal Probability Plot of the Standardised Residuals (UMS) for (a) Block Cracking, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Ravelling, and (g) Cracking (due to patching).

6.6.6.7 Models Adaption

Once a proposed model that gives a good description of the process has been identified, and the assessed results appear reasonable as discussed in 6.6.6.1, the time has come to adopt it. However, the proposed model gives the predicted values only. It is not enough to know the best fit values for the model. How precisely the best fit values of the parameters are also important. Therefore, confidence interval should be investigated to get a good sense about the prediction.

6.6.6.7.1 Confidence Interval

6.6.6.7.1.1 Background

As shown previously the nonlinear regression results can be interpreted only if the assumptions of nonlinear regression are true or at least not badly violated (Chatterjee 1991, Motulsky and Christopoulos 2004, and Ratkowsky 1983). Figures 6.1, 6.2, and 6.3 in section 6.6.6.1 show that the assumptions were not violated.

Confidence intervals give a sense of whether results are any good. If the confidence intervals are narrow, this indicates that the parameters precisely. Whereas if the confidence intervals are very wide, this indicates that parameters are not precisely determined. There are many methods where the confidence interval can be calculated. However, a brief is given for two methods, namely asymptotic method, and region contour method.

6.6.6.7.1.2 The Asymptotic Method

Nonlinear regression represents the best fit values for each parameter, along with a standard error and 95% confidence intervals. The standard errors assess the precision of the best fit values and are used to compute the confidence intervals. For example, 95% sure that the true value for the position of the first inflection point on the curve along the age axis is between 13.110 and 13.394, and the true value for the shape of the curve is between 0.560 and 0.615.

The asymptotic method determines a standard error for each parameter. It then multiplies that standard error by a value determined from t distribution, with a value of 1.96. It then adds and subtracts that value from the best fit value to obtain the 95% confidence interval. Since it is calculated this way, the confidence interval is symmetrical around the best fit value.

Although the intervals are always symmetrical, and the method is an approximation, the asymptotic standard error and confidence intervals reported by most nonlinear regression software have proven to be very useful in giving a good sense of how precisely the parameters vary (Motulsky and Christopoulos 2004).

6.6.6.7.1.3 Region Contour Method

The developed model is determined by two parameters. Each parameter has its own upper limit and lower limit with 95% confidence interval (CI). Since the two parameters are related, a confidence region gives useful information. The confidence region is a set of values for the two parameters. In other words, the confidence region is a multi-dimensional generalization of a confidence interval. It is a set of points in an *n*-dimensional space, often represented as an ellipsoid around a point which is an estimated solution to a problem, although any shape can occur. It is calculated in such way that if a set of measurements were repeated many times, then the upper limit takes the maximum value of the set of the measurement and the lower limit takes the minimum value of the set of the measurement.

For example, block cracking model has two parameters. The first is β1= 13.133 with upper confidence limit= 13.349, and lower confidence limit= 13.133. The second parameter is β2= 13.133 with upper confidence limit= 0.651 and lower confidence limit =0.560. Figure 4 shows the individual confidence limits and the joint confidence region. The boundary of joint confidence region is a combination of a value from the range of upper and lower limits for β1, and is a combination of a value from the range of upper and lower limits for β2. For example, a random of values fall in the confidence region can be used to plot the upper and lower limits by substituting them in the selected equation to plot the upper and lower limits.

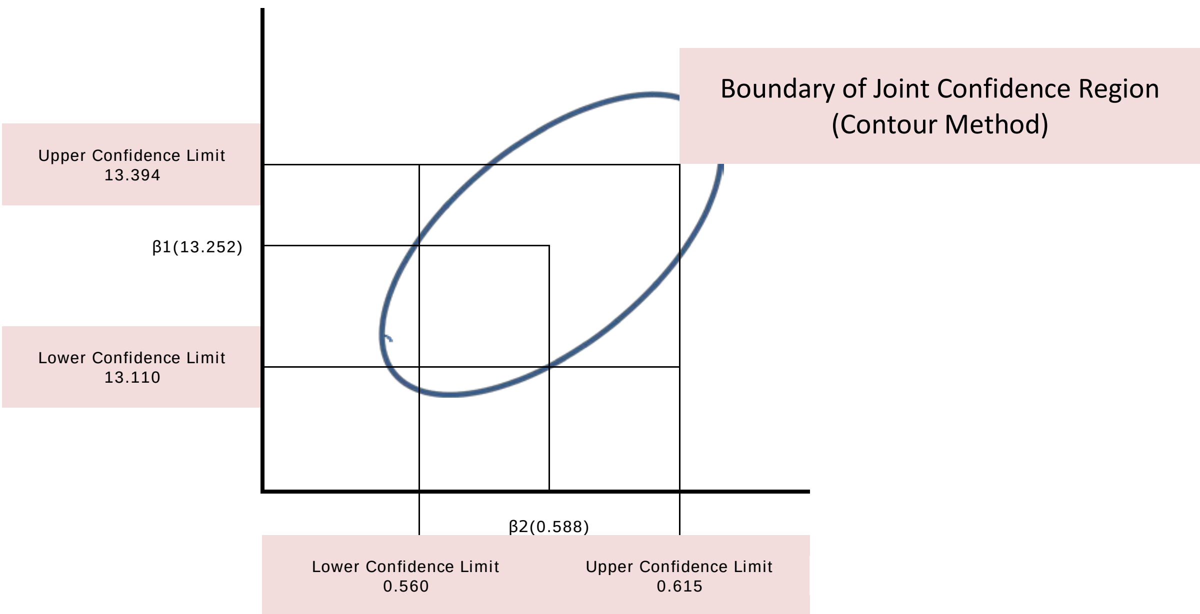
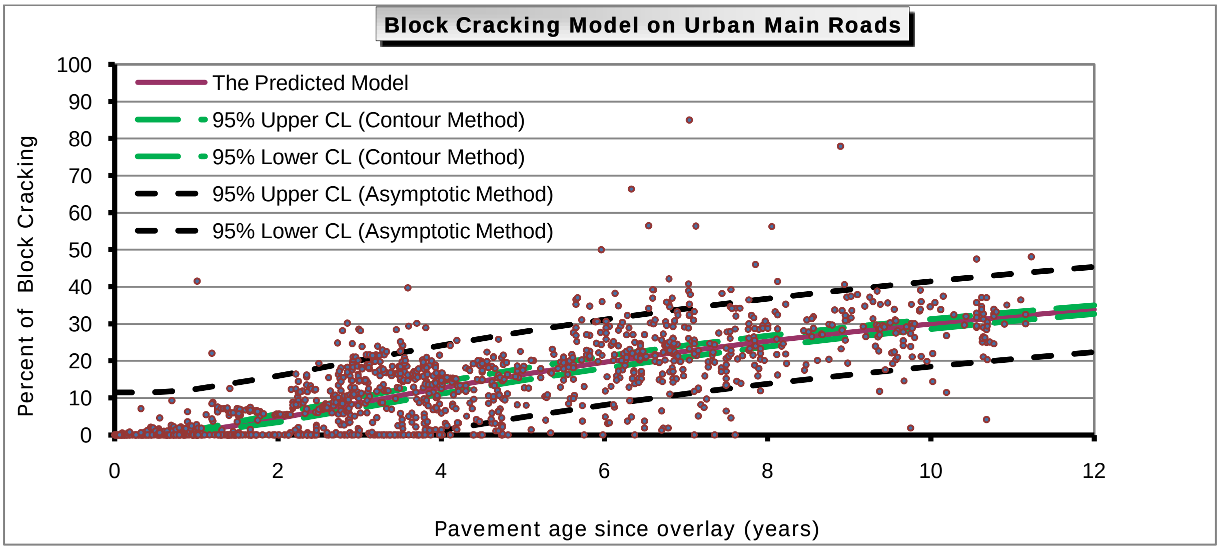


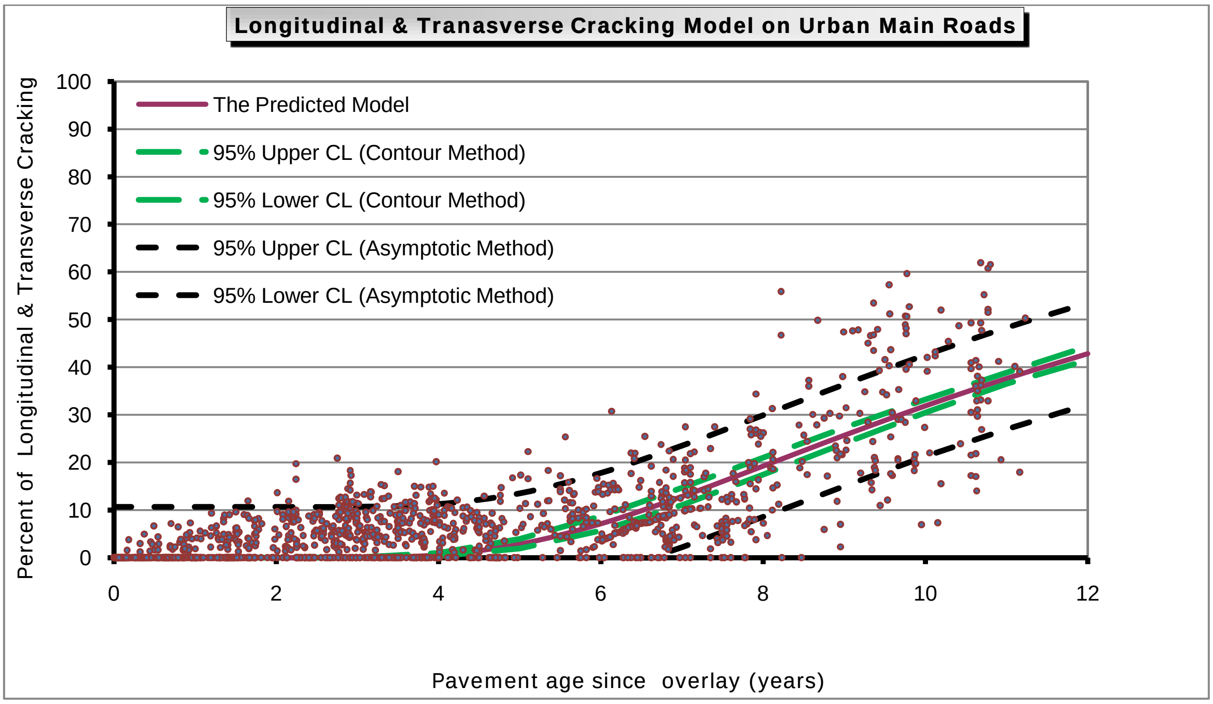
Figure 6.4 The Individual Confidence Limits and the Joint Confidence Region.

6.6.8 The Developed Models.

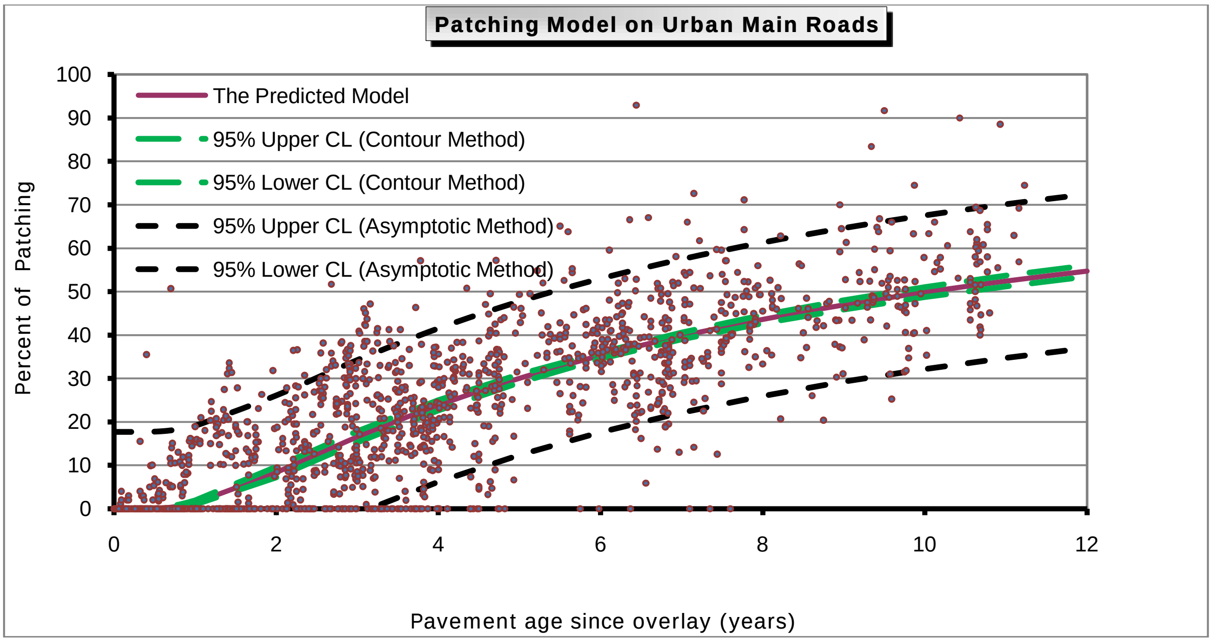
Seven models have been developed for urban main pavement distress models (UMPDM) using the modified function equation 9. The models are; Block Cracking Model, Longitudinal & Transverse Mode, Patching Model, Potholes Model, Depressions Model, Weathering & Ravelling Model, and Cracking due to patching Model. Table 6.2 section 6.6.2 summarizes the calculated shape coefficients for each distress. It can be used for estimation or prediction. Figure 6.4 (a-g) shows the distress prediction models for each flexible pavement distress in the SAURN-UMS. Five curves are plotted in Figure 6.4a to Figure 6.4g. The first and the foremost is the solid line which is the predicted model for a distress type. The coefficients in Table 6.2 have been used to obtain the predicted model. The second and the third curves are the 95% upper and lower confidence limits of the predicted values from the model. These curves were developed by generating a confidence region based on the upper and lower limits of the estimated parameters of the model. This method called contour method as explained in 6.6.7.1.2. These curves are the longer dotted lines that are surrounding the predicted model. The fourth and the fifth curves are the 95% upper and lower confidence intervals of the measured data. These curves were developed by the asymptotic method. The asymptotic method is a practical and a reasonable representation for the confidence limits. The interpretation of this method in nonlinear regression analysis is valid only if the assumptions of nonlinear regression are true or at least not badly violated. The assumptions are investigated fully on the section of assessing the selected models (Residual analysis) in section 6.6.6.1 where it concluded that the assumptions were met the requirements. Therefore, the 95% CI is supposed to be an interval that has a 95% chance of containing the true value.



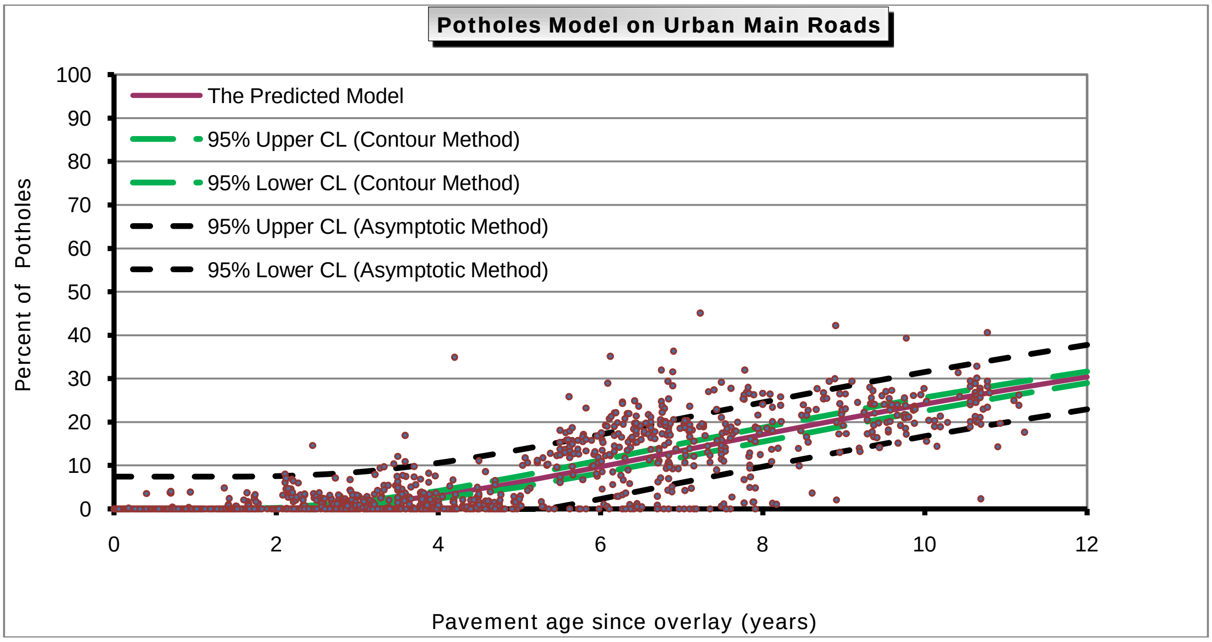
(a)


Longitudinal & Tranasverse Cracking Model on Urban Main Roads
Percent of Longitudinal & Transverse Cracking
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
Pavement age since overlay (years)
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12

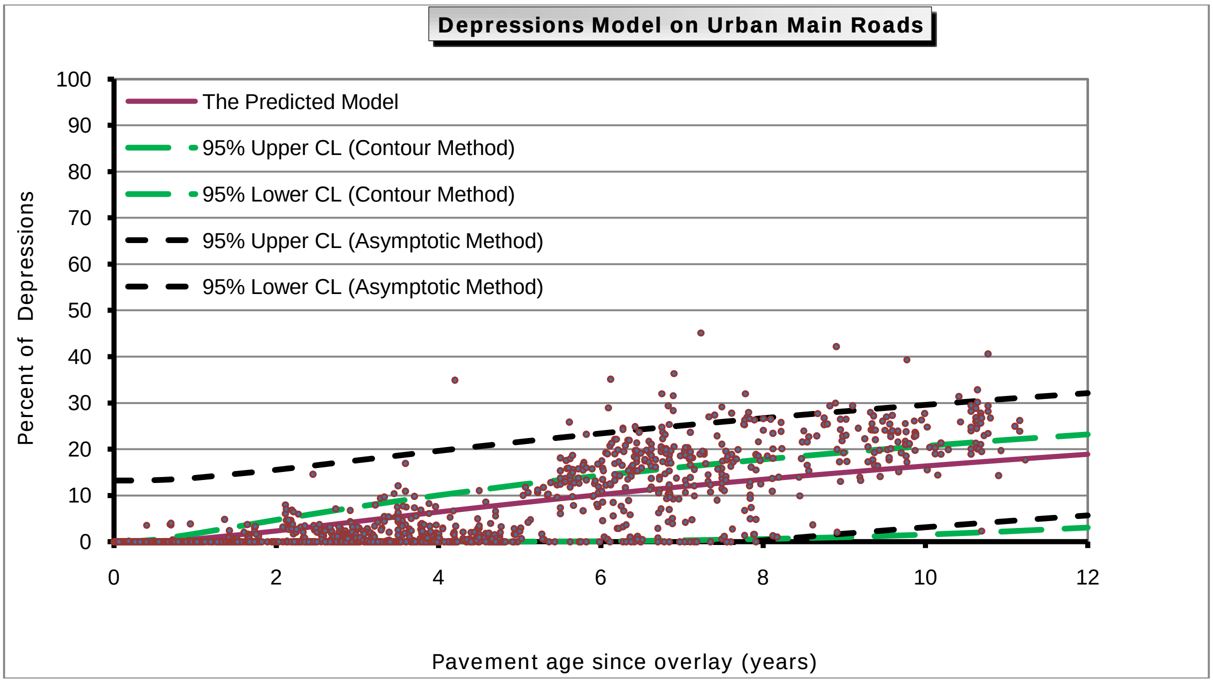
(b)


Patching Model on Urban Main Roads
Percent of Patching
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
Pavement age since overlay (years)
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12

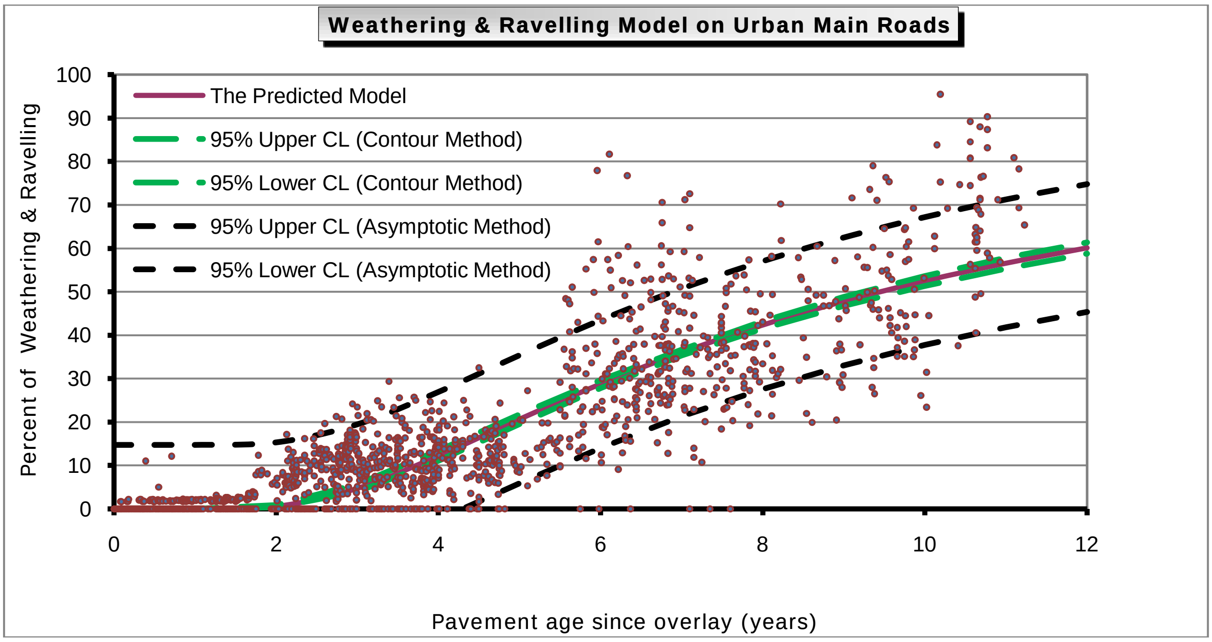
(c)


Potholes Model on Urban Main Roads
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
Percent of Potholes
Pavement age since overlay (years)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12

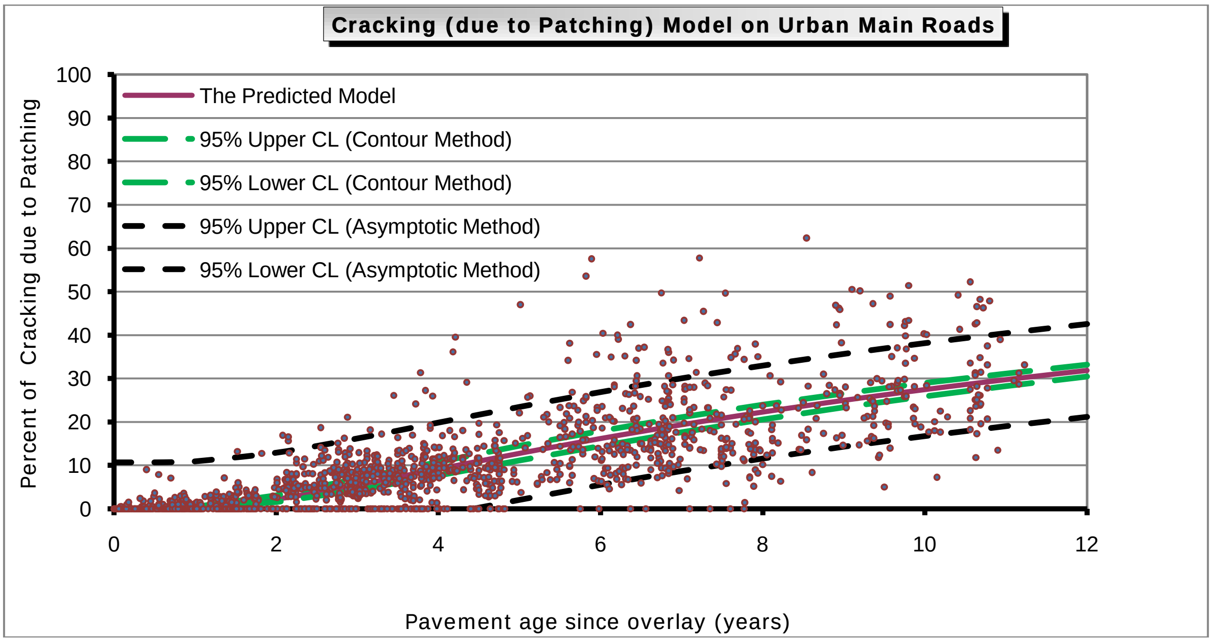
(d)


Depressions Model on Urban Main Roads
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
Percent of Depressions
Pavement age since overlay (years)
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12

(e)



(f)



(g)

Figure 6.5 Distress Prediction Model on Main Roads for (a) Block Cracking, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Revelling, and (g) Cracking (due to patching).

6.7 Modelling Process of Urban Secondary Roads

6.7.1 Selecting the Best Form

As discussed in 6.6.1 the most popular criterion for comparing different models is standard error of the model (MSE). Table 6.7 shows the standard error for the selected three equations for the urban secondary sections (USS).

Table 6.7 The Results of standard Error of Estimate for Comparing Three Selected Models-USS

Distress Code	Comparison Between Selected Models		
	Standard Error of Estimate		
	Equitation (1)	Equitation (3)	Equitation (9)
Block Cracks	5.97	6.15	3.536
Longitudinal & Transverse Cracking	5.74	5.27	3.203
Patching	8.95	9.33	8.289
Potholes	3.91	4.29	2.448
Depressions	6.95	6.91	2.496
Weathering & Ravelling	5.69	5.53	7.183

It can be concluded that equation 9 records the lowest values of standard error. Therefore, the proposed distress equation of the model will be:

$$y(t) = \frac{a}{e^{(\beta/t)^{\omega}}}$$

Where

α = an asymptote that controls the upper limit= 100,

β = the position of the first inflection point on the curve,

ω = a coefficient that controls the shape of the curve.

6.7.2 Method of Calculating Shape Coefficients

The nonlinear regression procedure in the SPSS software package (SPSS Manual version 16) was used to calculate coefficients for the proposed sigmoid function for each distress type. The nonlinear regression procedure allows for the specification of any equation form, any number of dependant variables and the ranges in which the dependant variables are expected to fall. Table 6.8 summarises the calculated shape coefficients for the Urban Secondary Roads distress prediction models. The proposed form has one predictor variable which is the pavement age.

Table 6.8 Shape Coefficients for Prediction Models for the Proposed Distress Equation-UUS

Distress Name	Model Shape Coefficients	
	β	ω
Block Cracks	27.768	0.598
Longitudinal & Transverse Cracking	31.830	0.491
Patching	14.179	0.415
Potholes	33.543	0.608
Depressions	30.407	0.749
Weathering & Ravelling	47.375	0.328

6.7.3 Calibration Methodology

As discussed and concluded in the chapter on descriptive and inductive analysis the pavement age is the only factor that is significant in the prediction modelling. If we consider the other predictor variable; which is drainage, the proposed distress equation would have been in the following form:

$$y(t) = \frac{a}{e^{(\delta * \beta / t)^{\omega}}}$$

Where

α = an asymptote that controls the upper limit= 100,

β = the position of the first inflection point on the curve,

ω = a coefficient that controls the shape on the curve,

δ = a modifying coefficient for drainage.

