PERFORMANCE MODELING OF SAUDI ARAMCO ROADS NETWORK

BY

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بسم الله الرحمن الرحيم

DEDICATION

This work is dedicated to Allah the Almighty, asking Him for His mercy and forgiveness.

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Praise and glory to Allah, the Almighty with whose gracious mercy we live.

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التخصــــص : هندسه مدنيه

تاريخ التـخرج : ديسمبر **2010**

تتميـز شـركة ارامكـو السـعودية بكونهـا اكبـر شـركات الـنفط علـي مسـتوي العـالم و بأمتلاكهـا 8500 كيلـومتر مـن الطـرق المسـفلتة. تسـاعد نمذجـه تقـدير حالـه الرصـفات فـي تطـوير نظـام صـيانة و اداره الطـرق بـارامكو السـعودية و بالتـالي تزويـد مسـئولى ارامكـو السـعودية بأفضـل أوقـات الصـيانة الدوريـة للطرق و تحديد المستلزمات المالية المطلوبه علي المدي القريب و البعيد.

يهـدف هـذا البحـث الـى أسـتنباط نمـاذج لتقـدير حالـة رصـف طـرق شـركة ارامكـو السـعودية بأسـتخدام المعلومـات المتـوفره عـن شـبكه الطـرق منـذ عـام 1998. فقـد اكـدت كافـه النمـاذج و المعـادلات المسـتنبطه في هذا البحث ان عامل الزمن هو المحرك و المؤثر الرئيسي لتحديد حالة رصف الطرق في المستقبل.

كمـا أكـدت النمـاذج الحديثـة المسـتنبطه مـن خـلال دراسـه و تحليـل حالـه شـبكة الطـرق الفعليـه للعشـر السـنوات الماضـيه و ادائهـا السـابق ان شـبكة الطـرق بـارامكو السـعودية تتـدهور بسـرعه اكثـر عـن مـا تقترحـه النمـاذج الحاليـه المسـتخدمة فـي نظـام صـيانة و ادارة الطـرق بـارامكو السـعودية. بالتـالي توصـي هـذه الدراسـة شـركة ارامكـو السـعودية بمراجعـه نظـام صـيانة و ادارة الطـرق و تقـديم بـرامج الصـيانة الدورية للطرق للحفاظ علي مستوى أداء جيد فما فوق.

درجة الماجستير في العلوم

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THESIS ABSTRACT

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TITLE: PERFORMANCE MODELING OF SAUDI ARAMCO ROADS NETWORK
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Saudi Aramco Oil Company is a major oil company in the Kingdom of Saudi Arabia. Saudi Aramco roads network consists of 8,500 standard lane km of flexible pavement. Pavement condition prediction models can greatly improve the capabilities of Saudi Aramco Pavement Maintenance Management System (PMMS) and allow Saudi Aramco officials to predict the condition of the network, thus predicting the timing of the maintenance activities and estimating the short- and long-range funding requirements. This research aimed to develop performance models for Saudi Aramco roads network utilizing the pavement condition data gathered since 1998. In this study, four models were developed and validated for the network with good precision and coefficient of determination where pavement age is the most significant factor that affects pavement performance indices. The new prediction models indicate that Saudi Aramco roads network deteriorate faster compared to the old prediction models, based on real pavement performance in the past ten years. Accordingly, preventive maintenance should be done at an early stage to maintain an acceptable level of service of the network.

MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

CHAPTER 1

INTRODUCTION

1.1 Background

Saudi Aramco Oil Company possesses relatively huge roads network compared to similar companies worldwide. This network serves as a vital vein for the company's daily activities. The network is spread all over the Kingdom of Saudi Arabia and extends from Turaif to Jaizan and from Jeddah to the Eastern Province. The majority of Saudi Aramco roads network lies in the Eastern Province specifically in the Southern area (Abqaiq and Udhailiyah districts) and in the Northern area (Dhahran and Ras Tanura districts). The network consists of Facility and Public Roads, Airstrips, Camp Streets, Lay Down Yards, Parking Areas, Facility Streets, and Plant Areas.

Saudi Aramco is a pioneer in roads construction in the Kingdom. It started in the 1950s overlaying existing dirt (skid) roads and adopting "touch on grade" methodology. Sand mix and marl mix were utilized at that time. Later, asphalt cold mix and chip seals were used to provide smooth surface.

Saudi Aramco Roads Department at its early stage was dependent on expatriate engineers, local operators, and labors who worked for the company to build the infrastructure. Whereas, the maintenance program was a collaborative effort that depended solely on the engineers' technical evaluation and experience.

It was deemed necessary to automate the evaluation process of the pavement in order to help the decision makers and reflect the actual and future pavement conditions. In 1998, the Roads and Heavy Equipment Department (RHED) / Roads Division of Saudi Aramco implemented the Pavement Maintenance Management System (PMMS) which was developed by Agile Assets Company (formerly TRDI), Austin, Texas, USA and customized it to Saudi Aramco requirements.

The PMMS is a powerful pavement management tool. It is designed to:

1. Assist decision makers in the process of managing a network of pavements.
2. Store, retrieve, and process pavement related condition and inventory data.
3. Allow the user to analyze the current condition, future performance, and expected monetary needs of the pavement network based on preliminary default models due to the lack of roads network data history.

The PMMS has been the main system on which Saudi Aramco depends in maintaining the pavement network and forecasting future work since 1998.

1.2 Problem Statement

Saudi Aramco Pavement Maintenance Management System (PMMS), similar to any other system, has to be customized according to the Roads Division requirements and local conditions such as the method by which rating will be calculated, distress types to be considered, priorities, etc. A steering committee was formed and “PMMS Setup Guidelines” manual was established. The steering committee selected eight distress types (including raveling, fatigue, failures, bleeding, patching, block cracking, linear cracking and rutting) and ten performance indices to measure the pavement condition. Some of the main setup parameters are as follows (PMMS Guidelines, 1997):

1. Distress converter.
2. Performance indices.
3. Default construction values.
4. Priority settings.
5. Building default models.
6. Prediction models.

Pavement condition prediction models which can run on the network and project levels are the most important factor for a complete pavement management system. Despite the several techniques available for developing pavement deterioration models, linear regression and multiple linear/non-linear regression (empirical) is the only method used by Agile Assets Company, the developer of Saudi Aramco PMMS. “Family Method” was used as an alternative to develop performance models due to the lack of historical records of Saudi Aramco pavement network with age. The method consists of the following steps (PMMS Guidelines, 1997):

1. Define the pavement families such as public roads, camp streets, etc.
2. Filter the data for errors or mistakes.
3. Conduct data outlier analysis. Data within $X \pm 2\sigma$ should be included for family model development.
4. Build the family model using regression technique.

Three prediction models were developed for Roads (including Public and Facility Roads), Streets (including Camp Streets and Facility Streets) and Paved Areas (including

Plant Areas, Parking Lots and Lay down Yards) according to the factorial conditions shown in Table 1.1 (PMMS Guidelines, 1997). Pavement condition data was collected from various locations on Saudi Aramco road network including Dhahran, Ras Tanura, Jubail, Abqaiq, Ain Dar, and Shedgum. The collected data was logged to specially prepared Excel sheets to calculate the Performance Index (PI) following the TRDI procedure.

The pavement Performance Index (PI) is a measure of the extent of pavement surface distress, and reliable PI projection models are necessary to estimate the pavement remaining service life. Many attempts have been made over the last three decades to develop models that can predict accurately the structural and functional performance of the highway pavement over time. Most of the developed models were based on theoretical assumptions and few of them were based on actual in-service pavement data. Moreover, the performance models developed based on in-service pavement data were function of one variable only, normally, the time and none of the structural, environmental and materials data elements was included in such models (Hand et al., 1998).

Data was analyzed to develop the overall PI-age models for Roads, Streets and Paved Areas. As a result, three models were developed as shown in Figures 1.1, 1.2 and 1.3. Similarly, eight distress PI models were developed as shown in Figures 1.4 to 1.11. Table 1.2 lists all the above-mentioned models developed by the PMMS team in 1997.

Table 1.1: Factorial Modeling Conditions

Variable	Facility Type		
	Roads	Streets	Paved Areas
Age & Condition	Three in addition to New Construction	Three in addition to New Construction	Three in addition to New Construction
Replicate Observation	Minimum of Three	Minimum of Three	Minimum of Three
Minimum Number of Observations	4×3 = 12	4×3 = 12	4×3 = 12

