Modeling of pavement condition and maintenance priority ranking for road networks.

Rezqallah Hasan Fayyadh. Ramadhan

Civil Engineering

July 1997

Abstract

Pavement represent an important asset to all nations. In Saudi Arabia huge investments have been made in constructing enormous pavement networks of roads and airfields. These networks require great care and attention through conducting continuous evaluation and timely maintenance to keep them operating under acceptable levels of service.

Pavement condition prediction models can greatly enhance the capabilities of a pavement mangement system (PMS). Among other benefits, these models allow pavement authorities to predict the timing of maintenance or rehabilitation activities and to estimate the long-range funding requirements for preserving the payment system.

In this study, pavement condition-related data were collected from all accessible sources in the Kingdom, including the Ministry of Communications, the Municipality of Riyadh, the Municipality of Dammam, the Industrial City of Al-Jubail, and from other research studies carried out by different researchers. These data were categorized, processed, analyzed and used to generate different prediction models from the related factors affecting the pavement condition. These models were evaluated to identify the most appropriate ones fitting the available data. The obtained models could adequately predict the pavement condition from the validation data with a reasonable level of significance.

On the other hand, opinions of different groups of individuals from all around the Kingdom about the weights of the factors affecting the maintenance priority ranking were collected. The collected data were checked for reliability and repeatability and then usd to obtain a general priority index procedure. This proceduer is used for ranking pavement sections in any network according to their importance or urgency for maintenance. The procedure was validated using two case studies, where it was concluded that the procedure could adequately duplicate the engineering judgment for maintenance priority ranking in addition to its capability to handle huge pavement networks systematically and efficiently.

The developed models and procedures were integrated into one sub-system that can handle data entry, retrieval and results reporting. This sub-system can be integrated in any pavement management system to complement other activities and to obtain a comprehensive PMS.

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

MODELING OF PAVEMENT CONDITION AND MAINTENANCE PRIORITY RANKING FOR ROAD NETWORKS

BY

Rezqallah Hasan Fayyadh Ramadhan

A Dissertation Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

In

CIVIL ENGINEERING

July, 1997

UMI Number: 9810893

UMI Microform 9810893
Copyright 1997, by UMI Company. All rights reserved.

This microform edition is protected against unauthorized copying under Title 17, United States Code.

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

King Fahd University of Petroleum and Minerals

Dhahran 31261, Saudi Arabia

COLLEGE OF GRADUATE STUDIES

This dissertation, written by **Rezqallah Hasan Fayydh Ramadhan** under the direction of his dissertation Advisor and approved by his Dissertation Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements of the degree of **DOCTOR OF PHILOSOPHY in CIVIL ENGINEERING.**

Dissertation Committee

Dr. Hamad I. Al-Abdul Wahhab
Dissertation Committee Chairman

Dr. Saleh O. Duffuaa
Member

17/9/97.

Dr. Abdulaziz A. Bubshait
Member

Dr. Nedhal T. Ratrout
Member

Dr. Walid S. Al-Sabah
Member

Dr. Khalaf A. Al-Ofi
Member

Dr. Sahel N. Abduljauwad
Department Chairman

Dr. Abdallah M. Al-Shehri
Dean, College of Graduate Studies

27-9-97
Date

كلية الدراسات العليا
COLLEGE OF GRADUATE STUDIES

إلى زوجتي الغالية

إلى أولادي وبناتي الأعزاء

أُهدي جهدي هذا..راجياً من الله التوفيق والسداد

In The Name of ALLAH, The Merciful, The Mercy-Giving

ACKNOWLEDGMENT

Praise and glory be to ALLAH, the Almighty with whose gracious help (first and last) it was possible to accomplish this work.

Acknowledgment is due to the Civil Engineering Department of King Fahd University of Petroleum and Minerals for extending the facilities to carry out this research. Acknowledgment is also due to the Research Institute of the University for giving me this opportunity to complete my study and providing help and support.

I wish to express my sincere and deep appreciation and gratitude to my advisor and dissertation committee chairman Dr. Hamad I. Al-Abdul Wahhab for his continuous, careful guidance, and valuable constructive comments throughout the course of my study. I am also very grateful for his brotherly sincere encouragement and support that I have received from hem. Appreciation and thanks are also due to other dissertation committee members: Dr. Saleh O. Duffuaa, Dr. Abdulaziz A. Bubshait, Dr. Nedhal T. Ratrout, Dr. Walid S. Al-Sabah, and Dr. Khalaf A. Al-Ofi for their continuous and constructive comments and suggestions provided to my work. For all, I pray for ALLAH to bless them and reward them better.

I particularly wish to thank my wife and children for treating my PhD study as an extra and important member of the family. Without their sacrifice, support, patience, and prayers, this work could not be completed. I am so grateful. My deep thanks are also to my father, sister, and brothers for their moral support, encouragement, and prayers throughout my work.

Thanks are also extended to the Ministry of Communications (MOC), Municipality of Riyadh, Municipality of Dammam, Municipality of Dubai (UAE), Saudi ARAMCO, and Royal Commission (Jubail) for their help and cooperation in the data collection phase of this study.

I am thankful to all my colleagues and friends especially Dr. Ibrahim Asi, Dr. Abdul Malik Abu Elshiekh, and Dr. Ibrahim Dubabe for their cooperation and help. My thanks are also due to Dr. Bradley Wilkinson (Omar) for editing the manuscript.

TABLE OF CONTENT

Title **Page**

TABLE OF CONTENT vi
LIST OF TABLES xi
LIST OF FIGURES xv
ABSTRACT (ARABIC) xxi
ABSTRACT (ENGLISH) xxii
LIST OF ABBREVIATIONS xxiii

CHAPTER ONE: INTRODUCTION 1

1.1 GENERAL 1

1.2 PROBLEM STATEMENT 4

1.3 OBJECTIVES 8

1.4 THESIS ORGANIZATION 8

CHAPTER TWO: LITERATURE REVIEW 11

2.1 DESCRIPTION 11

2.2 PAVEMENT MANAGEMENT SYSTEM 11

2.2.1 General 11
2.2.2 Operating Systems 17

2.3 DATA BASE REQUIREMENT 28

2.3.1 Traffic Data 28
2.3.2 Environmental Data 30
2.3.3 Pavement Structure-Related Data 30
2.3.3.1 Layer Thickness 31
2.3.3.2 Layer Composition 31
2.3.3.3 Subgrade Type and Strength 33
2.3.4 Pavement Performance Parameters 33
2.3.4.1 Pavement Distress 34
2.3.4.2 Pavement Roughness 34
2.3.4.3 Safety Condition 39
2.3.4.4 Structural Capacity 42

2.4 PAVEMENT PERFORMANCE 45
2.4.1 Pavement Serviceability 45
2.4.2 Pavement Condition Evaluation 48
2.4.2.1 Ministry of Communications (MOC), Riyadh-Saudi Arabia Method . 50
2.4.2.2 KFUPM- Research Institute Method 55
2.4.2.3 PAVER Method 59
2.4.3 Pavement Performance Modeling 62
2.4.3.1 Regression Performance Models 66
2.4.3.2 Probabilistic Performance Models :Markov Process 81
2.5 PAVEMENT MAINTENANCE PRIORITIZATION 91
2.5.1 General 91
2.5.2 Composite Index Ranking Methods 92
2.5.3 Economic-based methods 103
2.5.4 Neural Network Method 106
2.5.5 Analytical Hierarchy Process Method 108
2.5.5.1 General 108
2.5.5.2 Principles and Background of AHP [Saaty 1990[..... 116
2.5.5.3 Weight Vector Calculation 117
2.5.5.4 Comparison Matrix Consistency 119
2.5.5.5 Quantification of Consistency 119
2.5.6 Optimization Methods 124

CHAPTER THREE: RESEARCH METHODOLOGY 125

3.1 GENERAL 125

3.2 PRIORITY RANKING MODELING 125
3.2.1 Priority Factor Definition 127
3.2.1.1 Road Classification 128
3.2.1.2 Pavement Condition 129
3.2.1.3 Operating Traffic 131
3.2 .1.4 Riding Quality 132
3.2.1.5 Safety Condition 133
3.2.1.6 Maintenance Cost 135
3.2.1.7 Importance to Community 136
3.2.2 Data Collection: Factor Weight Determination 138

3.2.3 Data Analysis 140
3.2.4 Model Formulation 140
3.2.5 Model Validation 141

3.3 PAVEMENT CONDITION MODELING 141

3.3.1 Model Parameters Definition 141
3.3.2 Sample Size Determination 144
3.3.3 Data Collection 145
3.3.3.1 Study Area 145
3.3.3.2 Data Sources 146
3.3.4 Testing Collected Data 147
3.3.5 Model Calibration and Testing 147
3.3.6 Models for Combined Data 148
3.3.7 Model Validation 148
3.3.8 Model Applications 149

3.4 MODEL AUTOMATION 149

CHAPTER FOUR: PRIORITY MODELING DATA COLLECTION AND ANALYSIS 150

4.1 DESCRIPTION 150

4.2 MODEL DEFINITION 150

4.2.1 Road Class 152
4.2.2 Pavement Condition 153
4.2.3 Riding Quality 153
4.2.4 Safety Condition 160
4.2.5 Operating Traffic 164
4.2.6 Maintenance Cost 164
4.2.7 Importance to Community 169

4.3 PILOT SURVEY DATA COLLECTION 171

4.4 MAIN SURVEY DATA COLLECTION 178

4.5 RESULTS OF MAIN SURVEY DATA COLLECTION 181

4.6 DATA ANALYSIS 188

4.6.1 Statistical Comparison Tests 189

4.6.2 Factor Weights Statistical Comparison 198
4.6.3 Repeatability Checks 200
4.6.3.1 Within Data Variation: 200
4.6.3.2 AHP-Direct Assignment Comparison 202
4.6.3.3 Temporal-Based Data Variation 204
4.6.4 Comparison between Surveyed Groups 204
4.6.5 Comparison between Saudi and UAE Experience 210
4.6.6 Reliability Test 210

4.7 MODEL CALIBRATION 212

4.7.1 Factor Weight Adjustment 212
4.7.2 Final Model Form 215
4.7.3 Model Adjustment for Structural Distresses 216
4.7.4 Typical Example 219

4.8 MODEL VALIDATION 224

4.8.1 Case Study 1: Jubail Road Network 225
4.8.2 Case Study 2: Dammam Road Network 228

4.9 FACTOR ANALYSIS 232

4.10 SUMMARY 233

CHAPTER FIVE: PAVEMENT CONDITION DATA COLLECTION AND ANALYSIS 234

5.1 DESCRIPTION 234

5.2 MODEL DEFINITION 234

5.2.1 Model Parameters 234
5.2.2 A priori Hypothesis 235

5.3 DATA COLLECTION 237

5.3.1 Sampling Requirement 237
5.3.2 Data Sources 238
5.3.3 Preliminary Data Analysis 243

5.4 MODEL FORMULATION 253

5.4.1 Linear Regression Analysis 253
5.4.2 Non Linear Regression Analysis 254
5.4.3 Models Selection 256
5.4.3.1 PDR Models 256

5.4.3.2 PCR Models 259
5.4.3.3 PCI Models 262

5.5 MODEL EVALUATION AND TESTING 262

5.5.1 Model Evaluation 262
5.5.1.1 Basic Assumptions Check 265
5.5.1.2 Prediction Power 269
5.5.2 Statistical Testing 269

5.6 MODEL VALIDATION 280

5.7 MODELS FOR COMBINED DATA 285

5.8 APPLICATIONS 288

5.8.1 Different Models 288
5.8.2 Maintenance Planning 290

5.9 SUMMARY 296

CHAPTER SIX: MODELING AUTOMATION AND INTEGRATION 297

6.1 GENERAL 297

6.2 PREPARATION OF SYSTEM MENUS 298

6.3 SYSTEM LIMITATIONS AND MODIFICATIONS 303

CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS 307

7.1 PRIORITY RANKING CONCLUSIONS 307

7.2 CONDITION MODELING CONCLUSIONS 309

7.3 RECOMMENDATIONS 311

REFERENCES 312

APPENDICES ..... after page 324

APPENDIX A: QUESTIONNAIRE FORMS

APPENDIX B: COMPARISON BETWEEN SAUDI AND UAE EXPERIENCES

APPENDIX C: FACTOR ANALYSIS

VITA

LIST OF TABLES

Table 2.1. Safety-related pavement distresses....41

Table 2.2. Summary of proposed prediction models....71

Table 2.3. Performance models and service lives. 73

Table 2.4. Typical transition probability matrix. 85

Table 2.5. Different classes of priority programming methods. 93

Table 2.6. Membership functions and weights for secondary roads. 99

Table 2.7. Intensity of importance scale of AHP. 112

Table 2.8. AHP average random index. 121

Table 3.1. Criteria for road classification....130

Table 3.2. Riding quality-related pavement distresses....134

Table 4.1. Road class factor index values 154

Table 4.2. Measured roughness versus existing distresses of Al-Jubail road network....158

Table 4.3. Recommended indices for riding quality-pavement distress relationship 159

Table 4.4. Measured skid resistance versus existing distresses of Al-Jubail road network....163

Table 4.5. Recommended indices for safety condition-pavement distress relationship. 165

Table 4.6. Recommended indices for traffic ranges. 166

Table 4.7. Recommended indices for maintenance cost ranges. 168

Table 4.8. Sub-factors' value determination for importance to community factor 170

Table 4.9. Summary of individuals surveyed in the main survey data collection 180

Table 4.10. Summary of main survey collected data of Part I of the questionnaire. 182

Table 4.11. Summary of main survey collected data of Part II of the questionnaire. 183

Table 4.12. Summary of main survey collected data of Part III of the questionnaire. 184

Table 4.13. Summary of main survey collected data of Part IV of the questionnaire. 187

Table 4.14. K-S test results for normality checks. 194

Table 4.15. Summary of the comparison tests for priority factors. 199

Table 4.16. Summary of the comparison tests for within data variation 201

Table 4.17. Summary of the comparison tests for between-methods variation. 203

Table 4.18. Summary of old and repeated data of Part I. 205

Table 4.19. Summary of old and repeated data of Part II 206

Table 4.20. Summary of the comparison tests for temporal-basis data variation 207

Table 4.21. Summary of the comparison tests for individual groups data variation 209

Table 4.22. Priority factor weight adjustment process for individual experience.....213

Table 4.23. Priority sub-factor weight adjustment process for individual experience.....214

Table 4.24. Recommended indices for structural distress priority modification. 217

Table 4.25. Typical example of priority index (PI) calculation. 220

Table 4.26. Typical example for detailed PI calculation of a pavement section.....222

Table 4.27. Typical example for detailed PI calculation of the importance to community factor for a pavement section. 223

Table 4.28. Case study 1: Jubail road network sections' details. 226

Table 4.29. Case study 1: Jubail road network priority factors and PI calculation.....227

Table 4.30. Case study 2: Dammam road network sections' details. 229

Table 4.31. Case study 2: Dammam road network priority factors and PI calculation. 230

Table 5.1. Summary of the sources of the collected condition surveys data.....239

Table 5.2. Statistical summary of the collected data for all survey methods. 244

Table 5.3. K-S test results for normality check of the collected data.....247

Table 5.4. Correlation coefficient matrix for PDR data. 252

Table 5.5. Correlation coefficient matrix for PCR data. 252

Table 5.6. Correlation coefficient matrix for PCI data.....252

Table 5.7. Forward step-wise linear regression for PDR data.....255

Table 5.8. Forward step-wise linear regression for PCR data.....255

Table 5.9. Forward step-wise linear regression for PCI data. 255

Table 5.10 Summary of the selected models.....264

Table 5.11. Summary of the model validation process. 284

Table 5.12. Cost analysis for three maintenance policies. 295

LIST OF FIGURES

Figure 1.1. Effect of maintenance timing on overall cost.....6

Figure 1.2. Thesis organization. 10

Figure 2.1. General layout of chapter two. 12

Figure 2.2. Basic activities of pavement management system. 15

Figure 2.3. Main menu of Micro PAVER system. 20

Figure 2.4. Data entry and modification of Micro PAVER system.....20

Figure 2.5. Differences between developed and undeveloped countries in PMS.....21

Figure 2.6. Overview of Indonesian road management system.....22

Figure 2.7. The NPRA pavement management system.....27

Figure 2.8. Comparison of load equivalency methods as a function of gross load. 29

Figure 2.9. Typical flexible pavement cross-section. 32

Figure 2.10. Schematic of Bump Integrator and typical output profile.....37

Figure 2.11. Schematic of Mays ride meter and typical output profile. 38

Figure 2.12. Mu meter and typical output profile and printout. 43

Figure 2.13. NDT devices.....44

Figure 2.14. Present serviceability rating form. 46

Figure 2.15. MOC pavement condition rating (PCR) form.....53

Figure 2.16. Schematic illustrating various components of the laser RST.....54

Figure 2.17. Modified MOC pavement condition rating (PCR) form.....56

Figure 2.18. Pavement distress-based rating (PDR) form. 58

Figure 2.19. PAVER pavement condition index, (PCI) rating form. 60

Figure 2.20. PAVER PCI calculation procedure. 61

Figure 2.21. Modified PAVER PCI calculation method. 63

Figure 2.22 MMOPP attempts to model the actual variations in materials, thickness, and loads along the length of the road.....69

Figure 2.23. Scattergram of pavement condition data with age. 78

Figure 2.24. Pavement section prediction in relation to family model.....80

Figure 2.25. Basic structure of HDM3. 82

Figure 2.26. Schematic representation of state, state vector, and life cycle. 86

Figure 2.27. Typical PCI prediction curve using Markovian model 87

Figure 2.28. Typical example of initial transion probability matrix.....89

Figure 2.29. Concept of classical set and fuzzy set theories.....98

Figure 2.30. Membership of distress using fuzzy set theory 98

Figure 2.31. Priority index procedure used in URMS. 101

Figure 2.32. PEMMS priority matrix. 102

Figure 2.33. Prioritization using incremental benefit/cost ratio method. 105

Figure 2.34. Neural network structure 107

Figure 2.35. Typical hierarchy structure for prioritization. 111

Figure 2.36. Advantages of AHP method.....115

Figure 3.1. Research methodology of the study 126

Figure 4.1. Frequency distribution of Al-Jubail roughness measurements. 157

Figure 4.2. Frequency distribution of Al-Jubail skid resistance measurements. 162

Figure 4.3. Final form of priority ranking questionnaire. 174

Figure 4.4. Typical AHP example calculation of Part III. 177

Figure 4.5. Typical AHP example calculation of Part IV 186

Figure 4.6. Frequency distribution of Road class data. 190

Figure 4.7. Frequency distribution of Pavement condition data 190

Figure 4.8. Frequency distribution of Operating traffic data. 191

Figure 4.9. Frequency distribution of Riding quality data. 191

Figure 4.10. Frequency distribution of Safety condition data. 192

Figure 4.11. Frequency distribution of Maintenance cost data 192

Figure 4.12. Frequency distribution of Importance to community data 193

Figure 5.1. Frequency distributions of all collected data 246

Figure 5.2. Relationships between pavement condition and modeling factors of PDR data. 248

Figure 5.3. Relationships between pavement condition and modeling factors of PCR data 249

Figure 5.4. Relationships between pavement condition and modeling factors of PCI data. 250

Figure 5.5. Summary of the statistical regression of the PDR data selected model 1 257

Figure 5.6. Summary of the statistical regression of the PDR data selected model 2 257

Figure 5.7. Summary of the statistical regression of the PDR data selected model 3 258

Figure 5.8. Summary of the statistical regression of the PDR data selected model 4 258

Figure 5.9. Summary of the statistical regression of the PDR data selected model 5 258

Figure 5.10. Summary of the statistical regression of the PCR data selected model 1 260

Figure 5.11. Summary of the statistical regression of the PCR data selected model 2 260

Figure 5.12. Summary of the statistical regression of the PCR data selected model 3 261

Figure 5.13. Summary of the statistical regression of the PCR data selected model 4 261

Figure 5.14. Summary of the statistical regression of the PCI data selected model 1 263

Figure 5.15. Summary of the statistical regression of the PCI data selected model 2 263

Figure 5.16. Summary of the statistical regression of the PCI data selected model 3 263

Figure 5.17. PDR selected model using average values of independent variables 266

Figure 5.18. PCR selected model using average values of independent variables 267

Figure 5.19. PCI selected model using average values of independent variables. 268

Figure 5.20. Goodness of fit of the PDR selected prediction model. 270

Figure 5.21. Goodness of fit of the PCR selected prediction model 271

Figure 5.22. Goodness of fit of the PCI selected prediction model.....272

Figure 5.23. Scatter plots for the predicted values against residuals for normality assumptions 274

Figure 5.24. Frequency distribution and normal probability plot for PDR 275

Figure 5.25. Frequency distribution and normal probability plot for PCR 276

Figure 5.26. Frequency distribution and normal probability plot for PCI.....277

Figure 5.27. Predicted versus the residuals scatter plot for PDR model. 278

Figure 5.28. Predicted versus the residuals scatter plot for PCR model.....278

Figure 5.29. Predicted versus the residuals scatter plot for PCI model. 279

Figure 5.30. PDR model validation. 281

Figure 5.31. PCR model validation. 282

Figure 5.32. PCI model validation.....283

Figure 5.33. Polynomial model for the pooled PCI and PDR data. 286

Figure 5.34. Power model for the pooled PCI and PDR data.....286

Figure 5.35. Plots of the pooled data models. 287

Figure 5.36. PDR model sensitivity analysis at different thickness and truck levels.. 289

Figure 5.37. PCI model sensitivity analysis at different thickness and truck levels.. 291

Figure 5.38. Pavement performance with preventive maintenance.....293

Figure 5.39. Pavement performance with corrective maintenance.....293

Figure 6.1. Preparation and definition of system menus.....299

Figure 6.2. Main menu of the pavement modeling software.....300

Figure 6.3. System parameters menu of the pavement modeling software.....300

Figure 6.4. Priority ranking data entry menu.....301

Figure 6.5. Pavement condition prediction data entry menu.....301

Figure 6.6. Typical priority ranking section-wise report.....302

Figure 6.7. Typical pavement condition prediction section-wise report.....302

Figure 6.8. Data entry menu for riding quality index determination.....304

Figure 6.9. Data entry menu for safety condition index determination.....304

Figure 6.10. Data entry menu for importance to community factor index determination.....305

Figure 6.11. A recommended model integration procedure.....306

خلاصة الرسالـــة

إسم الطـــــــالب : رزق الله حسن فياض رمضان

عنوان الدراســـــة : نمذجة حالة الرصفات وتحديد أولويات الصيانة في شبكات الطرق.

التخصـــــــص : هندسة مدنية

تاريـــخ الشهـــادة : يوليو ١٩٩٧م

تمثل الرصفات أحد أهم عناصر البنية التحتية لدى الدول. ففي المملكة العربية السعودية جرى استثمار مبالغ هائلة لإنشاء رصفـــات شبكات ضخمة من الطرق والمطارات. وتحتاج هذه الشبكات إلى العناية بها من خلال إجراء تقويم دوري لها، وتنفيـــذ مشـــاريع الصيانة في الوقت المناسب للمحافظة على أداء الرصفات بمستوىً عالٍ من الخدمة.

تساعد نماذج تقدير حالة الرصفات على إثراء أي نظام لإدارتها. ومن أهم ما توفره هذه النماذج من ميّزات عدّة أنها تقدم للجهات المسئولة عن الرصفات تصوراً عن الحالة المستقبلية لها، مما يساعد على معرفة احتياجات الصيانة وتخطيط الإجراءات الوقائية في الوقت المناسب، والتخطيط بعيد المدى لمخصصات الصيانة والإصلاح للمحافظة على شبكة الرصفات.

وضمن إطار هذه الدراسة، تم تجميع البيانات المتعلقة بحالة الرصفات من كل المصادر التي أمكن الوصول إليها في المملكة، مثل وزارة المواصلات، وأمانة مدينة الرياض، وأمانة مدينة الدمام، ومدينة الجبيل الصناعية التابعة للهيئة الملكية للجبيل وينبع، إضافة إلى العديـــد من الدراسات البحثية التي تم إجراؤها من قبل متخصصين في مجال الرصفات وتقويمها وصيانتها. وتم تبويب هذه البيانات وتصنيفها ومعالجتها لاستخدامها في تطوير نماذج رياضية لتقدير حالة الرصفات بالاستعانة بالعوامل التي تؤثر فيها. كما جرى تقـــويم هـــذه النماذج لاختيار أفضلها. وتبين أن لهذه النماذج مقدرة معقولة على مطابقة حالات الرصفات المجمعة.

ومن جهة أخرى، جرى استطلاع آراء مجموعات من المختصين، فيما يتعلق بدرجة أهمية العناصر المؤثرة في تحديد أولويات الصيانة، وذلك من خلال استبانات جهزت خصيصاً لهذا الغرض. وتم تحليل نتائج هذه الاستبانات للتحقق من درجة اعتماديتها وتكرارها، ثم استخدمت النتائج التي تم التوصل إليها في تطوير أسلوب خاص لدليل الأولوية يتم بواسطته تحديد أولويات إجـــراءات الصيانـــة وأعمالها لكل مقطع في شبكة الرصفات. وقد تم التحقق من اعتمادية هذا الأسلوب ومقدرته من خلال تجربتين تبـــين منـــهما أن أسلوب تحديد دليل الأولوية يستطيع محاكاة الخبرة الهندسية للمختصين. إضافة إلى مقدرته على التعامل مـــع شبكـــة هائلـــة مـــن الرصفات بكفاءة عالية.

كما تم دمج نماذج تقدير حالة الرصفات وأسلوب تحديد أولوية صيانتها في برنامج كمبيوتر يستطيع التعامل مع بيانات الرصفـــات وتقديم نتائج يمكن استخدامها مع الأعمال والإمكانات الأخرى لأي نظام للحصول على نظام شامل لإدارة الرصفات.

درجة الدكتوراة في الفلسفة

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

يوليو ١٩٩٧م

DISSERTATION ABSTRACT

NAME : **REZQALLAH HASAN FAYYADH RAMADHAN**

TITLE OF STUDY : **MODELING OF PAVEMENT CONDITION AND MAINTENANCE PRIORITY RANKING FOR ROAD NETWORKS**

MAJOR FIELD : **CIVIL ENGINEERING**

DATE OF DEGREE : **JULY 1997**

Pavements represent an important asset to all nations. In Saudi Arabia, huge investments have been made in constructing enormous pavement networks of roads and airfields. These networks require great care and attention through conducting continuous evaluation and timely maintenance to keep them operating under acceptable levels of service.

Pavement condition prediction models can greatly enhance the capabilities of a pavement management system (PMS). Among other benefits, these models allow pavement authorities to predict the timing of maintenance or rehabilitation activities and to estimate the long-range funding requirements for preserving the pavement system.

In this study, pavement condition-related data were collected from all accessible sources in the Kingdom, including the Ministry of Communications, the Municipality of Riyadh, the Municipality of Dammam, the Industrial City of Al-Jubail, and from other research studies carried out by different researchers. These data were categorized, processed, analyzed, and used to generate different prediction models from the related factors affecting the pavement condition. These models were evaluated to identify the most appropriate ones fitting the available data. The obtained models could adequately predict the pavement condition from the validation data with a reasonable level of significance.

On the other hand, opinions of different groups of individuals from all around the Kingdom about the weights of the factors affecting the maintenance priority ranking were collected. The collected data were checked for reliability and repeatability and then used to obtain a general priority index procedure. This procedure is used for ranking pavement sections in any network according to their importance or urgency for maintenance. The procedure was validated using two case studies, where it was concluded that the procedure could adequately duplicate the engineering judgment for maintenance priority ranking in addition to its capability to handle huge pavement networks systematically and efficiently.

The developed models and procedures were integrated into one sub-system that can handle data entry, retrieval, and results reporting. This sub-system can be integrated in any pavement management system to complement other activities and to obtain a comprehensive PMS.

DOCTOR OF PHILOSOPHY DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia

JULY 1997

ABBREVIATIONS

AADT	=	Average Annual Daily Traffic
AASHTO	=	American Association of State Highway Transportation Officials
ACDM	=	Academicians
ACSB	=	Subbase or Aggregate Base layer Thickness
ACTH	=	Asphalt Layer Thickness
ADT	=	Average Daily Traffic
AGE	=	Age of the Pavement from Date of Construction or The last Major
AHP	=	Analytical Hierarchy Process
B&SMS	=	Bridge and Structures Management System
BHC	=	Bore Hole Camera
BMS	=	Bridge Management System
CAS	=	Cost Accounting System
CBD	=	Central Business District
CBR	=	California Bearing Ratio
CI	=	Consistency Index
CMP	=	Compatible Maintenance Priority
COST	=	Maintenance Cost Priority Factor Index
CR	=	Consistency Rating
DDP	=	Distress Deduct Point
DV	=	Dependent Variable
E/C	=	Effectiveness/Cost Ratio
EAUC	=	Equivalent Uniformly Annual Cost
EMS	=	Equipment management System
ENGR	=	Engineers
ESAL	=	Equivalent Single Axle Load
FHWA	=	Federal Highway Administration
FWD	=	Falling Weight Deflectometer
GA	=	Genetic Algorithm
GIS	=	Geographical Information System
GPR	=	Ground Penetration Radar

H_0	=	Null Hypothesis of statistical testing
H_1	=	Alternative Hypothesis of statistical testing
HDM3	=	Highway Design and Maintenance Standards Model Version 3
HMMS	=	Highway Maintenance Management System
IAPMS	=	Integrated Airports PMS
IF	=	Importance to Community priority Factor Index
ILLINET	=	Illinois Network Model
INTR	=	Interactions Of The Condition Prediction Factors
IP	=	Integer Programming
IV	=	Independent Variable
KFUPM	=	King Fahd University of Petroleum and Minerals
KFUPM-RI	=	King Fahd University of Petroleum and Minerals - Research
LINDO	=	Linear, Interactive, Discrete Optimizer
LLC	=	Least Life Cost
LP	=	Linear Programming
M&R	=	Maintenance and Rehabilitation
MARS	=	Multi Attribute Ranking System
MC	=	Maintenance Cost Index
MCOST	=	Maximum Maintenance Cost Incurred in the Pavement Network
MDP	=	Marcov Decision Process
MMOPP	=	Mathematical Model of Pavement Performance
Mn/DOT	=	Minnesota Department of Transportation
MOC	=	Ministry of Communication
MOD	=	Municipality of Dammam
MOMRA	=	Ministry of Municipal and Rural Affairs
MOR	=	Municipality of Riyadh
MPMS	=	Municipality Pavement Management System
MPR	=	Maximum Allowable Roughness in the Pavement Network
MSE	=	Mean Square Error
NDT	=	Non-Destructive Testing
NPRA	=	Norwegian Public Road Agency

NYSTA	=	New York State Thruway Authority
OAI	=	Overall Acceptability Index
ODOT	=	Ohio Department of Transportation
PC	=	Pavement Condition Priority Factor Index
PCI	=	Pavement Condition Index
PCR	=	Pavement Condition Rating
PDR	=	Pavement Distress-based Rating
PEMMS	=	Pavement Evaluation and Maintenance Management System
PI	=	Priority Index
PIX	=	Priority Index
PMS	=	Pavement Management System
PR	=	Pavement Roughness
PSI	=	Present Serviceability Index
PSR	=	Present Serviceability Rating
RCI	=	Riding Comfort Index
RD	=	Rut Depth
RI	=	Priority Index or Random Index
RMMS	=	Road Maintenance Management System
RQ	=	Riding Quality Priority Factor Index
RST	=	Road Surface Tester
RTAC	=	Road and Transportation Association of Canada
RTIM2	=	Road Transport Investment Model Version 2
RY	=	Rehabilitation Year
SAMP	=	System Analysis Method for Pavement
SAS	=	Statistical Analysis System
SF	=	Safety Condition Priority Factor Index
Sf	=	Importance to Community priority Sub-factor
SHA	=	State Highway Agency
SHRP	=	Strategic Highway Research Program
SN	=	Skid Number
SPMS	=	Singapore Pavement Management System

ST	=	Stabilized Pavement
SV	=	Slope Variance
TC1	=	Traffic Category Number 1
TI	=	Traffic Priority Factor Index
TPM	=	Transition Probability Matrix
TRAF	=	Operating Traffic
TRRL	=	Transport Road Research Laboratory
TRUK	=	Truck Percentage in The Traffic Mix
UAE	=	United Arab Emirates
UKPMS	=	United Kingdom PMS
URMS	=	Urban Roadway Management System
USACERL	=	United States Army Construction Engineering and Research
USI	=	Universal Serviceability Index
V/C	=	Volume/Capacity Ratio
VESYS	=	Viscoelastic System
VIP	=	Very Important Persons

CHAPTER ONE

INTRODUCTION

1.1 GENERAL

Pavement is the major portion of any highway or airfield system. Its primary function is to spread the wheel load over a sufficiently large area of underlying soil. Pavement is designed to carry highway and airfield traffic safely, conveniently, and economically over the design life. Moreover, its surface should provide smooth ride with sufficient skid resistance. There are many factors affecting the design of pavement, these include: traffic loading, environmental effects, material properties, and performance factors.

Pavement exhibits two types of failure: (i) Structural failure, which includes a collapse of the pavement structure or a breakdown of one or more of the its components, of such a magnitude, which makes the pavement incapable to sustain the loads imposed on its surface. (ii) Functional failure, which may or may not be accompanied by structural failure, such that pavement will not carry its intended function without causing discomfort to passengers or high stress to operating vehicles [Yoder and Witczak 1975]. These two types of failures are pronounced in different forms of distress, such as cracking, disintegration, and distortion. Distresses consume a considerable amount of funds when they are in high severity, therefore, continuous monitoring is

funds when they are in high severity, therefore, continuous monitoring is required to detect, correct, and prevent minor distresses from becoming major ones.

To manage pavements is a systematic approach, different activities should be considered. These activities, include: periodic evaluation of pavement performance, determination of maintenance and rehabilitation (M&R) requirements, and determination of the optimal maintenance policies in order to maximize the pavement preservation at minimum maintenance cost. Pavement evaluation consists of pavement condition surveys, structural adequacy, riding quality, and skid resistance measurements to determine the overall performance of the pavement system. These activities compose the pavement management system (PMS).

In many countries around the world, highway agencies and transportation authorities are urged to adapt, modify or develop a pavement management system to preserve their road networks. The Ministry of Communication (MOC) and the Ministry of Municipal and Rural Affairs (MOMRA) in the Kingdom of Saudi Arabia are no exception to this. They are very anxious to upgrade the existing pavement maintenance practices to rational, systematic, and practical ones. The MOC has specified and developed a number systems for managing the MOC road network that consists of 35,892 kilometers of main direction roads, with 11,880 links and 7169 nodes [MOC 1995]. This effort combines all road-related information such as: pavement and non-pavement elements, traffic attributes, accident records, and bridge system attributes. All these features are interfaced with the Geographical Information System (GIS). Presently, the data collection to a great extent

was accomplished. However, the MOC needs procedures and trained personnel to utilize such data to improve future road maintenance management [MOC 1995]. Maintenance management system for the Riyadh street network is being developed by the Municipality of Riyadh (MOR). The project aims to have a comprehensive system that includes procedures for pavement evaluation, pavement condition modeling, priority schemes, and budgeting [Al-Swailmi et al. 1995]. Another study to evaluate the effect of deferring maintenance actions on the overall maintenance cost in the Riyadh City street network was carried out by Al-Matham [1995]. In the Eastern province, road pavement maintenance is still far away from being systematically managed. In fact, there are no specific plans for conducting the maintenance activities. However, there is a great need for a maintenance management system to care for the huge road network and to allocate the limited maintenance funds efficiently [Dammam Municipality 1996]. Considering the above mentioned efforts undertaken in the Kingdom of Saudi Arabia, in general, and the Eastern Province in particular, there is an urgent need for developing, simple, flexible, practical procedures, for pavement evaluation and maintenance management in order to preserve the Kingdom roads network. Such a development should take into consideration the specific conditions of the Kingdom.

The Kingdom of Saudi Arabia has a unique environment of high ambient temperature, extreme soil salinity, and lack of precipitation combined with flash floods. These special environmental attributes have contributed to the rapid deterioration of some of the transportation system. This means that road performance in Saudi Arabia, in addition to its specific design and construction parameters, has serious environmental parameters that

affect it. These parameters need to be assessed for better road performance in Saudi Arabia [Stylianopoulos 1988].

1.2. PROBLEM STATEMENT

In countries that are in early stages of implementing pavement management technology, such as the Kingdom of Saudi Arabia, two approaches for PMS implementation are generally followed: one is to select, modify, and adapt a suitable developed system for local application; the other is to develop a new system taking into account local conditions and needs making advantage of the efforts and experiences of others. The second approach is more logical, since the local specific conditions can be incorporated in all activities of the PMS, and step-by-step development provides more understanding and visualization to the behavioral trends of the pavement network.

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

infrastructure and maximize its benefits, a good systematic maintenance management programs should be followed.

The harsh environment coupled with the marginal construction materials, such as the aggregate used in the asphaltic concrete mixture, and the high traffic loads operating on Saudi road network, make the pavement susceptible to wide range of distress. Moreover, the rate of pavement deterioration, and its mechanism, are generally different from those reported in other countries. For example the severe premature rutting problem existing in the Kingdom asphalt pavements was not due to traffic loads and environment factors only, but also due to the deficiencies in the materials used and poor construction practices and quality control [Fatani et al. 1988].

Timing of maintenance actions is also important since they must be carried out at the time of maximum return (benefit). Otherwise, the maintenance needs will be higher if the pavement is allowed to experience further deterioration. The pavement starts to deteriorate after opening to traffic. The deterioration starts at slow rate and with time this rate increases exponentially as shown in Figure 1.1. Many studies showed that the maintenance cost of the pavement while in a very poor condition four to five times the cost if pavement is maintained while in a good condition. Therefore, preventive maintenance actions taken earlier have a very important role in keeping the pavement in a good condition for longer time, and in reducing the overall maintenance costs significantly.

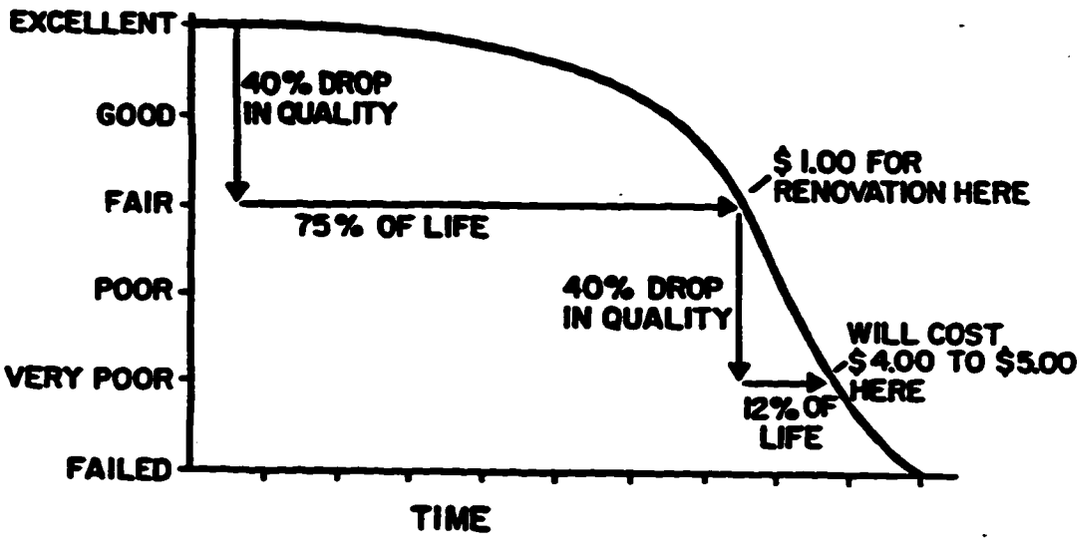


Figure 1.1. Effect of maintenance timing on the overall cost [Shahin and Walter 1990].

The techniques that are currently used, locally, for pavement evaluation and maintenance are basically subjective, inadequate and may lead to inefficient allocation of pavement maintenance funds. These techniques are based on "worst-first" and "spot-repair" concepts which mean that wherever and whenever a major defect is found, an action is taken. This action has limited forms, mainly patching, resurfacing, or reconstruction. In these techniques, errors in pavement evaluation are expected, distress causes are not investigated, maintenance actions may not be proper or suitable, and finally, the allocated funds are not utilized efficiently and rationally for maximum benefits.

There are many ready-made, well defined, and verified systems that can perform all pavement maintenance management system activities. However, these systems were developed for different environments and different pavement attributes which are not similar to those prevailing in the Kingdom. Moreover, they are usually based on certain assumptions that are not always clearly specified, and therefore may lead to misleading results when implemented without understanding these assumptions. The Kingdom has its own specific parameters for pavement management activities that include: cultural parameters, public perception parameters, priority decision making parameters, environmental parameters, and traffic parameters. The requirements of the Kingdom's specific conditions, have to be fully incorporated in any developed procedures and models. This can only be achieved through the development of these procedures and models locally.

1.3. OBJECTIVES

The main objective of this study is to develop pavement models that can be used in pavement management system for the specific conditions of the Kingdom of Saudi Arabia. The study included:

1. modeling of pavement performance in terms of pavement condition, and
2. programming of pavement maintenance priority ranking.

1.4. THESIS ORGANIZATION

This introduction chapter gave a general idea about the research need, problem to be studied, and specified the objectives. The background and previous experiences were reviewed in chapter two, while the research methodology is detailed in chapter three, where the steps followed in this research as well as the parameters involved are defined and evaluated. The description of data collection and analysis for maintenance priority ranking are given in chapter four, while the same for pavement condition modeling is given in chapter five. Chapter six explained the approach followed in integrating the developed models and procedures in a computer software for easy utilization of the results of this study. Finally, chapter seven contained the conclusions and recommendation resulted from this study, followed by the citations and references used. The appendices contained some of the results that were typically included in the body of

this dissertation and those parts that needed more elaboration. Figure 1.2 shows the flow chart of the thesis organization.

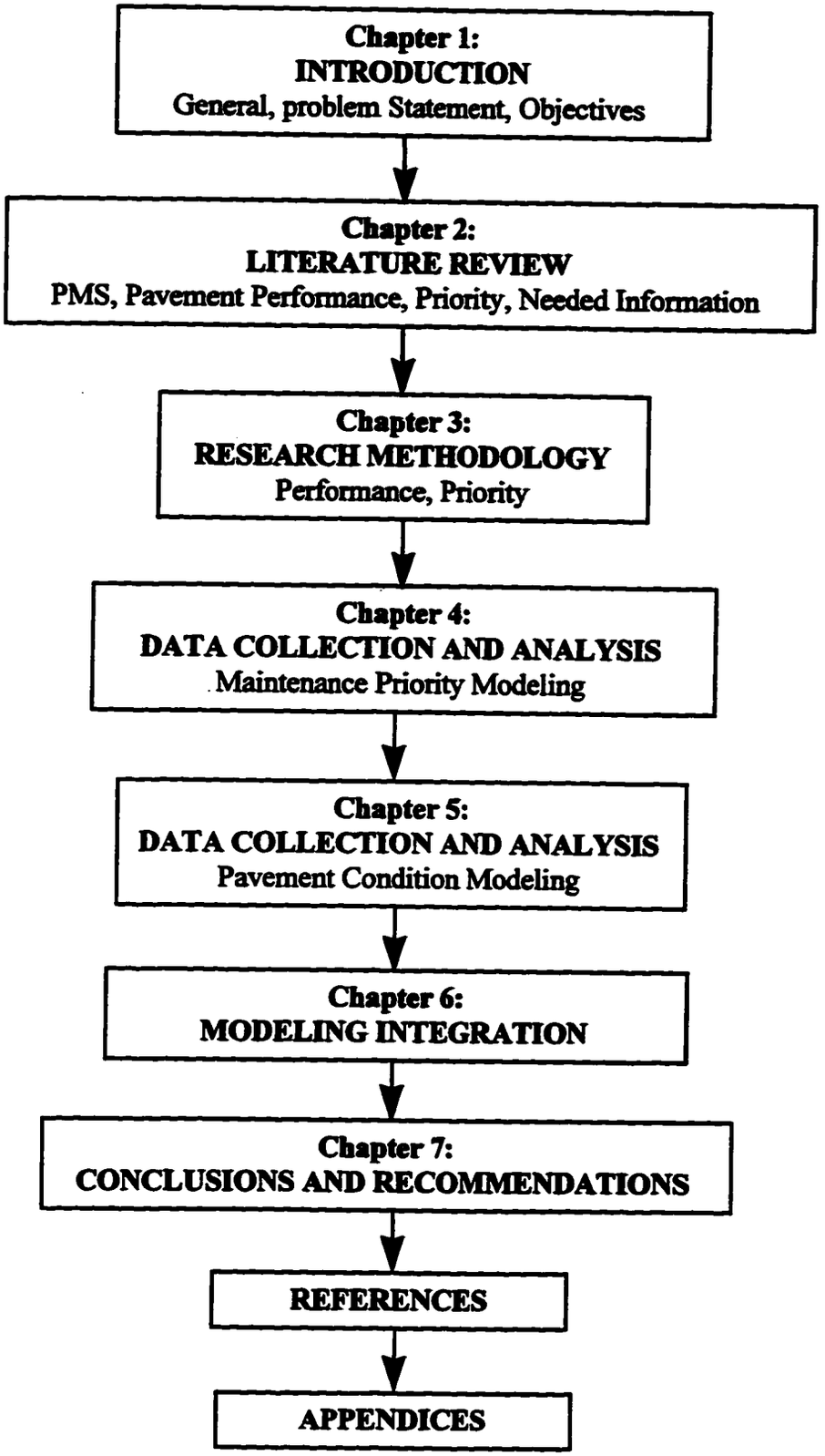


Figure 1.2. Dissertation organization.

CHAPTER TWO

LITERATURE REVIEW

2.1 DESCRIPTION

This chapter gives a general idea about the pavement management system (PMS) and describes some of the operating systems around the world. The data base as one of the essential components of any PMS is detailed with respect to its input parameters and their effect on the pavement performance. Four measures of pavement performance that are pavement condition evaluation, roughness, safety, and structural capacity have been addressed. Three methods of pavement condition evaluation (inspection), relevant to the collected data of this study, have been detailed. Various methods of pavement performance and pavement maintenance prioritization modeling have also been discussed with examples of some developed models. Figure 2.1 shows the layout of this chapter.

2.2 PAVEMENT MANAGEMENT SYSTEM

2.2.1 General

In the past, pavements were maintained but not managed [Shahin 1994]. The maintenance activities were very limited and they were according to complains and

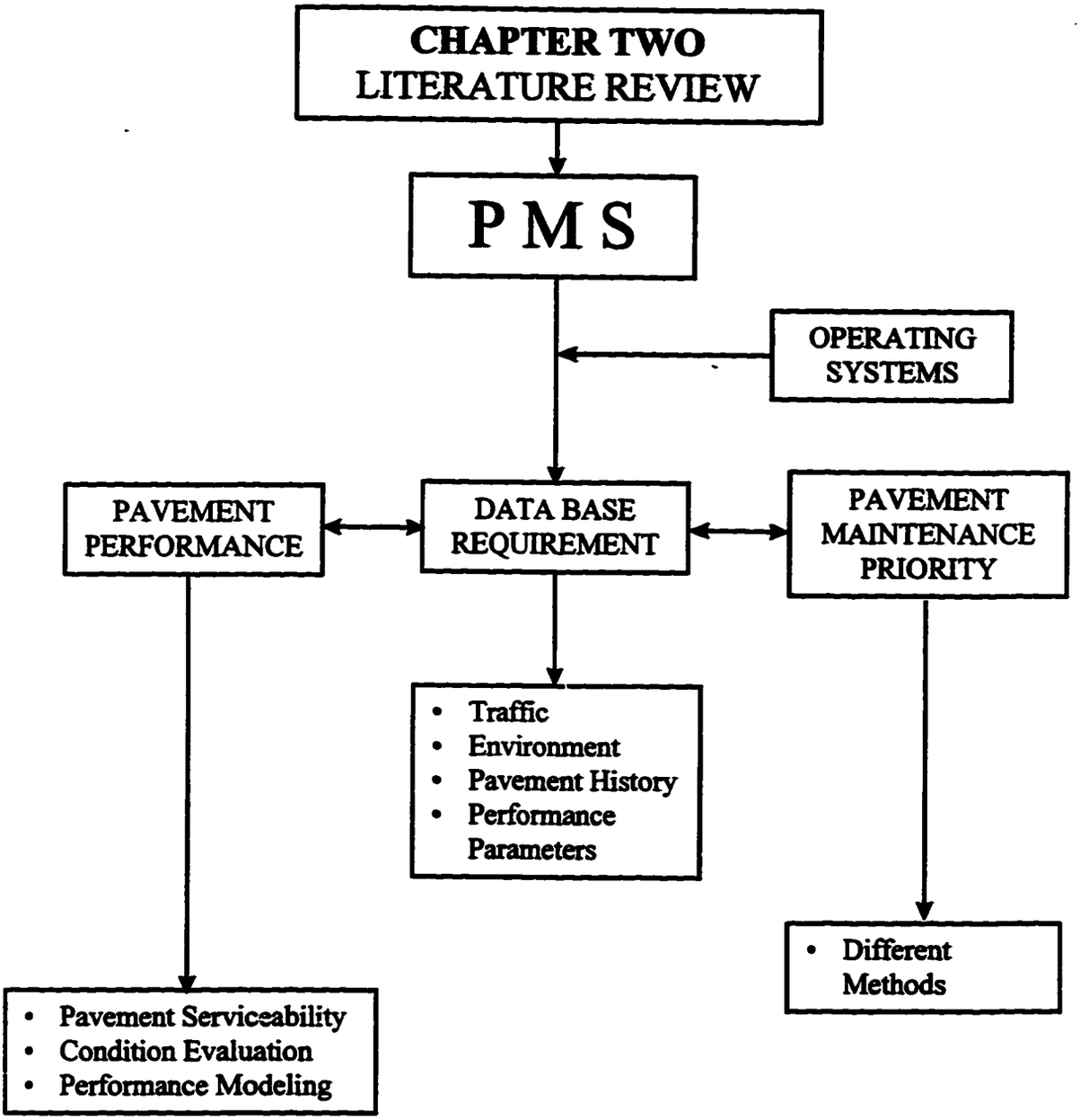


Figure 2.1. General layout of chapter two.

immediate need. The overall historic perspective of the pavement management system (PMS) was due to the research efforts done by three groups of researchers [Haas et al. 1994]. In 1966, the American Association of State Highway Officials (AASHTO), initiated a study to make new breakthrough in the pavement field, and to provide a theoretical basis for extending the results of AASHO Road Test in a pavement design area using systematic approach this was done by the researcher in the University of Texas. At the same time, the second independent effort was done in Canada to structure the overall design and management problem and several of subsystems. The third concurrent keystone effort in the same subject was done in the Texas Transportation Institute of Texas A&M University.

Much of the work by different researcher around the globe was directed to developing the components of the technology of pavement management, and into implementation of systems at state/provincial and local levels.

The Management is defined as the art of coordinating elements and factors of production towards the achievement of purposes of an organization, and also an accomplishment of objectives through the use of human labor, materials, and machines [Encyclopedia 1984]. Thus, in this context, pavement management is the efficient coordination of different activities in order to obtain systematic decision to provide users of highways with an uninterrupted, safe and smooth riding surface, and to keep the pavement structure in a good sound condition at minimum costs. Pavement management is a process by which decision makers rationalize management decisions concerning wide range of activities: planning and programming of activities, design, construction, maintenance and

rehabilitation, periodic evaluation of performance, and pavement research [Haas and Hudson 1982]. Figure 2.2 shows major classes of activities in pavement management system (PMS). In this figure, the pavement evaluation is the key of the PMS since it provides means to see how well the planning, design, and construction objectives have been satisfied [Haas et al. 1994]. Pavement evaluation includes four basic measurements: deflection for structural adequacy, pavement roughness for riding quality, surface skid resistance for safety, and pavement distresses for condition. The ultimate and final aim of the PMS is to get an optimal return from available resources.

Pavement management must be capable of being used in whole or in part by various technical and administrative levels of management in making decisions regarding both individual projects and an entire highway network. All functions involved in pavement are essential to comprehensive PMS, but not all functions need to be active at the same time. Following are a list of essential requirements for any PMS [Haas et al. 1994]:

1. Capability of being easily updated and/or modified as new information and better models becomes available,

2. Capability of considering alternative strategies,

3. Capability of identifying the optimum alternative or strategy,

4. Capability to base decisions on rational procedures with quantified attributes, criteria, and constraints, and

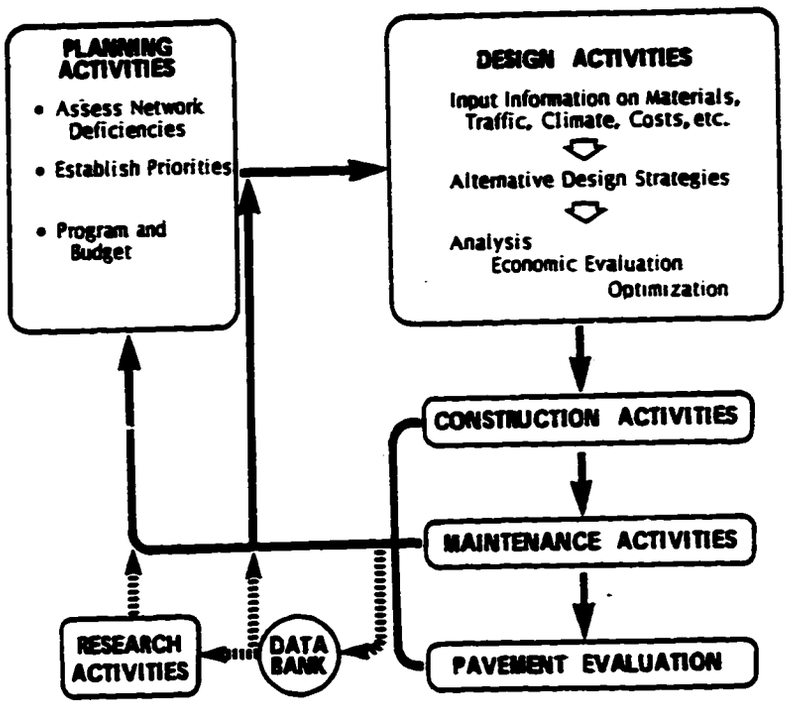


Figure 2.2. Basic activities of pavement management system [Haas and Hudson 1982].

5. Capability to use feedback information regarding the consequences of decisions.

Pavement surfaces should be managed and maintained in a systematic manner because they are: (a) the primary utility for the efficient movement of goods and services, (b) the portion of the roads most visible to the traveling public, and (c) the most significant functional and structural components of the network [Smith et al. 1993].

As highways are opened to traffic operations, they start to wear and deteriorate with time due to traffic loading and climatic effects. Pavement continues to deteriorate unless some upgrading actions to restore its condition are done. Actions such as maintenance and rehabilitation techniques are to be performed in a right way and at a right time before the pavement condition reaches to a point that these maintenance techniques may be very costly and will not be effective.

Many agencies and transportation authorities have been convinced to use systematic, organized, computerized maintenance management system. This was due to the difficulty in dealing with huge amount of information and maintenance data manually, in addition to the complication of the interrelation of these data. For example, manual data retrieval from record archives is tedious and time consuming, and analytical decisions on critical issues of great consequences are rarely made, due to the immensity of the data retrieval process [Brandon 1994].

2.2.2 Operating Systems

Pavement management has become a matured science after many highway agencies, all over the world, learned, practiced, and got involved in implementing this technology. Structuring a science of pavement management implies developing standard terminology, standard data collection, and structured analysis methodologies [Irrgang and Maze 1993]. Many studies and researches around the globe, adapted or developed a PMS for their pavement network.

The Washington PMS [Finn et al. 1976] contains four basic features: (i) the ability to predict performance, (i) the ability to compute costs for various maintenance strategies, (iii) the ability to respond to uncertainty or error in predicting actual performance, and (iv) the system is capable of being updated as more information is obtained.

Sharaf et al. [1988] developed a methodology through which the increased maintenance costs due to delay in maintenance actions were quantified. This methodology utilized three major data from several army installations in USA: pavement performance data, structural history data, and detailed cost data. As a conclusion, they found that each one dollar spent in M&R actions on pavements with good to fair condition, may save up to 4 dollars of M&R costs if the pavements were left to deteriorate to the poor condition.

PAVER pavement management system was developed by the Corps of Engieers [Shahin and Kohn 1981]. This system is field-tested and valiaded for airfield pavement network and extended for use by city and county highway agencies. The system includes

procedures for dividing the pavement into manageable sections, pavement condition survey and rating, rational determination of maintenance and repair (M&R) needs and priorities, performance of life-cycle costing on feasible M&R alternatives, and manual and automated systems for data storage and retrieval. An important part PAVER is condition survey and raing procedure which detailed later in this chapter.

Major improvement to PAVER system is the Micro PAVER which is a micro computer version of the mainframe PAVER PMS. It is a decision making tool which allows the user to develop cost-effective M&R alternatives for roads, streets, parking lots, airfields, and unsurfaced roads. Micro PAVER includes the following important capabilities [USACERL 1994]:

1. Data storage and retrieval,
2. Data administration,
3. Pavement network definition,
4. Pavement condition rating,
5. Inspection scheduling,
6. Determination of present and future network condition,
7. Determination of M&R needs,
8. Performance of economic analysis, and

9. Budget planning.

Figure 2.3 shows the main menu of Micro PAVER while Figure 2.4 shows the data entry and modification sub-menu.

Road maintenance management system (RMMS) for Indonesia, as one of the developing countries, was developed [Cox 1988] to consider the differences between developed and developing countries' practices and conditions with emphasis on the economic matters. These differences are shown in Figure 2.5, where the overview of the Indonesian road management system is shown in Figure 2.6.

The Research Institute in King Fahd University of Petroleum and Minerals (KFUPM-RI) has developed a pavement maintenance management system for programming road network maintenance of the Industrial City of Al-Jubail, Saudi Arabia. The system has five tasks summarized as follows [KFUPM-RI 1989]:

1. Distress evaluation using visual surveys for measuring the distresses in terms of severity and extent. Each road section or subsection is assigned a rating value out of 100 to indicate its condition.

2. Equipment-based evaluation: skid resistance, riding quality (roughness), and structural capacity (deflection measurement) are measured as the characteristics of road sections. Acceptable limits, of these characteristics, were set for the study area.

No Database Online

Micro PAVER

Micro PAVER Version 3.21 August 1994

[1] Data Entry and Modification
[2] Database Related Reports
[3] Data Analysis Program
[4] Database Administration
[5] System Utility
[6] Exit Micro PAVER

ENTER OPTION:

Figure 2.3. Main menu of Micro PAVER system [Micro PAVER 1993].

Database Online: C: CLASS

Micro PAVER

Micro PAVER Version 3.21 August 1994

[01]	Pavement Definition	[08]	Layer & Material Properties
[02]	Change Key Field	[09]	NDT
[03]	Inspection Data	[10]	Site Information
[04]	Traffic	[11]	PCI Re-Calculation
[05]	Work Requirement	[12]	Inspection Download
[6]	Work History	[13]	Field Inspection (PEN)
[07]	maintenance Policy	[14]	Inspection Upload (batch

[E] Exit Data Entry and Modification

ENTER OPTION: 1

Figure 2.4. Data entry and modification of Micro PAVER system [Micro PAVER 1993].

FACTOR	Western Developed Countries	Developing Countries
Climate	Cold/Temperate	Hot/Tropical
Standard of Living	High	Low/Medium
Opportunity Cost of Capital	Medium (6-10%)	High (10.25%)
Highway Network	Mature	Growing
Vehicle Utilization	High	Low
Traffic Growth Rate	Low (2-6%)	High (5-20%)
Subgrade Strength	Low (2-10)	Medium/Hugh (5-30)
Pavement Strength (Deflection)	High (0.2-1.5mm)	Low/Medium (0.6-3.0 mm)
Design Axle Loading (Cum. Axle Loads)	High ($1-20 \times 10^6$)	Low ($0.1-5 \times 10^6$)
Pavement Roughness - Bump Integrator	Very Good/Good 1,000-5,000 mm/km	Good/Fair/Poor 2,000-10,000 mm/km
- International Roughness Index	1 - 6	2 - 12

Figure 2.5. Differences between developed and undeveloped countries in PMS [Cox 1988].

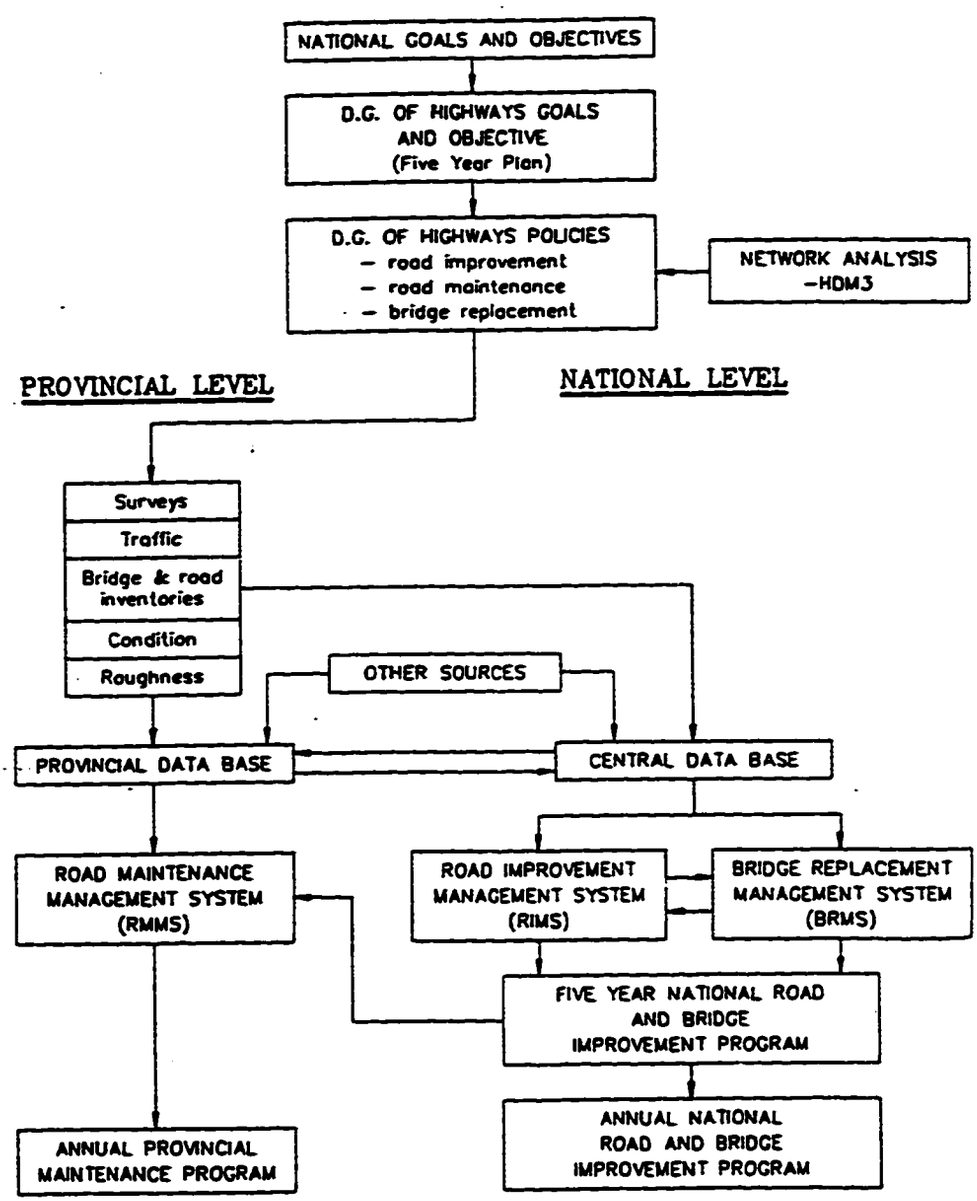


Figure 2.6. Overview of Indonesian road management system [Cox 1988].

3. Maintenance prioritization: based on four parameters in each pavement section; roughness, skid resistance, traffic, and pavement condition rating, a priority matrix was developed where each section has a ranking number for maintenance.

4. Maintenance strategies: a matrix based on distress and equipment-based evaluations was developed to select a maintenance action for each section.

5. Maintenance costing: unit cost for each maintenance strategy is used with the defective area to calculate the total cost of each selected maintenance action.

This system, called Pavement Evaluation and Maintenance Management System (PEMMS), comprises of microcomputer program written in dBase language, that is capable of storing and processing all collected data. The program is completely integrated, menu-driven, error-checking application.

PEMMS was made so flexible to be customized for any agency. Decision parameters such as distress deduct points, maintenance strategy matrix parameters, acceptable levels of equipment-based evaluation, and unit maintenance cost are all user-definable and changeable. It has a broad range of report generation capabilities. PEMMS, however, does not have the capability of performance prediction or optimization techniques.

Singapore pavement management system (SPMS) has been implemented since 1992 [Ong et al. 1996]. The system comprises a computer system for managing the database for retrieving and presenting the stored information that define the network and its condition. It is capable of presenting performance using proven performance models, and of selecting

appropriate treatments based on user-defined intervention levels. The system allows the user to study the effects of different budgetary strategies on the future conditions of the road network and also to analyze the effect of deferred maintenance.

In the United States, the Federal Highway Administration stated a policy that all State Highway Agencies (SHAs) should have a PMS operational by January 1993. In a survey to evaluate the status of PMS implementation, Irrgang and Maze [1993] reported that all SHAs have a PMS or were working to achieve an acceptable PMS. They concluded that there was no unanimity in the inputs to the pavement management process or to the analysis methods and objectives used. SHAs have selected diverse analysis tools for use within their PMSs.