The purpose of the drainage coefficient specified in the proposed distress model is to modify the distress equation to be as accurate as possible provided the data are available. The proposed distress equation makes use of only the variables β and ω, which have numerical values calibrated to all observed data for a particular distress type. From engineering point of view, the development of pavement distress is affected by a variety of variables other than age, such as drainage. The availability of data for this variable allows the calibration of the modifying coefficients in the sigmoid models. Table 6.9 shows classification of the modifying coefficients.

As indicated earlier that the data has one predictor variable which is the pavement age time *t* and the data has one factor. The researcher designated them as modifying coefficients.

Table 6.9 Modifying Coefficients-USS

Classification of Modifying Factors			
Modifying Factors	Coefficients symbol	Modifying Variables	Categories of variable
Availability of Drainage System	δ	Drainage	Absence Presence

6.7.3.1 Numerical Values and the 95% Confidence Interval.

Each modifying coefficient was calculated by the nonlinear regression technique in SPSS. For this analysis, the model coefficients were held as constant, and the only variable under consideration was the drainage. The best fit value of each coefficient to its relevant data set was calculated. The 95% confidence interval in the parameter estimates, using the nonlinear regression procedure in SPSS, was performed on the USS database to determine which variables were significant in the prediction of each distress type, therefore drainage was examined. Table 6.10 shows that 0 within the upper and lower bounds. This means the predictor drainage cannot be assumed to be different than 0. Therefore, drainage is not significant and consequently will be not included in the modelling process. This result strongly supports the inductive and descriptive analysis results. Therefore the drainage has no influence on the distress equation.

Table 6.10 Modifying Coefficients and 95% Confidence Interval-USS

Distress Code	Numerical Values for Modifying Coefficients	
	δ	Upper and Lower 95% CI
Block Cracks	15.30	0 within the bounds for traffic and drainage
Longitudinal & Transverse Cracking	14.40	0 within the bounds for traffic and drainage
Patching	7.30	0 within the bounds for traffic and drainage
Potholes	16.50	0 within the bounds for traffic and drainage
Depressionss	20.50	0 within the bounds for traffic and drainage
Weathering & Ravelling	10.80	0 within the bounds for traffic and drainage

6.7.3.2 T-test for All the Parameters

Table 6.11 summarises the calculated shape coefficients for the Urban Secondary Roads distress prediction models and corresponding t ratio values. The t ratio is calculated by dividing the parameter estimate by the standard error for the parameter (Montgomery and Peck 1982). This result indicates that the modifying coefficient is not important in the prediction equation. Again this result support supports the inductive and descriptive analysis result.

Table 6.11 Shape Coefficients for Prediction Models with Modifying Coefficient and t test -USS

Distress Code	Model Shape Coefficients δ	β	ω	t-ratio
Block Cracks	1.384	27.000	0.598	Not Significant for the 4-parameter
Long.& Trans. Cracking	1.210	32.500	0.491	Not Significant for the 4-parameter
Patching	0.678	15.000	0.415	Not Significant for the 4-parameter
Potholes	1.276	30.000	0.608	Not Significant for the 4-parameter
Depressionss	0.900	30.000	0.749	Not Significant for the 4-parameter
Weath.& Rave.	0.913	50.000	0.328	Not Significant for the 4-parameter

6.7.4 Test of Error Distribution

The modifying coefficient may intend to make the distress prediction models more accurate as additional data on drainage was available. After calculating the best value of the modifying coefficient, its accuracy when they were used in combination was tested against the general equation. The purpose of this test was to determine whether the prediction accuracy of the distress models was significantly improved by using the modifying coefficient. The F test will be used to investigate the error distribution as discussed before in 6.6.1.

The results of the test indicate, in Table 6.12 that no significant improvement in prediction accuracy is made for all distress types. This result supports the result in the previous chapter which says the drainage should not be in the sigmoid distress prediction or should be set equal to 1.0 in the sigmoid distress prediction at this stage of the PMS implementation.

Table 6.12 Results of F-Test-USS

Test				
F-test Results				
Output of the Test	F-test		Significance	
Distress	F-Calculated	F-Tabulated	P-value	Test Result
Block Cracks	0.93	1.000	0.000	Accept Ho
Longitudinal & Transverse Cracking	0.95	1.000	0.000	Accept Ho
Patching	0.94	1.000	0.000	Accept Ho
Potholes	0.97	1.000	0.000	Accept Ho
Depressionss	0.95	1.000	0.000	Accept Ho
Weathering & Ravelling	0.94	1.000	0.000	Accept Ho

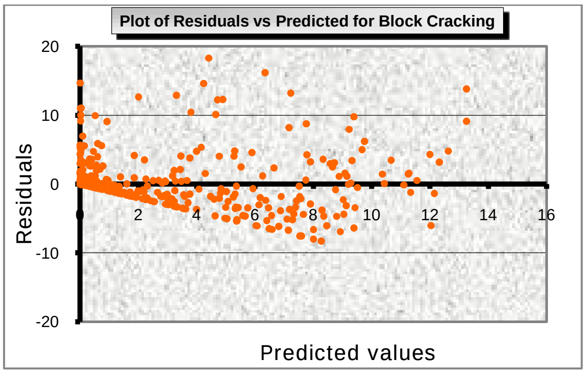
6.7.5 Importance of Pavement Age

As discussed in 6.5, age can be a surrogate for the effect of drainage in a prediction model.

6.7.6 Assessing the Selected Models

6.7.6.1 Non-Variance Constant

As discussed in 6.6.6.1.1 from this chapter, Figure 6.5 (a-f) illustrates a case in which in the variance of the error is appropriately independent of the value of each parameter. As a result, there is no big appearance change in the variation of the residuals for each distress type. Therefore, there are no obvious model defects in each distress model.



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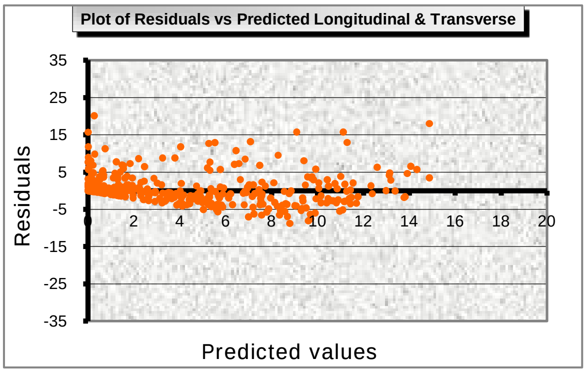

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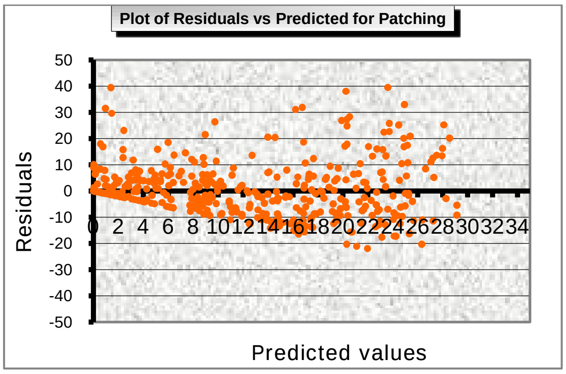

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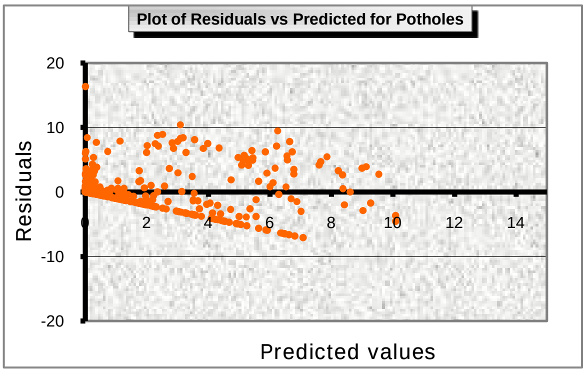

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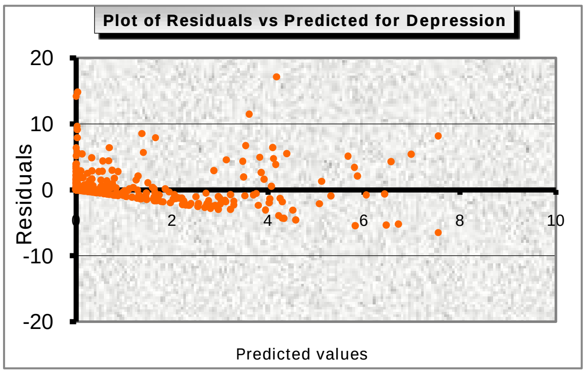

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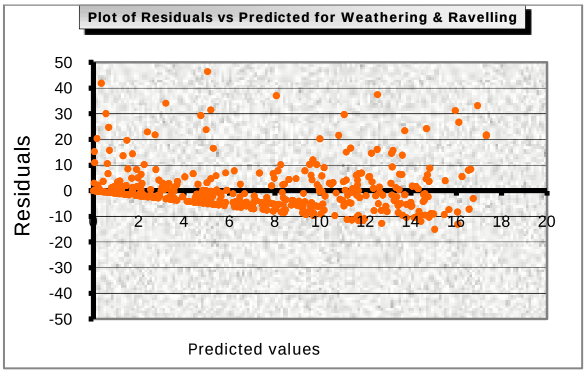
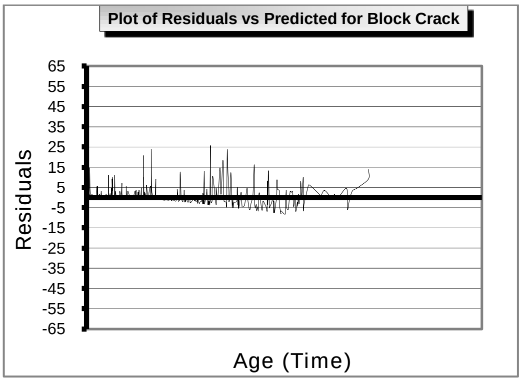


(f)

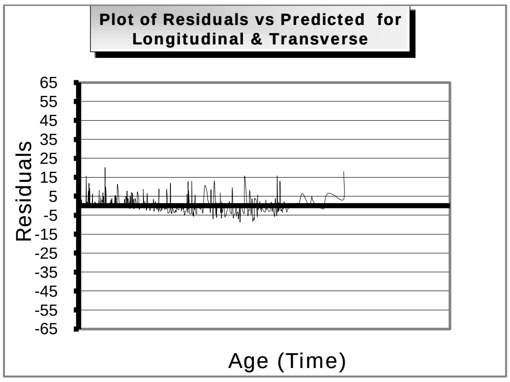
Figure 6.6 Plot of Predicted values versus Residuals (USS) for (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Ravelling.

6.7.6.2 Non-Independence of the Error Variable

As discussed in 6.6.6.1.2 from this chapter, Figure 6.6 (a-f) shows that the residuals appear to be randomly distributed over time periods for each distress.



(a)



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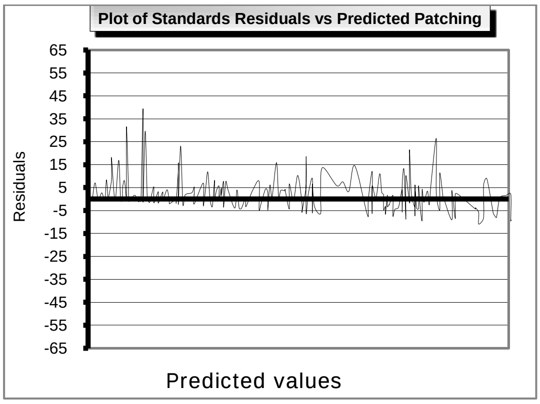

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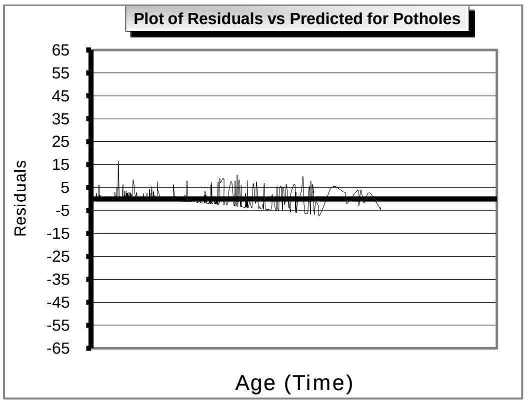

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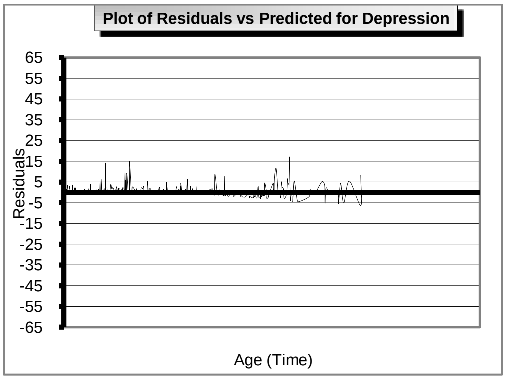

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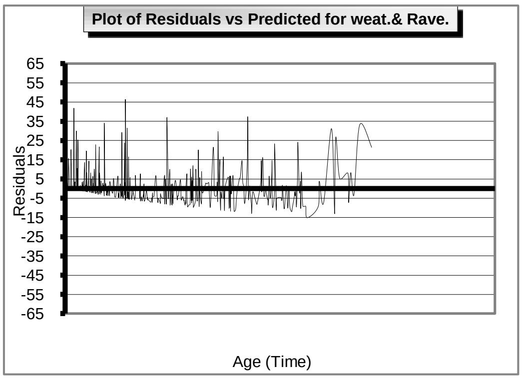
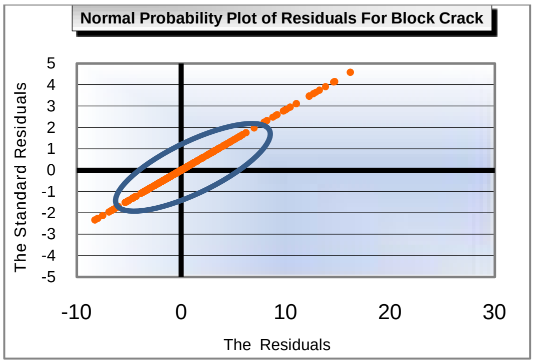


(f)

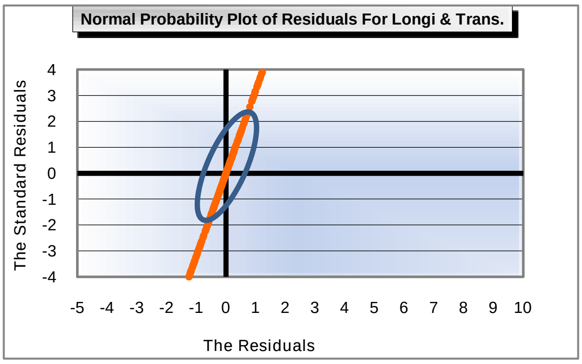
Figure 6.7 Plot of Residuals versus Time (USS) for (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Ravelling.

6.7.6.3 Non-Normality

As discussed in 6.6.6.1.3 from this chapter, Figure 6.7 (a-f) shows the points to lie along a straight line. For all distress types, most values fall between -2 and +2. This Figure, therefore, shows that the assumption about the disturbance is satisfied and therefore the model shows good accuracy.



(a)



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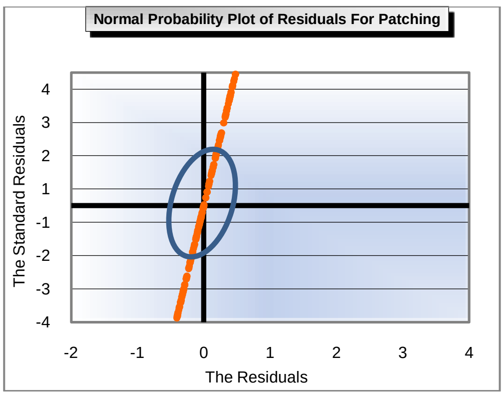

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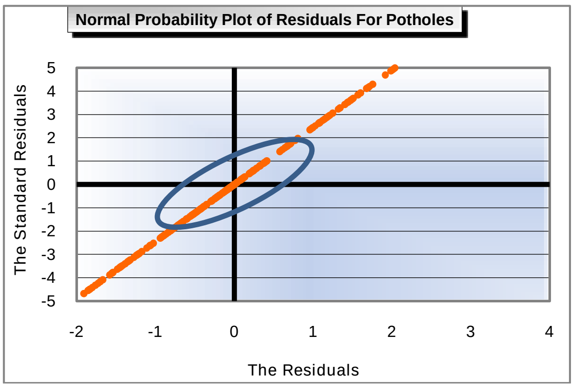

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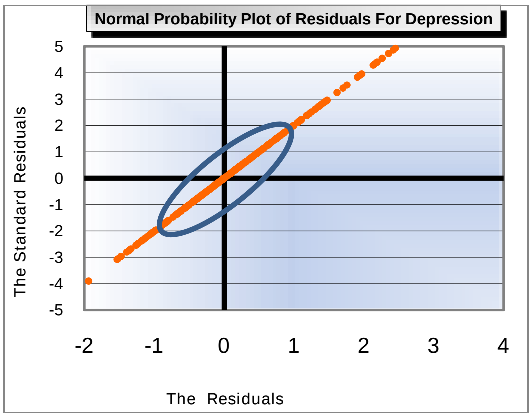

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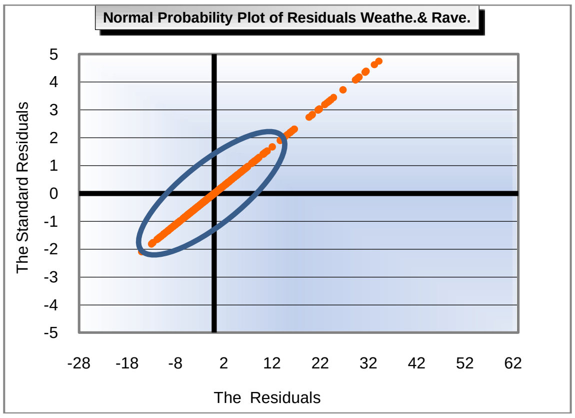
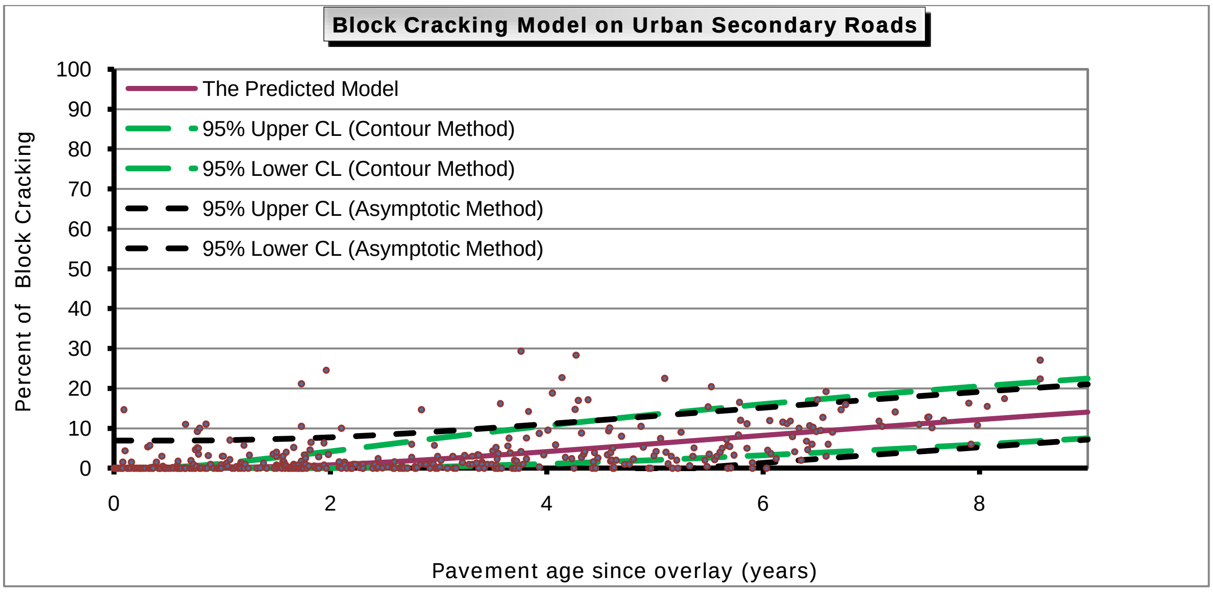


(f)

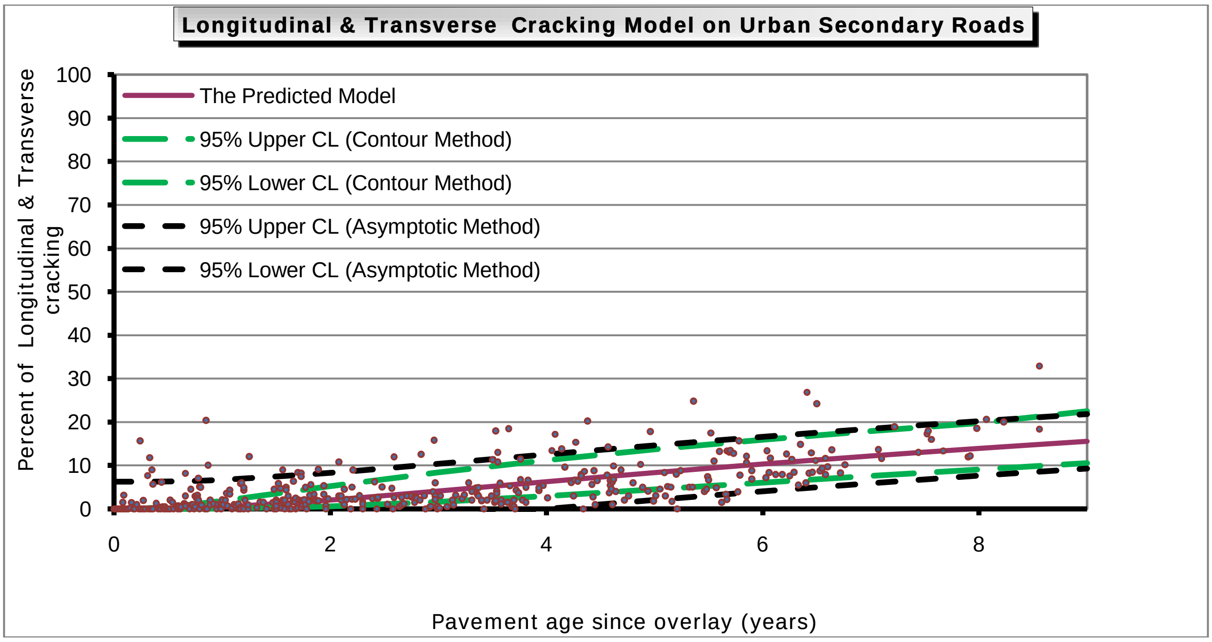
Figure 6.8 Normal Probability Plot of the Standardised Residuals (USS) for (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, and (f) Weathering & Ravelling.

6.7.7 The Developed Model

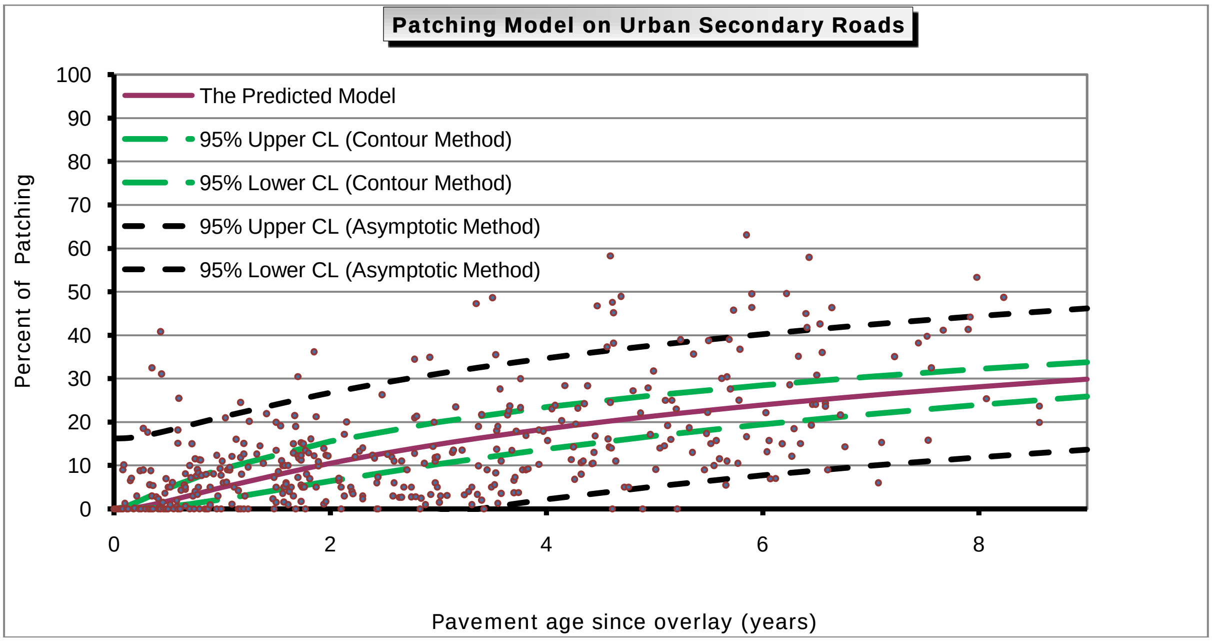
As discussed in 6.6.8, six models have been developed for urban secondary pavement distress models (USPDM) using the modified function equation 9. The models are; Block Cracking Model, Longitudinal & Transverse Mode, Patching Model, Potholes Model, Depressions Model, and Weathering & Ravelling Model. Table 6.8 section 6.7.2 summarizes the calculated shape coefficients for each distress model. It has been used for estimation or prediction. Figure 6.9 (a-g) shows the distress prediction models for each flexible pavement distress in the SAURN-USS.