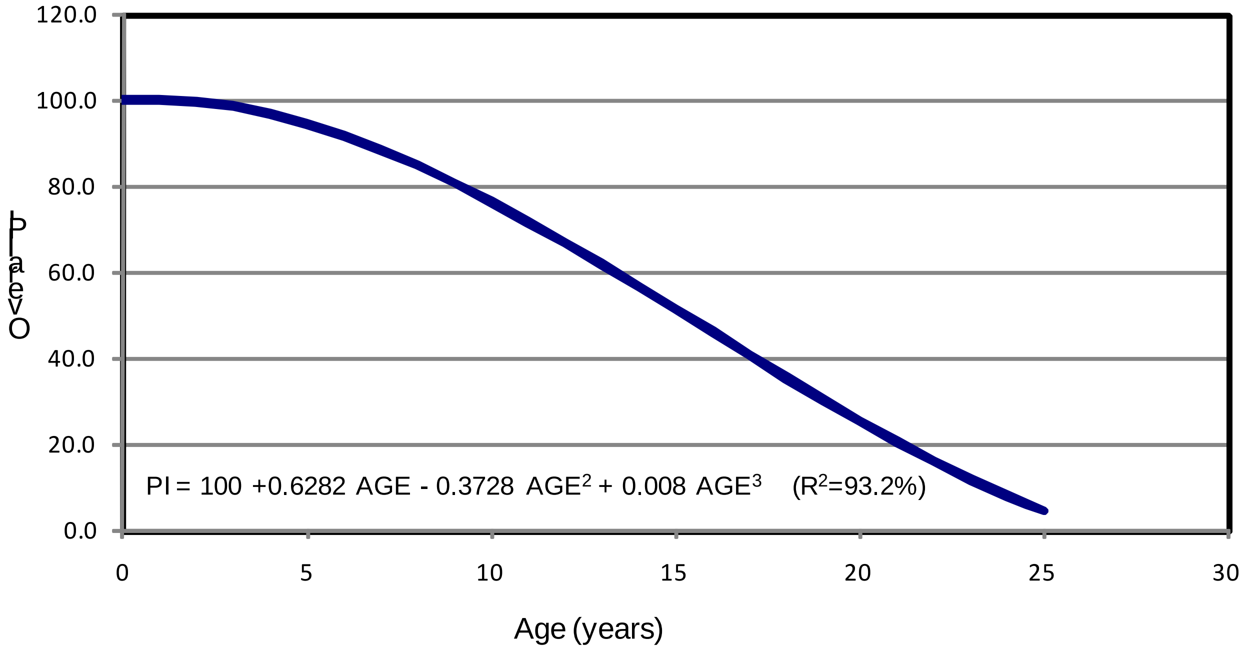

Figure 1.1: PMMS Current Public Overall PI Model

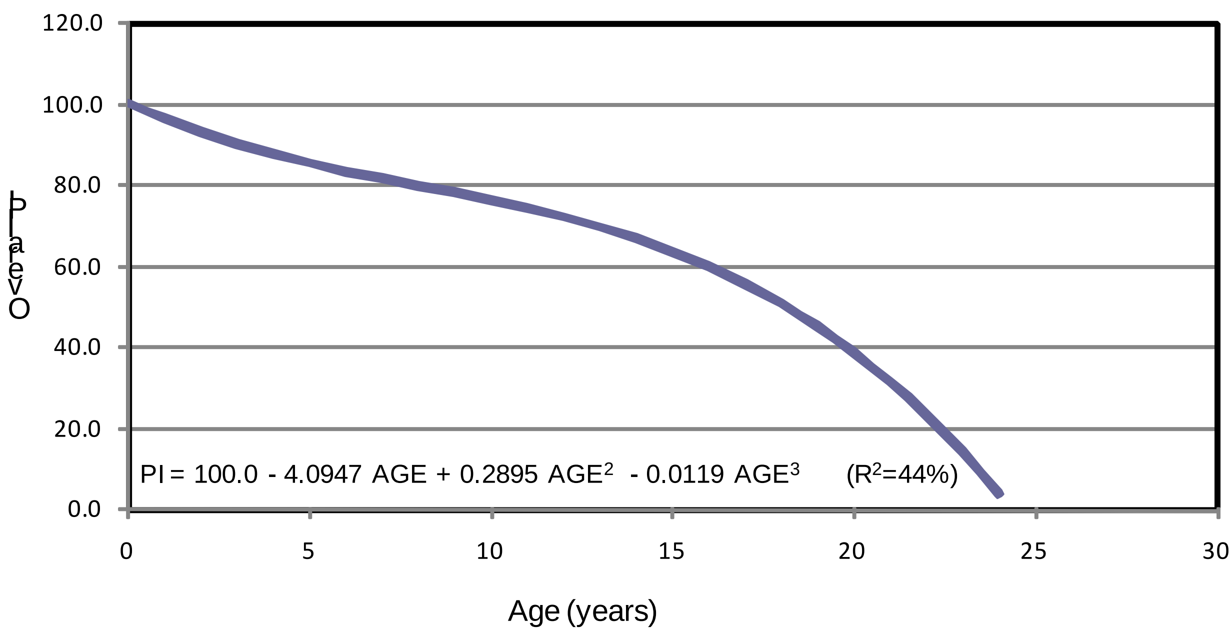

Figure 1.2: PMMS Current Camp Streets Overall PI Model

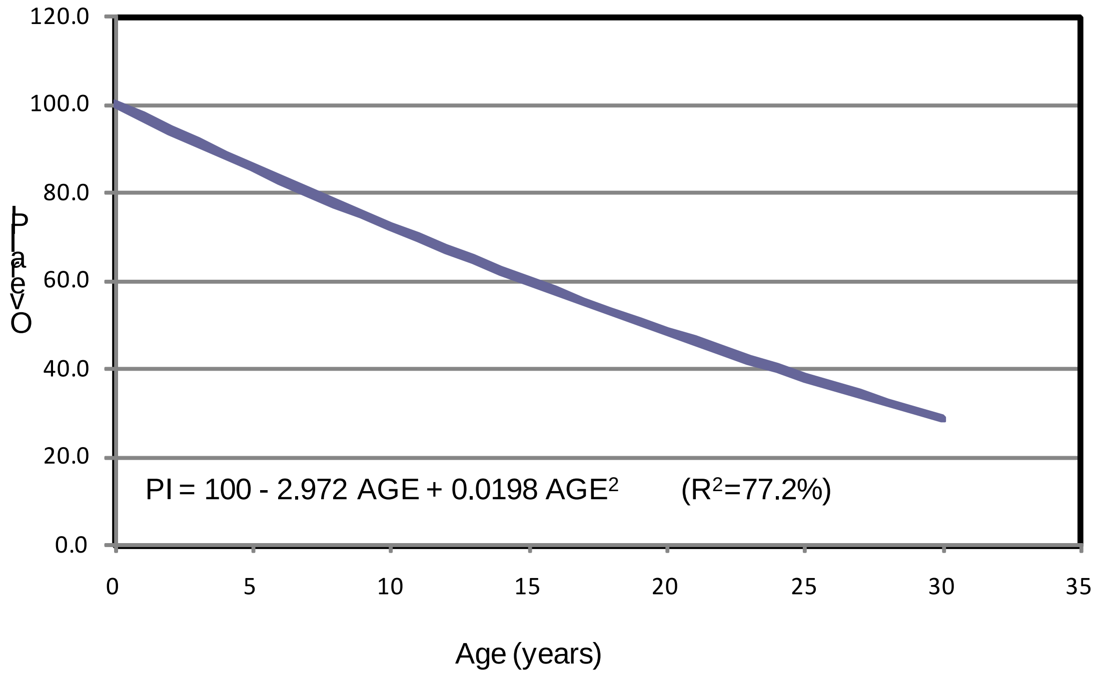

Figure 1.3: PMMS Current Parking Lots Overall PI Model

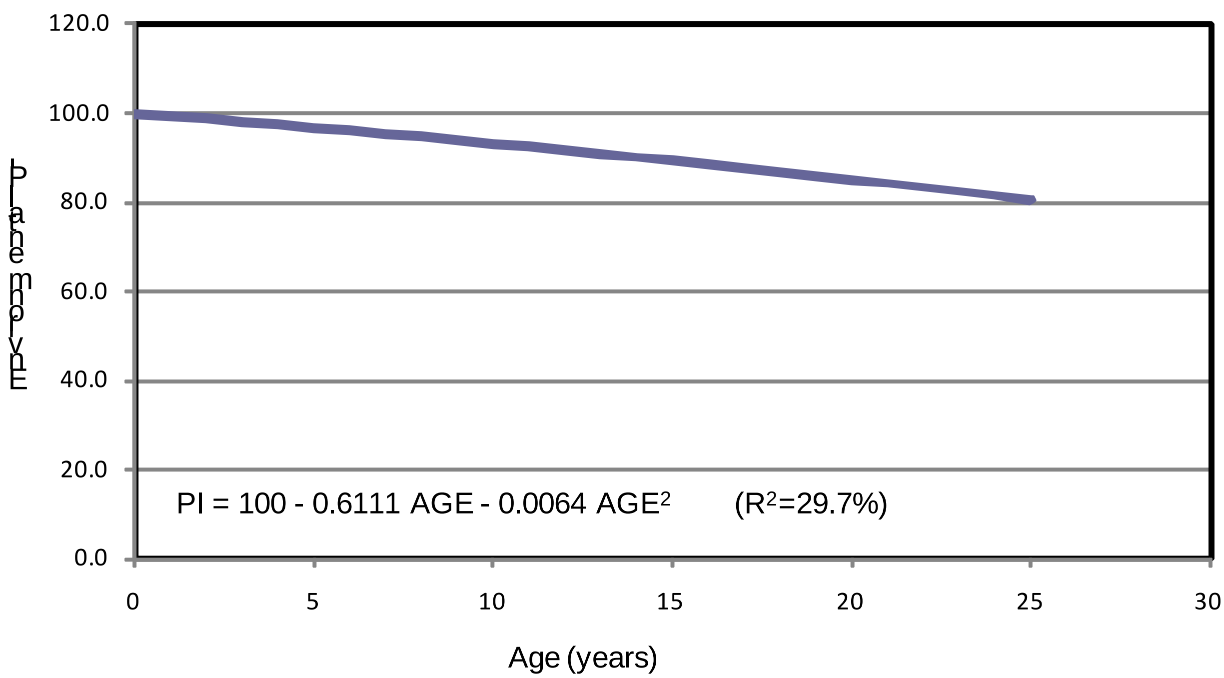

Figure 1.4: PMMS Current Environmental PI Model

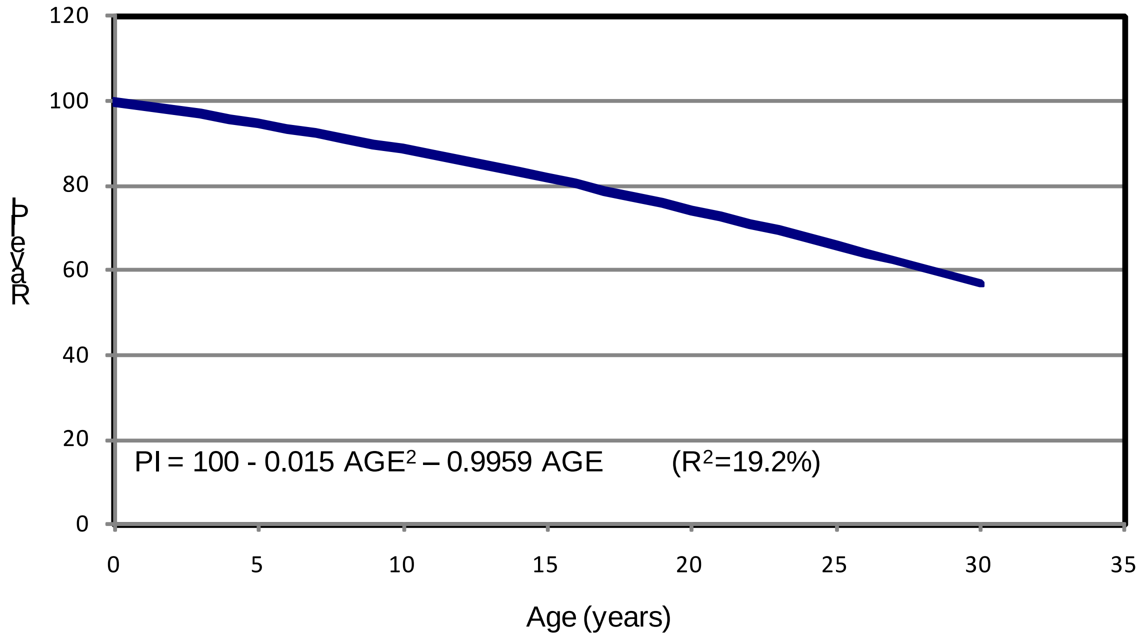

Figure 1.5: PMMS Current Ravel PI Model

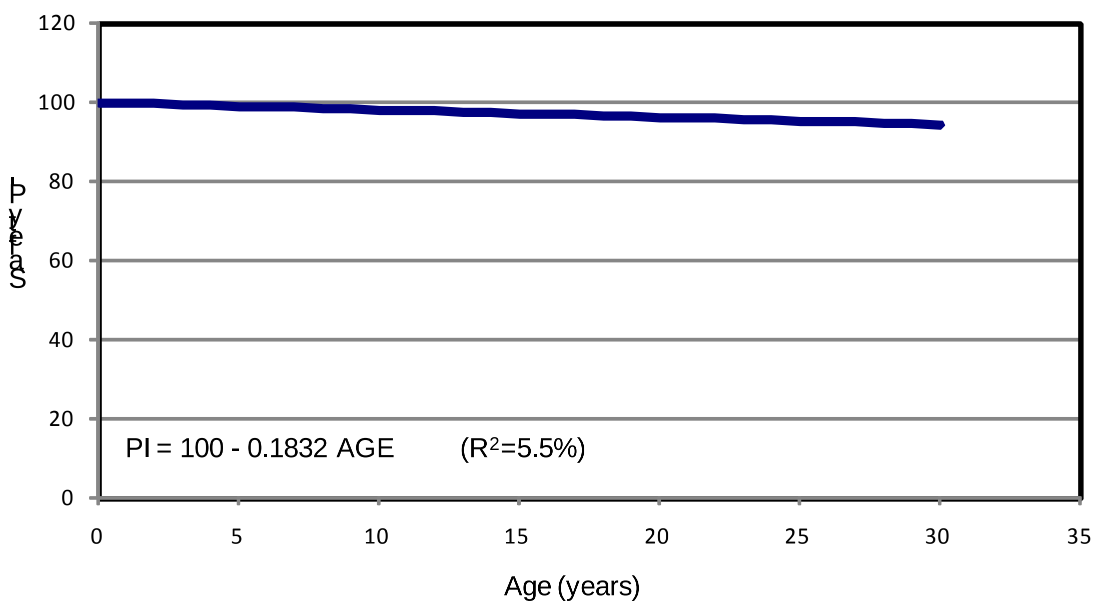

Figure 1.6: PMMS Current Safety PI Model

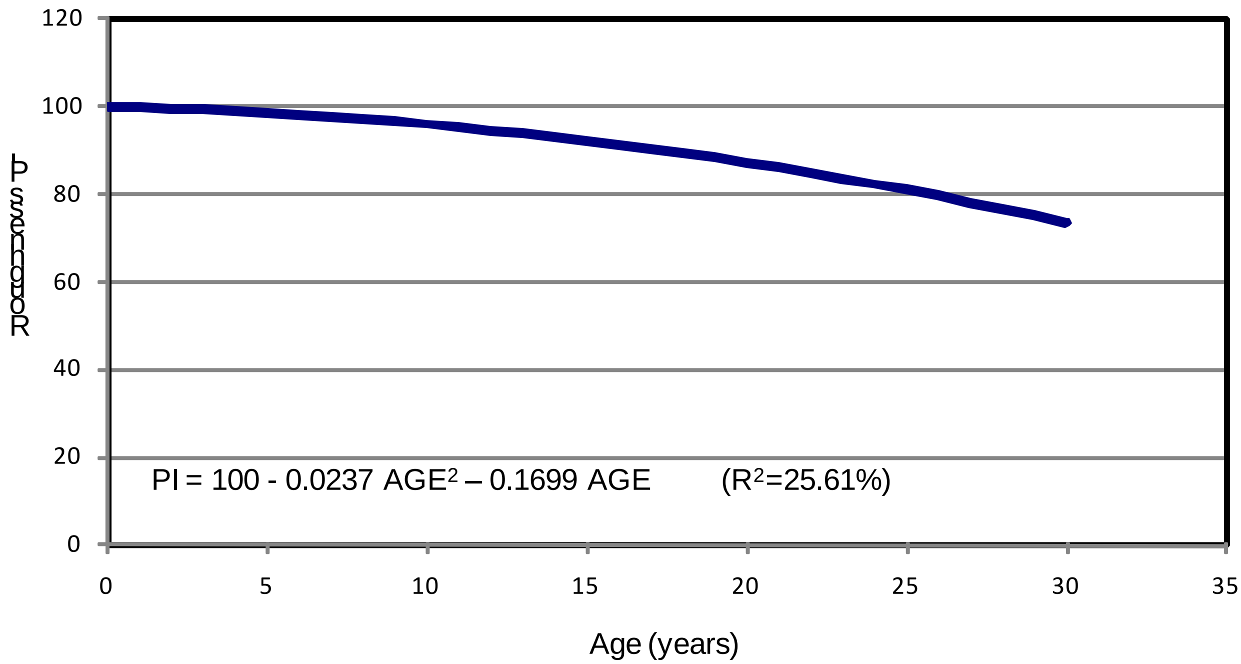

Figure 1.7: PMMS Current Roughness PI Model

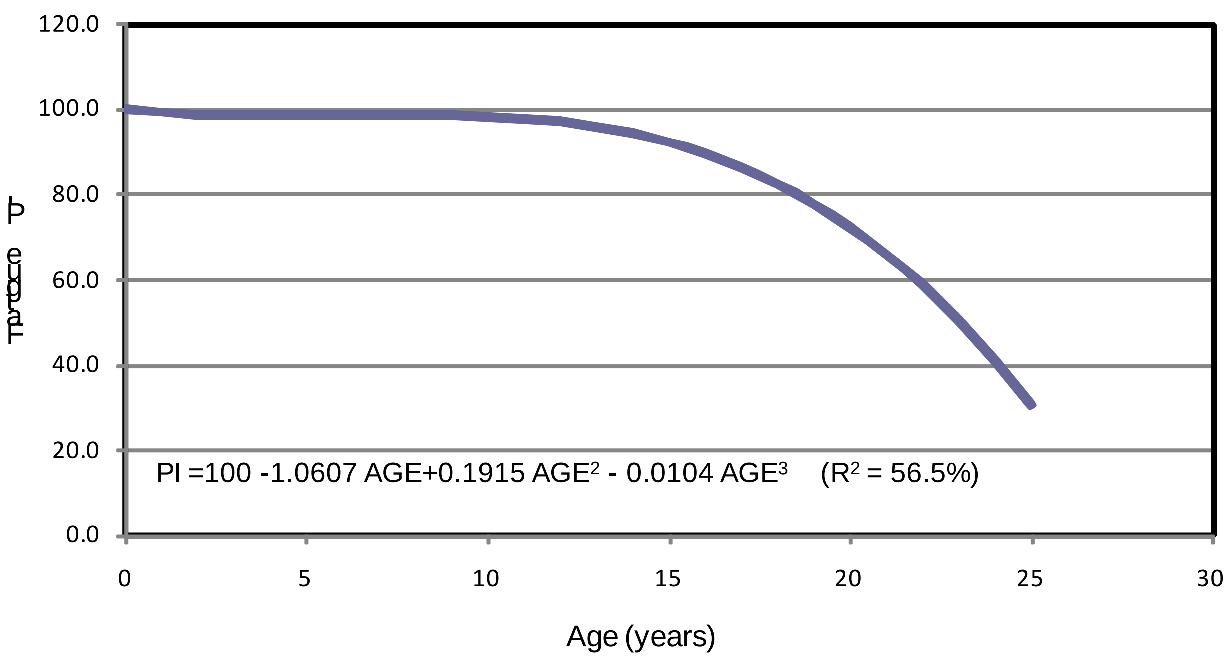

Figure 1.8: PMMS Current Fatigue PI Model

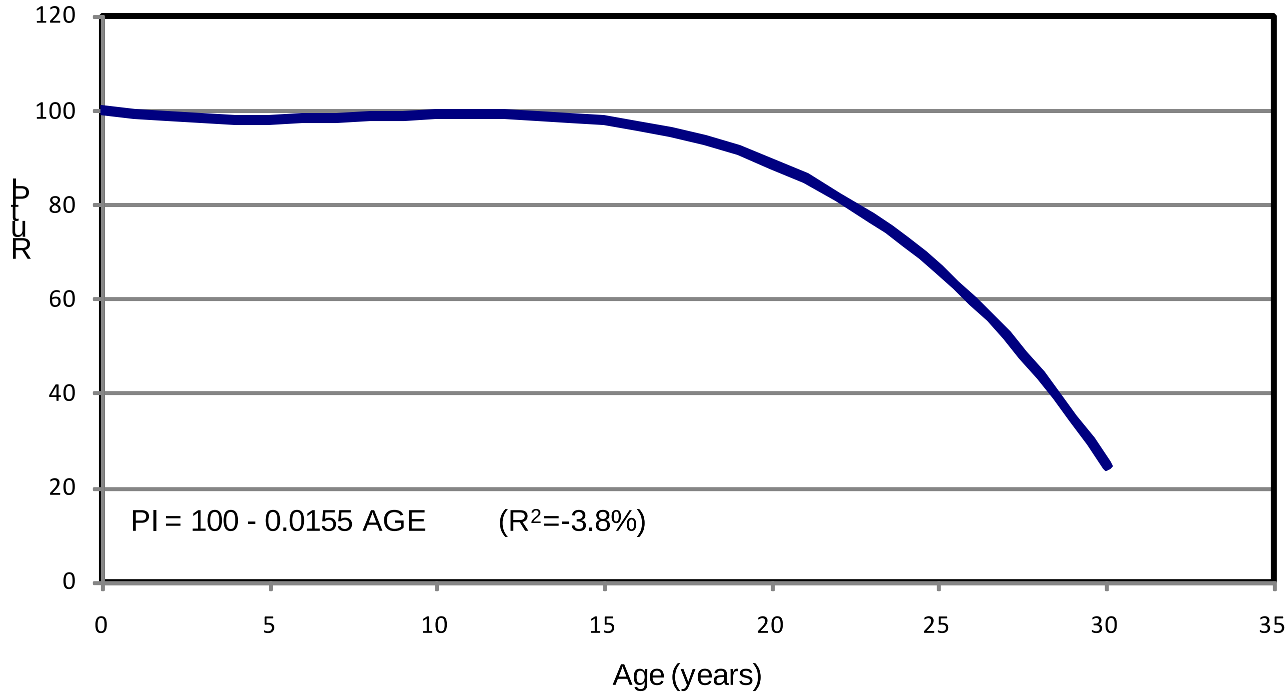

Figure 1.9: PMMS Current Rut PI Model

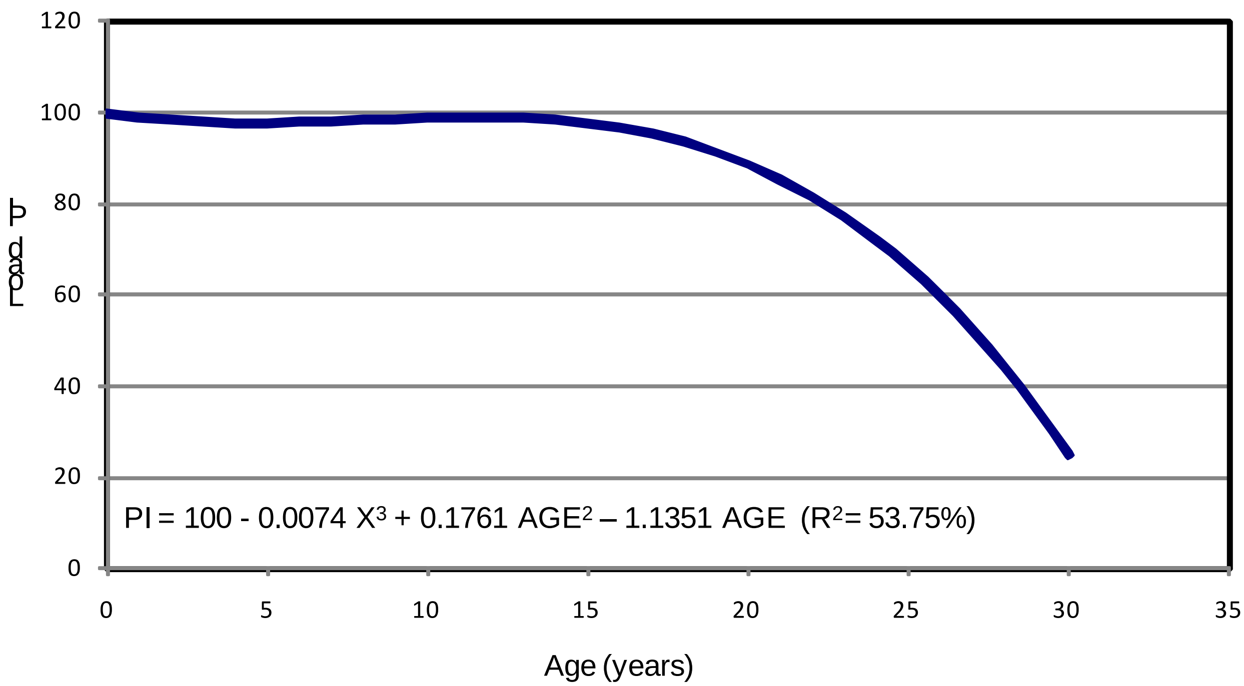

Figure 1.10: PMMS Current Load PI Model

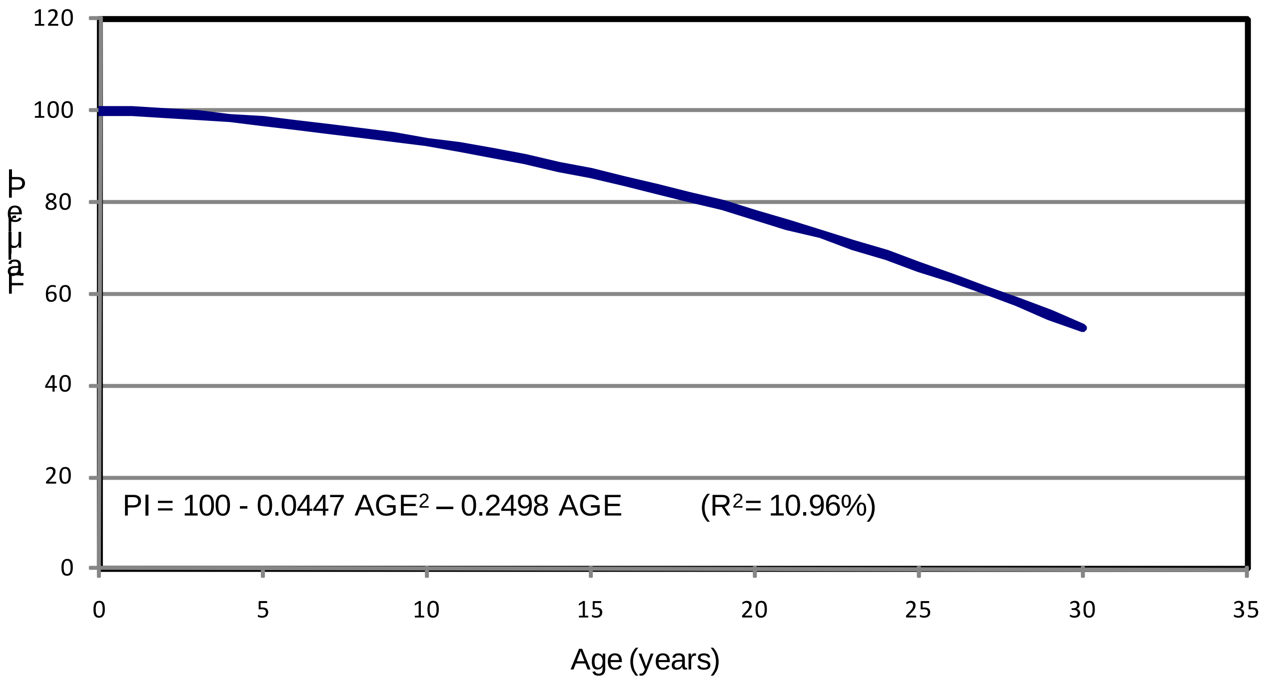

Figure 1.11: PMMS Current Failure PI Model

Table 1.2: Overall & Individual Distress Performance Index Models Developed by the Current System

Model Type	PI Model	Coefficient of Determination (R^2)
Roads Overall PI Model	$PI = 100 + 0.008\ AGE^3 – 0.3728\ AGE^2 + 0.6282\ AGE$	93.2%
Streets Overall PI Model	$PI = 100.0 – 0.0119\ AGE^3 + 0.2895\ AGE^2 – 4.0947\ AGE$	44%
Paved Areas Overall PI Model	$PI = 100 + 0.0198\ AGE^2 – 2.972\ AGE$	77.2%
Environmental PI Model	$PI = 100 – 0.0064\ AGE^2 – 0.6111\ AGE$	29.7%
Ravel PI Model	$PI = 100 – 0.015\ AGE^2 – 0.9959\ AGE$	19.21%
Safety PI Model	$PI = 100 – 0.1832\ AGE$	5.5%
Roughness PI Model	$PI = 100 – 0.0237\ AGE^2 – 0.1699\ AGE$	25.61%
Fatigue PI Model	$PI = 100 – 0.0104\ AGE^3 + 0.1915\ AGE^2 – 1.0607\ AGE$	56.52%
Rut PI Model	$PI = 100 – 0.0155\ AGE$	3.81%
Load PI Model	$PI = 100 – 0.0074\ AGE^3 + 0.1761\ AGE^2 – 1.1351\ AGE$	53.75%
Failure PI Model	$PI = 100 – 0.0447\ AGE^2 – 0.2498\ AGE$	10.96%

The distress performance index models for the eight pre-defined distresses shown in Table 1.2 raise doubts about the use of predicted individual distress performance index as the basis for the maintenance and rehabilitation planning. The performance index models of the distresses have very low coefficient of determination (R^2), which simply means that these models do not adequately represent Saudi Aramco roads network for the following reasons:

1. Does not include or count for the pavement condition data gathered by the PMMS team since 1998.

2. The population used to develop the pavement condition models has very low number of samples (twelve samples per model), which does not reflect the actual or realistic prediction trend and led to uncertainty in the output as indicated by the low values of the coefficient of determination (R^2).

3. The coefficient of determination (R^2) of the overall PI-age is relatively low for some facility types; in some cases, it reaches 0.44, which means that 44% variation in the prediction (the dependent variable) is explained by the linear relationship with the distresses (the independent variable).

4. The coefficient of correlation (r) of the overall PI-age is 0.66, which means that there is weak positive correlation between distress and the age. This could be related to the low number of samples used.

5. Individual distress performance index models have very low coefficient of determination, for example, safety (R^2) reached 0.055, similar to the coefficient of correlation (r), which indicates low reliability of the model.

1.3 Objective

The main objective of this research was to analyze the selected performance prediction models of Saudi Aramco PMMS and develop new prediction models using the available data of the PMMS for the past ten years. Aggregate Overall PI model, three Overall PI models (for Roads, Streets and Paved Areas) in addition to three Distress performance prediction models (for Raveling, Load and Cracking distresses) were developed and compared to similar current models in the PMMS.

1.4 Experimental Design

Consideration was given to all PMMS data for the past ten years and Saudi Aramco pavement network which was classified as shown in Table 1.3.

The above classification of Aramco roads was made to segregate the population into three categories since each category carries different types of traffic and has different operational functions. Moreover, the pavement structure differs significantly from one category to another.

Each facility type has population records covering the past ten years. Each record consists some of many parameters such as route ID and name, pavement management section number (PMS), physical measurement, distress PIs, overall PI, Average Annual Daily Traffic (AADT), facility type, and region. Approximately 10,421 records were analyzed as per the following process:

Table 1.3: Saudi Aramco Pavement Network Classification and Population

Number of PM-Sections	Description	Facility Type	Category
18	Runways, Taxiways, Aprons, etc.	Airstrips (A)	**Airstrips**
674	Highways which are mainly used by public users and Aramco employees	Public Roads (P)	**Roads**
3,857	Highways which are mainly used by Aramco employees	Facility Roads (F)	
1,247	Residential and recreational streets inside Aramco camps	Camp Streets (C)	**Streets**
1,580	Streets located inside the facility plant or in the light industrial area	Facility Streets (S)	
671	Paved areas inside the facility plant	Plant Areas (R)	**Paved Areas**
1,361	Parking lots in any facility or camp	Parking Lots (K)	
1013	Lay down yards in storehouse or facility plant	Lay down Yards (L)	

1. Tabulate the data for each facility type and extract all PM-Sections having a minimum of three data points representing logical deterioration trend.

2. Construct the pavement categories and conduct data outlier analysis to filter errors in the data within $X \pm 2\sigma$.

3. Two-thirds of each data family or the minimum number of records (whichever is bigger) was used to build an initial performance model for each category using statistical regression techniques.

4. Test hypothesis of the model at 95% confidence of interval:

   H_o: A relation exists between the Dependent Variables (DV) & Independent Variables (IV)

   H_1: A relation does not exist between the Dependent Variables (DV) & Independent Variables (IV)

   Testing parameters: Accept H_o if $F_{model} < F_{critical\ (table)}$ or $P < 0.025$

   Reject H_o if $F_{model} > F_{critical\ (table)}$ or $P > 0.025$

5. If H_o is rejected, go back to step number 3 and increase the data size.

6. If H_o is accepted, rebuild the final performance model using all the data.

Considering the available data in the PMMS, the Independent Variables (IV) that affect the Overall and Distress PI are in the following general form:

$$\text{Overall PI / Distress PI} = f\ (\text{AGE, AADT, THICK}) \qquad (1.1)$$

where,

PI = Pavement Index

AGE = Time, in years, from the construction date or the last major maintenance

AADT = Average Annual Daily Traffic

THICK = Combined thickness of all asphalt layers

Other common factors such as Subbase type were not included since there were no different types used in almost all pavement sections. Similarly, truck percentage and drainage factor were omitted due to insufficient data.

It was expected that Age and AADT were to be inversely proportional to the PI while pavement thickness was to be proportional to the PI in the general model mentioned above. Segregated populations are shown in Table 1.3. Approximately 10,421 underwent the process illustrated in Figure 1.12 and summarized in the above points.

Using Minitab statistical software, accepted data was analyzed to determine the significant independent variables and build new prediction PI models. The new prediction models experimental design that was developed for the overall and distress PI of different pavement categories including Roads category (public and facility roads), Streets category (camp streets and facility streets), and Paved Areas category (plant areas, parking lots and lay down yards) is shown in Tables 1.4 and 1.5.

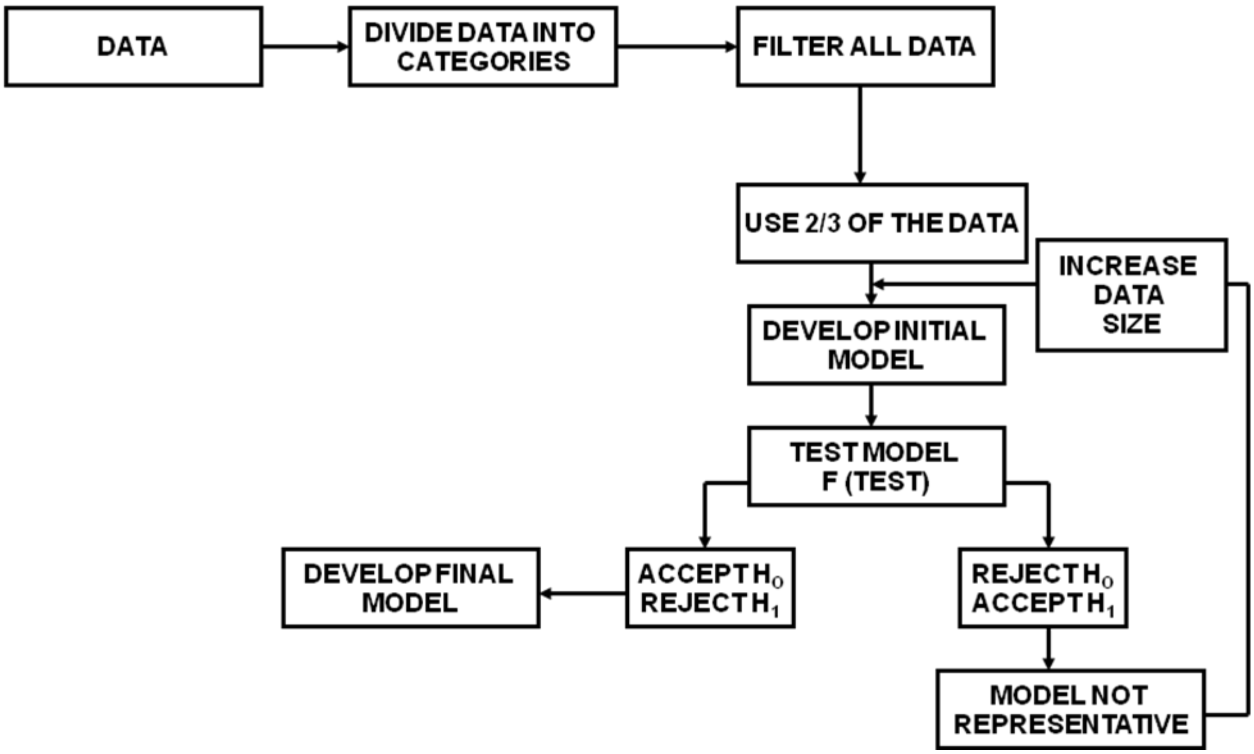

Figure 1.12: Experimental Design Flow Chart

Table 1.4: Aggregate and Overall Prediction PI Model Experimental Design (Part I)

Facility Types	Aggregate Overall PI Model	Roads Overall PI Model	Streets Overall PI Model	Paved Areas Overall PI Model	Min # of Samples
Airstrips	All Distresses & Attributes	-	-	-	4×3 = 12
Public Roads	All Distresses & Attributes	All Distresses & Attributes	-	-	4×3 = 12
Facility Roads	All Distresses & Attributes	All Distresses & Attributes	-	-	4×3 = 12
Camp Streets	All Distresses & Attributes	-	All Distresses & Attributes	-	4×3 = 12
Facility Streets	All Distresses & Attributes	-	All Distresses & Attributes	-	4×3 = 12
Plant Areas	All Distresses & Attributes	-	-	All Distresses & Attributes	4×3 = 12
Parking Lots	All Distresses & Attributes	-	-	All Distresses & Attributes	4×3 = 12
Lay down Yards	All Distresses & Attributes	-	-	All Distresses & Attributes	4×3 = 12

Table 1.5: Aggregate Distress Prediction PI Model Experimental Design (Part II)

Facility Types	Aggregate Ravel PI Model	Aggregate Load PI Model	Aggregate Cracking PI Model	Min # of Samples
Airstrips	Ravel Distress & Attributes	Load Distress & Attributes	Linear & Block Cracking Distress & Attributes	4×3 = 12
Public Roads	Same as above	Same as above	Same as above	4×3 = 12
Facility Roads	Same as above	Same as above	Same as above	4×3 = 12
Camp Streets	Same as above	Same as above	Same as above	4×3 = 12
Facility Streets	Same as above	Same as above	Same as above	4×3 = 12
Plant Areas	Same as above	Same as above	Same as above	4×3 = 12
Parking Lots	Same as above	Same as above	Same as above	4×3 = 12
Lay down Yards	Same as above	Same as above	Same as above	4×3 = 12

1.5 Expected Benefits

The output of this study is expected to be useful for Saudi Aramco. The new models shall:

1. Give a better understanding of the performance of the pavement under different environmental and traffic conditions based on 10 years of actual data.
2. Play a significant role in the short- and long-term planning.
3. Provide decision makers with prediction tools strategies derived through rational engineering procedures.