The main components of the Delaware PMS are: unique and unambiguous milepost referencing, dynamic segmentation, a decision-tree process to priority rank capital improvement and rehabilitation projects, interim pavement performance forecast model, multilayer planning capabilities, and color graphic and mapping capabilities [Smith et al. 1993].

In Turkey, a PMS implementation was initiated, as the first phase, in 1993 for a pilot road network of 360 km. The second phase was directed to PMS development and nation-wide implementation. Detailed planning for the PMS implementation has focused on two key components: (a) data acquisition - methods, equipment, analyses, etc. and (b) system design/engineering/development - hardware, software, database, performance prediction and needs analysis, maintenance programming, etc. [Yigit et al. 1995].

The Tokyo Metropolitan government has an effective PMS which has advanced techniques for data collection like ground penetrating radar (GPR) and borehole camera (BHC), where the GPR supplies overall pavement structure information, and BHC provides an accurate image of layer thickness and pavement material composition as boarder range of points [Sekiguchi et al. 1993]. Introduction of this system is considered to increase the accuracy of the PMS and thus of the formation of pavement management decisions.

A use of special PMS for low-volume and built-up roads was suggested by Roohanirad [1994] which depends basically on two models: the cost model that includes agency and user costs, and the performance model that predicts the future condition of a given roadway pavement. The system considers customized methods for low-volume and built-up roads such as chip seal, cold mix and gravel road and the associated M&R strategies.

A highway management system (HMMS) has been developed for the Ministry of Communication in Riyadh, Saudi Arabia [Harper and Majidzadeh 1993]. The system integrated PMS, bridges and structures management system (B&SMS), and non-pavement management system. The rational Oracle data base was used to perform the needed data storage and retrieval functions. However, this project is very huge to be completed due to its complex integration of different features. This is why only 50% of the intended surveys were accomplished since the system was initiated and its full implementation is far from being completed [Personal Consultation, 1996].

The United Kingdom PMS is a computer system developed for the economic management of the structural maintenance budget of a road network [Philips 1994]. It incorporates different subsystems of visual data collection, data analysis, and budget allocation. The core philosophy of the UKPMS is to defer M&R treatment where it is cost-effective and safe to do so, and to give priority instead to preventive maintenance.

A complete pavement management system was developed by the Norwegian Public Roads Administration, (NPRA) [Haugodegard et al. 1994]. The system consists of pavement condition surveys, road inventory surveys, road data bank, project planning and network optimization including performance trend, and life cycle cost analysis. It also includes tender preparation with as-built cost statistics. All these activities are interconnected by data processing links as shown in Figure 2.7.

In United Arab Emirate, Municipality Pavement Management System (MPMS) was developed for Dubai municipality which uses a condition survey method, falling weight deflectometer (FWD), and infrared roughness measuring device for the highway network performance measurements. It was concluded that by using the MPMS , a huge saving was made in the maintenance and rehabilitation costs [Zaghloul et al. 1996]

Highway Maintenance Management System (HMMS) in the Sultanate of Oman has five subsystems: pavement management system (PMS), the bridge and structures management system (BMS), the equipment management system (EMS), the traffic management system (TMS), and the cost accounting system (CAS). All these systems are interrelated [Al-Khoury 1996].

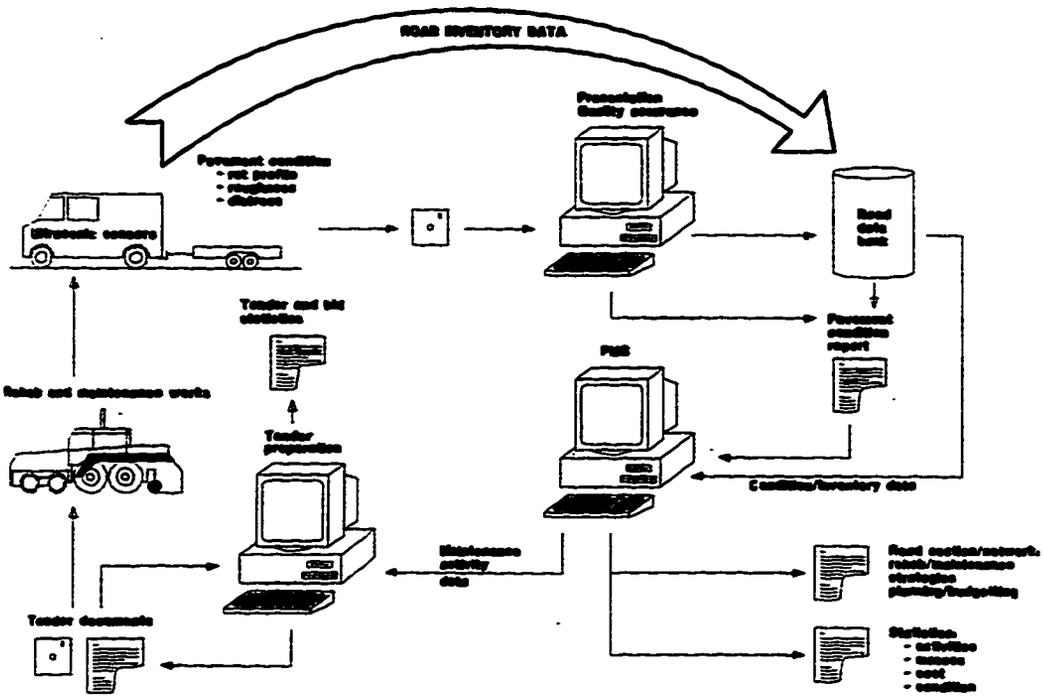


Figure 2.7. The NPRA pavement management system [Haugodegard et al. 1994].

2.3 DATA BASE REQUIREMENTS

2.3.1 Traffic Data

Traffic load is one of the major causes of pavement deterioration. Load-associated distresses such as alligator cracking, and rutting are mainly generated by traffic loads. These distresses usually have the highest deduct points in any pavement condition rating method.

Volumes, loads, and classification of traffic are usually needed for analyzing and scheduling maintenance operations properly [RTAC 1977]. The equivalent axle load concept is used to handle the large spectrum of axle loads (traffic mix) actually applied to a pavement. The standard equivalency most commonly used is 80 kN (18 Kips), Equivalent Single-Axle Load (ESAL). The basis of equivalency can be either calculated or measured stress, strain, or deflection at some point in the pavement structure, or equal conditions of stress or less of serviceability [RTAC 1977]. The effect of traffic load to pavement damage is obvious. It is for both flexible and rigid pavements, the damage varies roughly as the fourth power of the axle load. The fourth power concept states that if the axle load is doubled, it will affect to the pavement damage as much as sixteen times the old damage effect. It was concluded that there was a good agreement between various equivalency method developed by different agencies about the fourth power concept as shown in Figure 2.8 [Yoder and Witczak 1975].

The damage occurred in pavements of different states in USA due to variety of causes were studied in a comprehensive survey [Laytton et al 1981],. These cause were categorized into three main types: traffic loads, climate, and combination of the two. Pavement condition rating methods used by different states were studies to determine the approximate percentages of the total damage that is done to the pavement that may be attributes to traffic loads. Several performance equations were developed and used in determination of the damage ratios.

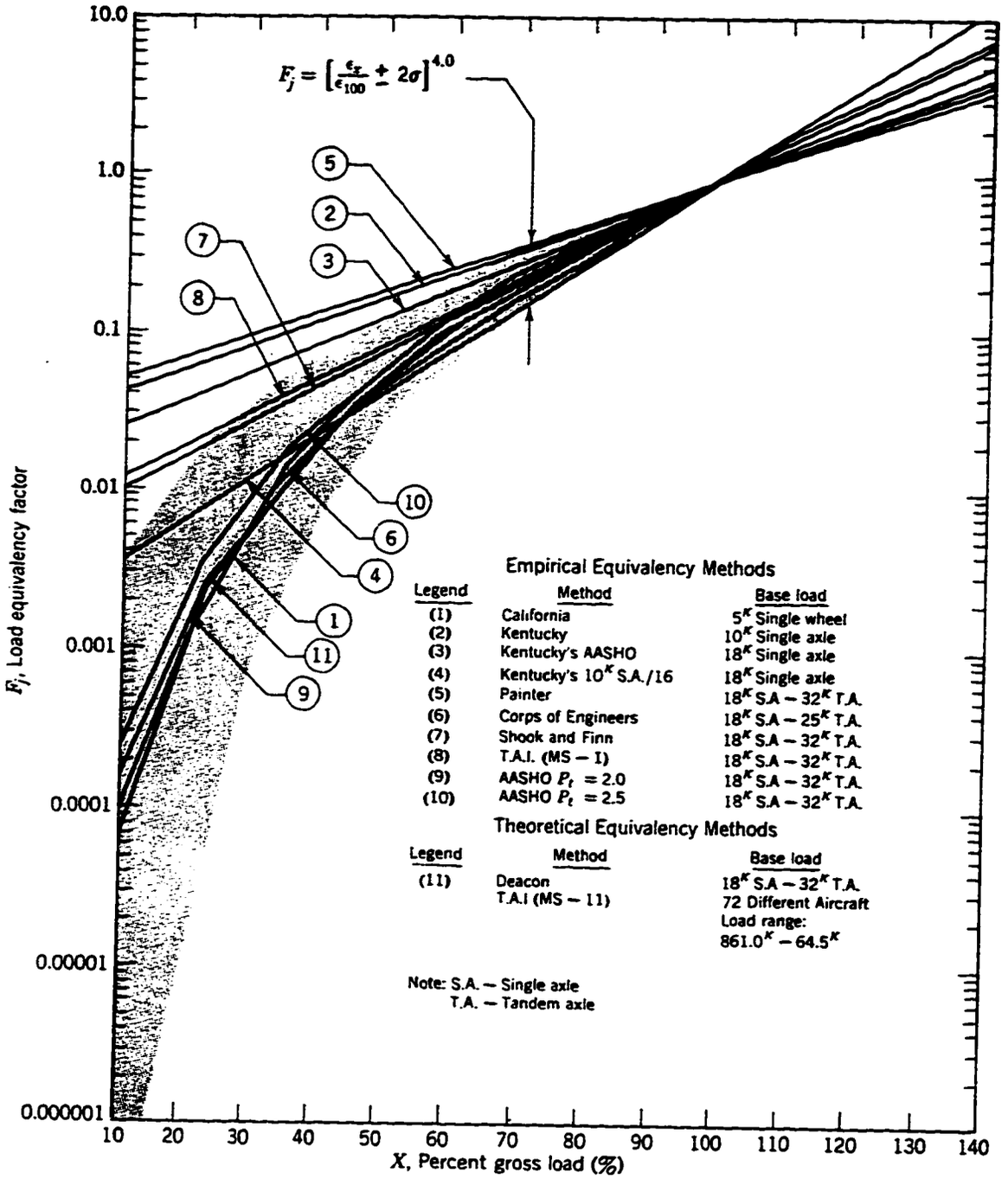


Figure 2.8. Comparison of load equivalency methods as a function of gross load [Yoder and Witczak 1975].

2.3.2 Environmental Data

Environmental factors (climate and drainage characteristics) are another major cause of pavement deterioration. The climatic factors such as temperature, frost action, and precipitation have a great effect on pavement performance.

In hot climate, such as the Saudi environment, asphalt concrete mix softens, and under loading conditions, the moduli of temperature-sensitive layers are reduced significantly by increased temperatures. This in turn reduces the strength of the whole pavement structure. At low temperature, on the other hand, as asphalt has the tendency to contract, the developed internal stresses may exceed the strength of asphalt mix, and this will create low temperature cracking. However, the asphalt binder used in Saudi Arabia and other Gulf countries is suitable to withstand the low-temperature conditions prevail in the region so that the low-temperature cracking problem will not occur [Ramadhan et al. 1995]. Also being in a hot arid region, Saudi Arabia pavement network does not have the problem of frost and heave, but the problem of high water table level especially in the coastal area such as Dammam, creates different types of pavement distresses particularly loss of support. This problem coupled with poor drainage extends the severity and extent of the problem [Aiban et al. 1996].

2.3.3 Pavement History-Related Data

Pavement history is related to the information about the structural component of the pavement that include: layer thickness, material types and properties, pavement performance, date of construction, and date of major maintenance applied to the pavement in its service life. These parameters are detailed below.

2.3.3.1 Layer Thickness

The structural design of flexible pavement consists of the selection of suitable materials for the pavement, the determination of the thickness of pavement layers having certain mechanical properties, and the determination of the composition of the materials that will provide these properties [Peattie 1978]. Flexible pavement consists of a series of layers constructed on the subgrade as shown typically in Figure 2.9. The top layers are usually composed of asphalt concrete mixes. In most flexible pavement structures, the stiffness (strength) of each layer is greater than that of the layer below and smaller than that of the layer above. Pavement is usually designed for 20 to 30 years. In the pavement service life, pavement structure undergoes a process of deterioration due to the traffic and environmental conditions. The relatively higher thickness can withstand most of pavement defects that may occur under normal conditions, and hence longer service life can be expected.

2.3.3.2 Layer Composition

The type of materials used in flexible pavement layers along with their properties have an important role in pavement performance. For example, the use of open-graded (pervious) mixes in the surface layer provides excellent drainage properties and so improving the pavement skid resistance [Lees 1978]. Another performance measure, pavement rutting, is highly affected by the materials properties used in the asphalt concrete mix in the flexible pavement. Critical values for design and maintenance of asphalt concrete mixes were developed for the rutting criteria. These critical values were for modulus of resilience, percentage of air voids, percentage of voids filled with asphalt, and mineral aggregates [Al-Abdul Wahhab et. al 1995].

The type of asphalt binder used in the asphalt concrete mixes has also an important impact on pavement performance. As a result of Strategic Highway Research Program (SHRP), limits have been established on various parameters of asphalt binder and asphalt concrete mixes to come up with pavement designs that are based on field performance [Wood 1995]. A research program has been completed about adaptation of SHRP asphalt

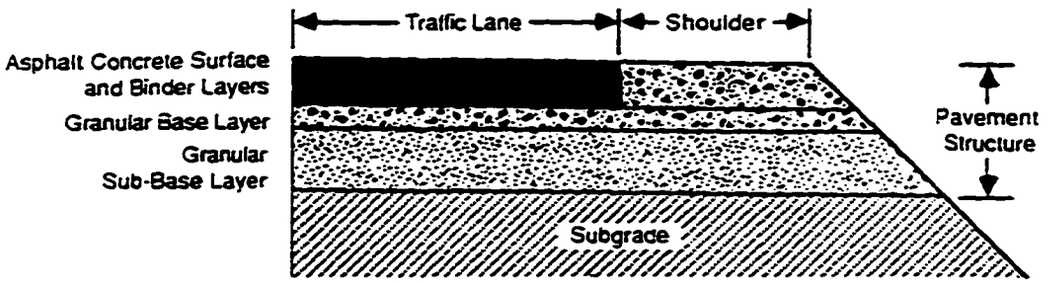


Figure 2.9. Typical flexible pavement cross-section [Haas et al. 1994].

binder performance-base specification on the Gulf countries. It was concluded from this project that the 50% of the asphalt binder used in the area is not suitable for the prevailing environmental conditions, and this amount has to be modified to meet the SHRP specifications [Al-Abdul Wahhab et. al 1996].

The properties of the aggregate base and subbase materials used in the flexible pavement determine some of the pavement performance properties, Layers consisting of cementitious materials such as lime, help supporting the asphaltic layers from being deformed or settled and reducing the stresses and strains developed on the subgrade.

2.3.3.3 Subgrade Type and Strength

The overall thickness of the pavement as well as that of individual layer depend partially of the quality of the subgrade that pavement rest on. Limiting strain criteria is most commonly applied using elastic layered theory to check the pavement structural adequacy against rutting. In this method, allowable number of load repetition (pavement life) is obtained from the compressive strain on the top of the subgrade. This method was adopted by many agencies. Another method uses the California Bearing Ratio (CBR) of the subgrade to determine pavement thickness as used by US Corps of Engineers [Yoder and Witczak 1975].

The subgrade soil properties are also important in determining the pavement performance. For example, in areas of high water table, subgrade soil with high swelling potential should be removed and/or treated before construction of pavement in order to avoid problems such as upheaval and swelling in the pavement that create a high surface roughness.

2.3.4 Pavement Performance Parameters

Pavement performance is related to those parameters that describe the behavior and the condition of the pavement at any time of its service life. These parameters include:

roughness, skid resistance, deflection, current layer materials properties, and surface distress [Haas et al. 1994]. During its service life, pavement exhibits different conditions (performance) at different ages. Therefore, pavement condition at a specific year from the date construction, or the date of the last major maintenance, is an input point in the pavement performance prediction model. These parameters are detailed below

2.3.4.1 Pavement Distress

Pavement Distress evaluation, or condition survey, includes detailed information about the existing defects on the pavement surface. These defects have four general groups: surface defects, permanent deformation, cracking, and patching. Different methods were developed to quantify and rate these pavement distresses. Some of these methods with their procedures are detailed in section 2.4.2.

2.3.4.2 Pavement Roughness

Pavement roughness is a phenomenon experienced by the passenger and the operator of a vehicle or the airplane traveling over the surface [Haas et al. 1994]. Riding quality is largely a function of pavement roughness which is a function of road surface profile, the characteristics of vehicle, and acceleration and speed sensibility of the driver. These factors can contribute to an undesirable or an uncomfortable ride (poor riding quality). Surface irregularity is an important factor in determining the degree of comfort of ride afforded by the road and can also be a guide to the overall condition of the road [Keir 1974]. Road roughness is caused by two factors: surface irregularities that are built into the pavement during construction and surface irregularities that develop after the construction due to

traffic, climate, and other factors [FHWA 1987]. High surface roughness, creates more public complains which, in turn, calls for higher maintenance priority.

Roughness is manifested in pavement surface by several riding quality-rated pavement distresses such as corrugation, potholes, depressions, upheaval, bumps and sags, raveling and weathering, and rutting. Cracking in high severity levels will also contribute to road roughness.

Roughness is quantified by different types of equipment: that which measures the response to pavement surface roughness such as Mays Ride meter (MRM) and Bump Integrator (BI) and that which measures actual pavement profiles (profilometers), such as Rainhart Profilograph. Two typical equipment for roughness measurement are detailed below:

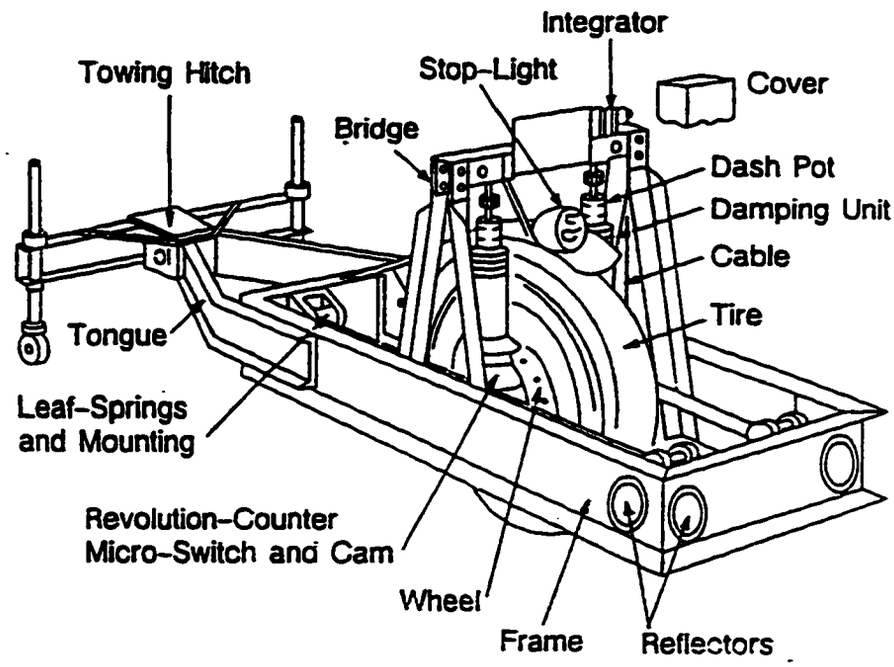
Bump Integrator: it consists of a single-wheel trailer that is towed on a wheel track at a speed of 32 km/h. It measures the sum of the downward movements of the wheel, produced by the longitudinal unevenness in the pavement profile, relative to the trailer chassis. The integrated downward movement (cm) divided by the distance traveled (km) gives the roughness of the pavement surface in cm/km. Two transducers are fitted to the BI trailer. A displacement transducer monitors the movement of the wheel relative to the chassis, while the high-resolution distance transducer measures the distance traveled. The system is equipped with a microprocessor unit fitted with a 10-bit analog digital converter, which processes the signals from the transducers. The transducer signals are sampled 100

times per second [Still et al. 1983]. Figure 2.10 shows schematic of the BI and a typical output profile.

Mays Ride Meter: it measures graphically the road roughness on chart paper with a continuous reference to the distance and locations along the highway. The three components of the MRM are the transmitter, the recorder, and the odometer which are all connected to a vehicle. As the vehicle travels over the road surface, the transmitter detects vertical excursions of the rear axle relative to the vehicle body with a resolution of 2.54 mm. The recorder and its associated systems employ electrically transmitted data to provide a continuous record of road surface roughness. The chart is given in increments of 0.4 mm for each 2.54 mm of rear axle/body excursion. One zig-zag trace of the odometer indicates a distance of 100 m. An event marker is activated by a push button switch which moves laterally to mark an event such as an approach to a bridge, intersection, etc. [KFUPM-RI 1988]. Figure 2.11 shows schematic of the MRM and a typical output profile.

The roughness data need are usually normalized to be used in any system. One method of this normalization of the roughness measurements scaling is the one suggested by FHWA [1987] which has the following steps:

1. Reduce the roughness data along the pavement section to the specified units of roughness (e.g. cm/km).



SSEC	M	CM/KM	KM/H
1	100	108	36.3
	44	7	
	> 5MM=	1	
2	200	105	37.5
	162	6	
	> 5MM=	1	
3	300	106	35.9
	> 5MM=	0	
4	400	138	35.8
	370	8	
	375	6	
	> 5MM=	2	
5	500	117	32.0
	> 5MM=	0	
6	600	136	32.4
	571	6	
	> 5MM=	1	
7	700	138	33.2
	632	6	
	> 5MM=	1	

Figure 2.10. Schematic of bump Integrator and typical output profile [Haas et al. 1994].

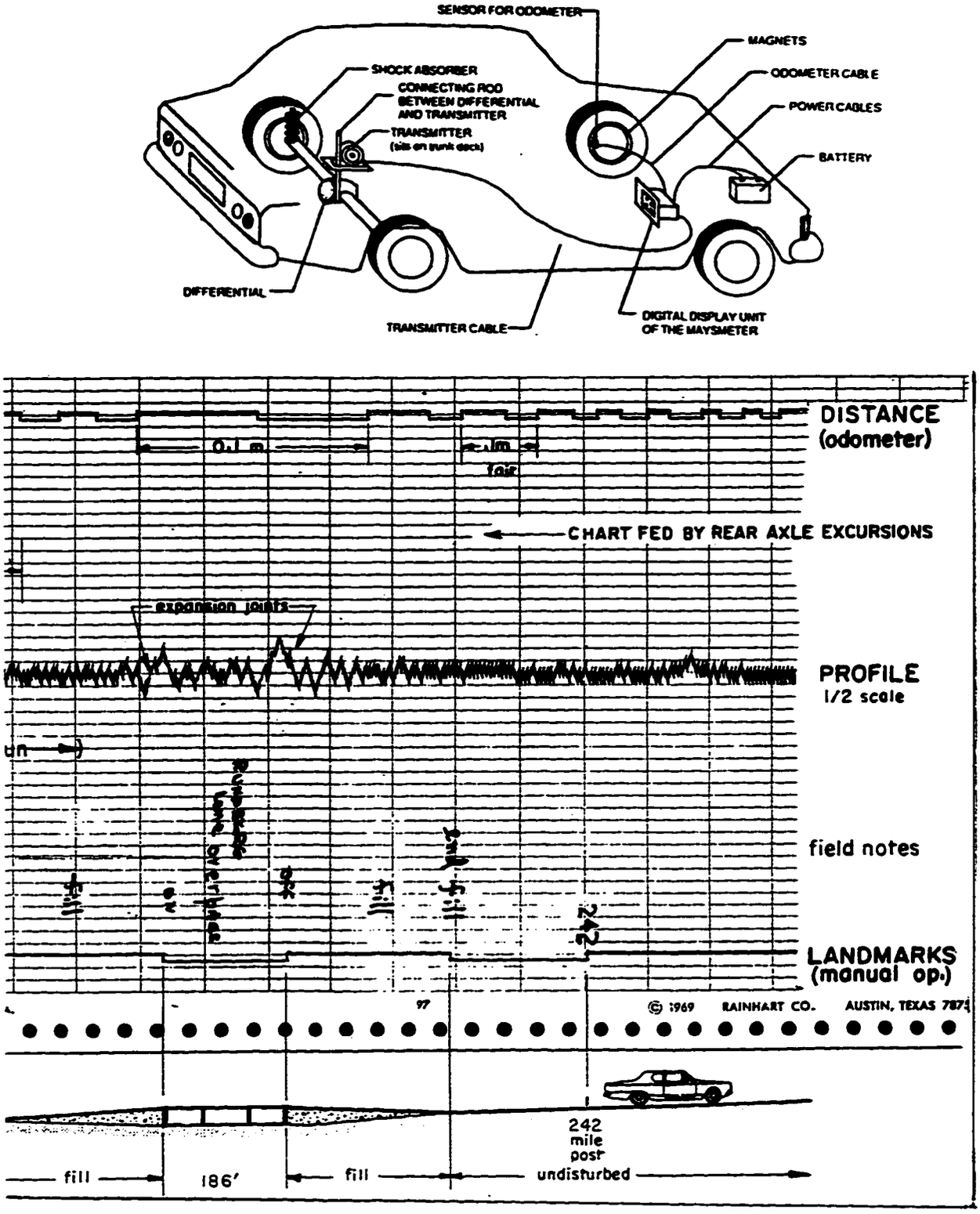


Figure 2.11. Schematic of Mays Ride meter and typical output profile [Haas et al. 1994; Rainhart 1972].

2. Establish an acceptable maximum roughness value (MPR) above which the pavement section is assumed to be unacceptable to users. This step can be achieved by panel rating technique.

3. The ride index (RI) of the pavement section can be considered as inversely proportional to the ration of the actual pavement roughness (PR) to the established maximum acceptable pavement roughness (MPR), while the minimum possible value of roughness is 0.

   Then the RI can be computes as:

$$RI = 100*PR/MPR \tag{2.1}$$

In this case, values of RI of 100 or more indicates very rough, unacceptable pavement section that calls for higher priority for maintenance, while lower values represent acceptable smooth pavement sections.

2.3.4.3 Safety Condition

Pavement safety is usually evaluated in terms of skid resistance. There are however, a number of other considerations in pavement safety, such as violation or unsafe acts by drivers or pedestrians, vehicular defects, pavement rutting (as it relates to accumulation of water and the danger of hydroplaning or ice formation), lane demarcation, night visibility (especially during rain), bad weather, and shoulder drop-off. But pavement slipperiness as measured by skid resistance is the most common and important factor [Pignataro, 1976;

Haas and Hudson, 1982]. Low value of skid resistance makes the pavement surface brone to traffic accidents with higher safety hazard

In a study for Al-Jubail Industrial City road network [Arora et al. 1991], it was found that visual inspection of pavement sections showing low-skid resistance revealed distress manifestations such as polishing aggregate, rutting, and binder bleeding and flushing. Other safety-related pavement distress are lane-shoulder drop off and availability of potholes. Table 2.1 defines the safety-related distresses according to PAVER method.

Skid resistance in pavement surface can be measured by different methods and equipment. Mu-meter is most proven performance and widely used device to identify pavements with low skid resistance so that suitable maintenance treatment can be planned in time to ensure traffic safety. Mu meter, which measures the sideways frictional force coefficient (SFC), is used to evaluate skid resistance. The Mu meter function and operation is detailed below:

Mu Meter: It is a two-wheel trailer with wheels at a fixed tow-out angle of 7.5 degrees and a third recording wheel. Since both wheels are at the same and opposite tow-out, the trailer is easy to tow. Pulling the Mu-meter causes a sideways friction force, which is sensed by transducers and then transmitted hydraulically to a Bourdon gauge and an automatic recording mechanism. Since all the control equipment is located in the cab of the towing truck, the Mu-meter is a versatile tool which enables tests to be made without stopping or interfering with traffic [ML Aviation, 1983]. The system is provided with an Automatic Printout Unit (APO) and with a self-watering device to simulate wet pavement

Table 2.1. Safety-related pavement distresses with safety-hazard criteria.

Distress Name	Description
Polished Aggregates	This distress is caused by repeated traffic applications. When the aggregate in the surface becomes smooth to touch, adhesion with vehicle tires is considerably reduced. When the portion of aggregate extending above the surface is small, the pavement texture does not contribute to reducing vehicle speed.
Rutting*	It is a surface depression in the wheel paths caused by consolidation or lateral movement of the materials due to traffic loads.
Bleeding	It is a film of bituminous materials on the pavement surface which creates a shiny, glasslike, reflecting surface that usually becomes quite sticky. Bleeding is caused by excessive asphalt cement or tar in the mix, excess application of bituminous sealant, and/or low air voids content. since the bleeding process is not reversible, during cold weather, asphalt or tar will accumulate on the surface.
Lane/Shoulder Drop off	It is the difference in elevation between pavement edge and the shoulder. This distress is caused by shoulder erosion.
Potholes	Potholes are small, bowel shaped depression (less than 0.9m in diameter) in the pavement surface. They are caused when traffic abrades small piece of the pavement surface. The pavement then continue to disintegrate because of poor surface mixture, weak spots in the base or subgrade, or because it has reached to the condition of high severity alligator cracking.

* Depression distress has similar effect or rutting at the wet conditions

conditions. The APO can print the average friction value at a present distance in tens, hundreds, or thousands of feet, thus providing friction for a maximum set distance of 9,990 ft (2,997 m). The SFC when multiplied by 100 gives the skid number (SN). Figure 2.12 shows schematic of the Mu meter and typical output results.

2.3.4.4 Structural Capacity

Structural capacity requires first monitoring of measuring some characteristics of the pavement. It then involves analysis of the resulting data, either on a theoretical or empirical basis, to estimate the load-carrying capabilities and the service life of the pavement under expected traffic condition [Haas et al. 1994]. Non-destructive deflection testing (NDT) is one the most reliable methods available for determining the structural condition of an in-service pavement [Shahin 1994].

NDT test results can explain the cause of pavement defects. Moreover it has the capability of detecting unforeseen pavement problems before they become reality. Impulse, steady-state dynamic, and dynamic loads are applied to the pavement through loading plates, or wheel, and the pavement deflection response is recorded. The stiffness or strength of the pavement can be related to the magnitude of these deflections. Nondestructive testing involves a large number of readings, and a statistical average is used. Figures 2.13 show schematic of three types of NDT testing devices.

Although destructive pavement testing should be avoided and kept to the absolute minimum, it occasionally becomes necessary to remove portions of pavement structure to

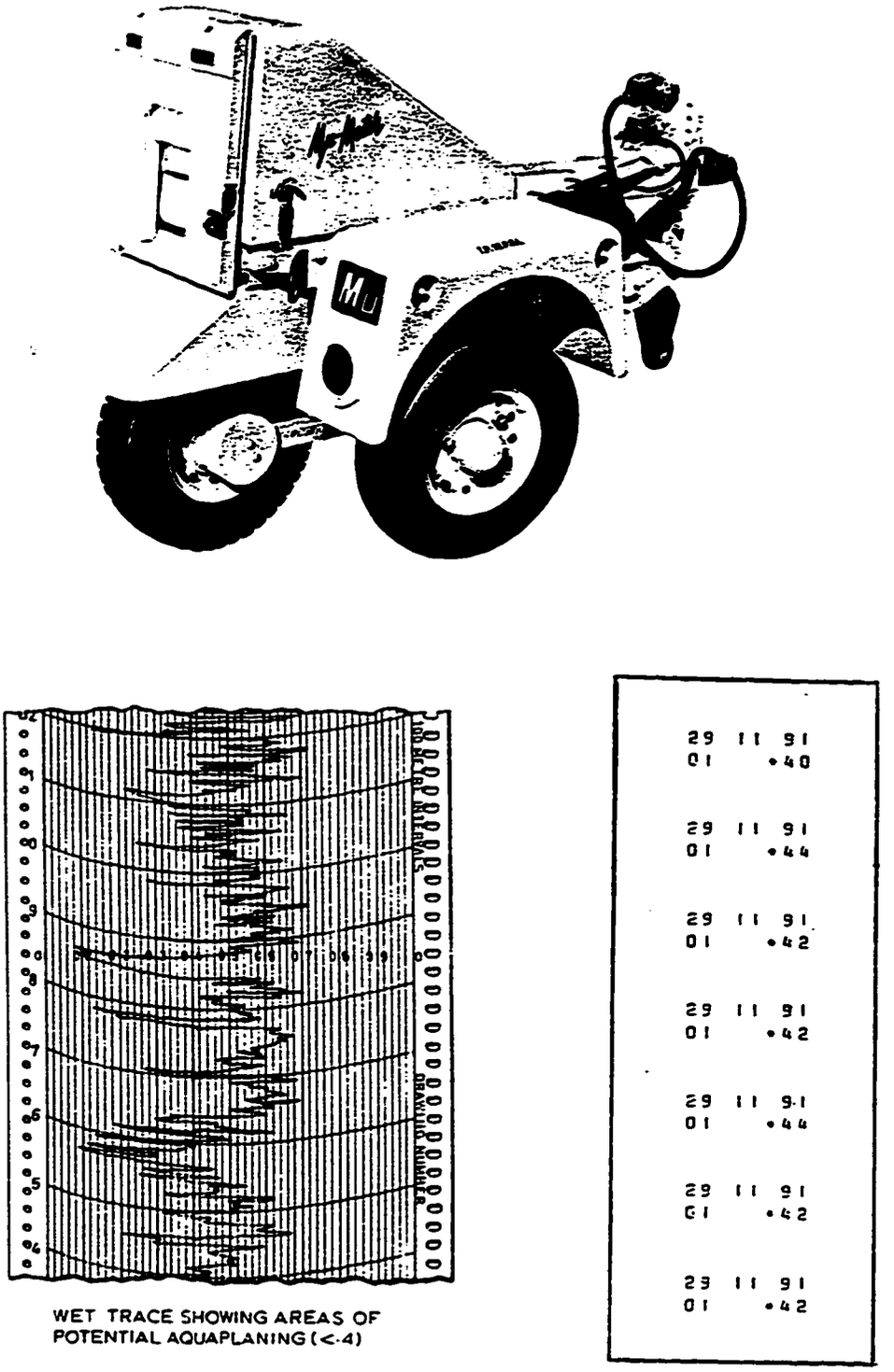
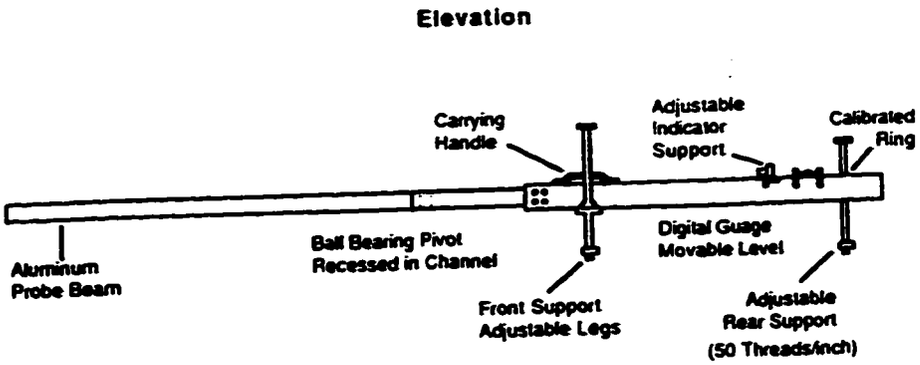
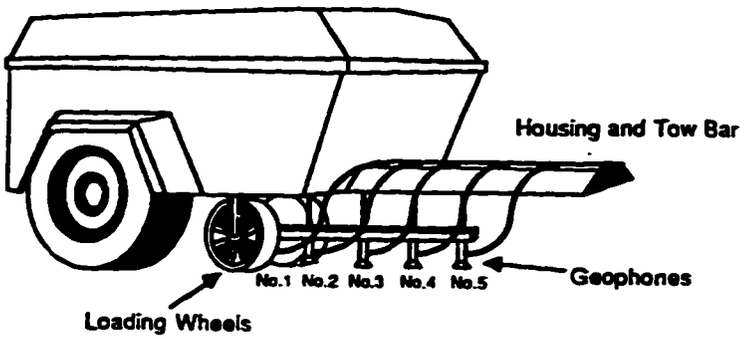


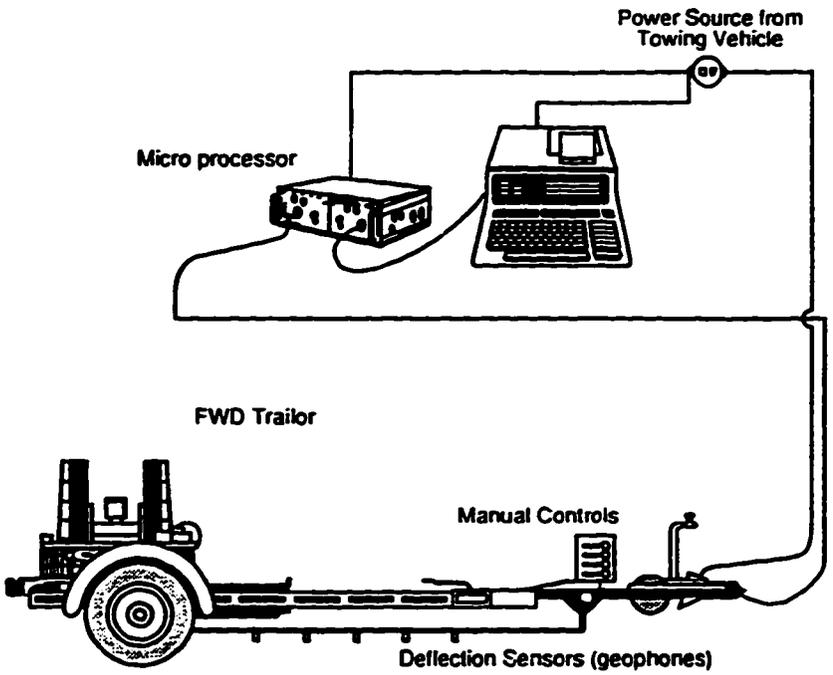
Figure 2.12. Mu meter and typical output profile and printout [ML Aviation 1985].



Schematic diagram of the Benkelman Beam



The Dynaflect with Load Wheels in the Test Position



FWD in Operating Position

Figure 2.13. NDT devices [Haas et al. 1994].

ascertain just where "failures" are occurring and why or to check for missing information such as layer thickness. The term "destructive testing" is applied to these evaluation methods because the original structure of the complete pavement is destroyed with respect to future testing at that particular location. Therefore, such evaluation procedures are restricted to pavements that show evidence of distresses.

2.4 PAVEMENT PERFORMANCE

2.4.1 Pavement Serviceability

Pavement performance curve describe serviceability-age relationship of the pavement. Pavement serviceability or condition is determined through the performance related parameters such as riding quality, safety, structural adequacy, and surface distresses. There are different methodologies developed to quantify pavement condition at any time of its service life using these parameters.

The Present Serviceability Index (PSI) is based upon the concept of correlating the users opinions with measurements of road roughness, cracking, patching, and rutting. This concept was first presented in 1962 by Carey and Irick using the AASHO Road Test [Haas et al. 1994]. PSI is formulated by rating a series of pavements by a group of individuals. The panel member drives over selected pavements and rate the pavement on a scale from 0-5 as the one shown in Figure 2.14 [Yoder et al. 1975, Haas et al. 1994]. The five fundamental assumptions associated with the serviceability concept are summarized as follows [Haas et al. 1994]:

Section No.	Highway No.		
Pave. Type	Vehicle	Date a.m. p.m.	Rater

5 — Very good
4 — Good
3 — Fair
2 — Poor
1 — Very poor
0

Acceptable	
Yes	
No	
Doubful	

Influence of behavior elements on present serviceability rating.

	No influence	Minor influence	Appreciable influence	Pronounced influence
Longitudinal distortion				
Transverse distortion				
Cracking				
Faulting				
Surface deterioration				

Remarks: _____

Figure 2.14. Present serviceability rating form [Yoder and Witczak 1978].

1. Highways are for the comfort and convenience of the traveling public. A good highway is one that is safe and smooth.

2. Users' opinions as to how they are being served by highways is by and large subjective.

3. There are, however, characteristics of highways that can be measured objectively and that, when properly weighed and combined, are in fact related to users' subjective evaluation of the ability of the highway to serve them.

4. The serviceability of a given highway may be expressed by the mean evaluation given by the all highway users.

5. Performance is assumed to be an overall appraisal of the serviceability history of the pavement.

The serviceability determined by PSI is correlated with objective measurements of roughness, cracking, patching, and rut depth with the mathematical form shown below for flexible pavement [Yoder and Witczak 1975]:

$$PSI = 5.03 - 1.90\log(1+SV) - 0.01\sqrt{C+P} - 1.38\overline{RD}^2 \qquad (2.2)$$

where:

PSI = Present Serviceability Index,

SV = Slope Variance,

C = Lineal feet of major cracking per 1000 ft^2 area,

P = Bituminous patching in 1000 ft^2 area, and

RD = Mean Rut Depth in inches (both wheel track) measured with 4-foot straightedge.

The above regression equation are unique and dependent upon the transformation applied to various physical measurements. In addition, the users' opinion concept has its own systematic errors such as: [Haas et al. 1994]:

1. Leniency error (i.e. a rater's tendency, for various reasons, to rate too high or too low),

2. Halo effect (i.e. a rater's tendency to force particular attribute rating toward his or her overall impression of the subject), and

3. Central tendency error (i.e. a rater's hesitation to give extreme judgments, thereby tending to ratings toward the mean of the rating panel).

2.4.2 Pavement Condition Evaluation

Distress evaluation is one of the important steps in pavement evaluation which in turn, is the most critical component of any pavement management system. Pavement distresses are usually grouped in different classes depending on the viewpoint of the evaluator and the purpose of the survey. These groups may be [Ramadhan 1996]:

1. Type-wise grouping: cracking, surface deformation, surface defect, and others,

2. Pavement-type grouping: flexible or rigid pavement distresses,

3. Failure type-wise grouping: structural or functional failure distresses,

4. Cause-wise grouping: load associated, environmental, built-in cause, and construction practice associated distresses,

5. Location-wise grouping: localized or wide-spread distresses, and

6. Performance-wise grouping: riding quality, skid resistance, or structural related distresses.

Distress evaluation, or condition survey, includes detailed identification of pavement distress type, severity, extent, and location. To combine these details, an index is assigned to each pavement which is transferred to a general rating (excellent to failed). Every highway agency, either develops a pavement distress evaluation procedure or select a developed one for its pavement condition survey. These procedure usually starts by a clear definition of of the different distresses and their severity and extent levels. There is a wide variety of pavement distress manuals available, example of those are found in Shahin and Kohn [1981], SHRP [1993], KFUPM-RI [1989], and MOC [1986].

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

value is the summation of the deduct values of all available distresses. An index representing the pavement condition (usually out of 100) is calculated by subtracting the total deduct (after correction for the interaction effect, if needed) from 100. The a general descriptive rating is assigned according to some specified ranges of this index. In the following sections, three condition survey methods are detailed.

2.4.2.1 Ministry of Communications (MOC), Riyadh-Saudi Arabia Method

MOC in the Kingdom of Saudi Arabia has selected the Ohio pavement condition procedure after some modification to suit the local conditions. The method was developed in Ohio state in USA based on the most occurring distresses available in the state pavement network [Luther and Majidzadeh 1979]. The rating method provides a procedure for uniformly identifying and describing, in terms of severity and extent, pavement distress. In this method, 13 types of pavement distresses are considered, each has three severity levels: low medium, and high, and three extent levels: occasional, frequent, and extensive. An extent level represents the percentage of the section length or area affected by that distress. A weight out of 100 is assigned to each distress: 15 for wheel track cracking, 10 for raveling, and 5 for bleeding are examples of these weights. Distress severity and extent are also assigned a fractional weight (maximum of 1.0 for high level of severity and extent. The deduct points for existing distress is determined by multiplying the distress weight times the weights for severity and extent for that distress. A pavement Condition Rating (PCR) provides an index reflecting the composite effect of various distress type, severity, and extent upon the overall condition of the pavement. PCR is computed by subtracting the total deduct points from 100.

The rating procedure of Ohio condition rating method is summarized in the following steps [Luther and Majidzadeh 1979]:

1. The rating team (consists of a driver and a rater) drives over the pavement section at a speed of 40 MPH. During this step, a readily visible distresses such as potholes, bleeding, and settlement are rated. Also the need for subdividing the section is evaluated.

2. A second pass along the pavement section is made with stops at approximately 1 mile intervals. At each stop, the raters evaluate the roadway by viewing the pavement for 100 feet in both the head and back directions for close inspection of cracking, rutting, raveling, etc. This inspection is done from the roadway shoulder.

3. Pavement condition form is completed for the entire roadway section which is based on observations in steps 1 and 2 above.

Pavement section is a one with uniform condition with a length of 2 to 4 miles. Directional lanes or multi-lane roadways are considered as separate roadways. For two-lane roadways, rating one direction is sufficient unless a significant difference in condition is observed between the two lanes.

The MOC has modified this procedure by the following:

1. Only one passage is needed for undivided highways. However, for divided highways, two separate trips are required.

2. A segment length of 10 km for the rating for a segment represents the average condition over the segment. If a major change in the condition of the pavement occurs on a segment, the station for the change is to be recorded in separate sheet. The shortage segment length is limited to 2 km. However, using the automated condition rating method (laser Road Surface Tester, RST), a segment length of 1 km is scheduled.

3. Rutting distress weight is changed from 10 to 15, and the wheel track cracking weight is changed from 15 to 10. This adjustment is due to the fact that the MOC pavement

network exhibits more of rutting problems than in cracking ones. Therefore, higher weight is given to rutting to reduce the PCR value and hence to call for maintenance and repair.

4. Present Serviceability Rating (PSR) is added to the pavement rating form. PSR is a simple rating of the pavement from good to bad based on the rater's judgment. In combination with the PCR value, the engineer can judge if a segment needs any remedy action. For example, a reasonably high PCR of a pavement with only one sever distress may still rated very poor from a serviceability point of view.

5. Shoulder rating is also added to the rating form. This will be a useful information when estimating type and extent of remedy action.

6. Other information such as road number, segment location and direction, and pavement width are also added to the rating form to be filled by the inspector.

Figure 2.15 shows a typical MOC pavement rating form. Due to the huge pavement network under the MOC jurisdiction, the distress condition evaluation was automated using the Laser Road Surface Tester (RST) developed by the Swedish Road and traffic Research Institute. This system use laser technology to measure crack depth and width, rut depth, longitudinal profile, macrotexture, cross profile, and distance. The tester has an on-board microcomputer that has the capability of transferring the sensor signals to quantities of pavement distresses with their severity and extent levels to arrive to a PCR value. The laser RST is fully automated data-analysis system where accurate, objective, and reliable measurements can be obtained rapidly, safely, and at very low cost [Haas et al. 1994, KFUPM 1993]. Figure 2.16 shows the schematic of the RST components.

Dist rict	Direc tion	Road No.	Pass age	Stretch		Date			Sheet	
				From node	To node	Year	Mon.	Day	No.	Tot.

Discriptiuon of location of 0.00 point

Segment rated on this form, station to station	BEG	
	END	
Locatio of segment		
From Intersection road no:		
To Intersection road no:		
Station for last major (condition) change		
Pavement width (excl. shoulder)		
Satation for last change of pavement width		

Maint. Project .....
Recorded by: .....

PAVEMENT CONDITION RATING (PCR)

DISTRESS	DISTRESS WEIGHT	SEVERITY WEIGHT			EXTENT WEIGHT			DEDUCT POINTS
		L	M	H	O	F	E	
RAVELING	10	0.3	0.6	1.0	0.5	0.8	1.0	
BLEEDING	5	0.8	0.8	1.0	0.6	0.9	1.0	
PATCHING	5	0.3	0.6	1.0	0.6	0.8	1.0	
POTHOLES	10	0.4	0.7	1.0	0.5	0.8	1.0#	
CRACK SEALING AND DEFICIENC	5	1.0	1.0	1.0	0.5	0.8	1.0	
RUTTING	15	0.3	0.7	1.0	0.6	0.8	1.0#	
SETTLEMENT	10	0.5	0.7	1.0	0.5	0.8	1.0	
CORRUGATION	5	0.4	0.8	1.0	0.5	0.8	1.0	
WHEEL TRACK CRACKING	10	0.4	0.7	1.0	0.5	0.7	1.0#	
BLOCK & TRANSVERSE CRACK.	10	0.4	0.7	1.0	0.5	0.7	1.0#	
LONGITUDINAL JOINT CRACK.	5	0.4	0.7	1.0	0.5	0.7	1.0	
EDGE CRACKING	5	0.4	0.7	1.0	0.5	0.7	1.0	
RANDOM CRACK	5	0.4	0.7	1.0	0.5	0.7	1.0#	

L=LOW O=OCCASIONAL
M=MEDIUM F=FREQUENT
H=HIGH E=EXTENSIVE

TOTAL DEDUCT =	
SUM OF STRUCTURL DEDUCT (#) =	
100 -TOTAL DEDUCT= PCR =	

PRESENT SERVICEABLITY RATING (PSR)

5	4	3	2	1
Very Good	Good	Fair	Poor	Very Poor

SHOULDER RATING

Type	
Width	
Cond.	

REMARKS:

Figure 2.15. MOC PDR pavement rating form [MOC 1986; Noureldin, et al. 1993].

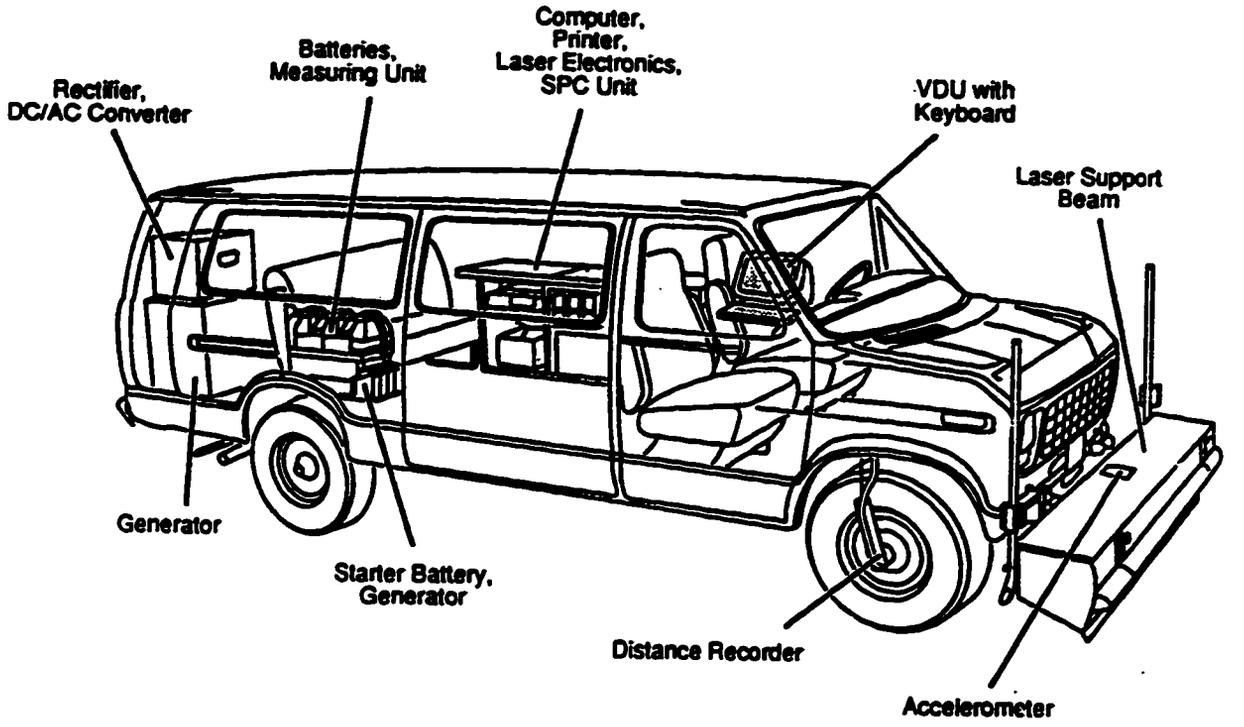


Figure 2.16. Schematic illustrating various components of the laser RST [Haas et al. 1994].

However, the major change that was made by using the RST for condition survey, was that weights for the different distresses have changed. Some of the distresses such as bleeding, patching, and edge cracking have zero weights since they can not be measured by the RST, while a new distress called roughness is added with high weight (i.e. 25). This distress was not included in the previous method manual method [KFUPM 1993]. Thus, it is difficult to compare manual collected data with the automated ones due to this change. Figure 2.17 shows the modified MOC pavement condition rating form.

2.4.2.2 KFUPM- Research Institute Method

Pavement condition surveys for the road network of Jubail Industrial City were carried out by the Research Institute pavement group using the Pavement Distress-based Rating (PDR) procedure.

A detailed pavement distress evaluation manual was developed which has the following main sections [KFUPM-RI 1989, Arora et al. 1995]:

1. Selection of evaluation sections and subsections: the entire road network under study is divided into a number of uniform mid-block sections that correspond to area located between consecutive major crossroads and signalized intersections. The later is treated as separate sections. If the mid-block section is too long (more that 2 km), or when there is a definite change in roadway conditions, it is divided to subsections.

2. Distress identification and rating: distress types are divided into four main groups: cracking, deformation, surface defect, and patching. Each distress type is evaluated in terms of extent of occurrence and severity. There are four levels of extent: "few", "intermittent", "frequent", and "extensive", these levels determine the percentage of area affected by any distress. Distress severity has three levels: "low", "medium", and "high" that determine how sever the distress is. Each distress is defined with its breakdown severity levels as detailed in the manual.

ROAD : _____

START NODE: _____

END NODE : _____

SEGMENT LOCATION FROM

START NODE: _____

SAMPLE NO :_____

HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

FLEXIBLE PAVEMENT CONDITION RATING

DATE: _____

BATCH: _____

DISTRESS	DISTRESS WEIGHT	SEVERITY WEIGHT * L	M	H	EXTENT WEIGHT * O	F	E	DEDUCT *** POINTS
RAVELING	15	0.3	0.6	1.0	0.5	0.8	1.0	
BLEEDING	0	0.8	0.8	1.0	0.6	0.9	1.0	
PATCHING	0	0.3	0.6	1.0	0.6	0.8	1.0	
POTHOLES	0	0.4	0.7	1.0	0.5	0.8	1.0#	
RUTTING	25	0.4	0.8	1.0	0.6	0.8	1.0#	
WHEEL TRACK CRACKING	20	0.4	0.7	1.0	0.5	0.7	1.0	
BLOCK & TRANSVERSE CRACK.	15	0.4	0.7	1.0	0.5	0.7	1.0	
LONGITUDINAL JOINT CRACK.	0	0.4	0.7	1.0	0.5	0.7	1.0	
EDGE CRACKING	0	0.4	0.7	1.0	0.5	0.7	1.0	
ROUGHNESS	25	0.5	0.8	1.0	0.6	0.8	1.0#	

* L=LOW

M=MEDIUM

H=HIGH

** O = OCCASIONAL

F = FREQUENT

E = EXTENSIVE

TOTAL DEDUCT =

SUM OF STRUCTURL DEDUCT (#) =

100 -TOTAL DEDUCT= PCR =

*** Deduct Pts. = Distress Wt. x Severity Wt. x Extent Wt.

REMARKS: _____

Figure 2.17. Modified MOC pavement condition rating method [KFUPM 1993].

3. Distress evaluation procedure: distress survey is performed by visual inspection of pavement distresses using simple tools such as measuring wheel, straight edge, string line, and measuring tape. The procedure has three steps: First: the rating team (consisting of a driver and a ratter) ride over the predetermined section at the posted speed and rate some distresses such as depressions, corrugations, and upheavals, if any; Second: the team drive on the shoulder at slow speed and stop at a location near the middle of the section, and the ratter walks 50 m in both directions evaluating pavement distresses by visual inspection; Third: the distress evaluation form is completed by filling in one line of composite information for each section/subsection and for each feature. Distress information is provided separately for each traffic lane and shoulder. In the case of a signalized intersection, information is collected separately for each approaching area and for each exclusive right turning lane where the latter exists. Figure 2.18 shows a typical evaluation form for this method.

5. Pavement distress-based rating (PDR): Deduct Points (DDPs) are assigned to each distress type based on its severity and extent levels. The assignment relates to the pavement condition description that is derived from the Pavement Distress-Based Rating (PDR). PDR for a section equals 100 minus the sum of the DDPs for that section. DDPs are assigned on the assumption that only one distress type exists. If there is more than one distress type (n = 2 or above), it is recommended that the sum of DDPs is corrected by multiplying by a correction factor (C) of 0.70. However the corrected sum of DDPs should never exceed 100 or be less than the maximum DDP of an individual distress involved. Three rating condition are specified: "Poor" for PDR values of 55 and below, "Fair" for PDR values of 56 to 75, and "Good" for PDR 76 to 100.

This distress evaluation procedure is integrated into a computerized system called pavement evaluation and maintenance management system (PEMMS) that can identify sections in need of maintenance, determining priorities for maintenance, selecting suitable maintenance strategies, and computing maintenance costing.

ZONE : Al-Daffi : 1
RATER : KFUPM RI
DATE : 12.12.87

Distress Severity: Low (L), Medium (M), High (H)
Distress Extent: Few (1) (1- 5%), Intermittent (2) (6-25%), Frequent (3) (26-50%), Extensive (4) (51-100%)

Road	Description										Cracking							Deformation					Surface Defect				Patching	Drainage Rating (A/U)**
	From	To	Section	Sub Section	Feature	ID	Length (m)	Area (m^2)	Classification	Traffic Category (TC)*	Wheel Track	Transverse or block	Joint	Mid Lane	Edge	Slippage	Random	Rutting	Depression	Corrugation	Shoving	Upheaval	Raveling	Bleeding	Pot Holes	Polished Aggregate		
MSJD	TS4N	TS4S	04	00	L1S	MSJD 0400 L1S	200	760	C	3		L1	L2															A
"	"	"	"	"	L2S	MSJD 0400 L2S	200	994	C	3		L2																A
"	"	"	"	"	SHS	MSJD 0400 SHS	120	276	C	4																		A
"	MSJD	TS4S	05	"	IAE	MSJD 0500 IAE	51	272	C	3													L2					A
"	"	"	"	"	IAN	MSJD 0500 IAN	110	1473	C	3													L3					A
"	"	"	"	"	IAS	MSJD 0500 IAS	118	1473	C	3								L3					L2					A
"	"	"	"	"	IAW	MSJD 0500 IAW	51	272	C	3																		A
"	"	"	"	"	ITN	MSJD 0500 ITN	91	192	C	3													L4					A

*TC 1 : > 5000 TC 2 : 3001 - 5000 TC 3 : 1000 - 3000 TC 4 : < 1000
** A : Acceptable U : Unacceptable

Figure 2.18. Pavement distress-based rating (PDR) Form [KFUPM-RI 1989].

2.4.2.3 PAVER Method

This procedure, developed by the US Corps of Engineers, is one the most detailed distress evaluation method implemented to date. This method depends on detailed visual inspection of up to 19 different pavement distresses for flexible pavement. Following is a summary of the features of PAVER method:

1. Pavement sectioning: the total pavement network is divided into identifiable branches. Each branch is a single entity and has a distinct function such as streets and parking lots. Since branches are large units of pavement network, they are rarely have consistent uniform characteristics along their entire length. Thus each branch is subdivided into sections with consistent characteristics of structural composition, traffic, and same construction history. The total pavement section is divided to survey sample units.

2. Inspection procedure: There are two methods to inspect pavement: entire section inspection and inspection by sampling. The number of sample units to be surveyed, in the second method, is determined based on allowable error and variability of observed distresses. In both methods, the inspector walks over each sample unit, measures each distress type and severity, and record these data on an inspection sheet as the one shown in Figure 2.19.

3. Pavement Condition Index (PCI) Calculation: using deduct value approach, PAVER method assigns a Pavement Condition Index (PCI) of 100 for a perfect pavement. This index is decreased by the a cumulative deduct value score based on the level and the severity of the observed distresses. These deduct values are obtained from a developed curves for all distresses. The total deduct value (TDV) is corrected using specified correction curves to obtain the corrected deduct value (CDV). This correction is due to the interaction of more that one distress exist at the same time. The detailed PCI calculation and rating is shown in Figure 2.20.

ASPHALT PAVEMENT INSPECTION SHEET

BRANCH _____ SECTION _____

DATE _____ SAMPLE UNIT _____

SURVEYED BY _____ AREA OF SAMPLE _____

Distress Types

1. Alligator Cracking
2. Bleeding
3. Block Cracking
4. * Bumps and Sags
5. Corrugation
6. Depression
7. * Edge Cracking
8. * Jt Reflection Cracking
9. * Lane/Shldr Drop Off
10. * Long & Trans Cracking
11. Patching & Util Cut Patching
12. Polished Aggregate
13. * Potholes
14. Railroad Crossing
15. Rutting
16. Shoving
17. Slippage Cracking
18. Swell
19. Weathering and Raveling

SKETCH:

	EXISTING DISTRESS TYPES					
TOTAL SEVERITY L						
TOTAL SEVERITY M						
TOTAL SEVERITY H						

PCI CALCULATION

DISTRESS TYPE	DENSITY	SEVERITY	DEDUCT VALUE
DEDUCT TOTAL			
CORRECTED DEDUCT VALUE (CDV)			

PCI = 100 - CDV = _____

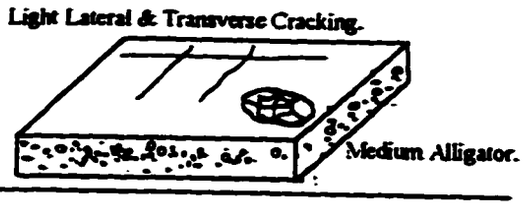
RATING = _____

* All Distresses Are Measured In Square Feet Except Distresses 4,7,8,9 and 10 Which Are Measured In Linear Ft; Distress 13 Is Measured In Number of Potholes.

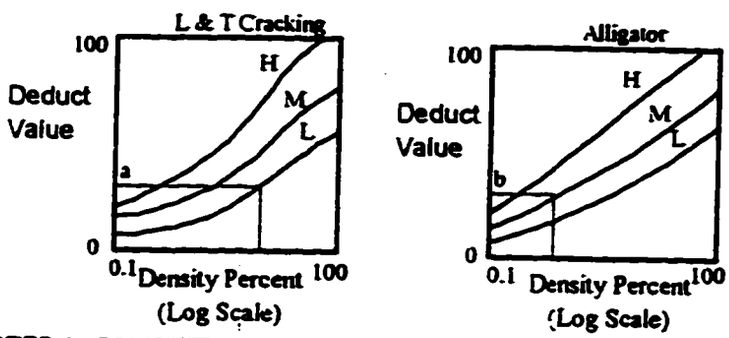
Figure 2.19. PAVER pavement condition index (PCI) form [Shahin and Kohn 1981].

STEP 1. DIVIDE PAVEMENT SECTION INTO SAMPLE UNITS.

STEP 2. INSPECT SAMPLE UNITS. DETERMINE DISTRESS TYPES AND SEVERITY LEVELS AND MEASURE DENSITY.

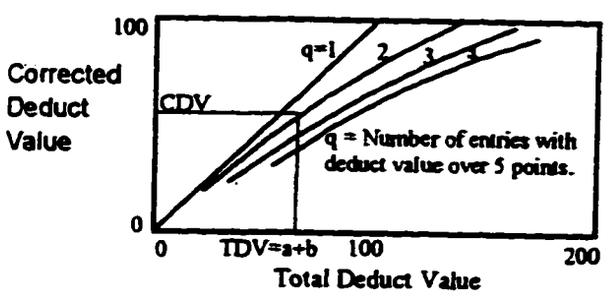


STEP 3. DETERMINE DEDUCT VALUES



STEP 4. COMPUTE TOTAL DEDUCT VALUE (TDV) a + b

STEP 5. ADJUST TOTAL DEDUCT VALUE.



STEP 6. COMPUTE CONDITION INDEX (PCI) 100-CDV FOR EACH SAMPLE UNIT INSPECTED.

STEP 7. COMPUTE PCI OF ENTIRE SECTION (AVERAGE PCI'S OF SAMPLE UNITS).

STEP 8. DETERMINE PAVEMENT CONDITION RATING OF SECTION.

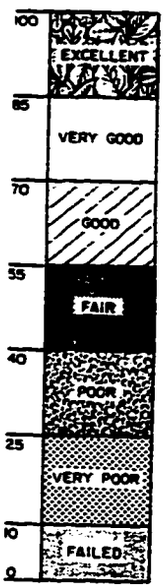


Figure 2.20. Steps for PCI calculation [Shahin and Walther 1990].

4. The PCI calculation procedure described above was modified as detailed in Shahin [1994]. The major change was in the CDV by determining the maximum allowable number of deduct, and the maximum corrected deduct value. Figure 2.21 shows the new procedure for calculating he PCI value.