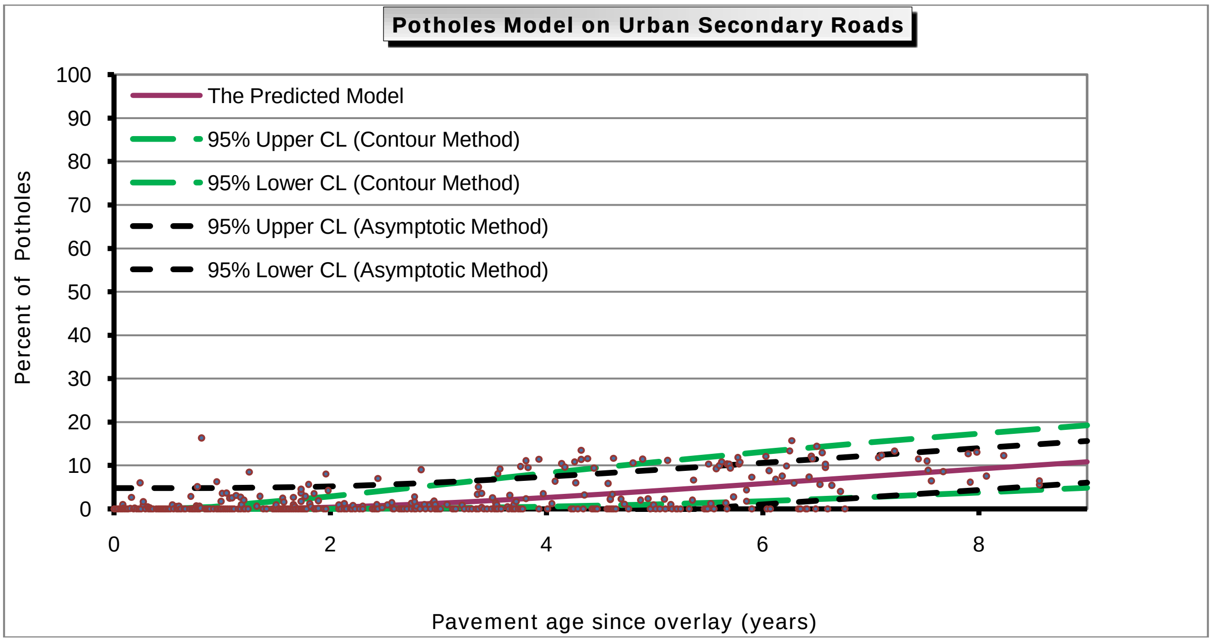
(a)


Longitudinal & Transverse Cracking Model on Urban Secondary Roads
Percent of Longitudinal & Transverse cracking
100
90
80
70
60
50
40
30
20
10
0
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
0
2
4
6
8
Pavement age since overlay (years)

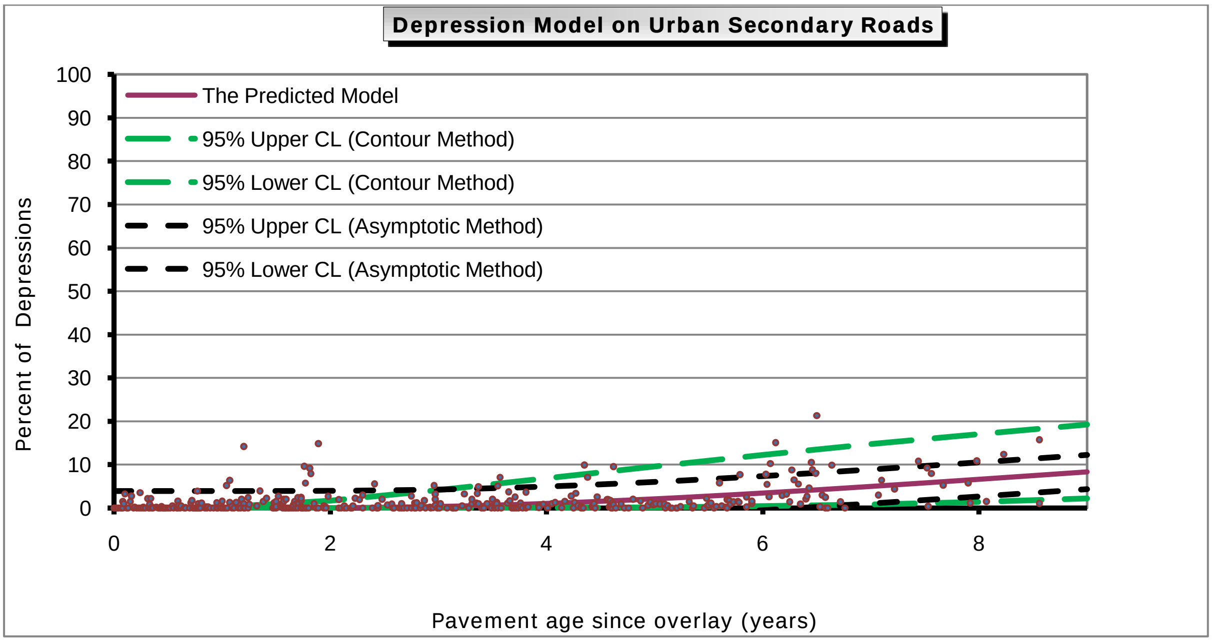
(b)


Patching Model on Urban Secondary Roads
Percent of Patching
100
90
80
70
60
50
40
30
20
10
0
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
0
2
4
6
8
Pavement age since overlay (years)

(c)


Potholes Model on Urban Secondary Roads
Percent of Potholes
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
Pavement age since overlay (years)

(d)


Depression Model on Urban Secondary Roads
Percent of Depressions
100
90
80
70
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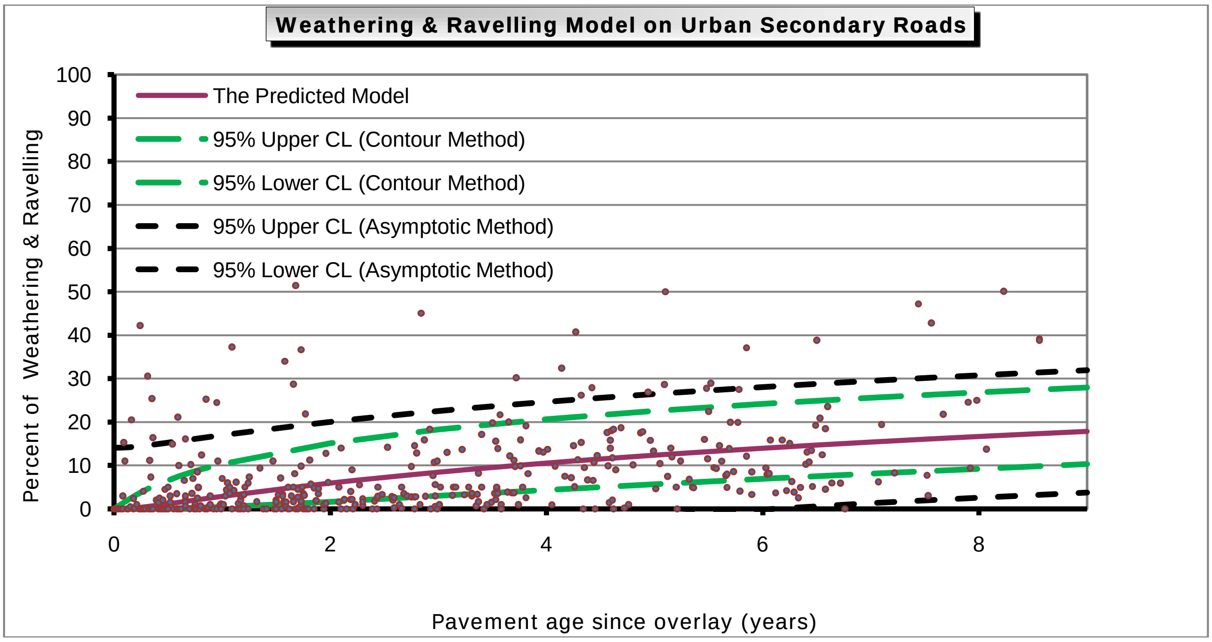
10
0
0
2
4
6
8
The Predicted Model
95% Upper CL (Contour Method)
95% Lower CL (Contour Method)
95% Upper CL (Asymptotic Method)
95% Lower CL (Asymptotic Method)
Pavement age since overlay (years)

(e)



(f)

Figure 6.9 Distress Prediction Model on Secondary Roads for (a) Block Crack, (b) Longitudinal and Transverse Cracking, (c) Patching, (d) Potholes, (e) Depressions, (f) Weathering & Revelling, and (g) Cracking.

6.8 Summary

In this study, historical data of distress on the Saudi Arabia Urban Roads Network (SAURN) have been employed in modelling the S-shape for each individual flexible pavement distress type under imposed boundary conditions. As formulated, age is a surrogate for traffic and drainage.

The developed models could provide a reasonable prediction of pavement condition. The models were assessed by standard error of estimate and residuals analysis. These models can be applied in PMS implementation by highway authorities for flexible pavements

Thirteen pavement distress models have been developed for the Saudi Arabia Urban Roads Network (SAURN). Seven for urban main pavement distress models (UMPDM) and six models for urban secondary pavement distress models (USPDM) using the following equation:

$$y(t) = \frac{a}{e^{(\beta / t)^{\omega}}}$$

Where

α = an asymptote that controls the upper limit= 100,

β = the position of the first inflection point on the curve,

ω = a coefficient that controls the shape of the curve.

In the following chapter the pavement condition models for SAURN will be investigated. The data will be analysed and then the models will be developed. The implantation of all developed models will be also detailed in the following chapter.

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CHAPTER SEVEN
APPLICATION OF DEVELOPED MODELS

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CHAPTER SEVEN
APPLICATION OF DEVELOPED MODELS

This chapter deals with pavement condition prediction models. After, a brief background this chapter highlights the factors that affect pavement condition. Then, modelling comes after analysis where two models have been developed for main roads and secondary roads. Importantly the implementation process of using the developed models was discussed. The developed models include the pavement distress models and pavement condition models.

7.1 General

The pavement condition prediction models are considered the main and the most important component in any pavement management system (PMS). They enable the road and highway agencies to plan for future years and to establish the necessary maintenance programs. The idea of this research has been to investigate the factors that affect the pavement condition of the Saudi Arabia Urban Roads Network (SAURN), to develop pavement condition models for SAURN, and to implement the pavement distress models and the condition models into a PMS for SAURN. Most of road and highway agencies that use a PMS have developed prediction models using either a theoretical approach or actual pavement data to predict current and future pavement condition. In this study, as explained in chapter 4, the data are available for a significant time period. The pavement–age prediction models are considered an excellent representation for pavement condition since other factors, notably traffic and drainage have only a minor effect on pavement condition. As discussed previously in chapter 6, pavement age is considered the crucial factor in the prediction of pavement distress as it implicitly includes the effect of both traffic and environmental factors. However, significance tests will be performed to check the effect of age, traffic, and drainage on the pavement condition. The two different classes of road behave differently as explained in chapter 3. As explained earlier the SAURN has main and secondary roads; therefore, separate models have been developed for each.

7.2 Significant Factors Affecting Condition

As explained in the chapter on database, the factors that affect pavement condition are pavement age, traffic, and availability of drainage. In the chapter on pavement distress data analysis, it has been proved that pavement age has a major effect on distress propagation whereas traffic and drainage have only a minor effect.

Since the pavement condition data are based on a mathematical formula and certain procedure as explained in chapter on database, it is preferred not to take the conclusion from the previous two chapters and ignore the significance tests on the factors. A suitably brief discussion of the effect of these factors is therefore presented to lead to the right decision before modelling.

As explained in the chapters on methodology and pavement distress data analysis, the first step in developing the pavement condition models was to identify a suitable classification scheme that would yield categories with homogenous pavement sections and an adequate number of data points. The layout of the experimental design with the data included in the model development is presented in Table 7.1.

Table 7.1 Experimental Design of Pavement Condition Models

		With Drainage System			Without Drainage System		
		Low Traffic	Medium Traffic	High Traffic	Low Traffic	Medium Traffic	High Traffic
Main Road Pavements	Young Sections (1733)	102	216	150	559	527	179
	Moderate Sections (450)	12	47	47	131	162	51
	Old Sections (147)	2	10	16	43	56	20
Secondary Road Pavements	Young Sections (420)	146	-	-	275	-	-
	Moderate Sections (143)	37	-	-	106	-	-
	Old Sections (78)	20	-	-	58	-	-

It is known that pavement age is one of the most important variables that affect pavement condition. Pavement age is measured from the date of an overlay. The scatter diagrams in Figures 7.1 and 7.2 show how pavement condition behaves with time for main and secondary roads respectively. Figures 7.3 expresses how the pavement condition behaves under different traffic levels. Figures 7.4 and 7.5 express how the pavement condition behaves with different drainage levels.

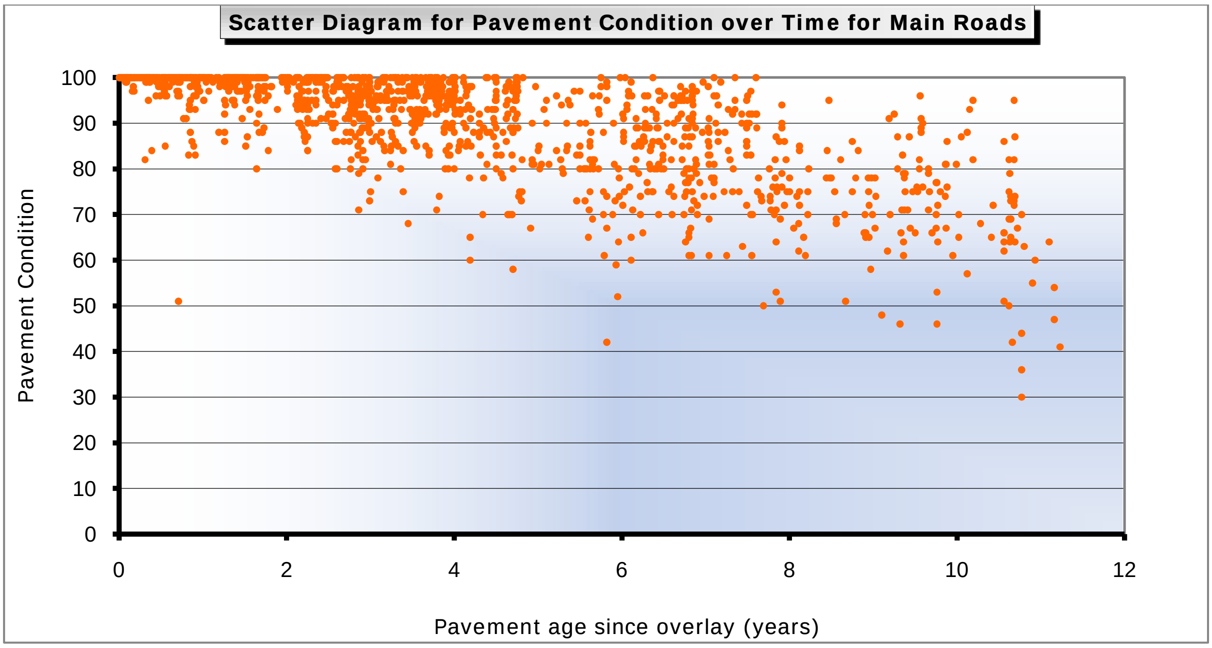

Figure 7.1 Scatter diagram for Pavement Age for Main Roads.

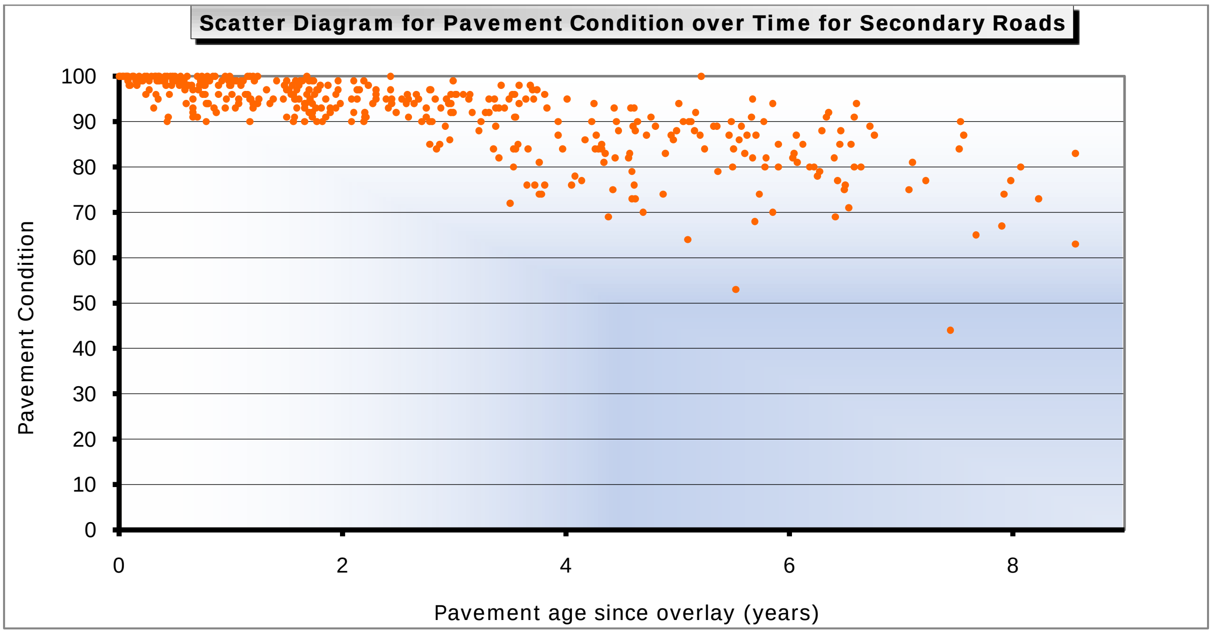

Figure 7.2 Scatter diagram for Pavement Age for Secondary Roads.

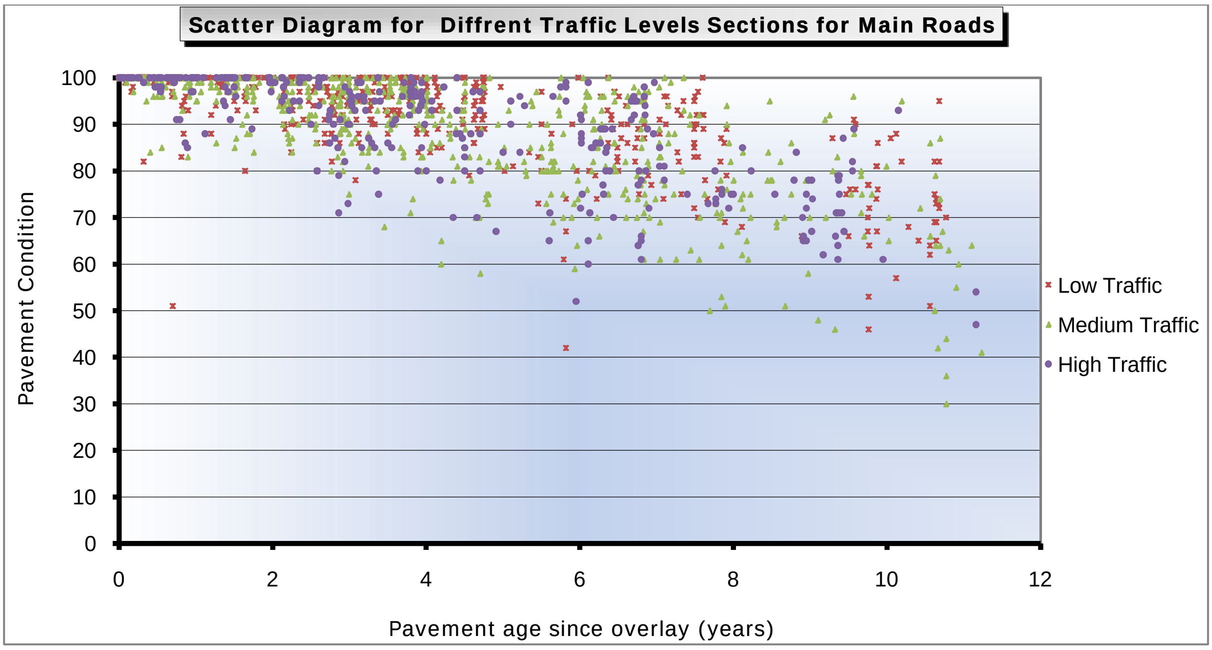

Figure 7.3 Scatter Diagram for Traffic for Main Roads.

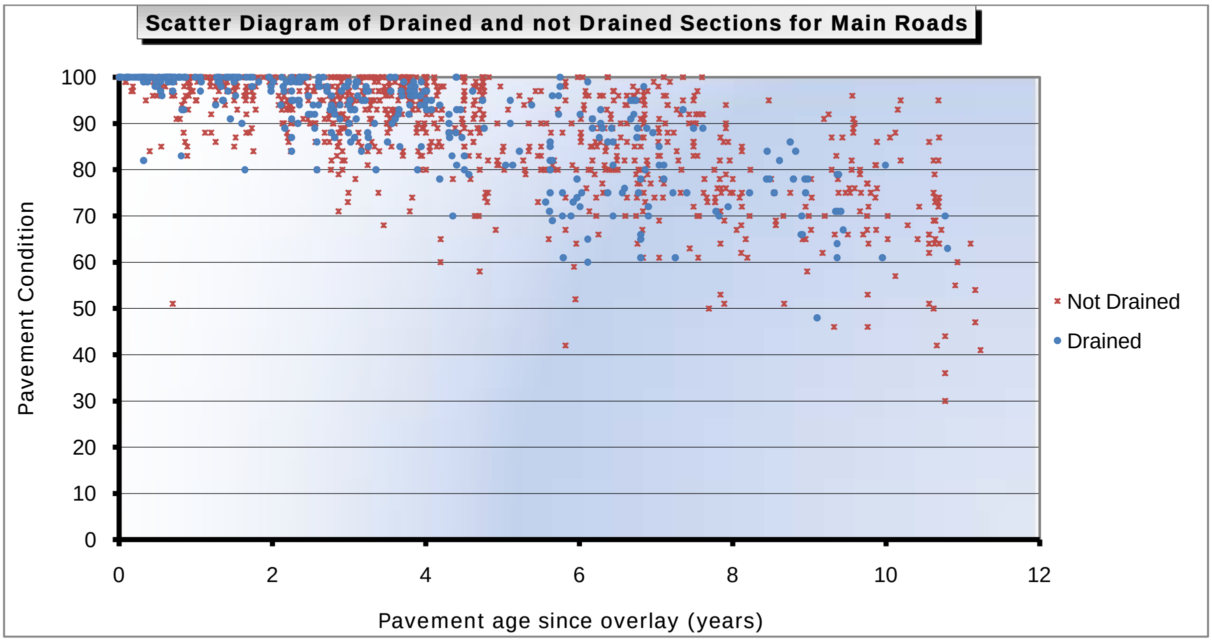

Figure 7.4 Scatter Diagram for Drainage for Main Roads.

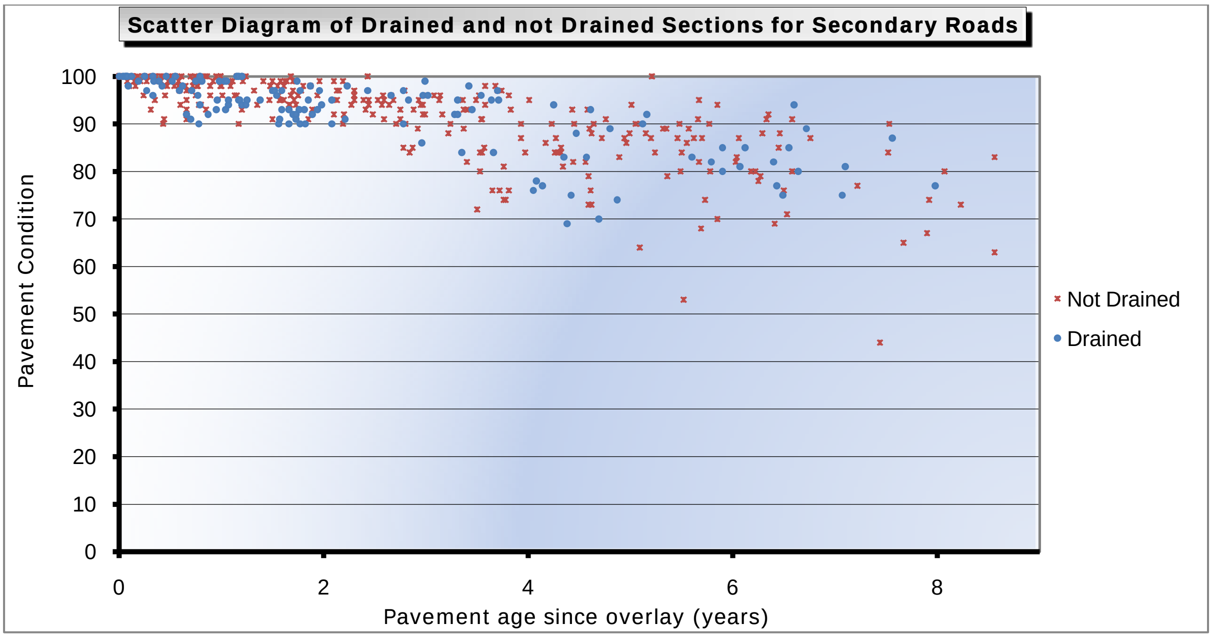

Figure 7.5 Scatter Diagram for Drainage for Secondary Roads.

Pavement sections were grouped into three categories. The average pavement condition values of pavement sections within each age group are shown in Figure 7.6 and Figure 7.7 for main and secondary roads. As expected, the average pavement condition value for old sections is the lowest among the three levels. This is true for main roads and secondary roads.

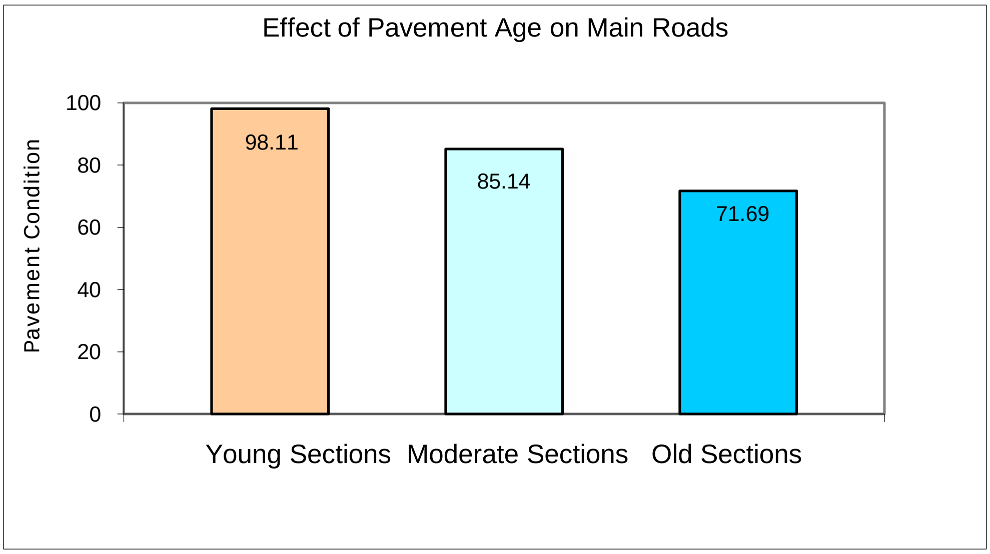

Figure 7.6 Effect on Pavement Condition of Age for Main Roads.