CHAPTER 2

LITERATURE REVIEW

The purpose of this chapter is to provide a general review on the available literature in the area of Pavement Management and Performance Prediction Modeling.

2.1 Pavement Management System Concept

AASHO defines Pavement Management System (PMS) as “a set of tools that assists decision makers in finding optimum strategies for providing, evaluating and maintaining pavements in a serviceable condition over a given period of time”.

The researchers view pavement management system as a systematic method for data collection, processing, condition evaluation and reporting, and decision making for the purpose of optimizing the maintenance and rehabilitation needs of the pavement network on the short- and long-term plans. Therefore, pavement management system is considered as a philosophy adopted by each road agency for managing road network using well-established procedures that satisfy their needs.

As shown in Figure 2.1, a pavement management system provides information at the network level used to develop a statewide program for maintenance or rehabilitation that will optimize the use of the available funds. Also, pavement management system provides more detailed information about the optimum design, construction and maintenance at the project level for a particular roadway section within the overall program.

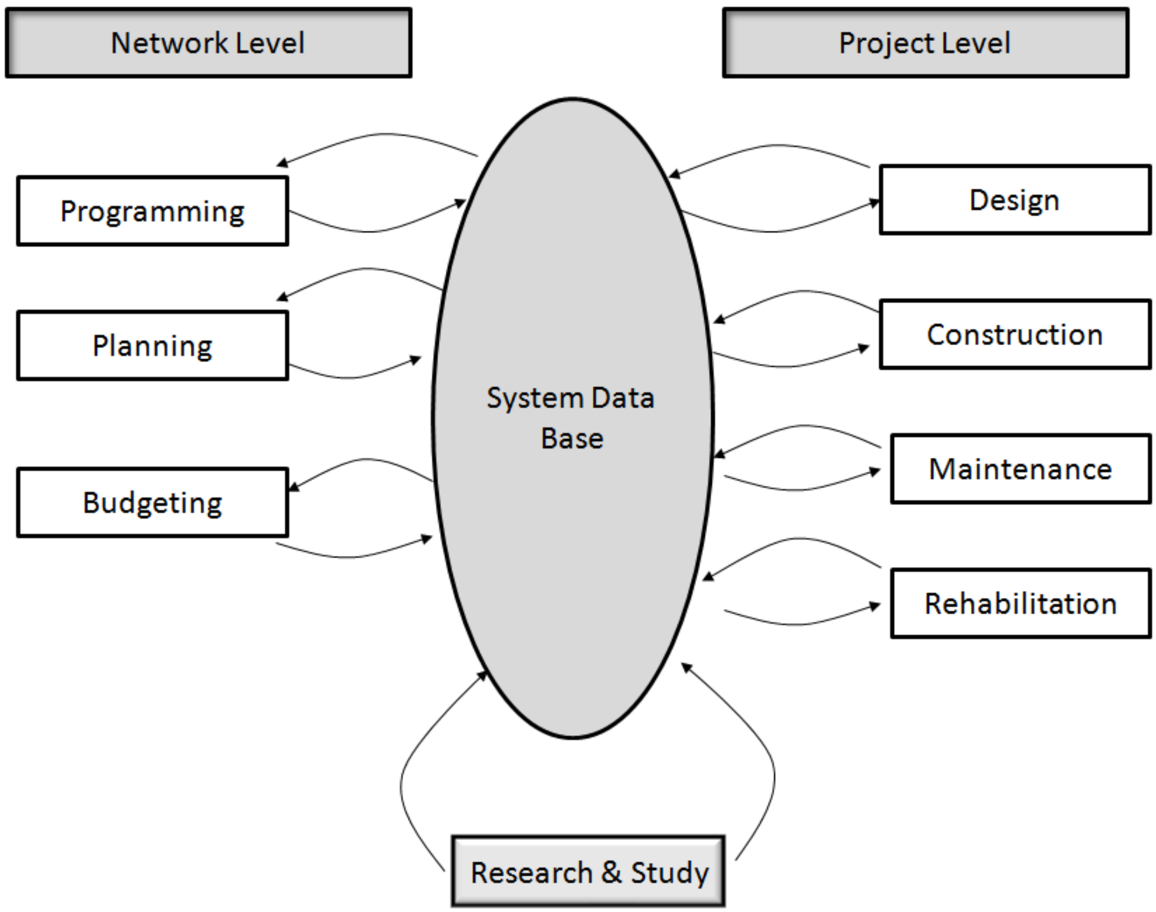

Figure 2.1: Different Activities of the Pavement Management System

In the last twenty years, many pavement management systems have been developed to enhance maintenance planning to assist maintenance engineers and decision makers in managing pavement assets in a systematic and reliable way. Despite all the developments in this field, further improvements are deemed necessary to make the PMS more comprehensive, reliable and practical.

Pavement performance is a measure of the adequacy of the pavement's structural and functional service over a specified design period (Al-Mansour, 2006). An essential element of any PMS is to provide reliable and accurate prediction of pavement condition or performance at any specific time during the service life of the pavement in order to determine the optimal maintenance requirements. Pavement performance models can be used for such a task and also to determine future maintenance needs, required maintenance budget and to set maintenance priorities based on available budget.

Road users and the public assess pavement performance in subjective ways. As users, they are concerned with the ride quality, safety, appearance and convenience of the roadway. Highway agencies expect pavements to last long enough before doing a preventive maintenance and to justify the cost of their construction.

There are, however, characteristics of pavements which can be measured quantitatively and can be correlated to the user's subjective assessments of performance. These characteristics are called "performance indicators" and include structural adequacy, surface friction, roughness and visible distress.

Most of the highway agencies incorporating PMS developed performance models using either a theoretical approach or actual pavement data to predict current and future pavement condition. In cases where actual pavement data is used, performance models predict pavement rate of deterioration as a function of the factors that affect pavement condition. Many of the existing performance models are simple and include only some illustrative variables. These models generally do not include the effect of type and level of maintenance on pavement performance. The more complex models that include number of variables in addition to the maintenance effect were found to be practical but have been proven to fit the data poorly.

In the following subsections, a review of the three major areas is given in addition to a summary of some of the models currently in use. The first step in developing pavement performance models is to determine the pavement performance indicators. Pavement condition is then evaluated based on these indicators.

2.2 Pavement Performance Indicators

It is difficult to utilize user's assessments of pavement performance directly in pavement design. However, it can be measured quantitatively by the characteristics of pavements, and then it can be correlated to the user's subjective assessments of performance. These characteristics are called "performance indicators". The four major performance indicators are (Al-Suhaibani and Al-Mansour, 2002):

1. Visible distress,
2. Roughness (serviceability),
3. Structural adequacy, and
4. Surface friction.

To quantify these characteristics, several condition indices have been developed, for example, the skid number (SN) which is generally quantified using some friction measurements such as friction factor or skid number (Shiyab, 2007).

$$\text{Coefficient of Friction } (f) = F/L \quad (2.1)$$

where,

F = Friction coefficient

F = Friction resistance force

L = Load applied in perpendicular form to the surface

The Skid Number is calculated as follows:

$$(SN) = f * 100 \quad (2.2)$$

Also, the International Roughness Index (IRI) for measuring roughness is one important way to measure the condition of the pavement. The IRI is defined as the average rectified slope which is the ratio of the accumulated suspension motion to the distance traveled obtained from a mathematical model of a standard quarter car traversing a measured profile at a standard speed of 80 km/hr.

$$IRI = \sum (D_v/D_h) \quad (2.3)$$

where,

IRI = International Roughness Index

D_v = Vertical displacement of the sprung mass with reference to the un-sprung mass

D_h = Horizontal traveled distance (m or km)

Individual distresses can be represented as indices; in pavement management systems, composite distress indices such as the Pavement Condition Index (PCI) and Performance Index (PI) have been successfully used. A composite distress index will indirectly provide a measure of roughness, skid, and structural integrity because of the relationship between the various distress types and each of the condition characteristics.

The significance of any condition index depends upon the number of the distresses considered in the model and their inter-correlation. For example, the results of the analysis indicate that PCI (PCI-age) using PAVER method is more capable in capturing the age effect on the Pavement Condition for different facilities than the overall Performance Index (PI-age) using TRDI method. This might be attributed to the fact that TRDI method considers eight types of distresses while PAVER method considers nineteen types of distresses (PMMS Guidelines, 1997).

2.3 Pavement Condition Evaluation

The evaluation of pavement condition or pavement performance is an important factor of pavement design, rehabilitation and management. It includes the evaluation of surface distresses, roughness, friction and structure. In general, pavement condition consists of four main components (Shiyab, 2007):

1. Load Bearing Capacity (Structural)
2. Riding Comfort (Roughness)
3. Safety (Skid Resistance)
4. Surface Distress

The collected pavement condition data are incorporated by most of maintenance organizations to assess the existing condition and to determine what type of corrective action is needed and when that action is needed. They are also used for establishing priorities and planning for short- and long-term budgeting.

There are considerable variations on the approaches used by maintenance organizations for development of a quantifiable method which characterizes the pavement condition. However, most organizations use all pavement evaluation parameters such as surface distresses, roughness data together with structural evaluation and skid resistance data to characterize pavement condition.

Nevertheless, there are basically two approaches which have been used by maintenance organizations in utilizing the pavement evaluation data for pavement condition assessment. In the first approach, a single index or rating number based on aggregated pavement condition data indicating the overall pavement condition is developed. The second approach assesses the pavement condition (without aggregating the data) and determines the appropriate maintenance action required using a specific methodology.

In 1960s, attempts were made to assess pavement condition on the basis of a quantifiable measurement of pavement distresses (AASHO Test Report No. 5, 1962). The output of the attempt was the development of the Present Serviceability Index (PSI). Serviceability of a pavement is defined as the pavement's ability to provide support and satisfactory ride at any specific time. The PSI is a number which indicates the pavement's ability to serve traffic at any specific time. This number is based on the roughness measurements and the surface distresses. The rating of pavement condition according to the PSI, ranges from zero to five as shown in Table 2.1.

The Present Serviceability Index (PSI), which is based on roughness and distresses, is given by following regression equation (AASHTO, 1986):

$$PSI = 5 - 1.91 \log (1 + SV) - 1.38 (RD)^2 - 0.01 (C + P)^{0.5} \quad (2.4)$$

where,

PSI = present serviceability index

SV = slope variance

RD = average rut depth

C = pavement cracking in feet/1000 ft

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

Using the same source of data used to develop the above equation and varying the principles of the analysis for incorporating patching, cracking and slope variance, a new equation for flexible pavement is obtained as follows (Shiyab, 2007):

$$PSI = 5 - 1.68 \log (s'/0.71) - 1.38 \log r'/(6.1*10^3 - 0.00871 \log (C/7*10^{-3}) \quad (2.5)$$

where,

PSI = present serviceability index

s’ = slope variance

r’ = average rut depth

C = density of cracking (ft^2/1000 ft^2)

Table 2.1: Present Serviceability Index (PSI) Rating

PSI Value	Pavement Condition
0 – 1	Very Poor
1 – 2	Poor
2 – 3	Fair
3 – 4	Good
4 – 5	Very Good

The other widely used single rating number is the Pavement Condition Index (PCI), which was developed by the Army Corps of Engineers (Shahin et al., 1981). The PCI is given as follows:

$$PCI = C - \sum \sum a\,(T_i, S_i, D_{ij}) \times F\,(t, q) \quad (2.6)$$

where,

C = constant (usually 100)

a = weighing factor

T_i = distress type i

S_i = severity level

D_{ij} = density of distress

F = adjustment factor for multiple distresses

q = number of deduct value > 5

t = distress type.

It is apparent from the above equation that the PCI uses only one pavement condition parameter (distress). The other parameters such as roughness, skid resistance and structural adequacy are not considered in pavement evaluation. The rating of pavement condition according to the PCI ranges from 0 to 100 as shown in Table 2.2.

Table 2.2: PCI Rating

PCI Value	Pavement Condition
0 – 10	Failed
10 – 25	Very Poor
25 – 40	Poor
40 – 55	Fair
55 – 70	Good
70 – 85	Very Good
85 – 100	Excellent

Although the concept of a single index which is composed of weighted pavement condition factors may help in the overall pavement condition assessment and in establishing the criteria for maintenance needs, it does not by itself indicate what maintenance action is needed. The single number does not reveal the type, severity and extent of the distresses since two pavement sections can have the same PCI value while the distresses in each section are different. This, however, does not mean that such indices are meaningless in pavement management. Rather, they are usually used in conjunction with the knowledge of other pavement condition parameters to determine the actual pavement's maintenance needs.

In the second approach, pavement organizations do not aggregate pavement data into a single index. Instead, a specific methodology is utilized for assessment of pavement condition and determination of the required maintenance action. Presented herein are some examples of this approach.

2.4 Saudi Aramco Pavement Maintenance Management System (PMMS)

In early 1970s with the beginning of the global booming, Saudi Aramco Roads Department has been neck to neck with the asphalt pavement technology. The Roads Department adopted the flexible pavement technology and hot mix asphalt, and outsourced the construction work to local contractors. It classified its network according to its primary functions and proponent (Agile Assets® Pavement Analyst 5, 2006). It includes Public Roads, Facility Roads, Airstrips, Camp Streets, Facility Streets, Parking Lots, Lay down Yards, and Plant Area.

The maintenance program of these facilities was a collaborative effort depending solely on the engineers' technical evaluation and experience which is considered as a drawback to the maintenance program (Agile Pavement Manager Users Guide, 2004) in addition to human errors and lack of rational prioritization.

It was deemed necessary to automate the evaluation process of the pavement in order to help the decision makers and reflect the actual and future pavement conditions. In 1998, the Roads and Heavy Equipment Department / Roads Division implemented the Pavement Management Maintenance System (PMMS) which was developed by Agile Assets Company (formerly TRDI), Austin, Texas, USA and customized the Pavement Management Maintenance System to the Roads Division requirements.

Each paved facility in Saudi Aramco is considered to be as one single "Route". This route could be a road, a camp street, a parking area, a lay down yard, a plant or an airstrip. This route is divided into several Pavement Management Sections (PM-Sections) based on the similarity in asphalt attributes such as asphalt condition, construction history or traffic. Then, each PM-Section is divided into almost equal number of distress survey units. These units are approximately 500 sq.m for parking areas, lay down yards or plants and 200 m for roads, camp streets or facility streets.

In general, the pavement should be divided into homogeneous PM sections in which all the relevant attributes such as pavement type and design, traffic, condition, subgrade, paving material characteristics and maintenance type are approximately uniform. These sections are commonly referred to as **P**avement **M**anagement **S**ections (**PMS**). It is expected that pavement management sections limits be defined along the limits where the same type of work is logically expected to be performed at the same time within one project. Often, these sections fall into the same section intervals as original and rehabilitation pavement projects. Thus, pavement management sections will have the same characteristics and construction history. Pavement management section is defined based on several factors including:

- Surface distresses are approximately the same.
- Pavement cross section is approximately the same.
- Pavement age is approximately the same.
- The classification variables for the section are unique to the section.

Saudi Aramco applies the overall Performance Index (PI) using TRDI method where only eight types of distresses are considered. These distresses are as follows (PMMS Flexible Pavement Distress Survey Guidelines, 2000):

2.4.1 Raveling

Weathering and raveling are the wearing away of the pavement surface caused by the loss of asphalt or tar binder and progressive disintegration of the surface due to dislodgment of aggregate particles. Raveling is calculated by percentage area of the section.

Severity Level

Low: The aggregate or binder has begun to wear away but has not progressed significantly; some loss of aggregate.

Moderate: Aggregate and/or binder has worn away and the surface texture is becoming rough and pitted; loose particles generally exist; loss of fine aggregate and some loss of coarse aggregate.

High: Aggregate and/or binder has worn away and the surface texture is very rough and pitted; loss of coarse aggregate.

2.4.2 Fatigue

Fatigue (or alligator) cracking is a series of interconnecting cracks caused by fatigue failure of the asphalt concrete surface under repeated traffic loading and usually occur in the wheel paths. Fatigue cracking, which is considered as a major structural distress, forms small, irregularly shaped blocks that resemble the patterns found on an alligator's skin. Polygons or blocks (formed by fatigue cracks) are less than 0.3 meter by 0.3 meter, larger blocks should be rated as block cracking. A mixture of small and large polygons or blocks should be rated as fatigue cracking. Fatigue crack, which has not formed a complete alligator pattern, will be rated in the low severity level as shown below.

Severity Level

Low: An area of longitudinal cracks with few connecting cracks not spalled or sealed and pumping is not evident.

Moderate: An area of interconnected cracks forming a complete pattern; cracks may be slightly spalled; cracks may be sealed; pumping is not evident. Crack width > 3 mm and < 6 mm wide.

High: An area of moderately or severely spalled interconnected cracks forming a complete pattern; pieces may move when subjected to traffic; cracks may be sealed; pumping may be evident. Cracks widths are > 6 mm.

The fatigue cracking area is rated by evaluating the fatigue cracking that occurs in or near the wheel paths throughout the section for the three severity levels. The rating value measures the percentage of the rated lane's total wheel path area that is covered by fatigue (alligator) cracking.

2.4.3 Failures (such as Shoving, Potholes, Utility Cuts, etc.)

A failure is a localized section of pavement where the surface has been severely eroded, badly cracked, or depressed. Failures are important to be rated because they identify specific structural deficiencies that may pose safety hazards.

Failures include:

1. Potholes greater than 15 cm in diameter of any depth.
2. Shoving with vertical displacement greater than 25 mm.
3. Deep rut depths or depressions greater than 50 mm.
4. Edge of pavement surface breaks off wider than 15 cm and longer than 15 cm.

Severity Level

Low: Potholes > 150 mm in diameter and < 25 mm deep.

Moderate: Potholes, shoving (or corrugations) or other depressions ≥ 25 to 50 mm deep.

High: Potholes, shoving, and rut depths or other depressions > 50 mm deep.

Rating is calculated by adding up all areas for all types of failures mentioned above to calculate the total percentage area of each severity level observed along the entire survey sample.

2.4.4 Rutting

A rut is a surface depression in the wheel path. Pavement uplift may occur along the sides of the rut, but, in many instances, low severity ruts are noticeable only after a rainfall, when the paths are filled with water. Rutting is developed from a permanent deformation in any of the pavement layers, usually caused by consolidated or lateral movement of the materials due to traffic loads. Significant rutting can lead to major structural failure of the pavement.

Rutting in the rated lane may occur in one or both wheel paths. A minimum of three rut depths should be measured in each PMS (pavement management section) and should be evenly spaced throughout the sample. Additional measurements may be needed if rut depths are not fairly uniform within the sample. Rutting should be measured using a straight edge (1.83-m minimum length) or a string with a small scale. The rater should observe rutting throughout the section length and compare them with measurements observed in the sample. A 1.0-km section will have 2.0 km of wheel paths. If one wheel path has 100% of its length with low severity rutting and the other wheel path has no rutting, then the estimated percentage of the length is 50% low severity rutting. Severity levels are described below.

Severity Level

Low: < 10 mm.

Moderate: 10 to 20 mm.

High: > 20 mm.

Special Cases for Rutting

1. If a rut is greater than 50 mm deep, measure its length and rate it as failures.
2. Other distress types within a rut should be rated separately.

2.4.5 Bleeding

Bleeding is the formation of a bituminous material film on the pavement surface, which creates a shiny, glass-like, reflecting surface that usually becomes quite sticky. Bleeding is caused by excessive asphalt cement in the mix, excess application of a bituminous sealant, and by low air void content. Bleeding is rated by the percentage area of each severity level.

Severity Level

Low: An area of pavement surface discolored relative to remainder of the pavement by excess asphalt.

Moderate: An area of pavement surface that is losing surface texture due to excess asphalt.

High: Excess asphalt gives the pavement surface a shiny appearance; the aggregate may be obscured by excess asphalt; tire marks may be evident in warm weather.

2.4.6 Patching

A patch is an area of pavement, which has been replaced with new material to repair the existing pavement. A patch is considered a defect no matter how well it is performing (a patched area or adjacent area usually does not perform as well as an original pavement section).

Patching is rated according to the percentage of the section area. The area of the patches is estimated then divided by the total area of the survey section and multiplied by 100 to get the percentage of the area. Rate patching that occurs anywhere in the lane that is shorter than 50 meters in length and regardless of the patching width. Patches do not receive a severity level. Further distress in a patch will be rated separately by one of the other definitions of distress.

2.4.7 Block Cracking

Block cracking consists of interconnecting cracks that divide the pavement surface into rectangular pieces, varying in size from 0.3 meter by 0.3 meter up to 3 meters by 3 meters. Although similar in appearance to fatigue cracking, block cracks are much larger. Block cracking is not load-associated. Instead, it is commonly caused by shrinkage of the asphalt concrete or underlying pavement material.

Severity Level

Severity levels are based on the estimated width of the cracks for the widest 25% of the crack.

Low: < 6 mm.

Moderate: 6 to 19 mm.

High: > 19 mm.

After assessing the total area of block cracking, the percentage of the section that block cracking represents for each severity level is calculated. The percentage of the section area should be recorded to the nearest whole number. Note that the addition of percentages of all severity levels should not exceed 100. This rule applies to all types of distresses except for Linear Cracking which is recorded in linear meters.

2.4.8 Linear Cracking

Linear cracking is divided into two types:

Longitudinal Cracking: consists of cracks or breaks that run predominantly parallel to the pavement centerline. These cracks are commonly caused by shrinkage of the asphalt base, asphalt construction joints, or flexion of cracks in the base or subgrade.

Transverse Cracking: consists of cracks or breaks that travel predominantly perpendicular to the pavement centerline or lay down direction. These cracks are commonly caused by shrinkage of the asphalt or flexion of cracks from stabilized underlying layers.

Severity Level

Severity levels are based on the estimated width of the cracks for the widest 25% of the crack or cracks within a localized area.

Low: < 6 mm.

Moderate: 6 to 19 mm.

High: > 19 mm.

The total linear meter of all linear cracking should be estimated and recorded to the nearest meter for each severity level. Transverse cracking can be estimated by counting the number of transverse cracks and multiplying them by the width of the lane. If transverse cracks cross only part of the lane, then the number of cracks may be estimated by counting the partial cracks as 1/4, 1/3, 1/2, etc. The length of longitudinal and edge cracks should be estimated and added to the transverse crack length. If multiple cracks occur within one section, count all linear meters of cracking.

Saudi Aramco also incorporated nine distress indices in addition to the overall Pavement Index (PI) in the PMMS. The individual distress indices values reflect the extension of failure in the pavement and indicate a pattern of failure along the service life of the pavement. The distress indices shown in Table 1.2 were taken for the eight distress types mentioned earlier in addition to the load index. Each distress index has a weight depending on its significance and contribution to the overall PI. The rating of pavement condition (PI) according to the PMMS that ranges from 0 to 100 is shown in Table 2.3.

The general process of developing pavement condition indices which is followed by Saudi Aramco PMMS consists of assigning deduct points to specific type, severity and density of distress and calculating the individual distress PI's. These PI's are used to calculate the overall PI as a single value index. However, the developed indices represent

Table 2.3: Saudi Aramco PI Rating

PI Value	Pavement Condition
0 – 20	Very Poor
20 – 40	Poor
40 – 60	Fair
60 – 80	Good
80 – 100	Very Good

the organization's professional judgment on what combination of distresses and weighted pavement condition factors is important to them. The pavement performance equation indices are calculated using the following equation (Agile Assets, 2006):

$$\mathrm{PI_k} = 100 \prod_{i=1}^{n} \left[1 - \left(1 - \frac{DI_i}{100} \right) w_{i,k} \right] \tag{2.7}$$

For K = 1 to 10

where,

PI_k = the k^{th} performance index

$w_{i,k}$ = the relative weight of the distress or condition

DI_i = the distress index for the condition measure I

i^{th} = distress out of a total number of "n" distresses

The following example describes Saudi Aramco PMMS overall PI calculation:

Given the following PI definition: Distress 1 weight = 0.45, Distress 2 weight = 0.45 and Distress 3 weight = 0.10. And that the distress indices for each of these distress types on a given section were calculated as Distress 1, PI = 90, Distress 2, PI = 85, and Distress 3, PI = 70.

a. *Calculate the deduct component for each distress index:*

Distress 1= $1-\left(1-\frac{90}{100}\right)*0.45=0.955$

Distress 2 = $1-\left(1-\frac{85}{100}\right)*0.45=0.9325$

Distress 3 = $1-\left(1-\frac{70}{100}\right)*0.1=0.97$

b. *Calculate the overall performance index for the section as:*

Overall PI = 100 ∗ (0.955∗0.9325∗0.97) = 86.38

2.5 Techniques for Developing Performance Model

A number of techniques are available for the development of pavement deterioration models. These techniques include mechanistic, empirical (regression), mechanistic-empirical and probabilistic models. While outlines of each technique are presented below, it should be noticed that the degree of accuracy required from a prediction model depends upon its intended use. For example, models prepared for project level need to be more accurate and precise than those for network level analysis.