Condition evaluation procedure and PCI determination is a part of the Micro PAVER system that has many other important capabilities, including: data storage and retrieval, database administration, pavement network definition, inspection scheduling, determination of present and future network condition, determination of maintenance and repair (M&R) needs, performance of economic analysis, and budget planning [Micro PAVER 1994].

2.4.3 Pavement Performance Modeling

A true performance prediction model is the one that can calculate the expected serviceability-age (or traffic) relationship over the entire design period, which can be extended to include the effects of any major rehabilitation [Haas and Hudson 1982].

Pavement performance has to have the following four basic requirements [Darter 1980]:

1. An adequate data base,

2. Inclusion of all significant variables affecting deterioration,

3. Careful selection of the fundamental form of the model to represent the physical, real-world situation, and

4. Criteria to assess the precision of the model.

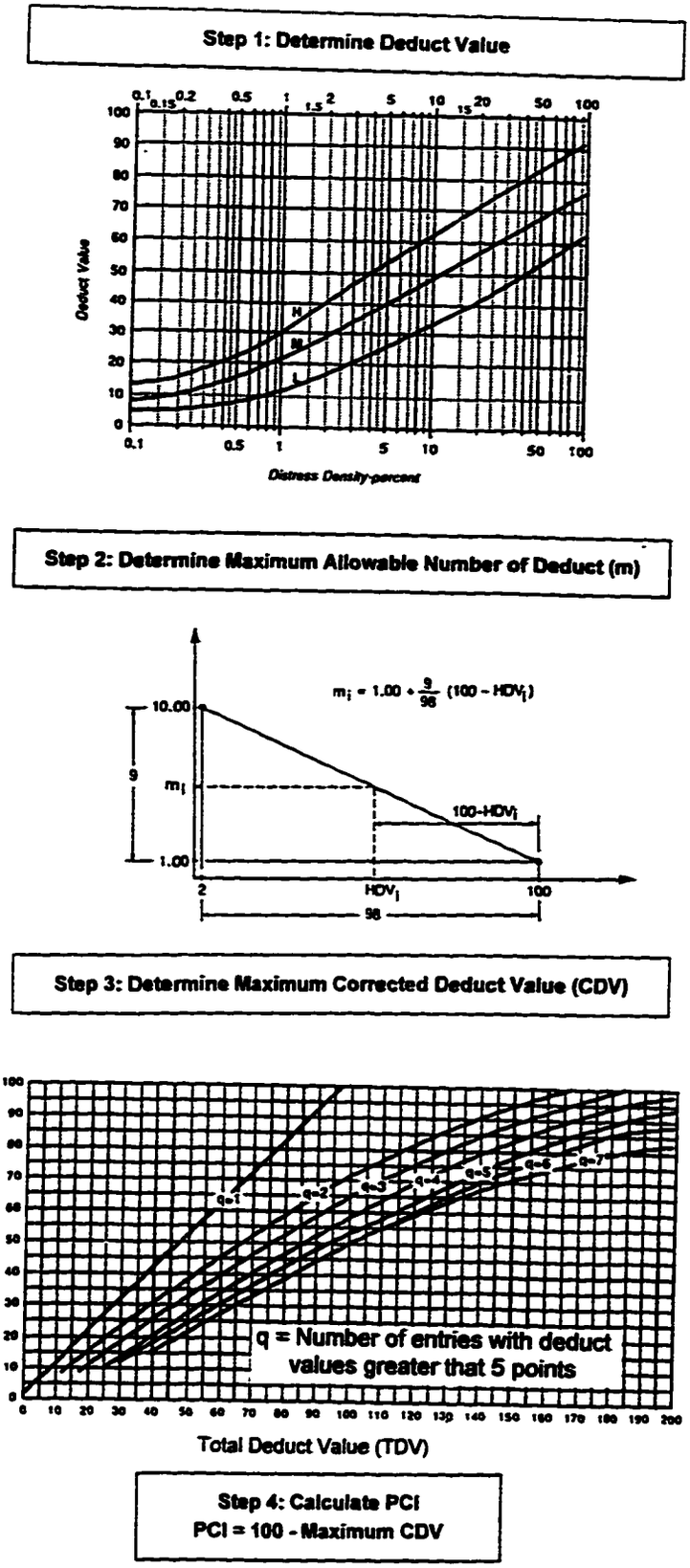


Figure 2.21. Modified PAVER PCI calculation method [Shahin 1994].

Pavement performance models have different forms and types. However, they can be categorized into the following four basic types [Haas et al. 1994]:

1. Purely mechanistic, based on some primary response (behavior) parameters such as stress, strain, or deflection,

2. Mechanistic-empirical, where a response parameter is related to measured structural or functional deterioration, such as distress or roughness through regression equations,

3. Regression, where the dependent variable of observed or measured structural or functional deterioration is related to one or more independent variables like subgrade strength, axle load reputations, pavement layer thickness and properties, environmental factors, and their interactions, and

4. Subjective, where experience is "captured" in a formalized or structured way, using transition process model, for example, to develop deterioration prediction model.

In terms of analysis method used in modeling, performance models can be divided into deterministic and probabilistic models. In pavement performance modeling, the most popular method for building deterministic models is the regression analysis, and for probabilistic models, is the Markov chain process [Chen et al. 1995]

Haas and Hudson [1982] listed some of those models used in pavement performance prediction like AASHTO Interim Guide method, Ontario method, System Analysis Method for Pavement (SAMP) versions 5 and 6, and ViscoElastic SYStem (VESYS) method.

The most desirable models for pavement performance are the purely mechanistic models. However, these models have not been developed and they do not exist for prediction of pavement distresses such as rutting, fatigue cracking, joint faulting, etc. [Majidzadeh 1988 and Haas 1994]. The second most desirable models are the mechanistic-empirical models that have been calibrated to local conditions. Here, "calibration function" is determined by applying the prediction model to local pavements and obtaining a calibration factor that is the ratio of observed distress (performance) to predicted distress. This factor is then regressed against the input variables to obtain the calibrating function which is used to calibrate the predicted distress [Majidzadeh 1988]. For example, a shift factor for fatigue cracking was specified by Bubshait [1985], where the actual number of load repetitions until failure for each season was divided by the calculated number of load repetitions to obtain the fatigue shift factor or relationship between distress and performance. On the other hand, a shift factor for VESYS model calibration of rut depth prediction for local use in the Saudi Arabia environment was specified [Al-Abdul Wahhab and Ramadhan 1990].

Examples of this type of modeling are the VESYS and Probabilistic Distress Models for Asphalt Pavements (PDMAP) models that use the calculated stresses, strains, and deflections in certain empirically derived equations to predict fatigue cracking, rutting, low-temperature cracking, and roughness

In terms of analysis method used in modeling, performance models can be divided into deterministic and probabilistic models. In pavement performance modeling, the most

popular method for building deterministic models is the regression analysis, and for probabilistic models, is the Markov chain process [Chen et al. 1995]

Markov process modeling is an application of a dynamic programming to the solution of stochastic (probabilistic) decision process. This method can be described by a finite number of states. The transition probabilities between the states are described by Markov chain [Taha 1992].

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

2.4.3.1 Regression Performance Models

Regression methods are frequently used to analyze data from unplanned experiments, such as those arise from observation of uncontrolled phenomena, or historical records [Montgomery 1984]. In these methods, there is a single dependent variable or response which depends on a set of independent or regressor variables. The relationship between these variables is determined in an equation form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_x + \varepsilon \qquad (2.3)$$

where:

Y = the dependent variable,

X_1 , X_2 , X_3 ,..., X_k are the independent (regressor) variables,

β_0 , β_1 , β_3 ..., β_k are the regression unknown coefficient, and

ε, is the random error

This form is called a multiple linear which is the simplest among other forms of regression equations including exponential, logarithmic, power, and combination of these forms. The adequacy of the regression model is judged by several statistics. The coefficient of determination (goodness of fit), R^2 is often used for this purpose. It is the proportion of variability in the data explained or accounted for by the regression model [Montagemry 1984]. The value of R^2 is between 0 and 1, generally, higher is the value, better is the model fit. The F-test is one of the statistics used for checking the hypothesis, in the multiple linear regression model, that at least one of the independent variables in the model contributes significantly to the fit. The t-test is another statistic used to check the hypothesis of significance of any individual coefficient β_j in the model.

A mathematical model of pavement performance (MMOPP) was developed by Ullidtz [1987] for flexible pavements. It has the capability of predicting the longitudinal roughness, rutting, and cracking of three layer pavements. The approach taken in MMOPP was to model the actual variation of layer thickness, stiffness, plastic, and strength parameters along the length of the road as well as the variation in load due to dynamic effects. If these

parameters do not vary along the length of the road, then the road will remain smooth. This approach is shown schematically in Figure 2.22.

Simplified pavement performance models that can be used for forecasting pavement conditions on the minimal amount of available data, were developed for different pavement types [Lee et al. 1993]. These models predict present serviceability rating (PSR) using knowledge of the pavement's age, cumulative equivalent single-axle loads, and pavement structure parameters. The models were extended by the development of adjustment factors to various functional groups and climatic zones using available performance data base.

The following nonlinear model is the general form of these prediction models:

$$PSR = PSR_I - a * STR^b * AGE^c * CESAL^d \qquad (2.4)$$

where

PSR_I = initial value of PSR at construction (4.5 used in analysis);

STR = existing pavement structure:

- structural number for flexible pavement,
- total AC overlay thickness for composite pavements (in.), or
- slab thickness for concrete pavements (in.);

AGE = age of pavement since construction or major rehabilitation (overlay) (years); and

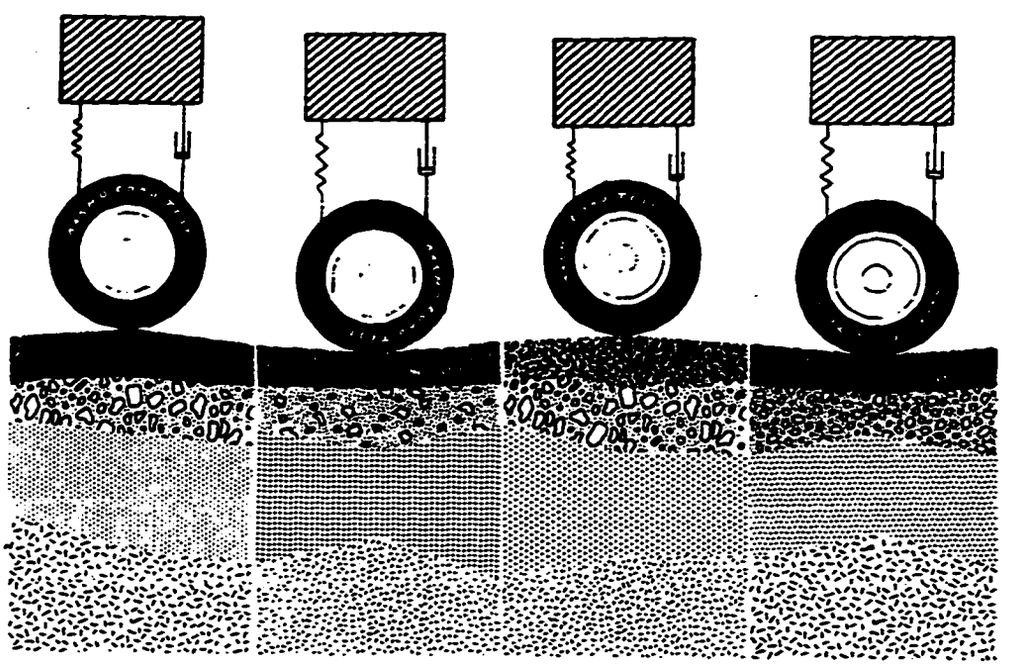


Figure 2.22 MMOPP attempts to model the actual variations in materials, thickness, and loads along the length of the road [Ullidtz 1987].

CESAL = cumulative 18-kip equivalent single-axle loads (ESALs) applied to pavement in the heaviest traffic lane (millions).

Table 2.2 summarize the results of the above model for different pavement types.

The performance-prediction model in PMS-III system for Ohio Department of Transportation (ODOT) includes the prediction models required for forecasting deterioration of pavement attributes with time [Majidzadeh et al. 1990]. These prediction models are dependent on traffic, pavement structure, and soil characteristics. The general form of this performance or damage equation is exponential and s-shaped, that is:

Damage Function = f [exp (traffic, pavement structure, soil characteristics) (2.5)

The damage functions were developed from historic performance data. Updating techniques have been incorporated so that performance prediction models can be updated annually as new pavement condition data become available.

Simple performance prediction curves were suggested by Sharaf [1991] that relate pavement condition index (PCI) values to the age of pavement. These curves can be generated for each family of sections with common characteristics. Sets of PCI and age values can be easily obtained for section in each family, and statistical techniques (typically regression analysis) can be applied to construct relationships between PCI and pavement age. The model suggested is as follows:

$$C = 100 - b * x^m \qquad (2.6)$$

Table 2.2. Summary of proposed prediction models [Lee et al. 1993].

Parameter	Model				
	FLEX	COMP	JPCP	JRCP	CRCP
$\log_{10}(a)$	1.155	-0.4185	0.5104	1.7241	0.7900
b	-1.872	-0.1458	-1.7701	-2.7359	-1.3121
c	0.3499	0.5732	1.0713	0.3800	0.1849
d	0.3385	0.1431	0.2493	0.6212	0.2634
R^2	0.52	0.58	0.79	0.57	0.37
SEE	0.45	0.38	0.26	0.4	0.31
N	522	509	117	254	1204

where

C = PCI value

x = pavement age in months measured from the date of last application of major activity

b = slope coefficient

m = value that controls the degree of curvature of performance curve.

Fixing the degree of curvature 'm' value to 1.5, several models for different maintenance alternatives could be obtained as shown in Table 2.3.

Some researchers considered the prediction of future distress levels rather than the prediction of a composite index. For example, Minnesota Department of Transportation (Mn/DOT) has a large pavement distress data base, which dates back to 1967 [Lukanen and Han 1994]. This large data base enabled researchers to develop performance prediction models for different distresses. The pavements were grouped in 100 different groups based on pavement structures, surface condition, and use.

Pavement performance using roughness and rut depth measures has the advantage that several site-specific conditions like wear resistance, cross section, axle load limit, traffic conditions, traveling speed, and climate, which are difficult to monitor, are reflected in surface condition recordings. Thus, they need not to be monitored separately for the purpose of pavement performance prediction. This way looks rather simplified, since a

Table 2.3. Performance models and service lives [Sharaf 1991].

Alternative	Performance Curve	Service Life At PCI = 30
Surface Treatment	$PCI = 100 - 0.0319\,(AGE)^{1.5}$	14
Thin Overlay	$PCI = 100 - 0.0158\,(AGE)^{1.5}$	22
Thick Overlay	$PCI = 100 - 0.0129\,(AGE)^{1.5}$	25
Reconstruction	$PCI = 100 - 0.0104\,(AGE)^{1.5}$	29

main problem appears in predicting pavement performance, when there are considerable changes in the above mentioned factors that have influences on the pavement performance, such as changes in axle load limit, traffic volume, or traveling speed [Haugodegard et al. 1994].

The United Kingdom PMS [Philips 1994] has also a pavement performance modeling for each defect on different pavement types. Deterioration curves for defects are user-definable and are specified as a series of discrete points; intermediate values are determined automatically by linear interpolation. Alternatively, default curves have been proposed for the first implementation of UKPMS, given that users may not have the data from which curves are defined.

Similar pavement performance prediction models were developed for Norwegian Public Roads based on rutting and roughness [Haugodegard et al. 1994]. These curves were partly empirical and partly mechanistic. An expert system, called DEkspert, was developed in Norway for distress diagnosis and for selecting maintenance and rehabilitation activities on roads with flexible pavements. This system is intended to supply alternative solutions to PMS system where the cost calculations and optimization will be performed.

Separate prediction models were developed for estimation of different modes of distress, for different types of surfaces, for major highways in India [Sood et al. 1994]. A total of 113 test sections were selected for collecting periodic performance data over a period of 3 to 5 years. These data were analyzed in three categories: (1) static data on pavement characteristics that included category of road type, pavement thickness, and

composition of different layers, pavement width, and shoulder; (2) dynamic data on pavement condition that included periodic pavement performance data such as roughness, characteristic deflection, subgrade moisture content, and different forms of pavement distress; and (3) traffic characterization data which included the details of traffic volume (time of day, direction, average daily commercial traffic) and axle load. The large amount of data collected were subjected to the following forms of analysis: graphical, linear and non-linear regression, and multivariate linear and nonlinear analysis. Separate models were developed for two different types of pavement surfaces normally used in India: asphaltic concrete and premix carpet surfaces. These models were in terms of roughness and crack progression.

Markow [1990] suggested a pavement deterioration prediction that predicts the annual reduction in PCI as a function of pavement structure, traffic loads, and an age-related term to reflect non-load causes of damage. Then the pavement maintenance was modeled as a periodic, limited adjustment in current PCI. Over time, the cumulative effects of these adjustments are to reduce the rate of pavement deterioration.

Empirical-mechanistic model for pavement performance prediction of three categories of pavement: 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 model for the performance prediction of flexible pavement with no overlay is as follows:

$$PCR(t) = 90 - a\left[\exp(Age)^b - 1\right]\log\left[\frac{ESAL}{SNC^c}\right] \tag{2.7}$$

with a = 0.6349; b = 0.4203; c = 2.7062; and $R^2 = 0.75$.

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,

$$SNC = \sum a_i h_i + SNg \tag{2.7a}$$

where

a_i = material layer coefficient,

h_i = layer thickness (in.),

SNg = subgrade condition, and

CBR = in situ California Bearing Ratio of subgrade (%),

The subgrade condition SNg, is defined as

$$SNg = 3.51 \log(CBR) - 0.85 (\log(CBR))^2 - 1.43 \tag{2.7b}$$

Similar equations were developed for flexible pavement with overlay and composite pavement, respectively, those equations are:

Pavement with overlay prediction model:

$$PCR(t) = 90 - a\left[\exp(Age)^{b} - 1\right]\log\left[\frac{ESAL}{SNC^{c} * T}\right] \tag{2.8}$$

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

Composite pavement prediction model:

$$PCR(t) = 90 - a\left[\exp\left(\frac{Age}{T}\right)^{b} - 1\right]\log(ESAL) \tag{2.9}$$

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

All other parameters are as explained before. Figure 2.23 shows a typical scattergram of pavement condition data (predicted PCR) with age, for ADT = 3000, and SNC = 3.0, using equation 2.7, and 95% confidence level. On conclusion of applying these models for life-cycle analysis, the life cycles are greatly increased if repairs are performed while the pavement is still in the first phase of degradation (slow rate of deterioration). Timely maintenance treatment will reduce the equivalent uniform annual cost (EUAC).

In PAVER method, as a part of analysis performed to obtain PCI prediction curves on family-by-family basis, deterministic, constrained polynomial curves are fitted for each family's data (PCI, age). These curves are then used on a section-level basis to predict the

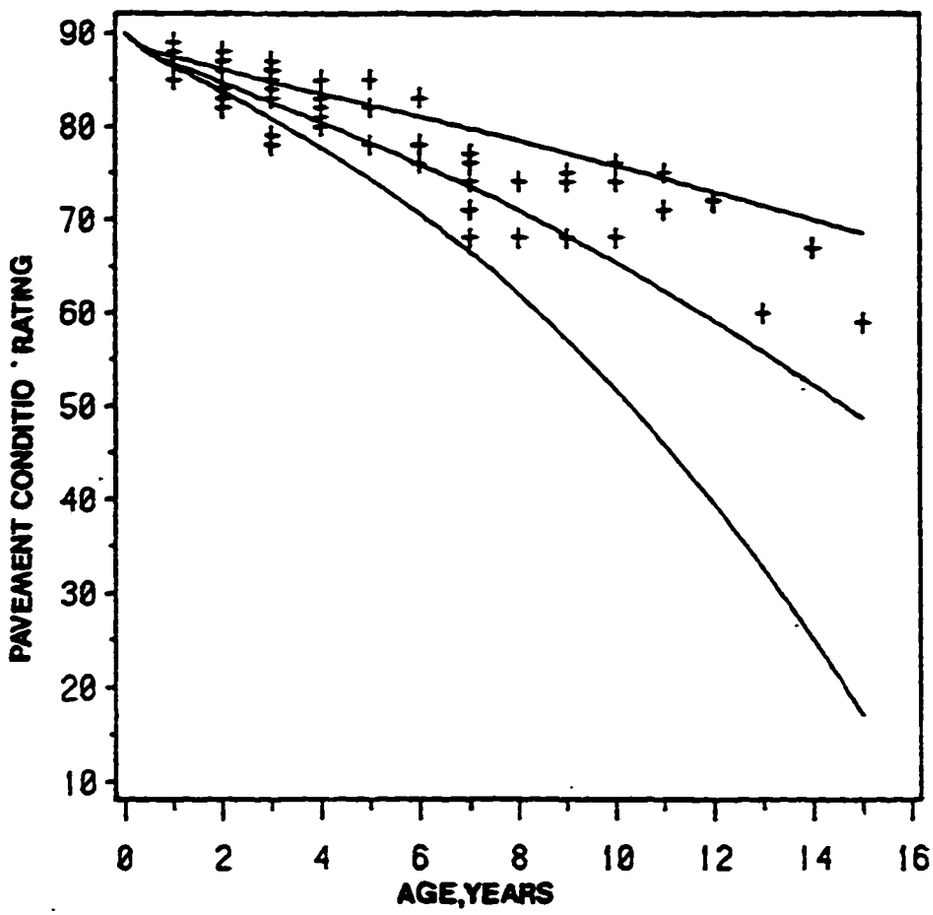


Figure 2.23. Scattergram of pavement condition data with age [George et al. 1989].

future PCI of each section [Feighan et al. 1989; Shahin and Walter 1990; and USAERL 1993]. This prediction method consistes of the following steps [Shahin 1994]:

1. Defiine the pavement family,

2. Filter the data,

3. Conduct data utlier analysis,

4. Develop the family model, and

5. Predict the pavement section condition.

Figure 2.24 shows a typical example for a pavement section condition prediction in relation to family model.

Rilett et al. [1989] have developed a pavement deterioration model that has the capability of separating the contributions of traffic and environment on pavement deterioration, and then the life-cycle costs attributable to traffic can be calculated. This model considers the loss of serviceability, as measured by riding comfort index (RCI), to be a measure of deterioration.

The same methodology of separating environmental effects from traffic effects on roughness was developed by Bein et al. [1989] for Canadian Saskatchewan area. They use the World Bank's Highway Design and Maintenance Standard Model (HDM3) for roughness progression after calibrating it for climatic conditions typical to Canadian Prairites. HDM3 models are based on mechanistic principles of pavement behavior and are

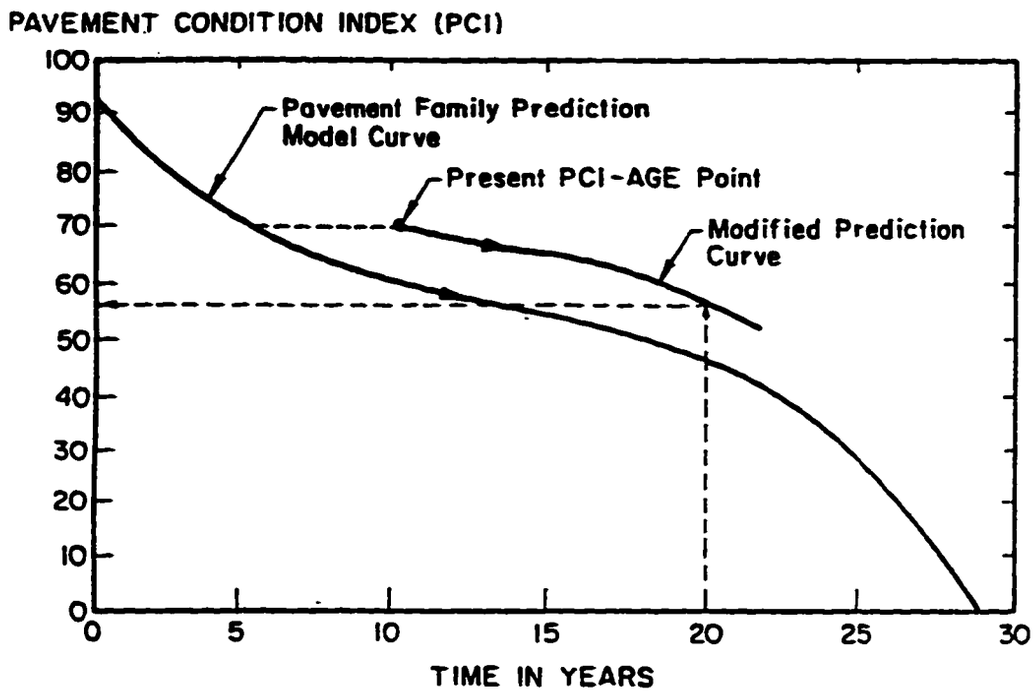


Figure 2.24. Pavement section prediction in relation to family model [Shahin 1994].

structured in a way that facilitates local adaptation. Variables relating to pavement structural properties and structural loading as well as to age, maintenance, environmental factors are included in the models [World Bank 1989]. Figure 2.25 shows the structure of HDM3 model.

2.4.3.2 Probabilistic Performance Models: Markov Process

The rate of pavement deterioration is not fixed and moreover is uncertain. Therefore, it is a rather simplified technique to use a fixed rate of deterioration in any pavement performance prediction model. Instead, probabilistic models should be used to capture the uncertainty of the rate of deterioration. This problem can be overcome by the use of Markov process.

Markov decision process is used to replace the deterministic deterioration modeling by the probabilistic one. In this method, the state that describes the current pavement condition is changed to the next state at certain probability level. A group of similar pavement sections (family) in good condition, for example, has certain probability that it will change to poor condition in a specific time period. This probability of the change of condition (state) is called transition probability.

A Markov process, therefore, is a stochastic system for which the occurrence of future state depends on the immediately preceding state and only on it. The probability:

$$P_{x(n-1),x(n)} = P\{a_{t(n)} = x_{(n)} | a_{(n-1)} = x_{(n-1)}\} \qquad (2.10)$$

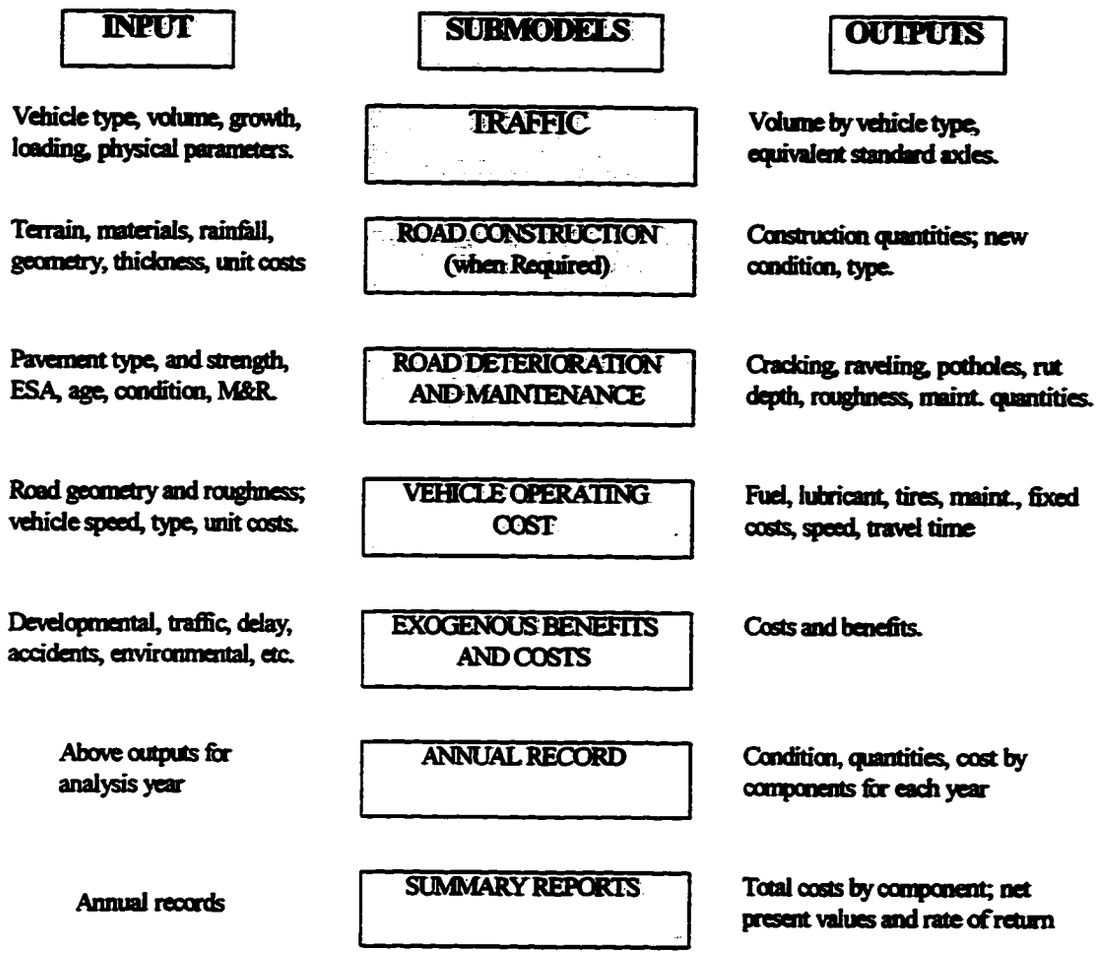


Figure 2.25. Basic structure of HDM3 [World Bank 1989].

is called the transition probability. It represents the conditional probability of the system being in state, $x_{(n)}$ at time, $t_{(n)}$, given it was in state, $x_{(n-1)}$ at time, $t_{(n-1)}$. This property is also referred to as one-step transition probability since it describes the system between $t_{(n-1)}$ and $t_{(n)}$ times [Taha 1992]. The transition probability is assumed to be fixed over time. The transition probability is usually arranged in a matrix form called transition probability matrix.

The Markov chain is a probabilistic model that accounts for the uncertainties present with respect to both the existing pavement condition and future pavement deterioration. The underlying concept of this method is that a pavement section may be in one of several states or conditions and that unless maintenance or rehabilitation is undertaken, the condition of the pavement will worsen over time. The amount of pavement deterioration in a given period, such as a year, is a random variable depending only on the most recent state of the pavement and the amount and type of traffic loading that the pavement has during that period of time.

For pavement prediction modeling, the transition probability matrix defines the probability that a pavement in an initial condition state will be in some future state. This matrix is usually obtained by using a formal interview method. The experts are asked to determine to the best of their ability, the probability a pavement in one condition state go to each of the future condition states in one time period [Haas et al. 1994]. Because the Markov process estimates the future condition state solely from the current condition state, other factors that affect the pavement behavior are handled by defining a transition matrix

for each combination of factors such as pavement type, pavement thickness, traffic volume or load, and environmental conditions.

As an example of using the Markov process modeling, Butt et al. [1994] developed a pavement deterioration model based on the Markov process. In their work, the state of a pavement is defined in terms of pavement condition index (PCI) rating, The PCI which ranges from 0 to 100, has been divided into 10 equal states, each of which has a PCI interval of 10 points. A duty cycle for a pavement is defined as 1-year duration of weather and traffic. A state vector indicates the probability of a pavement section being in each of the 10 states in any given year. All pavement sections are grouped into families of similar characteristics. For establishing the transition probability matrix, it is assumed that the pavement condition will not drop by more than one state (10 PCI points) in a single year. Table 2.4 shows typical transition probability matrix for five families of sections: asphaltic concrete pavement (AC), stabilized pavement (ST), asphaltic concrete thin overlay, asphaltic concrete structural overlay, and asphaltic concrete reconstruction. Thus a pavement will either stay in its current condition state or transit to the next lower state in 1 year. The state vector for any duty cycle, t, is obtained by multiplying the initial state vector p(0) by the transition probability matrix raised to the power t. This procedure is shown in Figure 2.26. With this procedure, if the transition matrix can be estimated, the future state of the pavement at any duty cycle, or age, can be predicted as shown typically in Figure 2.27

There are several advantages to the Markov process modeling including direct calibration, by formalized way, the experience of local engineer and the ability to develop

Table 2.4. Typical transition probability matrix [Fieghan et al. 1989].

FAMILY	STATE 1	STATE 2	STATE 3	STATE 4	STATE 5	STATE 6	STATE 7	STATE 8	STATE 9	STATE 10
1	0.7825	0.8656	0.8717	0.8752	0.0006	0.4144	0.2845	0.6346	0.3548	1.0000
	0.0001	0.5021	0.5015	0.5014	0.0013	0.0001	0.0000	0.0000	0.0000	1.0000
	0.0010	0.5000	0.4999	0.4999	0.4765	0.1364	0.0370	0.0112	0.0025	1.0000
	0.1374	0.6502	0.5021	0.5003	0.0001	0.0361	0.0010	0.0001	0.0005	1.0000
2	0.8481	0.4070	0.2631	0.4502	0.6058	0.4976	0.5000	0.4995	0.5880	1.0000
	0.1821	0.4714	0.4736	0.4815	0.0615	0.0029	0.0016	0.0000	0.0442	1.0000
	0.0000	0.5001	0.5000	0.5000	0.0012	0.0001	0.0000	0.0000	0.0000	1.0000
3	0.7764	0.8579	0.8627	0.8631	0.0007	0.4767	0.5376	0.4954	0.6414	1.0000
	0.0000	0.5000	0.5000	0.5000	0.0001	0.0302	0.0336	0.0008	0.0007	1.0000
	0.6862	0.8740	0.6205	0.3080	0.0010	0.0001	0.0000	0.0000	0.0000	1.0000
4	0.8136	0.7798	0.7829	0.7832	0.0038	0.0001	0.7491	0.2284	0.7604	1.0000
	0.0010	0.5000	0.4999	0.5000	0.0022	0.0006	0.0001	2.0000	0.2600	1.0000
	0.9853	0.5002	0.5000	0.4999	0.0001	0.0122	0.0327	0.0006	0.0003	1.0000
5	0.7825	0.8656	0.8717	0.8752	0.0006	0.4144	0.2845	0.6346	0.3546	1.0000
	0.0001	0.5021	0.5015	0.5014	0.0013	0.0001	0.0000	0.0000	0.0000	1.0000
	0.0010	0.5000	0.4999	0.4999	0.4765	0.1364	0.0370	0.0112	0.0025	1.0000
	0.1374	0.6502	0.5021	0.5003	0.0001	0.0361	0.0010	0.0001	0.0005	1.0000

FAMILY 1: AC PAVEMENTS
FAMILY 2: ST PAVEMENTS
FAMILY 3: AC THIN OVERLAY
FAMILY 4: AC STRUCTURAL OVERLAY
FAMILY 5: AC RECONSTRUCTION

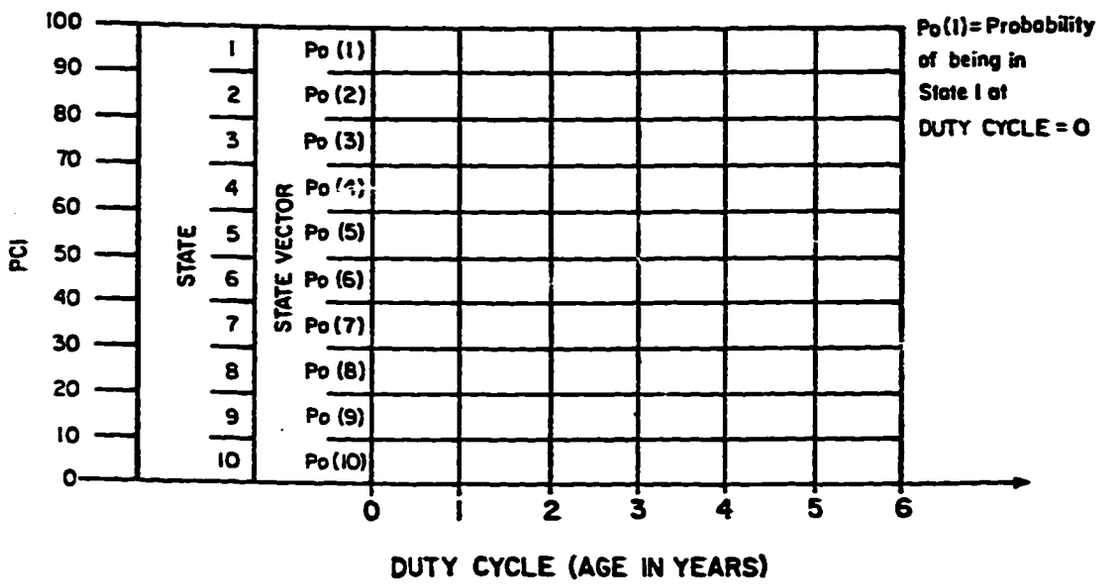


Figure 2.26. Schematic representation of state, state vector, and life cycle [Shahin 1994].

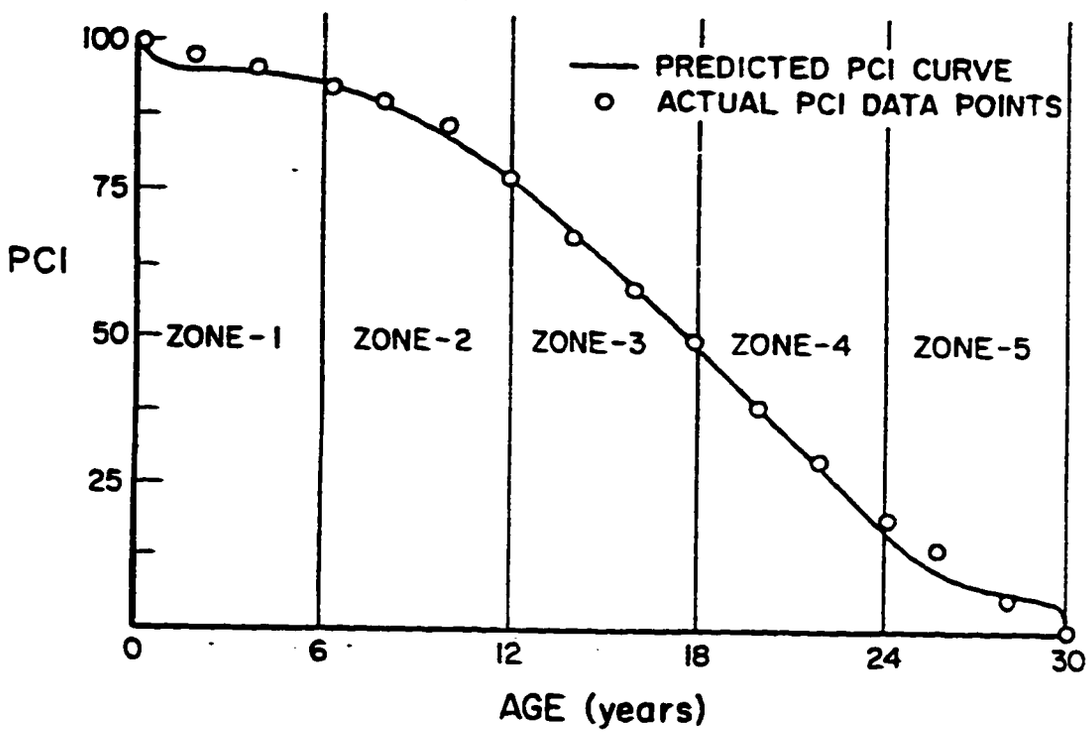


Figure 2.27. Typical PCI prediction curve using Markovian model[Butt et al. 1994].

the performance curves with out any historical data. However, there are several disadvantages as well including the need to a tedious effort of developing a transition probability matrix for each combination of factors that affect the pavement performance. In addition, pavement history is difficult to include in this modeling since the estimate of the future state is only based on the current state [Haas et al. 1994].

Markov process was selected to model the pavement performance or behavior using both subjective and objective data [Karan and Haas 1976]. In this Markov performance prediction model, serviceability of a pavement at any particular time is characterized in states, where the state is defined by the Urban Serviceability Index (USI). The total range of USI is divided into ten discrete ranges, each constitutes a state. Pavement class is another essential requirement for Markov performance model. Pavement network section is divided in groups (classes), each is common in important parameters such as pavement type and thickness, traffic volume composition, subgrade type, and environment. The next requirement for Markovian performance model is the development of "transition matrices" for each rehabilitation strategy and pavement class. Each (P_{ij}) in a transition matrix gives the probability that a particular class of pavement currently occupying a particular state (i) will change (e.g. makes a transition) to another particular state (j) after another year of service, under any given type of maintenance strategy. The initial transition matrices can be obtained using subjective opinions of experienced engineers, whereas periodic inventory information on pavement performance should be used to continually update these matrices. Figure 2.28 shows typical example of initial transition matrix, V(o) for one type of pavement. The Markov performance prediction model has the following form:

Thin Pavement : 15-20 inches
CLASS 1 = Low Traffic : 3000 <AADT <5000
Strong Subgrade: Granular

FROM STATE i \ TO STATE j	9	8	7	6	5	4	3	2	1	0	DESCRIPTION OF STATES: State No.	Average Roughness (in/mile)	Average % Damaged Area
9	95	5									9	0	0
8		90	5	5							8	20	0.4
7			85	5	5	5					7	65	1.5
6				80	7	7	6				6	110	4.0
5					60	25	10	5			5	160	12.0
4						40	30	20	5	5	4	210	25.0
3							20	40	30	10	3	260	43.0
2								10	70	20	2	310	63.0
1									5	95	1	370	80.0
0										100	0	>400	>90.0

Figure 2.28. Typical example of initial transition probability matrix [Karan and Hass 1976].

$$V(n) = V(o) * M^n \tag{2.11}$$

$$E_{USI}(n) = E * V(n) \tag{2.11a}$$

where

V(o) = initial state vector, which describes the present serviceability level of an existing pavement (or the serviceability level of a new pavement immediately after construction)

M = homogeneous, one step transition probability matrix

V(n) = marginal state vector for year n

E = expected state vector which is defined by the mean USI values of each state (i.e. 9.5, 8.5, 7.5, etc.), and

$E_{USI}(n)$ = expected (mean) USI level of the pavement in year n.

One of the difficulties of using a Markov chain model for predicting performance is that it predicts the proportion of the entire pavement network falling into each pavement condition category during each future period. Because it forecasts the distribution of future pavement conditions, it does not predict the specific condition of a specific section and does not allow any later project-level analysis. Therefore, Markov chain model is only useful for network-level analysis.

A mechanistic pavement performance submodel was included in the stochastic mechanistic PMS developed by Chua et al. [1993 and 1994]. This mechanistic modeling is achieved in two stages. The level of controlling structural response, the stress or strain in the pavement section causing the initiation and propagation of distress, is first determined through some structural analysis of the pavement. The level of distress in the individual mode is then determined as a function of the structural response via the mechanistic distress submodel. In this modeling, a stochastic mechanistic pavement distress submodels are developed to derive the transition probabilities.

2.5 PAVEMENT MAINTENANCE PRIORITIZATION

2.5.1 General

Priority-setting or ranking process, as used in PMS, aims to rank the pavement sections in an order of urgency for maintenance and repair. The importance of prioritization process in PMS comes from the fact that it is the main step before the final decision on maintenance program execution. The quality of priority-setting is directly influencing the effectiveness of available resources which are, in most cases, the primary judgment of the decision maker [Sharaf 1993].

Priority analysis is a systematic process that determines the best ranking list of candidate sections for maintenance based on specific criteria such as pavement condition, traffic level, pavement function, etc. These criteria are grouped to form an index that should consider all the factors that affect pavement performance. Various methods and schemes

are used for priority analysis ranging from simple listing based on engineering judgment to true optimization based on mathematical formulations as shown in Table 2.5. These methods can be divided into two broad groups: ranking methods and optimization methods. The ranking methods are subdivided into those based on a composite index determination and those based on economics [Karan 1984].

2.5.2 Composite Index Ranking Method

In a general survey about the status of pavement management systems adopted by SHAs in the United States [Irrgang and Maze 1993], several methods were used for developing priority indices. SHAs were found to use one or more of condition measures listed below:

- Pavement distress: The evidence of defects in the pavement (e.g., ruts, cracks, potholes, faulting, and blow-ups) is considered pavement distress.

- Ride or pavement roughness: Roughness is a measurement of a vehicle's response to roughness of the pavement profile.

- Traffic: Traffic is generally taken into account through using the average daily traffic volume or estimating equivalent single-axle loading that a pavement has received. Pavement sections with higher traffic volumes usually receive higher priorities.

Table 2.5. Different classes of priority programming methods [Haas et al. 1994].

No.	Class of Method	Advantages and Disadvantages
1	Simple subjective ranking of projects based on judgment.	Quick; subject to bias and inconsistency; may be far from optimal.
2	Ranking based on parameters, such as serviceability, deflection, etc.	Simple and easy to use; may be far from optimal.
3	Ranking parameters with economic analysis.	Reasonably simple; should be close to optimal.
4	Optimization by mathematical programming model for year-by-year basis	Less simple; may be close to optimal; effect of timing not considered.
5	Near optimization using heuristic and marginal cost-effective.	Reasonably simple; can be used in microcomputer environment; close to optimal results.
6	Comprehensive optimization by mathematical programming model taking into account timing effects.	Most complex; can give optimal program (maximum of benefits).

- Economic factors: When a treatment is assigned to a project on the basis of life-cycle cost analysis, several economic factors may be used in prioritization, including benefit-cost ratios and cost-effectiveness ratios.

- Functional class: Although several functional classification schemes are used by SHAs, functional classification is sometimes used in prioritization and results in higher-classification roadways' receiving a higher priority.

- Accidents: Accident rates are often taken into consideration when ranking projects, especially with regard to safety related maintenance activities.

- Friction or skid resistance: Skid resistance is a major component when safety-related maintenance is evaluated.

- Geometric deficiencies: Some SHAs consider the number of specific geometric deficiencies that could create safety problems when selecting MR&R projects. This assumes that the geometric deficiencies could be corrected through MR&R activities. Typical geometric deficiencies used are the number of narrow structures per mile, shoulder width, number of substandard stopping sight distances, lane width, and substandard horizontal curves per mile.

- Structural capacity: Most SHAs measure the structural capacity of a pavement through measuring the deflection or curve of the pavement that results from a static or repeated load.

- Engineering judgment: Some agencies structure their priority-ranking criteria to include engineering judgment or to be primarily based on engineering judgment.

- Age: When age is taken into account, it generally enters the priority analysis through measuring the number of years the pavement's performance will remain acceptable (remaining service life concept).

- Location: Some SHAs will provide a higher priority to a pavement on the basis of its strategic location. For example, highways that serve production centers, schools, and military facilities must be maintained in good condition without risking possible road closing.

Effective prioritization program should not only consider the current year conditions of pavement section, but also the consequences of likely changes in conditions in later years, that implies the ability to project pavement condition into future. Since treatments are not normally undertaken until at least one year after condition surveys are carried out, giving the time required for relative prioritization and establishing funding [Philips 1994].

Sharaf [1993] reported three models for priority setting. The first model calculates a priority index as follows:

$$\text{Priority Index} = \frac{\text{defect length}}{\text{traffic factor} * \text{defect factor}} \tag{2.12}$$

The traffic factor has values of 1.0, 0.5, 0.1 for average daily traffic levels of less than 2500 vehicle per day (vpd), between 2500-10,000 vpd, and more than 10,000 vpd,

respectively. The defect factor, on the other hand, is assigned for each section on the basis of the defect type (distress) and the required treatment (i.e. values between 0.1 and 1.0), lower values for major treatment (rehabilitation). After calculation of section indices, sections are ranked in descending order according to index values. The ranking list is converted to a cost list by using appropriate maintenance treatment unit cost. The second model is a modification of the previous model in a way that pavement sections are arranged according to road type (i.e. desert or agricultural roads) and traffic level into four classes, then this classification is used to determine the average treatment ages. Also in this model, predetermined budget shares are reserved for different maintenance treatments. This budget share is distributed on sections with highest-priority indices that require treatment. The third model is an extension of the second model in a way that the budget share is distributed among all the candidate sections in an optimization procedure.

There are different approaches to develop a priority combined index in pavement. These approaches include Unique Sum Approach, Utility Theory, Delphi Method, Factorial Rating Method, and Fuzzy Set Theory. A methodology for developing a comprehensive ranking index for flexible pavement using Fuzzy sets theory was presented by Zhang et al. [1993]. This methodology can capture the subjective judgment of pavement engineer and pavement user, and combine the most important pavement attributes such as, roughness, distress, structural capacity, and skid resistance into one index. The model developed is called the overall acceptability index (OAI).

The concept of Fuzzy set theory is useful for the presentation of imprecise knowledge of the type that is prevalent in human concept formulation and reasoning. Objects, in a fuzzy set, have a gradual, rather than an abrupt, transition from membership to non-membership as shown in Figure 2.29 [Zhang et al. 1993]. Each of the four pavement attributes, roughness, distress, structural capacity and skid resistance, has different level of severity. However, there is no distinct transition point between various levels but a gradual transition. Fuzzy set theory, therefore, is an ideal opportunity to be applied to ascertain severity level membership. The overall acceptability index (OAI) has the following form:

$$OAI = \left(\frac{W_1}{\Sigma W_i}\right) A_1 + \left(\frac{W_2}{\Sigma W_i}\right) A_2 + \left(\frac{W_3}{\Sigma W_i}\right) A_3 + \left(\frac{W_4}{\Sigma W_i}\right) A_4 \qquad (2.13)$$

where W_1, W_2, W_3, W_4 are the weighing factors for roughness, distress, structural capacity and skid resistance, respectively. The sum of all weighing factors, $\Sigma W_i = 1.0$. A membership A_i for each factor can be obtained from the membership curve developed using a nonlinear regression analysis for a subjective opinion survey about the level of acceptance for selected pavement attributes and their relative importance. This is typically shown in Figure 2.30. The OAI model is independent of the number of attributes included because the sum of the weighing values is always 1. Membership functions and weights for secondary roads are shown in Table 2.6.

A prioritization procedure was developed by Chen et al. [1993] as a part of an Urban Roadway Management System at network level (URMS). This procedure combines two

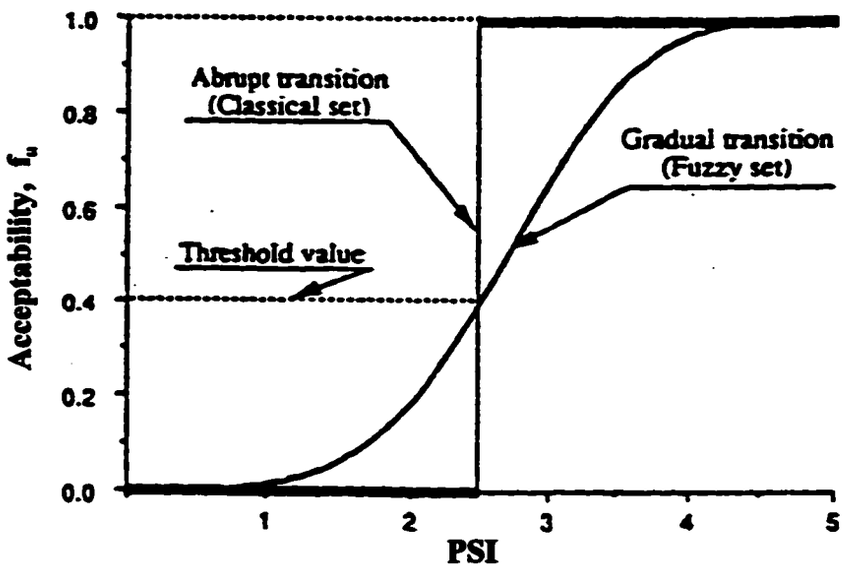


Figure 2.29. Concept of classical set and fuzzy set theories [Zhang et al. 1993].

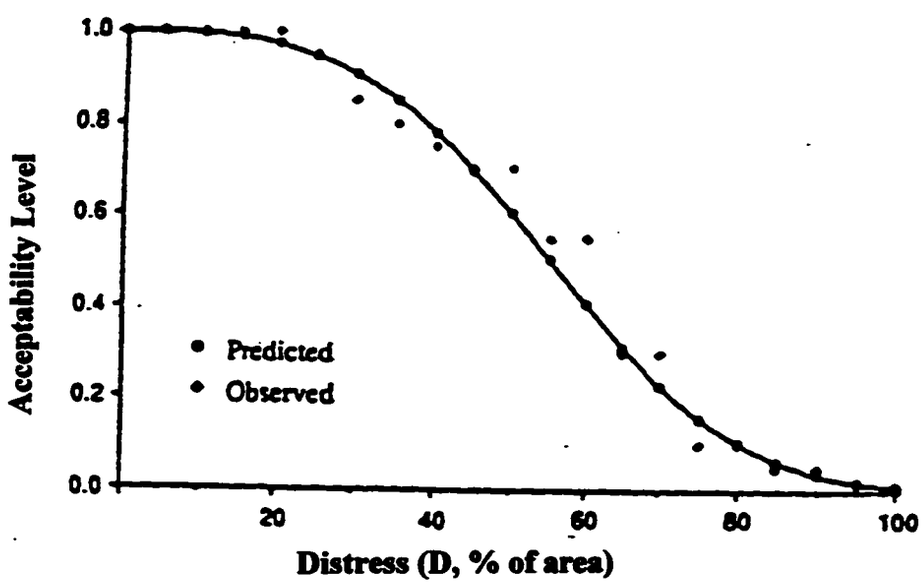


Figure 2.30. Membership of distress using fuzzy set theory [Zhang et al. 1993].

Table 2.6. Membership functions and weights for secondary roads [Zhang et al. 1993].

Attribute	Membership function	R^2	Weight
Roughness (PSI)	$A = 1 - \exp(-0.01274 * PSI^4)$	0.970	0.306
Distress (D)	$A = \exp(-0.00000185 * D^2)$	0.971	0.244
Structural Capacity (SC)	$A = 1 - \exp(-0.207 * (CS/50)^5)$	0.960	0.225
Skid Resistance (CF)	$A = -0.22 + 1.6308 * CF$	0.979	0.231

matrices and an equation for computing priority index (PIX). PIX is a function of PCI, pavement age, mixed traffic and street class. This procedure is shown in Figure 2.31.

The Research Institute, in KFUPM, has developed the PEMMS methodology for the industrial city of Al-Jubail road network [KFUPM-RI 1989]. A part of this system is maintenance prioritization procedure that includes important parameters such as pavement distress-based rating (PDR), roughness, skid resistance, and average daily traffic of each feature of a section/subsection to decide which road section/subsection should have a higher priority for maintenance treatment. Data processing and report generation include both the network-level and zone-level prioritization. Prioritization matrix combining all the above-mentioned parameters is shown in Figure 2.32. A number of features falling in the same prioritization categories is further prioritized according to their PDR values (lower PDR first). For example, all features having a traffic category TC1, pavement condition "fair", roughness rating as "acceptable", and skid resistance as "unacceptable", will fall under prioritization category F.13, and will be further prioritized according to their individual PDR in the form of F13.1, F13.2, F13.3, etc. in the descending order of PDR score. Another feature in this procedure is that all linked features like adjacent lanes in one direction of a divided highway or both directions in case of undivided highway, are linked together, and one value, which calls for highest priority, is applied to all linked features of a section/subsection. This revised priority is designated as compatible maintenance priority (CMP).

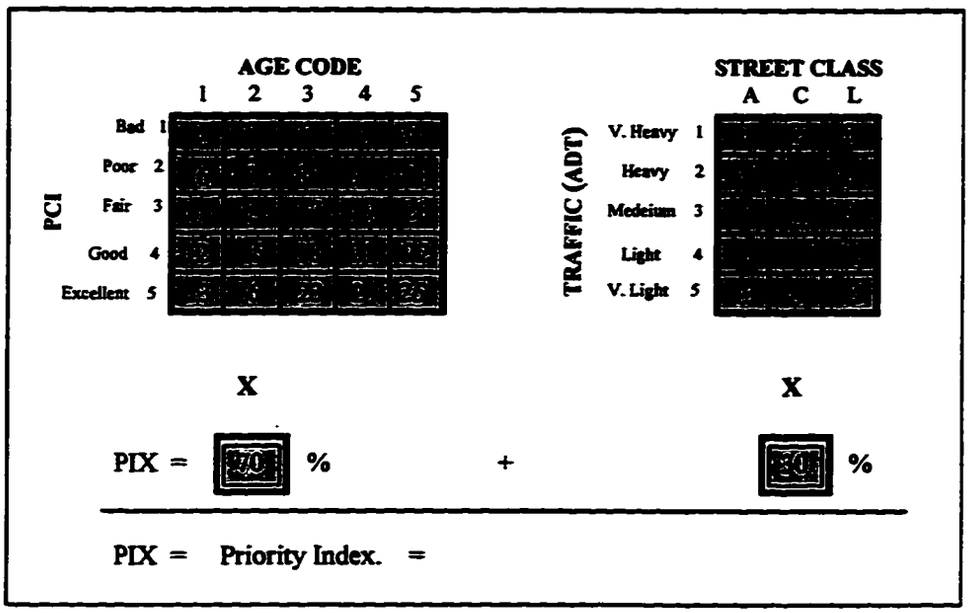


Figure 2.31. Priority index procedure used in URMS [Chen et al. 1993].

PAVEMENT DISTRESS RATING	ROUGHNESS RATING	TRAFFIC CATEGORY							
		TC1		TC2		TC3		TC4	
		SKID RATING							
		A	U	A	U	A	U	A	U
POOR	U	P1	P5	P2	P6	P3	P7	P4	P8
	A	P9	P13	P10	P14	P11	P15	P12	P16
FAIR	U	F1	F5	F2	F6	F3	F7	F4	F8
	A	F9	F13	F10	F14	F11	F15	F12	F16
GOOD	U	G1	G5	G2	G6	G3	G7	G4	G8
	A	G9	G13	G10	G14	G11	G15	G12	G16

A: ACCEPTABLE
U: UNACCEPTABLE

TC1:ADT>5000; TC2: ADT=3001-5000
TC3: ADT=1001-3000; TC4: ADT<1000 vph

Figure 2.32. PEMMS priority matrix [KFUPM-RI 1989]

For the application of PMS in Qinghai in China, Ningyuan and Haas [Ningyuan and Haas 1994] have developed a priority program that considers pavement type and life cycle, traffic volume and rank, and present pavement condition (structural capability and distress ratio). The formula for calculating the priority index is expressed as follows:

$$PI = \Sigma K_i . F_i \tag{2.14}$$

where

PI = priority index

F_i = priority factor (i.e., F_1, daily traffic volume; F_2, distress ratio; F_3, service life; F_4, pavement roughness; and F_5, pavement type); and

K_i = weight of corresponding factor, determined by type of pavement structure, traffic rank, and environmental condition; it can be adjusted in different regions.

2.5.3 Economic-based methods

Two prioritization methodologies have been developed in connection to PAVER method of pavement management system [Butt et al. 1994 and Feighan et al. 1989]. The first methodology is prioritization using optimal benefit/cost ratio, that uses the optimal M&R recommendations and corresponding benefit/cost ratios (or effectiveness/cost ratio) for each family-state combination produced from the dynamic programming. Each family consists of sections having common characteristics such as pavement type, traffic loading,

and surface thickness. On the basis of section PCI, the state is defined as a 10 PCI-wide bracket. For example, a section having PCI of 90-100 are defined to be in state 1. On the basis of user-defined weighing factors for each pavement section, all of the pavement sections in a given network are ranked with the use of weighted optimal effectiveness/cost (E/C) ratios. The higher the E/C ratio of a section, the higher the priority of that section for repair. The available budget is allocated to the pavement sections by selection of one section at a time from the ranked section list. The search for the section selection is stopped when the available budget is completely exhausted.

The second prioritization methodology is by using incremental benefit/cost ratio. This technique is a heuristic method for budget optimization. The overall flow chart for this algorithm is shown in Figure 2.33. This methodology differs from the previous one in that all feasible M&R alternatives of a section are identified and the corresponding inflated initial cost, present-worth costs, and weighted benefits are obtained. This information is used in the incremental benefit/cost ratio program to produce optimal M&R recommendations for each pavement section, including initial cost and type of treatment. The budget optimization also gives the total network-weighted benefits corresponding to optimal M&R recommendations [Butt et al. 1994].

An economic-based model for setting priorities for road maintenance and rehabilitation was suggested by Livneh and Craus [1990]. This model includes the grade for a condition of pavement distress (DR), grade of level of service (PSI), and the annual traffic (AADT). The model has the following mathematical form:

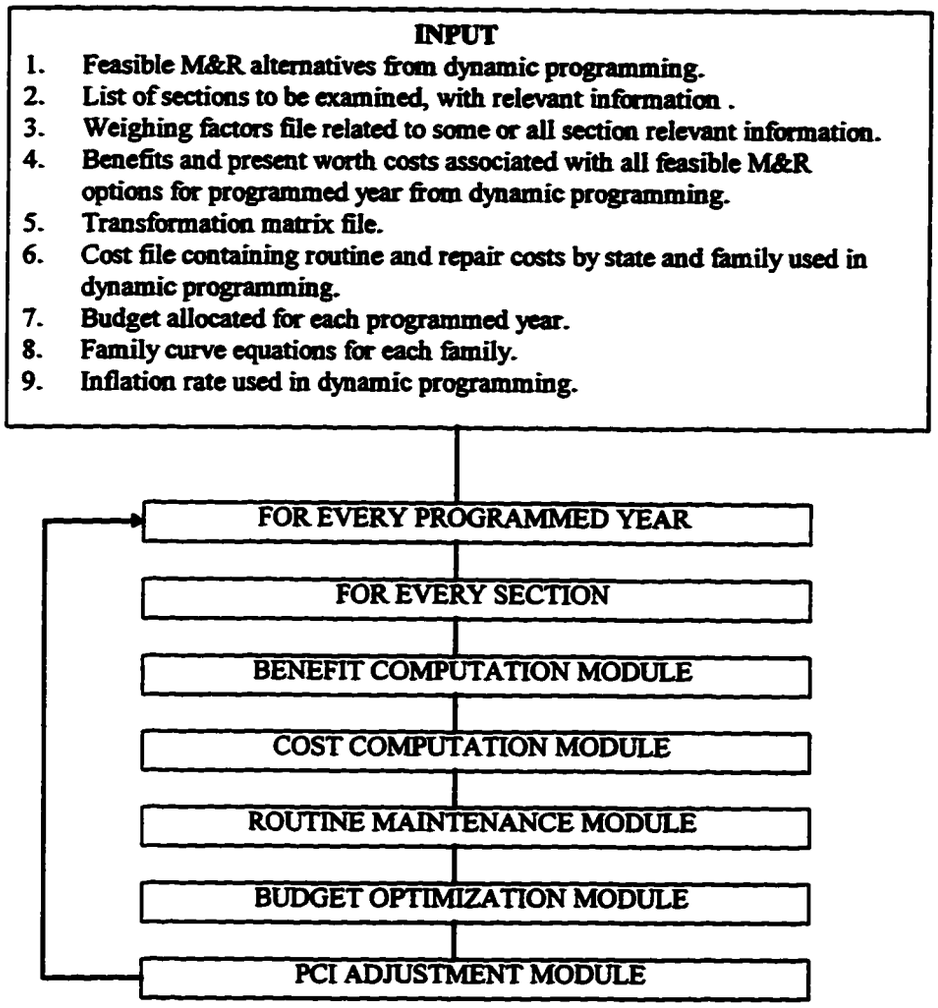


Figure 2.33. Prioritization using incremental benefit/cost ratio method [Butt et al. 1994].

$$P\% = k \times SN^{3.72} \times (5 - PSI) \times (AADT/1000) \quad (2.15)$$

where

P% = the first year rate of return, %,

SN = structural number, which is a function of distress grade DR (0 -100), using the following equation:

$$SN = 5 - 0.04\ DR \quad (2.15a)$$

PSI = Serviceability grade, (0 - 5),

AADT = Annual average daily traffic, and

k = numerical constant.

The first year rate of return is obtained for a given rehabilitation investment, that is the agency and road user's costs (before and after upgrading), and the benefits gained from investment in the maintenance and rehabilitation work. This model was found to be affected mainly by the AADT.