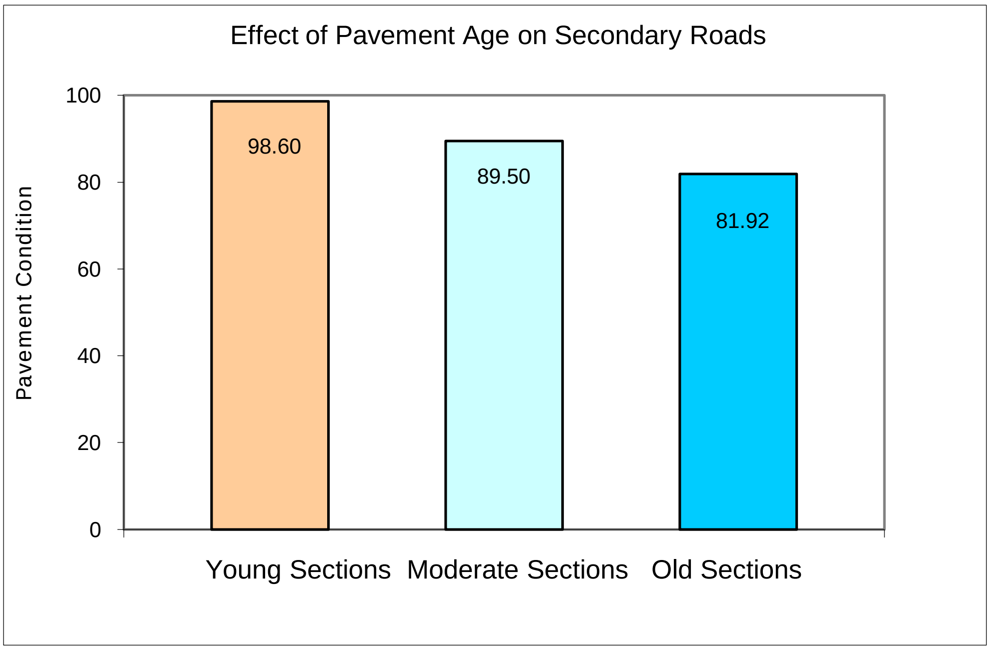

Figure 7.7 Effect on Pavement Condition of Age for Secondary Roads.

The traffic for main roads only was classified in three levels, low, medium, and high. The average pavement condition values of pavement sections within each traffic group are shown in Figure 7.8. Pavement sections tend to deteriorate more with high traffic. However, the difference shown is low.

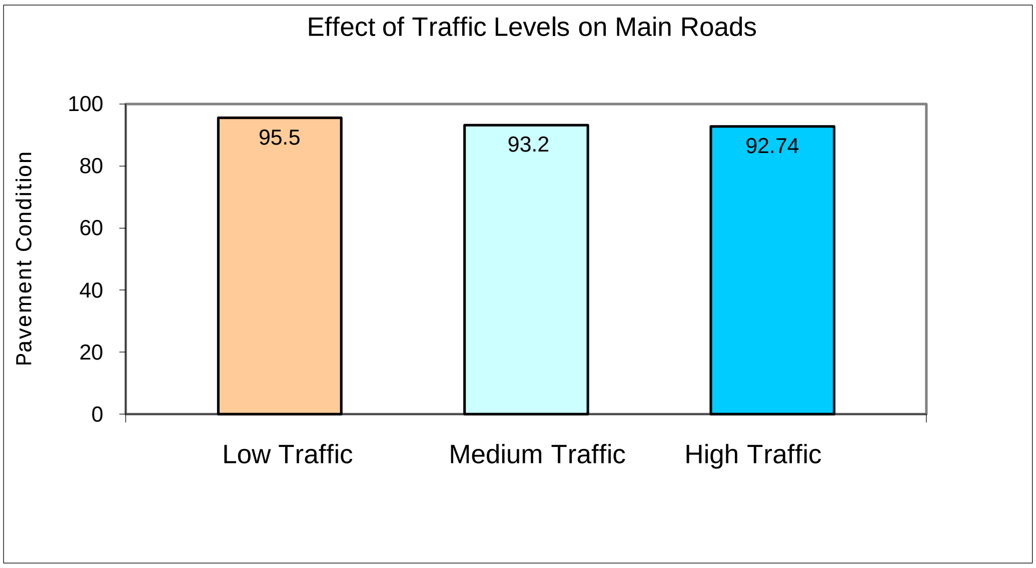

Figure 7.8 Effect on Pavement Condition of Traffic for Main Roads.

Pavement sections were also grouped into those sections with a drainage system and those sections without a drainage system. The average pavement condition values of pavement sections within each drainage group are shown in Figure 7.9 and in Figure 7.10 for main and secondary roads. The difference is very low for both main and secondary roads between the two groups.

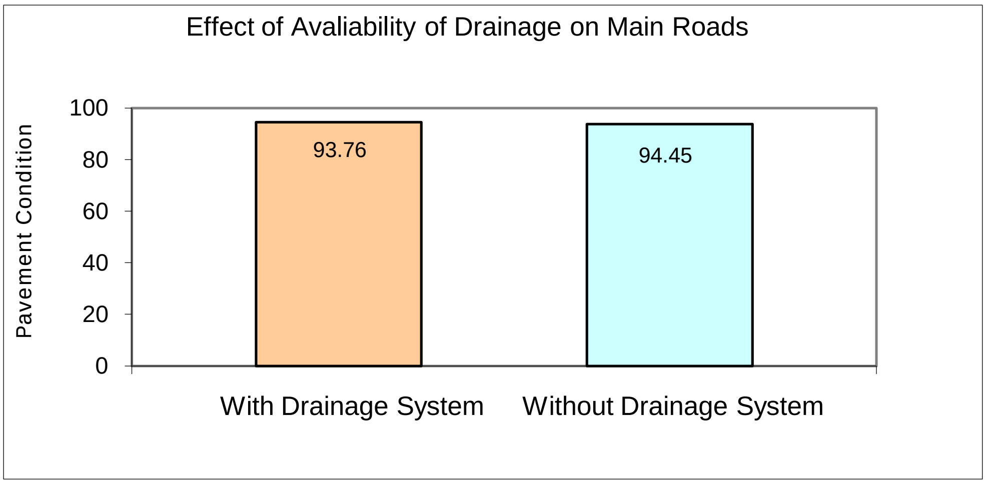

Figure 7.9 Effects on Pavement Condition of Drainage for Main Roads.

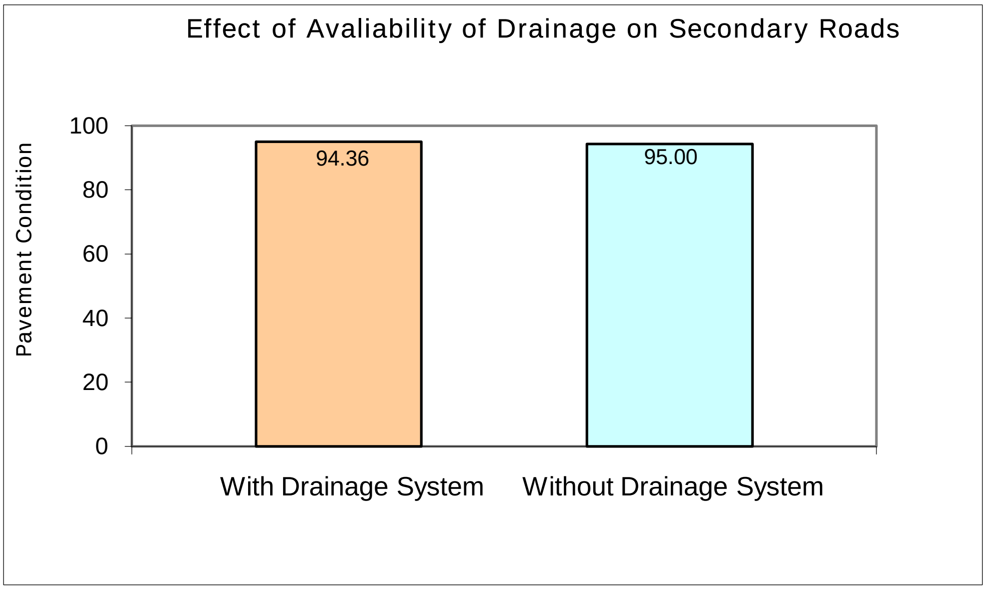

Figure 7.10 Effects on Pavement Condition of Drainage for Secondary Roads.

7.3 Normality test

As discussed in the chapter on pavement distress data analysis, the Kolmogrove–Smirnov test for pavement condition data shows that the P-values for pavement age levels, traffic levels, and drainage levels are less than 0.05. Therefore, the null hypothesis (Ho) is rejected and subsequently the data are not normal for all the three factors on main roads. Similarly, the data are not normal for pavement age and drainage on secondary roads.

However, the central limit theorem can be used here and on that basis it can be assumed that the data are normally distributed and hence the parametric test can be used to check the significance of each factor.

7.4 Test of Significance

As discussed in the chapter on pavement distress data analysis, a statistical hypothesis test for population mean was used to determine the factors that significantly affect pavement condition.

7.4.1 Pavement Age

The ANOVA F test and Post Hoc test have led to a rejection of the null hypothesis (Ho). Therefore, pavement age plays an important role in pavement condition on main and secondary roads.

7.4.2 Traffic

The ANOVA F test and Post Hoc test have led to an acceptance of the null hypothesis (Ho). Therefore, traffic plays a minor role in pavement condition compared to pavement age on main roads.

7.4.3 Drainage

The Two samples *t-test* has led to an acceptance of the null hypothesis (Ho). Therefore, drainage plays a minor role in pavement condition compared to pavement age on main and secondary roads.

7.5 Residual Analysis

Three important tests have been investigated to check model accuracy, namely: the constant variance test, independency of the error with time, and normality. The following Figures show the three tests for main and secondary roads. Each test indicates reasonable model accuracy. For example, Figures 7.11 and 7.14 illustrate that the variance of the error is independent, in other words the change in variation of the residuals is acceptable despite many zero points are there. Figures 7.12 and 7.15 show the error values are independent with time, in other words, time indicated independence and the residual show random behaviour. Figures 7.13 and 7.16 show that most the standardised residuals values fall between -2 and +2. This indicates normality is satisfied. To conclude, the selected function is appropriate function to model the pavement condition for SAURN.

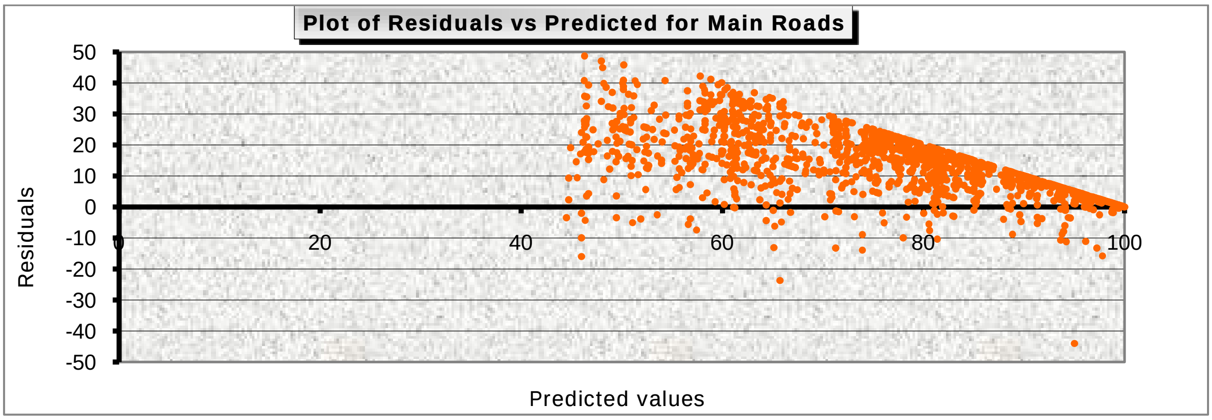

Figure 7.11 Plot of Predicted Values versus Residuals for Main Roads.

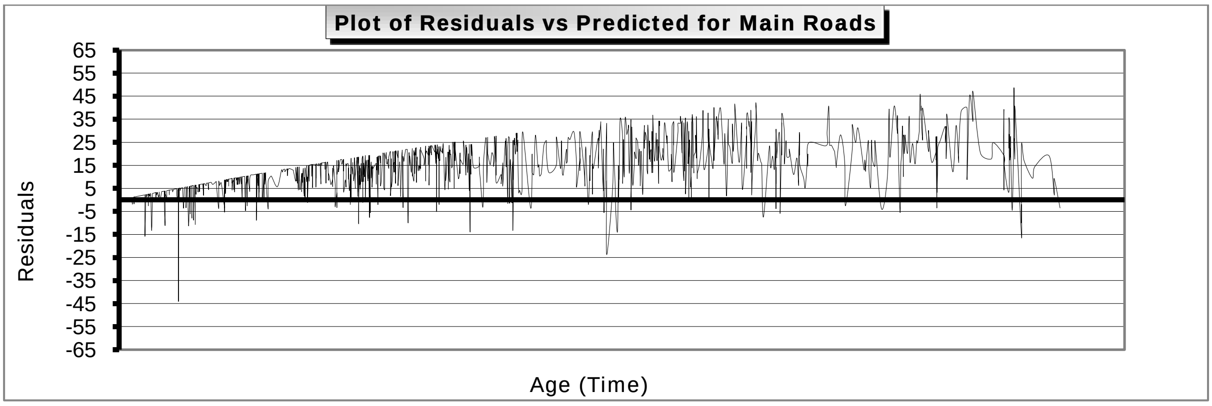

Figure 7.12 Plot of Residuals versus Time for Main Roads.

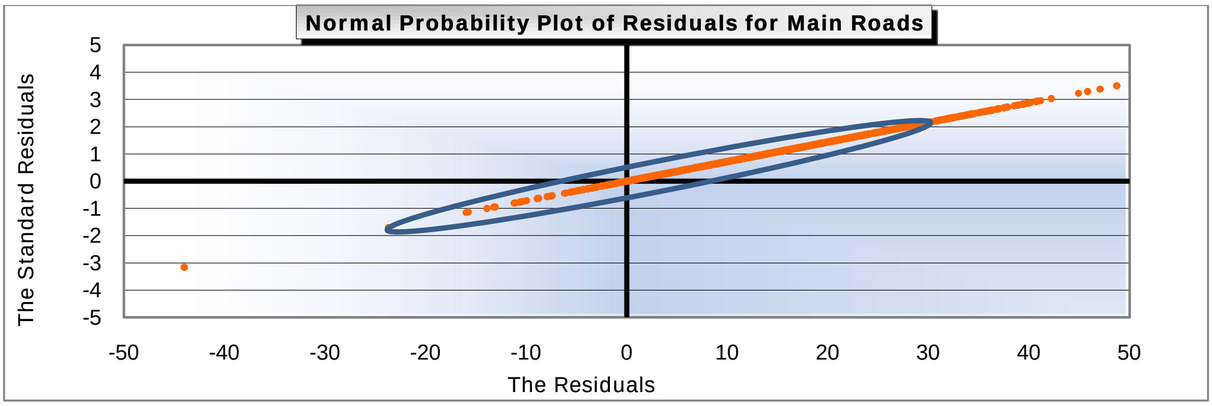

Figure 7.13 Normal Probability Plot of Residuals for Main Roads.

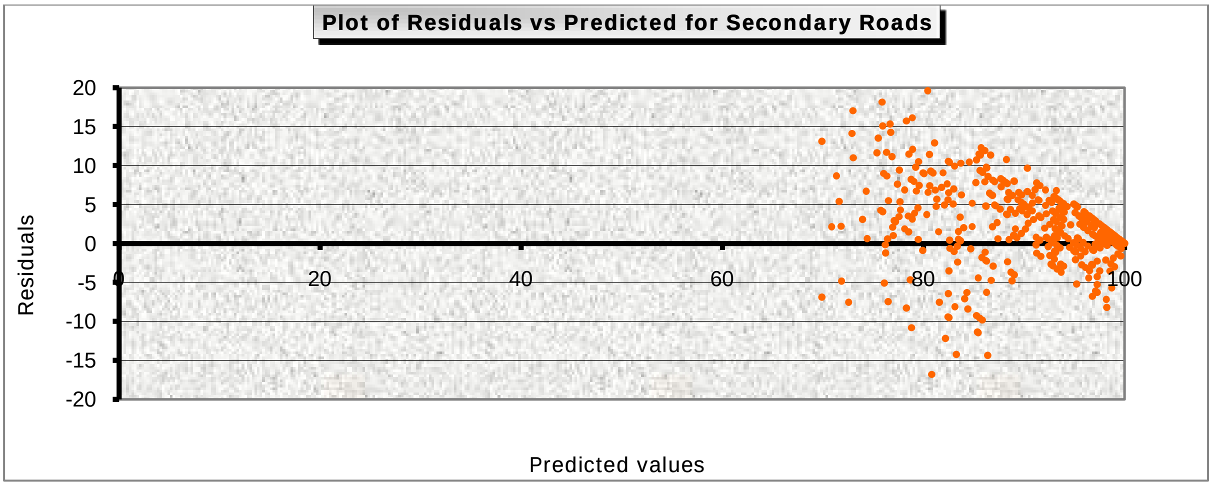

Figure 7.14 Plot of Predicted Values versus Residuals for Secondary Roads.

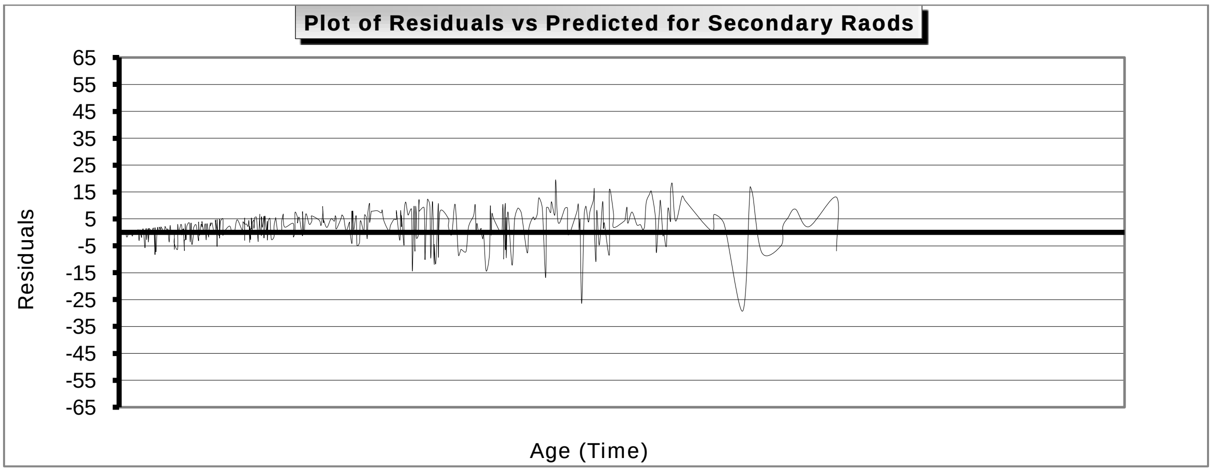

Figure 7.15 Plot of Residuals versus Time for Secondary Roads.

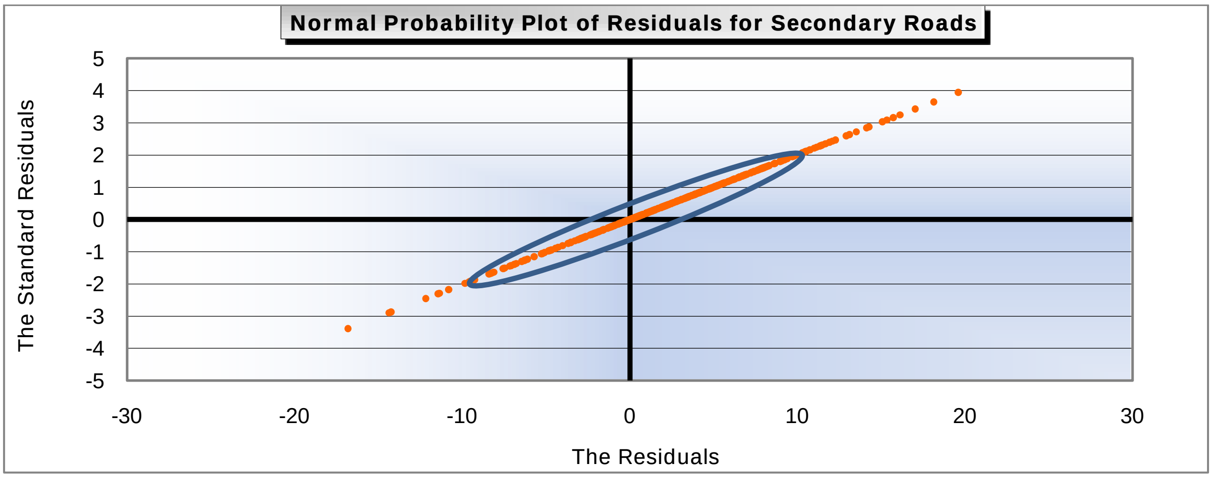

Figure 7.16 Normal Probability Plot of Residuals for secondary Raods.

7.6 Modelling

As explained in the chapter on pavement distress models, the s-shape curve fitting technique is useful when predicting the change in a variable, as a function of pavement age. However, the boundary conditions need to be stated in view of engineering principle s before modelling:

- The initial pavement condition value is 100.
- Pavement condition has a slope that is initially zero.
- Pavement condition deterioration is an irreversible process; the slope must always show a worsening of condition unless a treatment is applied.
- Pavement condition has a final slope of zero; damage reaches the horizontal line at 0.
- The pavement condition value for any damage should not be negative at any value of pavement age.

It is expected that the form of model developed for pavement distress will also express better for pavement condition.

$$y(t) = \frac{a}{e^{(t/\beta)^{\omega}}}$$

Where

α = an asymptote that controls the upper limit = 100,

β = the position of the first inflection point on the curve,

ω = a coefficient that controls the shape on the curve.

The two constants were determined using a regression analysis as discussed in the chapter on pavement distress models. The following Table shows a summary of values and the model standard errors. Figure 7.17 and 7.18 show the models developed for main and secondary roads. The 95% confidence limits for the data and for the model accuracy are also plotted.

Table 7.2 Estimated Regression Parameters of Prediction Models

Pavement Condition			$y(t) = \dfrac{a}{e^{(t/\beta)^{\omega}}}$		
Road Class	Overall Model Statistics		Estimated Parameters		
	N	S.Error	α	β	ω
Main Roads	2330	6.912	100	20.589	1.485
Secondary Roads	601	5.001	100	26.121	1.093

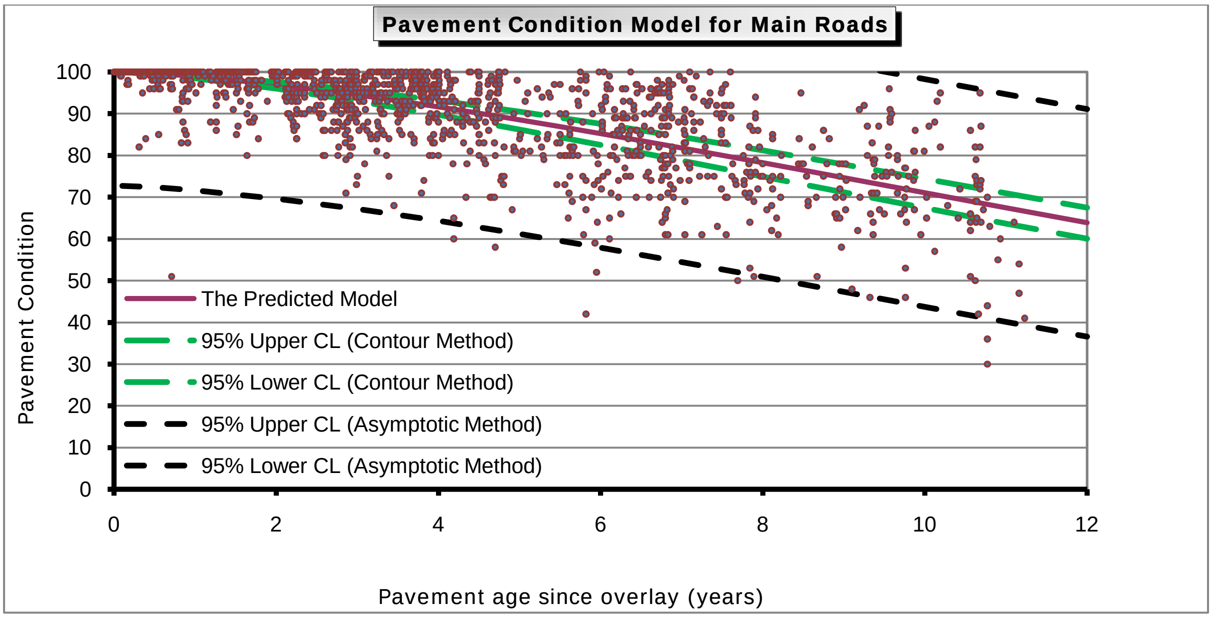

Figure 7.17 Urban Main Pavement Condition Model (UMPCM).

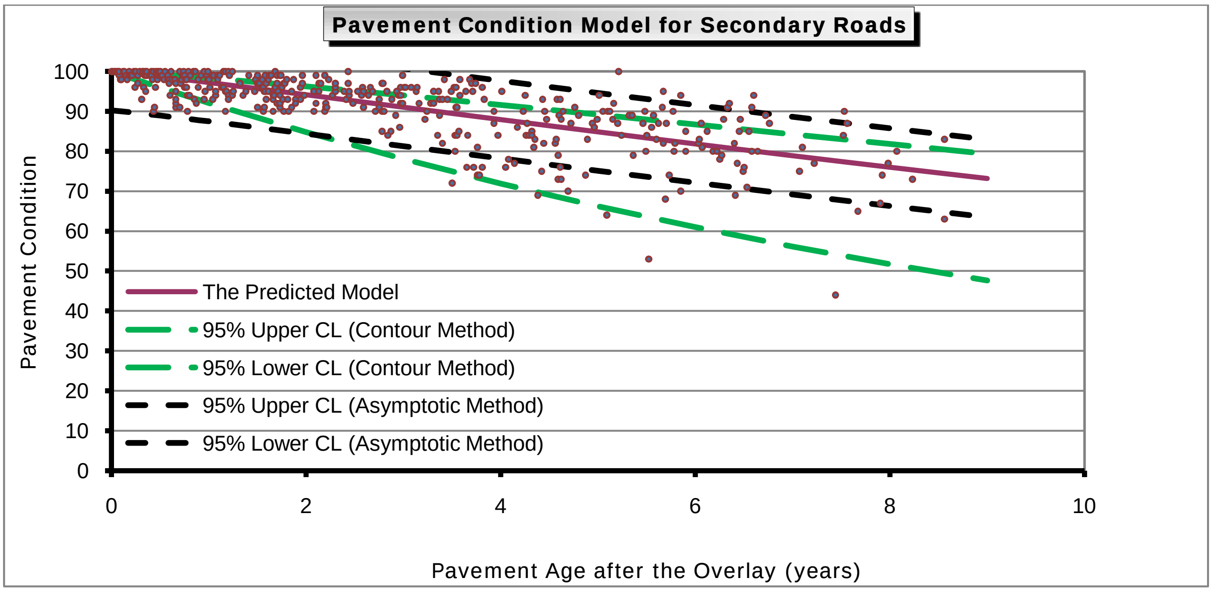

Figure 7.18 Urban Secondary Pavement Condition Model (USPCM).

7.7 Models Comparison

In a study performed by Shiyab (2007), for the use of PMS, some models for urban roads were developed. The study showed that the exponential function and polynomial function were found to have good fit with general data trends with sufficient accuracy to satisfy the general boundary conditions applied to the deterioration of the pavement system which had been stated on the methodology chapter. Some of the developed model as follows:

Local Residential

$$PQI = 100e^{-0.011\,Age}$$

$$PQI = 100 - 0.276Age - 0.030Age^2$$

Where PQI = pavement quality Index

Local Commercial

$$PQI = 100e^{-0.015\,Age}$$

$$PQI = 100 - 0.408Age - 0.035Age^2$$

Where PQI = pavement quality Index

Another study that used sigmoid and power functions for modelling overlaid sections was carried out by Adel et al (1996), as follows.