2.5.1 Mechanistic Model

These models are based on primary pavement response parameters such as stress, strain and deflection. The pavement responses are normally due to traffic and/or environmental conditions. However, this type of modeling has not yet been well developed mainly because response parameters are not considered to be the prime objective of prediction. Rather, they are only useful if they can be related to pavement condition (Haas, 1994).

2.5.2 Empirical (Regression) Model

This analysis is used to establish an empirical relationship between two or more variables. Each variable is described in terms of its mean and limits of minimum and maximum variation. The regression technique is the most popular method for developing deterministic empirical models. In the regression models, pavement condition is considered as dependent variable and a set of factors is selected as independent variables. A statistical technique can be used to select the factors that should be included as independent variables. The regression models can be linear or non-linear depending on the relationship between the dependent and independent variables (Haas, 1994).

2.5.3 Mechanistic–Empirical Model

In a purely mechanistic approach, pavement response parameters such as stress and strain are calculated. These responses are normally caused by factors created by traffic and/or climate. These models cannot be classified as prediction models. The calculated pavement response parameters can be used as input variables utilizing empirical approach such as regression. A mechanistic-empirical model is a prediction model that was developed by using regression technique with pavement response as the independent variable (Haas, 1994).

2.5.4 Probabilistic Model

In this technique, experience is translated into a formalized way through transition process models to develop performance models. This technique is mainly used for the development of individual distress prediction. The future state of a model pavement is estimated based on the current state of the pavement. The state of the pavement is defined by a range of condition measures, which may include roughness, pavement condition index and skid number.

In this method, pavement condition measure can be treated as a random variable with probabilities associated with its values. The probabilities associated with all the values of a 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, 1994).

The use of probability distribution in predicting pavement condition requires the background knowledge of the distribution law for the variable being predicted.

2.6 Data Required for Development of Pavement Performance Model

The type of data required for the development of pavement performance models depends greatly upon the approach and the technique to be used for the model development. In general, the following categories of data are required as inputs to a pavement performance model:

Pavement Characteristics: Pavement type, pavement strength, layer thickness, materials properties, construction and pavement age.

Traffic Data: Traffic volume, traffic composition and loading.

Environmental Conditions: Seasonal temperature, rainfall, regional factors and subgrade soil classification.

Pavement Conditions: Extent, severity and quantity of distress, roughness, structural capacity and skid resistance.

Maintenance Data: Maintenance techniques, expected lives of maintenance and maintenance unit cost.

The development of the performance models from the available data and updating these models as more data becomes available is one of the most important tasks for engineers and researchers in the field of pavement management. Predicting the actual performance of specific pavement sections under the combined action of traffic loading and environmental factors can provide valuable data to different departments of a highway agency. However, development of a perfect pavement performance model is the most difficult task in pavement management system, because of:

1. Uncertainties of the behavior of the pavement under changed traffic load, environmental conditions and other factors.
2. Difficulty of quantifying many factors affecting pavements.
3. Error associated with using discrete testing points to represent the total pavement area when estimating pavement condition, and the nature of the subjective condition survey.

In developing reliable pavement models, a research done on the comparison between statistical modeling techniques in pavement management indicates that the greater the data size the greater the possibility of minimizing the error in prediction. However, a reasonable amount of good data is better than tons of uninformed or erroneous data. Proper attention is therefore needed to maintain high accuracy in data and pertinent information (Ahammed and Tighe, 2008).

However, it may not always be feasible to obtain data to meet that requirement. A reasonable quantity within practical limitations is the only option for pavement engineers and researchers. Randomizing the observations or data collection is also important. Any bias or deviation should be recorded and presented.

In developing reliable pavement models, Darter (1984) noted four main criteria. These criteria include:

1. An adequate database built from in-service pavements
2. The inclusion of all variables that significantly affect pavement performance
3. An adequate functional form of the model
4. A model that meets the proper statistical criteria for precision and accuracy.

A number of highway agencies have recently completed studies to develop pavement performance curves based on information in their existing databases. All of these agencies have chosen to use functional performance indicators. This is partially due to the fact that functional performance indicators allow establishing and incorporating life cycle cost analysis into the models using their currently available databases and existing PMS program. The ability to model and predict pavement condition accurately is critical to the success of pavement management system. Most pavement performance databases currently contain information pertaining to a one-time survey for each section during the lifetime of the pavement. Therefore, a critical need exits for a model to predict pavement behavior when good historical condition data for a section are unavailable.

The purpose of developing the pavement life data is to provide information on how long a particular pavement type will typically last before it needs rehabilitation. It was found that many pavements are overlaid or reconstructed before this would have been needed on the basis of condition. Different methods or models exist to set priorities for rehabilitation projects. Factors used to establish priorities are pavement distress, ride, traffic, economy, functional classification, accidents, friction, geometric deficiencies, structural capacity, age and location.

Abaza (2004) estimated the Pavement Serviceability Index (PSI) as a function of the number of the 80 kN ESAL applications for a selected design period. The database that related the estimated mean PSI of pavement section to its age was used to develop models to predict future pavement condition. The final form of these models was found to be adequate in relating pavement performance to the incremental change in load application.

A three-year research aimed at investigating data analysis methods used in the development of pavement performance relationships was part of the UK collaborative program linked to the United States Strategic Highway Research Program (SHRP), in particular the Long-Term Pavement Performance (LTPP) experiment. The research met the primary objective of defining a statistical procedure to be followed during the development of pavement performance models. The four stages of analysis were (I) data familiarization, (II) data censorship, (III) model building, and (IV) statistical analysis. The research included statistical procedures involved in understanding and attempting to model road distress (rutting and deflection) as a function of traffic loading and construction parameters (base material and base thickness). The research reinforced the need to display the results of data collection for a number of test sites with different constructed sections. The results were as follows:

1. Base material and base thickness and their combined effect influence rutting, but in ways vary greatly from site to site.
2. The quadratic and cubic model forms appeared to adequately predict rutting; one model form on its own is not sufficient to predict rutting which might be due to early life performance on some pavement test sites.

3. The data used in the analysis gave conclusions in which it often exhibited unexpected performance, in engineering terms, between differently constructed sections. Later work identified the differing time variability from one rut measurement position to another.

2.7 USA Practices in Pavement Management

Asphalt agencies worldwide are continuously exploring the pavement condition deterioration rate from the date of the construction or the last rehabilitation in the simplest way. One way of doing that is to develop a pavement performance model function of the history data such as age, traffic, construction history, material, physical properties, etc. without the need to define the distresses. United States of America has led in this field as most of the states have a robust pavement management system and reliable data. The experience of some states is presented in the following sections:

2.7.1 Minnesota Department of Transportation

The Minnesota Department of Transportation (MNDOT) is known for its strong pavement management and modeling practices, especially when it comes to the integration of preventive maintenance into its pavement management practices. Having collected pavement distress and roughness information since the 1960s and having implemented pavement management software (HPMA – Santec Consulting) in the 1980s, MNDOT has a significant amount of experience with all pavement management practices, including pavement modeling.

The MNDOT has been using the same surface condition rating procedure since 2001. Referred to as the Surface Rating (SR), this rating procedure provides a numeric quantification of the pavement distress observed in the field. The SR is then used as an indicator of the potential maintenance and rehabilitation needs of the pavement. The SR ranges from 0 to 4 with a higher value indicating a pavement in better condition.

Given the level of effort required to determine the SR, MNDOT uses a 10 percent sampling rate that requires rating of the first 500 feet of each mile. The SR survey is conducted in the outside lane of either the north or east direction on undivided roads and in the outside lane of both directions of travel for divided roadways. The SR rating is then used to describe the condition of the entire mile section.

In addition to the SR, MNDOT also collects International Roughness Index (IRI) information that is converted into a Ride Quality Index (RQI) with a rating scale of 0 to 5 with a higher number indicating a pavement with a smoother ride.

Using the collected condition data, an overall pavement condition is represented in terms of a Pavement Quality Index (PQI). The PQI, which represents a combination of surface condition and ride quality, is calculated as the square root of the RQI times the SR (Equation 2.8). Based on the potential values of the RQI and SR, the PQI has a potential range of 0 to 4.5.

$$PQI = (SR * RQI)^{1/2} \tag{2.8}$$

MNDOT uses both individual section and default models to predict pavement condition over time. The individual section models are used when three or more data points are available for the pavement section since the last rehabilitation and necessary constraints are met.

For instance, to satisfy the constraint requirement, the predicted condition must meet a pre-defined minimal level of service between a specified “minimum” and “maximum” life limit for the type of rehabilitation that was conducted. For example, if a medium overlay was defined to have a life limit of 5 to 15 years, and the regression analysis shows that 3 years of condition surveys for a specific pavement section predict that the terminal serviceability is 4 years, the section’s behavior would be deemed “unrealistic” and a default curve would be used in its place. An “unrealistic” behavior might also be predicted if life extends beyond the “maximum” life limit. This is likely to occur if data points after rehabilitation show little deterioration in the condition. MNDOT noted that overprediction of terminal serviceability occurs more often than under-prediction.

Deterministic models are used for both site-specific and default models to predict RQI and individual distress quantities. Default RQI and individual distress models are created using a combination of surface type and prior maintenance activity. The creation of default models alone reaches into thousands given all the needed combinations. The creation of the RQI models is developed using either linear, polynomial or sigmoidal equations shown below.

$$RQI = a + b * Age \tag{2.9}$$

$$RQI = a + b * Age + c * Age^2 + d * Age^3 \tag{2.10}$$

$$RQI = a - \Delta RQI * e^{-(p/Age)ß} \tag{2.11}$$

where: a, b, c, d, and p are predicted coefficients.

In addition to the creation of predictive RQI equations, deterministic models are developed for use in predicting distress quantities for pavement families based on surface types and prior maintenance activities. Distress quantities in terms of percent area are predicted using the following equation:

$$\text{Distress Percent} = e^{-(-k/Age)} \tag{2.12}$$

2.7.2 North Dakota Department of Transportation

The North Dakota Department of Transportation (NDDOT) utilizes the dTIMS pavement management software that was designed and developed by Deighton & Associates, Ltd. Currently, their system is focused solely on predicting the change in IRI per year based on historical data. However, additional indexes are calculated to describe the current condition of the pavements.

Pavement condition surveys are conducted by NDDOT using a semi-automated survey based on LTPP distress definitions. The information collected is then used to determine various indices. The overall index that NDDOT uses is called the Distress Score, which is a 99-point index. A Distress Score of 99 indicates a pavement with no distress, while a value of 0 indicates a failed pavement. Deducts are then taken from 99 based on certain information/tables, where deducts for flexible pavements, continuously reinforced concrete pavement (CRCP), and jointed reinforced concrete pavements (JRCP) can be found. The result is a calculated Distress Score for the pavement section.

In addition to the calculated Distress Score, NDDOT also calculates a Structural Index for flexible pavements and a Slab Cracking Index for the JRC pavements. The Structural Index is calculated by taking deducts due to alligator cracking, patching and rutting, and subtracting them from 99. The Slab Cracking Index also begins with a value of 99 and is reduced based on deducts for corner breaks, longitudinal cracking, broken slabs, patching, and transverse cracking.

NDDOT also collects ride information in terms of IRI and uses that information to develop pavement performance models for use in its dTIMS pavement management system. Models for IRI were created for approximately 100 pavement families based on the last rehabilitation treatment, the highway performance classifications of the roadway, and the pavement type as listed below.

- Last rehabilitation treatment:
  - Preventive maintenance of flexible pavements
  - Preventive maintenance of rigid pavements
  - Minor rehabilitation of flexible pavements
  - Minor rehabilitation of rigid pavements
  - Structural overlay
  - Major reconstruction
- Highway performance classification:
  - Interstate
  - Interregional
  - State corridor
  - District corridor
  - District collector
- Pavement type:
  - Asphalt on CRCP
  - Asphalt on JRCP

- Full-depth asphalt
- JRCP
- CRCP

An example of NDDOT models for full-depth asphalt sections on the State corridor is shown in Figure 2.2. The predicted performance of the structural overlay is expected to maintain its IRI value longer than the thin-lift overlay, resulting in a smoother road. Similar models were developed for all pavement families (APT, Inc., 2010).

NDDOT has not done as much modeling as some of the other agencies in the USA. However, they are in the process of developing a performance modeling tool that will assist them in using historical condition data to develop equations based on a variety of selected criteria.

2.7.3 Oklahoma Department of Transportation

The Oklahoma Department of Transportation (OKDOT) first began its current pavement management efforts in 2000. Since that time, they have dedicated significant time and effort in developing strong pavement management practices, including a robust condition survey procedure and reliable pavement management models. OKDOT conducts its pavement management analysis using the dTIMS pavement management software developed by Deighton and Associates, Ltd.

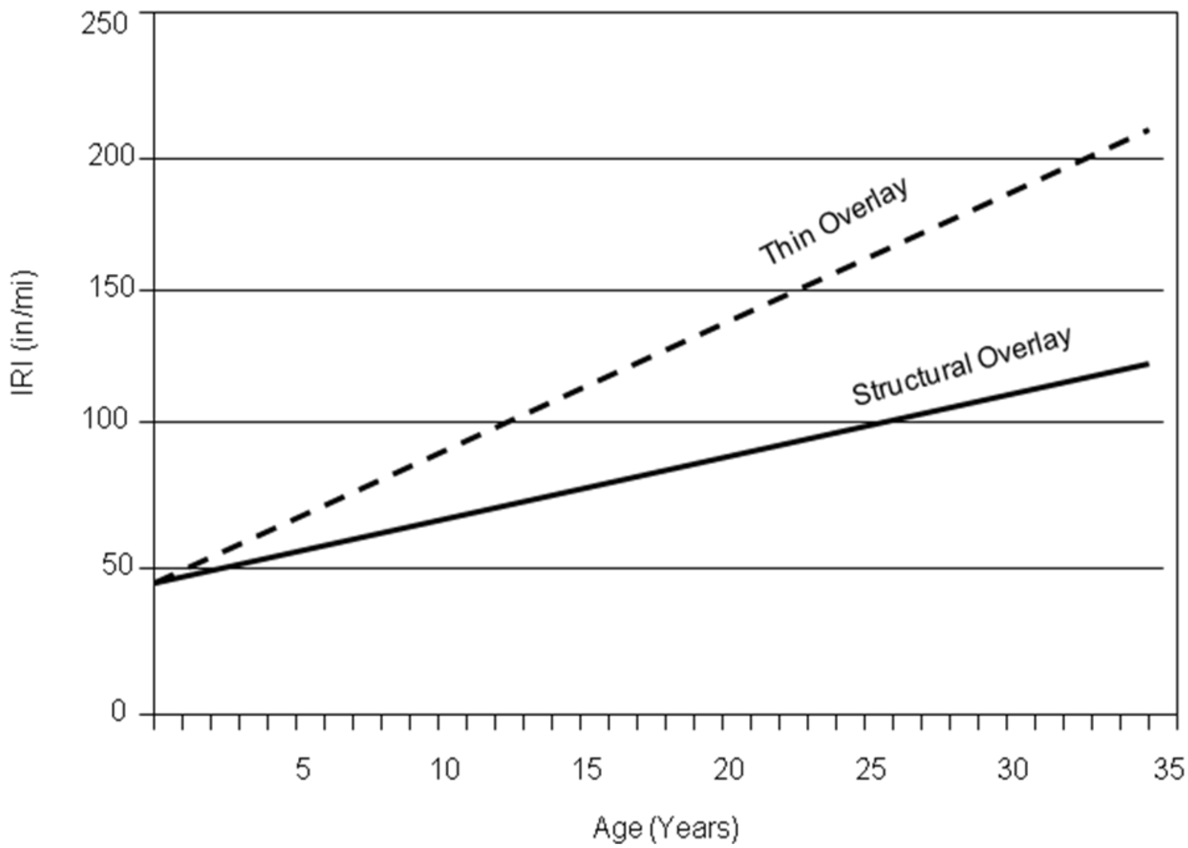

Figure 2.2: Example of IRI Performance Model

The survey procedure utilized by OKDOT is a semi-automated survey based on LTPP distress definitions. Information collected from the surveys is used to determine deducts associated with the distresses. The deducts are then used to calculate a variety of condition indices for each pavement surface type as detailed below:

- Hot mix asphalt (HMA):
  - Ride
  - Structural
  - Rutting
  - Functional
  - Overall Condition (PQI)
- JPCP:
  - Ride
  - Fault
  - Slab
  - Joint
  - Overall Condition (PQI)
- CRCP:
  - Ride
  - Structural
  - Overall Condition (PQI).

Each condition index is based on a 0 to 100 scale, with 100 representing a pavement in good condition and 0 representing a pavement in bad condition. A full explanation of the calculation of deducts and pavement condition indices is described in Appendix F. A sample calculation of the Structural Index for HMA pavements is shown in Equation (2.13).

$$\text{Structural Index} = 100 - \text{Minimum}((\text{Fatigue 1 DV} + \text{Fatigue 2 DV} + \text{Fatigue 3 DV}), 100) \quad (2.13)$$

where, Fatigue 1 DV = Low Severity Fatigue Deduct Value Fatigue, 2 DV = Medium Severity Fatigue Deduct Value Fatigue, and 3 DV = High Severity Fatigue Deduct Value.

Once individual indices are calculated for the pavement sections, the overall condition (PQI) can be calculated. A sample equation for PQI for HMA pavements is shown in Equation (2.14).

$$\text{PQI} = 0.40 * \text{Ride Index} + 0.30 * \text{Rut Index} + 0.15 * \text{Functional Index} + 0.15 * \text{Structural Index} \quad (2.14)$$

Therefore, the PQI is a weighted average of the individual indices for the given pavement type.

OKDOT uses deterministic family performance models that are focused on predicting the index as a function of age. The performance models were created for a given pavement family by plotting the condition of the sections versus the age of each corresponding section. Regression techniques were then applied to predict the behavior of the condition index based on the age of the pavement.

Before beginning the prediction of performance, pavement families were created for use in describing pavement types with similar expected performance. The pavement families used by OKDOT are described based on pavement type, traffic volume, and expected curve endpoint. An example of the pavement performance model for the structural index for HMA pavements with medium-high volume traffic is shown in Figure 2.3.

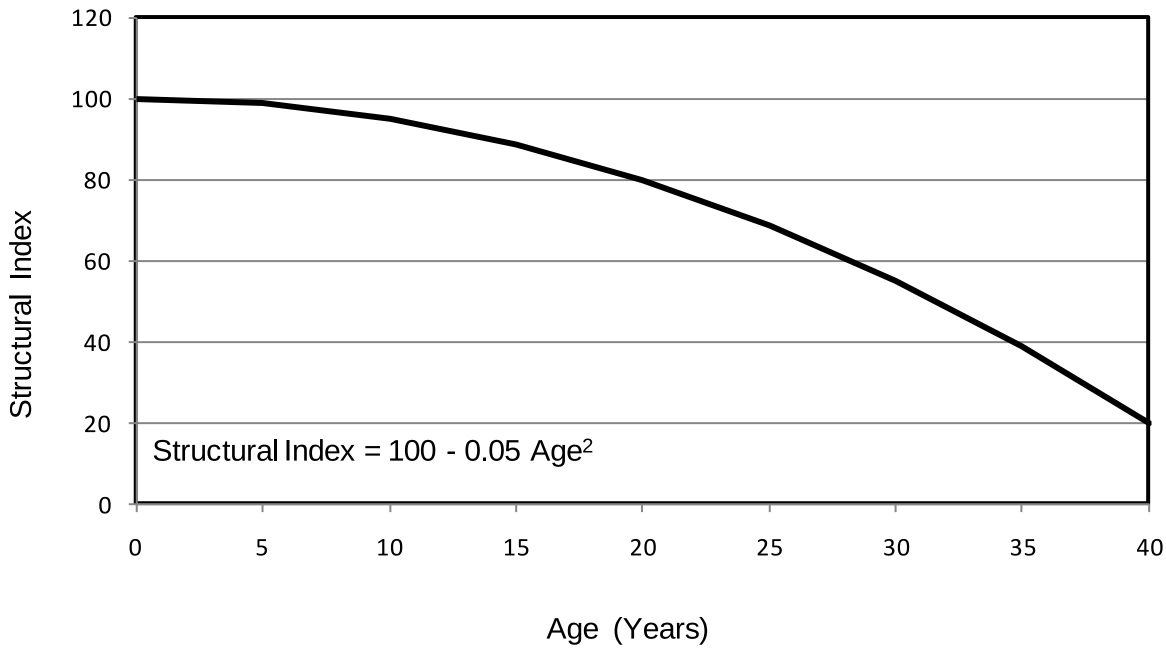

Figure 2.3: Structural Index Performance Model for HMA Medium-High Volume

OKDOT underwent a significant performance modeling study in 2001, which included the statistical analysis of performance data collected since developing their new condition indices. Since that time, OKDOT has used the results of additional pavement condition surveys to review and refine the pavement management models. As a result, a significant number of models and pavement family classifications have been changed to reflect the actual conditions. OKDOT has reported that the use of actual condition data as a feedback loop has resulted in improved pavement management models (APT, Inc., 2010).

2.7.4 Oregon Department of Transportation

The Oregon Department of Transportation (ODOT) is utilizing the pavement management software from Agile Assets, Inc. but has not fully employed the modeling capabilities available in the software. However, ODOT actively determines the remaining service life (RSL) of a pavement and uses it to predict the expected percentage of the network that will be in various condition levels (i.e., good, fair, poor, or very poor). RSL serves as an indicator of the amount of service life left for the pavement. Therefore, an RSL of 0 indicates that a pavement has exceeded its expected life.

ODOT currently uses a semi-automated pavement condition survey to determine the condition of all major roads. They are still using a manual survey on minor roads but expect to change over to an automated survey in the near future. Based on the conditions collected from the survey, ODOT determines the following condition indices for HMA and concrete (JPCP and CRCP) pavements:

- HMA:
  - Fatigue
  - Rut
  - Patching
  - Raveling
  - No-load (Environmental)
  - Overall
- JPCP and CRCP:
  - Fatigue
  - Rut
  - Patching
  - Overall.

ODOT has a documented procedure for calculating the condition indices, which is provided in Appendix G. The process includes the calculation of an index factor for each severity level of each distress for all O.I-mile increments that were surveyed. The index factor is calculated based on Equation (2.15).

$$\text{Factor (type X)(severity y)} = 1 - A * (\text{Measured Distress / Maximum Distress})^{B} \quad (2.15)$$

where, type X is the distress type (e.g., fatigue, transverse, rutting, etc.), severity y is the severity level (i.e. low, medium, high), and A and B are defined coefficients.

For those distresses with more than one severity level, a composite index factor is calculated and condition indices are determined based on the index factors.