2.5.4 Neural Network Method

The neural network, unlike other methodology, does not require that user to specify mathematical relationships between input and output variables. Neural networks have the ability to learn from examples fed to them. Figure 2.34 shows the general structure of the neural network system. In case of priority assessment, input would consist of condition

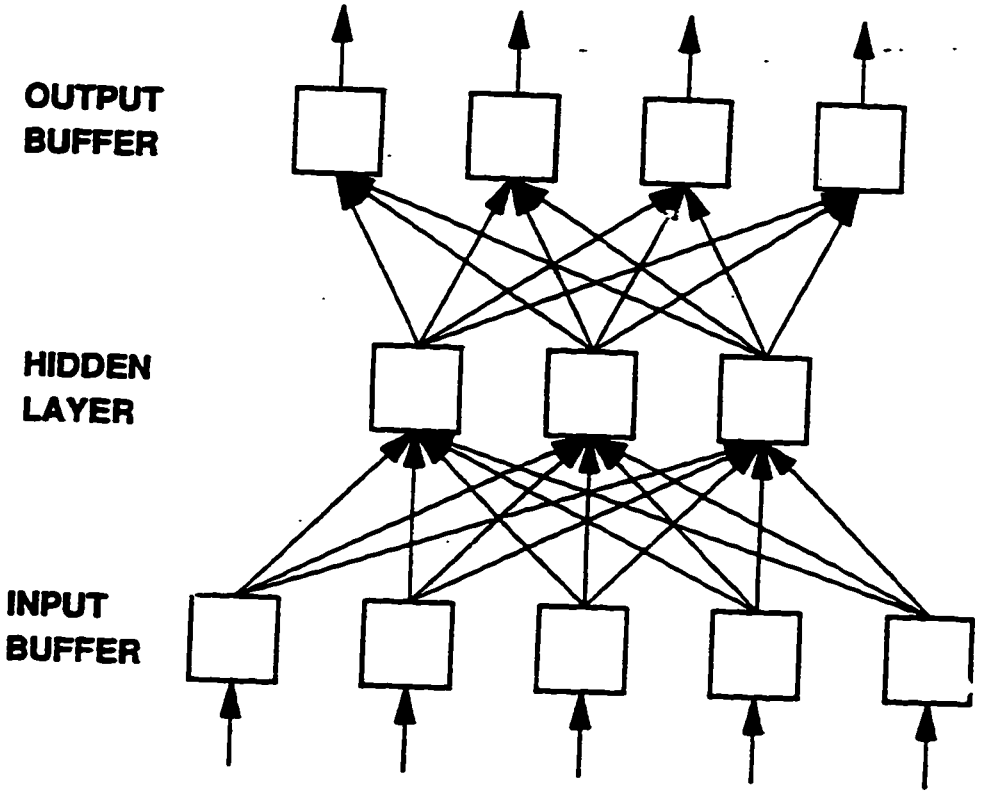


Figure 2.34. Neural network structure [Fwa and Chan 1994].

descriptions of road sections and the corresponding priority ratings awarded by highway engineers or maintenance personnel. Neural network model was used for priority rating of highway maintenance as the model used by Fwa and Chan [1994]. The adopted neural network model was tested separately by three different forms of priority-rating methods; linear and nonlinear condition index functions, and subjective priority assessments obtained from a pavement engineer. On conclusion, neural networks offer a procedure that, more closely, simulates priority-rating process specified by pavement maintenance personnel.

2.5.5 Analytical Hierarchy Process Method

2.5.5.1 General

Measurement in the real life involve quantifiaction that always concerns in how much of an attribute is present which requires a numerical statement of the amount. This measurement has different categories of scaling procedures. Following are some of the scale classifications [Munnally 1967]:

1. *Labels*: numbers are used purely as labels that have no implication of mathematical analysis.

2. *Categories*: numbers are used to group items with similar characterstics. These numbers have no quantitaive implications.

3. *Ordinal Scale*: its the scale in which: (1) a set of objects are ordered from "most" to "least" with respect to an attribute, (2) there is no indication of "how much" in an absolute sense any of the objects possess the attribute, and (3) there is no indication of how far apart the objects are with respect to each other. Rank ordering scale is an example of the ordinal scale.

4. *Interval Scale*: it is the one in which (1) the rank ordering of the objects is knwon with respect to the attribute and (2) it is known how much far aprat the objects are from one anotherwith respect to the attribute, but (3) no information is available about the absolute magnitude for any object.

5. *Ratio Scale*: this is obtained when (1) the rank order of the objects with an attribute is known, (2) the intervals between objects are known, and (3) in addition, the distance from a rational zero is known for at least one of the objects.

6. *Other Scales*: any possible variants of the above mentioned scales such as, orderd metric scale and logarithmic interval scale.

One of the methods used to scale and quantify measurements is Analytical Hierarchy Process (AHP). It is a theory, developed by Saaty in 1970s, for dealing with complex technological, economic, and sociopolitical problems. AHP aims at quantifying relative priorities for a given set of alternatives on a ratio scale [Saaty 1990; and Saaty and Vargas 1982].

There are three principles which one can recognize in problem solving. They are the principles of decomposition, comparative judgments, and synthesis of priorities. The decomposition principle calls for structuring the hierarchy to capture the basic elements of the problem [Saaty 1986]. In AHP, a hierarchy is an abstraction of the structure of a system to study the functional interactions of its components and their impact on the entire system. This abstraction can take several related forms, all of which essentially descend from an apex (an overall objective), down to sub-objectives, down further to forces, down to objective of the people who influence these forces, down to the objectives of the people and then to their policies, still further down to the strategies, and, finally, the outcomes which results from these strategies [Saaty 1990]. Figure 2.35 shows a typical schematic hierarchy of prioritization process. After the design of the problem components (hierarchy) is made, the second phase of the AHP is the evaluation which is base on the concept of paired comparisons. The elements in a level of the hierarchy are compared in relative terms as their importance or contribution to a given criterion that occupies the level immediately above the elements being compared. This process of comparison yields a relative scale of measurements of priorities or weights of the elements. These relative weights sum to unity [Vargas 1990].

A useful feature of the AHP is its applicability to the measurements of intangible criteria along with the tangible ones through a ratio scale. In AHP, a ratio scale between 1 and 9 is used to give the relative preference between two alternatives as shown in Table 2.7. This scale is able to capture a great deal of information and has proven to be extremely

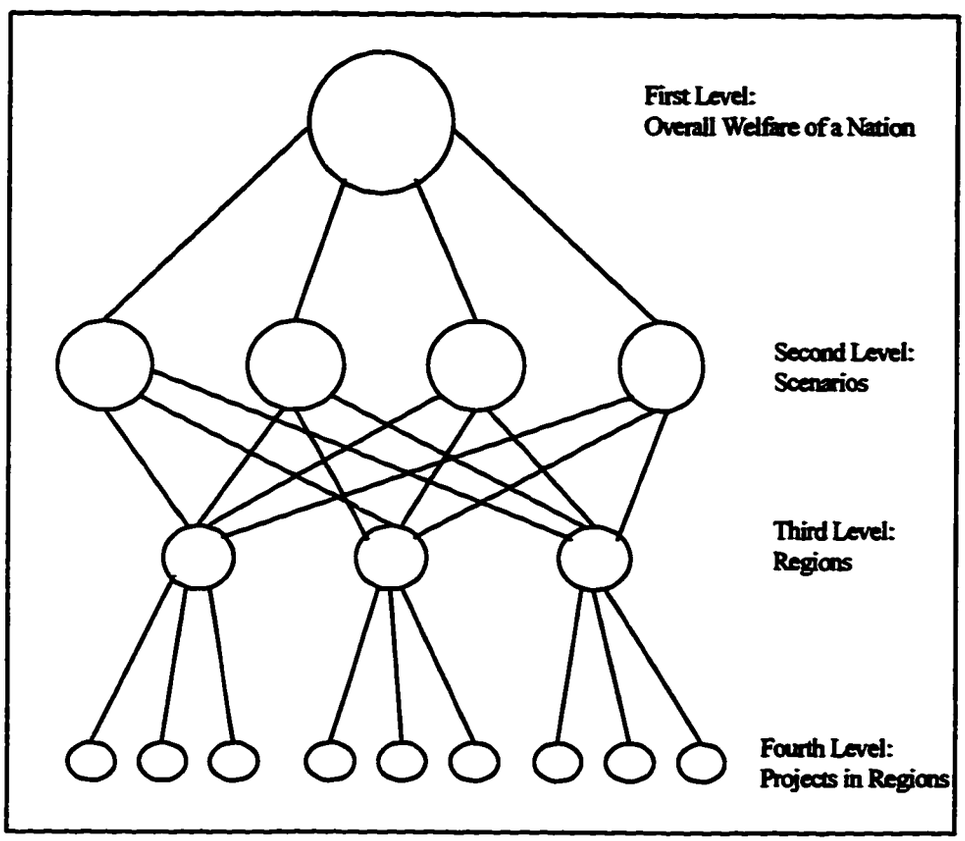


Figure 2.35. Typical hierarchy structure for prioritization [Saaty 1990].

Table 2.7 Intensity of importance scale of AHP [Saaty 1990].

Intensity of Importance	Definition	Explanation
1	Equal importance	two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favored and its dominance demonstrated in practice
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjustment judgments	when compromise is needed
Reciprocals of above nonzero numbers	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix.

useful due to the fact that the AHP is somewhat scale independent [Harher and Vargas 1987].

Saaty [1990] defended this scale by the following reasons:

1. The human ability to make qualitative distinctions is well represented by five attributes: equal, weak, strong, very strong, and absolute. Compromises between adjacent attributes can be made when greater precision is needed. The totality require nine values and they may be well consecutive.

2. There is a practical method often used to evaluated items by classification the stimuli into trichotomy of regions: rejection, indifference, and acceptance. For finer classification, each of these is subdivided into a trichotomy of low medium, and high, resulting nine shades of meaningful distinctions.

3. The human brain has a psychological limit of 7 ± 2 items simultaneous comparisons. This mind capacity has some thing to do with the number of fingers. Therefore, a nine-point scale will be sufficient to do the comparisons between items.

The AHP incorporates judgments and personal values in a logical way. It depends on imagination, experience, and knowledge to structure the hierarchy of the problem. It also depends on logic, intuition, and experience to provide judgments. Once accepted and followed, the AHP shows how to connect elements of one part of the problem with those of

another to obtain the combined outcome [Saaty 1982]. Figure 2.36 shows the advantages of the AHP.

The AHP differs from the other conventional scoring method in the following [Hagquist 1994]:

1. AHP uses a set of one-to-one comparison to evaluate alternatives under each criterion. These pair-wise comparisons are the smallest in decisions.

2. AHP uses one-to-one comparisons to assign criteria importance weights.

3. AHP does alternative comparisons and criteria weighting in separate steps.

4. AHP melds both objective measure and subjective preferences in the form of criteria weights. Typically, only one objective are quantified.

AHP has many advantages over the conventional scoring methods such as increase in accuracy and consistency, and that the subjective consideration is quantified in a structured framework. However, the major drawback in the use of AHP is the effort required to make all pair-wise comparisons [Millet and Harker 1990]. As the size of the hierarchy increases, the number of required pair-wise comparisons increases exponentially.

Also the AHP has its complexity in terms of higher level of details required by the evaluators when asked for their preferences and opinions. In pavement management, usually many factors are considered in any modeling process (e.g. prioritization), and in pavement network there are huge number of sections considered for evaluation, these facts

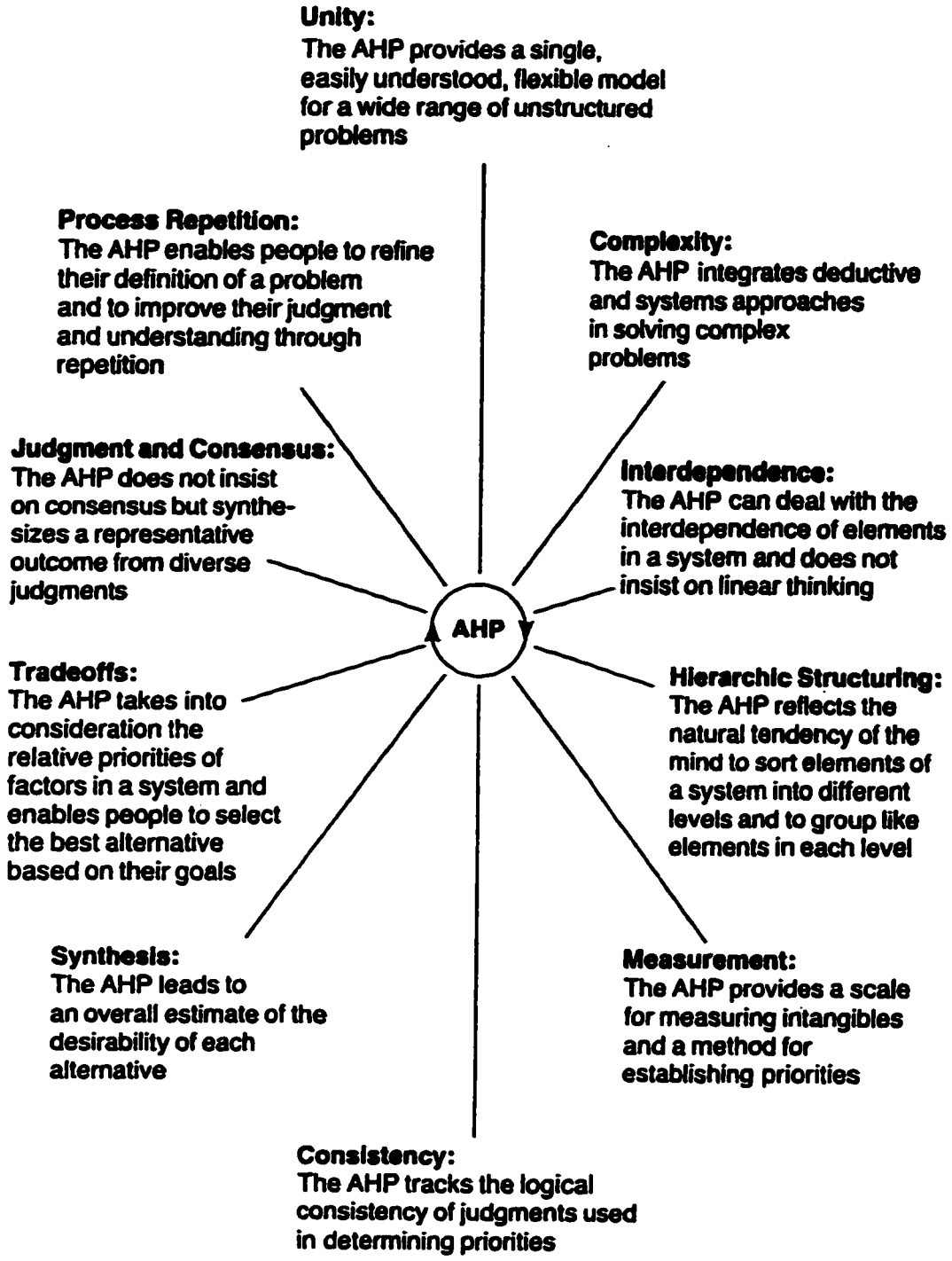


Figure 2.36. Advantages of the AHP [Saaty 1979].

makes the sections' comparison based on 9-point scale and for many criteria rather difficult task. However, for project-level evaluations where a few sections are to be considered simultaneously, AHP is an effective method for analysis.

2.5.5.2 Principles and Background of AHP [Saaty 1990]

When a group of activities (factors) are considered for evaluation by a group of people, the main objectives of this group are: (1) to provide judgment on the relative importance of these activities, and (2) to insure that the judgments are quantified to an extent which also permits a quantitative interpretation of the judgment among these activities (factors). The quantified judgment on pairs of activities ci, and cj are represented by an n-by-n matrix

$$A = (a_{ij}), \qquad (i,j = 1, 2, 3, ..., n) \tag{2.16}$$

The entries a_{ij} are defined by the following entry rules:

Rule 1. If $a_{ij} = \alpha$, the $a_{ji} = 1/\alpha$, $\alpha \neq 0$.

Rule 2. If C_i is judged to be of equal relative importance as C_j, then $a_{ij} = 1$, $a_{ji} = 1$; in particular $a_{ii} = 1$ for all i.

Thus the matrix A has tha form:

$$A=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{2.17}$$

where the a_{ij} is the relative importance of activity i to activity j. Having recorded the quantified judgments of comparisons on pairs (C_i, C_j) as numerical entries a_{ij} in the matrix A, what is left is to assign to the n contingencies C_1, C_2, C_3, ..., C_n a set of numerical weights w_1, w_2, w_3, ..., w_n that should reflect the recorded judgments.

The eignvector of the comparison matrix provides the priority ordering (weight), and the eigenvalue is a measure of consistency. To find the priority vector or the weight of each factor included in the priority ranking analysis, the eigenvector corresponding to the maximum eigenvalue is to be determined from matrix analysis.

One of the approximation method to get the weight of each factor in the pair-wise comparison process is described below.

2.5.5.3 Weight Vector Calculation

In mathematical terms, the principle eigenvector is computed, and when normalized becomes the vector of priorities (weights). In the absence of large scale computer to solve the problem exactly, and due to the results of complex numbers, good estimate of that vector can be obtained by dividing the elements of each column in the comparison matrix by the sum of that column (i.e. normalize the column). The elements in each resulting row are

added and the sum is divided by the number of the elements in the row. This is a process of averaging over the normalized columns. Mathematically, this process is shown below:

$$W_1 = \frac{1}{n}\left[\left(\frac{a_{11}}{\sum_i a_{i1}}\right) + \left(\frac{a_{12}}{\sum_i a_{i2}}\right) + \ldots + \left(\frac{a_{1n}}{\sum_i a_{in}}\right)\right] \tag{2.18}$$

or in general:

$$W_i = \frac{1}{n}\sum_j \left[\frac{a_{ij}}{\sum_i a_{ij}}\right] \tag{2.19}$$

where a_{ij} is the entry of row i and column j in a comparison matrix of order n.

An approximate calculation method for the principle eigenvalue, λ_{max} is as follows: the matrix of comparisons is multiplied on the right by the estimated solution vector, **W** (equation 2.18) above obtaining anew vector **W'**. If the first component of this vector is divided by the first component of the estimated solution vector **W**, the second component of **W'** by the second component of **W**, and so on, a new vector **W''**. The sum of components of **W''** divided by the number of components in this vector gives an approximation value of λ_{max}. Mathematically λ_{max} comes from the following equations:

$$\mathbf{W} = \left[W_1, W_2, W_3, \ldots, W_n\right]^T \tag{2.20}$$

$$\mathbf{W}' = \mathbf{A}.\mathbf{W} \tag{2.21}$$

or

$$\mathbf{W'} = \left[w'_1, w'_2, w'_3, \ldots, w'_n\right]^T \tag{2.22}$$

$$\mathbf{W''} = \left[w'_1/w_1, w'_2/w_2, \ldots, w'_n/w_n\right]^T \tag{2.23}$$

$$\lambda_{max} = \frac{1}{n}\left[w''_1 + w''_2 + \ldots + w''_n\right] \tag{2.24}$$

2.5.5.4 Comparison Matrix Consistency

Consistency in pair-wise comparison matrix means that when a basic data is available, all other data can be logically deduced from it. In doing pair-wise comparison to relate n activities or factors so that each one is represented in the data at least once, only n-1 pair-wise comparison judgments are needed. For example, if activity A_1 is 3 times more important that factor A_2 and factor A_1 is 6 times more important that factor A_3, then A1 = 3 A_2. and A_1 = 6 A_3. It should follow that $3A_2 = 6\ A_3$ or $A_2 = 2\ A_3$ and $A_3 = 1/2\ A_2$. If the numerical value of the judgment (comparison) in the (2,3) position is different that 2, then the matrix would be inconsistent.

2.5.5.5 Quantification of Consistency

It is usually very difficult to identify n-1 comparisons which relate all factors or activities and of which one is absolutely certain. It turns out that the consistency of a positive reciprocal matrix is equivalent to the requirement that its maximum eigenvalue λ_{max} should be equal to the number of factors, n. It is possible to estimate the departure of

consistence (inconsistency) by the difference λ_{max} - n divided by n-1, where $\lambda_{max} \geq n$. The value of $(\lambda_{max} - n)/(n - 1)$ which is called a consistency index (CI). The random index (RI). Table 2.8 shows the RI values for corresponding matrix order, n. is consistency index a randomly generated reciprocal matrix from a scale 1 to 9, with reciprocal forced. The ration of CI to RI, of the same matrix order, gives the consistency ratio (CR). A consistency ratio of 0.10 or less is considered acceptable.

A composite index of different factors affecting the prioritization process was determined using the AHP weighting method [Hagquist 1994]. The factors included were pavement type, pavement condition, drainage adequacy, lane width, shoulder width, alignment adequacy, volume/capacity (V/C) traffic ratio, and access control. The following equations were used:

$$CI = \sum (w_i).(r_i) \tag{2.25}$$

$$\sum w_i = 1 \tag{2.25a}$$

where

CI = Composite Index

W_i = Index weight for component i, and

r_i = rating with respect to component i.

Table 2.8. The average random index [Saaty 1990].

Matrix Order, n	Random Index, RI
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

Using the principle of AHP, a multiple criteria composite index was developed by [Cook and Kress 1994] for evaluating a set of alternatives relative to a combination of ordinal (qualitative) and cardinal (quantitative) criteria. This model has been incorporated in a menu-driven software package called Multi Attribute Ranking System (MARS). The basic feature of this model is that for a given number of alternatives N (e.g. projects or sections) to be evaluated, relative set of K_1 ordinal and K_2 cardinal criteria are established. For the kth cardinal measurable criteria, $a_k(i)$ denotes the value or worth associated with alternative i. These values are normalized as done in the AHP that is:

$$\sum_{i=1}^{N} a_k(i) = 1 \tag{2.26}$$

and

$$\sum_{k=1}^{K_1+K_2} W_k = 1 \tag{2.26a}$$

where

W_k is the supplied weight on the importance associated with criteria k, and

K_1 and K_2 ordinal and cardinal criteria.

For the ordinal criteria, K_1, there are no specified $a_k(i)$-values, instead rank position of the ith alternative on the kth criteria are supplied. That is:

$$d_{kl}(i) = \begin{cases} 1 & \text{- if i is ranked in the l th position on criteria k} \\ 0 & \text{- otherwise} \end{cases} \tag{2.27}$$

Then a set of equation were formulated to reach to a composite index considering both ordinal and cardinal criteria.

The above model was used in priority setting of pavement rehabilitation with the following identified criteria:

1. pavement condition index (PCI),
2. present traffic,
3. predicted future traffic,
4. percent commercial vehicles,
5. accident level,
6. vehicle operating cost, and
7. riding disrupt.

In all but the last two criteria, numerical vales are available. Since roads can be ranked according to the riding comfort or disrupt, and since the data of the vehicle operating costs are difficult to obtain, the last two criteria are ordinal (qualitative).

2.5.6 Optimization Methods

Priority programming by optimization is conceptually different from others methods. It combines the function of priority programming, program formulation, and project scheduling into one operation which gives the optimum schedule of projects through precise analytical techniques such as linear and dynamic programming. Generally, these method uses maintenance cost minimization or maintenance benefits maximization to generate the optimal maintenance plans.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 GENERAL

To achieve the stated objectives, this study was divided into two parts. The first part deals with the modeling of pavement condition, while the second part deals with priority ranking process. The research methodology for these two parts is shown Figure 3.1 and detailed below.

3.2 PRIORITY RANKING MODELING

Prioritization is a process that ranks pavement sections in an order of importance or urgency for maintenance and repair before further deterioration occurs, or for restoring the pavement condition to an acceptable level of service. In situation of limited maintenance funds, prioritization answers the question of what pavement sections should be maintained before others.

Priority can be determined by different methods, ranging from simple subjective ranking to the true optimization as summarized in Table 2.5. In this study, the pavement maintenance priority ranking modeling is done using the priority composite index method.

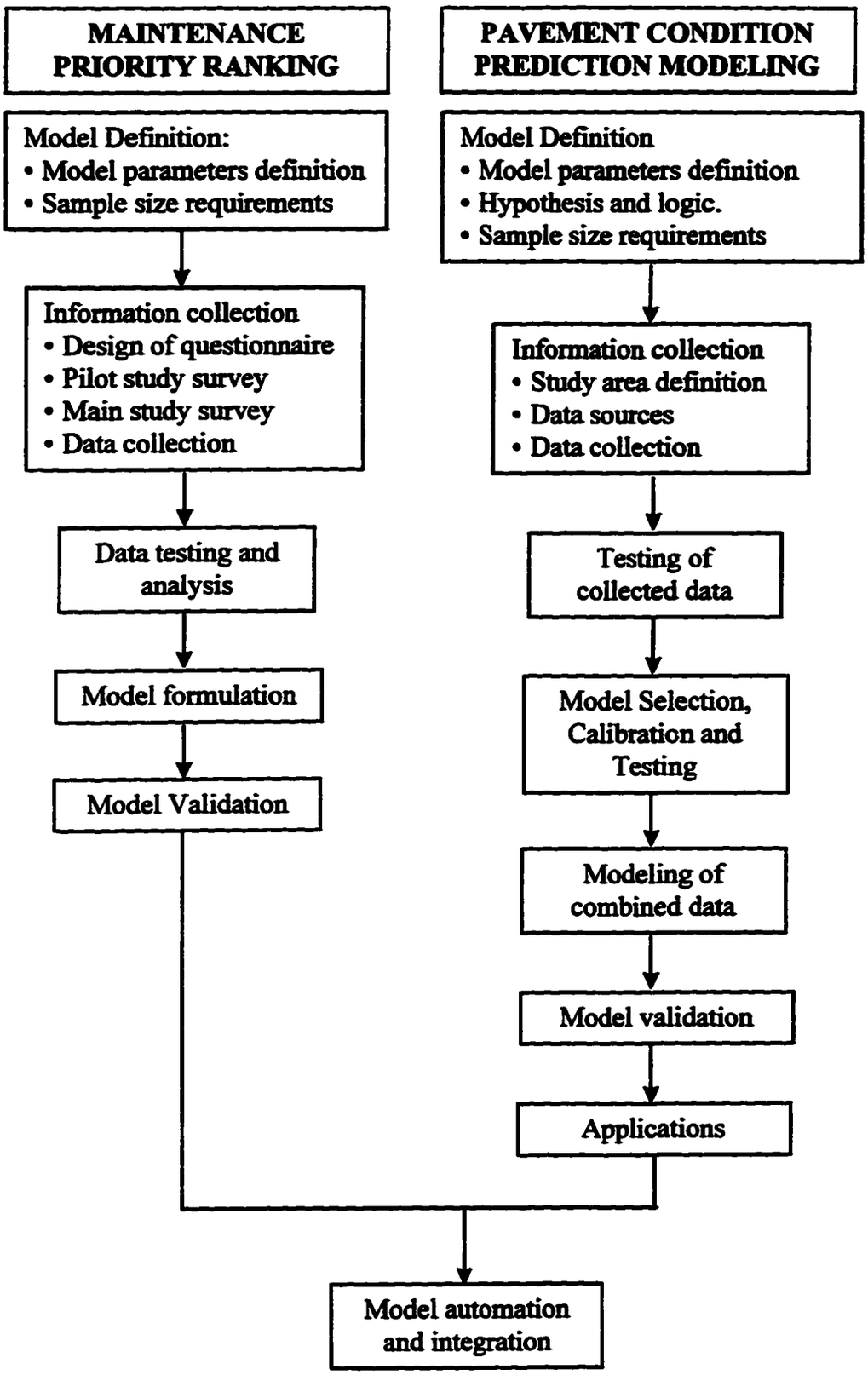


Figure 3.1. Research methodology of the study.

3.2.1 Priority Factors Definition

Based on the features of each priority method, the nature of the data collected, and the requirement of this study, the priority index method was selected. It was hypothesized that the parameters that affect the decision for maintenance priority include: road class, pavement condition, operating traffic, riding quality conditions, safety conditions, maintenance cost, and the importance of the road segment for community or the road utilization. These factors are detailed in the following sections. Pavement condition, safety conditions, and riding quality factors, are inversely proportional to priority decision, where as these values incease, the priority decreases. While the operating traffic, and importance to community factors are proportional to it, where as these the values of these factors increase, the priority increases as well. The relation of the overall maintenance cost to priority depends on the amount of funds allocated to maintenance and on the spending schemes. This means that although this amount is not enough to cover all maintenance needs, but depending of how much the shortage is, determines this relation. The relation is also dependent of the pavement maintenance spending strategy in distributing the allocated funds. For example, if the strategy is to subdivide the total funds into maintenance actions according to some proportions, then the priority-maintenance cost relation depends on the extent of each needed maintenance action. But in general, there is a tendency, in the engineering judgment, to execute the maintenance actions on road segments of low-cost before the higher-cost ones. This policy was followed in this

study since this covers the preventive manitenance activities, while the corrective maintenance ones such as overlay and reconstruction require special funds.

The general form of the proposed priority ranking model is:

$$PI = \Sigma W_i F_i \tag{3.1}$$

where

PI = Priority Index (out of 100 points),

F_i = Priority factor, i,

W_i = Weight of priority factor, i, and

ΣW_i = 100

Some of the factors (F_i's) used in the above equation have very high absolute values, such as operating traffic and maintenance cost. Using these absolute values will overpower other factors such as the skid resistance number and roughness values. Therefore, a procedure of normalizing all factors to a 100-point scale was followed on this study. The priority factors (F_i's) are described in the following sub-sections:

3.2.1.1 Road Classification

Highways are grouped into a number of different classirications for administrative, planning, and design purposes. They are most effectively classified by function. Highways have two major functions: to provide mobility and to provide land access. For

example, freeways provide a high degree of mobility with access provided only at spaced interchanges to preserve the high-speed, high-volume characteristics of the facility. The opposite is true for local, low-speed roads that must provide access to adjacent land areas. Between these two extremes are highways that comprise the bulk of existing highways [Baerwald 1976]. Table 3.1 provides criteria for highway system classification. In Saudi Arabia, Ministry of Communications (MOC) has classified the rural highway system into primary, secondary and feeder roads, while in urban areas, they are classified as arterial, collector, and local roads.

According to the above classification, each road class is assigned a number (out of 100) to represent its road factor required for maintenance priority ranking process. Higher numbers are assigned to more important roads that should receive higher priority for maintenance if needed. This is further detailed in Chapter Four.

3.2.1.2 Pavement Condition

Pavement condition, is measured by pavement condition index (PCI) and calculated by measuring the various distresses available in the pavement section under consideration. There are different method of obtaining this index as described in Chapter Two. PCI can also be obtained from the pavement condition prediction model using the prevailing conditions. PCI is a composite index that gives an indication of how the pavement section is affected by its utilization and usage. The pavement condition is one the most pronounced factors that people see in the road section they are driving, riding, or walking over.

Table 3.1. Criteria for road classification [Pignataro, 1973].

Area	Classification	Principle Service Function	Elements Linked by Road
Urban	Expressway	Through movement exclusively	CBD; major generators
	Arterial	Through movement; some land access	CBD; secondary generators
	Collector	Through movement and some land access	Local areas
	Local	Land access	Individual land sites
Rural	Interstate	Through movement exclusively	Major cities
	Primary	Through movement; some land access	Smaller cities
	Secondary	Through movement and land access	Small cities and outlying regions
	Tertiary	Land Access; some through movement	Farm-to-market

On all pavement condition survey methods, 100-point scale is usually used. The lower the PCI value is, the higher the priority for that section will be. Therefore, to comply with the priority model (equation 3.1) requirement, the pavement condition factor (PC) for any section, equals to 100 minus PCI value for that section.

3.2.1.3 Operating Traffic

Traffic load is one of the major causes of pavement deterioration. Load-associated distresses such as alligator cracking, and rutting are mainly generated by traffic loads. These distresses usually have the highest deduct points in any pavement condition rating method.

Volumes, loads, and classification of traffic are usually needed for analyzing and scheduling maintenance operations properly. The equivalent axle load concept is used to handle the large spectrum of axle loads (traffic mix) actually applied to a pavement. The standard equivalency most commonly used is 80 kN (18 Kips), Equivalent Single-Axle Load (ESAL). The basis of equivalency can be either calculated or measured by stress, strain, or deflection at some point in the pavement structure [RTAC 1977].

For planning purposes such as priority ranking process, traffic volume as measured in average daily traffic (ADT) plays an important role in determining the priority index of different pavement sections. This factor determines how much the road section is utilized by the community. High-traffic volume roads (such as arterials or freeways), usually call for higher maintenance priority compared with the low-traffic volume roads such as local

or feeder roads. Therefore, a traffic index (out of 100) is calculated or obtained for each traffic (ADT) range as shown in Chapter Four.

In situation where the operating traffic volumes are not available, descriptive measures can be used, such as low, medium, or high, that can be related to some ranges. The functional road classification can also be used as indicators of traffic exposure.

3.2.1.4 Riding Quality

Riding quality is largely a function of pavement roughness which is a function of road surface profile, the characteristics of vehicle, and acceleration and speed sensibility of the driver. These factors can contribute to an undesirable or an uncomfortable ride (poor riding quality). Surface irregularity is an important factor in determining the degree of comfort of ride afforded by the road, and can also be a guide to the overall condition of the road [Keir 1974]. Road roughness is caused by two factors: surface irregularities that are built into the pavement during construction and surface irregularities that develop after the construction due to traffic, climate, and other factors [FHWA 1987]. High surface roughness, creates more public complains which, in turn, calls for higher maintenance priority.

Riding quality is measured by different types of equipment such as, the Bump Integrator (BI) and the Mays Ride Meter (MRM). The features of these equipment were explained in Chapter Two.

Ride index of a pavement section, for this study, is calculated by using roughness measurement data scaled to 100-point scale as recommended by FHWA [1987]. On situations where no roughness equipment are available, the riding quality can be indexed based on the distress survey data. Table 3.2 details the riding quality-related distresses according to PAVER distress manual.. Riding quality index, needed for priority ranking is discussed in Chapter Four.

3.2.1.5 Safety Condition

Pavement safety is usually evaluated in terms of skid resistance. There are however, a number of other considerations in pavement safety, such as violation or unsafe acts by drivers or pedestrians, vehicular defects, pavement rutting (as it relates to accumulation of water and the danger of hydroplaning or ice formation), lane demarcation, night visibility (especially during rain), bad weather, and lane/shoulder drop-off. But pavement slipperiness as measured by skid resistance is the most common and important factor [Pignataro, 1976; Haas and Hudson, 1982]. Low value of skid resistance makes the pavement surface borne to traffic accidents with higher safety hazard.

Skid resistance in pavement surface can be measured by different methods and equipment. Mu-meter is most proven performance and widely used device to identify pavements with low skid resistance so that suitable maintenance treatment can be planned in time to ensure traffic safety. This equipment is described in Chapter Two.

Table 3.2. Riding quality-related pavement distresses [Shahin and Walter 1990].

Distress Name	Description
Bumps & Sags	Bumps are small localized upward displacement of pavement surface, while sags are downward displacements. They can be caused by different factors such as buckling of the underlying PCC slabs, frost heave, and infiltration and buildup of materials in the cracks.
Corrugation	It is a series of closely spaced ridges and valleys occurring at fairly intervals of less than 3 meters along the pavement. It is usually caused by traffic action combined with unstable pavement surface or base.
Railroad Crossing	Railroad crossing defects are depressions or bumps around and/or between tracks.
Depression	It is a localized surface area with elevations lower than those of the surrounding pavement. It is created by the settlement of the foundation soil or a result of improper construction.
Shoving	It is a permanent, longitudinal displacement of localized area of pavement surface caused by traffic loading.
Swelling	It is characterized by an upward bulge in the pavement surface as a long gradual wave of more than 3 meters. It is usually caused by frost action of the subgrade or swelling soil
Weathering & Raveling	It is the wearing away of pavement surface cause by the loss of asphalt and dislodged aggregate particles. This can be caused by using poor quality mixtures or by hardening (aging) effect.
Potholes	Potholes are small, bowel shaped depression (less than 0.9m in diameter) in the pavement surface. They are caused when traffic abrades small piece of the pavement surface. The pavement then continue to disintegrate because of poor surface mixture, weak spots in the base or subgrade, or because it has reached to the condition of high severity alligator cracking.

For priority ranking process, skid resistance values measures as Skid Number (SN) can be used directly to represent the safety factor, since it is out of 100. Higher the value of SN for a pavement section, lower is the maintenance priority for that section. Thus the priority safety factor (SF) is 100 minus the skid number.

In the absence of skid resistance measurements, pavement distresses that cause the loss of pavement friction (skid resistance) and/or other safety hazardous conditions can be used as safety condition index of pavement sections as discussed Chapter Four.

3.2.1.6 Maintenance Cost

Overall maintenance cost is the total cost of every maintenance action needed for the pavement section under consideration. This cost includes the preparation of the defective locations, the cost of materials to be used in the repair, the cost of man-power and equipment used in executing the repair, and any additional cost needed such as traffic detouring. Usually, maintenance contractors specify a unit cost for each maintenance and repair activity. The cost of any repair activity (slurry seal, for example) has a direct effect on the priority ranking. If this cost is relatively small, it may be viewed that this maintenance activity can either be postponed to later stage, or it can be executed directly depending on other maintenance costs and the funds allocation strategy as mentioned before.

Maintenance cost, similar to the traffic factor, has high absolute value. Thus, using this value, may overpowers other priority factor. Therefore, it must be scaled to a 100-point scale to facilitate the priority index calculation as discussed in Chapter Four.

3.2.1.7 Importance to Community

The overall importance of the road section to the community, or the overall utilization of that section, can be measured and quantified by the following sub-factors:

a. Road class, whether the road is primary, secondary, feeder, arterial, collector, local, residential, recreational, or commercial. Local streets, for example, may have lower importance than collectors or commercial roads since the utilization of the later is higher that the former.

b. Operating traffic, as described previously, determines the importance of the road to community. A busy street with high traffic volume has higher importance than that of low-volume.

c. Distance from central business district (CBD) or the down-town market area where most of people activities are located, also indicates higher importance of the road to the community.

d. The use of the road section for official visitors, VIPs, etc., also determines the importance of this road. If the road passes through official buildings, such as palaces or governor office (IMARAH), call for higher maintenance priority.

e. Availability of alternative roads for the road under consideration at times of maintenance and repair also indicates the importance of this road.

f. Distance form the other important locations such as, police stations, civil defense departments, hospitals, schools, airports, and mosques, etc. This factor, and the previous one, are so important that, sometimes, they override other factors for calling higher maintenance priorities.

The values of these sub-factors are determined based on measurable values such as traffic or based on other index values using similar procedures, described before for other priority ranking factors. This is further detailed in Chapter Four.

The overall importance factor is calculated using similar methodology of determining the priority index using the following equation:

$$IF = \sum W_i (Sf)_i \tag{3.2}$$

where

IF = Importance to Community factor (out of 100 points),

Sf_i = Importance value of sub-factor, i,

W_i = Weight of importance sub-factor, i, and

ΣW_i = 100

3.2.2 Data Collection: Factor Weight Determination

The above mentioned factors and sub-factors have different weights in determining the pavement maintenance priority. These weights depends on the evaluation of people who are using road pavements. Different groups of people having different opinions about these weights. Generally, there are three different method for collecting the subjective information: observations, interviews, and self-administrated questionnaires. The self-administrative questionnaire should have the following important features to give good and accurate results [Stopher and Meyburg 1979]:

1. It should have a brief non-technical summary, on a cover letter with established letterhead, about the purpose for which the survey is being carried out. A signature of respected public personage should be included,

2. The questionnaire should maintain the simplicity and directness of questions,

3. The confidence of the respondents should be considered in making them feel that their contribution is important, and that contribution is of equal importance to that of anyone else,

4. Complete confidentiality of the survey responses should be promised and given,

5. The questionnaire should have a proper sequence of questions,

6. Each respondent should be given the space and the opportunity on the questionnaire to express his or her feeling about the survey and its purpose, and on certain specific aspects of the questionnaire, and

8. The questionnaire forms should be easy to handle, as compact as possible, with two-sided sheets, and as legible as possible. They should also be clear, logical, and uncluttered.

Based on the above criteria and requirements, a special questionnaire was prepared. In this questionnaire, the evaluators were asked to rank each of the above factors with estimated percentile weight (sum of weights equals to 100). For the last factor, importance to community, the evaluators were asked to rank each of the sub-factors (a to f) with a percentage weight in order to quantify the importance of the road section to community.

The data collection was done in two stages: (i) pilot survey data collection and (ii) main survey data collection. In the pilot survey, the designed questionnaire was distributed to individuals of good experience in pavement maintenance field with the main objectives to check the factors to be considered in the main survey and any other comments and suggestions. Consequently, the main survey questionnaire was then prepared and distributed to different groups of individuals including: academicians, managers, engineers, and other road users. Two data collection methods were followed: the direct assignment method and the analytical hierarchy process (AHP) method that is described in detail in Chapter Two.

The main survey data collection was extended to the pavement specialists and other road users in the United Arab Emirate as an example of other Gulf countries. This was done to compare the Saudi and the Emirates pavement experiences in terms of maintenance priority ranking. The questionnaire content is detailed in Chapter Four.

3.2.3 Data Analysis

The collected main survey data were subjected to checking, filtering, and statistical testing to insure the consistency and repeatability. Then the final data were adjusted for different types of individual experience and used in the model formulation as detailed in Chapter Four.

3.2.4 Model Formulation

The maintenance priority factors' values as specified and determined in section 3.2.2 were combined with the weight of importance of these factors as obtained in the above section. Each factor value with its corresponding weight were used in equations 3.1 and 3.2 to calculate the priority index (PI) for each section. Further, the obtained PI values were adjusted for the effect of structural distresses if they existed in the pavement section under consideration.

3.2.5 Model Validation

To check the validity of the developed procedure of maintenance priority ranking, two case studies were designed. Two sets of pavement sections in need of urgent maintenance were selected in Dammam road network and Jubail Industrial City road network. In these two studies, it was assumed that only those sections are in need of maintenance and the total amount of allocated funds to maintain these section was not adequate. The priority ranking obtained by applying the developed procedure and that is currently being used by engineering judgment method by maintenance personnel were compared. The results of these comparisons are detailed in Chapter Four.

3.3 PAVEMENT CONDITION MODELING

The general layout of the research methodology of pavement performance modeling is shown in Figure 3.1. As shown in this figure, there are several interconnected phases in this part. These phases are explained in the following sections.

3.3.1 Model Definition

The main objective of pavement performance modeling is to forecast pavement condition at any time of its service life given a set of factors affecting this performance. Such modeling will help greatly in assessing the maintenance and repair needs. There are different categories of pavement condition and performance modeling as described in section 2.4. The mechanistic approach requires a huge detailed data base of structural,

field, and laboratory testing, in addition to pavement-characterization-performance-related parameters which is not an easy task. On the other hand, the probabilistic modeling, such as Markovian approach, depends primarily on very skilled and expert pavement engineers to develop transition probability matrices for different combination of pavement condition. This is also not readily available so far. Therefore, due to the lack of this type of experts, this model was not selected. The empirical deterministic regression modeling was selected for this study for the following reasons:

1. It is simple and easy to implement and update,

2. It captures as many factors as available that affect the pavement performance both quantitative measurable and qualitative subjective,

3. It does not require elaborate involvement of any mechanistic structural testing for the fundamental pavement responses, and

4. It does not require any engineering judgment for transition probability matrices.

Considering types and amount of collected data, described in the following section, multiple independent variables (IVs) were used as regressors against one dependent variable (DV), the Pavement Condition Index (PCI) as the predictor in the following general form:

$$PCI = f(AGE, ACTH, SBTH, TRAF, TRUK, INTR) \qquad (3.4)$$

where,

PCI = Condition Index of any pavement condition rating method,

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

ACTH = The combined thickness of all asphalt layers, cm, (including overlays),

SBTH = Subbase (stabilized or aggregate) layer thickness, cm,

TRAF = Average daily traffic (ADT), vehicle per day per lane,

TRUK = Number of trucks in the traffic mix, and

INTER = any possible interaction of the preceding factors.

It was found from the collected data that the above factors were the ones commonly available or accessible. Other factors were either not available or not reliable, if found. On the other hand, data regarding the subbase and subgrade type were not included in the above model because it was found that there were no different types used in almost all pavement sections considered in the study. Therefore, there will be no use of this factor in the analysis since it will not add any significance or importance to the prediction model. For drainage facilities factor, there was not enough data available for those section considered in the analysis, therefore, this factor was also excluded.

The study area, in this research, included all pavement sections that have pavement condition and performance-related information in Saudi Arabia. However, most of the collected data were from areas of hot climate, which is one of the characteristics of Saudi

environment. Therefore, the temperature factor was also excluded from the analysis since there were no significant variability of this factors in the collected data.

In the above performance model, the hypothesis that AGE, TRAF, and TRUK, are inversely proportional to the PCI. But ACTH, SBTH, are proportional to PCI. The effect of these factors on pavement condition was detailed in Chapter Two. Another set of logical and engineering judgment criteria were used as a set of a priori hypothesis as shown in Chapter Five.

3.3.2 Sample Size Determination

The performance model needs sufficient data points or cases in order to be adequately explaining or predicting the pavement performance. Although there is no firmly agreed-on minimum case to variable ratio, at least three considerations are relevant: skewness in dependent variable, effective size, and measurement error. The lower case-to-variable ratio, the more important it becomes that the residuals be normally distributed. The minimum number of cases or data points was determined, for this study, on the basis of the following recommendations and criteria [Tabachnick and Fidell 1983]:

1. One must have more cases than variables included in the regression model or the regression solution will be perfect any yet meaningless.

2. Ideally one should have 20 times more cases than variables.

3. If stepwise regression is to be used, the case-to-variable ratio should be 40 to 1.

4. A suggested minimum required is to have at least 4 to 5 times more cases than independent variables (IVs).

Considering the above criteria, and the fact that stepwise regression will be used, there is a need of 40 data points for each independent variable. There are five independent variables in the condition model, that means a minimum of 200 cases are required (case-to-variable ratio is 40). For this study about 1000 cases were collected. However, the minimum sample size was also checked by statistical parameters as detailed later. Portions of the collected data were used for model calibration and the other portions were used for model validation as detailed in Chapter Five.

3.3.3 Data Collection

3.3.3.1 Study Area

To obtain generic models that can be utilized with a significant level of confidence, the study covered all accessible pavement ranges of Saudi pavement network. The study included both intercity highways as well as municipal and local roads and streets. Roads under the authority of MOC both in Riyadh and Dammam areas were considered to represent the intercity highways. Municipal roads in Dammam, Dhahran, Khobar, Jubail, and KFUPM campus roads and streets were considered as urban pavements. Other road

pavements, in the cities of Jeddah, Makkah, Medinah, etc. were not considered since no relevant pavement condition data were available.

3.3.3.2 Data Sources

MOC was one of the sources contacted to collect pavement condition and related information of the intercity road network. The MOC condition rating method called pavement condition rating (PCR) was used in generating a huge pavement data base. Data for roads between Riyadh, Dammam, Jubail, Hafouf, Qasim, and Al-Kharj were collected.

Royal Commission of Al-Juabil was also contacted and all pavement-related information were collected, these data included: pavement condition rating measured by pavement distress-based rating (PDR), pavement thickness, traffic, and pavement history-related information.

Civil Engineering Department of KFUPM has carried out several researches as master projects that contained pavement condition surveys at different years for the highway pavements in Dhahran. Dammam, Khobar, and Jubail areas. These surveys were carried out using Pavement Condition Index (PCI) PAVER method.

Dammam Municipality Maintenance Department is developing a pavement management system where the PCI PAVER method was selected as a pavement condition rating method. Condition surveys data were also collected from this source.

Riyadh Municipality was another source for the data collection in this study. The PCI method was also selected for data collection for the pavement maintenance management system being developed. However, a new method was developed for the data collection similar to the PCI method, called Urban Deduct Index (UDI), where new deduct schemes were followed [Al-Swailmi et al. 1996].

The required data for pavement condition modeling, were collected from the sources mentioned above. These data included condition survey data determined in any of the three pavement inspection methods, MOC, KFUPM-RI, and PAVER, as abbreviated by PCR, PDR, and PCI, respectively. These method were explained in Chapter Two.

3.3.4 Testing Collected Data

The normalized collected data were checked for outlier cases. The outliers are extreme cases on one or more variables. The collected data were checked for any irrational, irregular, or illogical behavior.

Basic statistics of the collected data were summarized and tabulated, and general observations on these data were made. Data collected by each condition survey method were pooled together.

3.3.5 Model Formulation and Testing

The collected screened data were processed, tabulated and entered to STATASTICA PC-package to obtain the regression model. Step-wise regression was first used to check

those factors that were significant to pavement condition prediction. Different linear and non-linear models were tried according to a set of a priori hypothesis. Three different models were finally selected to represent the three different condition survey method (PDR, PCR, and PCI). The final models were checked against several model adequacy tests such as normality, linearity, and homoscedasticity, for the residuals (errors) between the observed and predicted pavement condition values. This work is detailed in Chapter Five.

3.3.6 Models for Combined Data

A trial was made to combine the collected data of PDR and PCI methods to represent the urban road pavements. The generated models for this step were subjected to statistical and logical testing as shown in Chapter Five..

3.3.7 Model Validation

The final prediction models were used with the data points (cases) reserved for model validation. Predicted pavement condition values were compared with the actual measured values to check the reliability and the level of significance of the developed model in explaining or presenting the actual data points.

3.3.8 Model Applications

Some areas of application of the developed models were specified. Different models for different combinations of the pavement parameters, such as thickness and traffic levels, were generated. The use of pavement condition models for planning the maintenance policies over the design life of the pavement was also tried. This is detailed in Chapter Five.

3.4 MODEL AUTOMATION

The pavement condition prediction models and the maintenance priority ranking procedure developed in this study were put into a simple working menus. These menus were formatted using Micro Soft EXEL files. An integration methodology was aslo suggested to include these models and procedure in a more comprehensive pavement management system.

CHAPTER FOUR

PRIORY MODELING

DATA COLLECTION AND ANALYSIS

4.1 DESCRIPTION

This chapter deals with the data collection and analysis of the maintenance priority ranking. It details the developed procedure in terms of its factors evaluation and quantification, and explains end results of the pilot data collection survey that are used to form the main data collection survey, where different forms of questionnaires were utilized. The collected data have been filttered and statistically checked for repatablity and reaibality, and then used in the formualtion of the ranking procedure. The chapter also presents the evalaution and validation of the developed procedure by two case studies.

4.2 MODEL DEFINITION

The composite maintenance priority index was the method selected for this study. This method is relatively simple and gives close to optimal results, and it has been applied

by many researchers as detailed in Chapter Two.. The priority index (PI) used in this study for pavement maintenance priority has the following form:

$$PI = \Sigma W_j F_j \tag{4.1}$$

where:

PI = Priority index for any section (out of 100),

W_j = Factor 'j' weight of importance to priority ranking,

F_j = Factor 'j' value, and

j = the factor number from 1 to 7 (factors detailed in Chapter Three)

To obtain the priority index of each pavement section in the road pavement network, the value of each of the seven priority factors should be determined. This determination is based on location, utilization, condition, performance parameters, operating traffic, and the needed maintenance cost for that pavement section.

As mentioned in Chapter Three, all values of priority factors need to be normalized to 100 in order to facilitate the priority index calculation by avoiding the overpower of some factors by others. Some factors need to be quantified since they do not have absolute values such as road class and importance to community.

The priority factor value is either a measurable one such as pavement condition, traffic, measured skid resistance, and maintenance cost, or it is a qualitative one such as

road class, and importance to community. Riding quality and safety (if no equipment to measure these factors are available) are also qualitative factors that need to be quantified. To quantify these non-measurable factors, different researchers and pavement maintenance management specialists were consulted, in addition to the analysis of local ranges of roughness and skid resistance measurements.

Pavement maintenance priority ranking factors were detailed in Chapter Three, in terms of definition and evaluation. In the following sections, these factors are quantified as values, and their weights of importance is determined.

4.2.1 Road Class

The type of road, where the pavement section is located, determines the section maintenance priority. Major roads such as freeways and arterial should have higher priority for maintenance since these roads are classified as high-speed and high-volume ones. In these road, mobility or high continued speed are desirable, and variable or low speeds are undesirable. At time of maintenance, speed in these roads, is restrained by the defects in pavement surface, then high traffic jams and congestion occur. Consequently, extremely hazardous conditions will be created, therefore, high maintenance priority should be given to this class of roads. On the other hand, local and feeder roads have usually low volumes and low speeds which are desirable to provide land access to adjacent areas. Therefore, lower maintenance priorities are given to these roads. According to this, a 100-point scale (index values) for road class factor as shown in Table

4.1 was prepared. In this table both rural and urban roads are considered. A road with alternatives, when maintained, has lower index that the one with out alternatives. The scale has equal interval which means that a collector road is twice as important as a local road.

4.2.2 Pavement Condition

Pavement condition, as measured by PCI or any other scale, is a 100-point scale. The lower the PCI value is, the higher the priority for that section will be. Therefore, to comply with the priority model (equation 4.1) requirement, the pavement condition factor (PC) for any section, equals to:

$$PC = 100 - PCI. \tag{4.2}$$

4.2.3 Riding Quality

The selected procedure for the roughness measurements scaling is the one suggested by FHWA [1987] which has been explained in Chapter Two. The riding quality index (RQ) can be computed as:

$$RQ = 100*PR/MPR \tag{4.3}$$

where,

RQ= Riding Quality index (out of 100),

Table 4.1. Road class priority factor.

Class	Description	Factor Value
I	**Urban:** Arterial roads that have high traffic volumes and high speed limits that connect the major traffic origins and destination. But these roads do not have alternatives when maintained **Rural:** Primary highways such as freeways with high speed limits and with out adjacent service roads	100
II	**Urban:** Arterial roads that have high traffic volumes and high speed limits that connect the major traffic origins and destinations. But these road do have alternative when they are under maintenance. **Rural:** Primary highways such as freeways with high speed limits and with adjacent service roads	75
III	**Urban:** Collector road that have medium traffic volumes and speed limits. They feed the arterial roads by traffic and connect the traffic major generators **Rural**: Secondary highways such as expressways with some traffic control with high speed limits and with or without adjacent service roads	50
IV	**Urban:** Local roads and streets that have low traffic volumes and low speed limits; connect local residential areas; provide high access facilities. **Rural:** Feeder roads such as with low traffic volumes and speed limits; fully controlled roads	25

PR = pavement roughness, in cm/km, and

MPR= Maximum pavement roughness.

In this case, values of RQ of 100 or more indicates very rough, unacceptable pavement section that calls for higher priority for maintenance, while lower values represent acceptable smooth pavement sections. The main advantage of calculating the RI on a 100-point scale is that it matches with the priority ranking model (equation 4.1). The maximum acceptable roughness (MPR) value selected for this study was 1800 mm/km as obtained from the panel rating study to define the acceptable limit of pavement roughness [Arora et al. 1995].

Roughness is manifested in pavement surface by several riding quality-rated pavement distresses such as corrugation, potholes, depressions, upheaval, bumps and sags, raveling and weathering, and rutting. Cracking in high severity levels will also contribute to road roughness. Definition and rating of these distresses are summarized in Table 3.2. Following is a procedure to scale the riding quality to roughness-related distresses.

The roughness measurement, using the Mays Ride meter (MRM) described in Chapter Two, was carried out for Al-Jubail Industrial City road network. These measurements covered 462 pavement sections [KFUPM-RI 1989]. The collected roughness were used to generate relationships between roughness index (100-point scale) and distresses that are related to roughness such as rutting, raveling, patching, upheaval,

depression, and potholes. These relationships are needed for the priority ranking procedure if the roughness measuring devices are not available. Figure 4.1 shows the frequency distribution of the collected roughness measurements. The mean roughness value for all sections was 90.5 cm/km with a standard deviation of 38.3 cm/km, and the available range was 17.6 to 2509 cm/km.

Table 4.2 shows cross tabulation between roughness ranges and the existing distresses with their severity levels for each range. From this table it can be seen that at high levels of pavement roughness (greater than 180 cm/km), the intensity (percentage) with all severity are high. For example, patching with high severity exists at 27.3% of the sections under that roughness range, while this value is maximum of 1.8% at the second roughness range. The highest roughness group contains all types of roughness-related distress. From this table the existence of roughness-related distresses in pavement surface can be indexed to represent the roughness level or index. The highest level of roughness can be assigned a roughness index of 100 if one or more of the above distress is available at high severity. Pavement surface is not perfectly smooth due to the microtexture characteristics of the asphalt pavement mix, therefore a value of roughness index of 25 is a reasonable assignment for the pavement surface that is free of any roughness-related distresses. This value is around the minimum obtained value of this roughness measurement study. The intermediate roughness indices (i.e. 50 and 75) can be assigned to for the intermediate situation where the pavement surface has low severity or medium severity roughness-related distresses. These riding quality index assignment is summarized in Table 4.3.

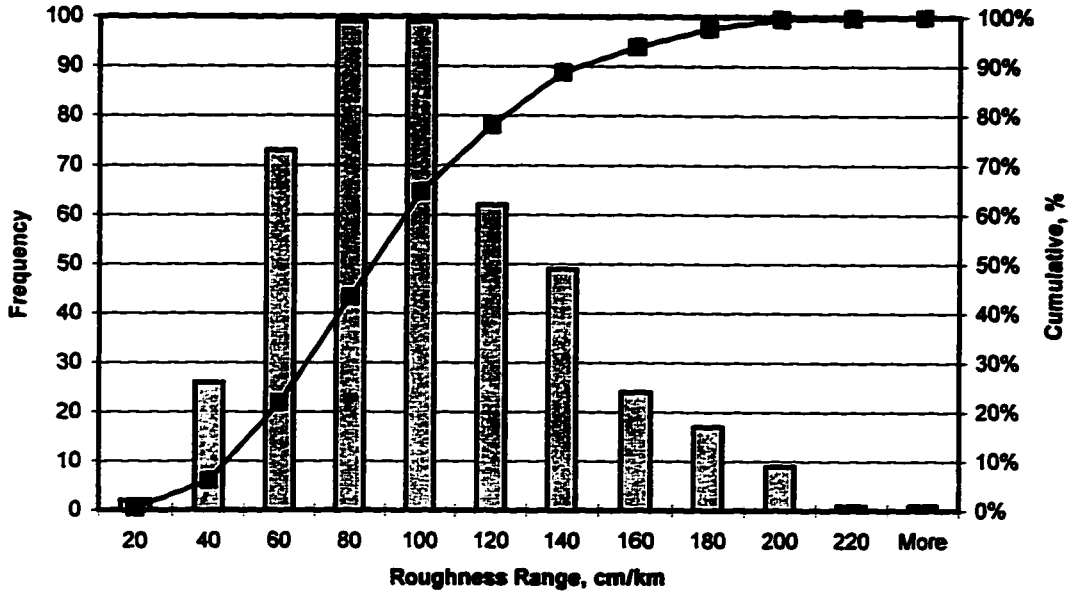


Figure 4.1. Frequency distribution of measured roughness of Al-Jubail road network.

Table 4.2. Measured roughness versus the existing distresses for Al-Jubail road network.

Group	Roughness Range, cm/km	No. of Sections	Severity Level	Rutting		Raveling		Patching		Upheaval		Depression		Potholes	
				Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number	Percent
I	≤ 100	299	L	37	12.4	105	35.1	9	3.0	0	0.0	13	4.3	0	0.0
			M	23	7.7	0	0.0	2	0.7	6	2.0	2	0.7	0	0.0
			H	5	1.7	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
II	101-140	111	L	5	4.5	0	0.0	13	11.7	0	0.0	9	8.1	0	0.0
			M	5	4.5	16	14.4	3	2.7	0	0.0	4	3.6	0	0.0
			H	3	2.7	1	0.9	2	1.8	0	0.0	0	0.0	0	0.0
III	141-180	41	L	3	7.3	21	51.2	3	7.3	0	0.0	5	12.2	0	0.0
			M	3	7.3	6	14.6	3	7.3	0	0.0	1	2.4	0	0.0
			H	0	0.0	1	2.4	0	0.0	0	0.0	0	0.0	0	0.0
IV	> 180	11	L	2	18.2	6	54.5	1	9.1	0	0.0	2	18.2	0	0.0
			M	2	18.2	4	36.4	0	0.0	0	0.0	3	27.3	0	0.0
			H	1	9.1	0	0.0	3	27.3	0	0.0	0	0.0	1	9.1

Table 4.3. Recommended indices for riding quality-pavement distress relationship.

Class	condition	Factor Value
I	**One or more of the following prevail:** high severity of corrugation, bumps and sags, extensive swelling and upheaval levels, raveling and weathering, and rutting.	100
II	**One or more of the following prevail:** medium severity of corrugation, bumps and sags, moderate density swelling and upheaval levels, raveling and weathering, and rutting.	75
III	**One or more of the following prevail:** low severity of corrugation, bumps and sags, raveling and weathering, and rutting; low severity and low density swelling and upheaval.	50
IV	**Pavement condition is good from riding quality point of view**	25

In another study in Riyadh Municipality road network, the roughness measurements had a range of 14 to 271 cm/km for about 800 sections of Riyadh Municipality [Al-Swailmi et al. 1996]. These results compare well with the results of Al-Jubail roughness measurements. This confirms the riding quality index assignments discussed before.

4.2.4 Safety Condition

As discussed before, in Chapter Three, skid number measured value is used to represent the safety condition of any pavement section. The safety factor index (SF)value for priority ranking calculation is determined subtracting the skid number value (SN) from 100 using the equation below:

$$SF = 100 - SN. \tag{4.4}$$

However, in the absence of skid resistance measuring equipment, pavement distresses that cause the loss of pavement friction (skid resistance) and/or other safety hazardous conditions can be used to index safety condition of pavement sections. Following is a procedure to scale the safety condition to skid resistance-related distresses.

The skid resistance measurement, using Mu meter equipment described in Chapter two, was carried out for Al-Jubail Industrial City road network. These measurements covered 100 pavement sections [KFUPM-RI 1989]. The collected skid resistance were used to generate relationships between safety condition index (100-point scale) and distresses that are related to roughness such as rutting, depression, bleeding, and polished

aggregate. These relationships are needed for the priority ranking procedure if the skid resistance measuring devices are not available. Figure 4.2 shows the frequency distribution of the collected measurements. The mean skid number value for all sections was 47.7 with a standard deviation of 8.8, and available measurement range of 31 to 66.

Table 4.4 shows cross tabulation between skid resistance ranges and the existing distresses with their severity levels for each range. From this table it can be seen that at high levels of skid resistance (greater than 60), which is preferred situation from safety point of view, the all tested pavement section are completely free of any skid-related distresses. On the other hand, at low levels of skid resistance (below 40), which is safety-hazardous situation, the tested pavement sections have all types of these distresses. For example, polished aggregate distress that reflects the smoothness of the pavement surface, exists in 48% of the pavement sections. To assign safety condition index with relation to pavement distresses, an index value of 80 (100-point scale) is assigned to pavement sections that are completely free of any skid resistance-related distresses. This selection is based on that the maximum skid number value that can be obtained is around 80, and that the calibration of the Mu meter equipment requires a calibration value of 77 ± 3 [ML Aviation 1983]. The Mu meter calibration is done on a friction board representing the good skid resistance surfaces. The minimum value of skid number obtained in this study was 31, however, in more sever situations, especially in wet conditions such as rainy seasons, a lower values can be obtained. Based on this a value of 20 is assigned to the situation where the pavement surface contains one or more of the skid-related distresses at their high severity levels. The intermediate roughness indices (i.e. 40 and

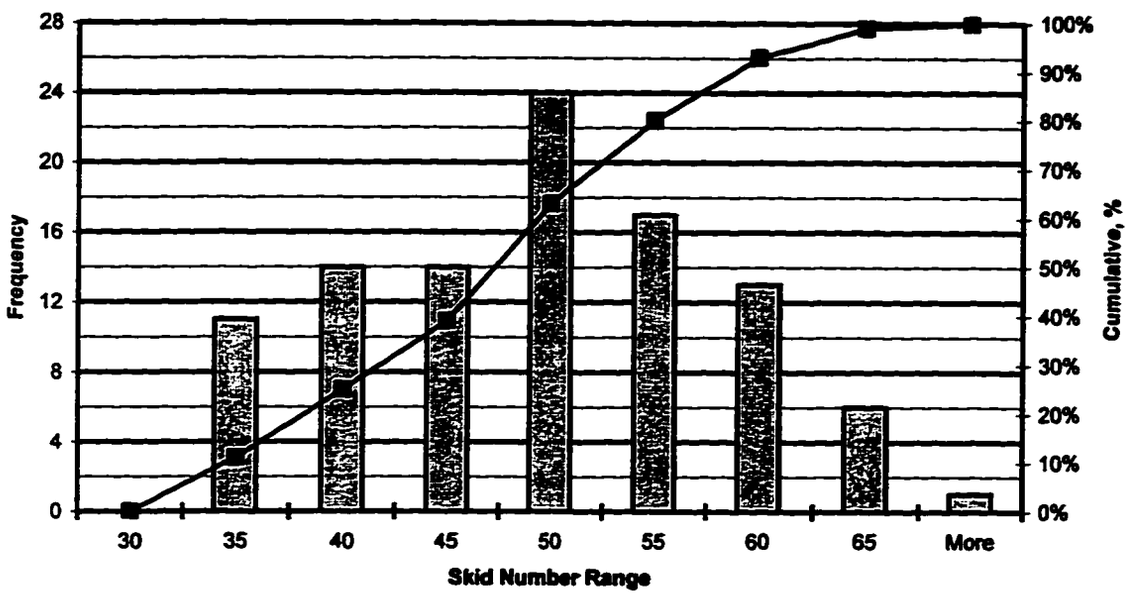


Figure 4.2. Frequency distribution of measured skid resistance of Al-Jubail road network.

Table 4.4. Measured skid resistance ranges versus existing disresses for Al-Jubail road network.

Group	Roughness Range, cm/km	No. of Sections	Severity Level	Rutting		Depression		Polished Aggregate*	
				Number	Percent	Number	Percent	Number	Percent
I	≤ 40	25	L	6	24	1	4	12	48
			M	3	12	0	0	0	0
			H	3	12	0	0	0	0
II	41 – 50	38	L	4	10.5	3	7.9	13	34.2
			M	4	10.5	0	0	0	0
			H	0	0	0	0	0	0
III	51 – 60	30	L	5	16.7	3	10	0	0
			M	2	6.7	0	0	7	18.4
			H	0	0	0	0	0	0
Iς	> 60	7	L	0	0	0	0	0	0
			M	0	0	0	0	0	0
			H	0	0	0	0	0	0

* Polished Aggregate does not have a severity Level.

60) can be assigned for the intermediate situations where the pavement surface has low severity or medium severity skid-related distresses. These safety condition index assignment is summarized in Table 4.5.