The power form is

$$DMR = 100 - 5.17(Age)^{0.58}$$

Where DMR = Distress Maintenance Rating

The sigmoid Form is

$$DMR = 100 - 43.96e^{\left(\frac{-2.49}{Age^{-0.56}}\right)}$$

From the point of view of comparison between the models developed for Saudi Arabia Urban Roads and those from the above studies, three points will be discussed. Comparison will be conducted in the light of the mathematical form, presentation of the data, and boundary conditions.

Sigmoid functions presuppose that the growth rate is dependent on pavement distress density and has an inflection and one upper limit and lower limit. The exponential functions have their variable as the power (or exponent) while in the power function, the variable is the thing that's being raised to a power. A polynomial function consists of a variable raised to integer exponents and multiplied by different coefficients, and has multiple elements. A polynomial function will end up with positive or negative infinite value which fails to satisfy the boundary conditions in road deterioration modelling. No function can satisfy the boundary condition except the sigmoid function. The five different functions were plotted together for comparison in Figures 7.19 and 7.20. The power and exponential functions show good representation for this study but cannot satisfy the boundary condition of the study. To conclude, the developed sigmoid function in this study is more appropriate than the exponential, polynomial, or power functions. In addition, the developed sigmoid function for this is more practical versus the sigmoid function (Virginia's Model) developed by other study. Because the Virginia's model will never reach zero value or even small values as pavement gets older. Consequently the output of applications of such model in a PMS will lead to wrong decisions.

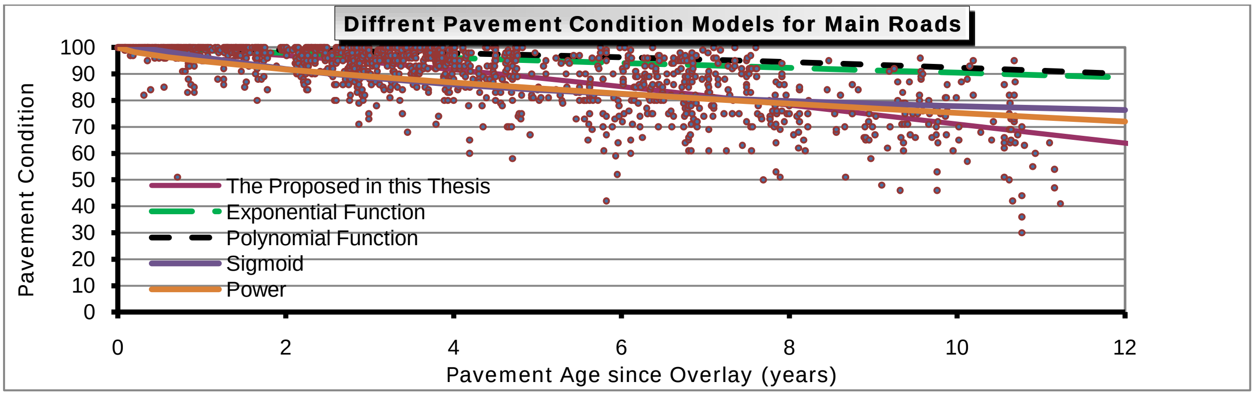

Figure 7.19 Comparisons of Five Different Models for Main Pavement Condition Roads

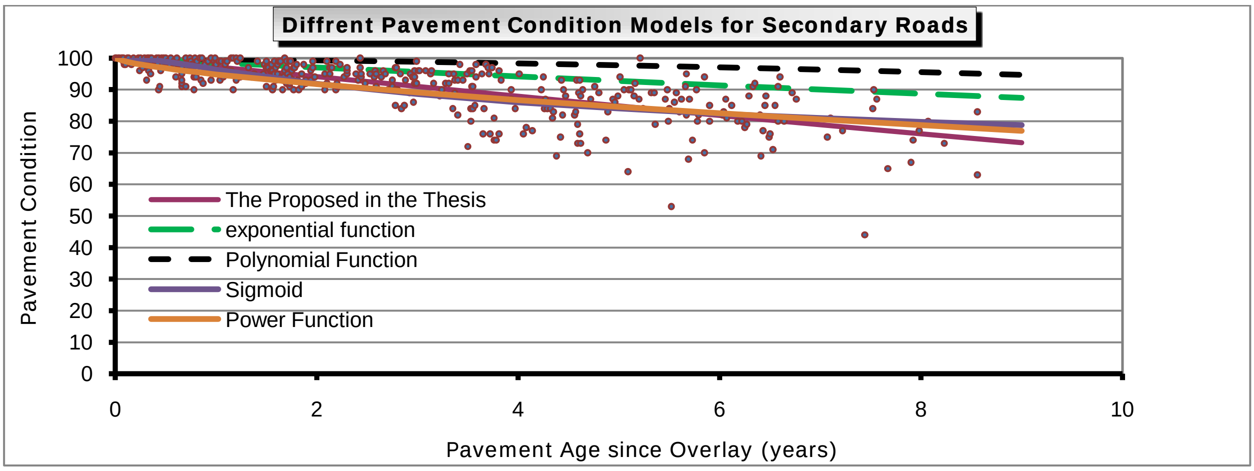

Figure 7.20 Comparisons of Five Different Models for Secondary Pavement Condition Roads

With regard to pavement distress models, the comparison will be to one other model only due to lack of other work in this topic. The following two models were selected from the Texas pavement system for comparison (Robinson et al. 1996). Both the Texas model and the developed model are sigmoid functions. Conclusions from the comparison are limited because the derivation of the distress values may be different (e.g. in terms of severity levels and weighting). However, Figure 7.21, for patching model, shows similar form of deterioration trend with pavement age but a higher level of distress in the developed model for this study. Figure 7.22, for longitudinal model, shows the progression of distress is different between the models; both models start same progression but Texas model shows more accelerating to higher levels compared to the developed one for this study.

Patching Model (Texas) = 478.60*exp [-(150)/t) ^.37]

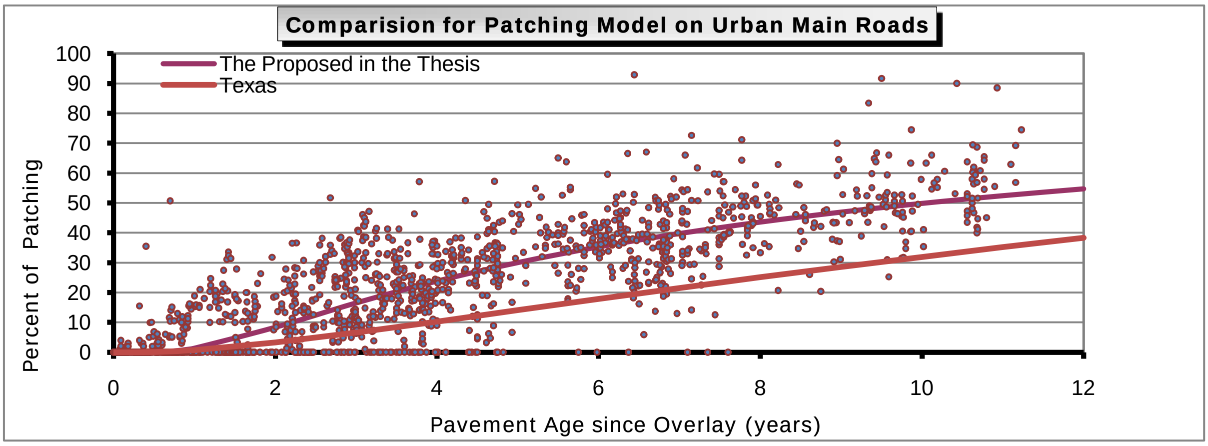

Figure 7.21 Comparison of two Different Models for Patching Model on Main Roads

Longitudinal Model (Texas) = 34.47*exp [-(240)/t) ^.52]

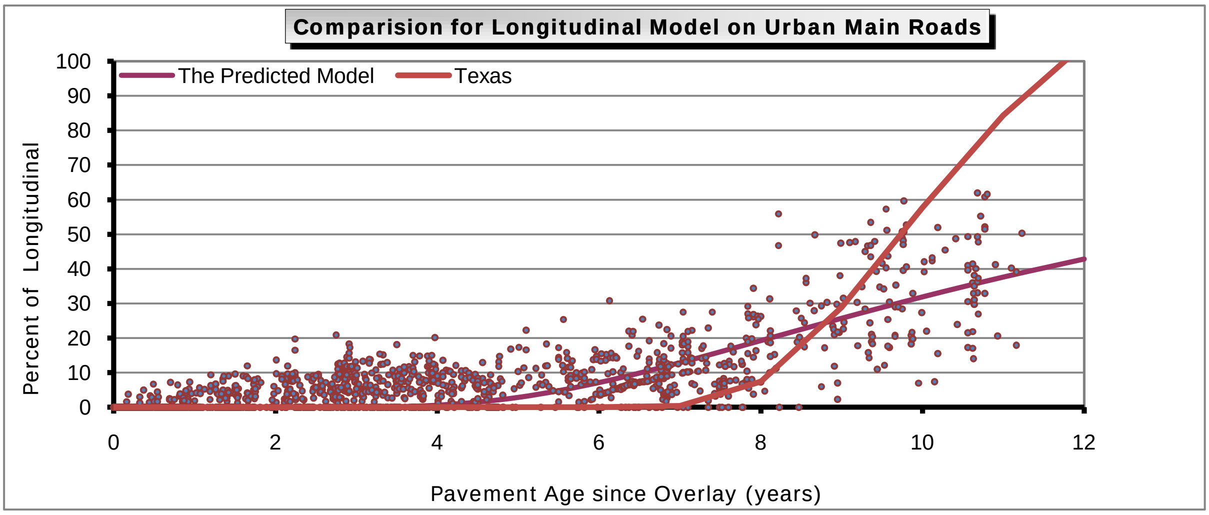

Figure 7.22 Comparison of two Different Models for Longitudinal Model on Main Roads

7.8 Applications

In this subsection, the following points would be discussed.

- The correlation between the distress types and its applications.
- The correlation between pavement condition and distress types and its applications.
- Suggested Maintenance Programs.
- Components of a Maintenance Program.
- Maintenance treatments based on network level.
- Maintenance treatments based on project level.
- Damage Contribution to Pavement Condition.
- Priority Setting Procedure.

7.8.1 Distress Types Correlation

Correlation analysis between distress types has been investigated. The Correlation coefficient provides a measure of the association between any two variables. It has a value between +1 and -1. Perfect statistically independent variables have a correlation coefficient value of zero (Walpole et al. 2001).

Table 7.3 shows the correlation matrix for main roads for any two distress types occurring together on the same section at the 99 % significance level. Table 7.3 shows that potholes (D5) have a relatively high correlation (85%) of occurring together with weathering & Ravelling (D11) whereas depressions (D6) have a relatively low correlation (54%) of occurring together with longitudinal & transverse (D3). For example, there is 83% correlation between block cracking (D2) and weathering and ravelling (D11) and a Figure of 74% between patching (D4) and potholes (D5). Generally distress types are approximately dependent of each other. Table 7.3 also point out that the depressions are significantly less dependent on other distress types.

Table 7.3 Correlation Values between Distress Types on Main Roads

	D2	D3	D4	D5	D6	D11	D12
Block Cracking (D2)	1.00	0.69	0.83	0.76	0.58	0.83	0.78
Longitudinal & Transverse Cracking (D3)	0.69	1.00	0.69	0.74	0.54	0.78	0.71
Patching (D4)	0.83	0.69	1.00	0.74	0.57	0.83	0.80
Potholes (D5)	0.76	0.74	0.74	1.00	0.58	0.85	0.76
Depressions (D6)	0.58	0.54	0.57	0.58	1.00	0.59	0.57
Weathering & Ravelling (D11)	0.83	0.78	0.83	0.85	0.59	1.00	0.81
Cracking (due to patching) (D12)	0.78	0.71	0.80	0.76	0.57	0.81	1.00

Table 7.4 shows the correlation matrix for secondary roads for any two distress types occurring together on the same section at 99% significance level. For example, there is 60% correlation between longitudinal & transverse cracking (D3) and potholes (D5). The Figure 50% between patching (D4) blocks cracking (D2). Also, for example, when there are depressions (D6), correlation with other distress types is lower.

Table 7.4 Correlation Values between Distress Types on Secondary Roads

	D2	D3	D4	D5	D6	D11
Block Cracking (D2)	1.00	0.69	0.50	0.58	0.45	0.57
Longitudinal & Transverse Cracking (D3)	0.69	1.00	0.65	0.60	0.57	0.61
Patching (D4)	0.50	0.65	1.00	0.51	0.44	0.54
Potholes (D5)	0.58	0.60	0.51	1.00	0.51	0.51
Depressions (D6)	0.45	0.57	0.44	0.51	1.00	0.42
Weathering & Ravelling (D11)	0.57	0.61	0.54	0.51	0.42	1.00

The correletation test shows that there is a colinearity between distress types. Co-linearity is a situation where there is close to a near perfect linear relationship among some or all of the independent variables. In other words, some degree of redundancy between the variables is present and it makes interpretation more difficult. .

In Tables 7.3, and 7.4, the correlation coefficient between distress types with each other values vary from 0.42 to 0.85. Interpretation is difficult in this situation, because these distress types were found on the road network by different shapes, severities, and quantities in which they dropped the pavement quality by different weights. It is hard to envision what it means to change or reduce the number of distress types while these distress types are existed. It should be noted, though, that the data make sense, even co-linearity is present. However, this could be interpreted to mean that distress types should be combined on urban roads. However, experience from range of road authorities over the world (Al-Swailmi and Al-Abd Wahab 2001) have not recommended this approach. Because the nature of pavement distress types on urban roads are highly varied and they are less correlated to traffic. On other hand, reducing the distress types is reasonable on rural roads. Because of pavement distress types on rural road are less varied especially when the environmental factors, construction standards, and traffic are the same.

7.8.2 Pavement Condition Correlation.

The relation between the rate of pavement deterioration and the propagation of each distress can be investigated through the correlation test. Table 7.5 shows that there is a high correlation between pavement condition (UDI) values and distress density values for each distress types on main roads least for depressions. The negative value designates that the relation is an inverse. As distress density propagates, as pavement condition deteriorates. The Table also shows that all distresses are correlated to the pavement condition by more than 70% except depressions by more than where 50%.

Table 7.5 Correlation Values between Distress Types and Pavement Condition on Main Roads

	Correlation Value Based on Pavement Condition (UDI)
Block Cracking (D2)	-0.76
Longitudinal & Transverse Cracking (D3)	-0.72
Patching (D4)	-0.78
Potholes (D5)	-0.74
Depressions (D6)	-0.53
Weathering & Ravelling (D11)	-0.77
Cracking (due to patching) (D12)	-0.75

Similarly Table 7.6 shows that there is a slightly less correlation between pavement condition (UDI) values and distress density values for each distress types on secondary roads compared to main roads.

Table 7.6 Correlation Values between Distress Types and Pavement Condition on Secondary Roads

	Correlation Value Based on Pavement Condition (UDI)
Block Cracking (D2)	-0.67
Longitudinal & Transverse Cracking (D3)	-0.79
Patching (D4)	-0.77
Potholes (D5)	-0.60
Depressions (D6)	-0.52
Weathering & Ravelling (D11)	-0.64

7.8.3 Maintenance and Rehabilitation Programs

The definition of maintenance varies among road agencies. According to Haas (1994), in a physical sense, maintenance consists of a set of preventive activities directed toward limiting the rate of deterioration of a structure, or corrective activities directed toward keeping the structure in a serviceable state.

For pavement, this includes such preventive as crack sealing and such corrective work as patching. In an administrative sense, maintenance may be separated from rehabilitation by budgetary identification. Since the time, type, frequency, and degree of maintenance on pavements can significantly influence performance, a complete pavement management system (PMS) must therefore include maintenance and rehabilitation. A prime relationship of maintenance to PMS is to provide cost information associated with various levels of planning and programming, design, and construction.

A major objective of developing the pavement distress models and pavement condition models for Saudi Arabia Urban Road Network (SAURN) is to assist the municipalities in making consistent and cost effective decisions to maintain the city network at an acceptable level of service.

Although there are many maintenance activities and options where each option provides a measurable benefit to the network, every municipality has limited available funds and it has a large number of roads, and therefore every municipality should identify the right treatment to the right pavement at the right time. This strategy insures the maintenance program to be cost effective.

The municipalities across Saudi Arabia can use UMPDM and UMPCM to set up a maintenance management system (MMS). A maintenance management system (MMS) is a technique or operational methodology for managing or directing and controlling maintenance resources for optimum benefits (TAC 2002). The current maintenance alternatives practiced in municipalities across Saudi Arabia are crack sealing, and overlay. However, in systems developed for municipalities across the world, there are many options, which may be grouped under headings such as localized safety, localized preventive, global preventive and major maintenance and rehabilitation (M&R) (Shain 2002).

The ‘localized safety’ category represents localized distress repairs needed to keep the pavement operational in a safe condition, such as deep patching for potholes. ‘Localized preventive’ represents maintenance activities performed with the primary objective of slowing the rate of deterioration, such as crack sealing. ‘Global preventive’ applies to entire pavement sections, also with the primary objective of slowing the rate of deterioration, for example slurry sealing. Major M&R activities also apply to entire pavement sections to correct or improve existing structural or functional requirements, activities such as reconstruction and structural overlays.

In this thesis maintenance is classified according to maintenance programs. Namely, the first program is corrective maintenance, the second program is preventive maintenance, the third program is structural overlay work, and the final program is reconstruction.

Corrective Maintenance Program:

Corrective Maintenance consists of activities carried out for the purpose of slowing the rate of pavement deterioration and keeping the pavement in a safe and operational condition. Adoption of this strategy requires that the pavement is structurally sound. The types of maintenance included in this program are patching and/or crack sealing. Therefore, visual inspection is required for selection at project level.

Preventive Maintenance Program:

The corrective maintenance program tends to slow the pavement deterioration process. However, this program will not be cost effective when the pavement deteriorates beyond a certain period and a preventive maintenance program is then performed. The types of work included in this program are slurry sealing and/or thin overlays. The prime objective of a preventive maintenance program is to hold the pavement condition above the critical level. The application of a preventive maintenance program below the critical pavement condition may not be cost effective (Sharaf et al. 1987, Al-Mansour et al. 1993, and FCM and NRC 2003). Many agencies have found that applying a series of preventive maintenance program extends the service life of pavements. Several US agencies have initiated a joint effort to promote preventive maintenance programs (FCM and NRC 2003). However, the practise of preventive maintenance is relatively weak in Saudi Arabia municipal agencies

Structural Overlay Program:

Structural overlay is dependent on the structural adequacy of the pavement section and it is normally applied when pavement condition is below the critical value. The Structural overlay thickness should not be more than 8 cm; if greater thickness is needed then reconstruction is likely to be more cost effective.

Reconstruction Program:

Reconstruction is adopted when the pavement condition is far below the critical value, or when the required overlay is more than 8 cm.

7.8.4 Components of a Maintenance Program

As discussed previously, municipalities are responsible for the preservation of many roads. Thus, procedures need to be developed to identify those sections that would benefit most from a preventive maintenance program, to identify pavement needs in a timely manner, and to select the most beneficial treatment. Figure 7.23 shows a suggested flow chart plan to insure cost effectiveness of maintenance treatment. The flow chart contains three important pillars or components in a maintenance program. They are the pavement, time, and the treatment. The flow chart suggests steps under each component. In this study, the measures that have been used for identifying the current and future needs include the following:

- Urban Main Pavement Condition Model (UMPCM).
- Urban Secondary Pavement Condition Model (USPCM).
- Urban Main Pavement Distress Models (UMPDM), seven models are available.
- Urban Secondary Pavement Distress Models (UMPDM), six models are available.

7.8.5 Maintenance Treatments Based on Network Level

7.8.5.1 The Methodology Approach

Identifying deficient pavement sections can be subjective, based on judgment of the engineer. However, a more systematic approach, especially on network level, could be followed to provide an objective basis for identifying the current and future needs, and to provide consistency in the comparison of pavement sections. In addition to that, criteria also exist at project level and these are useful in terms of specifications for quality and assurance purposes, or for assessing contractor performance. Assigning critical levels or trigger values for pavement condition is significant in modern pavement management. Usually, on the scale of 0 to 100, where 100 represents a new pavement, most, if not all, road agencies all over the world assign one minimum recommended condition level typically (50 or 55) to prevent the need for major maintenance; in other words, to save the investment in road infrastructure (Shain 2002).

Suggested Plan to Insure the Right Treatment to the Right Pavement at the Right Time

The Right Pavement

STEP ONE
All Pavement Sections Must be Inventoried

STEP TWO
All Pavement Sections Must be Surveyed to Know:

Distress Types	Distress Severity	Distress Density

This study has developed models for each distress type on SAURN

Urban Main Pavement Distress Models (UMPDM)

. Block Cracking Model
. Longitudinal & Transverse Cracking Model
. Patching Model
. Potholes Model
. Depressions Model
. Weathering & Ravelling Model
. Cracking (due to patching) Model

Urban Secondary Pavement Distress Models (USPDM)

. Block Cracking Model
. Longitudinal & Transverse Cracking Model
. Patching Model
. Potholes Model
. Depressions Model
. Weathering & Ravelling Model

The Right Time

STEP ONE
Pavement Condition Models Must be used

This study has developed two pavement condition models to extrapolate the future:

Urban Main Pavement Condition Model (UMPCM)
Urban Secondary Pavement Condition Model (USPCM)

STEP TWO
Timely Maintenance Program

Construct a maintenance construction program in a timely manner based on step one

STEP THREE
Dedicating Funding

Funding for maintenance programs must be made available in time because timing is essential for achieving cost effectiveness

The Right Treatment

STEP ONE
Determine the Possible Treatment

Based on Experience, the following treatments are suggested

. Shallow Patching
. Deep Patching
. Slurry Seal
. Thin Overlay (3-5 cm)
. Mill & Repave
. Structural Overlay (8 cm)
. Reconstruction

STEP TWO
Treatment selection for individual sections

Based on UMPCM and UMPDM for Main Roads
Based on USPCM and USPDM for Secondary Roads
Based on Time Since Construction or Major Rehabilitation

Based on Cost Effectiveness

STEP THREE
Select the Most Promising Treatments especially the preventive maintenance program

By help of

1. Cost -Benefit Evaluation

Cost effectiveness is a ratio of unit costs and benefits (additional years the pavement is expected to last)

2. Life-cycle cost

The municipalities must consider the following:
The preventive maintenance program postpones more expensive treatment
The preventive maintenance program must be done without delay in time
The cost of preventive maintenance program must be paid without delay because money has changing economic value over time.

STEP FOUR
Listing the Priorities

A priority listing of all maintenance program needs especially the preventive program because the amount of recommended work may exceed the available funds.

STEP FIVE
Selection of Materials and Construction Methods

Practice guides and manuals must be provided

Figure 7.23 Flow Chart of A Maintenance Plan.

In this study, the proposed methodology is based on the assumption that it is more economical to maintain pavements above rather than below the critical pavement condition. The critical pavement condition can be defined as a pavement condition value or index at which the rate of the pavement condition loss increases with associated increase in the cost of applying maintenance. However, in order to implement the proposed methodology evidence from real practise is needed. This experience is not available at present and so the approach proposed is to develop a family of curves for different maintenance strategies and to monitor the cost of each maintenance strategy. Considerations of the effect of applying different strategies are important; applying major maintenance will increase the pavement condition of the pavement to 100; applying preventive maintenance is likely to increase the life of the pavement section (but to less than 100), applying corrective maintenance is not likely to increase the life of the pavement section but it will ensure safe operation. Furthermore, it will be necessary to perform many life cycle cost analyses on different projects. Therefore, it is recommended that a study of extended pavement life due to preventive maintenance types is carried out in order to draw a family of curves for every possible treatment and to select the critical levels based on a scientific approach and engineering judgment rather than only on engineering judgment.

The proposed methodology suggests three intervention levels rather than one level. The first level accounts for corrective maintenance to ensure safety issues; the second level accounts for preventive maintenance to ensure cost effectiveness; the third level accounts for structural overlay or reconstruction (major maintenance) to ensure saving of the investment in road infrastructure. Therefore, by assigning these three critical levels, the aim is to minimize the maintenance spending. For the time being, the assigned levels are based on a general knowledge of the maintenance types and they are suggested as interim values to be used until all the necessary information becomes available. Similarly, this can be true for maintenance treatment at a project level. At project level, road agencies suggest maintenance treatment based on distress density and severity. However, this study has proposed distress density propagation models to be used as interim guidance. These models need to be verified with time and linked to pavement condition models, to be useful for practical engineers.

7.8.5.2 Urban Main Pavement Condition Model (UMPCM)

Generally the road agencies assign a critical level or trigger value for pavement condition. This trigger value is based on experience and judgement. However, in this thesis, two critical pavement condition levels and one minimum recommended pavement condition have been assigned for the model. The systematic way to determine the critical levels and the minimum recommended level is from the developed models. Specifically, the critical value is usually defined as the pavement condition value below which the pavement condition deteriorates rapidly and should ideally be determined from prediction models.

Based on the mechanism of the deterioration rate of UMPCM, a suggested or a recommended value for the first critical pavement condition values is 90. This first critical value requires that the pavement is structurally sound, which is usually the case, and no structural overlay is needed (TAC 2002). This study suggests the first critical pavement condition to be at 90 and the second critical pavement condition is 70 for two reasons. The first is the behaviour of the deterioration rate from 100 to 70, this assumption based experience on Riyadh network where deflection test can used to judge about structural condition of the pavement (1998b). The second reason is that the pavement is usually structurally sound before 70. However, the treatments are not same for the two critical levels. Corrective would be adequate between 100 and 90 whereas preventive maintenance adequate between 90 and 70. The selection of corrective and preventive maintenance types is based on visual inspection at project level. However, the aim of corrective maintenance as discussed earlier is to slow the rate of pavement deterioration and to keep the operational condition safe. This study suggests that the corrective maintenance types could be applied, such as patching or crack sealing (visual inspection) for pavement sections with condition in the range of 100 to 90 for three reasons. The aim of corrective maintenance is to keep the operation of traffic smooth, and the cost of shallow patching, deep patching, and crack sealing is reasonable and cost effective because the pavement condition is excellent. Preventive maintenance types could be applied for pavement sections that have condition values between 90 and 70 for three reasons. The first is to slow the deterioration rate such that condition does not go below 70 in a short time period, in other words to hold the pavement condition above the critical level because application of a preventive maintenance program below the critical pavement condition may not be cost effective, as discussed previously. The second is that many agencies have found that applying a series of preventive maintenance program extends the service life of pavements (Al-Mansour et al. 1993).

This study suggests another critical value called the minimum recommended condition in addition to the previous levels. After the second critical has been passed, it is no longer cost effective to use corrective or preventive maintenance. Structural overlays of thickness 8 cm or reconstruction are more likely to be cost effective because there is real structural damage which could be confirmed by deflection test. An overlay of 8 cm should be performed for pavement sections that have not yet reached a minimum recommended condition. The minimum recommended pavement condition is 50 for main roads for three reasons. The first is that when the pavement condition is below 50 where the pavement condition is poor condition; this indicates that the pavement is not structurally sound and overlays or reconstruction are most likely to be cost effective. The second is that a structural overlay is dependent on the structural adequacy of the pavement section and should therefore normally be applied when the pavement condition is below the critical value of 70.