ODOT performance modeling practices focus on the determination of RSL based on the use of the lowest of three RSL values: model, age, and rut. The Model RSL value is based on the use of the curves shown in Figure 2.4, in which the overall index of 45

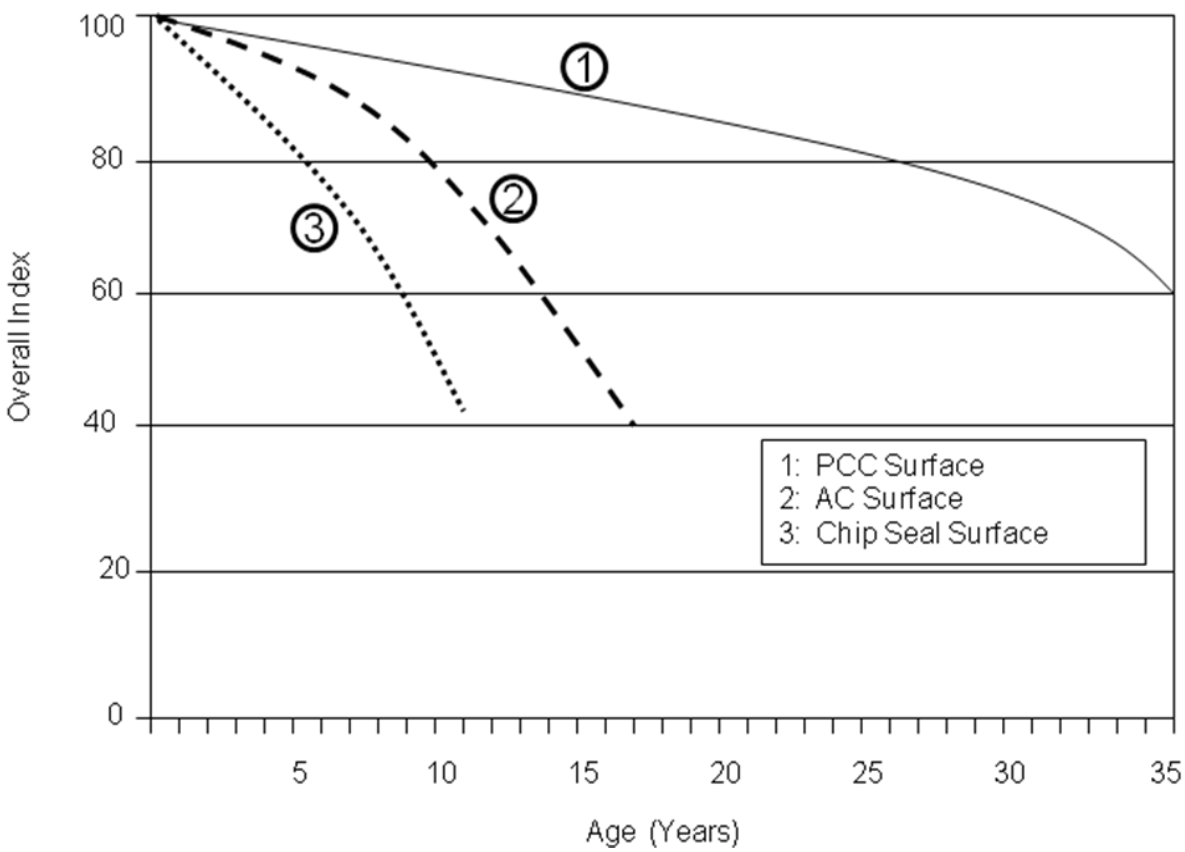

Figure 2.4: Model RSL Used by ODOT

corresponds to an RSL of 0. The Age RSL is the estimated treatment life of the pavement minus the age since the last treatment. Each year, the ODOT pavement management engineer manually adjusts the treatment life from the standard value for all the 2,300 pavement sections in the ODOT network, using the past 5 years of condition ratings, rut depths, and IRI information as a basis for engineering judgment. Finally, the Rut RSL is calculated based on routes with high average daily traffic (ADT) and studded snow tire use. ODOT estimates that the wear rate of studded tire use is approximately 0.08 to 0.10 inch per year and estimates Rut RSL to be 0 when average rutting is 0.75 inch (APT Inc., 2010).

Once the RSL is determined from the lowest of the Model, Age, and Rut RSL, the information is used by ODOT to forecast pavement condition and treatment selection using the following condition categories:

- RSL $\geq$ 5 is Good
- 0 > RSL > 5 is Fair
- RSL = 0 is Poor

ODOT has considered creating additional models, such as percent cracking or IRI, but has not done so since the modeling of RSL has provided them with the information they need to forecast conditions and identify potential treatments.

2.7.5 Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) has utilized pavement management practices since the 1980s. Because of the significant amount of documentation available on its performance modeling practices, the steps involved in creating well-functioning performance models are clearly laid out. WSDOT has incorporated their pavement performance models into the Washington State Pavement Management System (WSPMS).

WSDOT uses a semi-automated pavement condition survey to determine the condition of all roadways. WSDOT then uses the collected condition information to determine a pavement structural condition (PSC) index which ranges from 100 (good) to 0 (poor). This is done by relating surface distresses to alligator cracking for flexible pavements and by relating surface distresses to cracking for rigid pavements to determine the applicable deduct values. The deduct values are then subtracted from a value of 100 to determine the PSC.

WSDOT also collects rutting and ride information that is used in the pavement management system. The rut and ride data may be used in their raw state for some applications, but is also used to calculate and report pavement rutting condition (PRC) and pavement profile condition (PPC), respectively.

The PSC is modeled for each individual pavement section using a power model as shown in Equation (2.16) and Figure 2.5.

$$PSC = C - mA^{p} \tag{2.16}$$

Approximately 8,000 individual pavement section models are created for all sections with three or more data points. For those sections with less than 3 data points, default performance models are used to describe the expected pavement performance.

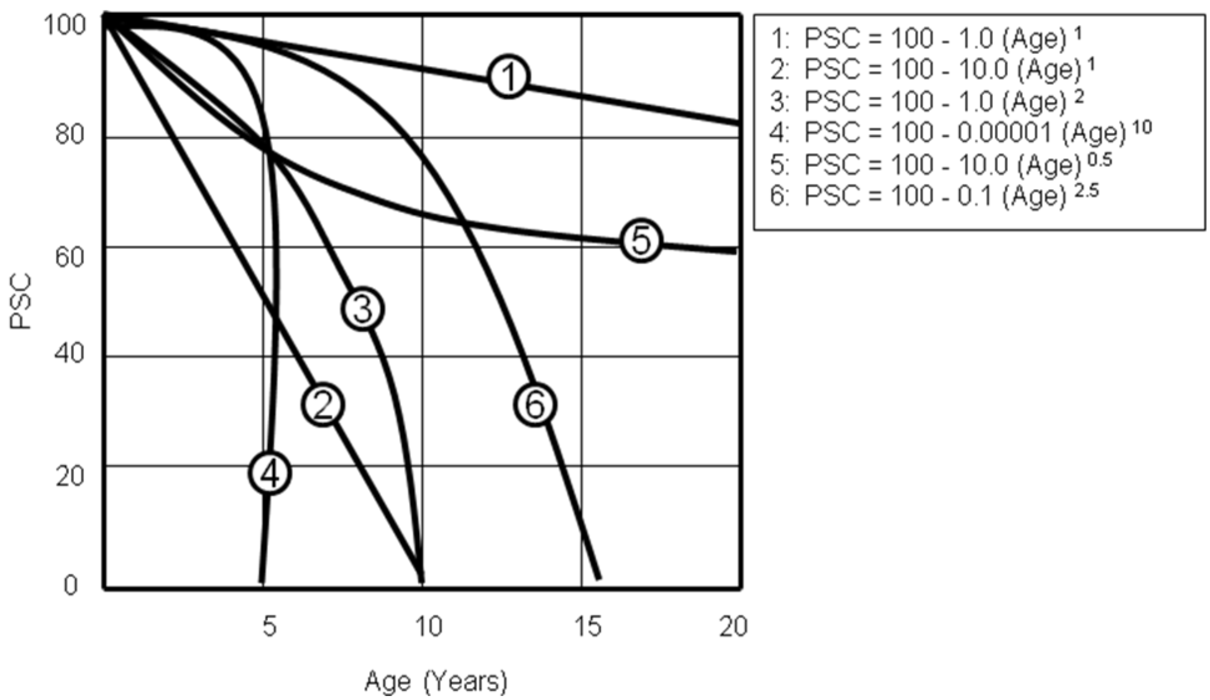

Figure 2.5: Example of PSC Power Models (WSDOT, 1993)

The WSDOT default pavement models for PSC are created based on surface type, functional classification, and state districts, while the default linear models for PPC and PRC are shown in Equations (2.17) and (2.18), respectively.

$$PPC = 100 - 1.0 * Age \quad (2.17)$$

$$PRC = 160 - 5.0 * Age \quad (2.18)$$

The predictions developed in the WSPMS for each section are modeled in a way to let the given section "speak for itself." However, this process often resulted in overestimations of condition. Therefore, to better predict the predicted performance, a process was established whereby two data points are added to the available data from the standard (default) curve. Together, the actual and default data are used to get a final prediction of condition. Because it utilizes past performance trends and incorporates the knowledge of typical pavement performance to give the most likely rate of future deterioration, WSDOT reported that the process results in a more realistic estimate of the project performance than if the adjustments were not made.

WSDOT recently conducted a study to revise the pavement condition indices for rigid pavements. This was done to address specific pavement distress types that had been proposed and to take into account pavement condition trigger levels now used by WSDOT. The resulting research report provides the details necessary for WSDOT to update these models in their pavement management system.

2.8 KSA Practices in Pavement Management

The Kingdom of Saudi Arabia (KSA) has a huge roads network starting from a local street to an interstate highway. Similar to other countries, the Ministry of Transport (MOT) adopted a pavement management system to manage the highways under their responsibilities. Also, some of the major municipalities apply the pavement management system on the pavements within their district limits. The following sections shed light on the pavement management system in Saudi Arabia.

2.8.1 Modeling of Pavement Condition for KSA Roads Network

The Kingdom of Saudi Arabia has a huge roads network connecting between its cities and also has a huge municipal and urban roads network. Modeling of pavement performance in terms of pavement condition is done based on the available data at the Ministry of Transport (MOT) on Riyadh and Dammam cities while other agencies are being contacted for additional information. The study focused on intercity highways as well as municipal and local roads and streets (Ramadhan, 1997).

Considering the types and amount of data collected, the independent variables that affect the pavement condition index are in the following general form

$$PCI \text{ or } PDR \text{ or } PCR = f\,(AGE, ACTH, SBTH, TRAF, TRUK, INTR) \qquad (2.19)$$

where,

PCI = Pavement Condition Index of any pavement condition rating method

PDR = Pavement Distress-based Rating

PCR = Pavement Condition Rating

AGE = The time, in years, from the construction or the last major maintenance date

ACTH = The combined thickness of all asphalt layers

SBTH = Subbase layer thickness

TRAF = Average daily traffic (ADT)

TRUK = Number of trucks in traffic mix

INTR = Any possible interaction of the proceeding factor.

Other factors such as the Subbase and Subgrade types were not included because there were no different types used in almost all pavement sections considered in the study. Similarly, the drainage factor was omitted due to insufficient data.

The hypothesis in the general model of the PCI in Equation (2.19) is that AGE, TRAF, and TRUK are inversely proportional to the PCI, while ACTH and SBTH are proportional to the PCI, similarly for PDR and PCR.

Various linear and non-linear regression analyses were conducted, which show that AGE is the most important and influential independent variable. Therefore, second, third and fourth degrees of AGE were used in the general form while other variables ACTH, SBTH, TRAF and TRUK were kept in the linear form. The general form of the model is as follows:

$$\text{PCI or PDR or PCR} = a + b.(\text{AGE}) + c.(\text{AGE})^2 + d.(\text{AGE})^3 + e.(\text{AGE})^4 + f.(\text{ACTH}) + g.(\text{SBTH}) + h.(\text{TRAF}) + i.(\text{TRUK}) + \text{error} \tag{2.20}$$

Whereas, the final selected models are as follows:

$$\text{PDR} = 100 - 38.3 * (\text{AGE})^{1.25} * (\text{ACTH})^{-0.185} * (\text{TRUK})^{0.018} \tag{2.21}$$

$$PCR = 100 - 2.045 * (AGE)^{1.1239} \tag{2.22}$$

$$PCI = 100 - 0.8181 * (AGE)^{1.2224} * (TRUK)^{0.1363} \tag{2.23}$$

The adjusted R^2 for the above three final equations are 0.775, 0.796 and 0.658, respectively. The models revealed that AGE is the main common factor among the three indices. Other independent variables have limited effect on the pavement condition.

2.8.2 Riyadh Pavement Maintenance Management System (RPMMS)

As an example of the Pavement Management System application in Saudi Arabia, Riyadh Pavement Maintenance Management System (RPMMS) developed a combined index of pavement distresses called Urban Distress Index (UDI) that includes fifteen structural and functional distresses. UDI is calculated based on pavement distress type, severity and area. Deduct values were developed based on experience and judgment of local pavement managers, engineers and technicians (Al-Swailmi et al., 1998). Riyadh UDI pavement condition rating, shown in Table 2.4, is calculated by the following equation:

$$UDI = 100 - 20 \sum (T_{ij} D_j / 100) \tag{2.24}$$

where,

UDI = Urban Distress Index (pavement condition index)

T_{ij} = Deduct value

D_j = Adjusted density.

Table 2.4: Riyadh UDI Rating

UDI Value	**Pavement Condition**
0 – 39	Poor
40 – 69	Fair
70 – 89	Good
90 – 100	Excellent

The model has gone through a series of updates; however, it did not predict changes on individual distress data. The condition of individual distress over time is very essential in planning maintenance activities on a project level. Therefore, distress prediction models for Riyadh streets were developed and covered all the common distresses that appear on Riyadh's main streets network.

Riyadh's street network is divided into two main categories: Main streets and Secondary streets. Main streets represent about 27% of the total network area and are defined as the streets with a middle island or with total width of more than 30 meters without a middle island. Secondary streets account for approximately 73% of the total network area and represent the streets inside a defined region.

Three comprehensive pavement condition surveys were already completed for main streets. A period of two years separated between two consecutive surveys. The total analysis period for main and secondary streets was six years. Several common distress types were identified on the main and secondary streets. These common distresses are longitudinal and transverse cracks, patching, weathering and raveling, potholes, and depression. The percentages of the distresses on the network considering the three surveys are shown in Table 2.5 (Al-Mansour et al., 2004).

The models were developed for different distress behaviors, which are function of distress type, distress severity, percentage of distress density, time, etc. The general form of the models is as follows:

$$DEN = ae^{bT} \tag{2.25}$$

Table 2.5: Distribution of Common Distress Types on Riyadh Network

Distress Type	**Percentage**
Main Streets	
Long. & Trans. Cracks	31.97%
Patching	22.37%
Weathering & Raveling	17.63%
Potholes	3.71%
Depression	2.03%
Secondary Streets	
Long. & Trans. Cracks	26.56%
Patching	25.77%
Weathering & Raveling	20.64%
Potholes	15.08%

where,

DEN = Distress density in percentage

T = Time in years

a & b = Regression coefficients.

The model predicts distress density over time associated with each severity level, pavement condition, traffic level and highway class combinations. A total of 61 and 28 cases were developed for main and secondary streets, respectively. All the cases for the developed model were found to be statistically significant in predicting distress density. The model was validated using reserved data points and indicated that the model could adequately predict the distress density with reasonable accuracy. Therefore, the developed model could be used to update the distress data prior to each maintenance program, thus minimizing the need for comprehensive visual inspection which proved to be costly and time consuming (Al-Mansour and Al-Mubaraky, 2007).

In general, there are two broad approaches used for predicting pavement performance and its relation to pavement maintenance. One approach predicts the performance of a pavement as an aggregate measure. Examples of this approach would be the AASHO road test concept of pavement serviceability.

The other approach (disaggregate approach) predicts the pavement performance by estimating the extent and severity of individual pavement distresses. The basic measurement of the pavement condition is the existing distresses which fall into two classes of pavement distress: structural and functional. The structural distress is associated with the ability of the pavement to carry the design load, and the functional distress deals mainly with ride quality and safety of the pavement surface.

The two approaches differ significantly in the form of data required. The disaggregate approach requires detailed damage data for individual distress types. Moreover, this data should be updated for each analysis period. The aggregate approach requires one condition index at the beginning of the analysis year, which it updates for each analysis period. The two approaches also differ significantly in the way in which pavement deterioration is calculated.

2.9 Other Pavement Condition Performance Models

Several researches were done worldwide studying the pavement performance under various conditions. Prediction models have been developed to predict the pavement condition through limited data in an easy and reliable way.

A simplified pavement performance model that can be used for forecasting pavement condition was developed for different pavement types. The model can predict the PSR using the pavement's age, ESAL (equivalent single axle load) and structural number. The following equation is the general form of the model (Lee et al., 1993):

$$PSR = PSR_1 - a * (STR)^b * (AGE)^c * (CESAL)^d \tag{2.26}$$

where,

PSR_1 = initial value of PSR at construction (4.5 is used in the analysis)

STR = existing pavement structure

AGE = the time, in years, from the construction or the last major maintenance date

CESAL = cumulative 18-kip equivalent single axle load.

The above model has been solved for five types of pavement such as flexible, composite, rigid, etc. with R^2 ranging between 52 and 79%. The flexible pavement has the following form:

$$PSR = PSR_1 - 14.29 * (STR)^{-1.872} * (AGE)^{0.3499} * (CESAL)^{0.3385} \qquad (2.27)$$

R^2 = 52% and SEE (Error Sum of Squares) = 0.45

Another set of models have been developed by Sharaf (1991) that relates pavement condition index to age. Sets of PCI and age can be easily obtained for section in each family with the same characteristic. The model has the following general form:

$$C = 100 - b * X^m \qquad (2.28)$$

where,

C = PCI value

X = pavement age in month

b = slope coefficient

m = value that controls the degree of curvature.

The general form has been solved for four types of flexible pavement maintenance treatment as shown in the following models:

Surface Treatment

$$PCI = 100 - 0.0319 * AGE^{1.5} \qquad (2.29)$$

Thin Overlay

$$PCI = 100 - 0.0158 * AGE^{1.5} \quad (2.30)$$

Thick Overlay

$$PCI = 100 - 0.0129 * AGE^{1.5} \quad (2.31)$$

Reconstruction

$$PCI = 100 - 0.0104 * AGE^{1.5} \quad (2.32)$$

Similarly, pavement prediction models for three pavement categories: flexible pavement with no overlay, flexible pavement with overlay and composite pavements (asphalt concrete surface over rigid base), were developed by George et al. (1989). The best fit models for the three pavement categories are as follows:

Flexible pavement with no overlay prediction model:

$$PCR(t) = 90 - a\ (\exp\ (AGE)^{b} - 1)\ \log\ (ESAL\ /\ SNC^{c}) \quad (2.33)$$

with a = 0.6349; b = 0.4203; c = 2.7062; and R^2 = 75%.

where,

PCR(t) = Pavement condition rating at time t

ESAL = Yearly equivalent single axle loads

SNC = AASHTO modified Structural Number to account for subgrade support

$$SNC = \sum a_i h_i + SN_g \quad (2.34)$$

where,

a_i = material layer coefficient

h_i = layer thickness (in.)

SN_g = subgrade condition.

The subgrade coefficient is defined as:

$$SN_g = 3.51 \log(CBR) - 0.85 (\log(CBR))^2 - 1.43 \quad (2.35)$$

where CRB is the in-situ California Bearing Ratio of subgrade (%).

Flexible pavement with overlay prediction model:

$$PCR(t) = 90 - a (\exp(AGE)^b - 1) \log(ESAL / (SNC^c * T)) \quad (2.36)$$

with a = 0.8122; b = 0.3990; c = 0.8082; and T = the last overlay thickness (in.).

Composite pavements (asphalt concrete surface over rigid base) prediction model:

$$PCR(t) = 90 - a (\exp(AGE/T)^b - 1) \log(ESAL) \quad (2.37)$$

with a = 1.7661; b = 0.2826; and T = the thickness of the asphaltic concrete layer (in.).

2.10 Summary

The following points summarize the previous literature review of pavement performance model development. This summary shows the variables and the model types that have been used in the literature:

1. Pavement structural adequacy, pavement serviceability index and pavement condition index were all used in the literature as reasonable measures of pavement performance.

2. In pavement performance prediction models, type of pavement surface, pavement age, traffic level, and environmental and local conditions were the most often used factors.

3. The empirical modeling technique was found to be very practical, simple and easy to develop provided that adequate data is available. However, acquisition of historical database or grouping of homogenous sections is necessary for model development.

4. In the probabilistic modeling technique, pavement condition state is predicted based on the current state. Historical data is not required. However, proper development depends primarily on very skilled and expert pavement engineers to develop transition probability matrices for the different combinations of pavement conditions.

5. The aggregate performance prediction models were found to be very useful. Variables and methodology used by the aggregate approach give an indication of the possible effects of various factors on pavement condition.

6. The disaggregate distress prediction models were found to be useful in predicting pavement condition. These models were used in conjunction with pavement rating system to develop a measure of pavement performance. It, however, requires extensive data on the extent and severity of pavement distresses.

7. Several studies conducted on the relation between pavement condition and the associated common characteristics of the pavement revealed that the most

significant factor affecting the pavement condition is its age since construction or the last major rehabilitation. Traffic load, pavement structure and drainage come as secondary factors.

CHAPTER 3

DATA COLLECTION

This chapter sheds light on the data collection process and filtering. But first, a background on how the data was originally collected by the Roads Division is explained.

3.1 PMMS Data Collection History

Saudi Aramco Oil Company represented in the Roads Division decided at the beginning of the project in 1998 to assign the distress survey and data collection to the professional civil engineers working in the Aramco Roads Division. Ultimately, each area engineer was responsible to do this task annually on his respective area as per the PMMS team guidelines in addition to his normal work. This process continued until the Roads Division outsourced this task to a professional contractor in 2007 onward.

The Roads Division's strategy was set to concentrate on the three main districts in Dhahran, the Southern area (including Abqaiq, Udhailiyah and their suburbs) and the Northern area (including Ras Tanura, Tanajib and their suburbs) in order to cover the majority of Aramco paved network including community camps and industrial areas.

Therefore, the Roads Division embarked on extensive training sessions in 1998 to all the engineers and later to the contractors in 2008 to acquaint them with the Pavement Maintenance Management System (PMMS) and to train them in collecting the required data and conducting distress surveys at their respective areas. The PMMS team is responsible to operate the PMMS, administer the data collection process, verify the distress surveys, and update the PMMS with sound and realistic data.

3.2 PMMS Route ID File

In this process, a hard copy file was created for each route ID that represents one single roadway from station zero to the end of the roadway. Each file included several forms in addition to layout plans showing the entire roadway and the pavement management (PM) section(s) details. The most important forms are the PMMS route identification form, the PM section distress survey form, traffic form, and the service order authorization pavement structure form (SOAPS). These forms which are shown in Figures 3.1, 3.2, 3.3 and 3.4, respectively, are designed to capture all available information about the roadways such as:

1. Road name, Route ID number and Length
2. Construction date
3. Asphalt thickness & sub-layers thickness
4. Average daily traffic volume (AADT)
5. PM section condition (distress survey)

The purpose of the route ID file is to document the past and present conditions for each roadway to serve as a robust and reliable reference. Yet, a problem was ultimately raised with regard to the construction date, asphalt and sub-layers thicknesses, and the AADT due to the lack of these information in written documents.

Route ID		Proponent Department	
Proponent (Organization Code)		Total Number of PM-sections	
Physical Description			
Start point Description			
End point Description			
From		Total Length (Roads & Streets) KM	
To		Total Area (Yards, Plant Areas and Parking Lots) Sq.M	

Figure 3.1: PMMS Route Identification Form

PM – Section									
	Date		Surveyor		PMS No.		Out of		
	Route Description						Proponent		
	Route Id		Extension		Lane Dir		Lane ID		
	From		To		# Of Lanes		Area/ k-SQ.M		
	Width, M		Location		District			Drawing #	
	Physical Description From						Region	Costal	Desert
	Physical Description To						Sub Grade	Sand	Marl	Sabkha

Pavement Condition					Quantity				
					Selected Sample # / From & To				
					#	#	#	#	#
Distress Type		Extent	Severity Level		Area Of Sample SQ.M	Area Of Sample SQ.M	Area Of Sample SQ.M	Area Of Sample SQ.M	Area Of Sample SQ.M
Rutting		% Both WPS	< 10 mm	L					
			10-20 MM	M					
			> 20 MM	H					
Cracking	Block	% Area	< 6 mm	L					
			6-9 mm	M					
			> 19mm	H					
	Fatigue	% Area	< 3 mm	L					
			3-6 mm	M					
			> 6 mm	H					
	Linear	Length M	< 6 mm	L					
			6-19 mm	M					
			> 19 mm	H					
Raveling And Polished Agg.		% Area	Some loss of fine agg. Or < 50% polishing	L					
			some Loss of coarse agg. Or > 50% polishing	M					
			Loss of coarse agg.	H					
Bleeding		% Both WPS	Discolored surface	L					
			Loss of surface texture	M					
			shiny and tire marks	H					
Patching		% Area	(Patching Areas/Section Area) x 100	N/A					
Failures		% Area	< 25 mm	L					
			25-50 mm	M					
			> 50 mm	H					

Figure 3.2: PM Section Distress Survey Form

Route ID			Extension		
Lane Direction			Lane ID		
From			To		
ADT					
NO. Of Trucks					
Average Daily Traffic			No. Of Trucks		
ADT/Lane	From	To	Trucks/Lane	From	To
Low	0	1000	Low	0	200
Medium	1001	5000	High	201	+
High	5001	+			

Figure 3.3: PMMS Traffic Form

85

Service Authorization #			
Work Description			
Route Id		**Extension**	
Lane Direction		**Lane Id**	
From		**To**	
Length (km)		**Width (m)**	
Area (/k-sm)			
Year Completed			
Quarter			
Historic Work Code			
Beginning Location			
Ending Location			
Project Cost ($)			

Layer Id	**Material Code**	**Thickness**	**Historic Work Code**	
1			1.	Preventive Maintenance
2			2.	2.5&4 cm Overlay
3			3.	5&6 cm Overlay
B			4.	New/Reconstruction
S			5.	4&5 cm Fabrics Overlay
R				

Material Code	**Material Description**	**Material Code**	**Material Description**
A	Class A Asphalt	I	Rubber Asphalt C
B	Class B Asphalt	M	Micro Surfacing II
C	Class C Asphalt	N	Micro Surfacing III
BA	Class A Binder	S	Slurry Seal
BB	Class B Binder	T	Fog Seal
D	Polymer Modified A	BM	Selected Marl Base
E	Polymer Modified B	BS	Crushed Stone Base
F	Polymer Modified C	SF	Suitable Fill Sub-base
G	Rubber Asphalt A	SM	Selected Marl Sub-base
H	Rubber Asphalt B		

Figure 3.4: PMMS Service Order Authorization Pavement Structure (SOAPS) Form

The idea of gathering these information from the sites by coring and traffic counters for each roadway was not practical due to the huge network size to be covered and the volume of work associated with such a task that would impede the PMMS progress and delay the output.