4.2.5 Operating Traffic

The operating traffic factor has high absolute values which if used, will overpower other priority factors. Therefore, it must be scaled to a 100-point scale to facilitate the priority index calculation. There are two ways to obtain this scale; the first is to use some established scale such as the one shown in Table 4.6 that was suggested by Stevens [1984]; the second way is normalizing all traffic values to 100 using the following equation:

$$OT = 100*ADT/MADT \tag{4.5}$$

where,

OT = Operating Traffic index (out of 100)

ADT = Measured average daily traffic, in vehicle/day, and,

MADT = Maximum measured ADT for the road network under study.

4.2.6 Maintenance Cost

Similar to operating traffic, maintenance cost has also high absolute values. Thus, using these value, will overpower other priority factors. Therefore, it must be scaled to a

Table 4.5. Recommended indices for safety condition-pavement distress relationship.

Class	Condition	Factor Value
I	**One or more of the following prevail:** high severity of bleeding and rutting; extensive level of polishing aggregate; high severity lane-shoulder drop off; lane demarcation is severely removed; high severity potholes with high number; sever drainage problems	80
II	**One or more of the following prevail:** medium severity of bleeding and rutting; moderate extent level of polishing aggregate; medium severity lane-shoulder drop off; lane demarcation is partially removed; low to medium severity potholes with few in number; some drainage problems	60
III	**One or more of the following prevail:** low severity of bleeding and rutting; low extent level of polishing aggregate; low severity lane-shoulder drop off; lane demarcation is in fair to good condition	40
IV	**Pavement condition is good from safety point of view**	20

Table 4.6. Recommended indices for traffic ranges [Stevens 1985].

No.	ADT Range	Traffic Factor (TF)
1	0 - 99	10
2	100 - 499	20
3	500 - 999	30
4	1000 - 1,999	40
5	2000 - 4,999	50
6	> 5,000	100

100-point scale. Similar to traffic factor scaling equation, the maintenance cost index value can be calculated using the following:

$$MC = 100*(1- COST/MCOST) \tag{4.6}$$

where,

MC = Maintenance Cost Index (out of 100)

COST = Required overall maintenance for a particular section in SR, and,

MCOST = Maximum overall maintenance cost incurred in all sections considered.

Alternatively, considering the maintenance unit cost values and the section length used locally for pavement evaluation, Table 4.7 gives the breakdown of 100-point scale for maintenance cost priority factor. In this table, the cost figures represents the preventive maintenance actions only. However, if the pavement section needs complete reconstruction, it has to be considered separately. The preventive maintenance is the one that upgrades the pavement condition to a level that major maintenance actions are avoided. Examples of preventive maintenance activities include crack sealing, surface slurry seal, surface patching, and leveling.

Table 4.7. Recommended indices for maintenance cost ranges.

No.	Maintenance Cost Range (SR)*	Maintenance Factor
1	< 1,000	10
2	1,000 - 5,000	20
3	5,001 - 10,000	30
4	10,001 - 15,000	40
5	15,001 - 20,000	50
6	20,001 - 50,000	70
6	> 50,000	100

* Section-wise overall maintenance cost

4.2.7 Importance to Community

The factors that quantify the overall importance or the utilization of a road section by the community, were detailed in Chapter Three. The factors represent the proportions of this factor (Importance to Community) by the six sub-factors.

The values of these sub-factors depend on the location of the road section in terms of its distance from center business district (CBD) of main market, or from the main official buildings, etc. and depend on the extent of utilization of this road section in terms of road type and operating traffic. Thus, these values can be either dichotomy(Yes/No) or values. On this basis, Table 4.8 was prepared for these sub-factor index assignment. In this table, if the road is passing through a CBD (YES), a value of 100 is assigned to this sub-factor to reflect its importance, otherwise, a zero value is assigned for NO answer. On the other hand, if the road, where the pavement section exists, has an alternative when it is subjected to maintenance (YES), then this road is not as important as the one that does not have an alternatives (NO), therefore, a value of 100 is assigned to the road with out alternatives, and a value of zero to the other one.

The overall importance factor is calculated using similar methodology of determining the priority index using the following equation:

$$IF = \Sigma\, SW_i\, (SF)_i \qquad (4.7)$$

where,

Table 4.8. Sub-factor values determination for importance to community factor.

No.	Factor	Level	Factor Value
1	Road Class	See Table 4.1	-
2	Road is Passing Through CBD ?	Yes	100
		No	0
3	Road is Near Official Building or used by VIPs ?	Yes	100
		No	0
4	Operating Traffic (ADT)	See Equation 4.5	-
5	Availability of Alternative Roads during maintenance ?	No	100
		Yes	0
6	Road is Near Other Important Public Centers ?	Yes	100
		No	0

IF = Importance to Community factor (out of 100 points),

SF_i = Importance value of sub-factor, i, obtained from Table 4.8,

SW_i = Weight of importance sub-factor, i, obtained from Table 4.23, and

ΣSW_i = 100

4.3 PILOT SURVEY DATA COLLECTION

A pilot survey was conducted to check the factors to be finally included in the main survey and the possibility of including new factors or removing some of the included factors. The initial version of the questionnaire included the important factors that affect the maintenance priority was prepared.

More than hundred forms of the initial questionnaire were distributed to different groups of people which included academicians in transportation and pavement fields, managers of road maintenance departments, site engineers and technicians, and ordinary road users. According to the comments and suggestions received from the individuals participated in the pilot study, the questionnaire has gone under several modifications. More than forty filled forms were collected and analyzed. The comments, suggestions, and recommendations were studied and categorized. Following were the most important ones:

1. Addition of road classification in the list of factors affecting the pavement maintenance priority.

2. Provision for drainage condition in the questionnaire form.

3. Addition of the availability of an alternative road or roads when considering the importance to community factor.

4. Removing some of the unclear and unproved sentences from the content of the questionnaire. For example, the accident rate included, as a measure of safety in roads, was removed due to: (i) the lack of information and records of this matter, and (ii) the lack of verification and association of the road conditions as a main cause of accidents.

5. Removing the percentage of trucks in the traffic mix as one of the factors that affect the maintenance priority and determining the importance to community factor.

6. The most important suggestion was to use another more rational and verified method of determining the weights of the maintenance priority factors. That was the analytical hierarchy process (AHP). The reason for this method was to examine the extent of confidence relative to the first direct assignment method. AHP method depends on the pair-wise comparison of all the factors. This methodology is detailed in Chapter Two.

7. To quantify the individual experience factor for those participated in the main survey data collection, another AHP pair-wise comparison between the groups of individuals was suggested to determine the weight of each individual group's experience in determining the weight of the priority factors in the ranking process.

The above comments and suggestion were considered in the main survey of data collection. Another questionnaire was prepared using the AHP to determine the pair-wise comparison between all the factors as well as the groups of individuals included in the survey. This questionnaire has undergone different revisions according to comments and suggestion. The final form of the questionnaire has four parts as shown in Figure 4.3, while the complete form is shown in Appendix A.

The final questionnaire (Figure 4.3) consists of four parts: Part I is for collecting the respondent's opinion about the weight of importance (out of 100) of seven factors: road class, pavement condition, operating traffic, riding quality, safety condition, maintenance cost, and importance to community, on the maintenance priority ranking. Part II is to quantify factor 7 "importance of road to community", by assigning weights (out of 100) for six sub-factors: road class, distance from CBD, operating traffic, VIP usage, alternative roads, and other public road utilization. The respondents were asked to fill a blank column by a value out of 100 that reflect the importance weight of the priority for Part I and the proportion of weight of the "importance of road to community" factor for part II. The total sum of these entries should be 100 in the two parts.

Part III was designed for the AHP method to pair-wise compare all the seven factors considered in part I. Since the AHP assumes that the pair-wise comparison of any two factors i and j is the reciprocal of the pair-wise entry for factors j and i, therefore, only 21 comparisons were needed as shown in Figure 4.4. For example, if the road class is three

Part I: In the following table, please fill out the blank column by the approximate percentage of importance of the corresponding factor in determining the priority for pavement section maintenance:

Factor	Description	Importance Weight (%)
1. Road Class	Major/Minor Road; Arterial, Collector, or Local; Commercial or Residential	
2. Pavement Condition	Existence of pavement defects in the road surface such as cracking, rutting, potholes, settlements, and others.	
3. Operating Traffic	Operating traffic volume determines the extent of road utilization by the public.	
4. Riding Quality	Existence of bumps, longitudinal corrugation, and unevenness in the road surface that cause high stresses to vehicles and discomfort to the road users (drivers and passengers). High road roughness.	
5. Safety Conditions	Smoothness of the road surface that causes safety hazards to vehicle stopping and braking; Low skid resistance or surface friction; High accident rates (rear-end type).	
6. Maintenance Cost	The overall maintenance cost for the road section in need of maintenance, this includes closing and detouring costs.	
7. Importance to Community	Overall importance to community determined by its distance from official buildings or important locations such as hospital, schools, mosques, etc. See Part II.	
	OVERALL	100%

Part II: The importance to community factor (the last in Part I) can be measured by different sub-factors; a list is shown in the following table. In order to quantify the weight of this factor in priority ranking, you are requested to give your estimated weight for each of these sub-factors, based on your experience and common sense of maintenance priority ranking practices:

Factor	Description	Importance Weight (%)
1. Road Class	Major/Minor road; Arterial, Collector, or Local; Commercial or Residential	
2. Distance from CBD	The distance from down-town or City Business Center determines the importance of the road section.	
3. Distance from official buildings (IMARAH, etc.)	If the road section under consideration passing through an official complex or used for VIPs may call for higher priority.	
4. Operating Traffic	Higher traffic volume roads calls for higher priority	
5. Availability of alternative roads	At maintenance time, this availability affects the maintenance priority of the road under consideration.	
6. Distance from other important buildings	Other buildings such as Civil Defense, Hospitals, Schools, etc. may call for higher maintenance priority	
	OVERALL	100%

Figure 4.3. The content of parts I and II of the questionnaire.

Part III: Pair-wise Comparison of Factors Considered in the Priority Ranking Process.

Factor to be compared		Priority weight of importance pair-wise comparison *																
Factor 1	Factor 2	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
Road Class	Pavement Condition																	
Road Class	Riding Quality																	
Road Class	Safety Conditions																	
Road Class	Operating Traffic																	
Road Class	Maintenance Cost																	
Road Class	Importance to Community																	
Pavement Condition	Riding Quality																	
Pavement Condition	Safety Conditions																	
Pavement Condition	Operating Traffic																	
Pavement Condition	Maintenance Cost																	
Pavement Condition	Importance to Community																	
Riding Quality	Safety Conditions																	
Riding Quality	Operating Traffic																	
Riding Quality	Maintenance Cost																	
Riding Quality	Importance to Community																	
Safety Conditions	Operating Traffic																	
Safety Conditions	Maintenance Cost																	
Safety Conditions	Importance to Community																	
Operating Traffic	Maintenance Cost																	
Operating Traffic	Importance to Community																	
Maintenance Cost	Importance to Community																	

* Required: Please check the square by (X) for the ratio of importance of factor 1 to factor 2. Example Road Class to Pavement Condition importance ratio is 1:5 means that the pavement condition is five times more important in *priority ranking process* than road class. Therefore the box under the heading of 1/5 is to be checked.

Figure 4.3. (Cont'd.) The content of Part III of the questionnaire.

Individuals involved in Priority Ranking Study

Person Group	Explanation
Academician	Highway Pavement/Traffic Management with experience in maintenance management
Managers	Pavement management department officials in ministries, municipalities, or road construction and maintenance companies
Engineers	Highway pavement or traffic engineer in highway departments or companies
Supervisors	Pavement maintenance supervisors or technicians working in pavement evaluation or maintenance firms or offices
Non-pavement Qualified	Qualified persons (not in pavement) such as journalists, education's staff, economists, businessmen, etc.
Others	Any ordinary road users other than the above

Part IV: Pair-wise Comparison between individuals.

Groups to be compared		Priority weight of importance pair-wise comparison *																
Group 1	Group 2	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
Academician	Managers																	
Academician	Engineers																	
Academician	Supervisors																	
Academician	Non-pavement Qualified																	
Academician	Others																	
Managers	Engineers																	
Managers	Supervisors																	
Managers	Non-pavement Qualified																	
Managers	Others																	
Engineers	Supervisors																	
Engineers	Non-pavement Qualified																	
Engineers	Others																	
Supervisors	Non-pavement Qualified																	
Supervisors	Others																	
Non-pavement Qualified	Others																	

* Required: Please check the square by (X) for the ratio of importance of Group 1 to Group 2. Example Engineers to supervisors importance ratio is 3:1 means that an engineer's opinion is three times more important in *priority ranking process* than that of a supervisor. Therefore the box under the heading of 3/1 is to be checked.

Figure 4.3. (Cont'd.) The content of Part IV of the questionnaire.

	Factor 1 Road Class	Factor 2 Pavement Condition	Factor 3 Operating Traffic	Factor 4 Riding Quality	Factor 5 Safety Condition	Factor 6 Maint. Cost	Factor 7 Importance	Eigenvector	Consistency	
Factor 1, Road Class	1.00	0.50	1.00	1.00	0.50	2.00	2.00	0.130	λ max =	7.074
Factor 2 Pavement Condition	2.00	1.00	2.00	2.00	1.00	4.00	3.00	0.248	C.I. =	0.012
Factor 3 Operating Traffic	1.00	0.50	1.00	1.00	0.50	2.00	1.00	0.117	C.R. =	0.009
Factor 4 Riding Quality	1.00	0.50	1.00	1.00	0.50	2.00	1.00	0.117		
Factor 5 Safety Condition	2.00	1.00	2.00	2.00	1.00	3.00	2.00	0.225		
Factor 6 Maint. Cost	0.50	0.25	0.50	0.50	0.33	1.00	1.00	0.068		
Factor 7 Importance	0.50	0.33	1.00	1.00	0.50	1.00	1.00	0.093		
Total =	8.00	4.08	8.50	8.50	4.33	15.00	11.00	1.000		

Figure 4.4. Typical AHP calculation example of Part III.

times more important, to priority ranking, than pavement condition (entry will be 3), then the pavement condition to road class comparison is one-third (entry will be 1/3).

Part IV is Similarly, Part IV is for pair-wise comparison of individual groups participated in the survey. Only fifteen entries are needed.

4.4 MAIN SURVEY DATA COLLECTION

The final questionnaire was again re-distributed to the individuals surveyed before in the pilot study and other new individuals. The forms were distributed by mail, fax, and by personal contact with the individuals and agencies. The forms were also collected back by the same means. The collected filled questionnaires represent about 65% of the total forms distributed.

Since Part I and III of the questionnaire have seven variables, a minimum of 28 individuals are required to be surveyed. This is according to the sample size requirement explained in Chapter Three.

The individuals included in the survey were: academicians in the area of traffic, highway, pavement maintenance, and pavement management, highway and pavement maintenance department officials (managers) and engineers, pavement maintenance supervisors and technicians, non-pavement qualified individuals, and ordinary road users. The institutions and agencies included in this survey were: KFUPM, King Saud University, King Abdulaziz University, MOC, Dammam and Riyadh municipalities, Saudi Aramco, Royal Commission of Jubail, and local companies and establishments

involved in pavement maintenance. The opinions of those selected people about the importance level of the factors affecting the maintenance priority were collected according to the questionnaire forms. The data collection was extended to the pavement specialists and other road users in the United Arab Emirate (UAE) as an example of other Gulf countries. This was done to compare the Saudi Arabian and the Emirates pavement experiences in terms of maintenance priority ranking, as shown in Appendix B.

To quantify the effect of each person involved in this survey, in the process of priority ranking determination, a special form of AHP (Part IV) was prepared to pair-wise compare each group of individuals to determine the weight factor for that group. These weight factors, called the individual experience factor, are needed for priority model calibration.

For parts I and II, a total number of sixty-five respondents were collected as summarized in Table 4.9. The opinions of experts working in the area of pavement maintenance were more emphasized. The surveyed individuals include: twenty six engineers and five supervisors and technicians working in the field of pavement maintenance in different parts of the Kingdom; sixteen academicians from different Saudi universities, and sixteen other non-pavement qualified and ordinary road users.

The data of Parts I and II were entered into spread sheet files for processing and analysis. For Part III and IV, a special spread sheet was prepared to calculate the factor weights of importance as per the AHP procedures detailed in section 2.5.5.3. Figure 4.4 shows a typical seven-factor spread sheet for factor weight determination. This figure

Table 4.9. Summary of the individuals surveyed in the main survey data collection.

Individual Group	Explanation	Participated Number
Academician	Highway Pavement/Traffic Management with experience in maintenance management	16
Managers	Pavement management department officials in ministries, municipalities, or road construction and maintenance companies	2
Engineers	Highway pavement or traffic engineer in highway departments or companies	26
Supervisors	Pavement maintenance supervisors or technicians working in pavement evaluation or maintenance firms and offices	5
Non-pavement Qualified	Qualified persons (not in pavement) such as other engineering fields journalists, education's staff, economists, businessmen, etc.	11
Others	Any ordinary road users other than the above	5

contains the determination of eigenvector, maximum eigenvalue λ_{max}, consistency index (CI), and the consistency rating (CR). The calculated weights for each questionnaire were stored in another spread sheet for further analysis.

4.5 RESULTS OF MAIN SURVEY DATA COLLECTION

Tables 4.10 and 4.11 show the summary of the collected data for Part I and Part II of the survey. The weights of importance of all seven factors for each data point (filled questionnaire) of Part I add to 100. Similarly, in Part II, the sum of weights of the sub-factors related to the "importance of the road to community" factor also add to 100. Average and standard deviation values of all factors and sub-factors were also determined.

In Part III, a total of fifty-one forms were collected, out of which thirty forms were considered and the rest were excluded due to the high inconsistency (consistency rating, CR is greater that 0.1) as specified in section 2.5.5.5. The considered data points are shown in Table 4.12 along with the average and standard deviation values of each factor. The calculation of the factors' weights were made using the procedure explained in section 2.5.5.3 and typically shown in Figure 4.4.

The pavement condition factor had the highest average weight, while the maintenance cost had the lowest weight. However, as Table 4.10 indicates, the pavement condition factor had substantial disagreements (measured as standard deviation) among the respondents, and the riding quality factor has the highest agreement (lowest standard deviation value).

Table 4.10. Summary of main survey collected data of Part I.

No.	Experience Code	Factor 1, Road Class	Factor 2 Pavement Condition	Factor 3 Operating Traffic	Factor 4 Riding Quality	Factor 5 Safety Condition	Factor 6 Maint. Cost	Factor 7 Importance	Sum
1	1	15	20	15	15	15	10	10	100
2	1	5	20	5	30	30	0	10	100
3	1	5	25	5	10	15	25	15	100
4	1	10	25	5	10	20	15	15	100
5	1	5	30	15	10	10	10	20	100
6	1	10	30	10	10	15	5	20	100
7	1	25	10	15	10	15	10	15	100
8	1	15	25	15	10	10	12	13	100
9	1	10	25	10	20	15	10	10	100
10	1	15	10	15	10	20	20	10	100
11	1	20	7	5	18	22	13	15	100
12	1	20	18	13	12	18	7	12	100
13	1	5	10	20	8	12	15	30	100
14	1	10	15	15	10	20	10	20	100
15	1	5	15	15	20	20	5	20	100
16	1	15	20	10	25	10	10	10	100
17	2	10	20	10	20	20	10	10	100
18	2	10	10	20	15	15	10	20	100
19	3	25	30	5	5	10	10	15	100
20	3	15	15	25	12	12	10	11	100
21	3	15	12	25	11	10	7	20	100
22	3	18	20	16	12	11	14	9	100
23	3	7	25	20	10	8	10	20	100
24	3	25	25	20	7	7	6	10	100
25	3	16	20	11	16	16	5	16	100
26	3	10	20	10	10	20	10	20	100
27	3	15	10	20	15	10	10	20	100
28	3	10	30	10	20	20	5	5	100
29	3	10	40	5	20	10	0	15	100
30	3	10	55	6	10	3	6	10	100
31	3	15	60	0	6	0	4	15	100
32	3	15	55	5	10	1	5	9	100
33	3	14	18	9	9	27	9	14	100
34	3	15	15	10	15	25	10	10	100
35	3	15	20	15	15	15	5	15	100
36	3	10	20	5	10	30	20	5	100
37	3	10	20	15	20	20	10	5	100
38	3	15	15	12	14	14	15	15	100
39	3	10	10	15	15	10	30	10	100
40	3	18	15	13	8	8	20	18	100
41	3	40	10	20	5	10	10	5	100
42	3	20	5	30	5	10	20	10	100
43	3	15	20	20	5	10	15	15	100
44	3	20	20	5	10	30	10	5	100
45	4	10	15	15	20	20	10	10	100
46	4	10	25	5	10	35	5	10	100
47	4	10	10	20	15	10	5	30	100
48	4	20	15	5	15	5	20	20	100
49	4	10	25	10	25	20	5	5	100
50	5	5	10	20	10	10	5	40	100
51	5	15	25	13	11	20	7	9	100
52	5	10	5	15	5	10	25	30	100
53	5	30	10	20	5	5	10	20	100
54	5	5	5	15	10	15	5	45	100
55	5	10	10	15	15	25	15	10	100
56	5	10	25	10	8	20	12	15	100
57	5	5	14	9	23	32	5	14	100
58	5	12	11	15	10	21	19	12	100
59	5	15	15	10	10	20	5	25	100
60	5	10	20	10	10	20	5	25	100
61	6	10	45	5	10	10	10	10	100
62	6	15	10	30	5	10	20	10	100
63	6	10	12	20	15	18	13	12	100
64	6	20	10	20	5	10	5	30	100
65	6	15	20	10	10	20	10	15	100
Average		13.5	19.6	13.2	12.4	15.5	10.6	15.3	
Standard Dev.		6.4	11.4	6.4	5.5	7.5	6.1	8.0	

Table 4.11. Summary of main survey collected data of Part II.

No.	Experience Code	Sub-Factor 1, Road Class	Sub-Factor 2 Dist. form CBD	Sub-Factor 3 Use of VIPs	Sub-Factor 4 Operating Traffic	Sub-Factor 5 Maint. Alternatives	Sub-Factor 6 Other Imp. Locations	Sum
1	1	25	20	10	20	10	15	100
2	1	5	10	20	40	20	5	100
3	1	20	10	15	40	10	15	110
4	1	20	20	15	15	15	15	100
5	1	10	10	20	40	10	10	100
6	1	10	10	35	10	15	20	100
7	1	15	20	25	15	10	15	100
8	1	30	15	15	20	15	5	100
9	1	20	10	20	25	10	15	100
10	1	10	20	10	30	15	15	100
11	1	30	12	20	15	8	15	100
12	1	25	13	15	16	10	21	100
13	1	3	4	30	15	40	8	100
14	1	6	16	21	26	26	5	100
15	1	10	15	15	15	25	20	100
16	1	15	20	25	15	10	15	100
17	2	10	20	25	25	5	15	100
18	2	20	10	10	30	10	20	100
19	3	20	20	20	10	20	10	100
20	3	15	15	25	15	10	20	100
21	3	18	13	25	14	10	20	100
22	3	10	25	20	12	15	18	100
23	3	7	10	8	30	20	25	100
24	3	20	20	20	20	10	10	100
25	3	20	25	10	20	10	15	100
26	3	20	20	15	15	10	20	100
27	3	20	5	5	30	25	15	100
28	3	10	20	10	30	15	15	100
29	3	5	0	30	20	15	30	100
30	3	10	0	30	20	10	30	100
31	3	15	0	50	3	2	30	100
32	3	10	0	30	20	10	30	100
33	3	20	15	10	25	15	15	100
34	3	25	15	10	25	10	15	100
35	3	25	15	20	25	5	10	100
36	3	10	20	10	20	20	20	100
37	3	10	15	10	30	20	15	100
38	3	20	17	20	15	10	18	100
39	3	15	25	15	15	10	20	100
40	3	20	18	24	12	12	14	100
41	3	40	10	20	20	5	5	100
42	3	5	5	30	30	20	10	100
43	3	28	28	11	11	11	11	100
44	3	10	20	10	25	15	20	100
45	4	10	15	20	20	10	25	100
46	4	5	10	20	40	10	15	100
47	4	10	20	25	15	10	20	100
48	4	20	10	20	20	10	20	100
49	4	20	25	15	15	20	5	100
50	5	10	15	10	30	15	20	100
51	5	21	26	11	15	11	16	100
52	5	30	20	10	15	15	10	100
53	5	30	10	10	20	15	15	100
54	5	10	18	15	30	17	10	100
55	5	10	10	15	30	15	20	100
56	5	10	20	10	25	20	15	100
57	5	15	25	15	15	10	20	100
58	5	20	20	12	18	16	14	100
59	5	10	25	10	20	10	25	100
60	5	10	15	20	30	10	15	100
61	6	10	10	10	35	25	10	100
62	6	20	15	15	30	10	10	100
63	6	20	15	18	25	10	12	100
64	6	20	20	10	20	15	15	100
65	6	20	25	5	15	10	25	100
Average		16.0	15.4	17.4	21.6	13.6	16.1	
Standard Dev.		7.7	6.8	8.1	8.1	6.1	6.2	

Table 4.12. Summary of main survey collected data of Parts III.

No.	Exp. Code	Factor 1, Road Class	Factor 2 Pavement Condition	Factor 3 Operating Traffic	Factor 4 Riding Quality	Factor 5 Safety Condition	Factor 6 Maint. Cost	Factor 7 Importance	Sum
1	1	19.2	6.0	22.9	7.3	11.9	7.4	25.3	100
2	1	8.7	18.5	19.1	13.0	21.1	7.0	12.6	100
3	1	11.2	4.3	11.7	6.4	29.8	8.9	27.7	100
4	1	7.8	6.0	5.0	37.6	16.2	3.8	23.5	100
5	1	7.0	16.2	17.1	31.0	12.0	8.3	8.5	100
6	1	15.2	21.9	21.9	10.0	10.0	11.0	10.0	100
7	2	32.3	20.4	14.8	15.1	4.6	5.9	7.0	100
8	2	23.5	9.5	14.1	13.7	12.6	14.1	12.4	100
9	3	6.4	26.4	4.3	16.5	33.0	6.8	6.6	100
10	3	17.3	6.5	15.1	3.9	2.2	27.1	28.1	100
11	3	23.7	12.5	17.7	9.0	10.1	12.2	14.7	100
12	3	6.5	16.9	16.9	11.6	16.5	14.5	17.1	100
13	3	7.2	17.2	14.6	16.4	22.8	12.9	8.9	100
14	3	18.7	37.0	7.8	17.2	8.2	4.3	6.7	100
15	3	40.0	10.0	20.0	5.0	10.0	10.0	5.0	100
16	5	4.2	7.8	19.3	10.6	11.3	4.7	42.2	100
17	5	13.0	24.8	11.7	11.7	22.5	6.8	9.3	100
18	5	6.3	28.7	9.3	11.4	20.0	15.4	8.9	100
19	5	16.1	24.5	21.8	13.3	7.7	6.9	9.7	100
20	5	22.6	15.2	16.1	7.9	4.6	16.5	17.1	100
21	5	7.5	9.4	10.4	4.9	27.8	10.5	29.6	100
22	5	19.0	2.9	13.8	9.3	9.3	5.1	40.6	100
23	5	14.8	21.8	9.0	9.0	21.8	9.0	14.8	100
24	6	2.8	28.7	4.8	28.7	28.7	3.2	3.2	100
25	6	9.4	15.6	19.8	10.6	18.2	8.4	17.9	100
26	6	22.3	25.2	19.6	16.2	6.9	7.7	2.1	100
27	6	7.8	16.5	14.2	17.2	15.5	13.7	15.1	100
28	6	7.1	8.8	15.1	9.0	11.9	3.9	44.0	100
29	6	11.6	9.3	17.3	7.3	26.8	8.9	18.9	100
30	6	3.7	16.4	9.6	16.2	28.2	15.1	10.8	100
Average		13.8	16.2	14.5	13.2	16.1	9.7	16.6	
Standard Dev.		8.8	8.5	5.2	7.6	8.5	5.0	11.4	

In Part IV of the questionnaire, only ten individuals were surveyed, the people that was expected to have good ability to judge about the weight of experience and importance level of every group of individuals in the process of priority ranking. This group included academicians and pavement management engineers. In this part, six groups were pair-wise compared and the weight of each group was calculated using the same procedure followed in Part III. All collected data were consistent (CR is less than 0.1). Figure 4.5 shows typical calculation example and Table 4.13 summarizes of the results of this part. However, this part was initially designed for the adjusting of the weights of the priority factors. This is, if the different surveyed groups showed significant difference in their means of the collected data, which is detailed later in section 4.7.1.

The collected data were checked and verified for any possible errors. In Part I and Part II of the questionnaire, the only numerical data required was the percentile weight of importance of each priority factor. The only check in these parts was to make sure that the total sum of factor weights adds to 100. Only three questionnaire forms had a total sum of weights for Part I other than 100 which were corrected by proportioning. In Parts III and IV, the required information was filling blank squares by (X) for the estimated pair-wise comparisons. In Part III of the questionnaire, some entries were left blanks without crossing the estimated comparison. Those forms were discarded from the analysis.

	Group 1, Academician	Group 2 Managers	Group 3 Engineers	Group 4 Supervisors	Group 5 Non-Pavement	Group 6 Others	Eigenvector	Consistency	
Group 1, Academician	1.00	1.00	2.00	4.00	9.00	9.00	0.329	λ max =	6.069
Group 2 Managers	1.00	1.00	2.00	4.00	8.00	9.00	0.323	C.I. =	0.014
Group 3 Engineers	0.50	0.50	1.00	3.00	5.00	6.00	0.189	C.R. =	0.011
Group 4 Supervisors	0.25	0.25	0.33	1.00	3.00	4.00	0.092		
Group 5 Non-Pavement	0.11	0.13	0.20	0.33	1.00	1.00	0.035		
Group 6 Others	0.11	0.11	0.17	0.25	1.00	1.00	0.032		
Total =	2.97	2.99	5.70	12.58	27.00	30.00	1.000		

Figure 4.5. Typical AHP calculation example of Part IV.

Table 4.13. Summary of main survey collected data of Parts IV.

No.	Experience Code	Group 1, Academicians	Group 2 Managers	Group 3 Engineers	Group 4 Supervisors	Group 5 Non-pavement Qualified	Group 6 Other Road Users	Sum	λ max	C.I.	C.R.
1	1	40.0	28.6	13.8	11.5	3.6	2.5	100	6.49	0.10	0.08
2	1	34.1	33.0	15.3	7.6	7.4	2.6	100	6.38	0.08	0.06
3	1	36.5	28.1	14.5	11.8	5.6	3.4	100	6.20	0.04	0.03
4	1	32.1	32.1	16.6	9.4	6.1	3.7	100	6.04	0.01	0.01
5	1	31.8	28.3	22.8	6.4	6.4	4.2	100	6.08	0.02	0.01
6	1	40.9	15.7	25.2	11.2	4.3	2.6	100	6.24	0.05	0.04
7	1	23.8	23.8	34.6	12.7	2.6	2.6	100	6.44	0.09	0.07
8	1	32.9	32.3	18.9	9.2	3.5	3.2	100	6.07	0.01	0.01
9	2	40.8	21.8	15.2	15.9	4.1	2.3	100	6.35	0.07	0.06
10	2	36.4	19.5	26.8	11.4	3.1	2.8	100	6.38	0.08	0.06
Average		34.9	26.3	20.4	10.7	4.7	3.0				
Standard Dev.		5.2	5.9	6.8	2.7	1.6	0.6				

4.6 DATA ANALYSIS

The use of parametric hypothesis testing require the assumption that the random samples are selected from normal population. If there is no knowledge about the distribution of the population, the non-parametric testing procedure such as Wilcoxon test, sign test, rank correlation coefficient, and Kurskal-Wallis test should be used [Walpole and Myers 1978]. The nonparametric hypothesis testing do not rely on the estimation of the parameters, such as means and standard deviations, describing the distribution of the variable population. Therefore, these testing methods are called parameter-free of distribution-free methods. The parametric methods are more efficient than the nonparametric methods since the former utilize the information provided by the samples while the later do not.

To verify the use of parametric hypothesis testing, the normality test of the collected data should be carried out using different methods. One trivial method is to visually inspect the shape of the frequency distribution histogram of collected data when plotted against the expected normal distribution at a specified significant level. Other methods is to run normality check tests such as Kolmogrov-Smirnov K-S test and Shapiro-Wilk, W-test [STATITICA 1995; Conover 1980; Sprent 1989].

The type of measurements or data collected in this study are of ordinal nature, since the opinions of different people were collected regarding the weight of importance of different factors on maintenance priority ranking. There was only one attribute which is the priority and seven items or factors describing this attribute. However, these

measurements are made in a continuous and summative manner where the sum of all weights of factors has to add to 100. In this case the simple sum of the factor scores is a linear combination of these scores.

Measurements are reliable to the extent that they are repeatable and that any random influence which tends to make measurements different from occasion to occasion is a source of measurement error [Nunnally 1967]. Therefore, in order to check that the collected data of the priority ranking method through the designed questionnaires were repeatable and reproducible, several checks of repeatability were carried using parametric methods as detailed in the following sections.

Figures 4.6 to 4.12 show the frequency distribution plots of all factors of the collected data. From the visual inspection of these figures, it appears that the data, to a good extent, are normally distributed with some skewness. Furthermore, Table 4.14 shows the results of K-S test, where it is clear that all factors statistically represent normal distributions at a significance level of 95% for Factor 3 (Operating Traffic) and 99% of other factors. Based on this result, the parametric hypothesis testing can be used since the normality assumption is satisfied.

4.6.1 Statistical Comparison Tests

The criteria set to check the repeatability was that if any randomly selected two subsets of the collected data were compared, all seven factors included in the study should have statistically equal means for these two subsets. If it was concluded that, for any of the factors, the null hypothesis of equal means was rejected, then the two subsets have

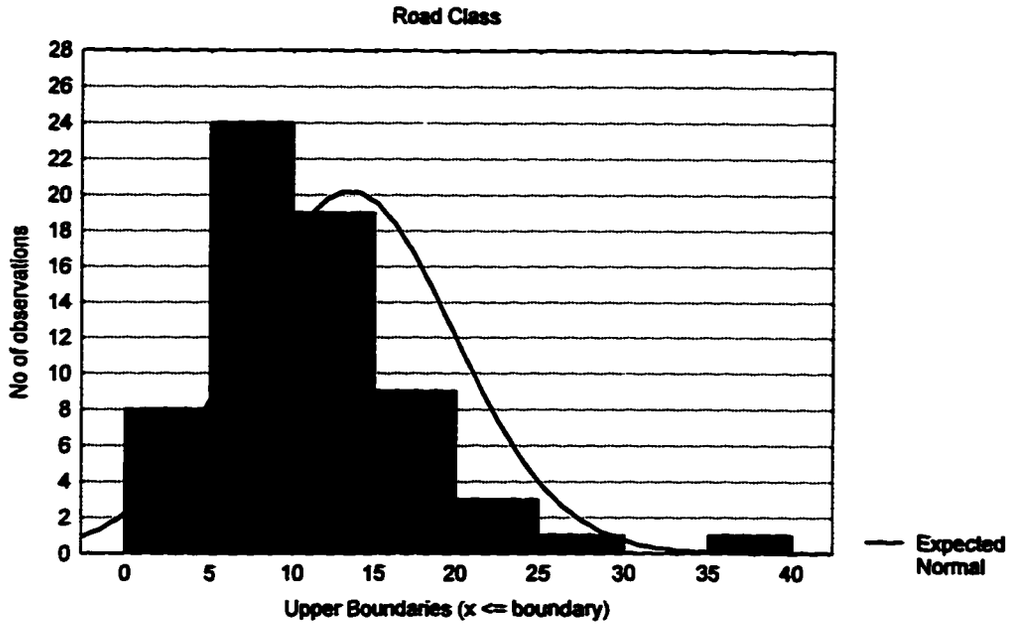


Figure 4.6. Frequency distribution of road class data.

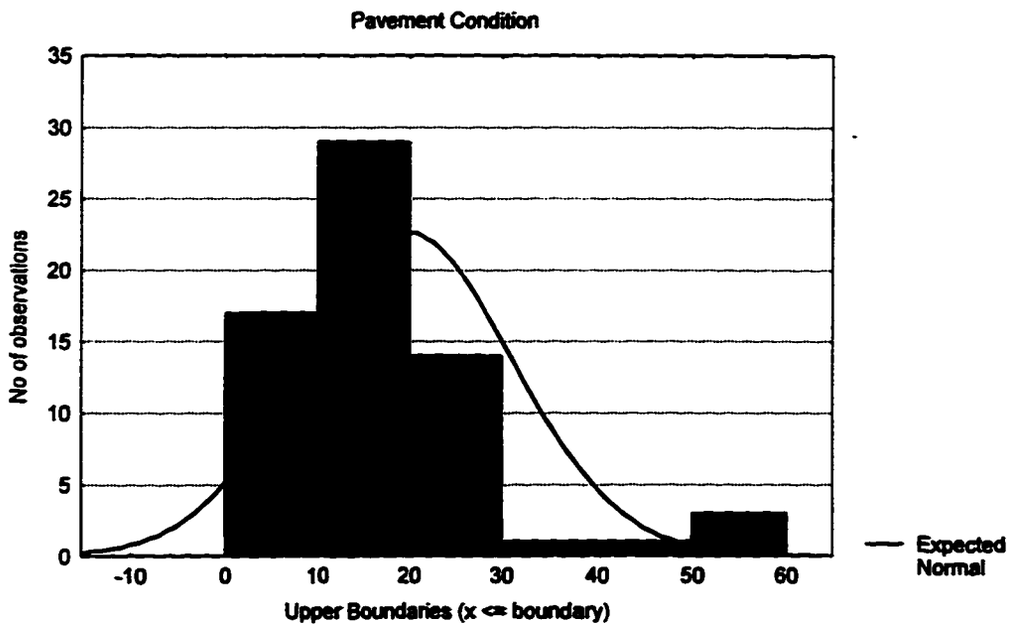


Figure 4. 7. Frequency distribution of pavement Condition data.

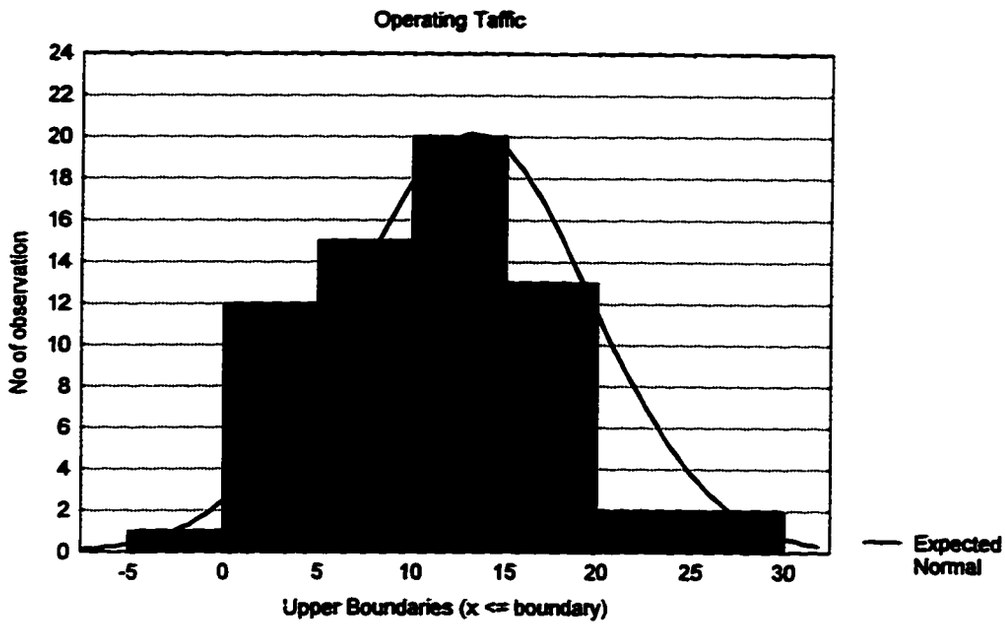


Figure 4.8. Frequency distribution of operating traffic data.

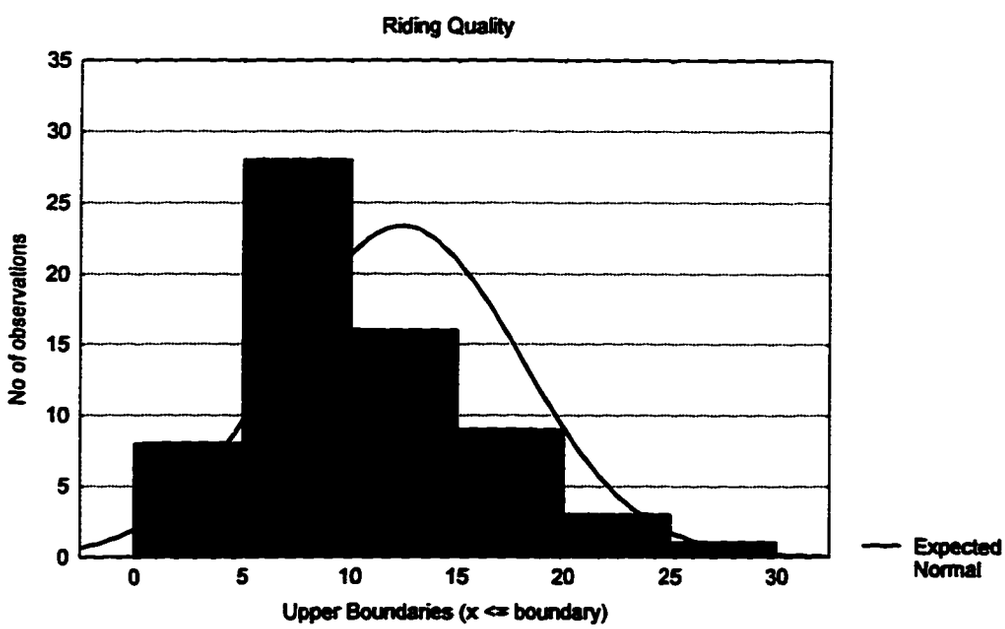


Figure 4.9. Frequency distribution of riding quality data.

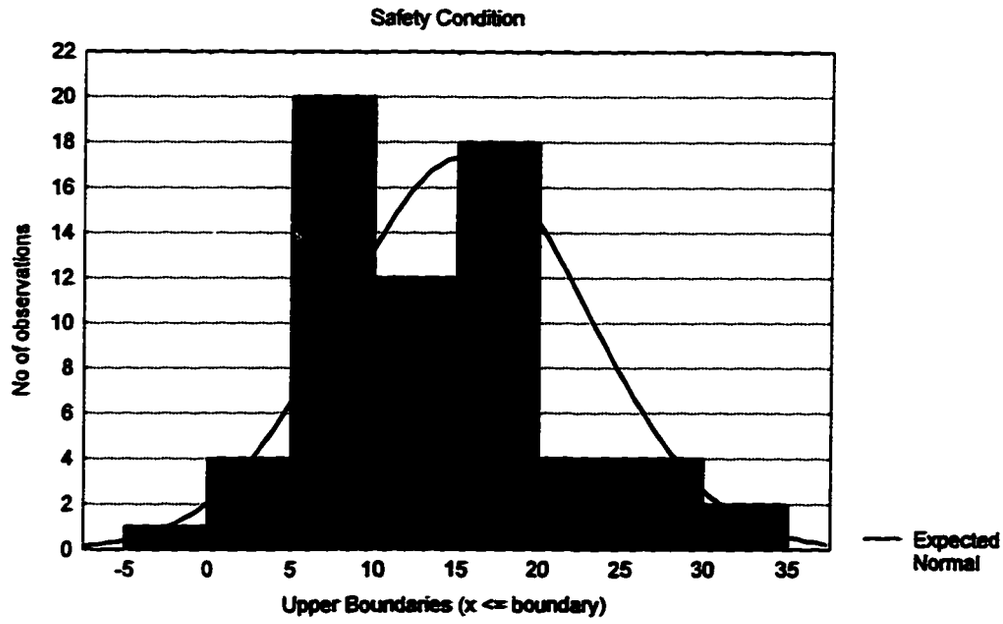


Figure 4.10. Frequency distribution of safety condition data.

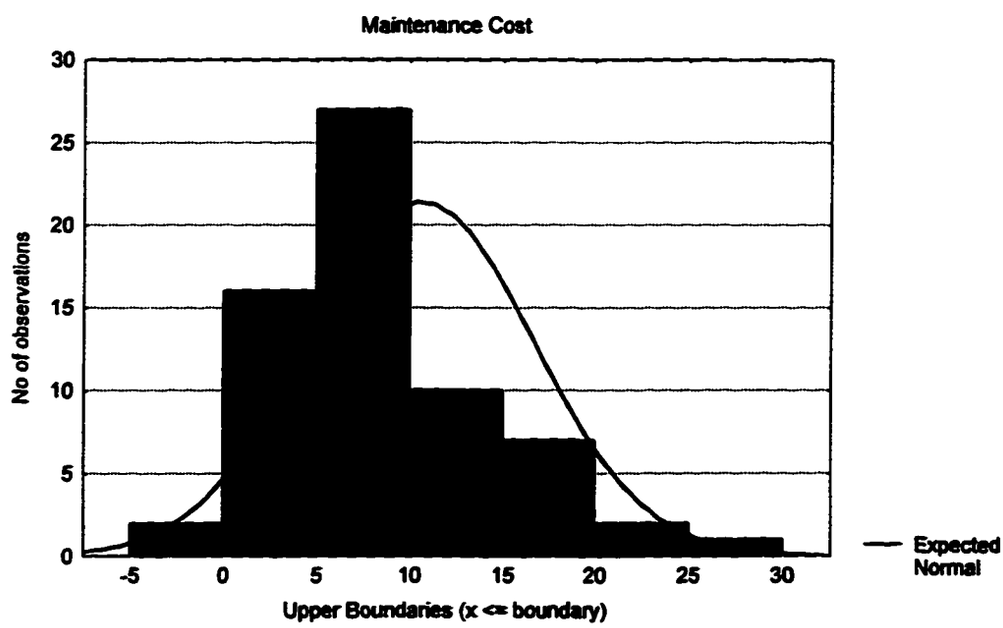


Figure 4.11. Frequency distribution of maintenance cost data.

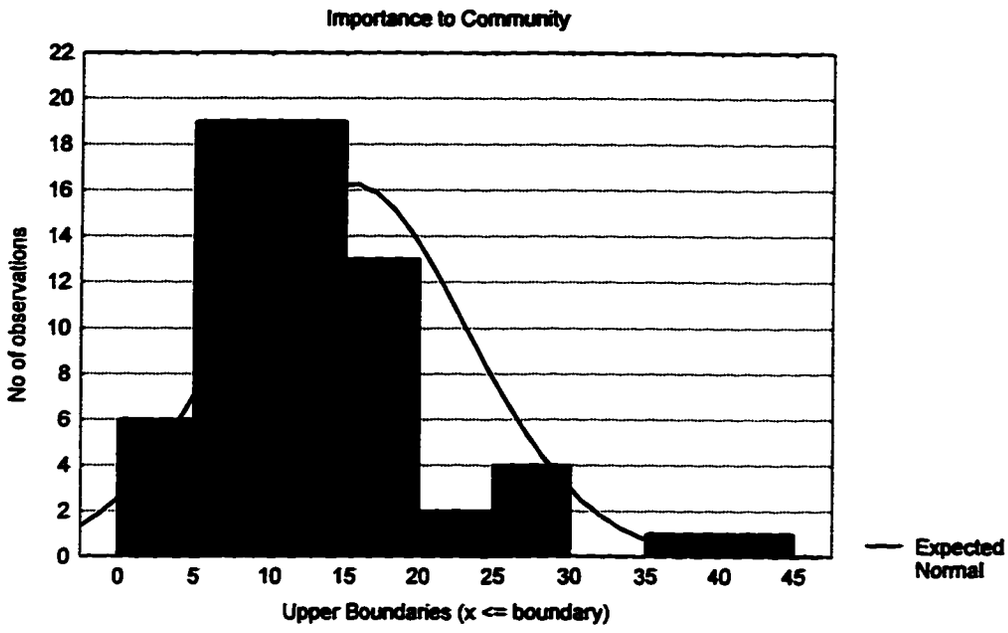


Figure 4.12. Frequency distribution of importance to community data.

Table 4.14. K-S test results for normality checking.

Factor	N	Max D	Probability	Significance Level
Road Class	65	0.197609	$p < 0.01$	99%
Pavement Condition	65	0.195135	$p < 0.01$	99%
Operating Traffic	65	0.127491	$p < 0.05$	95%
Riding Quality	65	0.220235	$p < 0.01$	99%
Safety Condition	65	0.152687	$p < 0.01$	99%
Maintenance Cost	65	0.231280	$p < 0.01$	99%
Importance to Community	65	0.191277	$p < 0.01$	99%

different means and consequently they are not repeatable. The statistical comparison technique has two steps [Montgomery 1984]: (i) checking the equality of the variances of the two subsets using the F-test and (ii) checking the equality of the means of the two subsets using the t-test. Since the choice of t-test statistic, to test the equality of means, depends on the equality of variances of the two populations from which the subset samples of any of the priority factors data were drawn, therefore, prior to conducting the t-test, it is important to test the equality of the variances of each pair of factors data.

The first step has the following hypothesis:

$$H_0: \sigma_1 = \sigma_2, \text{ and } H_1: \sigma_1 \neq \sigma_2, \tag{4.8}$$

where

σ^2_1 = the variance value of Factor 1 in Group 1

σ^2_2, = the variance value of Factor 1 in Group 2, and similarly for other factors

Using the fact that the following statistics:

$$F_o = \frac{S_1^2}{S_2^2} \tag{4.9}$$

is distributed as F, with n_1-1 and n_2-1 degrees of freedom, the null hypothesis H_0 will be rejected if:

$$F_0 > F_{\alpha/2,\, n1-1,\, n2-1} \tag{4.10}$$

and conclude that the two population variances are unequal, otherwise the variances are assumed equal.

The second step has the following hypothesis:

$$H_0: \mu_1 = \mu_2, \text{ and } H_1: \mu_1 \neq \mu_2, \tag{4.11}$$

where,

μ_1 = the mean value of Factor 1 in Group 1

μ_2, = the mean value of Factor 1 in Group 2, and similarly for other factors.

If the null hypothesis of the first step was rejected (unequal variances), the following approximate t*-test to check the equality of the two sample means will be used:

$$t^* = \frac{\mu_1 - \mu_2}{\left[\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right]^{1/2}} \tag{4.12}$$

which is distributed approximately as 't' with a degrees of freedom given by the following:

$$v = \frac{\left[\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right]^2}{\left[\frac{(S_1^2/n_1)^2}{n_1 + 1} + \frac{(S_2^2/n_2)^2}{n_2 + 1}\right]} - 2 \tag{4.13}$$

where,

ν = degrees of freedom;

S_1^2 = the variance of the first group data of any of the priority factors;

S_2^2 = the variance of the second group data of the corresponding factor;

n_1 = the number of cases of the first group data of any of the priority factors; and

n_2 = the number of cases of the second group data of the corresponding factor.

However, the null hypothesis H_o of the first step is accepted, i.e. if

$$F_0 < F_{\alpha/2,\, n1-1,\, n2-1} \tag{4.14}$$

and conclude that the two population variances are equal, then the following exact 't-test' will be used to test the equality of the samples means with degrees of freedom of $n_1 + n_2 - 1$:

$$T_o = \frac{\mu_1 - \mu_2}{S_p\left[\frac{1}{n_1} + \frac{1}{n_2}\right]^{1/2}} \tag{4.15}$$

and

$$S_P^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \tag{4.16}$$

where, S_p is the pooled standard deviation of the two groups.

A value of $\alpha = 0.05$ was selected for the above analysis which means that a confidence level of 95% was selected. The rejection criteria for equality of means for both t-test and t*-test are the following:

$$T_0 > T_{\alpha/2} \text{ or } T_0 < -T_{\alpha/2} \qquad (4.17)$$

where $T_{\alpha/2}$ is from statistical table with the corresponding α=0.05 and degrees of freedom.

4.6.2 Factor Weights Statistical Comparison

The factor weights obtained from the mains survey shown in Table 4.10 were subjected to the statistical tow-step comparison test described in the previous section. This test is required to check whether the factor weights are statically different or they may all have same value (overall average value). Thus, this comparison justify the need for the data collection phase of this part of the study.

Table 4.15 shows the results of the two statistical comparison test. In this table, 'R' stands for rejection the null hypothesis (H_0) for comparison of both variances and means of any two factors, while 'A' stands for accepting H_0. The results in the shaded area is similar to the other one since the comparison matrix is symmetrical. If the variances comparison test has a result of 'A', then the t-test will be used to compare the means, otherwise, the t*-test will be used.

Table 4.15. Summary of statistical comparion tests for maintenance priority factors.

	Factor 1, Road Class		Factor 2 Pavement Condition		Factor 3 Operating Traffic		Factor 4 Riding Qualility		Factor 5 Safety Condition		Factor 6 Maint. Cost		Factor 7 Importance	
	Variances	Means	Variances	Means	Variances	Means	Variances	Means	Variances	Means	Variances	Means	Variances	Means
Factor 1, Road Class			R	R	R	A	A	A	R	A	A	R	R	A
Factor 2 Pavement Condition					R	R	R	R	R	R	R	R	R	R
Factor 3 Operating Traffic							A	A	R	A	A	R	R	A
Factor 4 Riding Qualility									R	A	R	R	R	A
Factor 5 Safety Condition											A	R	R	A
Factor 6 Maint. Cost													R	R
Factor 7 Importance														

R: Reject Ho that variances or means are same

A: Accept Ho that variances or means are same

From this table, it can be seen that Factor 2 (Pavement Condition) and Factor 6 (Maintenance Cost) have mean values statistically different from all other factors. Other factors have means that are either statistically same or different than each other, such as Factor 1 (Road Class) that has a statistically different mean than those of Factor 2 and Factor 6, but same as those of other factors.

Therefor, as a conclusion of this comparison, the factors included in the priority ranking procedure can not be having one average value which is a clear evident that the data collection for factor weight determination was necessarily required.

4.6.3 Repeatability Checks

Three schemes were designed for checking the repeatability of the obtained data for the weight of importance of priority factors. These schemes were: (i) checking the variation within the data, (ii) checking the variation on temporal basis (different times), and (iii) checking the repeatability in using different data collection methods. In all of these schemes, the two-step statistical comparison of two subsets was used as detailed before.

4.6.3.1 Within Data Variation

The collected data of one type of individuals (engineers) were randomly divided into two subsets or groups; each group has 12 data points. Table 4.16 shows the results of the first step of the comparison between the variances of the two groups. From this table,

Table 4.16. Summary of the comparison test for within data variations.

Statistic	Factor 1		Factor 2		Factor 3		Factor 4		Factor 5		Factor 6		Factor 7	
	GROUP 1	GROUP 2	GROUP 1	GROUP 2	GROUP 1	GROUP 2	GROUP 1	GROUP 2	GROUP 1	GROUP 2	GROUP 1	GROUP 2	GROUP 1	GROUP 2
Mean	17.08	14.83	21.08	21.00	14.67	13.83	10.42	12.00	12.58	15.50	11.58	11.08	12.58	11.75
Variance	60.63	35.42	269.54	36.55	59.52	45.42	11.54	27.09	62.63	64.64	22.99	55.54	22.99	34.02
Observations	12	12	12	12	12	12	12	12	12	12	12	12	12	12
F	1.712		7.375		1.310		0.426		0.969		0.414		1.480	
F Critical one-tail	2.818		2.818		2.818		0.355		0.355		0.355		0.355	
Conclusion 1	Accept Ho, Use t-test		Reject Ho, Use t*-test		Accept Ho, Use t-test		Reject Ho, Use t*-test		Reject Ho, Use t*-test		Reject Ho, Use t*-test		Reject Ho, Use t*-test	
t or t* statistic	0.795		0.017		0.282		-0.882		-0.898		0.195		0.382	
t Critical two-tail	2.074		2.145		2.074		2.093		2.074		2.093		2.080	
Conclusion 2	Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho	

the first conclusion row shows that only the Factor 1 (Road Class) and Factor 3 (Operating Traffic) had similar variances (Accept H_o), other factors have different (unequal) variances (Reject H_o). Based on this conclusion, the second comparison step was carried out where the exact t-test was done for testing the means of Factor 1 and Factor 3, while the approximate t*-test is done for the rest of the factors. In both tests, the null hypothesis H_o of all factor means comparison was accepted as shown in the second conclusion row. This implied that all factors in the two subsets had similar statistical means, therefore, measurements are repeatable from within variation point of view.

4.6.3.2 AHP-Direct Assignment Comparison

The AHP collected data (Part III) shown in Table 4.12 and the direct weight assignment data (Part I) shown in Table 4.10 were compared using the same statistical comparison technique. Table 4.17 shows the results of the first step of variance comparison. Factor 3 (Operating Traffic) and Factor 6 (Maintenance Cost) had similar statistical variances (Accept H_o), while other factors the H_o was rejected implying they do not have similar variances. Accordingly, the t-test and the t*-test results for equal and unequal variances assumption, respectively, are also shown in Table 4.17. In all factors comparison of both tests, 'H_o' was accepted which implies that the collected data are repeatable even if different methods of data collection were used. It is also concluded that the direct assignment method of factor weight of importance is a consistent method since its results match with the well defined, widely accepted, and verified AHP method. Similar comparison of AHP and direct assignment methods yielded the same conclusion as reported by Hagquist [1994].

Table 4.17. Summary of the comparison test for between methods data variations.

Statistic	Factor 1		Factor 2		Factor 3		Factor 4		Factor 5		Factor 6		Factor 7	
	DIRECT	AHP	DIRECT	AHP	DIRECT	AHP	DIRECT	AHP	DIRECT	AHP	DIRECT	AHP	DIRECT	AHP
Mean	13.45	13.73	19.64	16.53	13.19	13.75	12.38	13.34	15.46	16.12	10.59	9.75	15.29	15.29
Variance	40.97	74.39	130.36	68.13	41.42	26.32	30.65	58.06	55.53	73.37	36.73	25.03	63.48	103.62
Observations	65	30	65	30	65	30	65	30	65	30	65	30	65	30
F	1.816		1.913		1.574		1.894		1.321		1.467		1.632	
F Critical one-tail	0.572		1.747		1.747		0.572		0.572		1.747		0.572	
Conclusion 1	Reject Ho, Use t*-test		Reject Ho, Use t*-test		Accept Ho, Use t-test		Reject Ho, Use t*-test		Reject Ho, Use t*-test		Accept Ho, Use t-test		Reject Ho, Use t*-test	
t or t* statistic	-0.156		1.505		-0.420		-0.615		-0.383		0.662		-0.003	
t Critical two-tail	2.015		1.992		1.986		2.015		2.007		1.986		2.013	
Conclusion 2	Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho	

4.6.3.3 Temporal-Based Data Variation

A set of twelve individuals were resurveyed by filling Part I and Part II of the questionnaire in order to check the repeatability over time of the data collection. The collected data of the new round of survey (NEW), compared with the responses of the same group of individuals collected before (OLD), are shown in Table 4.18 and Table 4.19 along with averages and standard deviations of all factors and sub-factors.

The two data groups, OLD and NEW, were subjected to the statistical comparison test used before. Table 4.20 shows the results of the two-step comparison between the variances and means of the two data groups. From this table, Factor 1 (Road Class), Factor 3 (Operating Traffic), Factor 5 (Safety Condition), and Factor 6 (Maintenance Cost) have similar variances (Accept H_o), other factors have different (unequal) variances (Reject H_o) as shown in the first conclusion row. Based on this conclusion, the exact t-test was done for testing the means where the H_o was accepted, while the approximate t*-test is done for the rest of the factors where the H_o was rejected. In both test, the null hypothesis H_o of all factor means comparison was accepted. This implied that for all factors in the two data groups had similar statistical means, therefore, measurements are repeatable from temporal point of view.

4.6.4 Comparison between Surveyed Groups

As stated earlier, different groups of individuals were surveyed in this study as shown in Table 4.9. To quantify the differences (if any) between these groups, three main

Table 4.18. Summary of old and repeated data of Part I.

No.	Factor 1 Road Class		Factor 2 Pavement Condition		Factor 3 Operating Traffic		Factor 4 Riding Quality		Factor 5 Safety Condition		Factor 6 Maint. Cost		Factor 7 Importance	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
1	5	10	25	25	5	5	10	10	15	20	25	15	15	15
2	10	10	25	25	5	10	10	25	35	20	5	5	10	5
3	5	10	30	30	15	10	10	10	10	15	10	5	20	20
4	15	10	25	25	15	10	10	20	10	15	12	10	13	10
5	15	10	25	25	13	10	11	8	20	20	7	12	9	15
6	10	5	45	14	5	9	10	23	10	32	10	5	10	14
7	10	12	12	11	20	15	15	10	18	20	13	18	12	12
8	20	20	7	18	5	13	18	12	22	18	13	7	15	12
9	10	15	5	15	15	10	5	10	10	20	25	5	30	25
10	15	15	20	10	10	20	10	15	20	10	10	10	15	20
11	5	10	5	20	15	10	10	10	15	20	5	5	45	25
12	10	5	15	15	15	15	10	20	20	20	10	5	20	20
Average	10.8	11.0	19.9	19.4	11.5	11.4	10.8	14.4	17.1	19.2	12.1	8.5	17.8	16.1
Standard Dev.	4.7	4.2	11.8	6.5	5.3	3.8	3.1	5.9	7.3	5.1	6.6	4.6	10.3	6.1

Table 4.19. Summary of old and repeated data of Part II.

No.	Sub-Factor 1 Road Class		Sub-Factor 2 Dist. form CBD		Sub-Factor 3 Use of VIPs		Sub-Factor 4 Operating Traffic		Sub-Factor 5 Maint. Alternatives		Sub-Factor 6 Other Imp. Locations	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
1	5	10	25	20	5	10	10	30	15	15	25	15
2	10	18	25	13	5	25	10	14	35	10	5	20
3	5	10	30	20	15	10	10	25	10	15	10	20
4	15	28	25	28	15	11	10	11	10	11	12	11
5	15	25	25	15	13	20	11	25	20	5	7	10
6	10	20	45	25	5	10	10	20	10	10	10	15
7	10	20	12	20	20	20	15	20	18	10	13	10
8	20	10	7	15	5	10	18	30	22	20	13	15
9	10	15	5	25	15	15	5	15	10	10	25	20
10	15	10	20	20	10	10	10	20	20	20	10	20
11	5	20	5	20	15	20	10	10	15	20	5	10
12	10	7	15	10	15	8	10	30	20	20	10	25
Average	10.8	16.1	19.9	19.3	11.5	14.1	10.8	20.8	17.1	13.8	12.1	15.9
Standard Dev.	4.7	6.8	11.8	5.3	5.3	5.7	3.1	7.3	7.3	5.2	6.6	5.1

Table 4.20. Summary of the comparison test for temporal basis data variation.

Statistic	Factor 1		Factor 2		Factor 3		Factor 4		Factor 5		Factor 6		Factor 7	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
Mean	10.83	10.98	19.92	19.41	11.50	11.45	10.75	14.41	17.08	19.19	12.08	8.49	17.83	16.07
Variance	21.97	18.02	139.36	42.48	27.91	14.80	9.84	35.14	52.81	25.99	43.54	21.41	107.06	36.78
Observations	12	12	12	12	12	12	12	12	12	12	12	12	12	12
F	1.219		3.281		1.886		3.571		2.032		2.034		2.911	
F Critical one-tail	2.818		2.818		2.818		0.355		2.818		2.818		2.818	
Conclusion 1	Accept Ho, Use t-test		Reject Ho, Use t*-test		Accept Ho, Use t-test		Reject Ho, Use t*-test		Accept Ho, Use t-test		Accept Ho, Use t-test		Reject Ho, Use t*-test	
t or t* statistic	-0.082		0.131		0.027		-1.891		-0.820		1.543		0.508	
t Critical two-tail	2.074		2.110		2.074		2.110		2.074		2.074		2.101	
Conclusion 2	Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho	

groups were formed: (i) academicians and managers (ACDM), (ii) engineers and supervisors (ENGR), and (iii) non-pavement qualified and ordinary road users (OTHR). These main groups were formed since there were not enough data points in 'managers', 'supervisor', and 'others' groups. The statistical comparison technique was employed for the variances and means of these three groups for all factors. Tables 4.21 shows the summary of the results of the first step of variance comparison and the second step for means comparison of all seven factors. Based on the results shown on first conclusion row, the t or t* test were done for all factors and groups. The results of these two tests were summarized in the second conclusion row. From this row, Factor 4 (Riding Quality) where the ACDM and OTHR groups showed statistically different means, and for Factor 7 (Importance to Community) where the ENGR and OTHR groups showed also statistically different means. All other comparisons of means of the three main individual groups with all factors have same statistical means. This is another evident that the within variation of the data is statistically minimal, and it can be concluded that the collected data are repeatable.

Another conclusion is that the collected data can not be pooled together, and it needs to be adjusted for the type of individuals and their experiences. In this case, Part IV of the data shown in Table 4.13 will be used for priority factor weight determination, as detailed later.

Table 4.21. Summary of comparison test results for individual groups data variation.