However, deflection measurement is useful here and allows a decision as to whether the pavement is structurally sound or not; for example, in some cases where the pavement condition is between 70 and 50, the pavement is still structurally sound but, to improve the ride quality, a thin overlay (preventive maintenance) may be applied. Furthermore, deflection measurements are useful to determine the required overlay thickness. This study suggests that a high structural overlay thickness (>8 cm) should not be adopted, instead reconstruction would be more cost effective (RPM 1998b).

Figure 7.24 shows the relationship between the pavement condition and the four maintenance programs. The Figure depicts two critical pavement conditions and minimum recommended condition. The critical pavement conditions are 90 and 70, and the minimum acceptable level is 50.

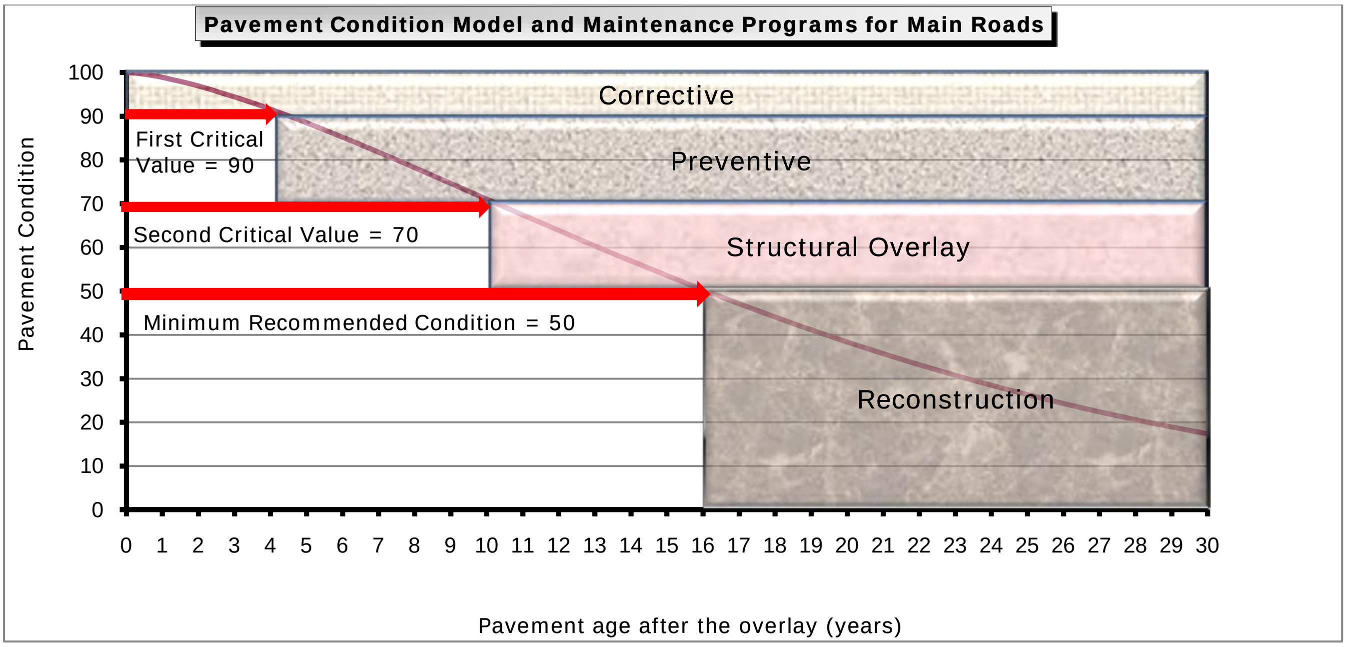

Figure 7.24 Pavement Condition Model and Maintenance on Main Roads.

7.8.5.3 Urban Secondary Pavement Condition Model (USPCM)

Similarly, but based on the USPCM, one critical pavement condition level and one minimum recommended pavement condition have been assigned for the model. This initial suggestion is that a critical condition for secondary roads could be 60. This critical value requires that the pavement is structurally sound; this is usually the case for secondary roads where these roads are accommodating only low traffic volumes, and no structural overlay is needed. Implementation of the corrective maintenance would be adopted until the selected critical pavement condition is reached. The preventive maintenance such as thin overlay (3-5 cm) should be applied because there is a real damage after the critical value has been passed. In addition to that, this study suggests minimum recommended condition to be 40 because the pavement condition must be poor condition and consequently the structural overlay is the most cost effective.

The critical and the minimum levels are less for secondary compared to main roads. For example, the minimum recommended condition is used to trigger applications of reconstruction and structural overlay on main roads and secondary roads respectively. Furthermore, there are two critical levels before the minimum recommended level for main roads whereas only one critical level before the minimum recommended level, therefore, the preventive maintenance would be applied after the first critical condition level which is 90 for main roads whereas the preventive maintenance would applied after a critical level at 60. The reason behind that is basically because the importance of the road is different for the road users. The main roads are more important than secondary in terms accommodating traffic volumes, and therefore, the behaviour of the deterioration is not the same. Assigning different condition levels for two different classes of road are useful in planning maintenance budget where the main roads are needed more maintenance compared to secondary roads, also they are useful in selection of maintenance treatments that are feasible. For example, structural overlays are more feasible for main roads for pavement condition value of 60, but for same pavement condition value would likely result in thin overlays (preventive maintenance) being cost effective for secondary roads. It is very obvious the cost of structural overly is very high compared to thin overlay. Figure 7.25 shows the relationship between the pavement condition and the three maintenance programs. The Figure depicts both critical pavement condition and minimum acceptable level of service. The critical pavement condition is 60 and the minimum acceptable level is 40. However, the structural condition needs to be confirmed by deflection test and then by the maintenance priority the decision will be taken.

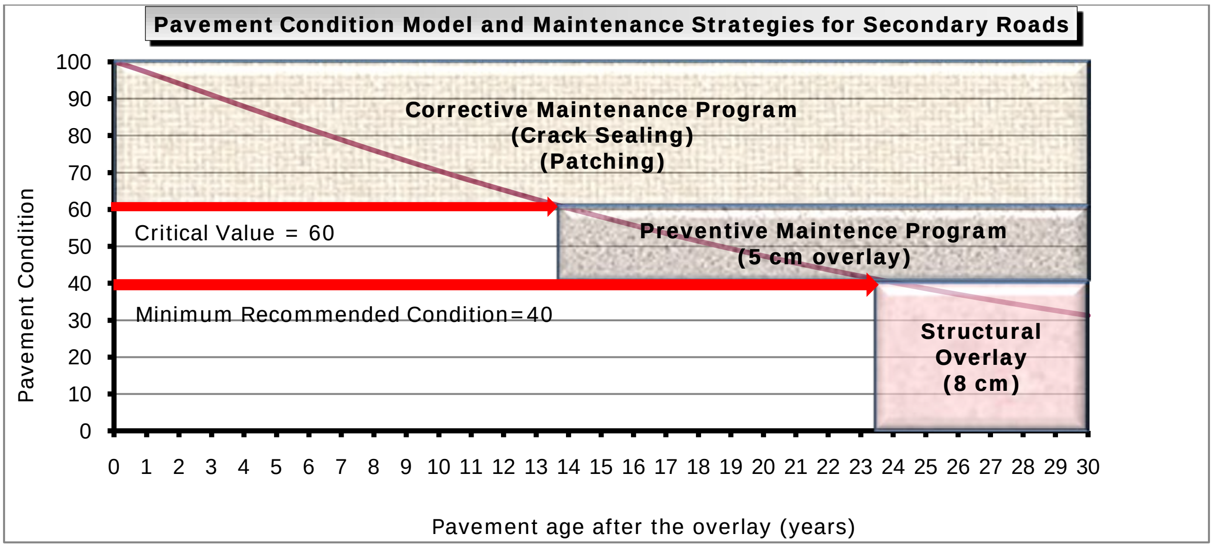

Figure 7.25 Pavement Condition Model and Maintenance on Secondary Roads.

7.8.6 Maintenance Treatments Based on Project Level

The suggested guidelines and plans are adopted from reports published by well known organization like American Association of State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), Department of Transport (DOTs), Transportation Association of Canada (TAC). Most of these organizations proposed maintenance treatment based on severity level and distress density whereas in this study the proposed methodology is based on the distress density from the developed models. They are also based on local practise and experience, international practise and experience, and engineering judgement (Al-Mansour et al. 1993).

7.8.6.1 Urban Main Pavement Distress Model (UMPDM)

7.8.6.1.1 Suggested Plan for Block Cracking

Figure 7.26 shows how the maintenance programs progress from simple to complex applications. Table 7.7 shows guidance on maintenance treatment for block cracking on main roads at project level. In early pavement life, shallow patching and deep patching can be effective in maintaining the pavement. Shallow patching is suitable for repairing minor surface defects. When shallow patching is not feasible or desirable, deeper patching can be used. If the pavement is affected by no more than an amount up to 5% of block cracking, the shallow patching can fix these defects. From 6% to 15%, it is more appropriate to repair by deep patching and/or crack sealing. The application of a slurry seal will significantly extend the life of a pavement by protecting the under surface from the effects of ageing and the environment.

From the block cracking model, the good time to apply slurry seal is at 4.5 to 10 years when the block cracking density is between 15 % and 30% because slurry seal is a more cost effective solution in that particular time range or at that particular density. Many studies including the Strategic Highway Research Program (SHRP) Project H-101, Experiment SPS-3, and the National Cooperative Highway Research Program (NCHRP) Synthesis 223 found slurry seal to be useful treatment (FCM and NRC 2003). The NCHRP Synthesis study concluded that the most cost effective pavement management strategy is to perform preventive maintenance on the better rated pavements first and then fund the rehabilitation of poorer rated pavements.

If we ignore preventive maintenance, block cracking damage will increase to a point where a structural overlay (8 cm) or reconstruction is the only solution, not a desirable option for the municipalities. Figure 7.26 and Table 7.7 explain the above discussion.

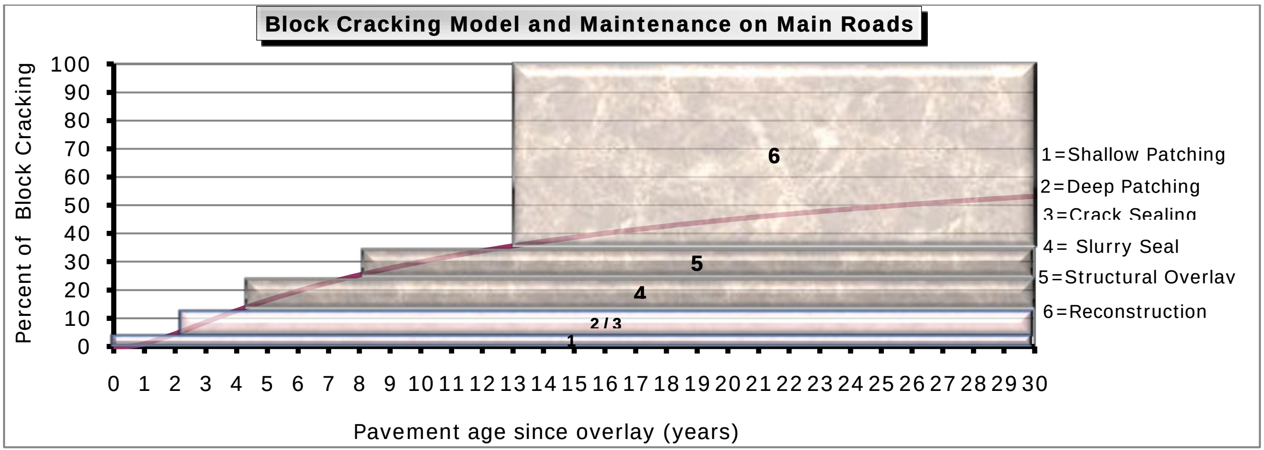

Figure 7.26 Relations between the Percent of Block Cracking and Maintenance Programs on Main Roads.

Table 7.7 Maintenance Guide of Block Cracking at Project Level

Density %	Block Cracking Recommended Maintenance Based on UMPDM & UMPCM
0-5	Shallow Patching
6-15	Deep Patching /Crack Sealing
16-30	Slurry Seal
30-40	Structural Overlay (8 cm) or Reconstruction
>40	Block Cracking Model predicts this amount at age more than 16.0 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. Therefore corrective or preventive programs are not cost effective.

7.8.6.1.2 Suggested Plan for Longitudinal & Transverse Cracking

For longitudinal & transverse cracking, it is recommended to start crack sealing when crack numbers are few and the density is not more than 35%. Crack sealing has the potential to greatly extend the service life of a pavement (Thom 2008). If the pavement is left unsealed, longitudinal & transverse cracking will increase penetrating the thickness of the asphalt under traffic loading. This will lead to the need to overlay the pavement section or reconstruct. Figure 7.27 shows how the situation changes from simple treatment to expensive maintenance. Table 7.8 gives guidance on maintenance treatment for longitudinal & transverse cracking on main roads at project level.

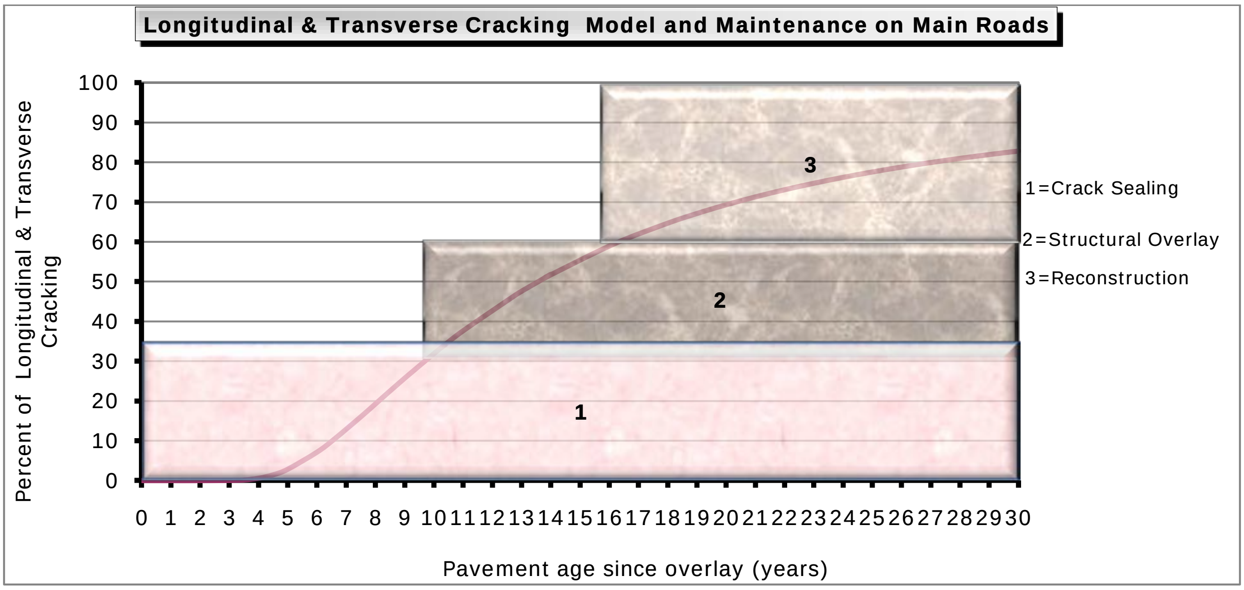

Figure 7.27 Relations Between the Percent of Longitudinal & Transverse Cracking and Maintenance Programs on Main Roads.

Table 7.8 Maintenance Guide of Longitudinal & Transverse Cracking at Project Level

Density %	Longitudinal & Transverse Cracking Recommended Maintenance Based on UMPDM & UMPCM
0-35	Crack Sealing
36-60	Structural Overlay (8 cm) or Reconstruction
>60	Longitudinal & Transverse Cracking Model predicts this amount at age more than 16.0 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. Structural Overlay is not cost effective

7.8.6.1.3 Suggested Plan for Patching

Corrective and preventive maintenance are considered cost effective programs for distress density up to 50%. Corrective maintenance includes shallow and deep patching and can be applied until 25% damage and preventive maintenance program including slurry seal and thin overlay can be applied at greater than 25% damage. More than 50% patching means that the pavement section needs structural overlay because a structural overlay is more cost effective. Figure 7.28 shows how the options vary with increasing damage and Table 7.9 expresses the suggested guidance for patching.

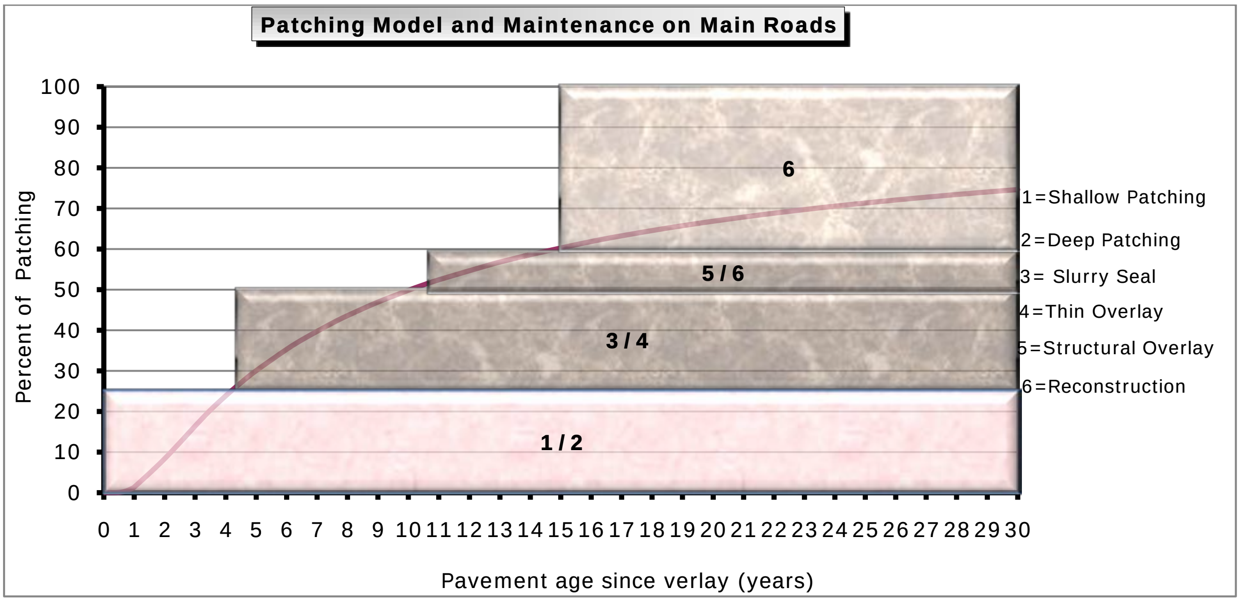

Figure 7.28 Relations Between the Percent of Patching and Maintenance Programs on Main Roads.

Table 7.9 Maintenance Guide of Patching at Project Level

Density %	Patching Recommended Maintenance Based on UMPDM & UMPCM
0-25	Shallow Patching/Deep Patching
26-50	Slurry Seal/Thin Overlay(3-5 cm)
51-60	Structural Overlay (8 cm) or Reconstruction
>60	Patching Model predicts this amount at age more than 16 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. Therefore corrective, preventive programs or structural overlay are not cost effective.

7.8.6.1.4 Suggested Plan for Potholes

The potholes need immediate action because it causes dangerous driving. Therefore, shallow or deep patching must be performed to keep the pavement safe. Leaving the potholes unmaintained cause deficiency in the layers and subsequently the most expensive structural overlay or reconstruction actions are required. Figure 7.26 shows that the potholes should be treated immediately by crack sealing or deep patching before reaching density of 25%. After 25%, the crack sealing and deep patching are not any more cost effective. Options of structural overlay or reconstruction will be carried out. Figure 7.29 shows the options for maintaining the potholes. Table 7.10 points out the suggested guidance for potholes treatment.

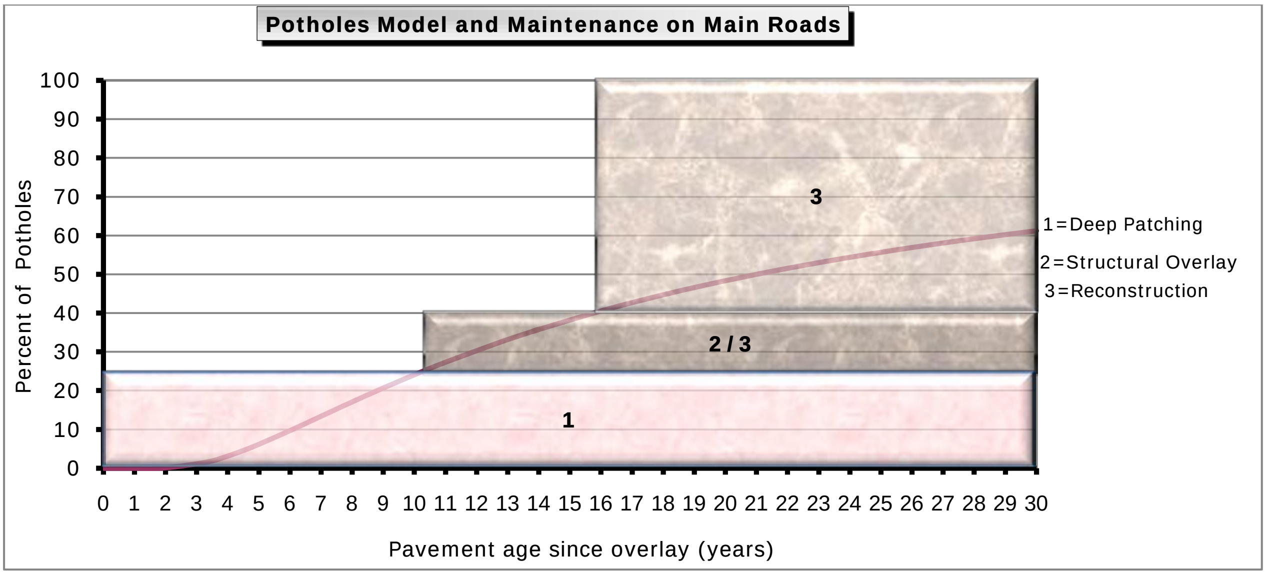

Figure 7.29 Relations Between the Percent of Potholes and Maintenance Programs on Main Roads.

Table 7.10 Maintenance Guide of Patching at Project Level

Density %	Potholes Recommended Maintenance Based on UMPDM & UMPCM
0-25	Shallow Patching/Deep Patching
26-40	Structural Overlay (8 cm) or Reconstruction
>40	Potholes Model predicts this amount at age more than 16.0 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. shallow and deep Patching, and structural overlay are not cost effective

7.8.6.1.5 Suggested Plan for Depressions

The depressions need immediate action because depressions means problem in the foundation. Therefore, deep patching can be performed to keep the pavement safe if the damage is relatively small less than 10%. More than 10% to 20% need a mill and repave However, a reconstruction is the possible treatment in case of damage increases. Figure 7.30 shows that the depressions should be treated immediately by deep patching or mill and repave before reconstructing takes place. Table 7.11 displays the suggested guidance for depressions treatment.

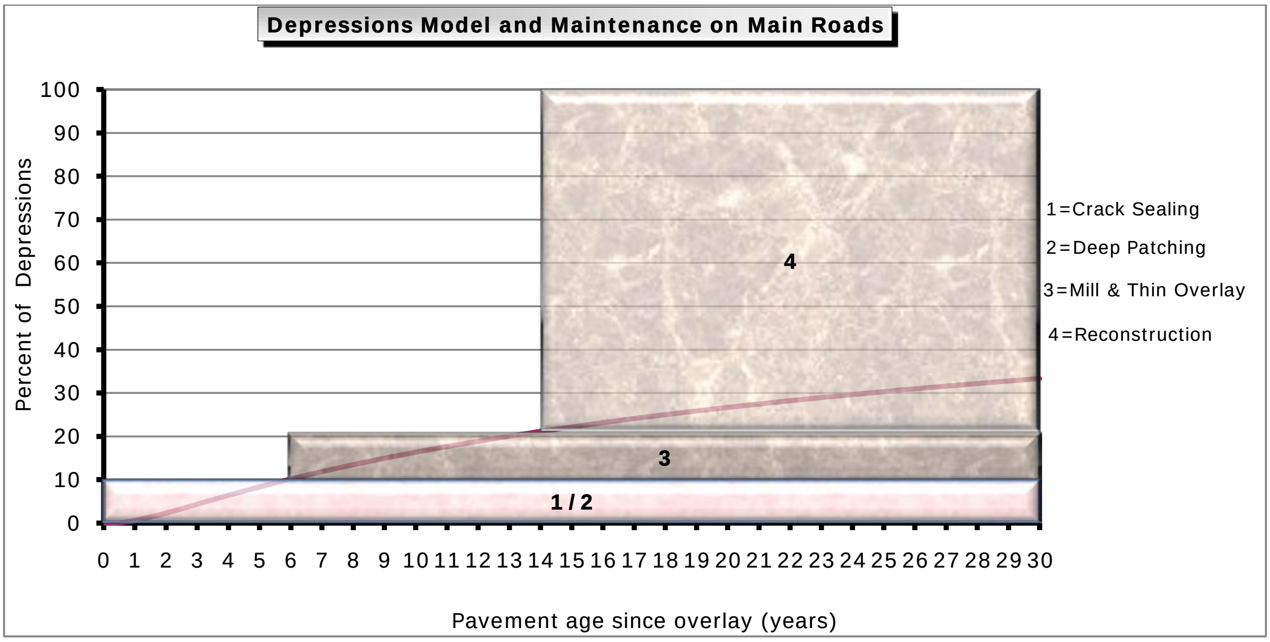

Figure 7.30 Relations Between the Percent of Depressions and Maintenance Programs on Main Roads.

Table 7.11 Maintenance Guide of Depressions at Project Level

Density %	Depressions Recommended Maintenance Based on UMPDM & UMPCM
0-10	Shallow Patching/Deep Patching
11-20	Mill & Repave (3-5 cm)
>20	Depressions Model predicts this amount at age more than 16.0 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. Therefore corrective or preventive programs are not cost effective.

7.8.6.1.6 Suggested Plan for Weathering & Ravelling

Weathering and ravelling occurs when the adhesion between binder and aggregate is breaking. Therefore, at early age of pavement, it is recommended to start by crack sealing. If the pavement is left unsealed, damage could be a serious and implies a much reduced structural life for the pavement. For example, according to the mechanism behaviour in the Figure 7.31, if damage increases to more than 50%, a structural overlay is the most effective maintenance that would be applied. Table 7.12 expresses guidance on maintenance treatment for weathering and ravelling on main roads at project level.