Therefore, the PMMS team took an alternative approach and depended on the senior engineers' and inspectors' memories to find out the construction date, asphalt and sub-layers thicknesses, and the AADT.

3.3 Data Collection and Resources

The best source of PMMS data is the PMMS software, since all the data entered throughout the years are saved in a designated server and maintained regularly. A typical PMMS data output Excel format is shown in Figure 3.5 where each row represents a unique PM section. The labels of the first row are as follows:

1. Preference year at which the record was taken
2. Route ID number followed by the road name
3. Extensions
4. Lane direction and ID
5. From / to points
6. PM section length and width
7. Number of lanes
8. Type of wearing course
9. Overall PI

A	B	C	D	E	F	G	H	I	J	K	L	M	N	
prf_ye	route_i	road_na	extensi	lane_d	lane_i	from_po	to_poi	lengh	sec_wid	nber_of	wc	Overall	Ravelli	Fa
1998	ABC001	ARNOT RO	None	Both	All	0	0.61	0.61	11.6	2	Asphalt	100	100	
2005	ABC001	ARNOT RO	None	Both	All	0	0.61	0.61	11.6	2	Asphalt	95.8	100	
2006	ABC001	ARNOT RO	None	Both	All	0	0.61	0.61	11.6	2	Asphalt	95.8	100	
2009	ABC001	ARNOT RO	None	Both	All	0	0.61	0.61	11.6	2	Asphalt	54.9	100	
2004	ABC002	BALAH STR	None	Both	All	0	0.24	0.24	15	2	Asphalt	100	100	
2005	ABC002	BALAH STR	None	Both	All	0	0.24	0.24	15	2	Asphalt	98.1	100	
2006	ABC002	BALAH STR	None	Both	All	0	0.24	0.24	15	2	Asphalt	98.1	100	
2007	ABC002	BALAH STR	None	Both	All	0	0.24	0.24	15	2	Asphalt	98.1	100	
2009	ABC002	BALAH STR	None	Both	All	0	0.24	0.24	15	2	Asphalt	80.1	100	
2004	ABC002	BALAH STR	None	Both	All	0.27	0.34	0.07	15	2	Asphalt	100	100	
2005	ABC002	BALAH STR	None	Both	All	0.27	0.34	0.07	15	2	Asphalt	97.5	100	
2006	ABC002	BALAH STR	None	Both	All	0.27	0.34	0.07	15	2	Asphalt	97.5	100	
2007	ABC002	BALAH STR	None	Both	All	0.27	0.34	0.07	15	2	Asphalt	97.5	100	
2009	ABC002	BALAH STR	None	Both	All	0.27	0.34	0.07	15	2	Asphalt	90.2	100	
2004	ABC002	BALAH STR	None	Both	All	0.36	0.45	0.09	15	2	Asphalt	100	100	
2005	ABC002	BALAH STR	None	Both	All	0.36	0.45	0.09	15	2	Asphalt	96.5	100	
2006	ABC002	BALAH STR	None	Both	All	0.36	0.45	0.09	15	2	Asphalt	96.5	100	
2007	ABC002	BALAH STR	None	Both	All	0.36	0.45	0.09	15	2	Asphalt	96.5	100	
2009	ABC002	BALAH STR	None	Both	All	0.36	0.45	0.09	15	2	Asphalt	91.8	100	
1998	ABC004	CARAVAN	None	Both	All	0.36	0.51	0.15	28	2	Asphalt	100	100	
2009	ABC004	CARAVAN	None	Both	All	0.36	0.51	0.15	28	2	Asphalt	92.4	100	
1998	ABC005	COUNTRY (	None	Both	All	0	0.6	0.6	11.4	2	Asphalt	100	100	
2009	ABC005	COUNTRY (	None	Both	All	0	0.6	0.6	11.4	2	Asphalt	82	100	
1998	ABC006	DAHAB STF	None	Both	All	0	1	1	9.1	2	Asphalt	84.4	85.3	

Figure 3.5: Typical PMMS Data Output Excel Format

10. Distress PI value (fatigue, raveling, failures, rutting, load, patching, block cracking and linear cracking)
11. Other properties such as Average Annual Daily Traffic (AADT), facility category, region, soil type, construction date, etc.

The data of the eight different facility types mentioned in Table 1.3 were extracted from the PMMS system and were considered as the raw data of this research. The total number of the PM sections for all categories exceeded 10,000 records covering one decade of data collection.

Screening the raw data exposed some problems and deficiencies in the data collection and data entry. Understanding these problems and how to overcome the significant ones were deemed necessary before performing the statistical analysis on them.

3.4 Observations on the Data

Some of the problems listed below are a common factor among the eight facility types of the PMMS.

1. Many of the Pavement Management Sections have one or two records in ten years.

2. Repetitive overall and distress PI values for the same PMS throughout the years.

3. The overall PI value and the distress individual PI values were mistakenly entered in the PMMS for some PMS. For example, instead of having overall

PI value of 100 which means perfect condition, a zero value was entered instead which means complete failure.

4. Missing data of the total thickness of the pavement, the road structure category, the construction date, and the AADT for many PM sections.

These deficiencies among the categories imply that there was a misperception in the data collection process at a certain stage, which could be due to inexperienced engineers or frequent rotation of the area engineers, and secondly, the integrity of the data entry and verification was not accurate for some PM sections.

Taking a deep look into Saudi Aramco operation system, one can see that some facility types such as Airstrips, Parking Lots, Lay down Yards, Plant Areas, Camp Streets and Facility Streets are owned by different departments in Saudi Aramco other than the Roads and Heavy Equipment Department.

The proponent departments of these categories are in charge of their facilities with regard to operation and maintenance management; hence, the decision makers in these departments either expedite or ignore the maintenance of these facilities based on their operational requirements rather than the PMMS forecast output based upon funds availability.

Accordingly, some of these categories, as will be shown later in this thesis, did not result in steady performance trend line due to unscheduled or delay of maintenance. On the other side, the Aramco Roads Division, being the proponent of the facility and public roads, exercised the PMMS output recommendation on timely basis as funds became available on their paved assets.

3.5 Data Screening

All the data of the eight facility types have been screened using Microsoft Excel software to segregate and sort out the PMS records.

The following points, in order of sequence, describe the screening process:

1. All the data of all the facility types were retrieved from PMMS software Excel format.
2. Data of each facility type was segregated and placed in a separate Excel file.
3. Data were sorted based on the PMS number and brought to sequence. Corresponding overall and distress PI's, date of survey and other properties were highlighted.
4. Missing and abnormal data were also highlighted. Records which did not make sense, such as data having steady overall PI or data having repetitive overall PI, were deleted. PM sections which have a minimum of three overall PI readings starting from 100 and deteriorating normally are considered as accepted PM sections.
5. Construct the three pavement categories (Roads, Streets and Paved Areas). PI versus Age scatter plot for the accepted PM sections for each pavement category was generated to see the interference and the distribution of the plot.
6. Accepted PM sections' overall PI's and maintenance age were tabulated, and the arithmetic means and standard deviations for each year were computed.

Upper and lower limits of the overall PI for each year were calculated using $X \pm 2\sigma$. An example is shown in Table 3.1.

7. Trend lines showing the arithmetic means and the upper and lower limits were plotted to analyze the performance over time. An example is shown in Figure 3.6.

8. Reserve 20 to 30% of the accepted data for testing.

9. Final data were fed into the “Minitab” software and regression analysis was applied to develop initial model. The best model which satisfied the hypothesis was selected and tested.

10. Use all the data of the respective category (including the reserved testing points) and develop the final model which satisfies the hypothesis.

The above-mentioned points (from point 3 to point 10) were done for each pavement category unless the accepted PM sections of the pavement category in question do not meet the minimum number of samples or the scatter plot does not indicate an acceptable deteriorating trend over the years to develop a reliable performance prediction model. Similarly, the same procedure mentioned above was applied on each pavement category in a step to develop the distress performance prediction models.

3.6 Modeling Methodology

The general methodology used to develop the prediction models for all categories is shown in Figure 3.7, where aggregate overall PI model which includes all pavement categories is developed followed by subsequent categories and aggregate distress PI.

Table 3.1: Arithmetic Means, Standard Deviations, LL & UL of Accepted PM Sections for Roads Pavement Category

AGE	Mean OA PI	Standard Dev.	Lower Limit (LL)	Upper Limit (UL)
0	99.95	0.24	99.48	100.00
1	100.00	0.00	100.00	100.00
2	96.32	8.53	79.27	100.00
3	95.78	11.50	72.77	100.00
4	83.79	3.93	75.92	91.65
5	71.99	20.06	31.86	100.00
6	79.35	19.75	39.84	100.00
7	77.81	16.38	45.05	100.00
8	75.57	15.14	45.29	100.00
9	67.26	17.57	32.12	100.00
10	66.55	16.78	33.00	100.00
11	60.34	21.61	17.12	100.00

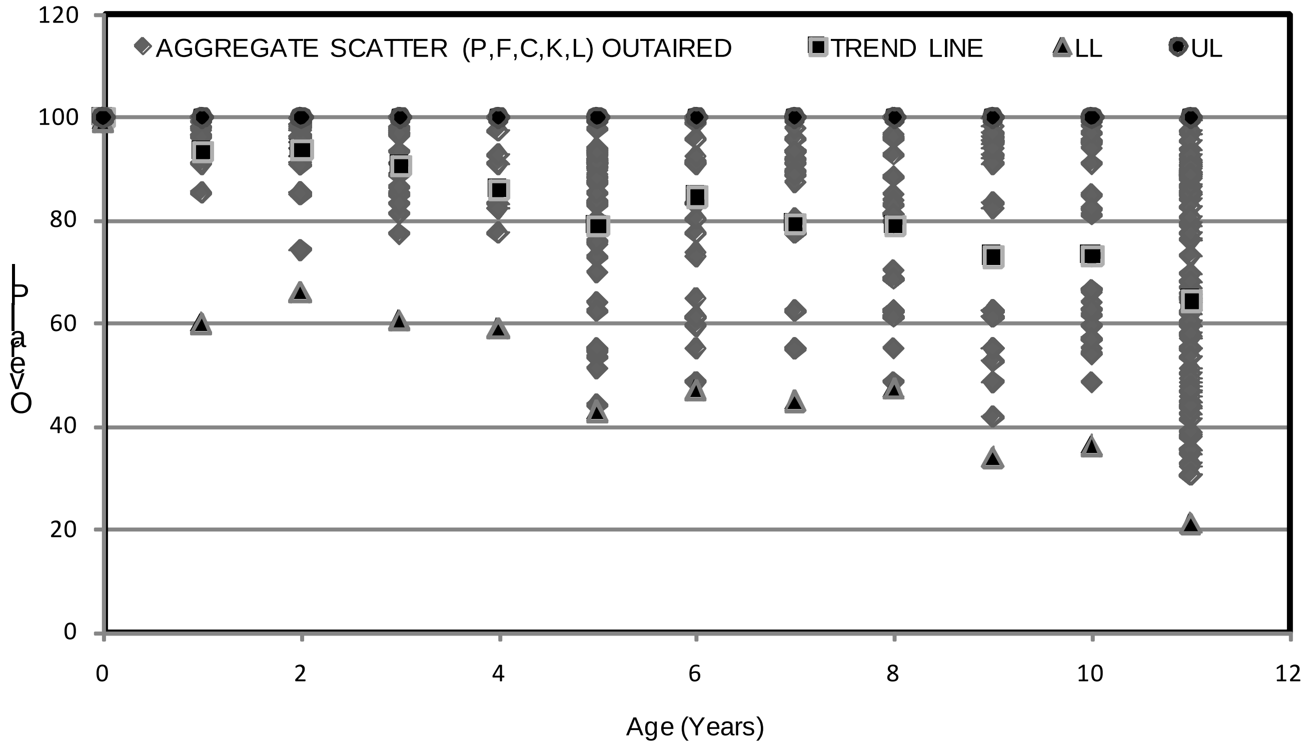

Figure 3.6: Aggregate Pavement Category Scatter Plot

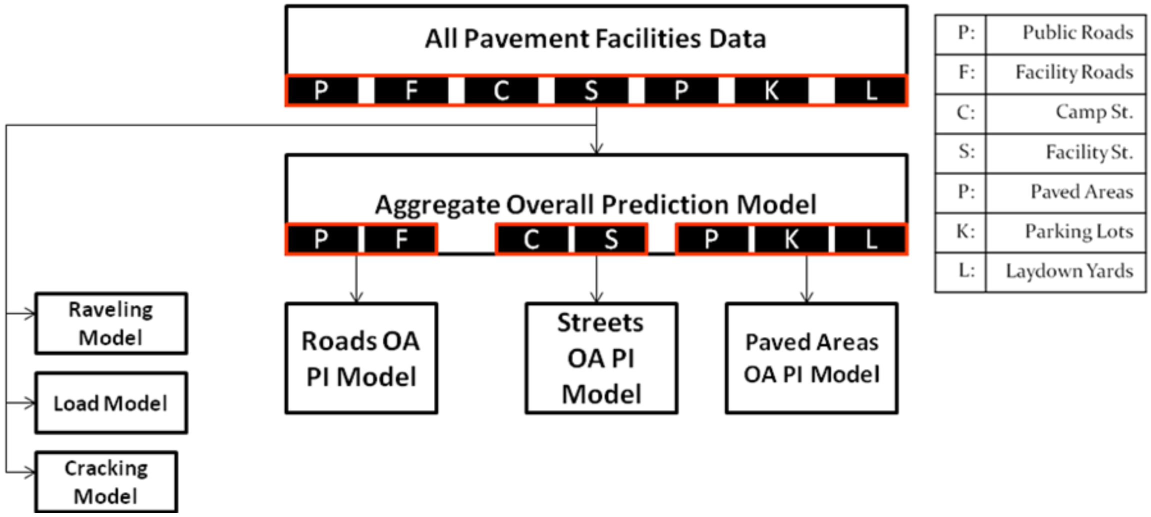

Figure 3.7: General Methodology to Develop Prediction Models

3.7 Summary

This chapter sheds light on the data collection process in Saudi Aramco since the beginning of the PMMS project in 1998, and highlighted the errors and deficiencies in that process which subsequently affected the data integrity.

Lots of repetitive overall PI for the same PM section throughout the years and other PM sections with only one or two readings in ten years for all the categories were observed, especially the categories owned by the departments within Saudi Aramco other than the Roads & Heavy Equipment Department.

It was also noted that there is a lot of rapid sudden drop in the PI values of many PM sections in a short period of time. This could be due to an error in evaluating some PM sections in some years. A professional and careful evaluation of each PM section is a key factor in developing a robust database.

In light of the above, the screening process has been done on all the eight facility types. Table 3.2 summarizes the screening process where five facility types (Public Roads, Facility Roads, Lay down Yards, Camp Streets and Parking Lots) revealed an accepted number of PM sections with reasonable data points while the other three facility types (Airstrips, Facility Streets and Plant Areas) did not meet the minimum number of accepted PM sections.

Table 3.2: Accepted PM Sections and Sum of Records

Pavement Category Type	Total Number of PM Sections	Accepted Number of PM Sections
Airstrips (A)	18	0
Public Roads (P)	674	305
Facility Roads (F)	3,857	200
Camp Streets (C)	1,247	214
Facility Streets (S)	1,580	3
Plant Areas (P)	671	6
Parking Lots (K)	1,361	47
Lay down Yards (L)	1,013	33
Total	10,421	808

CHAPTER 4

DATA ANALYSIS

All facility types' data were analyzed and screened for errors as mentioned in the previous chapter. Aggregate data were consolidated and three subsequent pavement categories were constructed to define their limits and attributes. The pavement categories which have undergone the statistical analysis are:

1. Aggregate data of the whole network
2. Roads category
3. Streets category
4. Paved Areas category

Regression analysis was performed on the above pavement categories to develop performance models for the Overall Performance Index and the Individual Distress Performance Indices.

Aggregate Distress performance indices including Raveling, Load and Cracking distresses were computed according to the following general format:

Aggregate Raveling PI = f (Raveling PI) (4.1)

Aggregate Load PI = f (Load PI) (4.2)

Aggregate Cracking PI = f (Av of Linear Cracking and Block Cracking PI's) (4.3)

4.1 Regression Analysis for Overall Performance Index (OA PI)

Considering the types and amount of data collected, the independent variables that affect the pavement index are in the following general form:

$$\text{Overall PI} = f\ (\text{AGE, AADT, THICK}) \quad (4.4)$$

where,

PI = Performance Index

AGE = Time, in years, from the construction or the last major maintenance

AADT = Average Annual Daily Traffic

THICK = Combined thickness of all asphalt layers

Other factors such as the Subbase type were not included because there were no different types used in almost all pavement sections considered in the study. The hypothesis in the general model of the PI in Equation (4.4) is that AGE and AADT are expected to be inversely proportional to the PI, while asphalt THICK is proportional to the PI.

Using MINITAB statistical software, accepted routes of each category were tabulated. Best subsets and forward regression techniques revealed that AGE is the most significant independent variable for all categories. The general form of the new prediction models which was considered in the analysis is as follows:

$$\text{Polynomial Model for Overall PI or Distress PI} = b_0 + b_1\ X + b_n\ X^n \quad (4.5)$$

$$\text{Linear Model for Distress PI} = b_0 + b_1\ X \quad (4.6)$$

4.1.1 Aggregate Overall Performance Index Model

As shown in Appendix A, forward regression analysis was done on the accepted routes of the aggregate data for the whole pavement network. AGE was highlighted as the significant IV, Quadratic and Cubic degrees of AGE were analyzed. The final form of the accepted performance model of the whole network is as follows:

$$\text{OA PI} = 100.7 - 4.209\ \text{AGE} + 0.4805\ \text{AGE}^2 - 0.04153\ \text{AGE}^3 \qquad (4.7)$$

Standard Deviation S = 12.5885, R^2 = 56%, R^2 (adj) = 55.9%.

Checking Hypothesis:

(H_o: F model < F critical (table) or P < 0.025

(H_1: F model > F critical (table) or P > 0.025

F model = 302.21 < F critical (table) since the Probability P = 0

H_o is accepted and H_1 is rejected.

Similarly, the t-test for the linear, quadratic and cubic coefficients was accepted as shown in Appendix A. The fitted line, Equation (4.7), is shown in Figure 4.1.

The aggregate Overall PI model indicates that Saudi Aramco pavement network deteriorates and reaches its maximum lifetime in 15 years from the construction date or the last major maintenance. Preventive maintenance should be done when the pavement PI reaches 75% at age of 8 to preserve an acceptable pavement condition for a longer period.

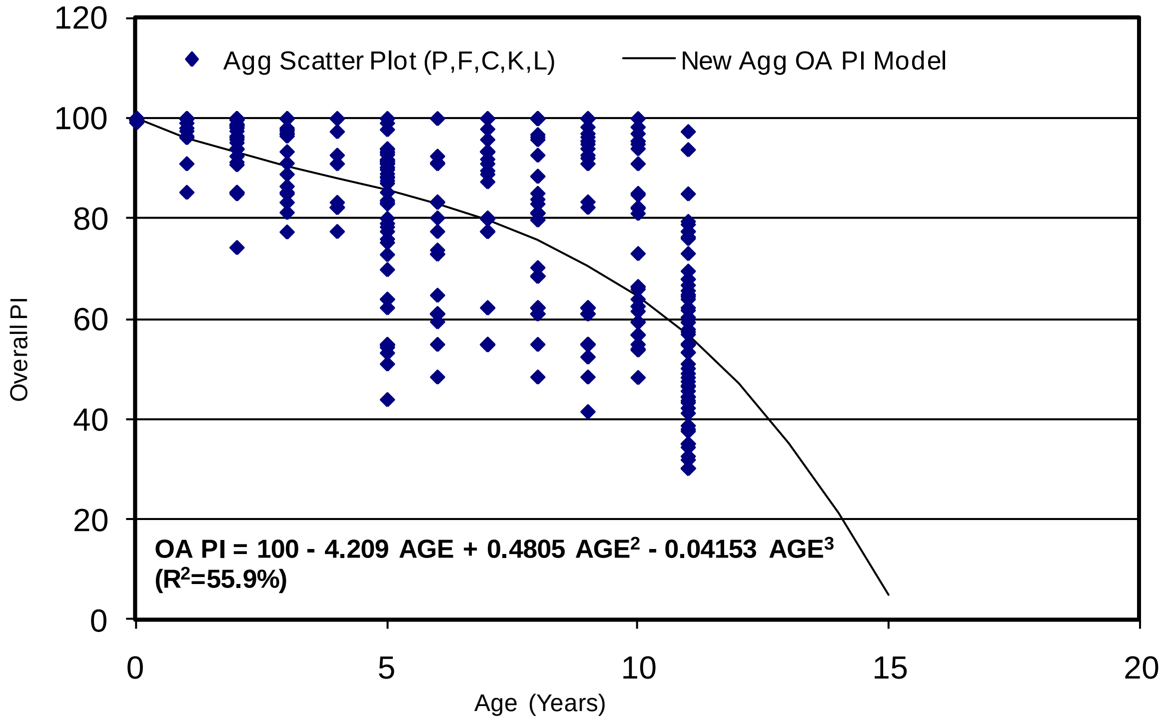

Figure 4.1: Aggregate Overall PI Model Fitted Line Plot

4.1.2 Roads Category Overall Performance Index Model

Roads category which considers only public and facility roads is of significant importance, since it represents 35% of the whole pavement network and is considered as the main vein for the transportation system in Saudi Aramco. As shown in Appendix B, forward regression analysis was done on the accepted routes of the roads category. AGE was highlighted as the significant IV affecting the performance index of the roads category. Quadratic and Cubic degrees of AGE were analyzed. The final form of the accepted performance model of the facility roads is as follows:

$$\text{OA PI} = 100 - 1.989\ \text{AGE} - 0.1733\ \text{AGE}^2 \tag{4.8}$$

S = 13.1776, R-Sq = 58.8%, R-Sq (adj) = 58.6%.

Checking Hypothesis:

(H_o: F model < F critical (table)

(H_1: F model > F critical (table)

F model = 335.56 < F critical (table) since the Probability P = 0

H_o is accepted and H_1 is rejected.