Statistic	Factor 1: Road Class						Factor 2: Pavement Condition						Factor 3: Operating Traffic						Factor 4: Riding Quality					
	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR
Mean	11.67	15.10	11.67	12.28	15.10	12.28	18.61	22.42	18.61	15.41	22.42	15.41	12.11	12.97	12.11	14.82	12.97	14.82	14.61	12.26	14.61	10.11	12.26	10.11
Variance	35.29	41.96	35.29	40.02	41.96	40.02	52.25	180.38	52.25	99.94	180.38	99.94	23.75	53.97	23.75	37.56	53.97	37.56	30.08	26.93	30.08	21.12	26.93	21.12
Observations	18	31	18	16	31	16	18	31	18	16	31	16	18	31	18	16	31	16	18	31	18	16	31	16
F	1.169		1.134		1.048		3.452		1.913		1.805		2.272		1.501		1.437		1.451		1.850		1.275	
F Critical one-tail	0.506		0.422		2.247		0.506		0.422		2.247		0.506		0.422		2.247		1.976		2.366		2.247	
Conclusion 1	Reject Ho, t*-test		Reject Ho, t*-test		Accept Ho, t-test		Reject Ho, t*-test		Reject Ho, t*-test		Accept Ho, t-test		Reject Ho, t*-test		Reject Ho, t*-test		Accept Ho, t-test		Accept Ho, t-test		Accept Ho, t-test		Accept Ho, t-test	
t or t* statistic	-1.884		-0.282		1.422		-1.299		1.057		1.836		-0.490		-1.414		-0.663		1.419		2.367		1.397	
t Critical two-tail	2.024		2.040		2.014		2.012		2.052		2.012		2.012		2.045		2.014		2.012		2.037		2.014	
Conclusion 2	Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Reject Ho		Accept Ho	

Statistic	Factor 5: Safety Condition						Factor 6: Maintenance Cost						Factor 7: Importance to Community					
	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR	ACDM	ENGR	ACDM	OTHR	ENGR	OTHR
Mean	16.78	14.10	16.78	16.61	14.10	16.61	10.94	10.35	10.94	10.66	10.35	10.66	15.28	12.81	15.28	20.10	12.81	20.10
Variance	25.59	75.76	25.59	49.08	75.76	49.08	31.23	40.50	31.23	40.05	40.50	40.05	30.09	35.83	26.93	127.62	35.83	127.62
Observations	18	31	18	16	31	16	18	31	18	16	31	16	18	31	20	16	31	16
F	2.960		1.918		1.544		1.297		1.282		1.011		1.101		4.739		3.562	
F Critical one-tail	0.506		0.422		2.247		0.506		0.422		2.247		0.506		0.427		0.445	
Conclusion 1	Reject Ho, t*-test		Reject Ho, t*-test		Accept Ho, t-test		Reject Ho, t*-test		Reject Ho, t*-test		Accept Ho, t-test		Reject Ho, t*-test		Reject Ho, t*-test		Reject Ho, t*-test	
t or t* statistic	1.364		0.077		-1.000		0.338		0.139		-0.156		1.470		-1.553		-2.049	
t Critical two-tail	2.012		2.052		2.014		2.021		2.042		2.014		2.024		2.080		2.083	
Conclusion 2	Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Reject Ho	

4.6.5 Comparison between Saudi and UAE Experience

The collected data of UAE were statistically compared with those collected in Saudi Arabia shown in Table 4.10, using the two-step technique. It was concluded as shown in Appendix B that the two experiences are statistically different in terms of pavement maintenance priority ranking.

4.6.6 Reliability Test

There are two measurement of reliability in psychometric studies. The first refers to the internal consistency of the test, while the second is the reproducibility of the score from that test [Kline 1979]. Reliability is a necessary but not a sufficient condition for validity [Nunnally 1967]. However, for any summative scale, like the one targeted in this study for priority ranking, it is essential to use some reliability measures. The reliability measure is referred to the internal consistency of all items (factors) considered in the scale. The reliability coefficient, as measured by Cronbach's coefficient alpha (α), is calculated using the variances of all items (factors) and the variance of the sum of all items as shown in the following form [Nunnally 1967]:

$$\alpha = \frac{K}{K-1}\left[1 - \sum \frac{S_i^2}{S_{sum}^2}\right] \tag{4.18}$$

where,

α = Cronbach's coefficient of Reliability,

K = Number of items (factors) involved in the test,

S_i^2 = Variance of item i, and

S_{sum}^2 = = Variance of the sum of all items.

However, the scale being developed in this study has the characteristic that the items being considered form a linear combination of the subject sought (priority), and that linear combination adds to 100 for all individuals surveyed. In this case, the variance of the sum of items weights is zero. Therefore, the reliability coefficient, α, can not be calculated in equation 4.18. In such a case, Nunnally [1967] has suggested two alternatives for estimating the reliability index, the first is by correlating alternative forms of linear combinations (e.g. two sets of data at different times), and the second alternative requires a computation of variance of linear combination, standard deviation of each variable (item), and to have foreknowledge of the reliability of each variables.

The problem with the first alternative is that, in the case of this study, all different forms of data sets have the factors sum to 100, where the variance is always zero, while the problem with the other alternative is that there is no foreknowledge of the factors reliability of any kind. Therefore, the repeatability checks done on previous sections are sufficient to show that the data are reproducible from different points of view.

4.7 MODEL CALIBRATION

4.7.1 Factor Weight Adjustment

The weights of importance of all priority factors as well as the sub-factors of importance to community factor, shown in Table 4.10 and Table 4.11, respectively, are to be adjusted for the individual experience factor, as concluded in Section 4.6.4, in the following manner:

$$CW_i = \frac{\sum_{j=1}^{n} W_j * E_j}{\sum_{j=1}^{n} E_j} \tag{4.19}$$

where

CW_i = Corrected overall weight of factor i,

W_j= Factor weight as estimated by individual j, obtained from Table 4.10 and Table 4.11,

E_j = Individual experience factor for individual j, obtained from Table 4.13,

i = Factor number (1 to 7 for main factors, and 1 to 6 for sub-factors), and

j = individual number (1 to 65).

Tables 4.22 and 4.23 shows the calculations of the above equation for adjusting the final factor weights of priority factors and the importance to community sub-factors. It can be seen from these tables that there are slight differences between the original and adjusted weights. The highest observed difference in Table 4.22 was in Factor 7 (Importance to Community) of -6.5%, while in Table 4.23 was in Sub-factor 3 (Use of VIPs) of +7.5%.

Table 4.22. Factor weight adjustment process for individiual experience.

No.	Exp. Code	Factor 1, Road Class	$(W_i E_i)/\Sigma E_i$	Factor 2 Pavement Condition	$(W_i E_i)/\Sigma E_i$	Factor 5 Operating Traffic	$(W_i E_i)/\Sigma E_i$	Factor 3 Riding Quality	$(W_i E_i)/\Sigma E_i$	Factor 4 Safety Condition	$(W_i E_i)/\Sigma E_i$	Factor 6 Maint. Cost	$(W_i E_i)/\Sigma E_i$	Factor 7 Importance	$(W_i E_i)/\Sigma E_i$
1	1	15	0.4149	20	0.553	15	0.415	15	0.415	15	0.415	10	0.277	10	0.277
2	1	5	0.1383	20	0.553	5	0.138	30	0.830	30	0.830	0	0.000	10	0.277
3	1	5	0.1383	30	0.830	0	0.000	10	0.277	15	0.415	25	0.692	15	0.415
4	1	5	0.1383	30	0.830	15	0.415	10	0.277	10	0.277	10	0.277	20	0.553
5	1	25	0.6916	10	0.277	15	0.415	10	0.277	15	0.415	10	0.277	15	0.415
6	1	15	0.4149	25	0.692	15	0.415	10	0.277	10	0.277	12	0.332	13	0.360
7	1	15	0.4149	10	0.277	15	0.415	10	0.277	20	0.553	20	0.553	10	0.277
8	1	20	0.5533	7	0.194	5	0.138	18	0.498	22	0.609	13	0.360	15	0.415
9	1	5	0.1383	10	0.277	20	0.553	8	0.221	12	0.332	15	0.415	30	0.830
10	1	10	0.2766	15	0.415	15	0.415	10	0.277	20	0.553	10	0.277	20	0.553
11	1	15	0.4149	20	0.553	10	0.277	25	0.692	10	0.277	10	0.277	10	0.277
12	1	10	0.2766	25	0.692	5	0.138	10	0.277	20	0.553	15	0.415	15	0.415
13	1	10	0.2766	30	0.830	10	0.277	10	0.277	15	0.415	5	0.138	20	0.553
14	1	10	0.2766	25	0.692	10	0.277	20	0.553	15	0.415	10	0.277	10	0.277
15	1	20	0.5533	18	0.498	13	0.360	12	0.332	18	0.498	7	0.194	12	0.332
16	1	5	0.1383	15	0.415	15	0.415	20	0.553	20	0.553	5	0.138	20	0.553
17	2	10	0.2085	20	0.417	10	0.208	20	0.417	20	0.417	10	0.208	10	0.208
18	2	10	0.2085	10	0.208	20	0.417	15	0.313	15	0.313	10	0.208	20	0.417
19	3	25	0.4042	30	0.485	5	0.081	5	0.081	10	0.162	10	0.162	15	0.243
20	3	15	0.2425	15	0.243	25	0.404	12	0.194	12	0.194	10	0.162	11	0.178
21	3	15	0.2425	12	0.194	25	0.404	11	0.178	10	0.162	7	0.113	20	0.323
22	3	18	0.2911	20	0.323	16	0.259	12	0.194	11	0.178	14	0.226	9	0.146
23	3	7	0.1132	25	0.404	20	0.323	10	0.162	8	0.129	10	0.162	20	0.323
24	3	25	0.4042	25	0.404	20	0.323	7	0.113	7	0.113	6	0.097	10	0.162
25	3	16	0.2587	20	0.323	11	0.178	16	0.259	16	0.259	5	0.081	16	0.259
26	3	10	0.1617	20	0.323	10	0.162	10	0.162	20	0.323	10	0.162	20	0.323
27	3	10	0.1617	30	0.485	10	0.162	20	0.323	20	0.323	5	0.081	5	0.081
28	3	10	0.1617	40	0.647	5	0.081	20	0.323	10	0.162	0	0.000	15	0.243
29	3	10	0.1617	55	0.889	6	0.097	10	0.162	3	0.049	6	0.097	10	0.162
30	3	15	0.2425	60	0.970	0	0.000	6	0.097	0	0.000	4	0.065	15	0.243
31	3	15	0.2425	55	0.889	5	0.081	10	0.162	1	0.016	5	0.081	9	0.146
32	3	14	0.2264	18	0.291	9	0.146	9	0.146	27	0.437	9	0.146	14	0.226
33	3	15	0.2425	15	0.243	10	0.162	15	0.243	25	0.404	10	0.162	10	0.162
34	3	15	0.2425	20	0.323	15	0.243	15	0.243	15	0.243	5	0.081	15	0.243
35	3	10	0.1617	20	0.323	5	0.081	10	0.162	30	0.485	20	0.323	5	0.081
36	3	10	0.1617	20	0.323	15	0.243	20	0.323	20	0.323	10	0.162	5	0.081
37	3	15	0.2425	15	0.243	12	0.194	14	0.226	14	0.226	15	0.243	15	0.243
38	3	10	0.1617	10	0.162	15	0.243	15	0.243	10	0.162	30	0.485	10	0.162
39	3	18	0.2911	15	0.243	13	0.210	8	0.129	8	0.129	20	0.323	18	0.291
40	3	40	0.6468	10	0.162	20	0.323	5	0.081	10	0.162	10	0.162	5	0.081
41	3	20	0.3234	5	0.081	30	0.485	5	0.081	10	0.162	20	0.323	10	0.162
42	3	15	0.2425	20	0.323	20	0.323	5	0.081	10	0.162	15	0.243	15	0.243
43	3	20	0.3234	20	0.323	5	0.081	10	0.162	30	0.485	10	0.162	5	0.081
44	3	15	0.2425	10	0.162	20	0.323	15	0.243	10	0.162	10	0.162	20	0.323
45	4	10	0.0848	15	0.127	15	0.127	20	0.170	20	0.170	10	0.085	10	0.085
46	4	10	0.0848	25	0.212	5	0.042	10	0.085	35	0.297	5	0.042	10	0.085
47	4	10	0.0848	10	0.085	20	0.170	15	0.127	10	0.085	5	0.042	30	0.254
48	4	20	0.1696	15	0.127	5	0.042	15	0.127	5	0.042	20	0.170	20	0.170
49	4	10	0.0848	25	0.212	10	0.085	25	0.212	20	0.170	5	0.042	5	0.042
50	5	5	0.0186	10	0.037	20	0.075	10	0.037	10	0.037	5	0.019	40	0.149
51	5	15	0.0559	25	0.093	13	0.048	11	0.041	20	0.075	7	0.026	9	0.034
52	5	10	0.0373	5	0.019	15	0.056	5	0.019	10	0.037	25	0.093	30	0.112
53	5	30	0.1118	10	0.037	20	0.075	5	0.019	5	0.019	10	0.037	20	0.075
54	5	5	0.0186	5	0.019	15	0.056	10	0.037	15	0.056	5	0.019	45	0.168
55	5	10	0.0373	10	0.037	15	0.056	15	0.056	25	0.093	15	0.056	10	0.037
56	5	10	0.0373	25	0.093	10	0.037	8	0.030	20	0.075	12	0.045	15	0.056
57	5	5	0.0169	14	0.051	9.1	0.034	23	0.085	32	0.119	5	0.017	14	0.051
58	5	12	0.0447	11	0.041	15	0.056	10	0.037	21	0.078	19	0.071	12	0.045
59	5	15	0.0559	15	0.056	10	0.037	10	0.037	20	0.075	5	0.019	25	0.093
60	5	10	0.0373	20	0.075	10	0.037	10	0.037	20	0.075	5	0.019	25	0.093
61	6	10	0.0238	45	0.107	5	0.012	10	0.024	10	0.024	10	0.024	10	0.024
62	6	15	0.0357	10	0.024	30	0.071	5	0.012	10	0.024	20	0.048	10	0.024
63	6	10	0.0238	12	0.029	20	0.048	15	0.036	18	0.043	13	0.031	12	0.029
64	6	20	0.0476	10	0.024	20	0.048	5	0.012	10	0.024	5	0.012	30	0.071
65	6	15	0.0357	20	0.048	10	0.024	10	0.024	20	0.048	10	0.024	15	0.036
Average		13.5		19.7		13.1		12.4		15.5		10.6		15.3	
Adjusted Average			13.4		20.5		12.5		13.1		15.4		10.7		14.3

Table 4.23. Factor weight adjustment process for individiual experience.

No.	Exp. Code	Factor 1, Road Class	(W, E)/ΣE,	Factor 2 Distance from CBD	(W, E)/ΣE,	Factor 3 Use by VIPs	(W, E)/ΣE,	Factor 4 Operating Traffic	(W, E)/ΣE,	Factor 4 Alternatives Available	(W, E)/ΣE,	Factor 4 Other Imp. Locations	(W, E)/ΣE,
1	1	25	0.692	20	0.553	10	0.277	20	0.553	10	0.277	15	0.415
2	1	5	0.138	10	0.277	20	0.553	40	1.107	20	0.553	5	0.138
3	1	20	0.553	10	0.277	15	0.415	40	1.107	10	0.277	15	0.415
4	1	10	0.277	10	0.277	20	0.553	40	1.107	10	0.277	10	0.277
5	1	15	0.415	20	0.553	25	0.692	15	0.415	10	0.277	15	0.415
6	1	30	0.830	15	0.415	15	0.415	20	0.553	15	0.415	5	0.138
7	1	10	0.277	20	0.553	10	0.277	30	0.830	15	0.415	15	0.415
8	1	30	0.830	12	0.332	20	0.553	15	0.415	8	0.221	15	0.415
9	1	3	0.083	4	0.111	30	0.830	15	0.415	40	1.107	8	0.221
10	1	6	0.166	16	0.443	21	0.581	26	0.719	26	0.719	5	0.138
11	1	15	0.415	20	0.553	25	0.692	15	0.415	10	0.277	15	0.415
12	1	20	0.553	20	0.553	15	0.415	15	0.415	15	0.415	15	0.415
13	1	10	0.277	10	0.277	35	0.968	10	0.277	15	0.415	20	0.553
14	1	20	0.553	10	0.277	20	0.553	25	0.692	10	0.277	15	0.415
15	1	25	0.692	13	0.360	15	0.415	16	0.443	10	0.277	21	0.581
16	1	10	0.277	15	0.415	15	0.415	15	0.415	25	0.692	20	0.553
17	2	10	0.208	20	0.417	25	0.521	25	0.521	5	0.104	15	0.313
18	2	20	0.417	10	0.208	10	0.208	30	0.625	10	0.208	20	0.417
19	3	20	0.323	20	0.323	20	0.323	10	0.162	20	0.323	10	0.162
20	3	15	0.243	15	0.243	25	0.404	15	0.243	10	0.162	20	0.323
21	3	18	0.291	13	0.210	25	0.404	14	0.226	10	0.162	20	0.323
22	3	10	0.162	25	0.404	20	0.323	12	0.194	15	0.243	18	0.291
23	3	7	0.113	10	0.162	8	0.129	30	0.485	20	0.323	25	0.404
24	3	20	0.323	20	0.323	20	0.323	20	0.323	10	0.162	10	0.162
25	3	20	0.323	25	0.404	10	0.162	20	0.323	10	0.162	15	0.243
26	3	20	0.323	20	0.323	15	0.243	15	0.243	10	0.162	20	0.323
27	3	10	0.162	20	0.323	10	0.162	30	0.485	15	0.243	15	0.243
28	3	5	0.081	0	0.000	30	0.485	20	0.323	15	0.243	30	0.485
29	3	10	0.162	0	0.000	30	0.485	20	0.323	10	0.162	30	0.485
30	3	15	0.243	0	0.000	50	0.808	3	0.049	2	0.032	30	0.485
31	3	10	0.162	0	0.000	30	0.485	20	0.323	10	0.162	30	0.485
32	3	20	0.323	15	0.243	10	0.162	25	0.404	15	0.243	15	0.243
33	3	25	0.404	15	0.243	10	0.162	25	0.404	10	0.162	15	0.243
34	3	25	0.404	15	0.243	20	0.323	25	0.404	5	0.081	10	0.162
35	3	10	0.162	20	0.323	10	0.162	20	0.323	20	0.323	20	0.323
36	3	10	0.162	15	0.243	10	0.162	30	0.485	20	0.323	15	0.243
37	3	20	0.323	17	0.275	20	0.323	15	0.243	10	0.162	18	0.291
38	3	15	0.243	25	0.404	15	0.243	15	0.243	10	0.162	20	0.323
39	3	20	0.323	18	0.291	24	0.388	12	0.194	12	0.194	14	0.226
40	3	40	0.647	10	0.162	20	0.323	20	0.323	5	0.081	5	0.081
41	3	5	0.081	5	0.081	30	0.485	30	0.485	20	0.323	10	0.162
42	3	28	0.453	28	0.453	11	0.178	11	0.178	11	0.178	11	0.178
43	3	10	0.162	20	0.323	10	0.162	25	0.404	15	0.243	20	0.323
44	3	20	0.323	5	0.081	5	0.081	30	0.485	25	0.404	15	0.243
45	4	10	0.085	15	0.127	20	0.170	20	0.170	10	0.085	25	0.212
46	4	5	0.042	10	0.085	20	0.170	40	0.339	10	0.085	15	0.127
47	4	10	0.085	20	0.170	25	0.212	15	0.127	10	0.085	20	0.170
48	4	20	0.170	10	0.085	20	0.170	20	0.170	10	0.085	20	0.170
49	4	20	0.170	25	0.212	15	0.127	15	0.127	20	0.170	5	0.042
50	5	10	0.037	15	0.056	10	0.037	30	0.112	15	0.056	20	0.075
51	5	21	0.078	26	0.097	11	0.041	15	0.056	11	0.041	16	0.060
52	5	30	0.112	20	0.075	10	0.037	15	0.056	15	0.056	10	0.037
53	5	30	0.112	10	0.037	10	0.037	20	0.075	15	0.056	15	0.056
54	5	10	0.037	18	0.067	15	0.056	30	0.112	17	0.063	10	0.037
55	5	10	0.037	10	0.037	15	0.056	30	0.112	15	0.056	20	0.075
56	5	10	0.037	20	0.075	10	0.037	25	0.093	20	0.075	15	0.056
57	5	15	0.056	25	0.093	15	0.056	15	0.056	10	0.037	20	0.075
58	5	20	0.075	20	0.075	12	0.045	18	0.067	16	0.060	14	0.052
59	5	10	0.037	25	0.093	10	0.037	20	0.075	10	0.037	25	0.093
60	5	10	0.037	15	0.056	20	0.075	30	0.112	10	0.037	15	0.056
61	6	10	0.024	10	0.024	10	0.024	35	0.083	25	0.059	10	0.024
62	6	20	0.048	15	0.036	15	0.036	30	0.071	10	0.024	10	0.024
63	6	20	0.048	15	0.036	18	0.043	25	0.059	10	0.024	12	0.029
64	6	20	0.048	20	0.048	10	0.024	20	0.048	15	0.036	15	0.036
65	6	20	0.048	25	0.059	5	0.012	15	0.036	10	0.024	25	0.059
Average		16.0		15.4		17.4		21.6		13.6		16.1	
Adjusted Average			16.0		14.6		18.7		21.5		13.9		15.7

4.7.2 Final Model Form

From the results of previous sections, the final form of developed maintenance priority ranking procedure is:

$$PI = \Sigma Wi\ Fi \tag{4.20}$$

where,

PI = Priority index (out of 100),

W_1=0.134, W_2=0.205, W_3=0.125, W_4=0.131, W_5=0.154, W_6=0.107, and W_7=0.143,

F_1 = Road Class obtained from Table 4.1,

F_2 = Pavement Condition (PC) obtained from Equation 4.2,

F_3 = Operating Traffic (OP) obtained from Table 4.6,

F_4 = Riding Quality (RQ) obtained from Equation 4.3 or Table 4.3,

F_5 = Safety Condition (SF)obtained from Equation 4.4 or Table 4.5,

F_6 = Maintenance Cost (MC) obtained from Table 4.7,

F_7 = Importance to Community (IF) obtained from Table 4.8 and the following sub-factor weights equation:

$$IF = \Sigma SW_i\ Sf_i \tag{4.21}$$

where'

IF = Importance to community factor,

Sf_i = Sub-factor values obtained from Table 4.8, and

$SW_1 = 0.160$, $SW_2 = 0.146$, $SW_3 = 0.187$, $SW_4 = 0.215$, $SW_5 = 0.139$, and

$SW_6 = 0.157$,

4.7.3 Model Adjustment for Structural Distresses

Further, the obtained PI value has to be subjected to the structural distress adjustment if they exist in the pavement section under consideration. This adjustment is needed to reflect future condition of pavement. If the structural distresses such as alligator cracking or rutting exist, their deterioration rate and mechanism have higher effect on pavement condition than other distresses. Therefore, this should be reflected in the priority ranking of those sections since the combined index method does not consider the predicted futuristic pavement condition directly.

In order to make the priority ranking procedure accounts for this adjustment, the priority procedure was modified using adjustment factors for some important distresses if they exist while carrying out the condition survey. In the case where a pavement section has some structural distresses such as alligator cracking, rutting, or other types of cracking, the priority ranking of this section should be raised, by some percentage, to account for this effect. Therefore, Table 4.24 shows the criteria for the structural distress adjustment factor. These criteria were obtained by consulting different pavement maintenance specialists.

Table 4.24. Recommeded stuctural distress priority adjustment factor.

No.	Distress Type	Adjustment Factor Value, %
1.	Low severity Alligator Cracking	5
2.	Medium severity Alligator Cracking	7
3.	High severity Alligator Cracking	10
4.	Low severity Rutting	2
5.	Medium severity Rutting	6
6.	High severity Rutting	8
7.	Low severity other types of cracks	1
8.	Medium severity other types of cracks	2
9.	High severity other types of cracks	3

In order to make the priority ranking procedure accounts for this adjustment, the priority procedure was modified using adjustment factors for some important distresses if they exist while carrying out the condition survey. In the case where a pavement section has some structural distresses such as alligator cracking, rutting, or other types of cracking, the priority ranking of this section should be raised, by some percentage, to account for this effect. Therefore, Table 4.24 shows the criteria for the structural distress adjustment factor. These adjustment factors were based on the fact that the structural distresses such as alligator cracking and rutting have higher deduct points than other ones such as raveling and polished aggregates [Shahin and Walter 1990]. Moreover, structural distresses, once started, have higher progression rate than other distresses. Therefore, the rate of pavement deterioration is higher, especially at later stages, when structural distresses exist compared when pavement does not have any structural distresses.

On the other hand, the World Bank highway design and maintenance model (HDM-III) has built-in models for structural distresses such as cracking with a calibration progression factor of 0.1-0.3 for cracking model [Kannemeyer and Visser 1995] which makes an adjustment factor for distress progression up to 30% of the original values.

Based on the above consideration Table 4.24 was prepared as suggested structural distresses adjustment factors for pavement maintenance priority consideration.

To include this factor in the priority index calculation, equation 4.20 is modified as follows:

$$PI = (1 + a)\ \Sigma\ Wi\ Fi \qquad (4.22)$$

where,

a = Structural distresses adjustment factor, in percent, obtained from Table 4.24.

4.7.4 Typical Example

Using each priority factor values with their corresponding weights (Table 4.22), the priority index (PI) can be calculated for each pavement section.

As an example of PI calculation, Table 4.25 shows the details of five pavement sections with their respective maintenance priority factor values, and the overall priority ranking calculation. Tables and equations specified in previous sections were used to quantify the priority factors. Typical calculation example for section number 2 of Table 4.25 is shown in Table 4.26 and Table 4.27. Table 4.27 shows the calculation procedure for importance to community factor using the value of the six sub-factors with their corresponding weights (last two columns). The result of Table 4.27 is an index (IF=49.4) that is to be used for the last factor of Table 4.26. The final priority index (PI) is calculated by multiplying the last two columns of in Table 4.26 and sum up the results. The PI value for this section is 46.18. This value is adjusted for structural distress effect. From Table 4.24, since the section has longitudinal and transverse cracking of medium severity (case no. 7), the PI value should be multiplied by (1+ 0.02) to have the final adjusted PI value of 47.11. PI values for other section are shown in Table 4.25.

Table 4.25. Typical example of priority index (PI) calculation.

Road Name	Description		Problems & Solutions		Available Data					
	Length	Location	Problems/Distresses	Recommended Maintenance	Road Class	PCI	Roughness (cm/km)	Skid Number	Cost (SR)	Traffic (ADT)
St.1	500	Passing through CBD; no alternatives; used by VIPs	Alligator Cr.(M); Depression(H) ; Raveling (L)	Full depth patching	Arterial	40	200	55	20,000	10,000
St.2	200	Passing through CBD; no alternatives; not used by VIPs	Polished aggregate; L&T Cr. (M);	Crack Sealing	Collector	85	80	65	400	6,000
St.3	600	Away from CBD; not used by VIPs; has alternatives; near hospital	Alligator Cr.(L); Block Cr. (L); polished agg.	Crack sealing & Slurry seal	Local	65	120	30	7,500	900
St.4	150	Away from CBD; near Civil Defense building; not used by VIP; has alternatives	Block&Transv. Cr. (L); polished aggregate (extensive)	Crack Sealing	Collector	95	-	-	6,000	300
St.5	1000	Used by VIPs; near official site; has alternatives; away from CBD	Rutting (H); Depression (H); Patching (H); Bleeding (H)	Milling and Repave	Arterial	30	-	-	65,000	1,750

Table 4.25. (Cont'd.) Typical example of priority index (PI) calculation.

Road Name	Priority Factor Value							Priority Index, PI (8)	Adjusted Priority Index, PI (9)	Priority Ranking
	Road Class (1)	Condition (2)	Traffic (3)	Riding Quality (4)	Safety (5)	Cost (6)	Importance to Community (7)			
St.1	100	60	100.0	111.1	45	69.2	100.0	81.39	87.09	1
St.2	50	15	60.0	44.4	35	99.4	49.4	46.19	47.11	4
St.3	25	35	9.0	66.7	70	88.5	44.9	47.04	49.39	3
St.4	50	5	3.0	25	50	90.8	28.0	32.79	33.45	5
St.5	75	70	17.5	75	25	0.0	55.0	48.13	51.98	2

(1) Using Table 4.1.
(2) Using equation 4.2
(3) Using Equation 4.5
(4) Using equation 4.3 or Table 4.3
(5) Using equation 4.4 or Table 4.5
(6) Using Equation 4.6
(7) Using Table 4.8 and equation 4.1
(8) Using equation 4.20
(9) Using Table 4.26 and Equation 4.22

Table 4.26. Typical example for detailed PI calculation of a pavement section.

Factor	Value	Use	Index	Weight
Road Class	Collector	Table 4.1	50	0.134
Pavement Condition	PCI = 85	Equation 4.2, PC = 100-PCI	15	0.205
Operating Traffic	ADT = 6000	Equation 4.5, OT = 100*ADT/MADT	60	0.125
Riding Quality	PR = 80	Equation 4.3: RI = 100*PR/MPR	44.4	0.131
Safety Condition	SN = 65	Equation 4.4, SF= 100-SN	35	0.154
Maintenance Cost	COST = SR. 400	Equation 4.6, MC = 100(1-COST/MCOST)	99.4	0.107
Importance to Community	Six Sub-factors	Equation 4.20 and Table 4.8	49.4	0.143

PI=0.134*50+0.205*15+0.125*60+0.131*44.4+0.154*35+

0.107*99.4+0.143*49.4= **46.18**

Adjusted PI = (1 + 0.02) * 46.18 = 47.11

Table 4.27. Typical example for detailed PI calculation of the importance to community factor for a pavement section.

Sub-Factor	Value	Use	Index	Weight
Road Class	Collector	Table 4.1	50	0.16
Road passing through CBD ?	YES	Table 4.8	100	0.146
Road is near official building or used by VIPs ?	NO	Table 4.8	0	0.187
Operating Traffic	ADT = 6000	Equation 4.5	60	0.215
Are alternatives available ?	NO	Table 4.8	100	0.139
Road is near other important building ?	NO	Table 4.8	0	0.157

IF = 0.160*50 + 0.146*100 + 0.187*0 + 0.215*60 + 0.139*100 +0.157*0 = **49.4**

4.8 MODEL VALIDATION

The validity of any model is measured by checking how this model can predict or duplicate a set of real data, or by measuring how the model results compare with another verified model or adopted procedures. The priority ranking model was generated from the local experience and opinions of different people representing the local perceptions regarding the maintenance priority, therefore, the results obtained from this model should compare to the current adopted procedures based on engineering judgments. To quantify this comparison, two case studies were considered. Two sets of pavement sections in need of urgent maintenance were selected from Jubail industrial city road network and Dammam municipality road network. The sections in these case studies were selected to represent a complete range of all maintenance priority factors, and all the situations considered in the model development.

The sections selected from Jubail road network were having equipment-based performance survey measurements: roughness and skid resistance. On the other hand, these measurements are not available for the other sections selected from Dammam road network, therefore, the recommended values for roughness and skid resistance factors were extracted from the pavement condition (distress) surveys.

The assumption made, in these two case studies, was that only those selected sections were in need of urgent maintenance and repair, and the allocated funds for maintenance were not enough to cover all these sections. Thus, the priority procedure should be implemented to rank these sections.

4.8.1 Case Study 1: Al-Jubail Road Network

Table 4.28 shows the details of the first case study of Al-Jubail road network. In this table, nine pavement sections representing different road classes, pavement condition, operating traffic, and locations are summarized. The available distresses with the recommended maintenance activities are shown in this table. The roughness and skid resistance measurements were made by Mays Ride meter and Mu meter, respectively. The maintenance costs were based on the unit cost rate provided by the maintenance contractor, and the pavement condition was measured by the PDR method described in Chapter Two.

The priority factor value determination was done using equations and tables shown in the previous sections, and the results are presented in Table 4.29. The priority ranking determined by the engineering judgment as provided by the pavement maintenance management personnel along with the one determined by the developed procedure are also shown in this table. The engineering judgment was provided by four persons: Group Manager, Principal Engineer, and Structural Engineer in the of Royal Commission Road Department, in addition to Road Maintenance Contractor Project Manager. The two values have exact matching in six sections out of nine which represents 67%. However, the three unmatched section priorities do not have big difference between the two rankings; two sections have a difference of only one point (4 to 3 and 5 to 4, for sections 4 and 7, respectively), the third unmatched section (section 1) has a difference of two points

Table 4.28. Case study 1: Jubail road network sections' details.

No.	Description				Problems & Solutions		Available Data					
	Road name	Section	Length (m)	From - To	Problems/Distresses	Recommended Maintenance	Road Class	PCI	Roughness (mm/km)	Skid Number	Cost (SR)	Traffic (ADT)
1	T241	0100-L2S	371	T100-T112	Joint Cr./ Rutting/ Depression/ Raveling	Surface Patching & Slurry Seal	Collector	48	1312	42	5,907	514
2	T130	1400-L1E	318	T195-T183	Raveling/ Unacceptable drainage level	Draining Flood Water	Collector	100	1429	75	160	450
3	DARI	0200-L1E	582	T101-HWLT	Cracking (Wheel Track, Block&Transv, and Edge)	Milling and Repave	Local	58	1216	75	101,605	713
4	HWLT	1100-L1N	237	DARI-TS6	Block&Transv. Cracking	Crack Sealing	Collector	90	1323	75	846	2500
5	T101	0402-L1S	720	SH22-T113	Depression/Raveling/ Polished aggregate	Surface Patching	Collector	85	942	31	12,198	1954
6	KHMS	0800-L1E	430	AHSA-TS6	Raveling	Slurry Seal	Collector	90	1707	50	6,080	850
7	KHMS	0200-L1W	430	LULU-TS6	Rutting/Raveling	Slurry Seal	Collector	95	1536	36	6,128	2000
8	T121	0100-L3S	350	T100-T112	Polished Aggregate	Slurry Seal	Expressway/ Arterial	100	1024	38	5,859	1783
9	T121	1800-L3N	1575	T272-T119	Polished Aggregate	Slurry Seal	Expressway/ Arterial	90	619	36	18,650	3167

Table 4.29. Case study 1: Jubail road network priority factors and PI calculation.

Description			Priority Factor Value							Priority Index, PI (8)	Priority Ranking	
Road No.	Road Name	From - To	Road Class (1)	Condition (2)	Traffic (3)	Riding Quality (4)	Safety (5)	Cost (6)	Importance to Community (7)		Engineering Judgment (9)	Developed Procedure
1	T241	T100-T112	50	52	16.2	72.9	58	94.2	11.5	50.6	3	5
2	T130	T195-T183	50	0	14.2	79.4	25	99.8	11.1	35.0	8	8
3	DARI	T101-HWLT	25	42	22.5	67.6	25	0.0	24.5	34.1	9	9
4	HWLT	DARI-TS6	50	10	78.9	73.5	25	99.2	55.3	51.6	4	3
5	T101	SH22-T113	50	15	61.7	52.3	69	88.0	37.0	49.7	6	6
6	KHMS	AHSA-TS6	50	10	26.8	94.8	50	94.0	13.8	44.3	7	7
7	KHMS	LULU-TS6	50	5	63.2	85.3	64	94.0	21.6	50.8	5	4
8	T121	T100-T112	100	0	56.3	56.9	62	94.2	60.7	56.2	2	2
9	T121	T272-T119	100	10	100.0	34.4	64	81.6	59.4	59.5	1	1

(1) Using Table 4.1.
(2) Using equation 4.2
(3) Using Equation 4.5
(4) Using equation 4.3 or Table 4.3
(5) Using equation 4.4 or Table 4.5
(6) Using Equation 4.6
(7) Using Table 4.8 and equation 4.21
(8) Using equation 4.22
(9) Operation & Maintenance: Road Department in Jubail.

(3 to 5). These mismatching can be explained by the fact that the engineering judgment has a limitation in ranking by not considering all attributes of priority consideration.

4.8.2 Case Study 2: Dammam Road Network

Table 4.30 shows the details of the second case study of Dammam road network where ten pavement sections representing different priority parameters were selected. Section number 2 is a in a very important road that passes through the CBD, in front of Governor Building (IMARAH), used by very important persons (VIPs), such as official visitors, has very high traffic volume, and in a bad need of maintenance. On the other hand, section number 3 located in an unimportant road with very low traffic volume, and far away from CBD and any other official or general public building. Other sections are in between these extremes. There was no equipment to measure the roughness and skid resistance, therefore index tables were used to quantify these factors. Also there was no traffic counts available, but descriptive measures.

Accordingly, Table 4.31 was prepared for priority factor determination using the recommended tables in the previous section. The priority ranking determined by the engineering judgment as provided by the pavement maintenance management personnel in Dammam Municipality along with the one determined by the developed procedure are also shown in this table. The engineering judgment, in this case, was provided by the manager of maintenance and operation section with consultation with other engineers in the road department. The two values have exact matching in five sections out of 10 which

Table 4.30. Case study 2: Dammam Municipality road network sections' details.

No.	Description					Problems & Solutions		Available Data			
	Road name	From	To	Length x Width	Location	Problems/Distresses	Recommended Maintenance	Road Class	PCI	Cost (SR)	Traffic (ADT)
1	St. 9	Prince Masha'l	South King Fahd	330x16	Near mail center; towards CBD;	Depression (L); L&T CR (M); Polished Agg.	Remove Subbase and repave Subbase (20cm)+ WC (4cm)+BC(7cm)	Arterial	77	124,925	Meduim
2	St. 11 (North Bound)	King Abdulaziz	King Saud	500x11	Near IMARAH; CBD; used by VIPs	L&T Cr. (M); Alligator Cr. (H); Edge Cr. (L); Patching (M)	Milling WC(4cm) and repaving	Arterial	42	54,841	Very High
3	Out of St. 9	St. 8	St. 9	250x8	Local; limited; unimportant	L&T Cr. (M); Patching (M); Raveling (H)	Removing Subbase; Repave Subbase (20cm)+ WC(7cm)	Local	25	124,925	Very Low
4	King Khalid	St. 11	St. 12	100x9	near CBD	L&T Cr. (M); Patching (M)	Milling WC(4cm) and repaving	Arterial	82	8,975	Very High
5	Prince Fisal	St. 18	St. 14	1000x9	near CBD	L&T Cr. (L); Edge Cr. (L); Patching (M); Bumps (M)	Removing Subbase; Repave Subbase (20cm)+ WC(7cm)	Arterial	69	162,000	Meduim
6	Dam-Khobr Coastal	King Khalid Crossing	Gasoline Station	600x10	Major; away form CBD	L&T Cr. (M); Alligator Cr. (M); Patching (M); Depression (H); Polished Agg.	Remove Subbase and repave Subbase (20cm)+ WC (4cm)+BC(7cm)	Arterial	33	141,960	Meduim
7	Ext. Prince Mansour	Railroad Round about	Ext. Najd St.	150x8	Away from CBD; near official building	Lane/Shoulder Drop(L); Patching (L); Potholes (L); Polished Agg.	Remove Subbase and repave Subbase (20cm)+ WC (4cm)+BC(7cm)	Local	76	28,392	Meduim
8	Prince Mash'al	First St.	Nasriyyah Roundabout	300x12	Not used by VIPs; near official buildings	L&T Cr. (L)); Patching (L); Depression (L); Polished Agg.	Removing Subbase; Repave Subbase (20cm)+ WC(7cm)	Collector	70	64,795	Meduim
9	King Saud (South Bound)	First St.	First crossing east bound	100x12	Near CBD;	L&T Cr. (M); Alligator Cr. (M); Edge Cr. (L); Patching (L); Pothole (L); Bock Cr. (L)	Remove Subbase and repave Subbase (20cm)+ WC (4cm)+BC(7cm)	Arterial	42	28,392	Low
10	From North to Mazro'yah Court	First St.	Cornich Road	700x15	Away from CBD; used by VIPs; near Chroniche	L&T Cr. (M); Alligator Cr. (L); Patching (M); Block (L); Potholes (L); Ploished Agg.	Remove Subbase and repave Subbase (20cm)+ WC (4cm)+BC(7cm)	Collector	61	116,737	High

Table 4.31. Case study 2: Dammam Municipality road network priority factors and PI calculation.

Description	Priority Factor Value							Priority Index, PI (8)	Priority Ranking	
Road Name	Road Class (1)	Condition (2)	Traffic (3)	Riding Quality (4)	Safety (5)	Cost (6)	Importance to Community (7)		Engineering Judgment (9)	Developed Procedure
St. 9	75	23	60	50	80	0.0	55.2	50.0	3	5
St. 11 (North Bound)	100	58	100	25	20	0.0	86.5	62.2	2	2
Out of St. 9	25	75	20	100	20	30.0	8.3	42.6	9	9
King Khalid	100	18	100	25	20	0.0	52.1	43.4	8	7
Prince Fisal	75	31	60	75	20	0.0	39.5	42.9	4	8
Dam-Khobr Coastal	75	67	60	100	80	0.0	40.6	66.9	1	1
Ext. Prince Mansour	25	24	60	25	80	0.0	32.6	36.0	10	10
Prince Mash'al	50	30	60	50	80	30.0	36.6	48.1	6	6
King Saud (South Bound)	100	58	40	25	60	0.0	55.0	54.2	5	4
From North to Mazro'yah Court	50	39	80	25	80	70.0	59.6	59.1	7	3

sing Table 4.1.
sing equation 4.3 or Table 4.3
sing Table 4.8 and equation 4.21

(2) Using equation 4.2
(5) Using equation 4.4 or Table 4.5
(8) Using equation 4.22

(3) Using Equation 4.5
(6) Using Equation 4.6 or Table 4.7
(9) Dammam Maintenence Management Officials.

represents 50% of the time. However, only two sections (5 and 10) showed relatively wide mismatch of four-point difference (4 to 8 and 7 to 3), one section (No. 1) showed two-point difference, and two sections (4 and 9) showed only one-point difference in priority ranking. These differences can be explained by the inability of engineering judgment to capture all priority attributes that the developed procedure considered

The above two case studies showed that the developed procedure for maintenance priority ranking give a good matching with the engineering judgment methods being currently adopted by maintenance management departments. However, the developed procedure was based on objective measurements as well as the local experience parameters that were excluded from both pavement specialists and other road users in the Kingdom. Assuming that one-point rank difference is acceptable, the procedure can be used with confidence reached up to 88.9% in ranking pavement sections for maintenance. Moreover, if two-point rank difference is acceptable, the matching between engineering judgment and the developed procedure reaches 100%. Generally the road networks consist of very big number of pavement sections, and all of these sections can not be efficiently considered by the engineering judgment. Therefore, the developed procedure can efficiently, economically, and systematically cope with any pavement network of any size.

The ranking results in the two case studies were also compared statically. Since there is no assumption about the normality of the two ranking method, a nonparametric measure of association between the engineering judgment ranking and the one of the

developed procedure. The Spearman rank correlation coefficient (r_s) was used for this purpose. This coefficient has the following equation [Walpole and Myers 1978]:

$$r_S = 1 - \frac{\Sigma d_i^2}{n(n^2 - 1)} \tag{4.23}$$

where,

r_s = Spearman rank correlation coefficient,

d_i = Difference between each pair (i) of sections, and

n = Total number of section considered in comparison.

Using the above equation for the two case studies considered for validation, case study number 1 has a rank correlation coefficient of 0.95 indicating a high positive correlation between the two methods of ranking, and case study number two has rank correlation coefficient of 0.77 which is a reasonable level, considering the limitations in the engineering judgment mentioned before. On average the developed procedures correlated with the engineering judgment 86% which can be considered a an acceptable level of correlation.

4.9 FACTOR ANALYSIS

Factor analysis is usually used as a data reduction method where the number of items or variables to be included in any model is huge. In this study, this test was

performed as a confirmatory tool since all seven factors considered were selected after different versions of questionnaire in th pilot survey. The conclusion was that only three main factors could be extracted from the considered seven. These three main factors could capture only 72% of the variations. This analysis with the obtained results are shown in Appendix C.

4.10 SUMMARY

This chapter detailed the development of maintenance priority ranking procedure. The factors affecting this ranking were quantified and scaled to a 100-point scale using approved and verified equations and logical assumptions. The weights of these factors were determined using designed questionnaires that were distributed to different groups of individuals representing the pavement specialists as well as other road users. The collected data were subjected to several logical and statistical checks. The validation of the developed procedure was checked by using two case studies. There was a good matching between the results of the developed procedure compared with the engineering judgment. Finally, a trail of factor analysis was made to obtain the factors (dimensions) that were adequately needed for this study.

CHAPTER FIVE

PAVEMENT CONDITION MODELING

5.1 DESCRIPTION

This chapter deals with the data collection and analysis of the pavement condition prediction modeling. It describes the model formulation and its parameters with their a priori hypothesis. Sources of the data have been detailed with the resulting observations on the collected data. The data have undergone preliminary testing and filtering, and then models for the three types of the collected data were developed using statistical regression methods. These models have been tested and validated, and finally, some data conversion between different pavement condition indices are presented.

5.2 MODEL FORMULATION

5.2.1 Model Parameters

The pavement condition is affected by several parameters, the ones included in this study are shown in the following general form of the pavement condition prediction model:

$$PCI = f(AGE, ACTH, SBTH, TRAF, TRUK, INTR) \quad (5.1)$$

where,

PCI = Pavement Condition measured by any distress survey method,

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

ACTH = The combined thickness of all asphalt layers, cm, (including overlays)

SBTH = Subbase (stabilized or aggregate) thickness, cm,

TRAF = Average daily traffic (ADT), vehicle per day per lane

TRUK = Number of trucks in the traffic mix,

INTER = Any possible interaction of the preceding factors.

It was found from the collected data that the above factors were the ones commonly available and accessible. Other factors such as subbase and subgrade types, when found, were either not available or not reliable.

The above general model can have any mathematical form such as linear, polynomial, or power function of the included parameters.

5.2.2 A priori Hypothesis

In the above pavement condition prediction model, the hypothesis that AGE, TRAF, and TRUK, are inversely proportional to the PCI. But ACTH, SBTH, are proportional to

pavement condition. The effects of these factors of pavement condition were explained in Chapter Two.

Based on the literature review, logic and engineering judgment, and developed models of similar studies, the following assumptions and boundary conditions can give a general idea about the expected shape and behavior of the targeted prediction model:

1. A new or a recently overlaid pavement section has a condition index value of 100, whatever the condition survey method was used (i.e. at AGE = 0, the condition index = 100). This could be achieved in prediction modeling by different ways. One way is to add or subtract from the intercept value the sum of each independent variable multiplied by its regression coefficient. Alternatively, by using the exponent or power function (e^{AGE} or AGE^{B}) with manipulating the variables to reach a PCI value of 100 at AGE = 0, since these function give a value of one at AGE = 0.

2. The total pavement thickness (ACTH+SBTH) is assumed to represent the supporting feature to the operating traffic load (TRAF or TRUK variable). Therefore to represent this in the modeling, a new variable was created by dividing the truck traffic (TRUK) by the pavement thickness as suggested by [George et al. 1989].

3. In general, pavement starts its deterioration process very slowly, but this deterioration accelerates very sharply at later stage. This can be represented

in the condition prediction model by the power, exponential function, or polynomial functions. However, the shape and the curvature of these functions can be controlled by the regression coefficients.

4. For relatively old pavements (AGE is much greater than 0), condition becomes very poor to failure stage, therefore, prediction model should capture the pavement condition of an index equals to zero at age of around the pavement design life (e.g. 20 to 30 years), if left without any maintenance.

From the above set of logical assumptions and hypothesis, the power and polynomial functions can reasonably represent the pavement condition behaviour. Therefore these two functions will be used for model generation.

5.3 DATA COLLECTION

5.3.1 Sampling Requirement

The minimum sample size required so that the predicted pavement condition can adequately represent the actual condition, depends on the allowable error in the prediction of the sample mean, standard deviation, and the desired degree of accuracy. The following equation was used for this purpose [Walpole and Myers 1978]:

$$n = \left(\frac{z_{\alpha/2} \quad \sigma}{e} \right)^2 \tag{5.2}$$

where,

n = required minimum number of cases for regression analysis,

$z_{\alpha/2}$ = normal distribution value for a given confidence level,

σ = standard deviation of the overall samples (cases) considered, and

e = allowable error in the estimate

A confidence level of 95% ($z_{\alpha/2}$ = 1.96) was selected as an accuracy level for the pavement condition estimates. The allowable permissible error in estimating the pavement condition was set to ± 5 points (100-point scale). Additionally the average variance (σ^2)of all collected data was 231.07 as state in Section 5.3.3. Using these values in the above equation, n equals to 35.5. Therefore, a minimum of 36 data points are needed for modeling the pavement condition. The available data cases are much more than this number. The total number of cases from the three survey methods are 433, 138, and 202, for PDR, PCR, and PCI method, respectively, with a total of 773. It should be noted that the deficiency of using the collected samples' variance instead of the unknown population variance was covered by using sample size much greater than 36.

5.3.2 Data Sources

The potential sources mentioned in Section 3.3.3 were approached and all possible and accessible information regarding pavement history and condition were collected. Table 5.1 summarizes the collected data with their corresponding source.

Table 5.1. Summary of the sources of the collected condition surveys data.

Source	Number of Data Points	Condition Survey Method	Remarks
Ministry of Communication (MOC) Riyadh	40,000	MOC Method (PCR)	Freeways and feeder road network in Riyadh and Dammam areas; One survey.
Ministry of Communication, Abqaiq Road	138	MOC Method, (PCR), and PAVER Method (PCI)	Data of 36-section test track of Dhahran-Abqaiq Road; Two surveys (PCR), and one survey (PCI).
Dhahran and Dammam Areas Road Network	135	PAVER Method (PCI)	Arterial, collector, and local roads; Several surveys.
Municipality of Riyadh	1080	PAVER Method (PCI)	10% of Riyadh city main road network; One survey.
Jubail Industrial City Road Network	800	KFUPM-RI Method (PDR)	Arterial, collector, and local road network; Mostly one survey data and two surveys data for some road sections

The collected data were sorted according to their sources and checked thoroughly. The following were the general important observations and comments on these data:

1. Some pavement sections had multiple condition survey information. These section were in the vicinity of KFUPM where many research studies were carried out at different times. These sections helped to judge the general pavement performance-time relationships in the modeling. However, the majority of the remaining sections (Jubail and MOC) had a single condition survey data, but wide range of. For example, pavement age ranged from 1 to 16 years of service, traffic ranges from 200 vpd/lane to more than 10,000 vpd/lane, and so on.

2. The collected data covered all road types and classes. Rural freeways and feeders, urban arterial, collectors, and locals were covered for pavement condition surveys.

3. Collected traffic volumes were generally reported in ADT and contained the overall truck percentages. Thus, the ESAL values could not be obtained due to the lack of traffic composition for most of the pavement sections considered. Therefore, it was decided to use the ADT figures in terms of vehicle per day per lane (vpdpl) for traffic factor (TRAF) and the combined number of commercial vehicles for truck factor (TRUK).

4. The combined layer thickness of asphalt wearing and base course was used for asphalt layer thickness factor (ACTH). Similarly, the combined layer thickness of subbase or aggregate base layers was used for the subbase thickness factor

(SBTH). No distinction was made for the type of the subbase or aggregate base (unstabilized, stabilized, or modified) since the detailed relevant information could not be obtained.

5. Some collected data were related to special road sections. Three experimental test tracks were constructed using sulfur-extended-asphalt (SEA) as binder. These sections are located in the Eastern Province of Saudi Arabia near Dhahran-Dammam area. They were phased in with the roads where they belong to while construction. Test Road 1 was in the Kuwait Diversion Road, Test Road 2 was in Abu Hadriyah Expressway, and Test Road 3 was KFUPM Road (Sulfur Asphalt Side). The long-term performance history of these test roads in terms of laboratory and field testing was reported and documented by [Akili and Arora 1984; Arora et al. 1994]. The collected condition survey data for these sections were excluded form this study.

6. Another special experimental road was the Dhahran-Abqaiq road, constructed in 1988 [MOC 1992]. This road has a set of 36 test sections with different materials, properties, and structural designs. Four types of wearing course, three types of binder course, and eight types of base course were used in constructing these sections. Some modifiers such as Novophalt, and Styrelf were used in the bituminous mixes of some of these sections. For the purpose of this study, all sections with modifying agents were excluded from the study, since these sections may have different behavior than other normal sections.

7. The data collected from the MOC for Riyadh and Dammam rural highways were not complete in relation with the required information. Pavement-history related data could not be obtained such as layer thickness and construction date. However, some of these road sections have been studied by different researchers [Saleem 1985; Asi, 1986; Ramadhan 1988], and missing information were reported by these researchers. Therefore, Only these sections that had complete information were included in this study. Moreover, the data for the selected sections were averaged out for traffic levels. This means that all data points of same traffic level were considered belonging to one section, and if the traffic level changed, a new section was considered separately. The collected data were about one-kilometer intervals.

8. The data collected from Municipality of Riyadh were for about 10% of the main roads of Riyadh City road network. Most of the data were not complete in terms of layer thickness and construction date. Traffic data were available but not the truck traffic percentage. Therefore, only these sections with complete information were considered, in addition to assuming a 5% truck percentages in the operating traffic, as provided by Municipality of Riyadh. This is because heavy commercial trucks are not allowed to enter the city roads. This 5% assumption is for the buses and light trucks.

5.3.3 Preliminary Data Analysis

The collected data were subjected to a filtering process for any unusual or illogical results. Two criteria were specified in this process: (i) Relatively old sections of more than 7 years in service, with a condition index of 100 (perfect condition) were excluded from the analysis. The perfect condition can only happen when the pavement is relatively new or the pavement was not exposed to any external factors of traffic and environment; (ii) Relatively new sections of less than 5 years in service, with condition index approaching zero (failure condition) were also excluded for the analysis. Situations may exist that some sections are exposed to very severe load and environmental conditions, or where pavement sections have some built-in defects during design or construction. These situations result in a premature failure to these sections.

The collected data from all sources, after checking, were stored and tabulated in worksheet files and then transferred to the STATISTICA computer package [STATISTICA 1995] format for pavement condition model development and calibration. The overall data points (cases), from each data collection method, are summarized in Table 5.2. The AGE has a rage of 1.5 to 15.3 years of service for the PDR, 1 to 14 years for the PCR, and 0.33 to 19.67 for the PCI data. These are considered good ranges for pavement condition and performance modeling. Other factors have also wide ranges as shown in the table. Combined asphalt layer thickness have a range of 9 to 25 cm for the PDR, 0 to 35 cm for the PCR, and 0 to 83 cm for the PCI data. The collected data of the three methods were also plotted as histograms to check their normality as shown in

Table 5.2. Statistical summary of the collected data for all survey methods.

Method	Statistic	Modeling Factor					
		AGE	PDR	ACTH	SBTH	TRAF	TRUK
PDR	Mean	5.4	83.7	15.4	38.0	1077.9	343.8
	Std. Dev.	3.2	16.2	5.5	7.9	1029.2	390.7
	Maximum	15.33	100	25	55	4662	1541
	Minimum	1.5	20.00	9	30	103	8
	Number	433	433	433	433	433	433
PCR	Mean	7.3	79.8	18.4	26.2	4661.1	1556.4
	Std. Dev.	4.7	13.1	6.3	8.4	2919.1	1136.3
	Maximum	14	100	26	35	21415	6931
	Minimum	1	47.6	6	0	44	21
	Number	141	141	141	141	141	141
PCI	Mean	76.5	6.0	14.1	25.2	4675.8	754.1
	Std. Dev.	16.1	5.1	4.8	7.8	3372.7	728.3
	Maximum	100	19.67	25	83	18319	2243
	Minimum	18	0.33	4	0	72	0
	Number	202	202	202	202	202	202

Figure 5.1. Furthermore, the normality check results using K-S test are shown in Table 5.3. All the three data sets collected by the three different methods represent normal distribution with a level of significance of 99%. Therefore, the basic parametric statistical testing can be safely used since the normality assumption is satisfied.

As stated before, the five variables that affect the pavement condition are age of the pavement (AGE), asphalt layer thickness (ACTH), subbase or aggregate base layer thickness (SBTH), operating traffic (TRAF), and truck percentage in the traffic mix (TRUK). Initially, the general relationships between the dependent variable, pavement condition (PDR, PCR, or PCI) with each of the other independent modeling variables (AGE, ACTH, SBTH, TRAF, and TRUK) in order to establish and confirm the logic of a priori hypothesis, stated earlier, for the general developed models. Figures 5.2 to 5.4 illustrate these relationships for PDR, PCR, and PCI data. The scattered plots as well as the general predicted trend are shown in these figures.

From these figures, the age factor (AGE) shows a very clear systematic decreasing (negative) relationship, which indicates that AGE is the most important factor affecting the predicted pavement condition. As the pavement gets older, its condition declines (deteriorated) under the prevailing traffic and environmental conditions. Similarly, the pavement asphalt layer thickness factor (ACTH) shows systematic relationship of increasing order for PDR and PCI data, but not for PCR data. Keeping other factors constant, the higher the asphalt layer thickness, the better in the pavement condition. Traffic parameters (TRAF and TRUK) showed unexpected positive relationships with

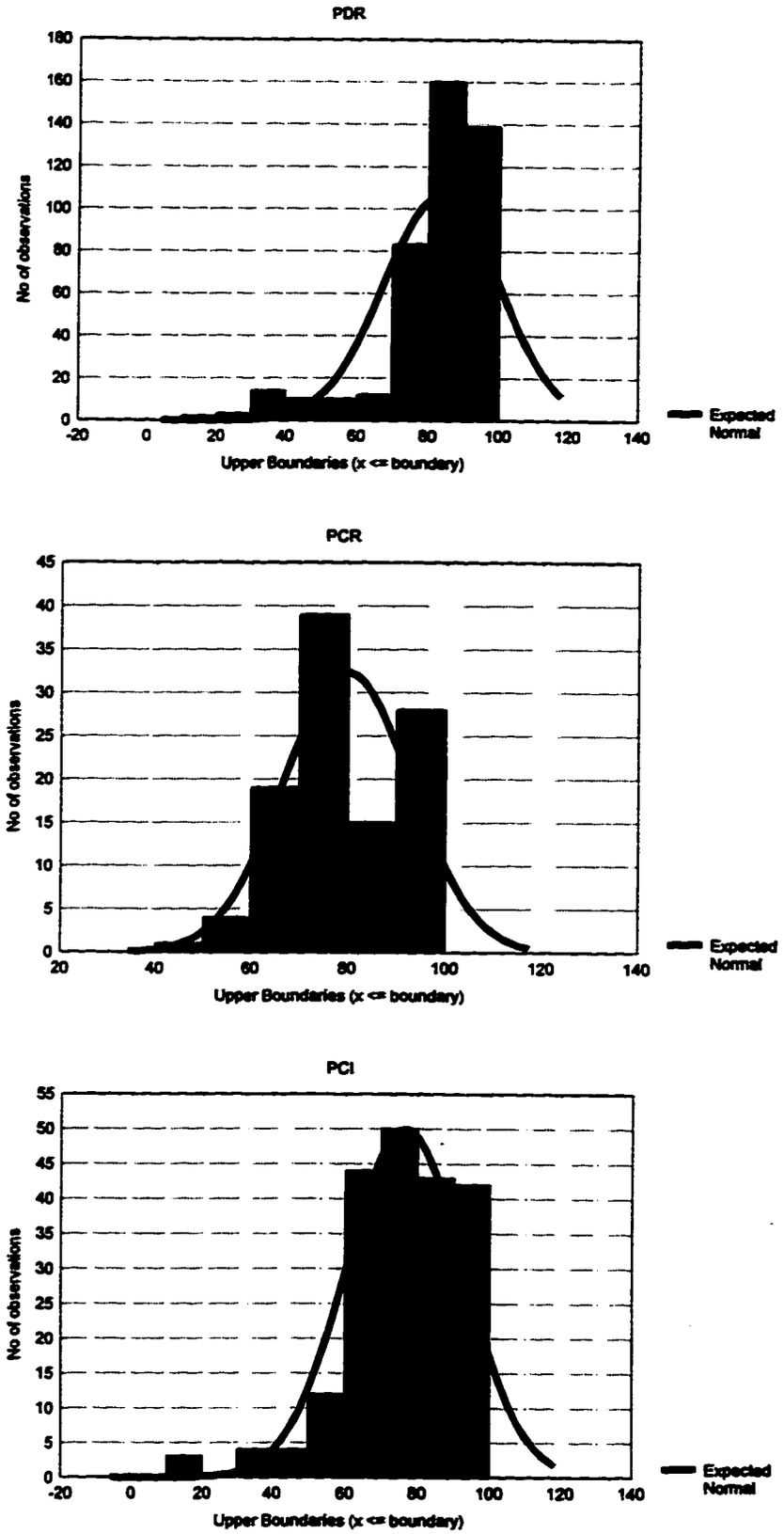


Figure 5.1. Frequency distributions of all collected data for normality check.

Table 5.3. K-S test results for normality check of the collected data.

Method	N	max. D	p	Significance Level, %
PDR data	433	0.193742	$p < .01$	99
PCR data	106	0.132691	$p < .01$	99
PCI data	202	0.072815	$p < .01$	99

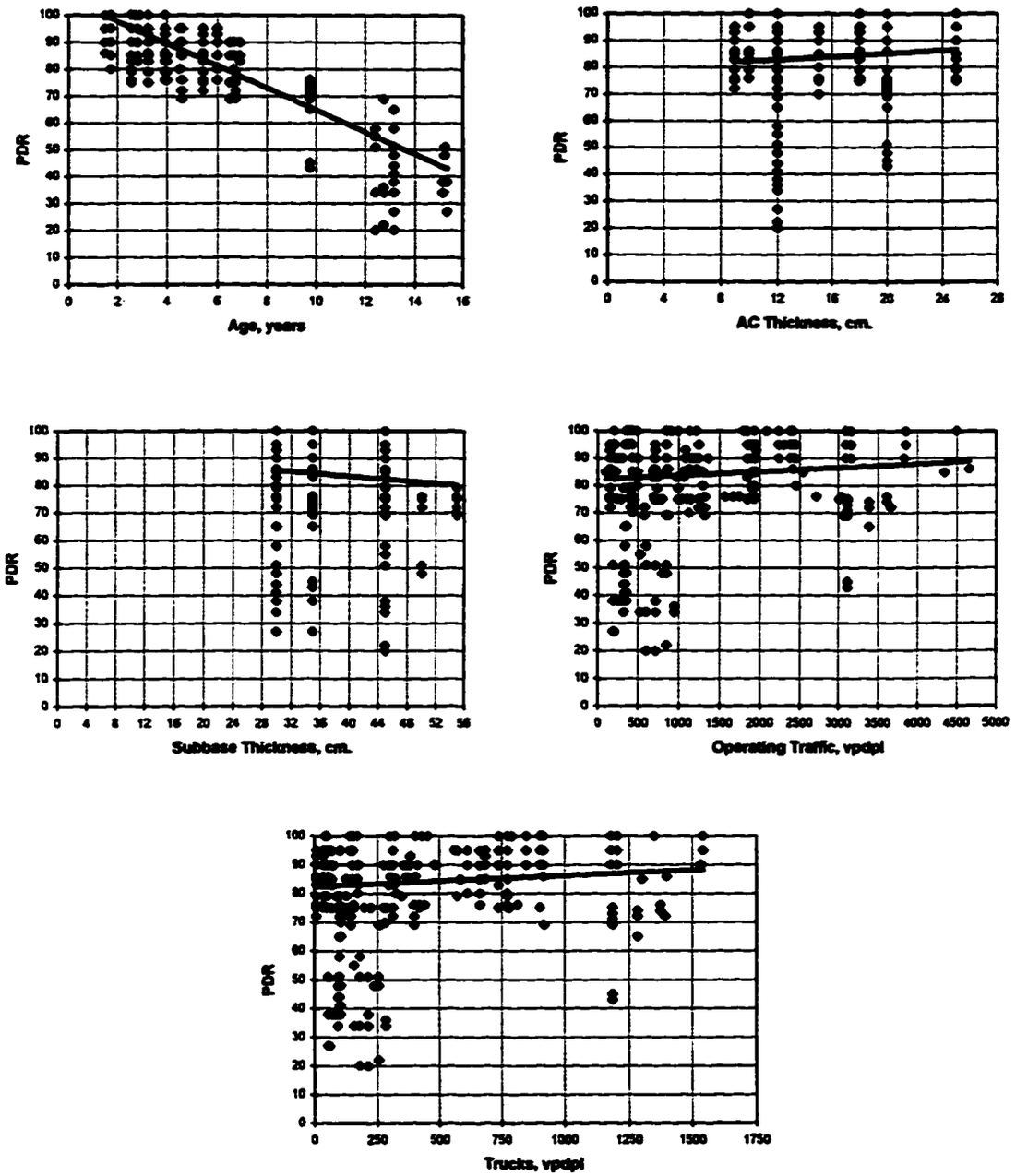


Figure 5.2. Relationships between the pavement condition and modeling factors for PDR data.