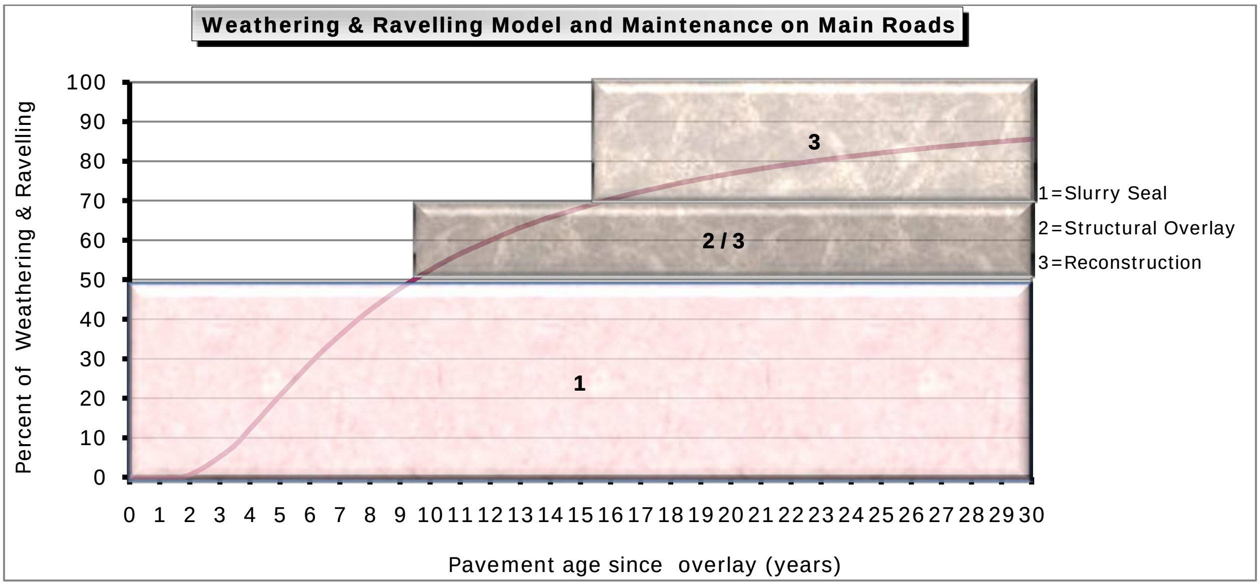

Figure 7.31 Relations Between the Percent of Weathering and Ravelling and Maintenance Programs on Main Roads.

Table 7.12 Maintenance Guide of Weathering and Ravelling at Project Level

Density %	Weathering & Ravelling Recommended Maintenance Based on UMPDM & UMPCM
0-50	Slurry Seal
51-70	Structural Overlay (8 cm) or reconstruction
>70	Weathering & Ravelling Model predicts this amount at age more than 16.0 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. Therefore slurry seal and structural overlay are not cost effective.

7.8.6.1.7 Suggested Plan for Cracking (due to Patching)

Figure 7.32 illustrates how the maintenance programs can be used. Sealing is a suitable treatment for crack at its early progress. Then deep patching would be more cost effective if damage increased to more than 10%. A structural overlay or a reconstruction will be used if damage reached more than 30%. Table 7.13 gives guidance on maintenance treatment for weathering and ravelling on main roads at project level.

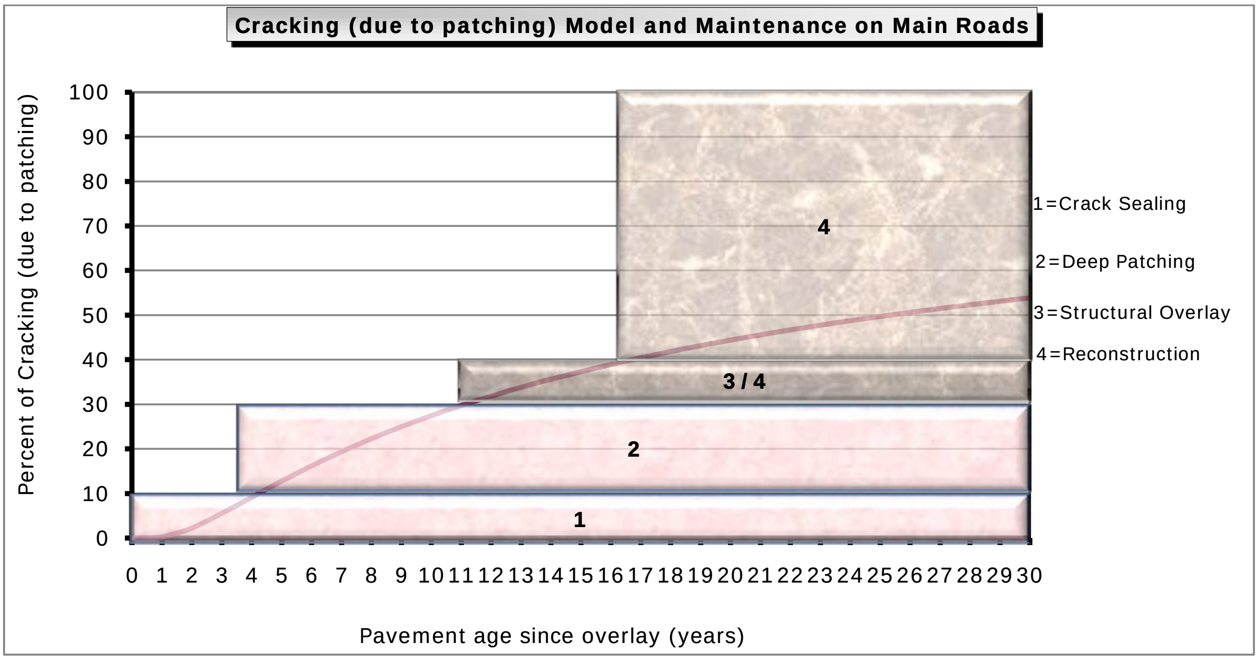

Figure 7.32 Relations between the Percent of cracking due to patching and Maintenance Programs on Main Roads.

Table 7.13 Maintenance Guide of Cracking (due to patching) at Project Level

Density %	Cracking (due to patching) Recommended Maintenance Based on UMPDM & UMPCM
0-10	Crack Sealing
11-30	Deep Patching
30-40	Structural Overlay (8 cm) or reconstruction
>40	Cracking (due to patching) Model predicts this amount at age more than 16.0 years. UMPCM recommends reconstruction at this age for the pavement section if the pavement section has not received a maintenance since construction or last major maintenance. Therefore corrective or preventive programs are not cost effective.

7.8.6.2 Urban Secondary Pavement Distress Model (USPDM)

7.8.6.2.1 Suggested Plan for Block Cracking

Corrective maintenance including shallow and deep patching and crack sealing can be used to repair the block cracking to distress density up to 20%. Preventive maintenance program such as slurry seal will be used if the distress density increases because slurry seal will more cost effective. However, both corrective and preventive maintenance programs are not cost effective if block cracking density increases more than 35%, and the structural overlay will be the most cost effective. Figure 7.33 explains the situation for block cracking treatments at project level for secondary roads. Table 7.14 expresses guidance on maintenance treatment for block cracking.

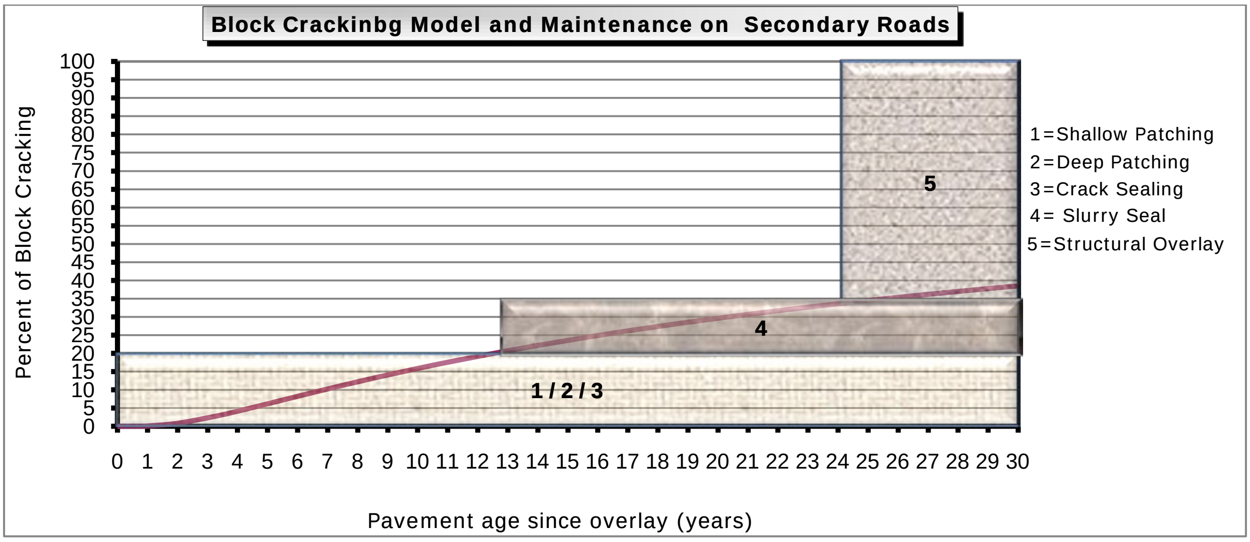

Figure 7.33 Relations Between the Percent of Block Cracking and Maintenance Programs on Secondary Roads.

Table 7.14 Maintenance Guide of Block Cracking at Project Level

Density %	Block Cracking Recommended Maintenance Based on USPDM & USPCM
0-20	Shallow Patching/Deep Patching/Crack Sealing
26-35	Slurry Seal
>35	Structural Overlay (8 cm)

7.8.6.2.2 Suggested Plan for Longitudinal & Transverse Cracking

Figure 7.34 shows that crack sealing is the cost effective treatment for small and few longitudinal and transverse cracking. However, a structural overlay will be more cost effective if damage density reaches more than 35%. Table 7.15 shows guidance on maintenance treatment for longitudinal & transverse cracking on secondary roads at project level.

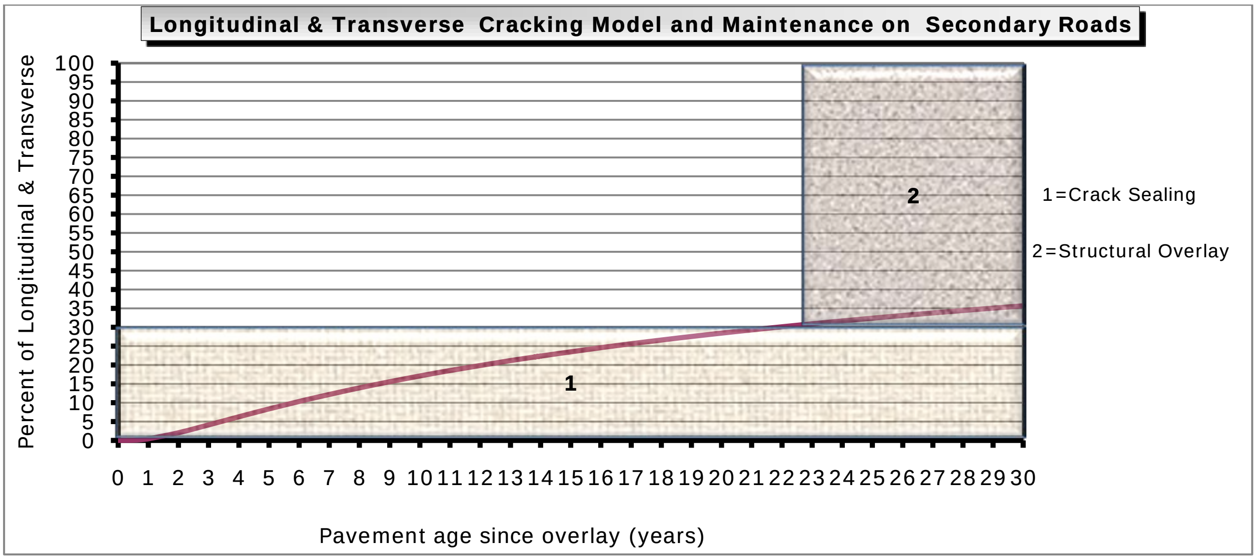

Figure 7.34 Relations Between the Percent of Longitudinal & Transverse Cracking and Maintenance Programs on Secondary Roads.

Table 7.15 Maintenance Guide of Longitudinal & Transverse at Project Level

Density %	Longitudinal & Transverse Cracking Recommended Maintenance Based on USPDM & USPCM
0-30	Crack Sealing
>30	Structural Overlay (8 cm)

7.8.6.2.3 Suggested Plan for Patching

Corrective maintenance is cost effective for distress density up to 35%. Preventive maintenance includes slurry seal and thin overlay are cost effective for distress density greater than 35% and less than 45%. Figure 7.35 depicts the suggested plan for patching treatment at project level and Table 7.16 gives the suggested guidance for patching.

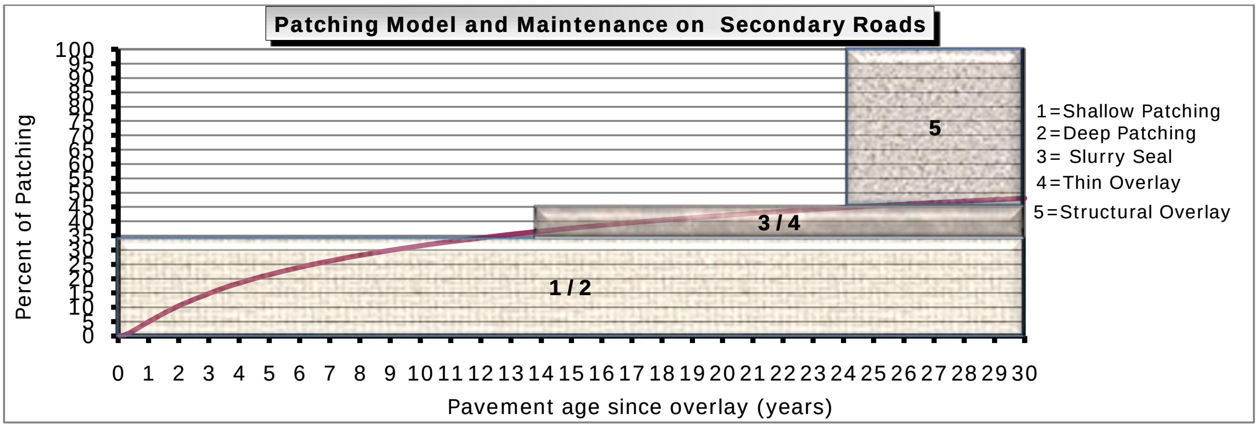

Figure 7.35 Relations Between the Percent of Patching and Maintenance Programs on Secondary Roads.

Table 7.16 Maintenance Guide of Patching at Project Level

Density %	Patching Recommended Maintenance Based on USPDM & USPCM
0-35	Shallow Patching/Deep Patching
36-45	Slurry Seal/Thin Overlay(3-5 cm)
>45	Structural Overlay (8 cm)

7.8.6.2.4 Suggested Plan for Potholes

As explained earlier, the potholes need immediate action because it causes dangerous driving. Therefore, shallow or deep patching must be performed to keep the pavement safe. Figure 7.36 shows that the potholes should be treated immediately by crack sealing or deep patching before reaching distress density value of 25%. If 25% has been passed, crack sealing and deep patching are not any more cost effective. Option of structural overlay will be carried out. Table 7.17 shows the suggested guidance for potholes treatment.

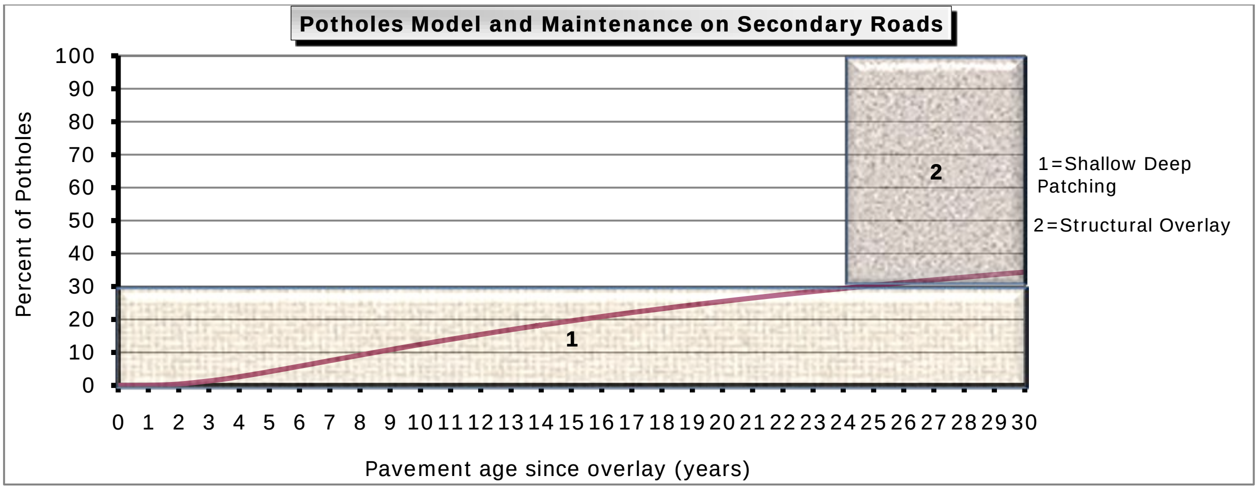

Figure 7.36 Relations between the Percent of Potholes and Maintenance Programs on Secondary Roads.

Table 7.17 Maintenance Guide of Potholes at Project Level

Density %	Potholes Recommended Maintenance Based on USPDM & USPCM
0-30	Shallow Patching/Deep Patching
>30	Structural Overlay (8 cm)

7.8.6.2.5 Suggested Plan for Depressions

Shallow and deep patching can be performed to keep the pavement safe if damage is relatively small, less than 15%. Greater than 15% to 30% need a mill and repave However, reconstruction is the possible treatment in case of the damage increased more.

Figure 7.37 shows that the depressions should be treated immediately by deep patching or mill and repave before structural overlaying takes place. Table 7.18 shows the suggested guidance for depressions treatment on secondary roads at project level.

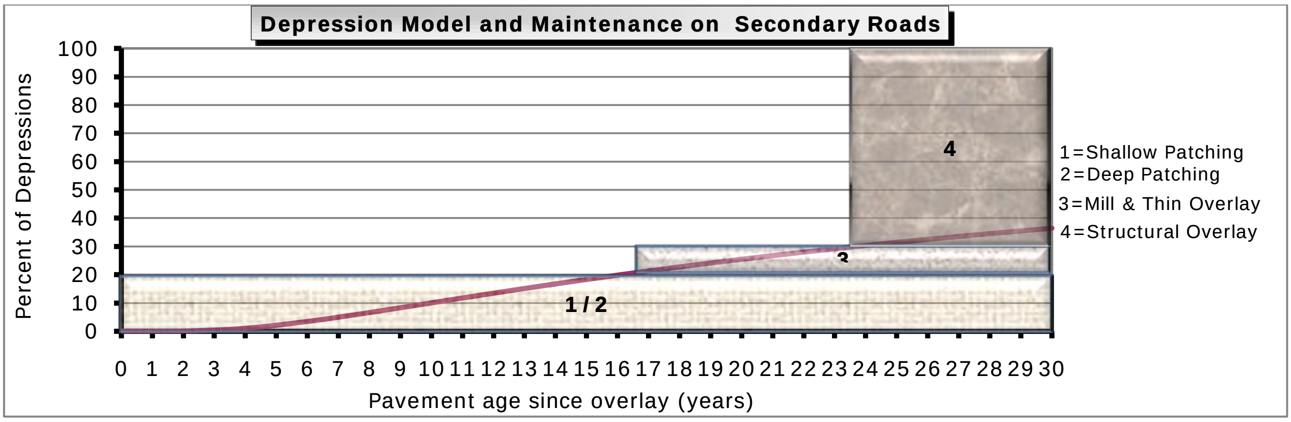

Figure 7.37 Relations between the Percent of Potholes and Maintenance Programs on Secondary Roads.

Table 7.18 Maintenance Guide of Depressions at Project Level

Density %	Depressions Recommended Maintenance Based on USPDM & USPCM
0-20	Shallow Patching/Deep Patching
21-30	Mill & Thin overlay (3-5 cm)
>30	Structural Overlay (8 cm)

7.8.6.2.6 Suggested Plan for Weathering & Ravelling

At early age of pavement, it is recommended to start crack sealing the damage by weathering and ravelling. According to the mechanism behaviour in the Figure 7.38, if the damage increases to greater than 30%, structural overlay is the most effective maintenance that would be applied. Table 7.19 shows guidance on maintenance treatment for weathering and ravelling on secondary roads at project level.

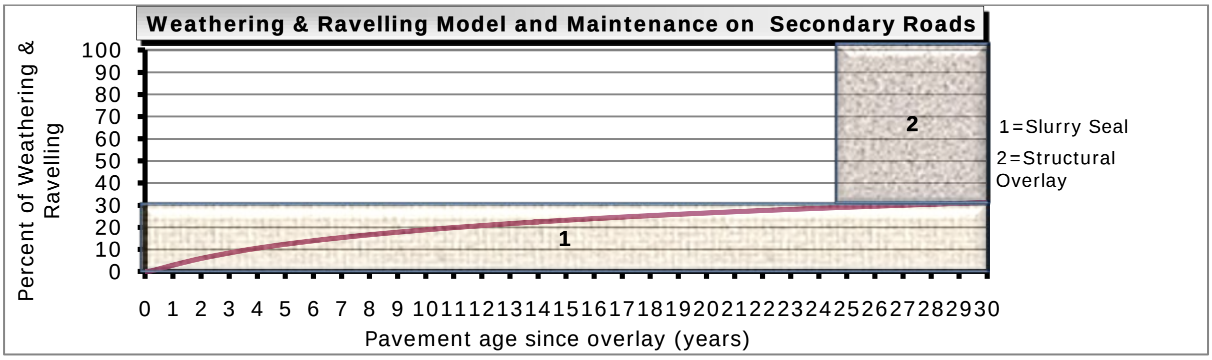

Figure 7.38 Relations between the Percent of Potholes and Maintenance Programs on Secondary Roads.

Table 7.19 Maintenance Guide of Weathering and Ravelling at Project Level

Density %	Weathering & Ravelling Recommended Maintenance Based on UMPDM & UMPCM
0-30	Slurry Seal
>30	Structural Overlay (8 cm)

7.8.7 Damage Contribution to pavement Condition

7.8.7.1 Damage Behaviour and Damage Quantity on Main Roads

The relation between UMPCM and UMPDM is expressed in Figure 7.39 for main roads. Each distress model will help in understanding its behaviour with time and how much damage contributed to pavement condition.

Consequently, the municipalities across Saudi Arabia could define the maintenance needs in terms of types of maintenance and damage quantities using the developed models. In addition to that, they can define the maintenance procedures, resources in terms of labour, equipment, and materials. Furthermore, they can predict the workload generated in terms of maintenance accomplishment units and, they can allocate the available resources in an efficient way.

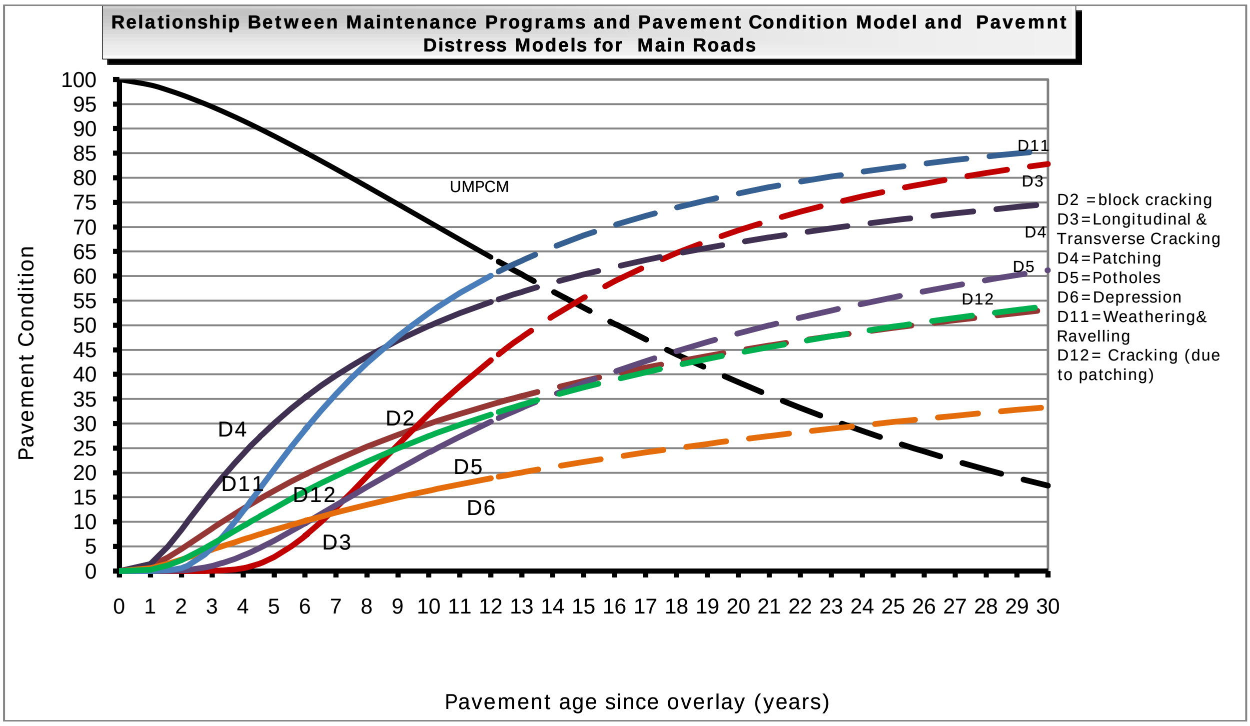

Figure 7.39 Pavement Condition Model and Pavement Distress Models and Maintenance Programs on Main Roads.

Table 7.20 expresses the relationship between the mechanism behaviour of each distress over 10 years and the drop in pavement condition for main roads. For example, at 95% significance level, the drop in pavement condition will be between 8.4 and 10.31 percent in 4 years.

On other hand, the damaged contributed to pavement condition by block cracking is in the range of 11.10 to 14.31 percent, the most damaged comes from patching whereas the least damage comes from longitudinal and transverse cracking. Around 30% drop in quality at 10 years, patching and weathering & ravelling have the most damage on pavement condition with amount of 49 to 53 percent.

Table 7.20 Damage Quantity on Main Roads

Age	Drop in Pavement Condition at 95% Significance Level	Damaged Quantity Contributed by Distress Types to Pavement condition at 95% Significance Level						
		Block Cracking	Long.& Transverse Cracking	Patching	Potholes	Depressions	Weathering & Ravelling	Cracking (due to Patching)
0	0.00-0.00	0.00-0.00	0.00-0.00	0.00-0.00	0.00-0.00	0.00-0.00	0.00-0.00	0.00-0.00
1	1.11-1.54	0.58-1.46	0.00-0.00	0.96-1.92	0.00-0.00	0.00-1.73	0.00-0.00	0.11-0.45
2	3.09-4.02	3.45-5.69	0.00-0.00	7.24-9.62	0.05-0.24	0.00-4.73	0.38-0.86	1.52-3.12
3	5.56-7.00	7.25-10.19	0.01-0.08	15.25-17.83	0.66-1.57	0.00-7.55	3.94-5.64	4.29-6.90
4	8.40-10.31	11.10-14.31	0.31-1.02	22.67-24.97	2.35-4.14	0.00-10.07	11.07-13.38	7.64-10.80
5	11.51-13.83	14.72-17.98	1.97-3.93	29.08-30.96	5.01-7.51	0.03-12.32	19.54-21.78	11.09-14.51
6	14.81-17.50	18.03-21.24	5.68-8.73	34.54-36.00	8.28-11.24	0.11-14.33	27.82-29.67	14.45-17.94
7	18.25-21.26	21.05-24.15	11.10-14.68	39.01-40.59	11.85-15.03	0.28-16.14	35.31-36.67	17.63-21.08
8	21.78-25.05	23.81-26.75	17.45-19.26	42.69-44.59	15.51-18.74	0.57-17.79	41.51-43.20	20.59-23.94
9	25.37-28.84	26.32-29.10	24.06-25.72	45.90-48.04	19.11-22.29	1.00-19.31	46.79-47.79	23.35-26.56
10	28.98-32.60	28.62-31.23	30.49-31.90	48.72-51.06	24.12-25.63	1.56-20.70	51.36-52.49	25.90-28.95

Also, the damage of a distress with respect to other distress can be calculated. Table 7.21 show the probability of each distress at a given age. For example, at age 6 years, depressions have a probability of 8% to drop the pavement condition by amount of 1.18% whereas weathering and ravelling has probability of 22.66% to drop the pavement condition by amount of 3.36. However, as explained in chapter 4, each distress has its own effect on calculating the pavement condition (UDI), for instance, potholes have more effect compared to others.