Similarly, the t-test for the linear and quadratic coefficients was accepted as shown in Appendix B. The third degree equation in Appendix B was not accepted since it fails the t-test as shown in Appendix B. Therefore, the second degree equation (4.8) was accepted as the final model and the fitted line equation is shown in Figure 4.2

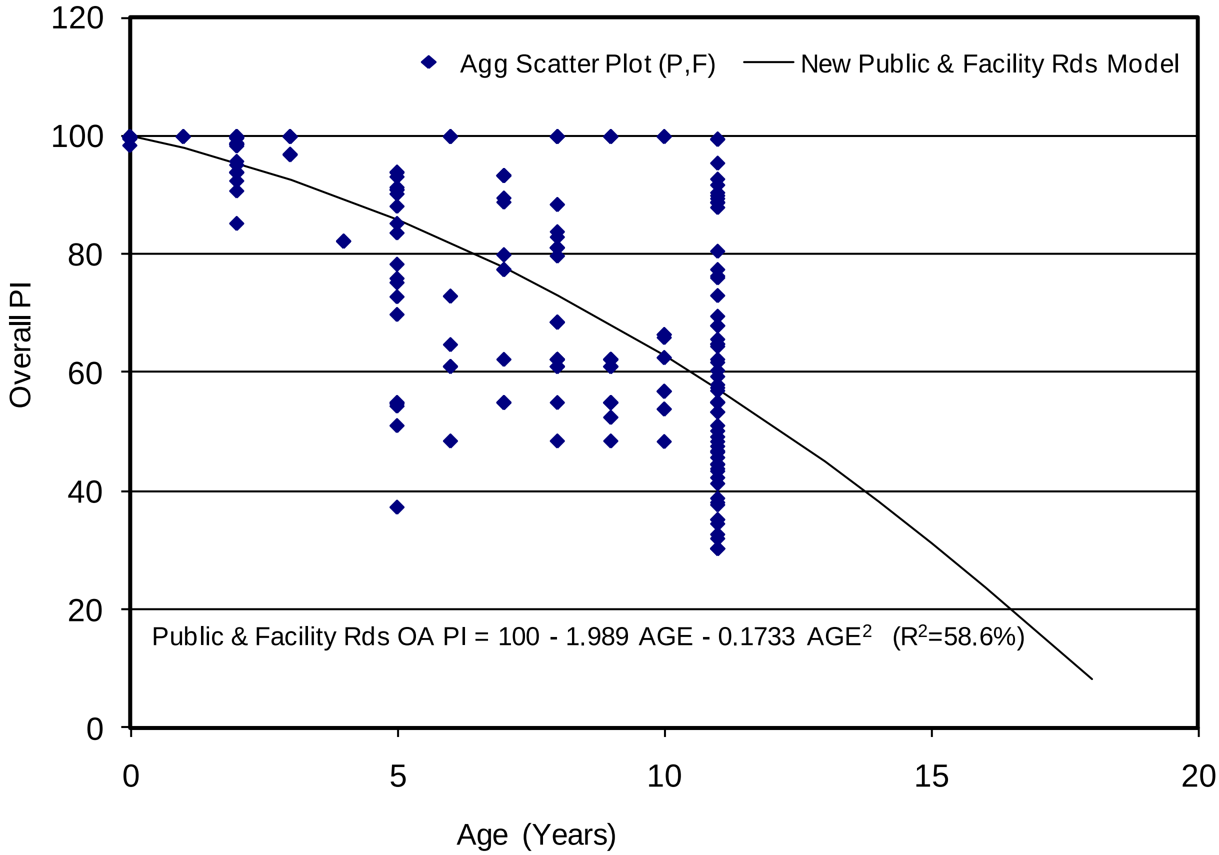

Figure 4.2: Roads Category Overall PI Fitted Line Plot

Roads category OA PI model in Figure 4.2 indicates a deterioration trend which is similar to the aggregate OA PI model of the whole pavement network, where the Roads category deteriorates and reaches its maximum lifetime in 18 years from the construction date or the last major maintenance. Preventive maintenance should be done when the pavement PI reaches 75% at age of 8 to preserve an acceptable pavement condition for a longer period. A comparison between the new and the current PMMS models of the Roads pavement category is detailed in the subsequent sections.

4.1.3 Streets Category Overall Performance Index Model

As shown in Appendix C, Streets category, which represents all types of streets in Saudi Aramco such as facility streets and camp streets, did not reveal an acceptable deteriorating trend. The scatter plot of the accepted PM-Sections did not support the development of a regression curve based on the preset hypothesis. In such a case, the aggregate OA PI model (Equation 4.7) should be used to predict the street category performance index.

4.1.4 Paved Areas Category Overall Performance Index Model

As shown in Appendix D, Paved areas category, which represents all types of paved areas in Saudi Aramco such as parking lot, plant areas and lay down yards, did not reveal an acceptable deteriorating trend. Although the statistical parameters of the second degree polynomial equation in Appendix D satisfy the F- and t-test, Age appears to be not inversely proportional to PI at age 6 onwards which is not logical. In such a case, the aggregate OA PI model (Equation 4.7) should be used to predict the paved areas category performance index.

4.2 Regression Analysis for Distress Performance Index (DPI)

Similar to the aggregate OA PI, Distress PI (DPI) regression analysis was performed on the aggregate data of all pavement categories. Raveling, Load and Cracking Distress PI were considered in this study as they represent the environmental effect and structural capacity of Aramco pavement network. Considering the types and amount of data collected, the independent variables (IV) that affect the distress pavement index are in the following general form:

$$\text{Distress PI} = f\ (\text{AGE, AADT, THICK}) \tag{4.9}$$

where,

Distress PI	=	Performance Index of Raveling, Load or Cracking
AGE	=	Time, in years, from the construction or the last major maintenance
AADT	=	Average Annual Daily Traffic
THICK	=	Combined thickness of all asphalt layers

The hypothesis in the general model of the PI in Equation (4.9) is that AGE and AADT are expected to be inversely proportional to the PI, while asphalt THICK is proportional to the PI.

Using Minitab statistical software, accepted routes of each category were tabulated. Best subsets and forward regression techniques revealed that AGE is the most significant independent variable for all categories. The general form mentioned in Equations (4.5) and (4.6) is used in the analysis of the distress PI.

4.2.1 Aggregate Raveling Performance Index Model

As shown in Appendix E, forward regression analysis was done on the accepted routes of the aggregate data for the whole pavement network. AGE was highlighted as the significant IV, Linear and Quadratic degrees of AGE were analyzed. The final form of the accepted performance model of the whole network is as follows:

$$\text{Raveling PI model} = 100 - 1.808\ \text{AGE} \tag{4.10}$$

Standard Deviation S = 11.3991, R^2 = 30.2%, R^2 (adj) = 30.1%.

Checking Hypothesis:

(H_o: F model < F critical (table) or P < 0.025

(H_1: F model > F critical (table) or P > 0.025

F model = 264.47 < F critical (table) since the Probability P = 0

H_o is accepted and H_1 is rejected.

Similarly, the t-test for the linear coefficients was accepted as shown in Appendix E. The fitted line, Equation (4.10), is shown in Figure 4.3.

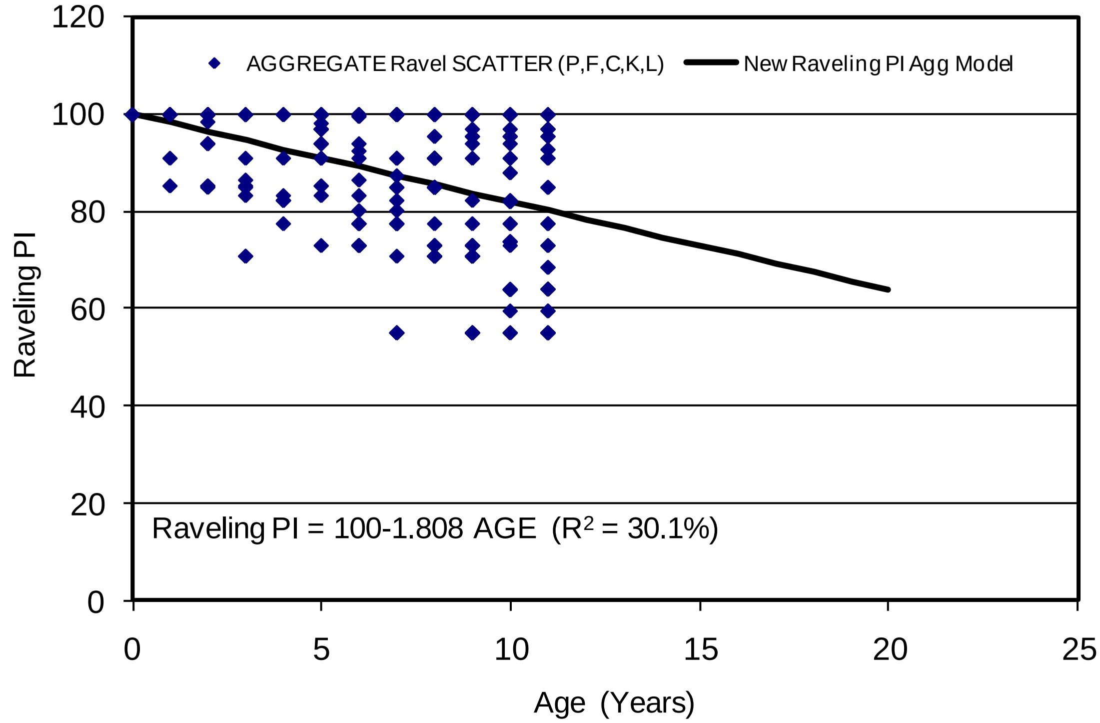

Figure 4.3: Aggregate Raveling PI Model Fitted Line Plot

The aggregate Raveling PI model indicates that Saudi Aramco pavement network deteriorates with regard to raveling distress in a linear pattern and loses 40% of its original value in 20 years. Preventive maintenance should be done in accordance with the OA PI model (Equation 4.7) when the pavement OA PI reaches 75% at age of 8 which corresponds to 20% reduction in the Raveling PI. A comparison between the new and the current PMMS model of the Raveling PI is detailed in the subsequent sections.

4.2.2 Aggregate Cracking Performance Index Model

As shown in Appendix F, forward regression analysis was done on the accepted routes of the aggregate data for the whole pavement network. AGE was highlighted as the significant IV, Linear and Quadratic degrees of AGE were analyzed. The final form of the accepted performance model of the whole network is as follows:

$$\text{Cracking PI model} = 99.61 + 0.3741\ \text{AGE} - 0.1084\ \text{AGE}^2 \qquad (4.11)$$

Standard Deviation S = 4.26, R^2 = 36.1%, R^2 (adj) = 36%

Checking Hypothesis:

(H_o: F model < F critical (table) or P < 0.025

(H_1: F model > F critical (table) or P > 0.025

F model = 217.09 < F critical (table) since the Probability P = 0

H_o is accepted and H_1 is rejected.

Similarly, the t-test for the linear and the quadratic coefficients were accepted as shown in Appendix F. The fitted line, Equation (4.11), is shown in Figure 4.4.

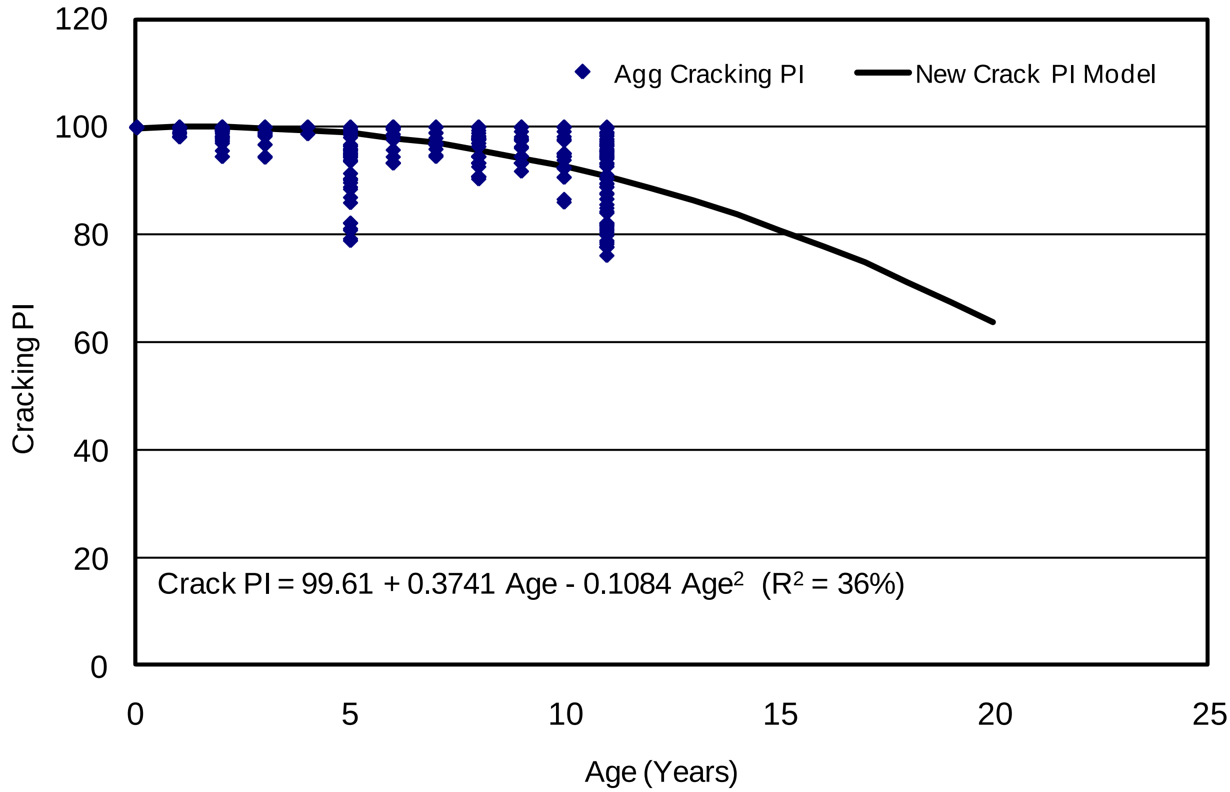

Figure 4.4: Aggregate Cracking PI Model Fitted Line Plot

4.2.3 Aggregate Load Performance Index Model

As shown in Figure 4.5, the aggregate Load PI is steady at 100 throughout the years except at the 11th year where it starts to drop. The scatter plot of the accepted PM-Sections did not support the development of a regression curve based on the preset hypothesis. On the other side, the scatter plot indicates that the network does not have structural problems and the load PI is at the high levels.

4.3 Model Validation

As stated earlier, 30% of the collected data was reserved for the validation process. The procedure followed for model validation testing was done by predicting the PI of the reserved points (predicted PI) according to its corresponding prediction model and plotted against the original PI of the reserved points (Original PI). Figures 4.6 to 4.9 show the validation data with respect to their Overall and Distress performance indices.

4.4 Comparison between PMMS Original and New Models

The main purpose of this section is to compare between the new models and the original models used in Saudi Aramco PMMS since 1998. Table 4.1 summarizes all the models where Roads Overall PI model and Aggregate Raveling PI model could be compared to the current models. Other models such as Streets, Paved Areas, Cracking and Load do not have a match.

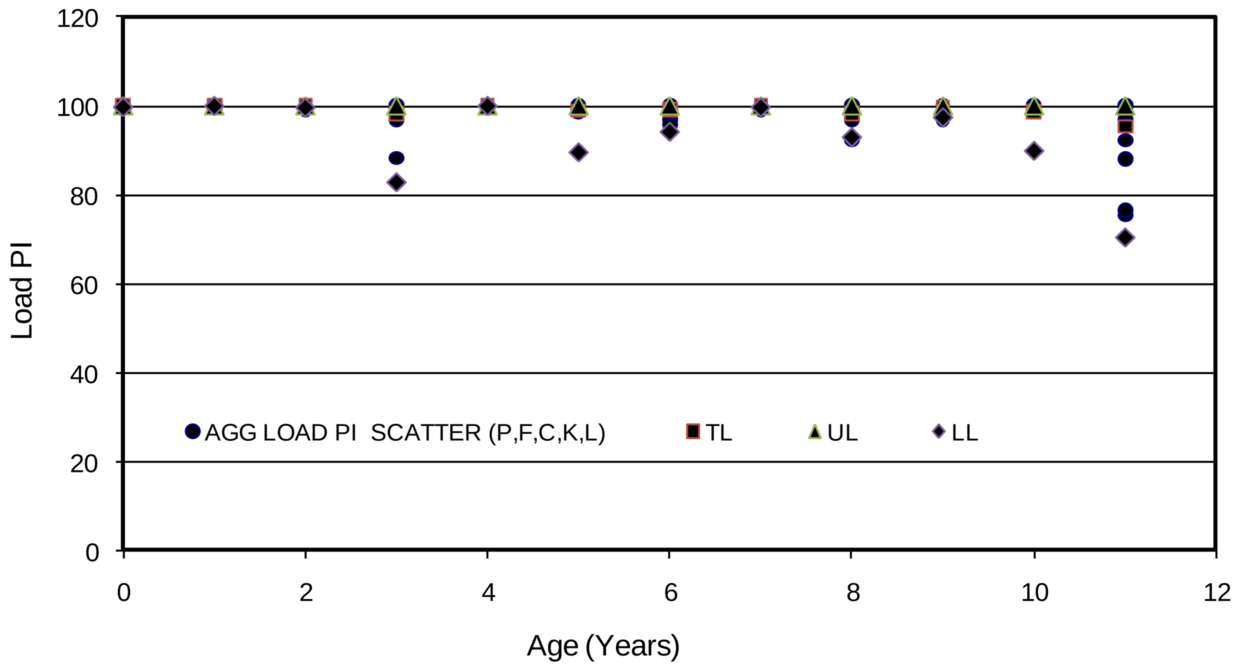

Figure 4.5: Aggregate Load PI Scatter Plot

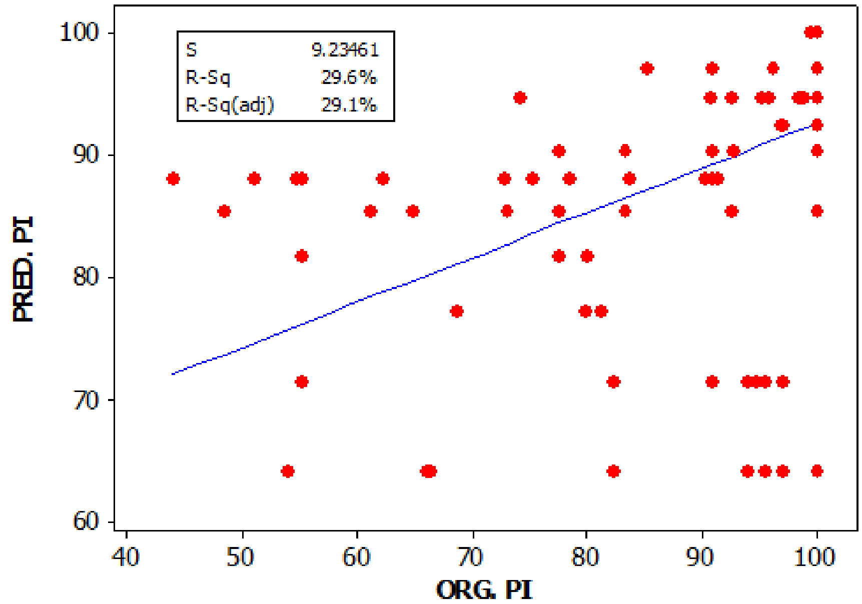

Figure 4.6: Aggregate Overall PI Goodness of Fit Plot

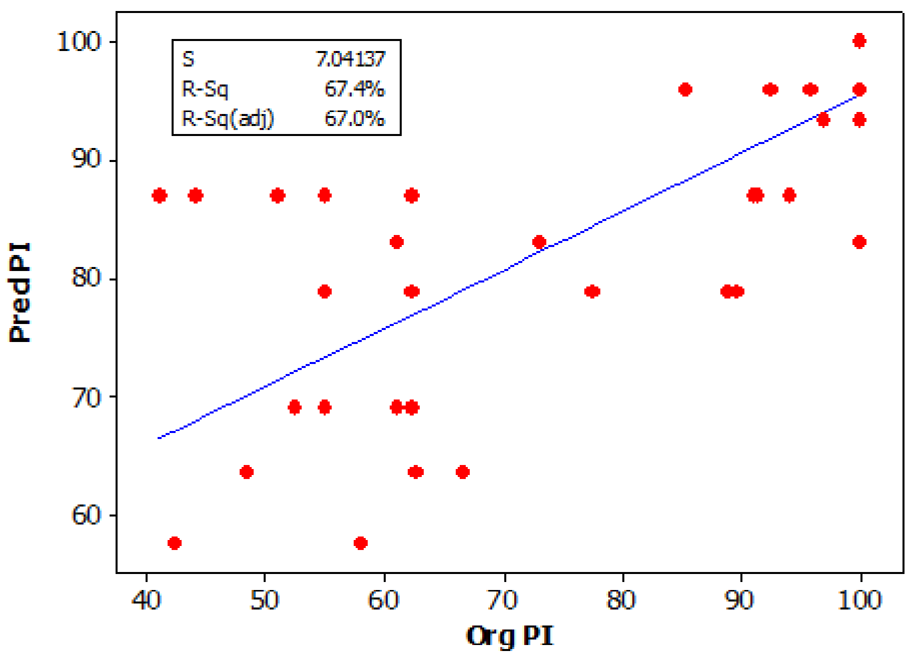

Figure 4.7: Roads Overall PI Goodness of Fit Plot

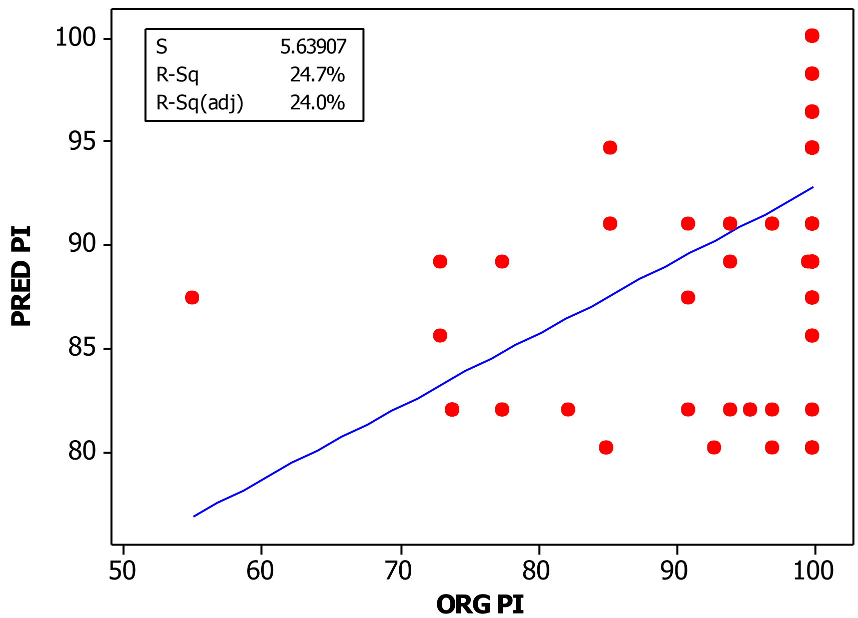

Figure 4.8: Aggregate Raveling PI Goodness of Fit Plot

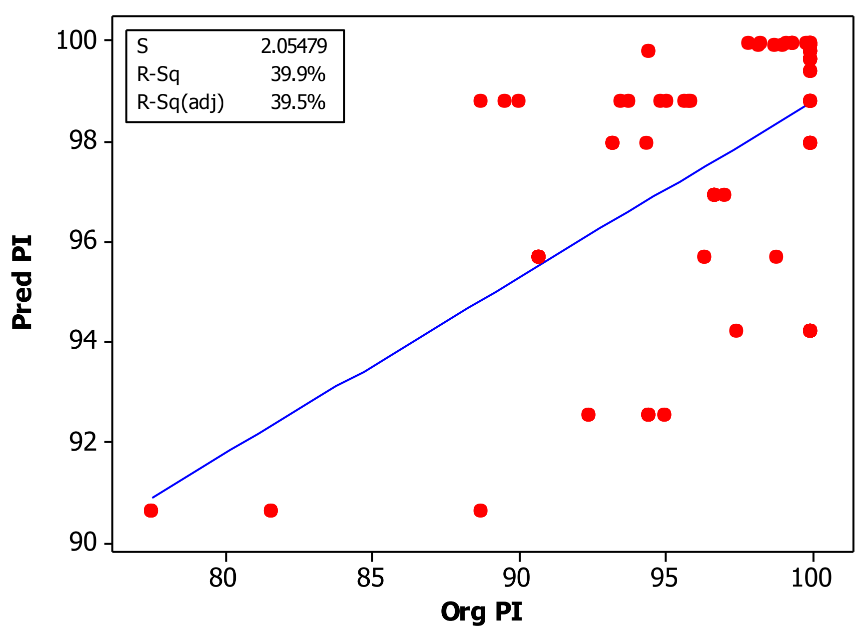

Figure 4.9: Aggregate Cracking PI Goodness of Fit Plot

Table 4.1: PMMS Original Models and the New Developed Models

MODEL TYPE	NEW MODEL	R^2	CURRENT MODEL	R^2
Aggregate OA PI	$100 - 4.209\ AGE + 0.4805\ AGE^2 - 0.04153\ AGE^3$	55.9%	Does not exist	-
Roads OA PI	$100 - 1.989\ AGE - 0.1733\ AGE^2$	58.6%	$100 + 0.6282\ AGE - 0.3728\ AGE^2 + 0.008\ AGE^3$	93.2%
Streets OA PI	No Trend	-	$100.0 - 4.0947\ AGE + 0.2895\ AGE^2 - 0.0119\ AGE^3$	44%
Paved Areas OA PI	No Trend	-	$100 - 2.972\ AGE + 0.0198\ AGE^2$	77.2%
Raveling PI	$100 - 1.808\ AGE$	30.1%	$100 - 0.015\ AGE^2 - 0.9959\ AGE$	19.2%
Cracking PI	$99.61 + 0.3741\ AGE - 0.1084\ AGE^2$	-	Does not exist	-
Load PI	Steady at 100	-	$100 - 0.0074\ AGE^3 + 0.1761\ AGE^2 - 1.1351\ AGE$	53.7%

4.4.1 Roads Overall Performance Models Comparison

As shown in Figure 4.10, Roads overall PI new model reads lower PI values than the current model by approximately 15 to 20%, which indicates that the Roads condition is deteriorating faster than what was originally predicted by PMMS. This difference could be referred to the number of samples considered in building the two models. The PMMS team has used 12 points and many assumptions to build the prediction model during the PMMS software setup, while in this study 473 points were used to develop Roads overall PI new model. The new model indicates that the public and facility road performance decreases more and faster than what the old model indicates. This scenario requires Saudi Aramco to do maintenance at an early stage to maintain an acceptable level of service. In other words, Saudi Aramco should do preventive maintenance at age 8 according to the new model rather than age 11 to preserve the level of service of the roads at PI equal to 75.