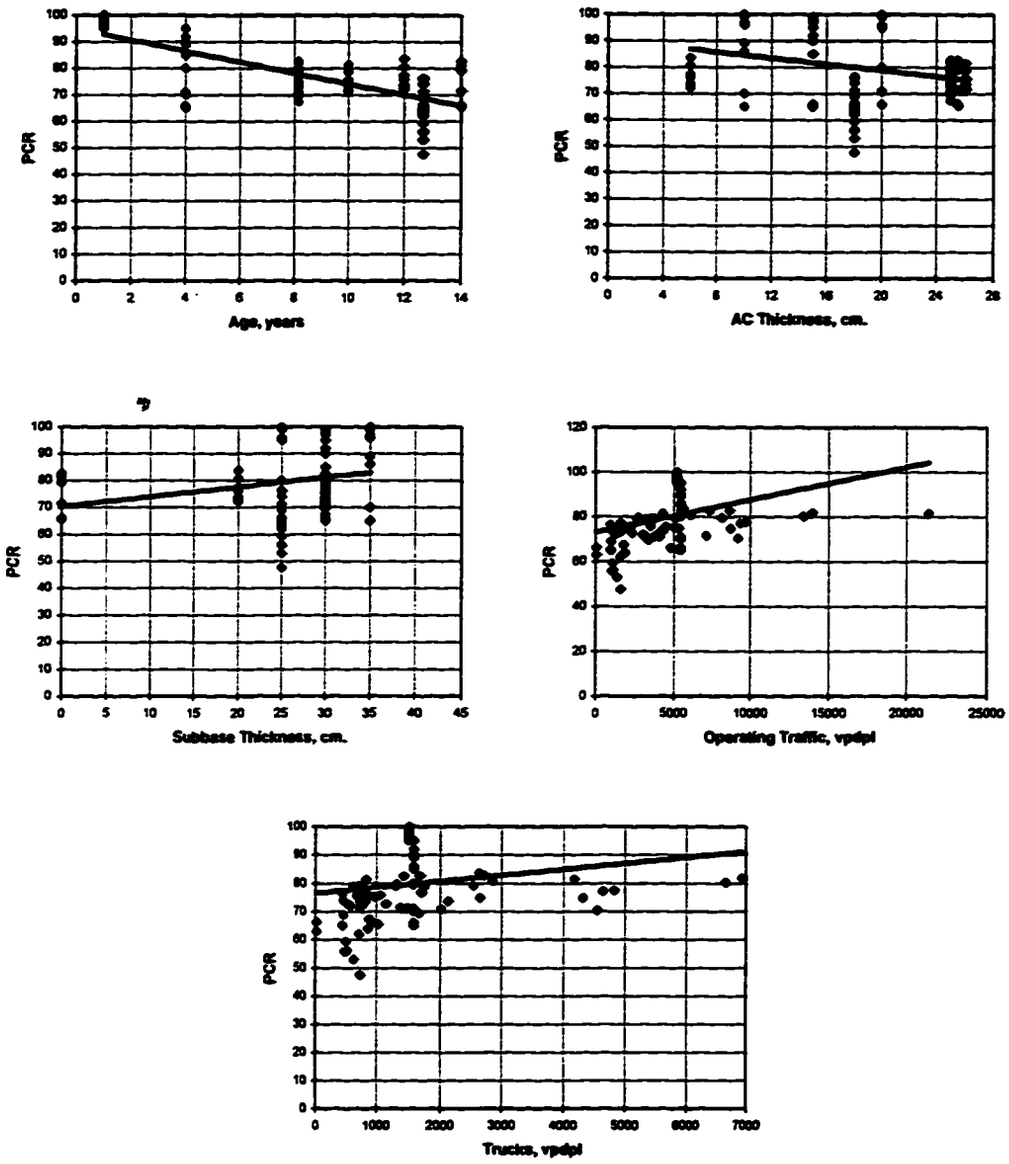


Figure 5.3. Relationships between the pavement condition and modeling factors for PCR data.

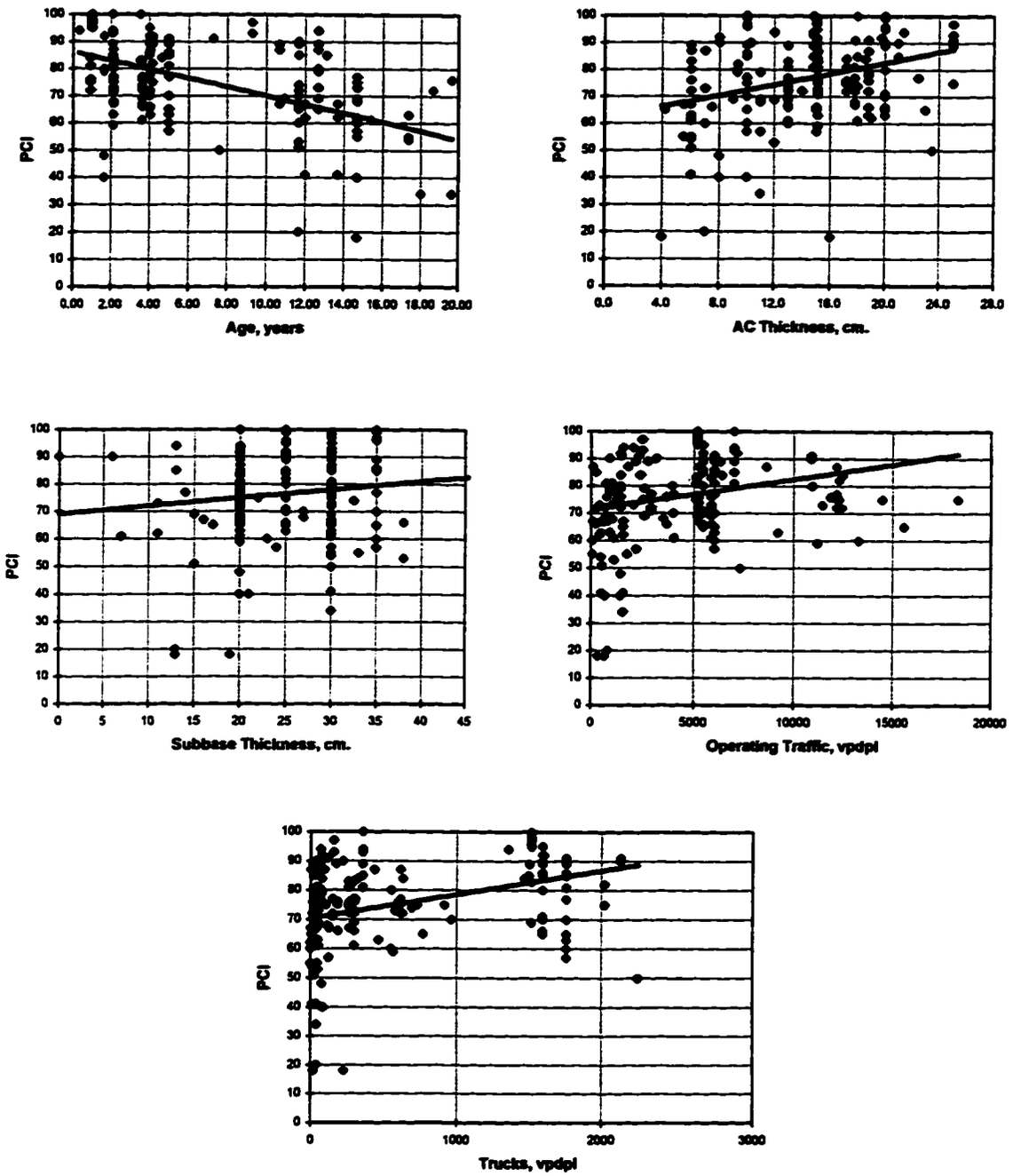


Figure 5.4. Relationships between the pavement condition and modeling factors for PCI data.

the pavement condition. However, this relationships can be attributed to the interaction of other factors such as pavement thickness (ACTH and SBTH). The actual relationship can be seen if other factors are kept constant.

Correlation coefficient provides a normalized and scale-free measure of the association between any two variables. It has a value between +1 to -1, perfect statistically independent variables have a correlation coefficient value of zero. As another measure of interrelation between the dependent variable (pavement condition) and other independent modeling variables, the correlation coefficient matrices shown in Tables 5.4 to 5.6 were calculated for PDR, PCR, and PCI data. From these tables, the pavement condition has relatively high negative correlation with the AGE factor of -0.82, -0.74, and -0.51, for PDR, PCR and PCI data, respectively. This confirms the previous observation in Figures 5.2 to 5.4. Other factors have similar observations like these obtained from these figures.

The disaggregate type of data could not be obtained due to lack of pavement management data bases for the pavement network in the Kingdom. If the pavement network has continuous records of condition survey data over time, the disaggregate modeling could be followed. Therefore, the main idea of plotting the previous figure was to show that due to the lack of disaggregate type of data, the aggregation of data modeling was followed which means that if certain category of pavement parameters are missing, similar data from other location could be used as representation of this missing data.

Table 5.4. Correlation coefficients of the PDR data

	PDR	AGE	ACTH	SBTH	TRAF	TRUK
PDR	1.000	-0.820	0.098	-0.110	0.088	0.092
AGE		1.000	-0.374	-0.061	-0.192	-0.202
ACTH			1.000	0.513	0.429	0.504
SBTH				1.000	0.085	0.115
TRAF					1.000	0.960
TRUK						1.000

Table 5.5. Correlation coefficients of the PCR data.

	PCR	AGE	ACTH	SBTH	TRAF	TRUK
PCI	1.000	-0.735	-0.277	0.235	0.326	0.182
AGE		1.000	0.315	-0.595	-0.265	-0.181
ACTH			1.000	-0.231	0.225	0.215
SBTH				1.000	0.030	0.189
TRAF					1.000	0.815
TRUK						1.000

Table 5.6. Correlation coefficients of the PCI data.

	PCI	AGE	ACTH	SBTH	TRAF	TRUK
PCI	1.000	-0.507	0.306	0.147	0.230	0.368
AGE		1.000	-0.386	0.074	-0.448	-0.443
ACTH			1.000	-0.174	0.237	0.258
SBTH				1.000	0.017	0.340
TRAF					1.000	0.475
TRUK						1.000

5.4 MODEL CALIBRATION

The process of building pavement condition prediction models from the collected data included running regression analysis for each data set separately. The power and polynomial functions specified in Section 5.2.2 were used to generate different possible regression models. However, initially, the step-wise regression analysis was done for all three data sets to check the significance of each of the independent variable in predicting the pavement condition. Model building process is detailed in the next sections.

5.4.1 Linear Regression Analysis

In the forward step-wise linear regression statistical procedure, each independent variable (IV) was entered into the model in order of its significance, as determined by the partial F-test. After each new IV was added, the procedure checked all previously entered IVs to insure they were still significant. The criteria for including any variable in the regression model was set to be 1.0. The variable will be include in the model if it adds to the starting F-ratio a value of 1.0 or greater. After the addition of each factor, staring with the one with that contributed the most to F-value, the contribution of each variable to the F-value of the model is recalculated. If the value of the contribution for any of the included variables dropped under 1.0, it was removed from the model. The selection procedure continued until the contribution of all variables inside the model was greater than or equal to 1.0, and the contribution of the factors outside the model was less than 1.0.

Tables 5.7 to 5.9 summarize the results of the step-wise linear regression analysis. for PDR, PCR and PCI data. the final models obtained were with the R^2 values of 0.755, 0.596, and 0.496 for the PDR, PCR, and PCI data sets. The total number of data points included in this modeling were 275 for PDR, 106 for PCR, and 135 for PCI. The PCI data model excluded only the SBTH variable, while the PCR model excluded ACTH, TRAF, and TRUK variables, and PDR model excluded the SBTH and TRAF variables. It was noted from the above tables that R^2 increases as the number of IV increases. Therefore, part of the increase in the R^2 is due to the increasing number of IV and not necessarily the improvement in the explanatory power of the models. This effect can be captured and eliminated by the adjusted value of R^2. The R^2 is a measure of the proportion of the total variation in the response or dependent variable (pavement condition) that is explained by the prediction model [Walpole and Myers 1978].

5.4.2 Non Linear Regression Analysis

To improve the fit or the ability to predict the pavement condition, various linear and non-linear transformation of the five independent variables were tried.

As stated earlier, the polynomial and power curves were selected for modeling the pavement condition. Polynomial curves used were of second, third, and fourth degree of the AGE independent variable, being the most important and influential variable to pavement condition. Other variables (i.e. ACTH, SBTH, TRAF, and TRUK), were kept in their linear form. These model have the following general form:

Table 5.7. Forward step-wise regression for PDR data.

Step	Variable	BETA	St. Err. of BETA	B	St. Err. of B	t(273)	p-level	Adjusted R^2
1	Intercpt	-	-	105.5083	1.09652	96.221	0.0000	
	AGE	-0.859322	0.030953	-4.3043	0.155044	-27.7618	0.0000	0.737476
2	Intercpt	-	-	112.4224	2.27109	49.5015	0.0000	
	AGE	-0.888063	0.031469	-4.4483	0.157629	-28.2198	0.0000	0.747596
	ACTH	-0.108768	0.031469	-0.3998	0.115684	-3.4563	0.0006	
3	Intercpt	-	-	113.2559	2.251405	50.3045	0.0000	
	AGE	-0.893019	0.031017	-4.4731	0.155363	-28.7913	0.0000	0.755446
	ACTH	-0.152062	0.033943	-0.559	0.124779	-4.4799	0.0000	
	TRUK	0.102326	0.032803	0.0049	0.001561	3.1194	0.0020	

Table 5.8. Forward step-wise regression for PCR data.

Step	Variable	BETA	St. Err. of BETA	B	St. Err. of B	t(106)	p-level	Adjusted R^2
1	Intercpt	-	-	94.7146	1.601442	59.1433	0.0000	
	AGE	-0.735356	0.066452	-2.05688	0.185874	-11.0659	0.0000	0.53633
2	Intercpt	-	-	111.1739	4.323209	25.7156	0.0000	
	AGE	-0.921369	0.077113	-2.5772	0.215693	-11.9484	0.0000	0.59634
	SBTH	-0.312863	0.077113	-0.4836	0.119204	-4.0572	0.0001	

Table 5.9. Forward step-wise regression for PCI data.

Step	Variable	BETA	St. Err. of BETA	B	St. Err. of B	t(135)	p-level	Adjusted R^2
1	Intercpt	-	-	93.35323	2.148921	43.44192	0.0000	
	AGE	-0.631453	0.067237	-2.15653	0.229627	-9.39146	0.0000	0.39421
2	Intercpt	-	-	114.8016	6.270294	18.3088	0.0000	
	AGE	-1.03369	0.128385	-3.5302	0.43846	-8.05148	0.0000	0.44478
	TRUK	-0.46489	0.128385	-0.011	0.003048	-3.62108	0.0004	
3	Intercpt	-	-	115.3797	6.204176	18.59711	0.0000	
	AGE	-1.0909	0.129994	-3.7256	0.443955	-8.3919	0.0000	0.45757
	TRUK	-0.66483	0.160687	-0.0158	0.003815	-4.13742	0.0001	
	TRAF	0.20027	0.098739	0.0013	0.000654	2.02822	0.0446	
4	Intercpt	-	-	109.8763	6.848123	16.04473	0.0000	
	AGE	-1.06621	0.129558	-3.6413	0.442465	-8.22959	0.0000	
	TRUK	-0.68019	0.159495	-0.0161	0.003787	-4.26463	0.0000	0.46707
	TRAF	0.18013	0.09849	0.0012	0.000652	1.82892	0.0697	
	ACTH	0.12733	0.069717	0.4246	0.232477	1.82646	0.0701	

$$PDR = a + b.(AGE) + c.(AGE)^2 + d.(AGE)^3 + e.(AGE)^4 + f.(ACTH) + g.(SBTH) + h.(TRAF) + i.(TRUK) + error \quad (5.3)$$

Similarly, the power curve of AGE, ACTH, SBTH, TRAF, and TRUK were tried using the logarithmic transformation stated below:

Power Form

$$PDR = 100 - a.(AGE)^b . (ACTH)^c . (SBTH)^d . (TRAF)^e . (TRUK)^f . error \quad (5.4)$$

Transformed Logarithmic Form

$$\log (100 - PDR) = \log (a) + b.\log(AGE) + c.\log(ACTH) + d.\log(SBTH) + e.\log(TRAF) + f.\log(TRUK) + error \quad (5.5)$$

The two general forms were used for the three data sets: PDR, PCR, and PCI and the following models were obtained

5.4.3 Models Selection

5.4.3.1 PDR Models

Figure 5.5 to 5.9 show five statistical summary results of regression models that could be obtained for the PDR data set. Several trials were made with different independent variables inclusion schemes. The above figure represent only those models that have all independent variables with 95% significant level and above.

Reported results include R^2, adjusted R^2, standard error for the model, analysis of variance (ANOVA) with model significant level, and finally, the model coefficients with their corresponding significant level and the 95% significant intervals (upper and lower).

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.889
R Square	0.791
Adjusted R Square	0.786
Standard Error	8.332
Observations	275

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	70237.09	11706.18	168.62	0.00
Residual	268	18605.91	69.43		
Total	274	88843.00			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	109.9149	9.5569	11.5011	0.0000	91.0987	128.7311
AGE	-9.8846	5.4692	-1.8073	0.0718	-20.6527	0.8835
AGE^2	2.2371	1.1940	1.8736	0.0621	-0.1137	4.5879
AGE^3	-0.2542	0.1022	-2.4869	0.0135	-0.4555	-0.0530
AGE^4	0.0086	0.0030	2.8802	0.0043	0.0027	0.0145
ACTH	-0.3547	0.1440	-2.4623	0.0144	-0.6383	-0.0711
TRUK	0.0038	0.0016	2.4507	0.0149	0.0008	0.0069

Figure 5.5. Summary of statistical regression of PDR data selected model 1.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.881
R Square	0.777
Adjusted R Square	0.774
Standard Error	8.567
Observations	275

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	69025.72	17256.43	235.11	0.00
Residual	270	19817.28	73.40		
Total	274	88843.00			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	100.2423	3.4824	28.7852	0.0000	93.3861	107.0985
AGE	-1.1775	0.7065	-1.6665	0.0968	-2.5685	0.2136
AGE^2	-0.2024	0.0424	-4.7725	0.0000	-0.2859	-0.1189
ACTH	-0.3201	0.1301	-2.4608	0.0145	-0.5761	-0.0640
TRUK	0.0033	0.0015	2.1493	0.0325	0.0003	0.0063

Figure 5.6. Summary of statistical regression of PDR data selected model 2.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.881
R Square	0.777
Adjusted R Square	0.775
Standard Error	0.328
Observations	275

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	28.625	9.542	88.464	0.0000
Residual	271	29.230	0.108		
Total	274	57.854			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.5870	0.2133	-2.3259	0.0208	-0.9162	-0.0762
log(AGE)	1.2500	0.0837	16.1187	0.0000	1.1850	1.5148
log(ACTH)	-0.1850	0.1814	3.7988	0.0002	0.3321	1.0465
log(TRUK)	0.0180	0.0362	-1.6290	0.1045	-0.1301	0.0123

Figure 5.7. Summary of statistical regression of PDR data selected model 3.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8550
R Square	0.7310
Adjusted R Square	0.7300
Standard Error	0.336
Observations	275

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	27.057	27.057	239.845	0.0000
Residual	273	30.797	0.113		
Total	274	57.854			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.2100	0.0602	4.2446	0.0000	0.1370	0.3739
log(AGE)	1.3550	0.0795	15.4869	0.0000	1.0753	1.3885

Figure 5.8. Summary of statistical regression of PDR data selected model 4.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8734
R Square	0.7629
Adjusted R Square	0.7610
Standard Error	0.336
Observations	275

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	28.3385	14.1693	130.5750	0.0000
Residual	272	29.5159	0.1085		
Total	274	57.8544			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.3655	0.2114	-2.0913	0.0374	-0.8582	-0.0259
log(AGE)	1.3590	0.0833	15.9948	0.0000	1.1681	1.4960
log(ACTH)	-0.1404	0.1574	3.4364	0.0007	0.2310	0.8508

Figure 5.9. Summary of statistical regression of PDR data selected model 5.

All PDR models have similar prediction ability as measured by R^2, they have high significant level (100%), and their coefficients are also highly significant. Examining all PDR models, the model shown in Figure 5.9 is selected to represent the PDR collected data set. The model has an adjusted R^2 of 0.775 with AGE, ACTH, and TRUK to the power of 1.25 and -0.185, and 0.018, respectively. Other models were not selected due to lower R^2 values as the ones shown in Figure 5.8. Some models with higher R^2 that the selected model were not selected because they include some coefficients with incorrect logical signs such as the plus sign of TRUK coefficient in the model shown in Figure 5.5, and the minus sign of ACTH coefficient in the same model.

5.4.3.2 PCR Models

Similar to PDR models, all possible and feasible PCR models generated from the collected data, were tried and the best ones are shown in Figure 5.10 to 5.13 which include all obtained statistics described in the previous section. The best model selected to represent the PCR data is the one shown in Figure 5.13 that has the highest obtained R^2 of 0.796 and a level of significance of 0.0 for both the whole model and the model coefficients. Here, only the AGE factor was included in the selected model, while other factors were either insignificant or were in lower R^2 or illogical models. Therefore, for the PCR data, there is no influence of all factors except the AGE on predicted pavement condition.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8527
R Square	0.7271
Adjusted R Squar	0.7106
Standard Error	7.0237
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	13015.661	2169.277	43.972	0.0000
Residual	99	4883.956	49.333		
Total	105	17899.617			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	123.1068	6.6739	18.4461	0.0000	109.8644	136.3492
AGE	-28.8646	5.5208	-5.2283	0.0000	-39.8192	-17.9101
AGE^2	6.8043	1.6884	4.0300	0.0001	3.4541	10.1544
AGE^3	-0.6414	0.1794	-3.5750	0.0005	-0.9974	-0.2854
AGE^4	0.0205	0.0062	3.3311	0.0012	0.0083	0.0327
ACTH	-0.4265	0.1759	-2.4244	0.0171	-0.7756	-0.0774
TRAF	0.0008	0.0003	2.8671	0.0051	0.0002	0.0013

Figure 5.10. Summary of statistical regression of PCR data selected model 1.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.7932
R Square	0.6292
Adjusted R Squar	0.6220
Standard Error	8.0272
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	11262.785	5631.392	87.396	0.0000
Residual	103	6636.832	64.435		
Total	105	17899.617			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	101.8146	2.0351	50.0283	0.000000	97.7784	105.8508
AGE	-5.5710	0.7284	-7.6478	0.000000	-7.0157	-4.1263
AGE^2	0.2478	0.0500	4.9575	0.000003	0.1487	0.3470

Figure 5.11. Summary of statistical regression of PCR data selelcted model 2.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8301
R Square	0.6891
Adjusted R Squar	0.6768
Standard Error	7.4224
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	12335.284	3083.821	55.975	0.0000
Residual	101	5564.333	55.092		
Total	105	17899.617			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	117.5935	4.0517	29.0234	0.0000	109.5560	125.6309
AGE	-24.1352	4.3698	-5.5232	0.0000	-32.8037	-15.4667
AGE^2	5.2659	1.2334	4.2696	0.0000	2.8193	7.7126
AGE^3	-0.4823	0.1271	-3.7946	0.0003	-0.7344	-0.2302
AGE^4	0.0152	0.0043	3.5239	0.0006	0.0067	0.0238

Figure 5.12. Summary of statistical regression of PCR data selected model 3.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8932
R Square	0.7979
Adjusted R Squar	0.7959
Standard Error	0.2449
Observations	106

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	24.618	24.618	410.519	0.0000
Residual	104	6.237	0.060		
Total	105	30.854			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.3107	0.0458	6.7870	0.00000	0.2199	0.4014
log (AGE)	1.1239	0.0555	20.2613	0.00000	1.0139	1.2339

Figure 5.13. Summary of statistical regression of PCR data selected model 4.

5.4.3.3 PCI Models

Figures 5.14 to 5.16 show the possible and feasible PCI models generated from the collected data. Two feasible power models (transformed logarithmic) shown in Figure 5.15 and 5.16 have higher R^2 values that the third and fourth degree polynomial model (Figure 5.14). Examining the two power models, the second one (Figure 5.16) has higher R^2 value and it gives more information since in includes the TRUK variable while the first one does not.

The three selected models for different data sets are shown in their final and summarized forms in Table 5.10.

5.5 MODEL EVALUATION AND TESTING

The selected models were subjected to different evaluation and testing schemes to check that their predictions conform with the basic engineering and logical assumptions made before. This includes model evaluation, and other statistical checks, as detailed in the following sub-section.

5.5.1 Model Evaluation

The selected models were subjected to an evaluation process to check that their predictions conform with the basic engineering and logical assumptions made before. This process included: (i) generating two-dimensional plots showing the pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.6946
R Square	0.4825
Adjusted R Squar	0.4664
Standard Error	13.5287
Observations	134

ANOVA

	df	SS	MS	F	Significance F
Regression	4	22012.800	5503.200	30.068	0.0000
Residual	129	23610.215	183.025		
Total	133	45623.015			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	111.0755	5.0129	22.1578	0.0000	101.1573	120.9937
AGE	-15.7011	4.0897	-3.8392	0.0002	-23.7926	-7.6096
AGE^2	2.5727	0.9823	2.6191	0.0099	0.6292	4.5162
AGE^3	-0.1758	0.0825	-2.1302	0.0351	-0.3392	-0.0125
AGE^4	0.0039	0.0022	1.7781	0.0778	-0.0004	0.0083

Figure 5.14. Summary of statistical regression of PCI data selected model 1.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.7976
R Square	0.6362
Adjusted R Squar	0.6335
Standard Error	0.3304
Observations	134

ANOVA

	df	SS	MS	F	Significance F
Regression	1	25.204	25.204	230.848	0.0000
Residual	132	14.412	0.109		
Total	133	39.616			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.4030	0.0562	7.1689	0.0000	0.2918	0.5141
log (AGE)	1.0220	0.0673	15.1937	0.0000	0.8890	1.1551

Figure 5.15. Summary of statistical regression of PCI data selected model 2.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8135
R Square	0.6632
Adjusted R Squar	0.6580
Standard Error	0.3189
Observations	135

ANOVA

	df	SS	MS	F	Significance F
Regression	2	26.2530	13.1265	129.1051	0.00000
Residual	132	13.4208	0.1017		
Total	134	39.6738			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.0872	0.1606	-0.5787	0.0564	-0.4107	0.2248
log(AGE)	1.2224	0.0896	13.6078	0.0000	1.0421	1.3966
log(TRUK))	0.1363	0.0420	3.3005	0.0012	0.0555	0.2217

Figure 5.16. Summary of statistical regression of PCI data selected model 3.

Table 5.10. Summary of the selected models.

Data Set	Model Form	Adjusted R^2
PDR	$PDR = 100 - 3.83 * (AGE)^{1.230} * (ACTH)^{-0.185} * (TRUK)^{0.018}$	0.775
PCR	$PCR = 100 - 2.045 * (AGE)^{1.1239}$	0.796
PCI	$PCI = 100 - 0.8181 * (AGE)^{1.2224} * (TRUK)^{0.1363}$	0.658

condition with age at average values of other independent variables, and (ii) generating fitting characteristic plots between the predicted values and the observed ones.

5.5.1.1 Basic Assumptions Check

Figures 5.17 to 5.19 show the three selected models for all data sets. In all selected models, the pavement condition starts at a perfect condition, (i.e. 100 index value), then the condition deteriorates with time till the failure condition (zero index value). The PDR model (Figure 5.17) and the PCI model (Figure 5.19), show the best logical and expected pavement behavior, the rate of pavement deterioration starts slowly, then it increases till. The PCR model (Figure 5.18), however, has similar behavior, except that the deterioration curve is fairly smooth and decreases slowly at same rate, this may be due that this model includes only the AGE factor.

On the other hand, the sign of the independent variables included in the models conform with the hypothesized one. For example, AGE factor in all models, has a reduction power to the condition index, that is, as the AGE increases, the pavement condition (PDR, PCR, or PCI) decreases. Similarly, the truck factor (TRUK) in PDR and PCI selected models (Figures 5.17 and 5.19) has also reduction power on the pavement condition. But the thickness variable (ACTH) in the PDR selected model (Figure 5.17) has an increasing effect on the pavement condition, that means, comparing two pavement section, the one with higher thickness, has a higher pavement condition index value at the same age and traffic level. From this, it can be concluded that the

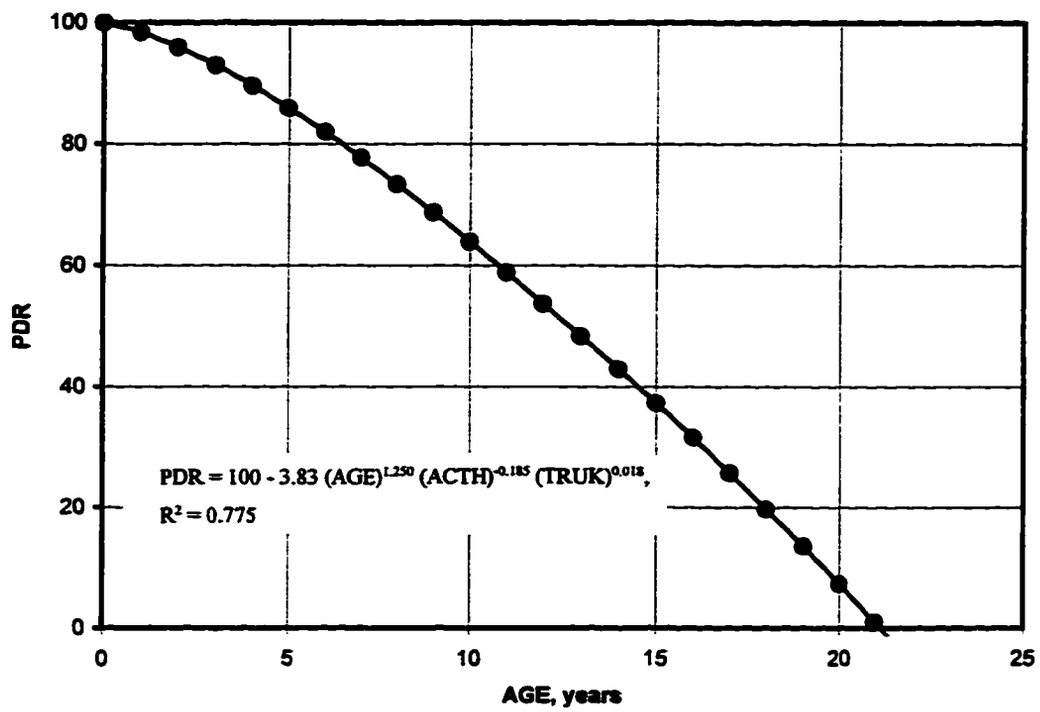


Figure 5.17. PDR selected model using average values of independent vairables

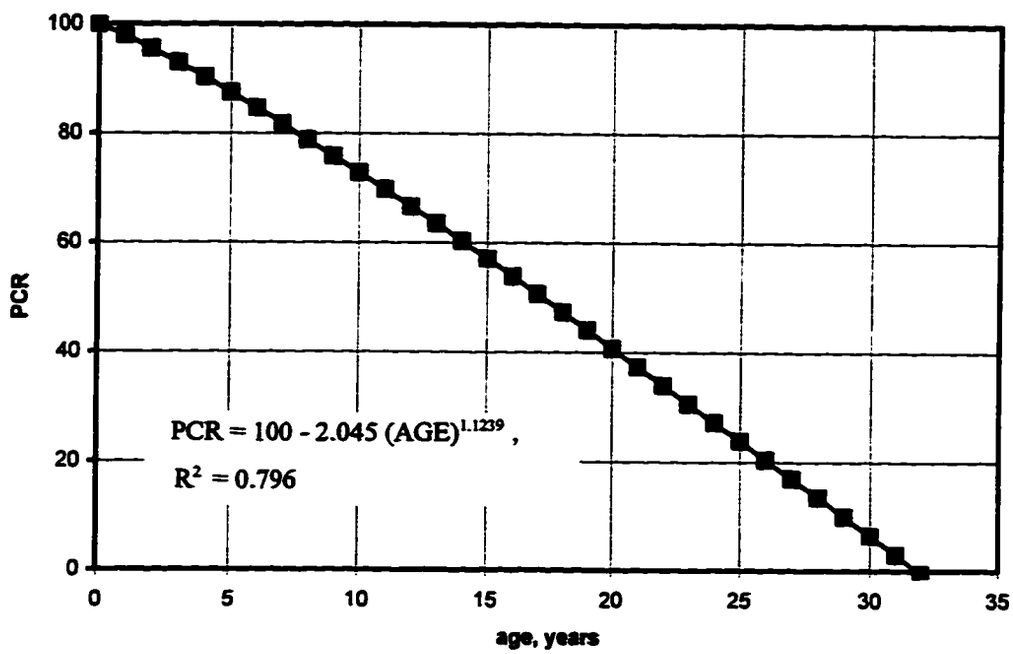


Figure 5.18. PCR selected model using average values of independent vairables.

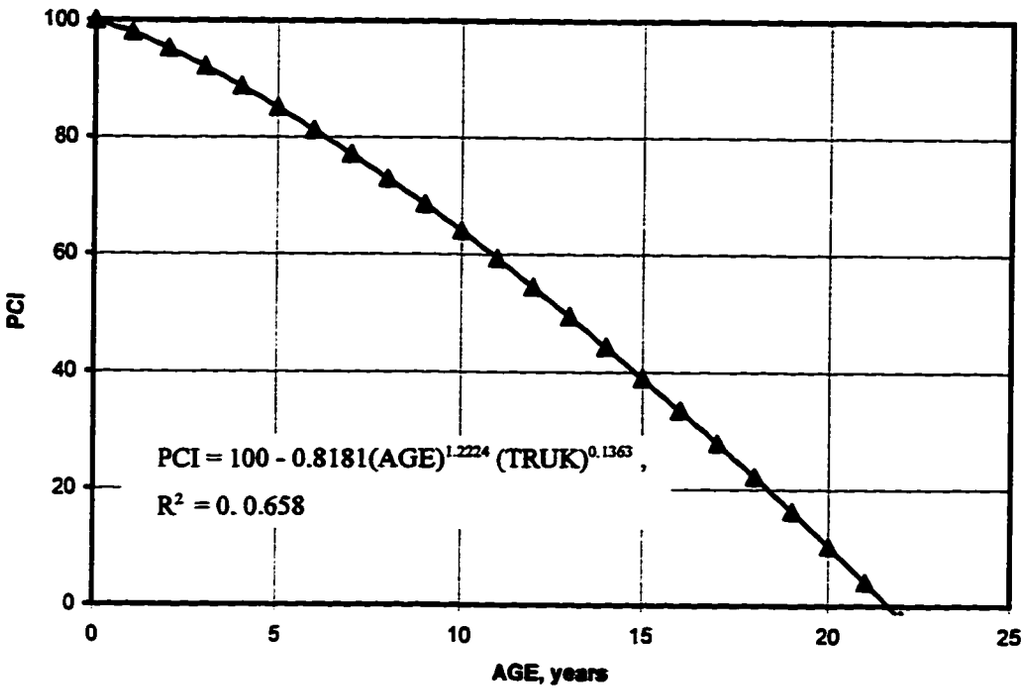


Figure 5.19. PCI selected model using average values of independent vairables.

selected models can reasonably represent the pavement condition performance, based on the logical assumptions and a priori hypothesis set before.

5.5.1.2 Prediction Power

The fitting characteristics of the developed models of the three data sets are shown in Figures 5.20 to 5.22 where the observed values were plotted against the model predicted values. Ideally the perfect fitting model should have all points on the 45° line. From these figures, it can be seen that the selected models exhibited different fitting powers, correlation, and standard errors with different data sets. The PDR models shows the best fitting characteristics, followed by the PCR model and finally the PCI model. However, according to the type of the collected data and the incurred variations of sources and methods, these prediction powers are reasonable.

5.5.2 Statistical Testing

There are several assumptions in regression analysis that need to be taken care of while running this analysis. These assumptions are normality, linearity, homoscedasticity, mutlicollinearity and singularity [Tabachnick and Fidell 1983]. These assumptions are checked for the selected prediction regression models as in the following.

Examination of the residuals (difference between actual and predicted values) scatter plots provides a test of the assumptions of normality, linearity, and homoscedasticity between predicted pavement condition as dependent variable (DV) and

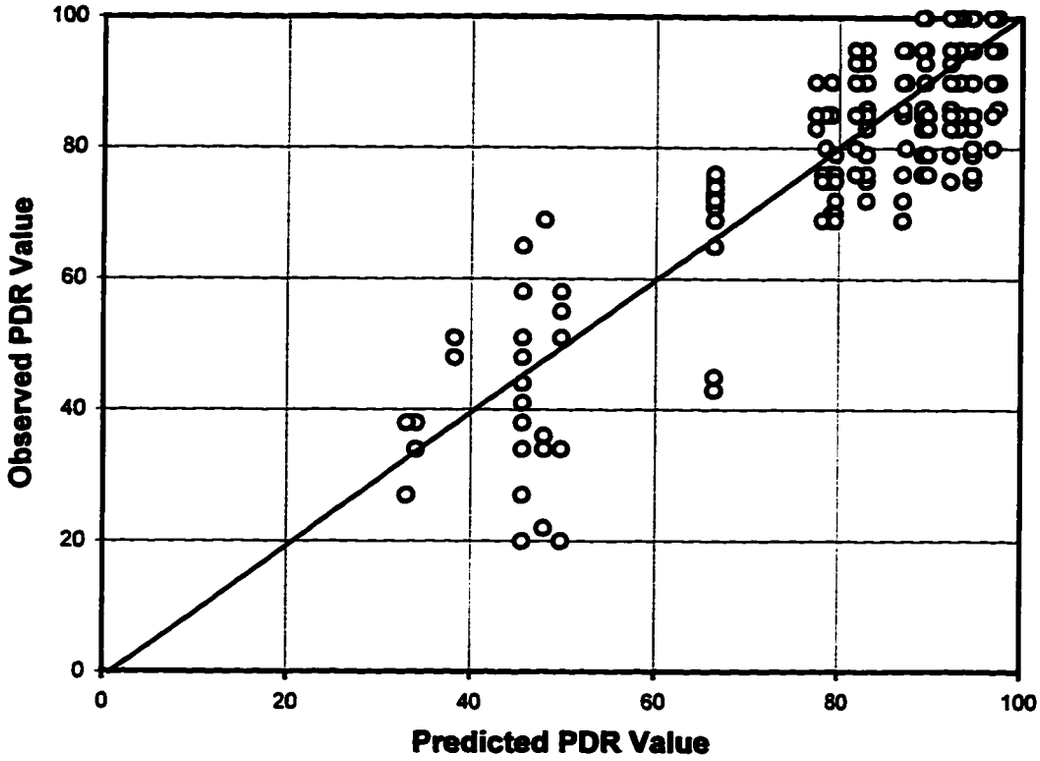


Figure 5.20. Goodness of fit of the PDR selected model.

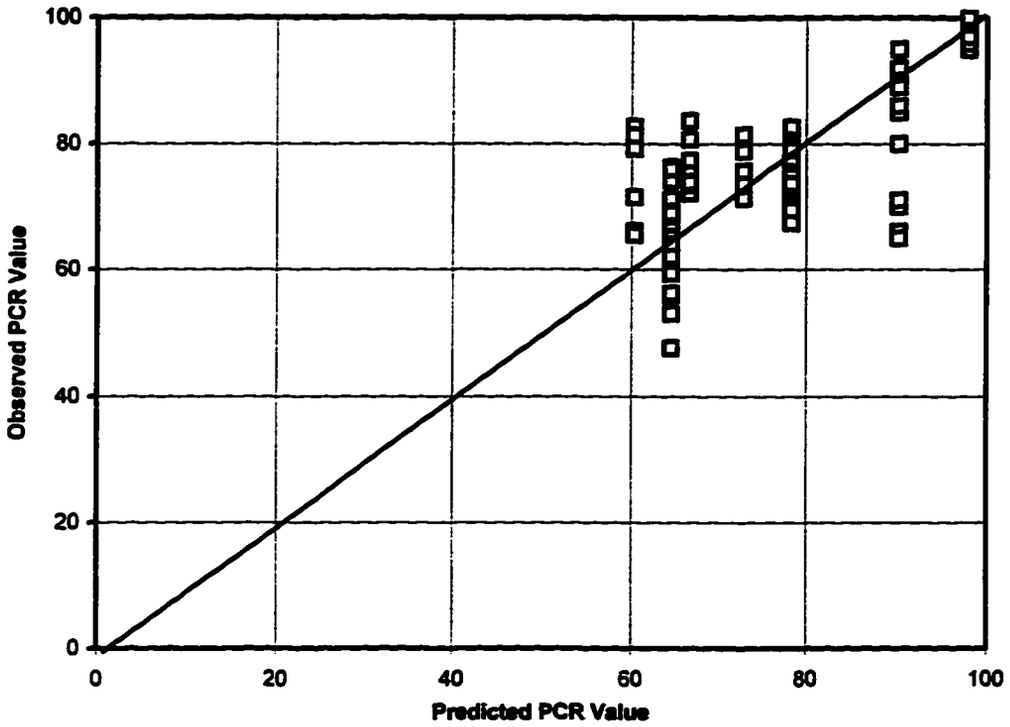


Figure 5.21. Goodness of fit of the PCR selected model.

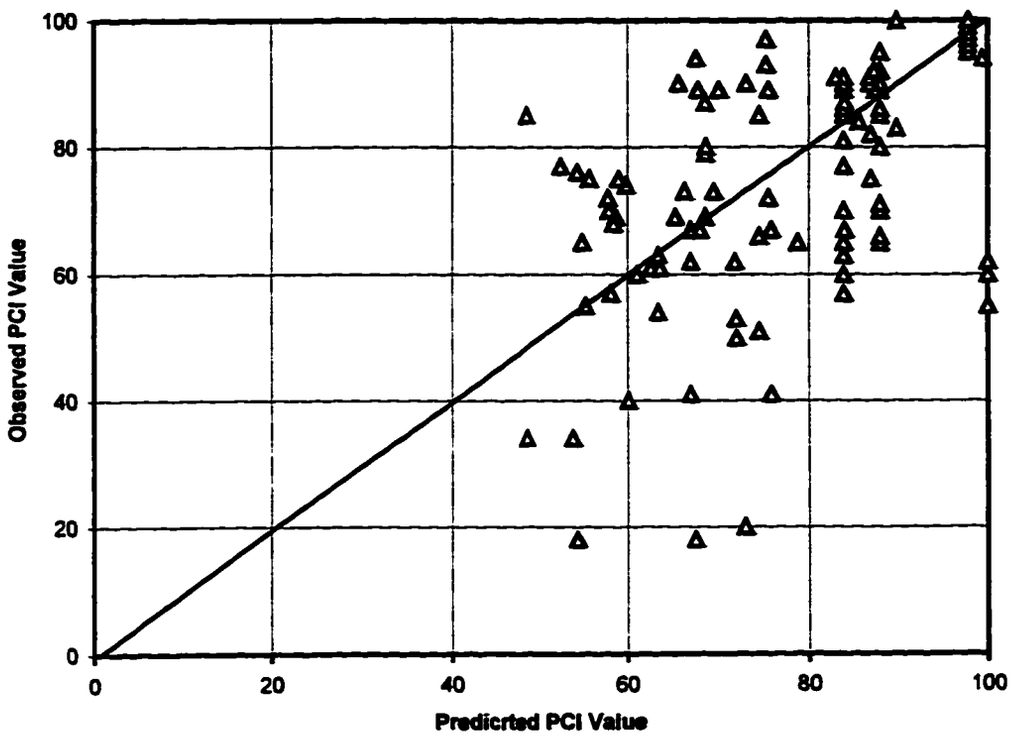


Figure 5.22. Goodness of fit of the PCI selected model.

error of prediction [Tabachnick and Fidell 1983]. These assumptions and their failures are all shown in Figure 5.23.

Normality need to be checked to ensure that the errors (residuals) are normally distributed. Two plots can be examined: the histogram of the residuals or the normal probability plot. Figures 5.24 to 5.26 show these two plots for PDR, PCR, and PCI, respectively. From visual inspection of these plots, it appears that the histogram curve (frequency distribution) has a bell-shaped normal distribution, and the line of normal probability is, to a good extent, linear. Therefore, the normality assumption of the error for the prediction model is met.

The homoscedasticity assumption implies that the standard deviations of errors of prediction are approximately equal at all predicted dependent variable levels, or the variability in scores in all independent variables are roughly the same. This can be captured by plotting the predicted dependent variable versus the residuals, where the points should be scattered equally around the zero-line. Figure 5.27 to 5.29 show scatter plots three selected models, where it is clear that this assumption is also met.

The linearity assumption implies that there is a linear relationship between the predicted dependent variable and the errors of prediction. If non-linearity is present, the overall shape of the scatter plot will be curved instead of rectangular as shown in Figure 5.23. However, for the selected prediction model, it can be seen from Figures 5.27 to 5.29 that the overall scatter plots are almost rectangular, which means that the linearity assumption is also met.

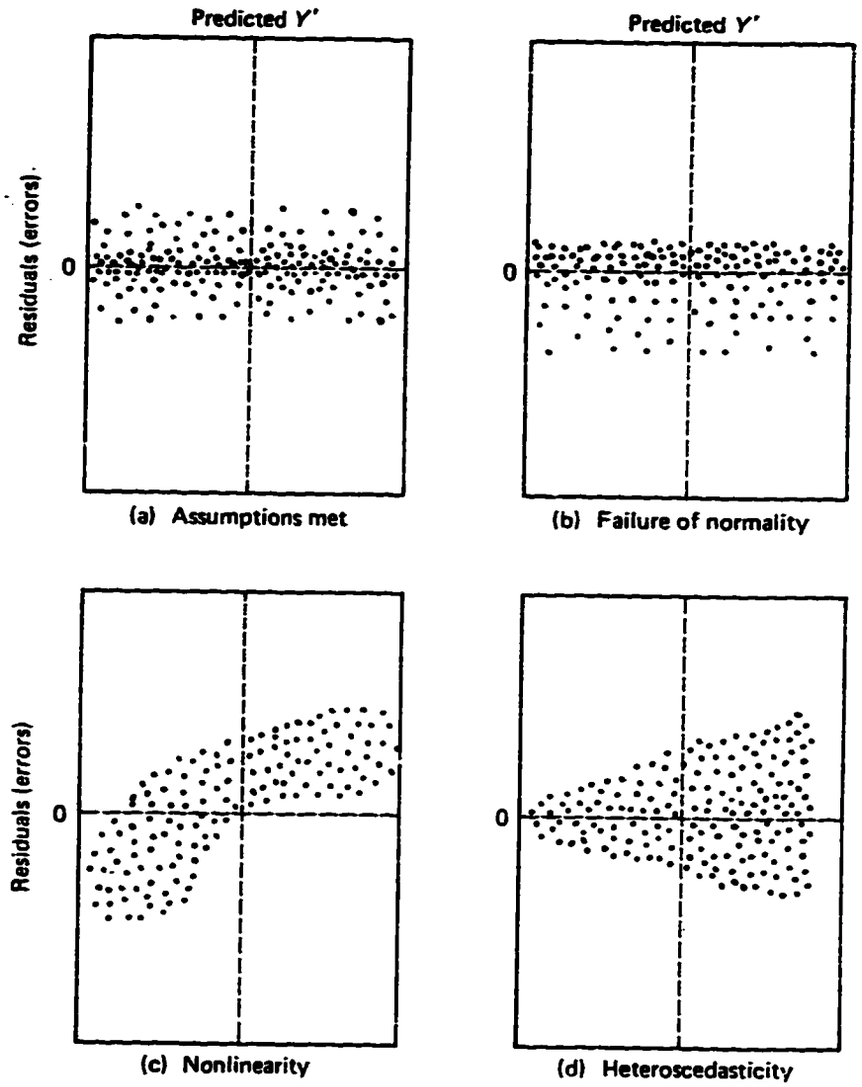
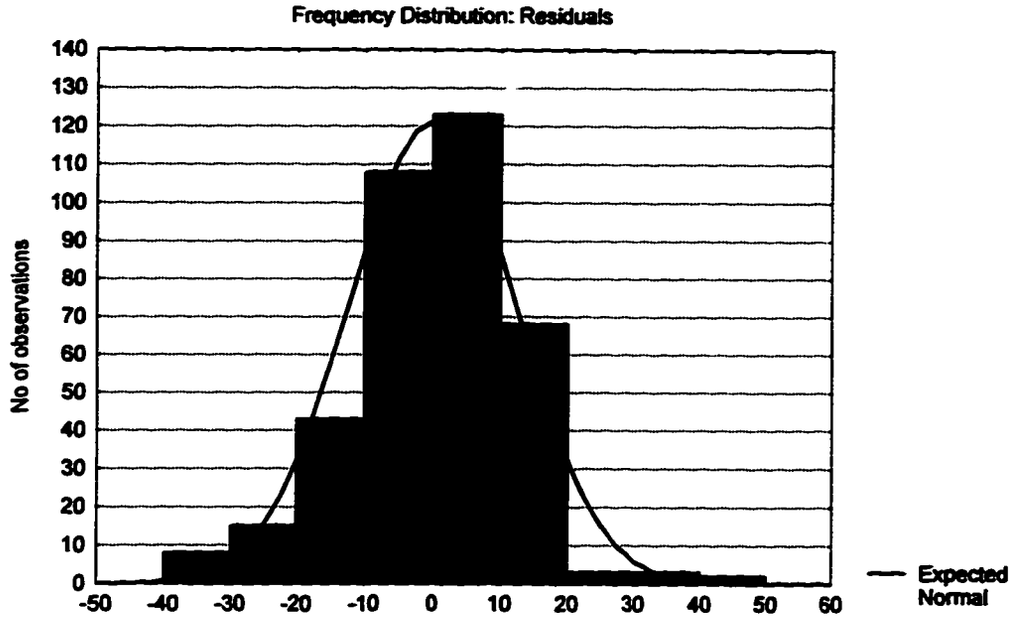


Figure 5.23. Scatter plots for the predicted values against residuals for normality assumptions [Tabachnick and Fidell 1983].



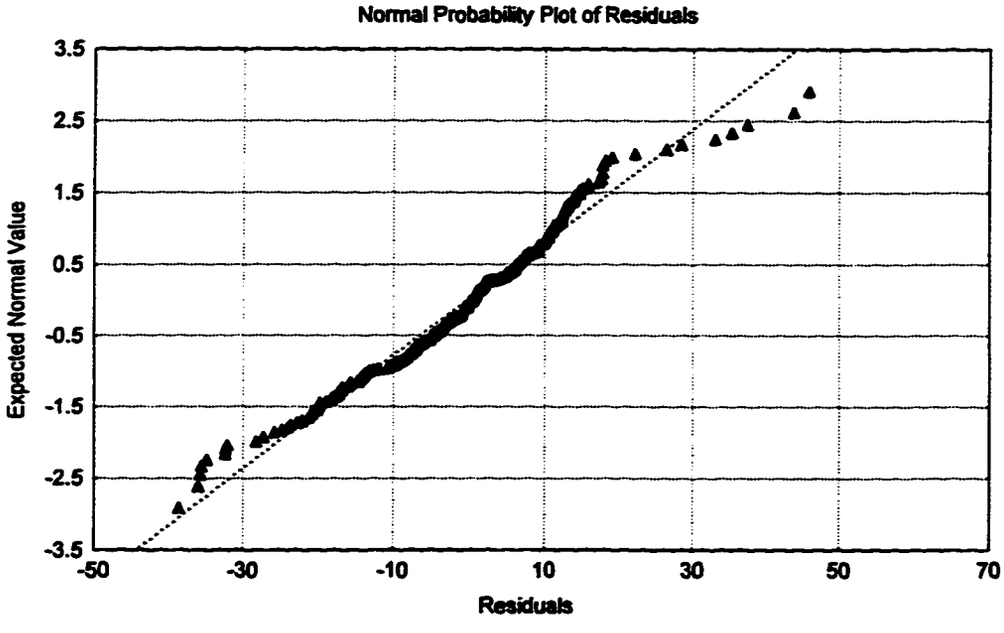
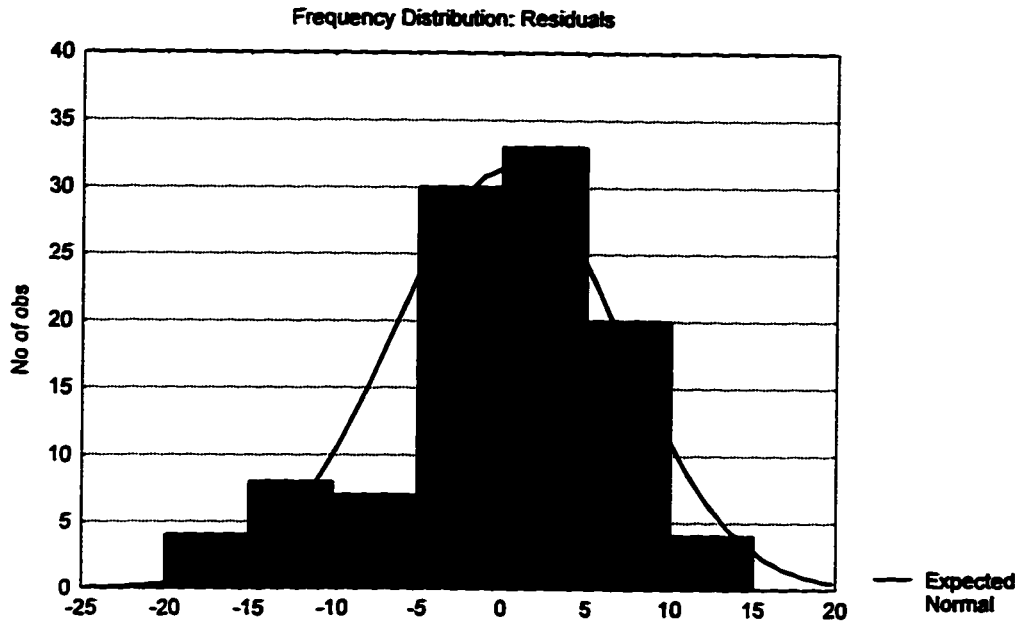


Figure 5.24. Frequency distribution and normal probability plot for PDR model.



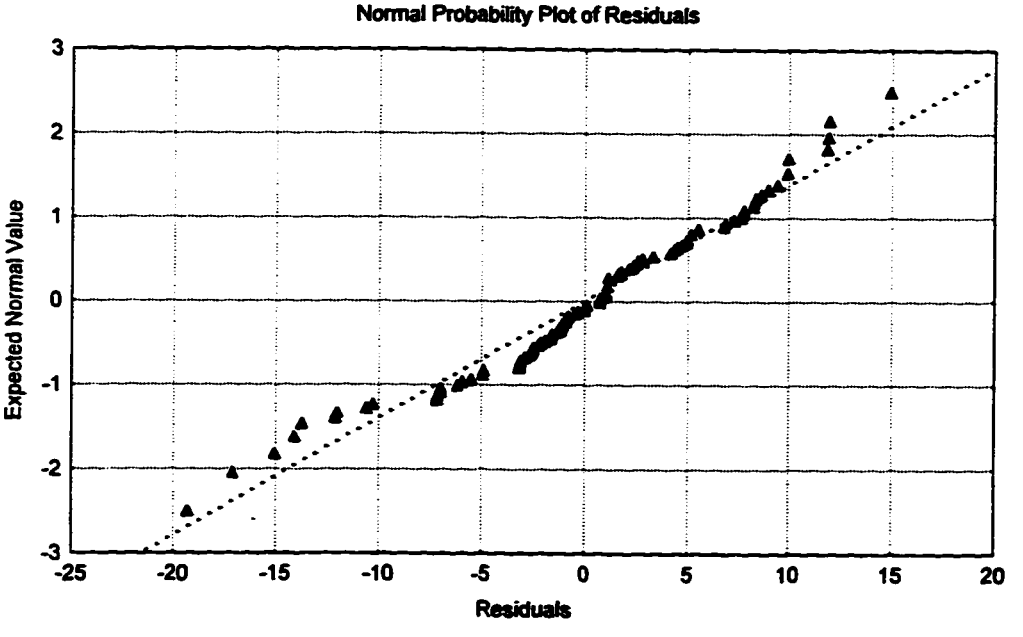
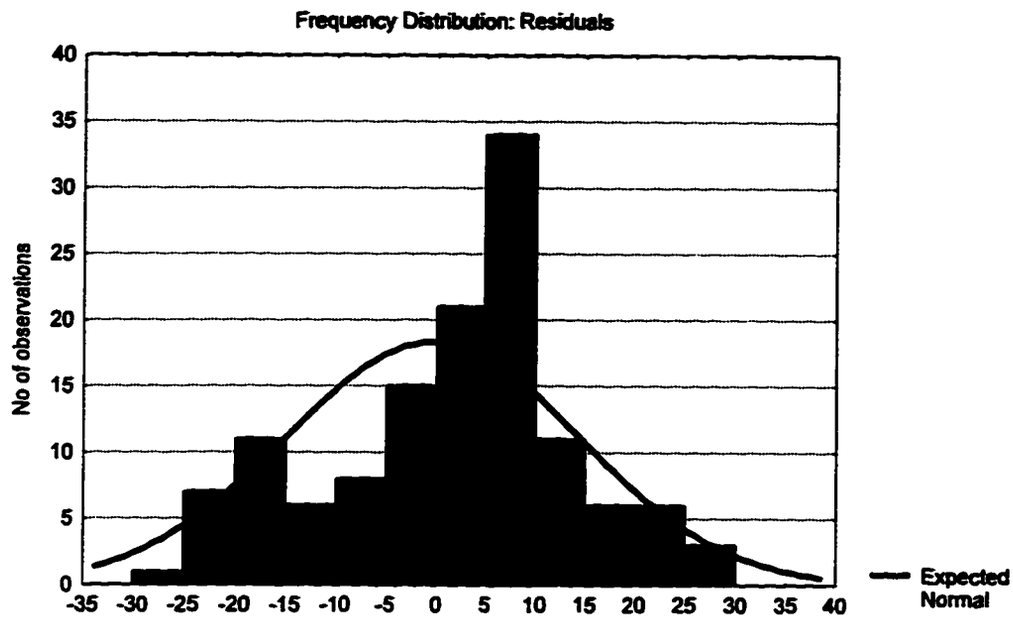


Figure 5.25. Frequency distribution and normal probability plot for PCR model.



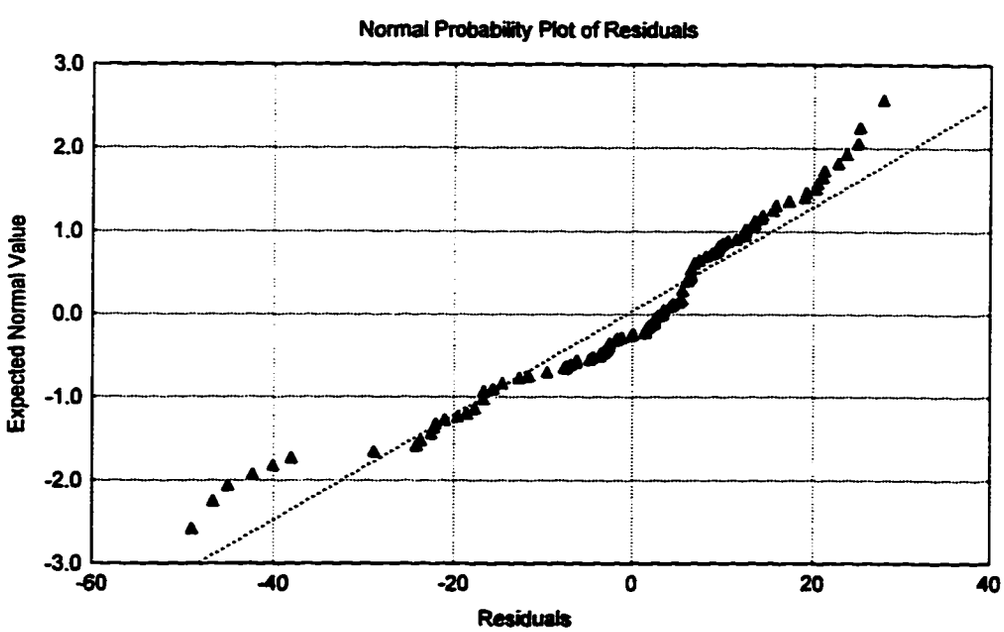


Figure 5.26. Frequency distribution and normal probability plot for PCI model.

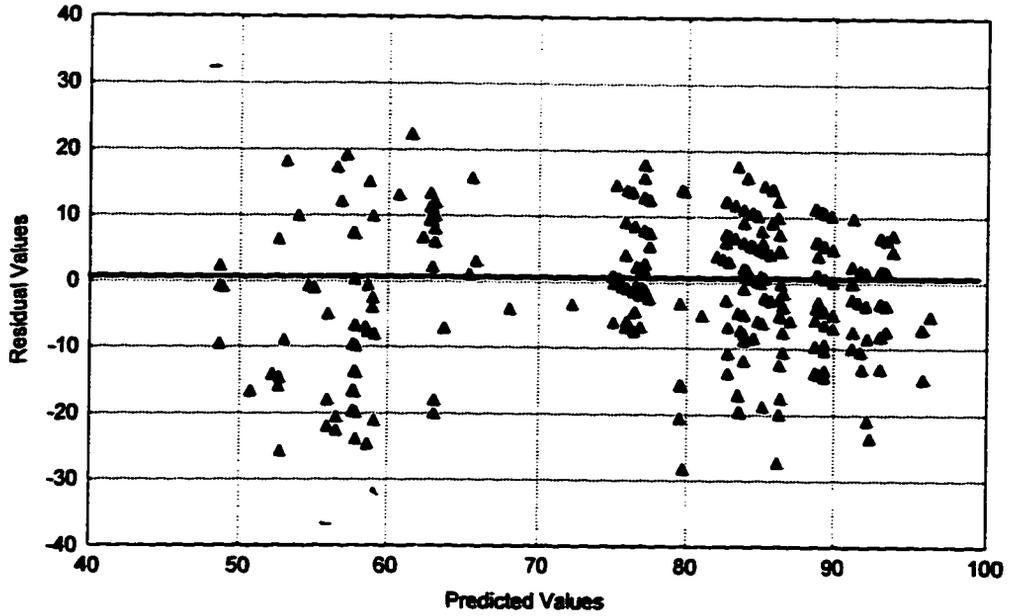


Figure 5.27. Predicted versus residuals scatter plot for PDR model.

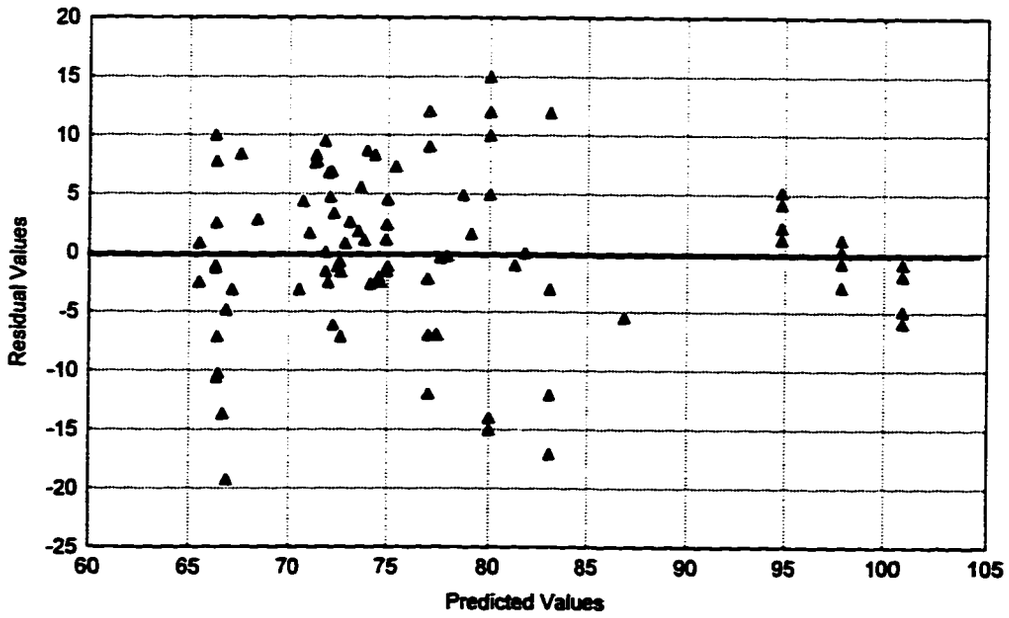


Figure 5.28. Predicted versus residuals scatter plot for PCR model.

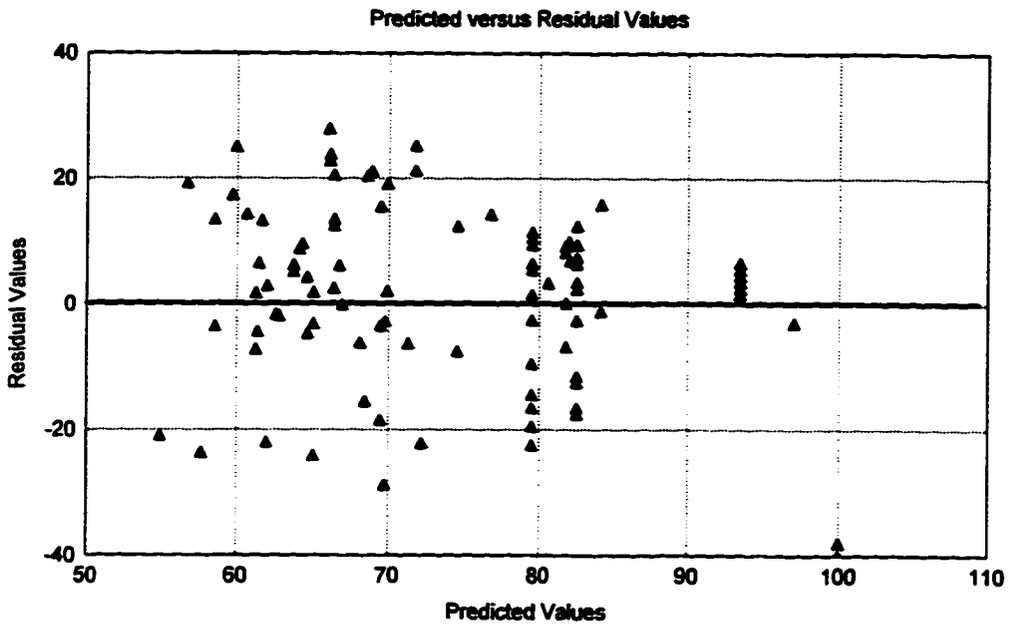


Figure 5.29. Predicted versus residuals scatter plot for PCI model.