Table 7.21 Probability Damage Quantity on Main Roads

Age	Drop in Pavement Condition at 95% Significance Level	Damaged Quantity Contributed by Distress Types to Pavement condition from the Predicted Models						
		Block Cracking	Long.& Transverse Cracking	Patching	Potholes	Depressions	Weathering & Ravelling	Cracking (due to Patching)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	1.11	29.98	0.00	44.23	0.01	18.31	0.01	7.46
2	3.09	24.72	0.00	46.37	0.64	12.78	3.21	12.28
3	5.56	21.16	0.07	40.48	2.56	10.67	11.59	13.47
4	8.40	18.61	0.87	35.05	4.66	9.42	17.94	13.45
5	11.51	16.79	2.92	30.92	6.37	8.60	21.26	13.14
6	14.81	15.47	5.62	27.82	7.66	8.02	22.66	12.75
7	18.25	14.50	8.25	25.51	8.61	7.62	23.10	12.41
8	21.78	13.79	10.50	23.79	9.34	7.35	23.09	12.14
9	25.37	13.28	12.32	22.48	9.92	7.16	22.88	11.96
10	28.98	12.90	14.86	20.70	10.79	6.97	22.04	11.74

Figure 7.39 can be simplified to Figure 7.40 to show a direct relationship between pavement condition and the average damage initiated by all distress types in a combined appearance by taking average of all damage by the distress types at given time.

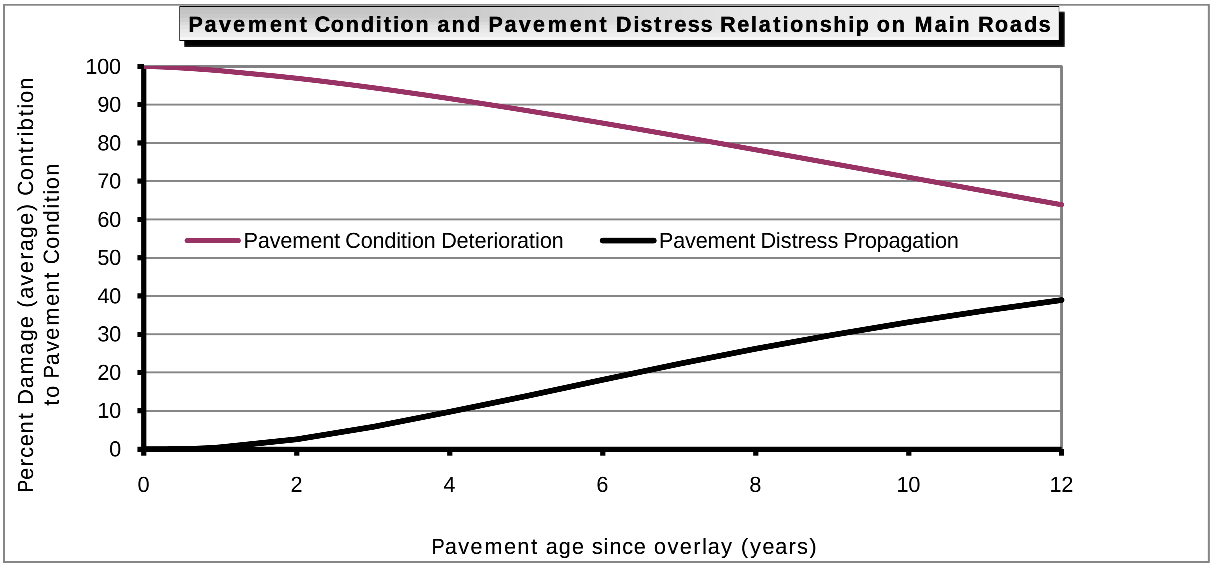

Figure 7.40 Pavement Condition Model and Combined Pavement Distress Models on Main Roads.

7.8.7.2 Damage Behaviour and Damage Quantity on Secondary Roads

Similarly, Figure 7.41 illustrates the relation between USPCM and USPDM for secondary roads. It has been noticed that the mechanism behaviour of all distress types on secondary roads have almost same trend except patching has a relatively higher progression.

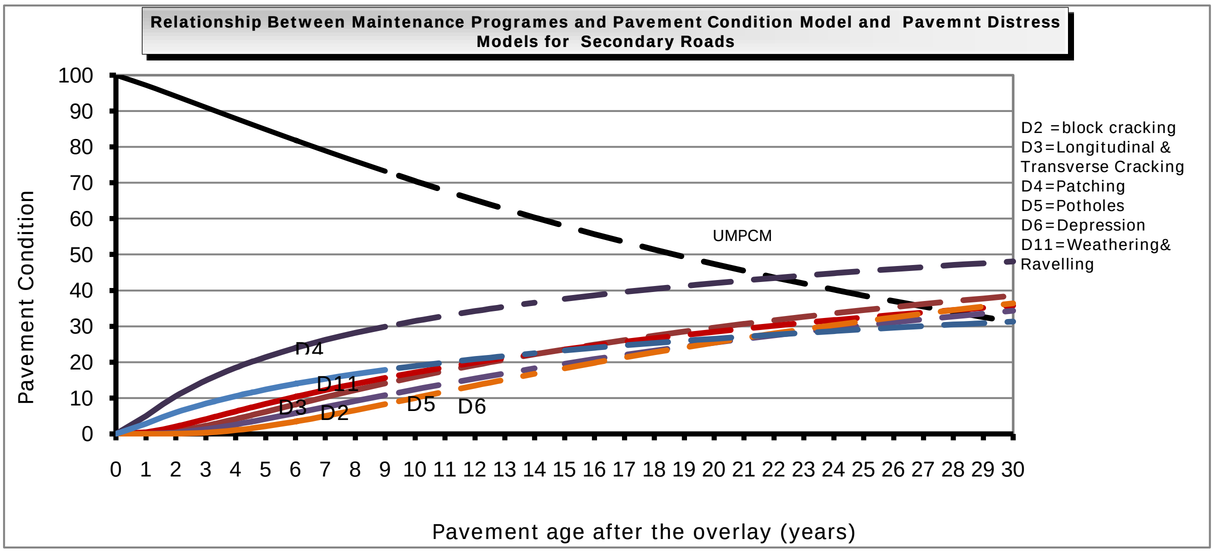

Figure 7.41 Pavement Condition Model and Pavement Distress Models and Maintenance Programs on Secondary Roads.

Table 7.22 gives damage quantity by each distress and Table 7.23 gives damage probability by each distress. Figure 7.43 shows the combined damage.

Table 7.22 Damage Quantity on Secondary Roads

Age	Drop in Pavement Condition at 95% Significance Level	Damaged Quantity Contributed by Distress Types to Pavement condition at 95% Significance Level					
		Block Cracking	Long.& Transverse Cracking	Patching	Potholes	Depressions	Weathering & Ravelling
0	0	0	0	0	0	0	0
1	0.00-12.52	0.00-1.15	0.05-1.87	2.21-9.21	0.00-0.62	0.00-0.21	0.44-10.35
2	0.00-15.58	0.06-4.23	0.58-5.23	6.41-15.55	0.02-2.83	0.00-1.72	1.63-15.09
3	0.00-18.69	0.38-7.55	1.63-8.40	10.34-20.00	0.14-5.53	0.00-4.14	2.99-18.26
4	2.34-21.80	1.04-10.67	2.97-11.22	13.79-23.41	0.48-8.22	0.04-6.86	4.36-20.66
5	5.41-24.87	2.01-13.51	4.46-13.72	16.81-26.17	1.04-10.76	0.15-9.59	5.68-22.59
6	8.42-27.89	3.20-16.07	6.01-15.95	19.48-28.49	1.80-13.13	0.40-12.23	6.94-24.21
7	11.38-30.84	4.54-18.4	7.56-17.95	21.84-30.47	2.72-15.32	0.82-14.73	8.12-25.61
8	14.26-33.72	5.97-20.53	9.07-19.76	23.97-32.21	3.76-17.34	1.42-17.07	9.24-26.84
9	17.07-36.54	7.46-22.47	10.55-22.47	25.90-33.75	4.88-19.21	2.17-19.26	10.30-27.94
10	45.70-65.16	8.35-24.12	11.25-23.25	21.12-34.59	8.35-21.40	3.02-20.33	11.97-28.55

Table 7.23 Probability Damage Quantity on Secondary Roads

Age	Drop in Pavement Condition at 95% Significance Level	Damaged Quantity Contributed by Distress Types to Pavement condition at 95% Significance Level					
		Block Cracking	Long.& Transverse Cracking	Patching	Potholes	Depressions	Weathering & Ravelling
0	0	0	0	0	0	0	0
1	2.79	0.81	5.05	59.30	0.25	0.00	34.59
2	5.85	4.08	10.36	53.24	1.97	0.23	30.12
3	8.96	7.25	13.14	47.44	4.16	1.10	26.91
4	12.07	9.61	14.58	42.84	6.08	2.41	24.50
5	15.14	11.29	15.33	39.26	7.62	3.84	22.66
6	18.15	12.50	15.74	36.47	8.83	5.22	21.24
7	21.11	13.39	15.97	34.25	9.79	6.49	20.12
8	23.99	14.06	16.09	32.46	10.57	7.61	19.22
9	26.81	14.58	16.15	30.99	11.20	8.60	18.48
10	55.43	14.99	16.18	29.77	11.72	9.47	17.87

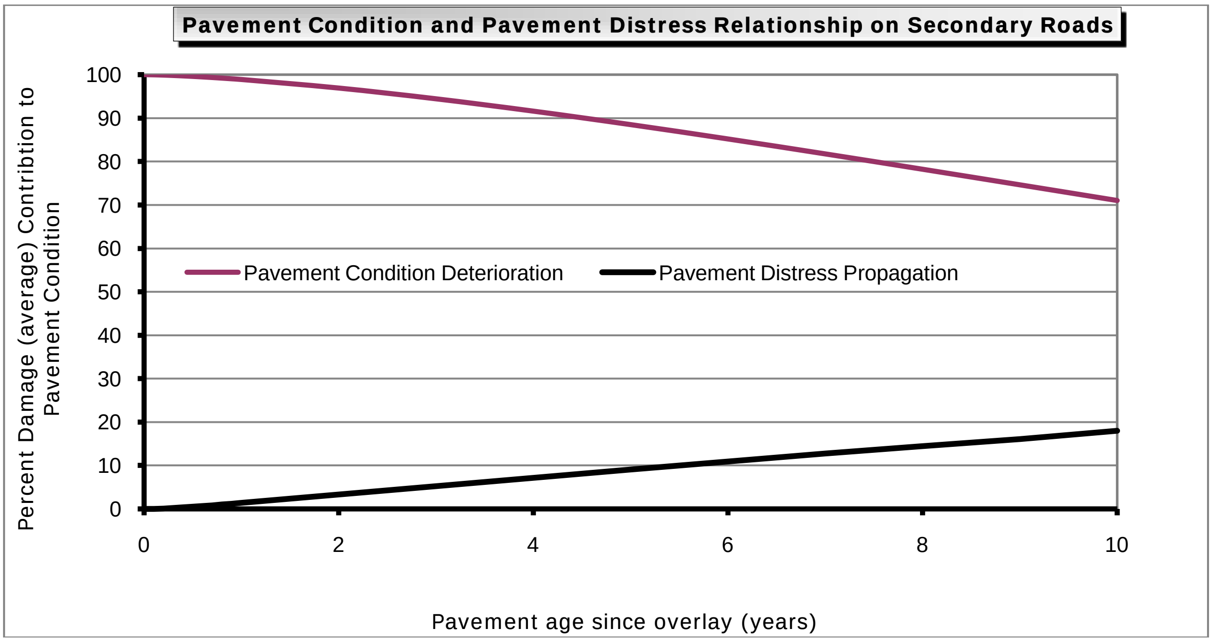

Figure 7.42 Pavement Condition Model and Combined (Average) Pavement Distress Models on Secondary Roads.

7.8.8 Priority Setting Procedure

The methodology of setting up a maintenance priority procedure depends on quantitative and qualitative factors. There are many priority programming methods ranging from simple subjective ranking to true optimization. One of the traditional practices of setting up maintenance priority is to list in a descending order all network roads that need maintenance. Priority is based on engineering and subjective judgment by help of pavement condition value. This approach might work for small network and sufficient budget. However, an approach insures the right treatment to the right pavement at the right time is not simple (Haas et al. 1994) because all possible combinations of the three points must be evaluated.

However, this study suggests a maintenance priority procedure. The idea of this suggestion is based on pavement condition models, traffic volumes, road classification, maintenance programs database, effectiveness of maintenance types, and cost of maintenance types. If a road agency has ability to have reliable information on all the five factors, the priority can be solved to a reasonable degree of acceptance.

General speaking, the first and foremost important factor is pavement condition, a road needs high priority of maintenance if its condition poor. Therefore, pavement condition value is inversely proportional to maintenance.

Using traffic volumes as Average Daily Traffic (ADT) in setting up the maintenance priority is vital and very practical especially those roads which have good condition because the ADT represents how busy the road is. Thus ADT range must be established. Table 7.24 gives a traffic factor for each ADT range. Road class has impact upon maintenance decision since main roads are more important than secondary roads. Table 7.25 gives a class factor.

Table 7.24 Traffic Factor (Modified from Al-Swailmi and Al-Abadwhab 2001)

Traffic Factor (TF)	
ADT Range	Value
0-100	10
101-500	20
501-1000	30
1001-2000	40
2001-5000	50
>5000	100

Table 7.25 Road Classification Factor (Modified from Al-Swailmi and Al-Abad Whab 2001)

Road Factor (RF)	
Class Road	Value
Main	1.2
Secondary	1.1

As discussed previously, maintenance programs contain certain types of maintenance. Each has expected life on the pavement condition and has cost as well. Availability of precise database on maintenance leads to increased maintenance efficiency and better utilization of resources. On the other hand, in the absence of proper database on maintenance, maintenance depends on existence surface condition of pavement. Therefore, Table 7.26 gives factor value for this issue to account for the amount of past maintenance that have been taken place The effectiveness of maintenance is very important factor in proper priority setting since it is more feasible to implement the most effective maintenance activity than activities otherwise. Also the cost is important factor. Cost effectiveness factor has been assigned for each. Table 7.27 shows the suggested values for cost effectiveness factor.

Table 7.26 Maintenance Record Factor (Modified from Al-Swailmi and Al-Abad Whab 2001)

Maintenance Factor (MF)	
Past Maintenance	Value
No	1.0
Poor	1.1
Fair	1.2
Moderate	1.3
High	1.4
Very High	1.5

Table 7.27 Cost Effectiveness Factor

Cost Effectiveness Factor (CEF)	
Maintenance Programs	value (Effectiveness)
Corrective	1
Preventive	2
Structural Overlay	3
Reconstruction	4

Or alternatively the cost effectiveness factor can be calculated as follows:

$CEF = (\triangle \text{Pavement Condition} \times t) / C$

This equation has been modified from Transportation Association of Canada (TAC 1997), where

$\triangle$Pavement Condition = Difference between pavement condition after and before activity application,

t= Expected life for a maintenance type,

C= Maintenance activity unit cost.

△Pavement Condition and t can be obtained from performance curve if the road agency has theses curves (this study does not cover these curves due to lack of data), or can be estimated from the developed prediction curves UMPCM and USPCM, or can be estimated from experience. However, for time being, the cost effectiveness will be excluded from maintenance priority procedure till a good database can gives the anticipated effect of a maintenance type, and the expected life for a maintenance type.

Based on that, maintenance priority can be calculated as follows:
Maintenance Priority (MP) = (TF x RF x MF)/ Pavement Condition

The TF, RF, and MF can be obtained from the suggested Tables and the pavement condition value can be obtained from the developed models. Higher values of MP indicate higher priority, means the maintenance budget is first allocated to pavement sections according to MP list. When the allocated budget is not sufficient for all sections, the remaining sections are deferred to the next year.

7.8.9 Work Plan

Each municipality in Saudi Arabia, by using the UMPDM, UMPCM, USPDM, USPCM, suggested maintenance guidance, and maintenance priority, can set up a maintenance program. For a network or portion of a network is very practical to develop a 3 year or 5 year program. The developed models can help in determine the workload, what projects or sections should be maintained, how can they maintained, and when should they be maintained.

7.9 Summary

Condition deterioration models for main and secondary roads have been developed in this chapter. However, his chapter has focused on implementation of developed models, the pavement distress models and the pavement condition models. Correlation between pavement distress types and correlation between pavement distress types and pavement condition have been discussed. Practical maintenance programs based on network and project levels have been suggested. The mechanism behaviour of pavement distress types, damage quantities, and probability damage on main and secondary roads have been also investigated. Simple scientific approach for maintenance priority has been suggested. It is expected that the SAURN will be better maintained when the developed models is fully implemented.

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CHAPTER EIGHT
SUMMARY, CONCLUSIONS, RECOMMENDATIONS, LIMITATIONS

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CHAPTER EIGHT

SUMMARY, CONCLUSIONS, LIMITATIONS, RECOMMENDATIONS

The main objectives of this research study were to develop pavement distress models and pavement condition models for Saudi Arabia Urban Road Network (SAURN). A summary, conclusions, limitations, and recommendations of the research are presented in this chapter.

8.1 Summary

- Pavement distress information is one of the best methods to evaluate the pavement condition as well as selecting the appropriate treatments.
- Basically there are four techniques in modelling pavement deterioration. They are; purely mechanistic technique, regression technique, mechanistic empirical technique, and probabilistic technique.
- Nonlinear regression technique was used due to type of data available.
- To obtain generic models for SAURN that can be utilized with a significant level of confidence, the study covered all accessible and reliable data. This study included both main and secondary roads data.
- Four datasets were developed. The first and the second were for pavement distress types on main and secondary roads. The third and the fourth were for pavement condition on main and secondary roads.
- These four datasets were used in pavement distress analysis, pavement condition analysis, pavement distress models, pavement condition models, and the implementation.
- Data for seven common distress types on main roads were used in the analysis of distress behavior as well modeling these distresses. These common distress types are Block Cracking, Longitudinal and Transverse Cracking, Patching, Potholes, Depressions, Weathering and Ravelling, and Cracking (due to patching).
- Data for six common distress types on secondary roads were used in the analysis of distress behavior as well modeling these distresses. These common

distress types are Block Cracking, Longitudinal and Transverse Cracking, Patching, Potholes, Depressions, and Weathering and Ravelling.

- The factors in the study are the ones commonly available and reliable. They are; percent of distress density, pavement condition, pavement age, traffic, and drainage.
- 701 main road pavement sections with 2320 reading points over about 12 years were found to be applicable for the study.
- 202 secondary road pavement sections with 641 reading points over about 9 years were found to be applicable for the study.
- In this study, only overlays are considered since an overlay increases the pavement condition to its maximum.
- The propagation of the pavement distress types were presented as combined sum of distress density at different severity levels using weight for each severity.
- The data was large and the variation on data was noticed. Normality was checked and then parametric and nonparametric tests were performed to check significance of the factors.
- Descriptive tests like numerical summaries reveal that the pavement distress density values for all types of distress under study show variation in distribution. Traffic and drainage show more variation and dispersion.
- Also descriptive tests conclude the data are not normal. The scatter diagrams reveal that most points of different levels for different factors are mixed together randomly and nonlinearity is present.
- Inferences from normality tests, parametric tests, and nonparametric tests showed that the data are not normally distributed and the pavement age factor shows high significance.
- The empirical technique (nonlinear regression) was the best technique to be used in modeling behavior distress due to first and foremost nature of the data, its practicality, simplicity, and ease in developing provided that adequate data is available.

- Boundary conditions have been constructed taking in consideration the engineering principles.
- The S-curve function showed better fitting capability in all data sets in terms of the pavement age compared to others nonlinear functions.
- The S-curve function showed better application for boundary conditions.
- Two modifying coefficients for traffic and drainage were input into the chosen function to see if the modifying coefficients have impact on the function accuracy. The 95% confidence interval, the T-test of all parameters, and the test of error distribution were showed no improvement in prediction accuracy. Therefore neither the traffic nor the drainage has influence on the distress equation.
- Two confidence intervals have been investigated, the asymptotes method and region contour method.
- Analysis of residuals showed the models were of acceptable accuracy and could therefore be applied in a PMS.
- Critical pavement condition levels have been proposed for main and secondary roads at both network and project levels in SAURN.
- Maintenance programs have been suggested for main and secondary roads at both network and project levels in SAURN.
- The drop in pavement quality and the damage quantity and probability are understandable and measurable.
- A maintenance priority procedure has been set up.

8.2 Conclusions

- Pavement age is most significant in the predicting pavement deterioration. Age is significant because it is a common factor in the estimation of both traffic and effect of drainage over the life cycle period. Age can be a surrogate for the effect of traffic and drainage in prediction model. So it can be concluded that age plays a pivotal role in predicting pavement condition.
- Traffic and drainage factors play a statistically less important role in predicting pavement deterioration in this study. This is in line with finding in Texas

(Robinson et al. 1996).

- Pavement age factor is the only factor in the prediction equation form for pavement distress models and pavement condition models.
- Thirteen pavement distress models have been developed for the Saudi Arabia Urban Roads Network (SAURN) in the form of sigmoid shape.

- Seven for urban main pavement distress models (UMPDM);
  - Block Cracking Model = $\dfrac{100}{e^{(13.752/t)0.588}}$
  - Longitudinal & Transverses Cracking Model = $\dfrac{100}{e^{(10.846/t)1.640}}$
  - Patching Model = $\dfrac{100}{e^{(6.317/t)0.789}}$
  - Potholes Model = $\dfrac{100}{e^{(14.388/t)0.968}}$
  - Depressions Model = $\dfrac{100}{e^{(36.896/t)0.455}}$
  - Weathering & Ravelling Model = $\dfrac{100}{e^{(7.116/t)1.291}}$
  - Cracking (due to patching) Model = $\dfrac{100}{e^{(14.665/t)0.671}}$

- Six models for urban secondary pavement distress models (USPDM);
  - Block Cracking Model = $\dfrac{100}{e^{(27.768/t)0.598}}$
  - Longitudinal & Transverses Cracking Model = $\dfrac{100}{e^{(31.830/t)0.491}}$
  - Patching Model = $\dfrac{100}{e^{(14.179/t)0.415}}$
  - Potholes Model = $\dfrac{100}{e^{(33.543/t)0.608}}$
  - Depressions Model = $\dfrac{100}{e^{(30.407/t)0.749}}$

- Weathering & Ravelling Model = $\frac{100}{e^{(47.375/t)0.328}}$

- Two pavement condition models have been developed for the Saudi Arabia Urban Roads Network (SAURN).

- One for urban main pavement condition models (UMPCM).

UMPCM = $\frac{100}{e^{(t/20.589)1.485}}$

- One for urban secondary pavement condition models (USPCM).

UMPCM = $\frac{100}{e^{(t/26.121)1.093}}$

- Developed models by using site data or historical data involve the use of an iterative non linear regression analysis to determine the model coefficients. The advantage of this modelling approach over other models is that the site models more closely match the reality on every section in the network.

- The developed models can be used by all municipalities across Saudi Arabia due to, first, construction and maintenance specifications are same, second, the environmental factors are almost same like temperature, and rainfall.

- Distress types are dependent of each other for both main and secondary roads except depressions are significantly less dependent on other distress types.

- Distress types on main roads are high correlated to the pavement condition by about 70% except depression by about 50%.

- Distress types on secondary roads are less correlated to the pavement condition compared to distress types on main roads.

- Critical pavement condition levels and minimum condition levels have been proposed based on deterioration behavior curves as guidance for municipalities and road agencies officials and engineers in pavement management.

- Three critical levels for pavement deterioration over time on main roads to trigger corrective, preventive, major maintenance

- Two critical levels for pavement deterioration over time on secondary roads to trigger preventive and major maintenance.

- Four maintenance programs with eight maintenance activities are defined as follows; corrective program (Crack sealing, Shallow and Deep patching), Preventive program (slurry sealing, thin overlay, Mill and Repave), Structural Overlay, and Reconstruction.
- Pavement distress behavior on main roads varies from distress to other distress.
- The deterioration rate for weathering and raveling was observed to be the fastest in propagation.
- The deterioration rate for depression was observed to be the slowest in propagation.
- Block cracking and cracking (due to patching) have similar propagation compared to others.
- Potholes propagation has moderate deterioration.
- Pavement distress behavior on secondary roads almost have same trend except patching has higher progression compared to others.
- Maintenance Priority (MP) can be found through some factors for traffic level, road classification (RF), maintenance record (MF), and cost effectiveness (CEF), and pavement condition.
- The following formulas was suggested Maintenance Priority (MP) = (TF x RF x MF)/ Pavement Condition

8.3 Recommendations

- The distress density models developed in this research should be utilized to evaluate the pavement condition.
- Distress density prediction curves are used to forecast the density propagation over time, so the maintenance strategies and activities as well as funds allocation can be scheduled a head of time at which the pavement should receive the suitable corrections.

- The developed models adequately predict the distress density and the drop in pavement quality over time. However, these models can be checked if necessary and modified when more data of distress surveys and related information are available especially traffic and drainage data.

- All municipalities across Saudi Arabia should start collect data on pavement condition periodically.

- The municipalities can start using the developed curves, at latter stages; they can refine the models based on the collection of pavement condition data for each city network.

- Many agencies have found that applying a series of low cost preventive treatments extend the service life of pavement, therefore, municipalities across Saudi Arabia may start apply preventive maintenance program.

- A study is needed to investigate the extended pavement life due to each maintenance type.

- Determining the required budget by defining the maintenance needs and the time

- The officials should increase the awareness of PMS and the asset management of municipal infrastructure for all the municipalities. They should support pavement inventory, condition assessment especially pavement distress survey, keeping all record and build central dataset contains everything related to the municipal infrastructure in general and pavement section in particular, building prediction and performance models based on the datasets, a framework to identify needs and set priorities. Also, they should ensure that funding is available for maintenance in general corrective and preventive maintenance programs in particular.

- Improving the current PMS and enhancing the calibration for the indices and models used.

- The ministry of transport (MOT) in Saudi Arabia have been applied the practice of PMS since 1986, currently they have good database, therefore, the researcher recommends the MOT's engineers to start building prediction and performance models for their PMS activities.

8.4 Limitations

- The data only for overlaid sections, overlay returns the pavement section to its maximum condition. Thus the predicted curves were predicted from excellent pavement condition. However, this is need assumption that new roads behave like overlaid sections when applying to

- The anticipated effect of a preventive maintenance is not included in this study because there are not data available, and this indicates that the municipalities in Saudi Arabia are not aware of keeping the maintenance records or they are not applying preventive activities.

- Type of the available data was pavement surface condition only.

- The proposed critical levels need to be verified by municipalities across Saudi Arabia when they start apply the models.