4.4.2 Raveling Performance Models Comparison

Similarly, the new Raveling performance model tends to read lower PI values than the current model as shown in Figure 4.11, which indicates that Aramco roads are subject to the Raveling distress more than what the PMMS currently predicts. Accordingly, maintenance should be done in advance to preserve the network at an acceptable level of the raveling PI. In other words, Saudi Aramco should do preventive maintenance at age 12 according to the new model rather than at age 17 to preserve the level of service of the roads at PI equal to 75 with regard to the raveling distress.

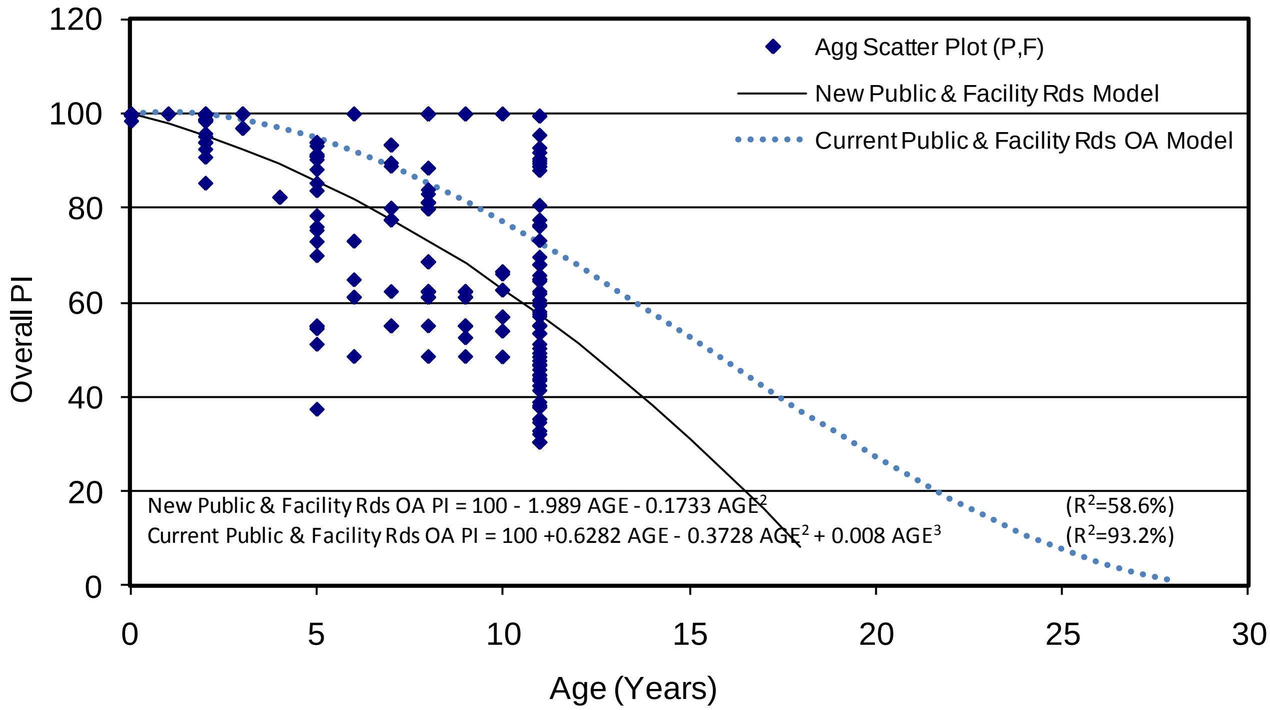

Figure 4.10: Current and New Roads Overall PI Models

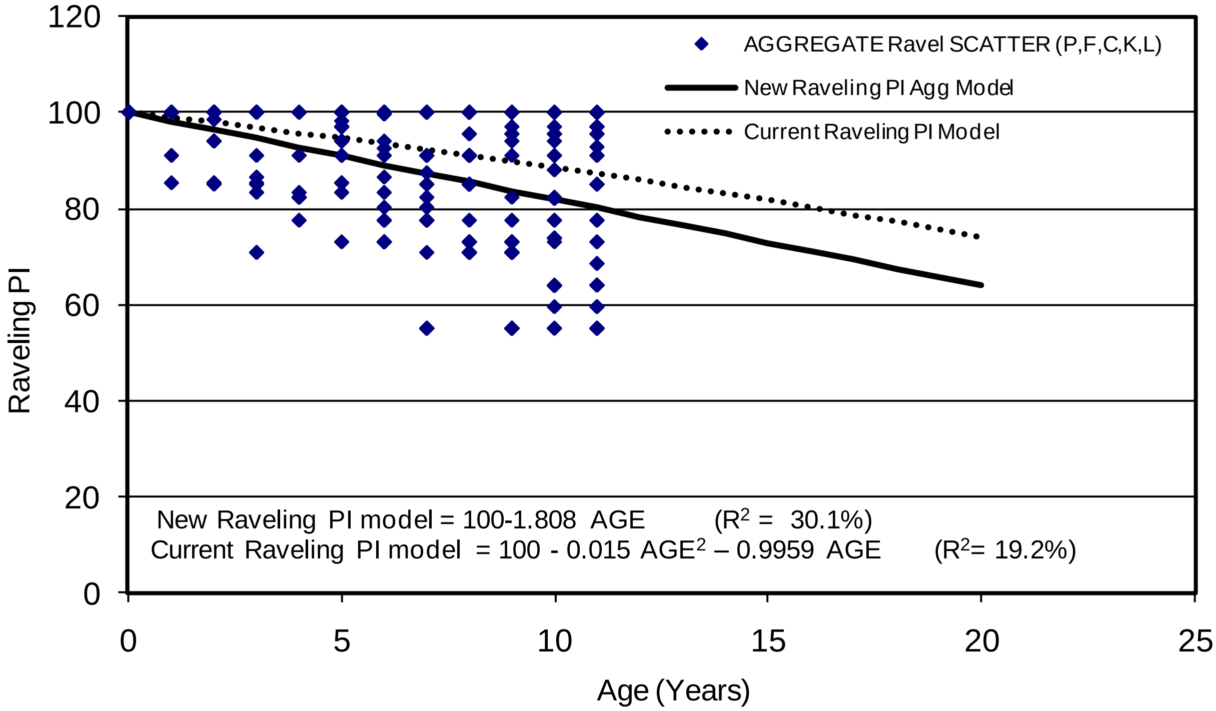

Figure 4.11: Current and New Raveling PI Models

4.5 Summary

This chapter dealt with the pavement condition prediction modeling of Saudi Aramco roads network. Prediction models were developed for the entire pavement network and for Roads category. Streets and Paved Areas categories data did not reveal an acceptable prediction model since there was no deteriorating trend that was observed.

Distress prediction models were developed for the entire pavement network with regard to Raveling and Cracking, whereas Load distress was very minimal to capture a deteriorating trend.

The comparison done between the current and the new prediction models indicates that Saudi Aramco pavement network deteriorates faster than what was predicted by the current models. Accordingly, the preventive maintenance zone in the new models requires an early intervention than the current practice in Saudi Aramco.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research study was to develop pavement condition prediction models for Saudi Aramco roads network based on the data obtained from Aramco PMMS. The following sections summarize the conclusions and the recommendations.

5.1 Conclusions

1. Aramco roads network was divided into three main categories: Roads, Streets and Paved areas to represent the entire pavement spectrum of Saudi Aramco roads network.

2. Age of the pavement or the time that elapsed from the last major maintenance is the most significant independent factor that affects the PI models of all pavement categories.

3. Aggregate Overall PI model was developed using the entire available data of the network. The aggregate Overall PI model indicates that Saudi Aramco pavement network deteriorates and reaches its maximum lifetime in 15 years from the construction date or the last major maintenance. In order to preserve an acceptable level of service of the network at PI equal to 75%, preventive maintenance should be done at age 8 of the pavement life.

4. The new Roads Overall PI model, which represents 34% of the network, indicates that Saudi Aramco roads deteriorate and reach its maximum lifetime in 18 years from the construction date or the last major maintenance. Preventive maintenance should be done at age of 8 to preserve an acceptable pavement condition of PI of 75%.

5. The comparison done between the current and the new Roads Overall PI models indicates that new model reads lower PI values than the current model by approximately 15 to 20%, which means that the Roads condition is deteriorating faster than what was originally predicted by PMMS. The new model also implies that Saudi Aramco should do preventive maintenance at age of 8 according to the new model rather than at age 11 to preserve the level of service of the roads at PI equal to 75.

6. Streets and Paved Areas categories did not reveal an acceptable deteriorating trend and therefore no model was developed for these two categories. The Aggregate Overall PI model could be used for these two categories to determine the Overall PI at different ages.

7. The Distress prediction models in terms of Aggregate Raveling PI model indicate that Saudi Aramco pavement network deteriorates with regard to raveling distress in a linear pattern and loses 40% of its original value in 20 years. Preventive maintenance should be done in conjunction with the OA PI model (Equation 4.7) when the pavement OA PI reaches 75% at age of 8 which corresponds to 20% reduction in the Raveling PI.

8. The comparison done between the new and current Raveling models indicates that new Raveling performance model tends to read lower PI values than the current model, which means that Aramco roads are subject to the Raveling distress more than what the PMMS currently predicts. Accordingly, maintenance should be done in advance to preserve the network at an acceptable level of the Raveling PI.

9. The aggregate Cracking model indicates that cracks development starts from the fifth year of the pavement age, however, their progression is slow where the Cracking PI reaches 75% in the 17^{th} year. Therefore, it could be safely assumed that cracks will not be a major concern since by eighth or ninth year of the pavement age, the pavement section will be due for preventive maintenance to restore their overall PI; hence, minor cracks will be sealed automatically.

10. Saudi Aramco pavement network is structurally sound and does not suffer from rutting, bleeding or failure/damages. The aggregate Load PI values are at high levels throughout the pavement age, therefore, no model could be developed since the deteriorating trend is very minimal.

5.2 Recommendations

In view of this research and the available information about Saudi Aramco pavement network and the PMMS, the following recommendations are intended to enhance Saudi Aramco’s pavement performance and PMMS utilization:

1. Implement the new developed models as appropriate in the Pavement Maintenance Management System. This will allow Saudi Aramco officials to set long range planning and secure the required funds promptly.

2. More attention is needed on the data collection. It was observed that most of the raw data obtained from the PMMS could not be used due to missing or illogical parameters.

3. Important parameters such as the AADT, pavement thickness, type of soil, etc., which could be of great significance in building the PI models, are mostly missing or inaccurate in the PMMS data. Therefore, it is recommended to rectify such an error and build a strong data structure for future models' enhancement.

4. Updating the history of the PM sections such as the maintenance cycles is of great importance in building strong data structure and developing future models.

5. Apply quality control and quality assurance (QC/QA) on the PMMS data collection, first by selecting trained professionals with good engineering sense to measure the distresses accurately and to re-select (if necessary) the PM sections that represent the condition of the pavement. Secondly, by making routine QC/QA checks on data survey and entry.

6. Roughness and Skid resistance indices are significant parameters in evaluating the pavement condition since they greatly affect the ridability of the road. Annual roughness and skid tests should be done on the pavement network and integrated in the overall PI calculation.

CHAPTER 6

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APPENDICES

Appendix A

Aggregate Overall Performance Index Model

Appendix A

Aggregate Overall Performance Index Model

Stepwise Regression: OA PI versus AGE; THICK; AADT

```
Forward selection.  Alpha-to-Enter: 0.25


Response is OA PI on 3 predictors, with N = 715


Step              1        2
Constant      101.6    113.3

AGE           -3.49    -3.50
T-Value      -29.13   -29.89
P-Value       0.000    0.000

THICK                 -0.288
T-Value                -5.70
P-Value                0.000

S              12.8     12.5
R-Sq          54.34    56.33
R-Sq(adj)     54.27    56.20
Mallows Cp     33.4      2.9
```

Polynomial Regression Analysis: OA PI versus AGE

```
The regression equation is
OA PI = 99.99 - 1.612 AGE - 0.1893 AGE**2


S = 12.6526   R-Sq = 55.5%   R-Sq(adj) = 55.4%


Analysis of Variance

Source       DF      SS       MS       F      P
Regression    2  142365  71182.4  444.65  0.000
Error       712  113982    160.1
Total       714  256347


Sequential Analysis of Variance

Source     DF      SS       F      P
Linear      1  139288  848.39  0.000
Quadratic   1    3077   19.22  0.000
```

Fitted Line: OA PI versus AGE

Residual Plots for OA PI

Polynomial Regression Analysis: OA PI versus AGE

The regression equation is
OA PI = 100.7 - 4.209 AGE + 0.4805 AGE2 - 0.04153 AGE**3**

S = 12.5885   R-Sq = 56.0%   R-Sq(adj) = 55.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	143675	47891.5	302.21	0.000
Error	711	112673	158.5		
Total	714	256347			

Sequential Analysis of Variance

Source	DF	SS	F	P
Linear	1	139288	848.39	0.000
Quadratic	1	3077	19.22	0.000
Cubic	1	1310	8.26	0.004

Appendix B

Roads Category Overall Performance Index Model

Appendix B

Roads Category Overall Performance Index Model

Polynomial Regression Analysis: OA PI versus AGE

```
The regression equation is
OA PI = 100.6 - 1.989 AGE - 0.1733 AGE**2


S = 13.1776   R-Sq = 58.8%   R-Sq(adj) = 58.6%


Analysis of Variance

Source       DF      SS       MS       F      P
Regression    2  116539  58269.7  335.56  0.000
Error       471   81789    173.6
Total       473  198328


Sequential Analysis of Variance

Source     DF      SS       F      P
Linear      1  114719  647.62  0.000
Quadratic   1    1821   10.49  0.001
```

Fitted Line: OA PI versus AGE

Residual Plots for OA PI

Polynomial Regression Analysis: OA PI versus AGE

```
The regression equation is
OA PI = 100.4 - 1.308 AGE - 0.3422 AGE**2 + 0.01016 AGE**3


S = 13.1872   R-Sq = 58.8%   R-Sq(adj) = 58.5%


Analysis of Variance

Source       DF      SS       MS       F      P
Regression    3  116594  38864.8  223.49  0.000
Error       470   81734    173.9
Total       473  198328


Sequential Analysis of Variance

Source     DF      SS       F      P
Linear      1  114719  647.62  0.000
Quadratic   1    1821   10.49  0.001
Cubic       1      55    0.32  0.575
```

Polynomial Regression Analysis: Overall PI versus MANT AGE

```
The regression equation is
Overall PI = 99.94 - 2.232 MANT AGE + 0.1482 MANT AGE**2 - 0.03089 MANT AGE**3


S = 6.81574   R-Sq = 84.5%   R-Sq(adj) = 84.2%


Analysis of Variance

Source       DF       SS       MS       F      P
Regression    3  37792.4  12597.5  271.18  0.000
Error       149   6921.7     46.5
Total       152  44714.1


Sequential Analysis of Variance

Source     DF       SS       F      P
Linear      1  35288.1  565.30  0.000
Quadratic   1   2389.6   50.94  0.000
Cubic       1    114.7    2.47  0.118
```

Fitted Line: Overall PI versus MANT AGE

Appendix C

Street Category Overall Performance Index Model

Appendix C

Street Category Overall Performance Index Model

Stepwise Regression: OA PI versus AGE; THICK; AADT

```
Forward selection.  Alpha-to-Enter: 0.25


Response is OA PI on 3 predictors, with N = 133
N(cases with missing observations) = 3 N(all cases) = 136


Step             1
Constant     100.0

AGE          -1.92
T-Value      -9.23
P-Value      0.000

S             9.24
R-Sq         39.41
R-Sq(adj)    38.95
Mallows Cp     1.3
```

Polynomial Regression Analysis: OA PI versus AGE

```
The regression equation is
OA PI = 101.1 - 3.361 AGE + 0.1427 AGE**2


S = 9.04118   R-Sq = 41.9%   R-Sq(adj) = 41.0%


Analysis of Variance

Source       DF       SS       MS      F      P
Regression    2   7839.7  3919.84  47.95  0.000
Error       133  10871.8    81.74
Total       135  18711.5


Sequential Analysis of Variance

Source     DF       SS      F      P
Linear      1  7506.54  89.77  0.000
Quadratic   1   333.14   4.08  0.046


Fitted Line: OA PI versus AGE
```

```
Welcome to Minitab, press F1 for help.
Retrieving project from file: 'J:\NEW PMMS FLASH\WORKE OUT LATEST\CAMP
STREETS\TRIAL CAMP STREET.MPJ'
```

Polynomial Regression Analysis: Camp Streets OA PI versus Age (2nd trial)

```
The regression equation is
Camp Streets OA PI = 99.88 - 2.436 Age - 0.00720 Age**2


S = 13.0555   R-Sq = 34.1%   R-Sq(adj) = 33.4%


Analysis of Variance

Source       DF       SS       MS      F      P
Regression    2  16498.4  8249.19  48.40  0.000
Error       187  31873.2   170.44
Total       189  48371.6


Sequential Analysis of Variance

Source     DF       SS      F      P
Linear      1  16497.1  97.30  0.000
Quadratic   1      1.3   0.01  0.930
```

Appendix D

Paved Areas Category Overall Performance Index Model

Appendix D

Paved Areas Category Overall Performance Index Model

Polynomial Regression Analysis: PI versus AGE

```
The regression equation is
PI = 97.57 - 5.565 AGE + 0.4517 AGE**2


S = 11.1856   R-Sq = 27.6%   R-Sq(adj) = 25.1%


Analysis of Variance

Source      DF       SS       MS      F      P
Regression   2   2812.5  1406.24  11.24  0.000
Error       59   7381.9   125.12
Total       61  10194.4


Sequential Analysis of Variance

Source     DF       SS      F      P
Linear      1  1408.03   9.62  0.003
Quadratic   1  1404.44  11.22  0.001
```

Fitted Line: PI versus AGE

Residual Plots for PI

Polynomial Regression Analysis: PI versus AGE

```
The regression equation is
PI = 99.20 - 13.09 AGE + 2.589 AGE**2 - 0.1398 AGE**3


S = 10.5311   R-Sq = 36.9%   R-Sq(adj) = 33.6%


Analysis of Variance

Source      DF       SS       MS      F      P
Regression   3   3761.9  1253.98  11.31  0.000
Error       58   6432.5   110.90
Total       61  10194.4


Sequential Analysis of Variance

Source     DF       SS      F      P
Linear      1  1408.03   9.62  0.003
```

```
Quadratic   1  1404.44  11.22  0.001
Cubic       1   949.46   8.56  0.005
```

Fitted Line: PI versus AGE

Polynomial Regression Analysis: Overall PI versus MANT AGE

```
The regression equation is
Overall PI = 99.73 + 1.413 MANT AGE - 0.9770 MANT AGE**2 + 0.03679 MANT AGE**3


S = 4.47671   R-Sq = 82.8%   R-Sq(adj) = 81.7%


Analysis of Variance

Source      DF       SS       MS      F      P
Regression   3  4438.27  1479.42  73.82  0.000
Error       46   921.88    20.04
Total       49  5360.16


Sequential Analysis of Variance

Source     DF       SS       F      P
Linear      1  3732.00  110.02  0.000
Quadratic   1   682.57   33.93  0.000
Cubic       1    23.70    1.18  0.282


Fitted Line: Overall PI versus MANT AGE
```

Appendix E

Aggregate Raveling Performance Index Model

Appendix E

Aggregate Raveling Performance Index Model

Stepwise Regression: RAVEL PI versus AGE; THICK; AADT

```
Forward selection.  Alpha-to-Enter: 0.25


Response is RAVEL PI on 3 predictors, with N = 623


Step              1
Constant      100.4

AGE           -1.81
T-Value      -16.38
P-Value       0.000

S              11.4
R-Sq          30.18
R-Sq(adj)     30.07
Mallows Cp      0.1
```

Regression Analysis: RAVEL PI versus AGE

```
The regression equation is
RAVEL PI = 100.4 - 1.808 AGE


S = 11.3991   R-Sq = 30.2%   R-Sq(adj) = 30.1%


Analysis of Variance

Source       DF      SS       MS       F      P
Regression    1   34884  34884.2  268.47  0.000
Error       621   80692    129.9
Total       622  115576
```

Fitted Line: RAVEL PI versus AGE

Residual Plots for RAVEL PI

Polynomial Regression Analysis: RAVEL PI versus AGE

```
The regression equation is
RAVEL PI = 100.8 - 2.420 AGE + 0.06092 AGE**2


S = 11.3875   R-Sq = 30.4%   R-Sq(adj) = 30.2%
```

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	35178	17589.0	135.64	0.000
Error	620	80398	129.7		
Total	622	115576			

Sequential Analysis of Variance

Source	DF	SS	F	P
Linear	1	34884.2	268.47	0.000
Quadratic	1	293.8	2.27	0.133

Fitted Line: RAVEL PI versus AGE

Residual Plots for RAVEL PI

Appendix F

Aggregate Cracking Performance Index Model

Appendix F

Aggregate Cracking Performance Index Model

Regression Analysis: Crack PI versus Age

```
The regression equation is
Crack PI = 100.6 - 0.7282 Age


S = 4.44048   R-Sq = 30.7%   R-Sq(adj) = 30.6%


Analysis of Variance

Source       DF       SS       MS       F      P
Regression    1   6698.1  6698.05  339.69  0.000
Error       768  15143.3    19.72
Total       769  21841.4
```

Fitted Line: Crack PI versus Age

Residual Plots for Crack PI

Polynomial Regression Analysis: Crack PI versus Age

```
The regression equation is
Crack PI = 99.61 + 0.3741 Age - 0.1084 Age**2


S = 4.26419   R-Sq = 36.1%   R-Sq(adj) = 36.0%


Analysis of Variance

Source       DF       SS       MS       F      P
Regression    2   7894.8  3947.40  217.09  0.000
Error       767  13946.6    18.18
Total       769  21841.4


Sequential Analysis of Variance

Source     DF       SS       F      P
Linear      1  6698.05  339.69  0.000
Quadratic   1  1196.75   65.82  0.000
```

Fitted Line: Crack PI versus Age

Residual Plots for Crack PI

VITAE

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