5.6 MODEL VALIDATION

As stated earlier, part of the collected data were used for model development while the other part were reserved for model validation. A set of 159 data points from PDR data, 55 data points from PCI data, and 35 data points from PCR data were used to validate the developed models.

The procedure followed for model validation testing was done by fitting the reserved data points (validation data) of each data set for the selected prediction model of the set, and determine the R^2 of these fittings. The R^2 values were compared with original model goodness of fit. Figures 5.30 to 5.32 show the validation data goodness of fit plots using the selected models of PDR, PCR and rural pavement, PCI, and urban pavement. Table 5.11 summarizes the results of this validation process. It can be seen that the selected models fitted the validation data with similar goodness of fit values to these of the original ones. For example, PCR model had R^2 of 0.851 compared to 0.752. The collected data for all sources had data of high condition index (more than 60) compared with the low condition values. Therefore, the developed prediction models showed good agreements between the observed (modeling data or validation data), and the predicted ones, at the high condition index points.

From this model validation process, it can be stated that the developed models could adequately predict the pavement condition with reasonable fitting power. The PDR data developed model was the best from model calibration as well as model

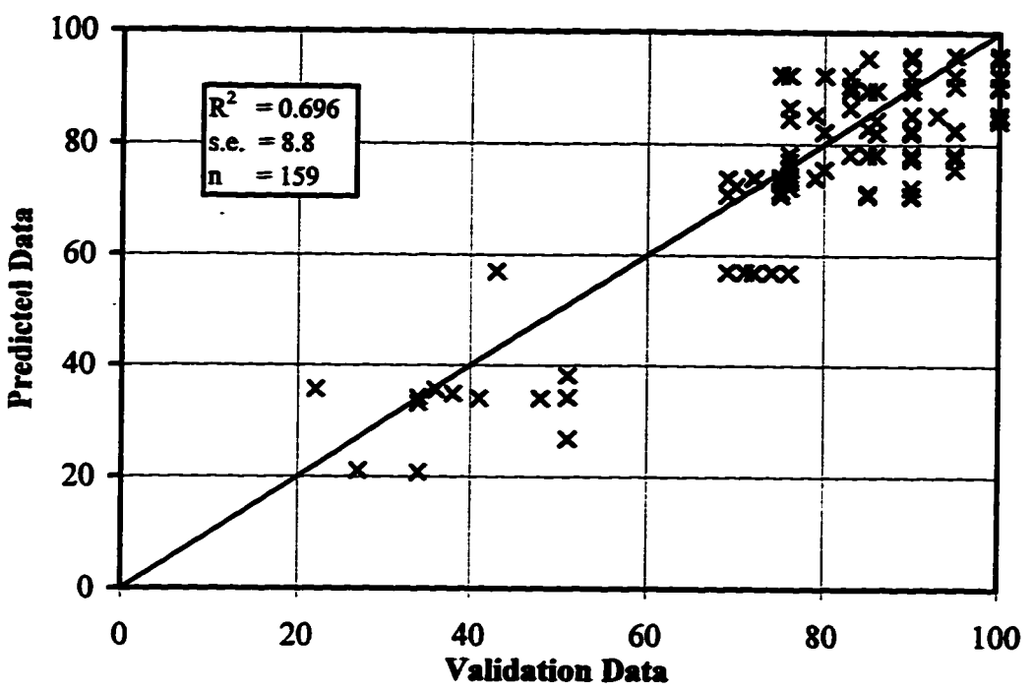


Figure 5.30. PDR model validation.

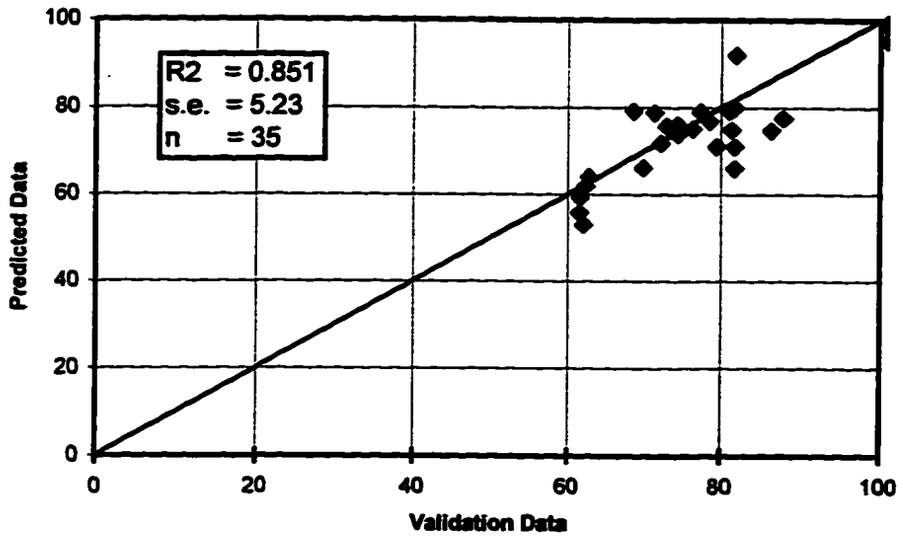


Figure 5.31. PCR and rural pavement model validation.

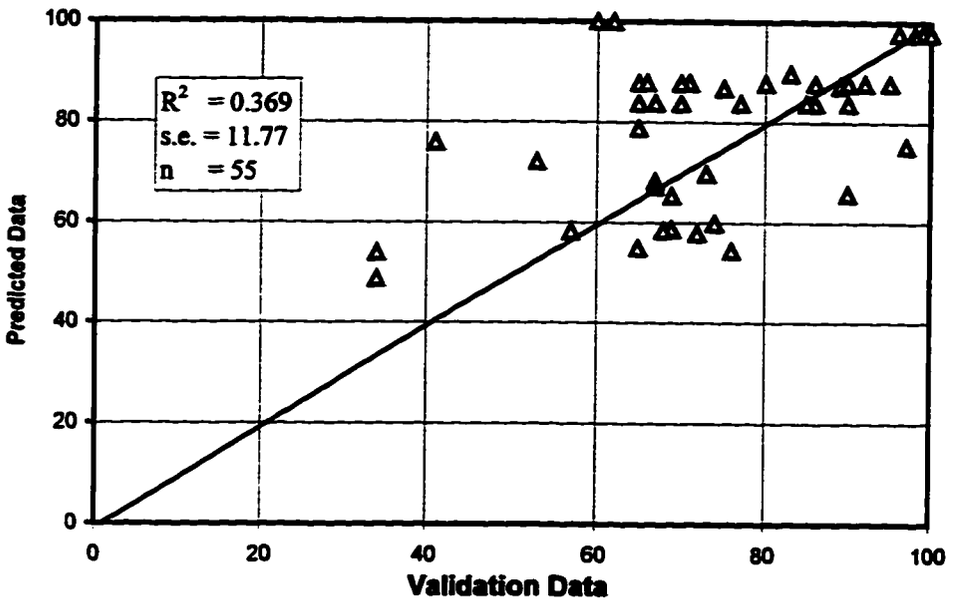


Figure 5.32. PCI model validation.

Table 5.11. Summary of the model validation process.

Data Set	Modeling			Validation		
	Adjusted R^2	Standard Error (s.e.)	Number of cases, n	Adjusted R^2	Standard Error (s.e.)	Number of cases, n
PDR data	0.775	8.89	275	0.696	8.80	159
PCI data	0.685	11.26	135	0.369	11.77	55
PCR Data	0.796	6.49	106	0.851	5.23	35

validation point of views. This confirms the previous observation that the data consistency and accuracy is utmost importance in pavement condition modeling. These models can be refined and modified when more consistent and accurate data of pavement condition and related information are available. Therefore, these models need to be used according to the data collection method.

5.7 MODELS FOR COMBINED DATA

In this section, the PCI and PDR data were pooled together to check the possibility of generating new prediction models to describe the pavement condition. This may be needed when the collected condition data is a mix of different survey methods.

A total of 635 data of PDR (433 points) and PCI (202 points) were pooled together, then a regression analysis was performed using the same engineering assumptions used before. Two feasible models could be obtained that have high significant levels for both the coefficients and the model as a whole. These models are detailed in Figures 5. 33 and 5.34. The polynomial model has a higher R^2 (0.493) than the power one (0.286), but both showed the expected general trend. The pavement condition behavior with time according to these models is shown in Figure 5.35. The power model makes the pavement fails (condition index = 0) at about 28 years while the polynomial model take the pavement till only 18 years. Both of these value are reasonable in urban pavements considering different pavement designs and traffic levels. However, both models can not explain the exact pavement condition with a high goodness of fit measured by R^2. A

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.705
R Square	0.497
Adjusted R Square	0.493
Standard Error	11.73
Observations	635

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	85640.0	17128.0	124.5	0.000
Residual	629	86566.6	137.6		
Total	634	172206.6			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	102.021	3.257	31.324	0.0000	95.626	108.417
AGE	-8.789	2.290	-3.839	0.0001	-13.285	-4.293
AGE^2	1.898	0.509	3.726	0.0002	0.898	2.899
AGE^3	-0.185	0.041	-4.484	0.0000	-0.266	-0.104
AGE^4	0.005	0.001	4.980	0.0000	0.003	0.008
TRUK	-0.002	0.001	-2.547	0.0111	-0.004	-0.001

Figure 5.33. Polynomial model for the pooled PCI and PDR data.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.536
R Square	0.287
Adjusted R Square	0.286
Standard Error	0.64
Observations	635

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	105.8	105.8	255.0	0.000
Residual	633	262.7	0.4		
Total	634	368.5			

	Coefficients	*P-value*	*Standard Error*	*t Stat*	*Upper 95.0%*	*Lower 95%*
Intercept	0.117	0.045	0.058	2.0102	0.231	0.003
log (AGE)	1.298	0.000	0.081	15.9686	1.458	1.138

Figure 5.34. Power model for the pooled PCI and PDR data.

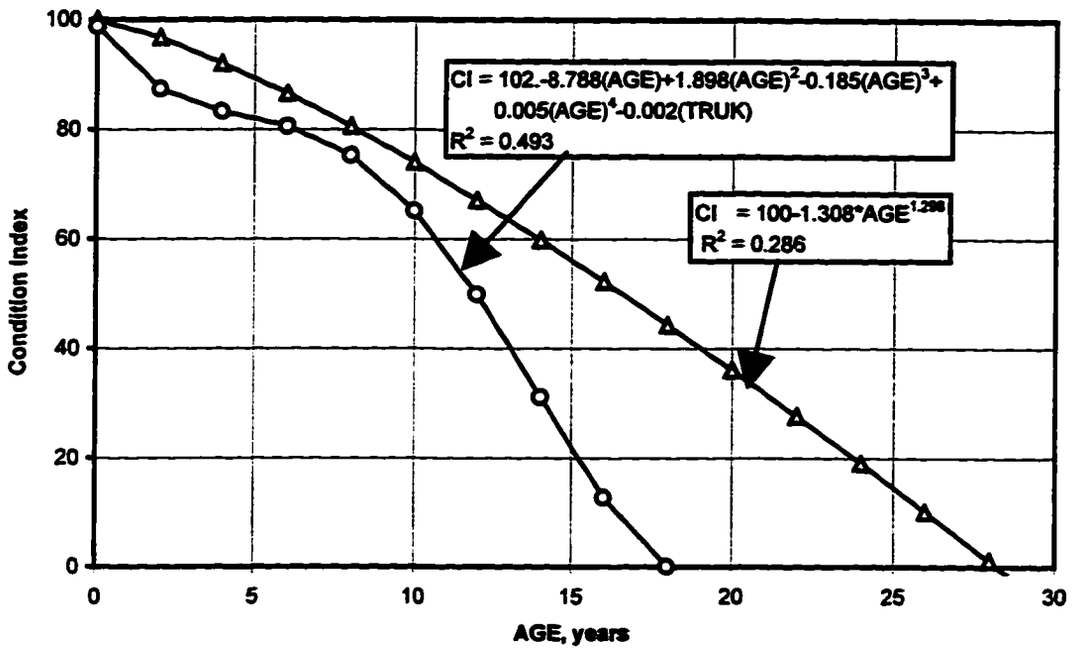


Figure 5.35. Plot of the pooled data models.

maximum of about 50% of the variations in the collected data can be explained by the polynomial model.

Therefore, from the above analysis, it can be concluded that modeling the pooled data is not necessary since it did not give a satisfactory results.

5.8 APPLICATION

5.8.1 Different Models

The PDR and PCI prediction model for pavement condition can both be used to represent the urban pavement since these models were generated from pavements inside cities such as Al-Khobar, Dammam, Riyadh, and Dhahran. While the PCR pavement prediction model can only be used for rural pavements between cities since the data collected from this type of road pavement.

As end results of this pavement condition modeling, several models for different pavement parameters combinations can be obtained. In urban road pavements, several combinations of asphalts layer thickness and truck percentages can be found, such as, 5, 10, and 15 cm levels of ACTH, and 100, 500, and 1000 levels of TRUK are usually found. Using these levels, nine different pavement prediction curves can be generated as the ones shown in Figure 5.36 for PDR prediction model. One assumption is made in this figure that the truck levels have an annual increment rate of 5%. From these curves, it can be seen that the ACTH factor has insignificant impact at earlier ages of pavement,

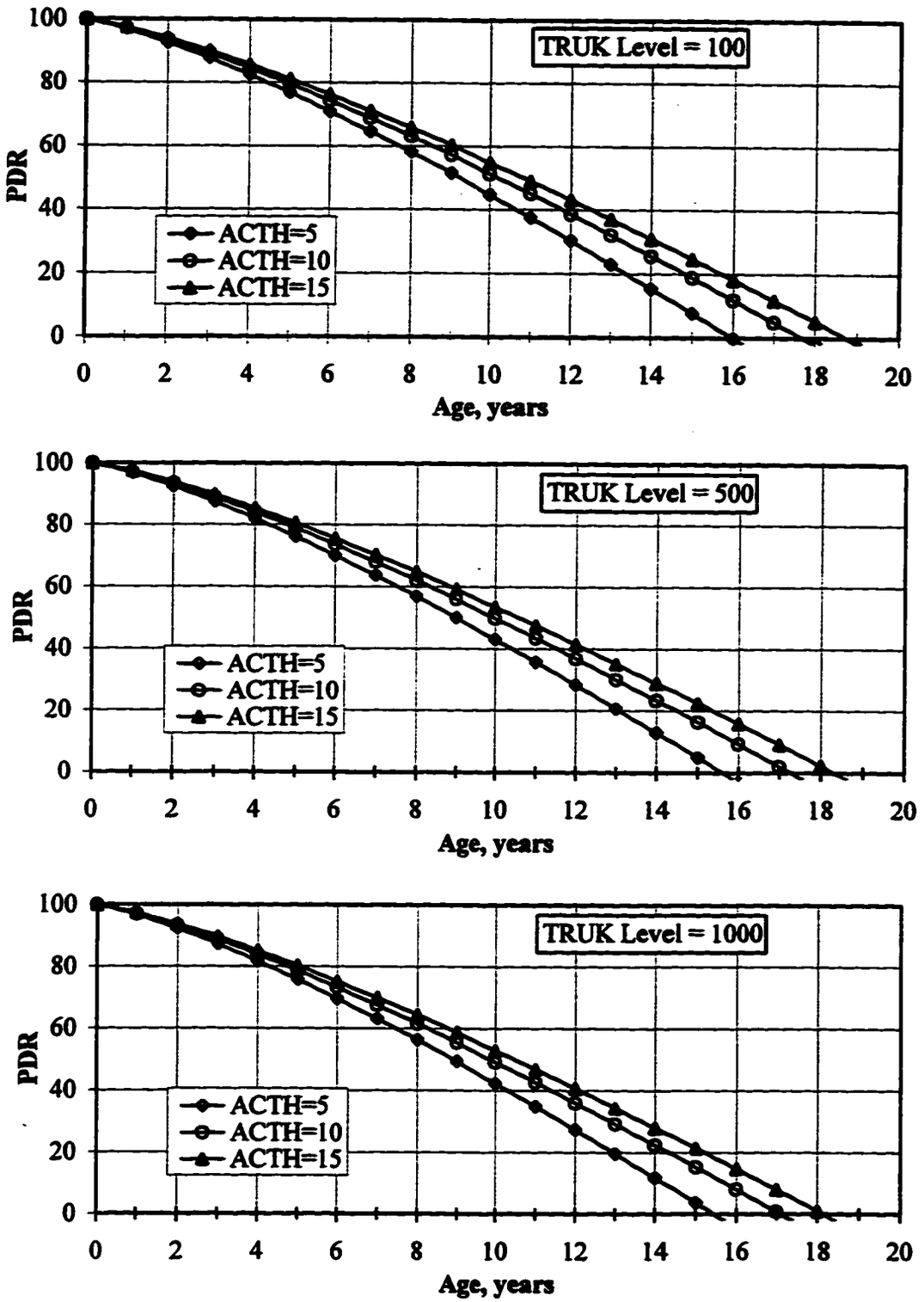


Figure 5.36. PDR model sensitivity analysis at different thickness and truck levels.

and some impact at later stages. This impact is similar for all TRUK levels. Similarly, the impact of TRUK level on the pavement condition is minimal as shown by the pavement life measured by the failure stage (PDR=0). Moreover, the TRUK impact from level 100 to 500 is higher than that of 500 to 1000, at all ACTH levels.

Figure 5.37 shows the pavement condition curves using PCI selected model. This is for a typical section of 10 cm thick and three levels of TRUK factor: 500, 1000, and 1500 with an annual increment rate of 5%. Similar to the PDR model, TRUK level has a slight significance to PCI value.

5.8.2 Maintenance Plans and Policies

Another application and use of the developed model is for maintenance planning and setting maintenance policies. Pavement condition prediction curves are usually used to forecast the pavement condition over time, so that maintenance activities as well as funds allocation can be scheduled a head of time. Using the principle of critical pavement condition index that is a triggered condition value at which the pavement should receive some correction measure, otherwise, its maintenance cost will be much higher if it was left for further deterioration. Therefore, a selection of the best maintenance policy is one of the advantages of the pavement condition prediction model.

Preventive pavement maintenance is the one that is carried out to minimize the damage to the pavement under normal service, which need to be implemented immediately to prevent further deterioration and to preserve the pavement components.

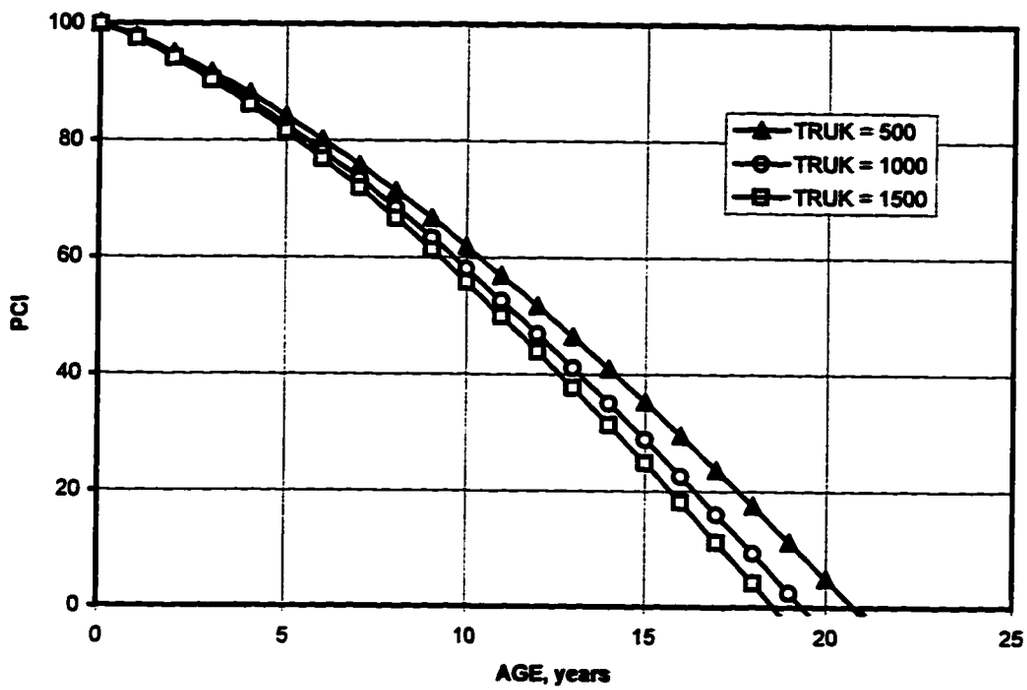


Figure 5.37. PCI model sensetivity analysis at different trcuk levels.

This maintenance type include surface treatments such as crack sealing and slurry sealing. The corrective maintenance, on the other hand, is the work performed to restore the pavement to its prescribed level of service after the damage has occurred. Examples of this type include overlays and reconstruction.

Two typical examples of preventive and corrective maintenance activities in relation to pavement condition are shown in Figures 5.38 and 5.39. The PDR developed model was used in these two figures. In the first figure, a preventive maintenance (slurry seal for example) is applied four time, one every 3.75 years, through the pavement section service life. The service life, where the PDR value equals to zero, is predicted to be 17 years. Therefore, four application of this type of maintenance are required to keep the pavement section above a PDR assumed acceptable level of 85. However, if this pavement section does not receive any maintenance during its service life, it will fail at an age of 17 years, and needs a reconstruction that costs much higher than the application preventive maintenance.

In Figure 5.39, another policy is selected, where a corrective maintenance action of an overly is applied when the pavement condition drops to a level of 60. Here, two applications are needed through the pavement section service life. Again, the cost of these two overlays will be less compared with the cost of reconstruction alternative at an age of 17 years.

A cost analysis can be done to compare the three maintenance policies: (i) application of four preventive maintenance actions, (ii) application of two corrective

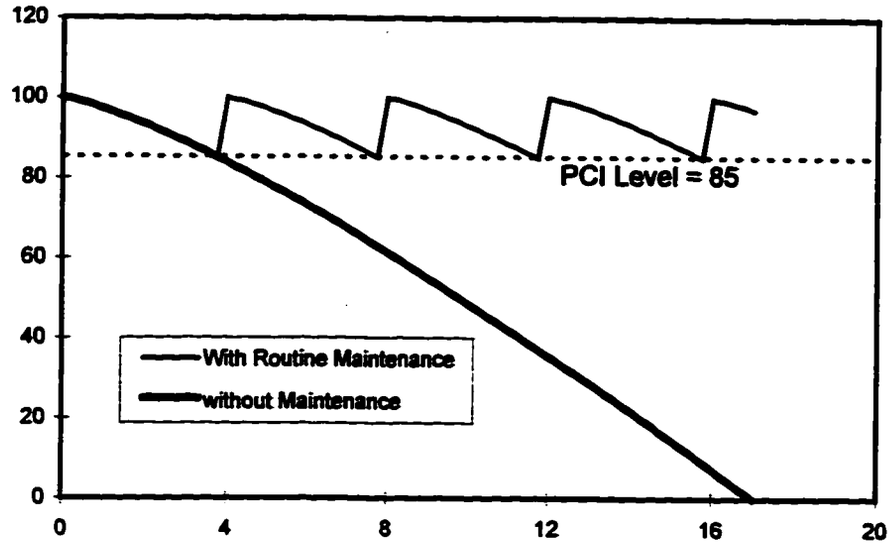


Figure 5.38. Pavement performance with preventive maintenance.

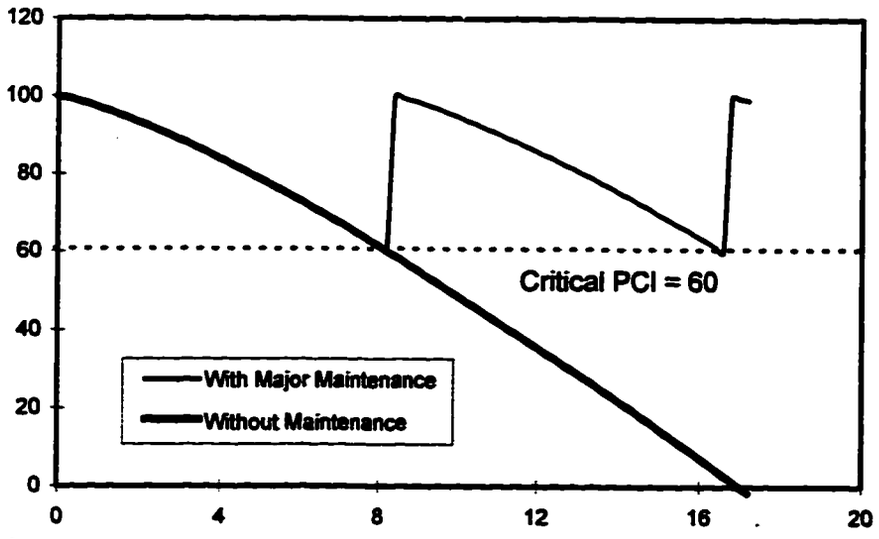


Figure 5.39. Pavement performance with corrective maintenance.

actions, and (iii) reconstruction. Depending on the cost of each alternative, pavement authorities can select the most cost-effective one.

A typical pavement section of 500 meters long and 10 meters wide is considered with the following assumptions:

1. The unit cost of slurry seal is. 3.0 SR/m^2,
2. The unit cost of 5 cm. Overlay is 15 SR/m^2,
3. Inflation or discount rate is 5 percent every year,
4. Reconstruction of new pavement is 80 SR/m^2, and
5. Other non-monetary parameters in both benefits and user costs are ignored.

Table 5.12 shows the calculation of cost analysis of this typical pavement section using the above assumptions. In this table, the present worth method was used, where the spending in the future is discounted to present values using the discount rate. From this table it is very clear that the application of preventive maintenance over the span of pavement service life will help not only keeping the pavement in a good acceptable level of service but it will reduce the overall maintenance cost to about one-half (0.54) compared with the corrective maintenance (i.e. 83,964 to 45,237), and to about one-fourth (0.259) compared with the reconstruction (i.e. 174,519 to 45,237). This is without considering the user cost, operation cost, etc.

Table 5.12. Cost analysis for three pavement maintenance policies.

Maintenance Alternativ	Maintenance Cost (SR)								
	No. 1		No. 2		No. 3		No. 4		Total
	Amount	Age	Amount	Age	Amount	Age	Amount	Age	
Preventive Maintenance	14,574	3.75	12,137	7.5	10,108	11.25	8,418	15	45,237
Corrective Maintenance	50,270	8.2	-	-	33,694	16.4	-	-	83,964
Reconstruction	-	-	-	-	-	-	174,519	17	174,519

This example can be used as a confirmation to the general conclusion, mentioned in Chapter One, that the maintenance cost of the pavement while in poor condition is four to five times the cost if the pavement is maintained while in good condition.

5.9 SUMMARY

This chapter dealt with the pavement condition prediction modeling. The collected data were subjected to different schemes of statistical and logical testing. Prediction models were generated for the data collected using the three survey methods: PDR, PCR, and PCI. Separate models were obtained for each data set. Pavement condition and related data from urban road pavements collected by PDR and PCI methods from Jubail, Dhahran, Dammam, Khobar, and Riyadh cities were represented by the urban prediction model. On the other hand, pavement condition and related data collected from pavement of highways between major cities such as Dammam, Riyadh, and Qasim were represented by the rural prediction model which was the PCR selected model. These models were validated using the reserved data. The obtained models were adequately predicting the pavement condition with reasonable fitting power. Combining the data from different data collection method was tried to generate general models, but it did not show a good statistical results. Some applications of the pavement prediction modeling were also presented.

CHAPTER SIX

MODELING AUTOMATION AND INTEGRATION

6.1 GENERAL

All the developed models obtained in the previous two chapters will not of any use if they were not formulated in an integrated system where they can be utilized by any pavement authority. This requires a development of a computer software to compile all these model in one package. This software should be characterized as menu-driven, error checking, design around the idea of limited programming knowledge, and friendly used application.

The developed sub-system should be capable for data entry, retrieval, and updating. It should also be able to deal with different possibilities of the data format. For example, in the maintenance priority data entry, there are two possibilities: (i) the roughness and skid resistance measurements representing the riding quality and safety condition, respectively, are available, and (ii) these measurements are not available. In such cases, the sub-system should prompt against each possibility and respond by the corresponding menu.

6.2 PREPARATION OF SYSTEM MENUS

To achieve this goal, different programming languages and methods can be used. However, for simplicity for both operator and end users, spread sheets meeting the above requirements was selected to make the necessary automation of the developed models of this study. EXCEL Package was utilized to prepare the required menus for this model automation task. Figure 6.1 shows the structure of the menu preparation.

Several menus were formatted to facilitate the data entry and results reporting. Figures 6.2 shows the main menu with four major activities: data entry, report generation, system parameters, and exiting the program. Figure 6.3 shows the system parameters menu that is used as reference in the built-in calculations.

The data entry consists of entering the required information about each section in the network. These information are used for calculating the priority index of each section and the pavement condition profile over time. This calculation is done internally and the results are automatically shown on the screen.

To show the capability of this system, Figure 6.4 and 6.5 show the data entry menu for one typical section for priority ranking and condition prediction, respectively. Using these entered data, the reporting module generates, upon request, two section-wise reports shown in Figure 6.6 and 6.7. These reports are based on the calculation of priority index described in Chapter Four where different options were considered, and based on the models developed in Chapter Five.

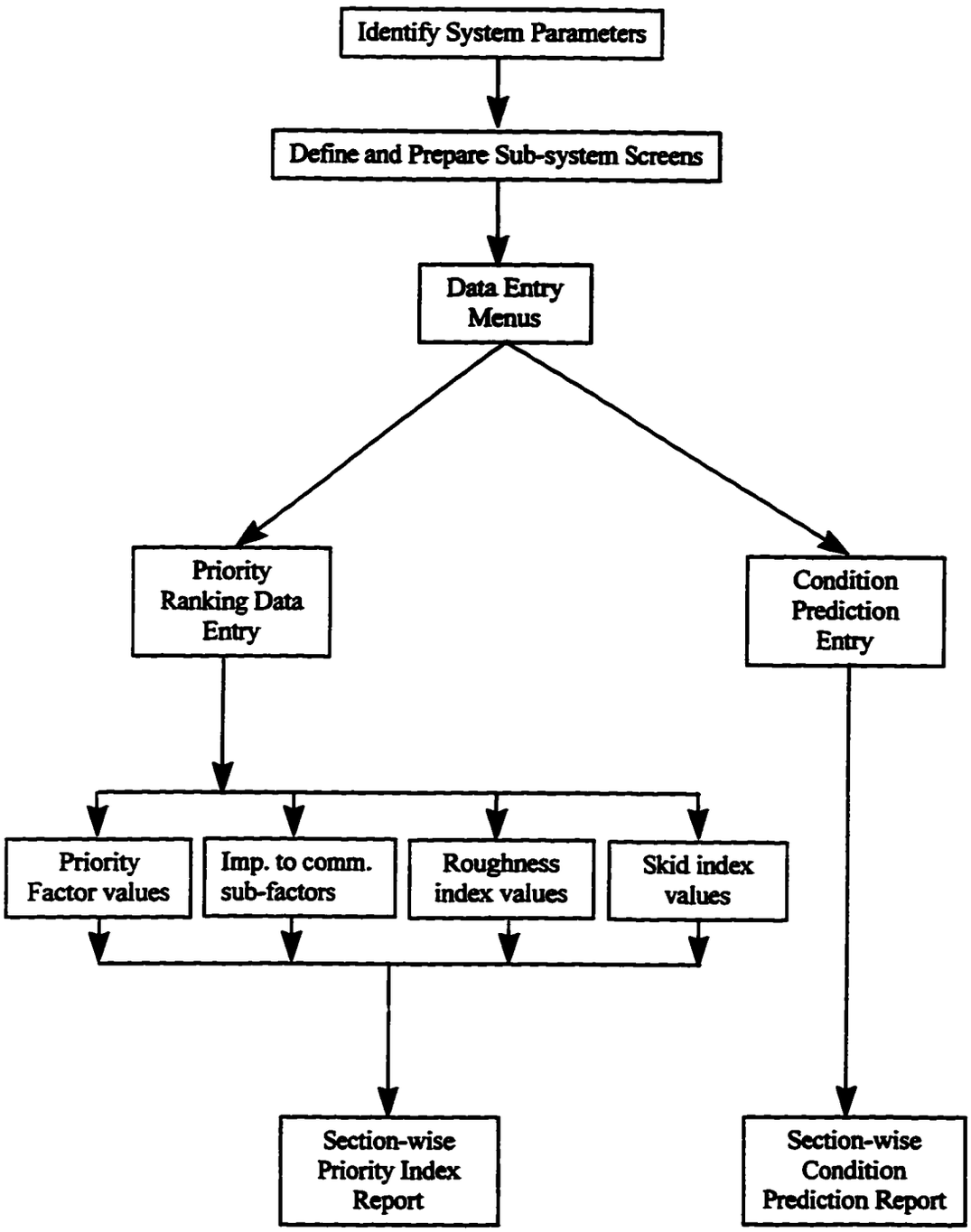


Figure 6.1. Preparation and definition of system menus.

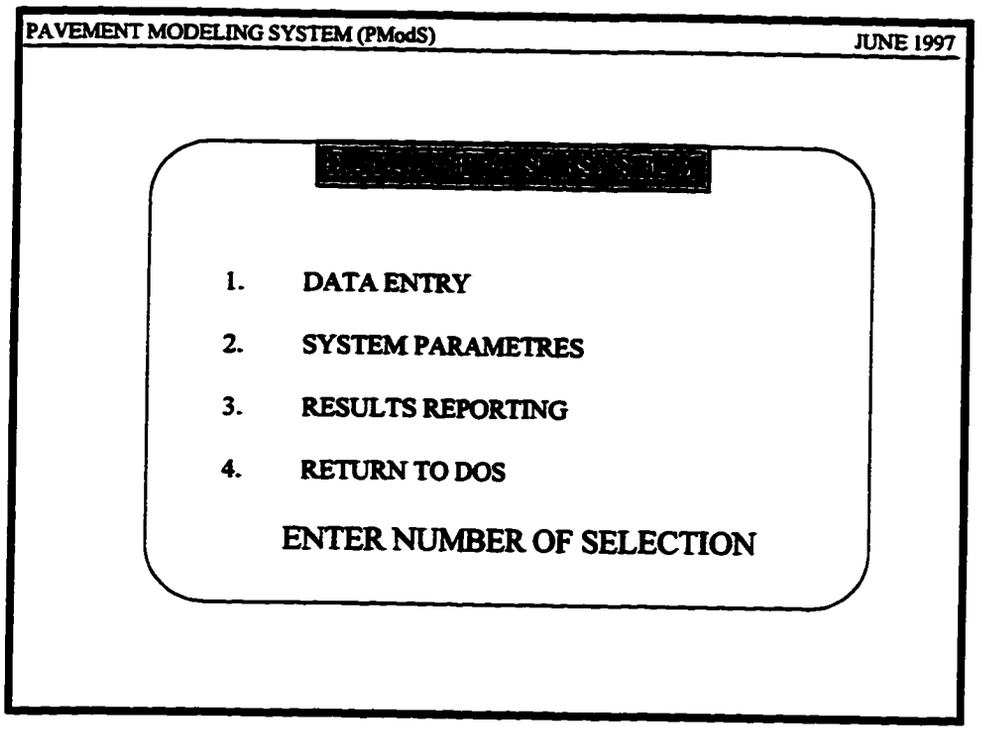


Figure 6.2. Main menu of the pavement modeling software.

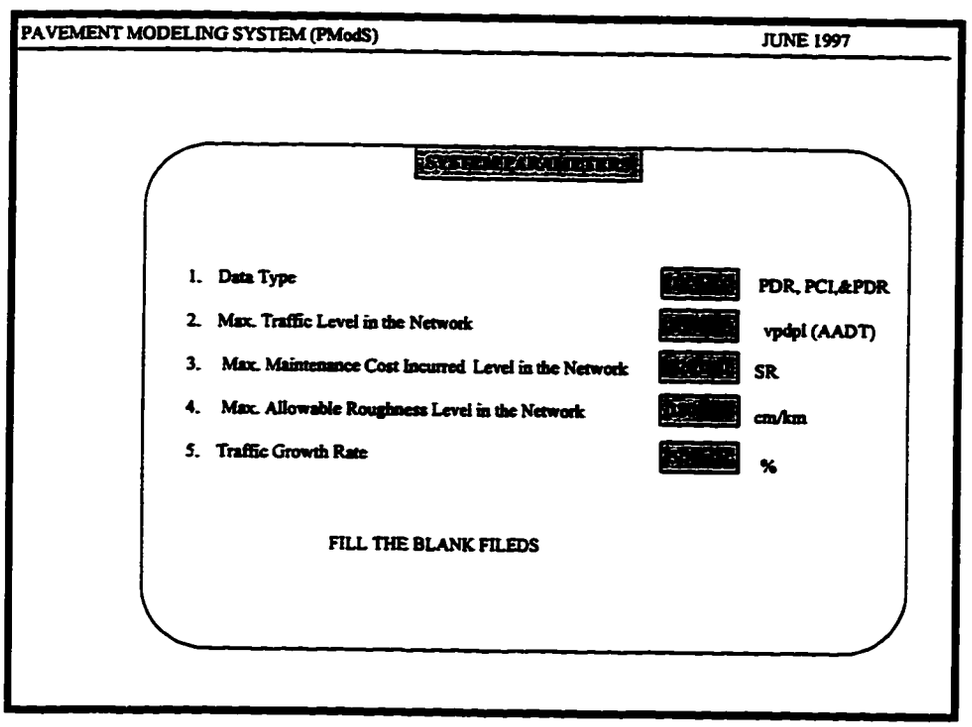


Figure 6.3. System parameters menu of the pavement modeling software.

PAVEMENT MODELING SYSTEM (PModS) JUNE 1997

Zone No.: Zone Name:

Road Name: Road Class:

Section No.: From: To:

Length: m Width: m Area: Sq..

Current PCI Value: Operating Traffic: vpd.

Maintenance Cost: SR.

Roughness Value Available: (Y/N) If Yes, Enter Value: cm/km

Skid Resistance Available: (Y/N) If Yes, Enter Value:

Figure 6.4. Priority ranking data entry menu.

PAVEMENT MODELING SYSTEM (PModS) JUNE 1997

SECTION INFORMATION ENTRY & CONDITION PREDICTION

Zone No.: Zone Name:

Road Name: Road Class:

Section No.: From: To:

Length: m Width: m Area: Sq..

Asphaltic Layers Thickness: mm Base Layer Thickness: mm

Operating Traffic: vpd. Percentage of Trucks: %

REMARKS:

Figure 6.5. Pavement condition prediction data entry menu.

PAVEMENT MODELING SYSTEM (PModS) JUNE 1997

Zone No.: Zone Name:

Road Name: Road Class:

Section No.: From: To:

Priority Factor	Normalized value	Factor Weight
Road Class	75	0.135
Pavement Condition	23	0.196
Operating Traffic	35	0.132
Riding Quality	50	0.124
Safety Condition	80	0.155
Maint. Cost	100	0.106
Importance to Comm.	51.1	0.153

Figure 6.6. Typical priority ranking section-wise report.

SECTION-WISE CONDITION PREDICTION REPORT

ZONE NO.
ZONE NAME
ROAD NAME
ROAD CLASS
SECTION NO.
FROM
TO

PAVEMENT COINDITION PREDICTION RESULTS

AGE	PREDECTED PCI
0	100
1	97
2	93
3	89
4	84
5	79
6	73
7	68
8	62
9	55
10	49

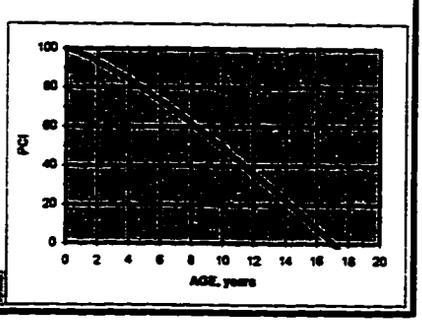


Figure 6.7. Typical pavement condition prediction section-wise report.

However, some data need to be entered other before Figure 6.5 can be obtained. These data are the roughness and skid resistance if no equipment are available, in which case index values are used to represent the pavement roughness and safety condition. Figure 6.8 to 6.9 represent those additional data. Moreover, the importance to community factor has qualitative sub-factors that need to be quantified. Figure 6.10 shows the menu for this matter. All calculation for indices of these factors and sub-factors are done internally.

6.3 SYSTEM LIMITATION AND MODIFICATION

The spread sheet system described above does not present an ideal and optimal system. It has the limitation of being non-programmable in a sense that it can not be compared with other programming languages such as dBase, Clipper, FoxPro, or Access. Using these packages help in integrating the developed systems with more flexible and powerful working environments. The system described above also does not present a complete pavement management system. Other system capabilities are still needed such as routines for condition survey data entry, routines for pavement evaluation, routines for pavement maintenance selection, and routines for maintenance funds allocation. These capabilities are out of scope of the research study. Figure 6.11 show one suggested integration of these models with the other in a working pavement management system.

PAVEMENT MODELING SYSTEM (PModS) JUNE 1997

Zone No.: Zone Name:

Road Name: Road Class:

Section No.: From: To:

Class	condition
1	One or more of the following prevail: high severity of corrugation, bumps and sags, extensive swelling and upheaval levels, raveling and weathering, and rutting.
2	One or more of the following prevail: medium severity of corrugation, bumps and sags, moderate density swelling and upheaval levels, raveling and weathering, and rutting.
3	One or more of the following prevail: low severity of corrugation, bumps and sags, raveling and weathering, and rutting; low severity and low density swelling and upheaval.
4	Pavement condition is good from riding quality point of view

Select A Number That Represents Section:

Figure 6.8. Data entry menu for riding quality index determination.

PAVEMENT MODELING SYSTEM (PModS) JUNE 1997

Zone No.: Zone Name:

Road Name: Road Class:

Section No.: From: To:

Class	Condition
1	One or more of the following prevail: high severity of bleeding and rutting; extensive level of polishing aggregate; high severity potholes with high number; sever drainage problems
2	One or more of the following prevail: medium severity of bleeding and rutting; moderate extent level of polishing aggregate; low to medium severity potholes with few in number; some drainage problems
3	One or more of the following prevail: low severity of bleeding and rutting; low extent level of polishing aggregate.
4	Pavement condition is good from safety point of view

Select A Number That Represents The Section:

Figure 6.9. Data entry menu for safety condition index determination.

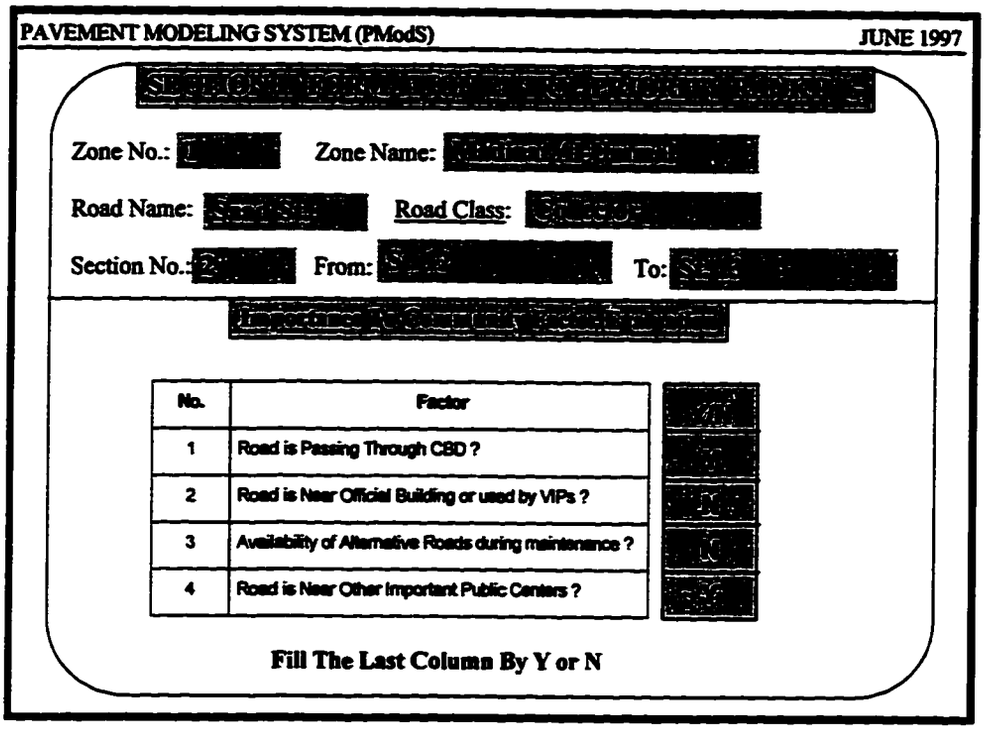


Figure 6.10. Data entry menu for importance to community factor index determination.

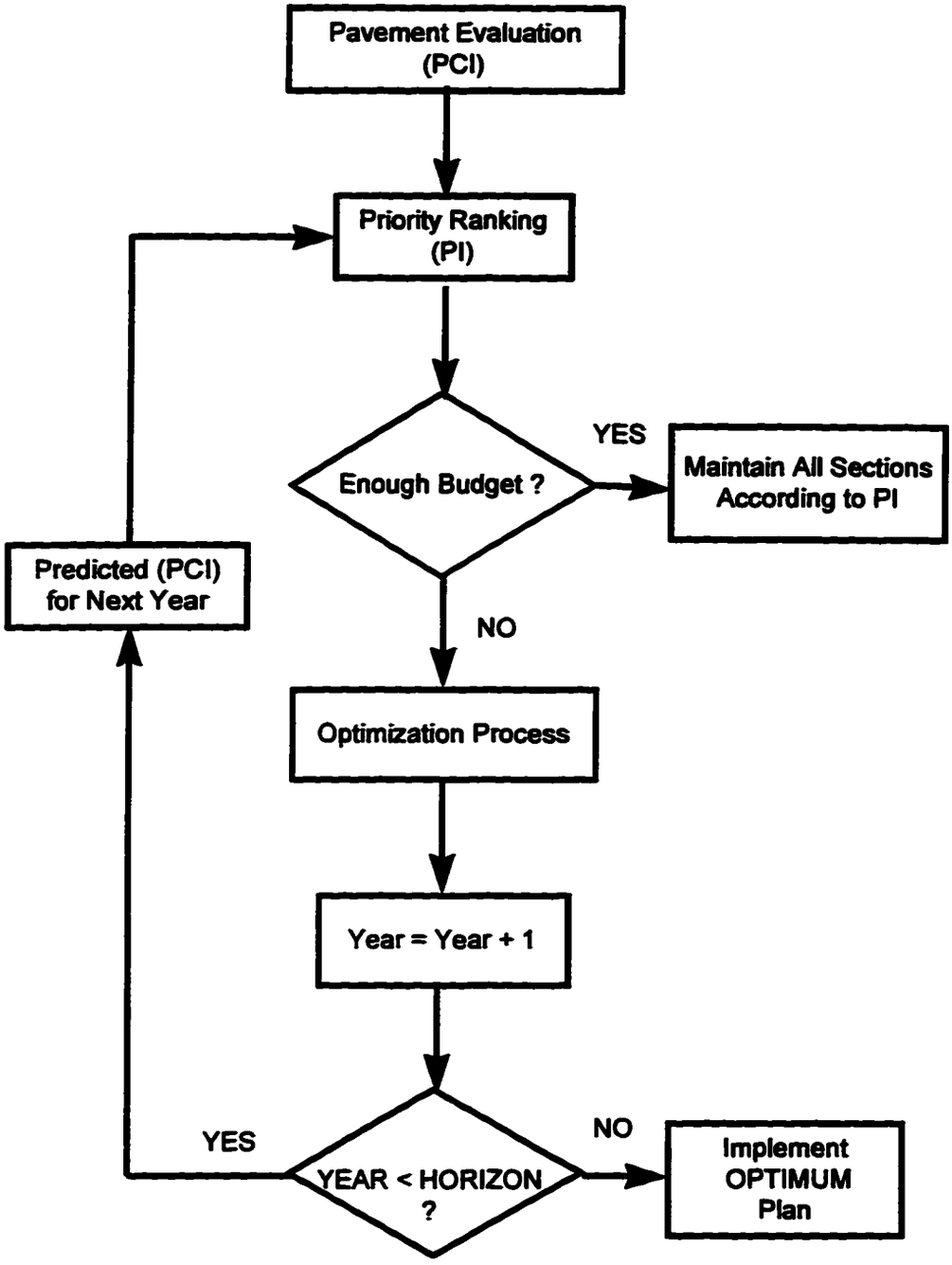


Figure 6.11. A recommended modeling integration.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this research study were to develop pavement condition prediction models from the collected condition and other related data from different areas in the Kingdom, and develop a pavement maintenance priority ranking based on the opinions of different group of people using the road network.

7.1 PRIORITY RANKING CONCLUSIONS

Based on the comprehensive data collection through the designed questionnaires, processing and analysis of these data, and based on the results of the comprehensive ranking procedure building and validation, the following conclusions can be stated:

1. The direct assignment method of collection individuals' opinions about the weight of importance of priority factors, showed a good agreement with the analytical hierarchy process (AHP) pair-wise comparison method. This agreement strengthen the direct assignment method since the AHP method is considered one of the pioneering psychometric-based method of prioritization.

2. The collected data showed a good consistency and repeatability through different statistical testing of comparisons: within consistency, time-related consistency, and individuals groups consistency. All of these comparisons showed that the collected data were statistically similar, where the null hypothesis of equal means could not be rejected.

3. The surveyed individuals groups: academicians, engineers, non-pavement qualified, and road users showed statistically different results in their opinions regarding the priority factors' weights. Therefore, adjustment for this effect was necessary.

4. The pavement condition had the highest weight of importance in priority ranking followed by safety condition, importance to community, road class, riding quality, operating traffic, and finally the maintenance cost.

5. The Saudi and UAE experience in pavement maintenance priority factors' weighing were found to be statistically different. The UAE respondents ranked the road class as the highest important factor, and the riding quality as he least important. Saudi respondents ranked the pavement condition as the most important and the maintenance cost as the least important factor.

6. The priority index developed procedure showed very good capability in capturing the engineering judgment method currently used in the pavement maintenance authorities. The matching capability reached about 80%. This was from two case

studies in Dammam and Jubail road network. If two-point difference was allowed between the two methods, a 100% matching level could be achieved.

7. The developed procedure can adequately and efficiently rank huge number of pavement sections for maintenance, unlike the engineering judgment which can handle relatively small number of pavement sections at the same time.

8. Factor analysis showed that only three factors could be extracted out of the seven considered. These factors are: pavement condition, importance to community, and road user perception. The last factor was a combination of riding quality and safety condition. These three extracted factors could explain 71% of the total variations.

7.2 CONDITION MODELING CONCLUSIONS

1. The PDR collected data showed the best consistency since it was collected by one uniform group of inspectors with similar experience. This data were also complete in terms of the performance-related factors for all surveyed sections. The PCR collected data showed also a good consistency since they were collected through an automated method using the road surface tester (RST), however, not all information regarding the surveyed sections were available. This reduces the number of data points considered in the analysis. The PCI data had the least consistency and uniformity, since they were collected by different inspectors with varying experiences.

2. Different condition prediction models were built using the available data from each of the three sets (PDR, PCR, and PCI). The coefficients of determination R^2 were in the range of 0.775, 0.796, and 0.658 for PDR, PCR, and PCI, respectively. The best feasible models, based on the coefficient of determination, R^2 , level of significance, and fitting capability of the actual data, were specified and selected to fit the actual data of each set.

3. The non-linear polynomial and power prediction models showed better fitting capability in all data sets

4. The AGE factor among all other modeling independent variables, had the most significant effect in modeling the pavement condition. It had a clear inversely relationship with the pavement condition.

5. Combining the transformed PDR data with the PCI original data did not show better matching and goodness of fit. About 50% of the variation could only be captured by modeling these combined data. The best R^2 obtained was in the range of 0.493.

6. The developed models fit the reserved data for validation with a reasonable goodness of fit. The fitting powers were similar to those of the modeling ones.

7. Most of the collected data were for high pavement condition indices (more than 60), therefore, the matching power between predicted and observed values was better for this range, while there were a lot of scatters below this range. This is also one of the reasons for the low goodness of fit for some models.

8. Two applications of the developed models were specified: generating of different models, and planning and scheduling of maintenance policies.

7.3 RECOMMENDATIONS

The developed pavement condition prediction model and the pavement maintenance ranking procedure were the main output of this study. The following recommendations are proposed for further research in this area:

1. Efforts should be made to use the collected data in building a reference pavement condition data base that can be used in the future for any pavement maintenance and management studies. This data base can be modified as and when needed according to the research and implementation requirements.

2. There is a need for a comprehensive PMS to take care of the pavement system in the Kingdom. This system should include:

   - Integrated sub-systems such as the developed models of condition prediction and priority ranking, maintenance selection procedure, and maintenance funds optimization,

   - Consideration of different climatological conditions existing in the Kingdom,

   - Effectiveness of maintenance policies on pavement performance, and

   - Cost effectiveness analysis of maintenance actions.

REFERENCES

Aiban, S., Al-Abdul Wahhab, H., and Al-Amodi, O. S. B. (1996). "Performance Evaluation of Stabilized Roads in Dammam, Saudi Arabia." *Proceedings Maintenance of Buildings, Public Structures, and Preventive Measures Symposium.* Umm-Al-Qura University, Makkah. Saudi Arabia, pp. 147-157.

Akili, W. and Arora, M. G. (1984). "Early Performance Results of Sulfur-Extended-Asphalt (SEA) Pavements in Saudi Arabia." *Proceeding of The First Saudi Engineering Conference*, King Abdulaziz University, Jeddah.

Al-Abdul Wahhab, H. I. and Ramadhan, R. H. (1990). "Prediction of Pavement Rutting in the Eastern Province, Saudi Arabia." *The Arabian Journal for Science and Engineering*, Vol. 15, No. 3, pp. 385-402.

Al-Abdul Wahhab, H. I. and Ramadhan, R. H. (1995). "Manifestation of Pavement Temperature Variation of Flexible and Rigid Pavements in Dhahran, Saudi Arabia." *Proceedings of Fourth Saudi Engineering Conference*. King Abdulaziz University, Jeddah, Saudi Arabia. Vol. II, pp. 479-485.

Al-Abdul Wahhab, H. I., Ali, F., Asi, I. M., and Al-Dubabe, I. A. (1996). *Adaptation of SHRP Performance-Based Asphalt Specification to Gulf Countries*. Final Report. King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia.

Al-Abdul Wahhab, H. I., Fatani, M., Al-Dubabe, I., Bubshait, A., and Noureldin, A. S. (1995). "Design and Maintenance Criteria for Local Asphalt Concrete Mixes." *Proceedings of Fourth Saudi Engineering Conference*. King Abdulaziz University, Jeddah, Saudi Arabia. Vol. II, pp. 457-463.

Al-Khoury, S. (1996). "Rehabilitation Needs and Material Selection". *Proceedings of Highway and Bridge Maintenance Forum*. Institute for International Research (IIR). Dubai , UAE.

Al-Matham, S. (1995). *Analysis of The Effect of Deferring Highway Flexible Pavement Maintenance on Maintenance Cost.* MS Thesis, King Saud University, Riyadh, 1995.

Al-Swailmi, S. H. (1995). *Road Network Maintenance Management (Arabic).* Al-Liuaa' House for Publishing and Distribution. Riyadh, Saudi Arabia.

Al-Swailmi, S., Al-Mansour, A., Al-Mulhem, M., Sharaf, E., Zaharan, S., and Al-kharashi, I. (1995). *Development of A Maintenance Management System for Riyadh Street Network.* On-going Research, Unpublished Progress Report No. 1.

Arora, M. G., Al-Mana, A. I., Al-Tayyib, A. J., Ramadhan, R. H., and Khan, Z. A. (1994). "Long-Term Pavement Performance History of Sulfur-Extended Asphalt Test Roads in Eastern Province of Saudi Arabia." *Transportation Research Record 1435*, Transportation Research Board, Washington, DC., pp. 77-85.

Asi, I. M. (1986). *Axle Loads and Pavement Performance Indicators for Typical Highways in Eastern Province.* MS Thesis, Civil Engineering Department. King Fahd University of Petroleum and Minerals.

Baerwald, J. E. (1976). *Transportation and Traffic Engineering Handbook.* Institute of Transportation Engineers. Prentice-Hall, Inc., Englewool Cliffs. N.J., USA.

Bein, P., Cox, J. B., Chursinoff, R. W., Heiman, G. H., and Huber, G. A. (1989). "Application of HDM3 Pavement Deterioration Model in Saskatchewan Pavement Management Information System.", *Transportation Research Record 1215*, Transportation Research Board, Washington, DC., pp. 60-69.

Brandon, R. O. (1994). "Solving the Mystery of Successfully Implementing a Computerized Maintenance Management System.", *Public Works*, pp. 36-40, August issue.

Bu-Bshait, A. A. (1985). *Development of Flexible Pavement Fatigue Model for Washington State.* PhD Dissertation. University of Washington, USA.

Butt, A. A., Shahin, M. Y., Carpeter, S. H., and Carnahan, J. V. (1994). "Application of Markov Process to Pavement Management Systems at Network Level.", *Proceedings of The Third International Conference on Managing Pavements.* Transportation Research Board, Texas., Vol. 2, pp. 159-172.

Chen, X., Hudson, S., Cumberledge, G., and Perrone, E. (1995). " Pavement Performance Modeling Program for Pennsylvania." *Transportation Research Record No. 1508.* Transportation Research Board, National Research Council. Washington DC. pp. 1-8.

Chen, X., Weissmann, J., Dossey, T., and Hudson, W. R. (1993). "URMS: A Graphical Urban Roadway Management System at Network Level.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 103-111.

Christory, J. P., and Laye, P. (1991) "Urban Roads in France: Overview and Recent Developments in Maintenance Management Aids.", *Transportation Research Record 1304*, Transportation Research Board, Washington, DC., pp. 3-11.

Chua, K. H., Monismith, C. L., and Crandall, K. C. (1993). "Dynamic Decision Model for Pavement Management Using Mechanistic Pavement Performance Submodel.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 15-24.

Chua, K. H., Monismith, C. L., and Crandall,, C. K. (1994). "Mechanistic Performance Model for Pavement Management.", *Proceedings of The Third International Conference on Managing Pavements*, Texas, Transportation Research Board, National Research Council, Vol. 1, pp. 85-94.

Conover, W. J. (1980). *Practical Nonparametric Statistics*. Second Edition. John Wiely & Sons, Inc. USA.

Cook, W. D. and Kress, M. (1984). "A Multiple-Criteria Composite Index Model for Quantitative and Qualitative Data." *European Journal of Operational Research*. No. 78. North Holland, pp. 367-379.

Cox, J. (1988). "Road Management Systems for Developing Countries.", *Proceedings of the Third International Road Federation Middle East Regional Meeting*, Riyadh, Saudi Arabia, Vol. 1, pp. 1.224-241.

Dammam Municipality (1996). *Training Course and Discussion on: Asphalt Pavement Maintenance Management*. Dammam Municipality with Cooperation of Civil Engineering Department of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

Darter, M. I. (1980). "Requirement for Reliable Predictive Pavement Models." *Transportation Research Record No. 766*. Transportation Research Board, National Research Council. Washington DC.

Davison, M. L. (1983). *Multidimensional Scaling*. John Wiley and Sons Inc., USA.

Encyclopedia Americana (1984). International Edition, Gorlier Incorporated, USA.

Fatani, M. Y., Al-AbdulWahhab, H. I., Balghunaim, F. A., Bubshait, A. A., and Al-Dhubeeb (1988). *Evaluation of Permanent Deformation of Asphalt Concrete Pavement in Saudi Arabia*. National Research Project. Progress Report No. 1. KACST, Riyadh, Saudi Arabia.

Faw, T. F., and Chan, W. T. (1993). "Priority Rating of Highway Maintenance Needs by Neural Network.", *Journal of Transportation Engineering*, Vol. 119, No. 3, pp. 419-432.

Feighan, K. J., Shahin, M. Y., Sinha, K., and White, T.(1989). "A Prioritization Scheme for the Micro PAVER Pavement Management System.", *Transportation Research Record 1215*, Transportation Research Board, Washington, DC., pp. 89-100.

FHWA (1987). *Techniques for Pavement Rehabilitation. Training Course Note*. The Federal Highway Administration. National Highway Institute. USA

Finn, F. N., Terrel, R. L., Le Clerc, R. V. (1976). "The Development of Pavement Management System for Programming Roadway Maintenance.", *Proceedings of The Association of Asphalt Paving Technologists*, Vol. 45, pp. 286-304.

Fwa, T. F., Tan, C. Y., and Chan, W. T. (1994). "Road Maintenance Planning Using Genetic Algorithms. I: Analysis." *Journal of Transportation Engineering*, Vol. 120, No. 5, pp. 710-722.

George, K. P., Pajagopal, A. S., and Lim, L. K. (1989). "Models for Predicting Pavement Deterioration.", *Transportation Research Record 1215*, Transportation Research Board, Washington, DC., pp. 1-7.

Haas, R. Hudson, W. R., and Zaniewski, J. (1994). *Modern Pavement Management*. Krieger Publishing Company. Florida, USA.

Haas, R., and Hudson, W. R. (1982). *Pavement Management System*. McGraw Hill Inc., Reprinted Edition, New York.

Hagquist, R. F. (1994). "High-Precision Prioritization Using The Analytical Hierarchy Process: Determining State HPMS Component Weighting Factors." *Transportation Research Record 1429*, Transportation Research Board, Washington, DC., pp. 7-14.

Harker, P. T. and Vargas, L. G. (1987). "The Theory of Ratio Scale Estimation: Saaty's Analytical Hierarchy Process." *Management Sciences*, Vol. 33. No. 11. pp. 1383-1403.

Harman, H. H. (1976). *Modern Factor Analysis*. 3rd Edition. University of Chicago Press, USA.

Harper, W. V., Majidzadeh, K. (1993) "Integrated Pavement and Bridge Management Optimization.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 83-89.

Haugodegard, T., Johansen, J., Berrelsen, D., and Gabestad, K. (1994). "Norwegian Public Roads Administration: A Complete Pavement Management System in Operation.", *Proceedings of The Third International Conference on Managing Pavements*. Transportation Research Board, Texas., USA. Vol. 2, pp. 25-33.

Hudson, W. R., Uddin, W., and Carmichael, R. F. (1988). "A methodology for Life Cycle Analysis Using Microcomputer." *Proceedings of the Third International*

Road Federation Middle East Regional Meeting, Riyadh, Saudi Arabia, Vol. 1, pp. 1.132-1.148.

Irrgang, F. C., and Maze, T. H. (1993). "Status of Pavement Management Systems and Data Analysis Models at State Highway Agencies.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 1-6.

Kannemeyer, L. and Visser, A. T. (1995). "Calibration of HDM-III Performance Models for Use in Pavement Management of South African National Roads.", *Transportation Research Record 1508*, Transportation Research Board, Washington, DC., pp. 31-38.

Karan, M. A. (1984). "Municipal Pavement Management System." *A Program of Study in Pavement Management*. Training Course Notes by The Center of Transportation Research, University of Texas at Austin, USA.

Karan, M. A., and Haas, R. C. G. (1976). "Determination Investment Priorities for Urban Pavement Improvements.", *Proceedings of The Association of Asphalt Paving Technologists*, Vol. 45, pp. 254-286.

KFUPM-RI (1989). *Programming Pavement Maintenance for Al-Jubail Road Network*, Final Report, Vol. I, Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.

KFUPM-RI (1989). *Programming Pavement Maintenance for Al-Jubail Road Network: Pavement Distress Manual*, Vol. III. Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.

Kier, W. G. (1974). *Bump Integrator Measurement in Routine Assessment of Highway Maintenance Needs*. Transport and Road Research Laboratory TRRL Supplementary Report 26 UC. Crowthorne, Berkshire, U.K.

Kline, P. (1979). *Psychometric and Psychology*. Academic Press Inc., London, UK.

Laytton, R. L., Scullion, T., Garrett, B. D., and Michalak, C. M. (1981). *Effect of Truck Weights on Pavement Deterioration.* Final Report RF 4087-2. Texas Transportation Institute, Texas, USA.

Lee, Y., Mohseni, A., and Darter, M. I. (1993). "Simplified Pavement Performance Models.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 7-14.

Lees, G. (1978). "Skid Resistance of Bituminous and Concrete Surfacing." *Development in Highway Pavement Engineering - 1.* Editor Pell, P. S. Applied Science Publisher Ltd. London.

Livneh, M. and Craus, J. (1990). "Economic Models for Setting Priorities for Road Maintenance and Rehabilitation in Israel." *Transportation Research Record 1268*, Transportation Research Board, Washington, DC., pp. 205-208

Lukanen, E. O., and Han, C. (1994). "Performance History and Prediction Modeling for Minnesota Pavements.", *Proceedings of The Third International Conference on Managing Pavements.* Transportation Research Board, Texas., Vol. 1, pp. 63-73.

Luther, M. S. and Majidzadeh, K. (1979). *Development and Implementation of System for Evaluation of Maintenance and Repair: A Pavement Condition Rating System for Ohio Department of Transportation.* Unpublished Interim Report of Project 3086.

Lyon, J. D. (1983). An Evaluation of The Pavement Condition Index Prediction Model for Flexible Pavements. MS Thesis. Air University, Air Force Institute of Technology, Ohio, USA.

Majidzadeh, K. (1988). "Performance-Prediction Model for a Third generation Pavement Management System.", *Proceedings of the Third International Road Federation Middle East Regional Meeting*, Riyadh, Saudi Arabia, Vol. 1, pp. 1.92-1.102.

Majidzadeh, K., Vedaie, B., and Kennedy, J. C. (1990). "Pavement Management System to Maximize Pavement Investment and Minimize Cost." *Transportation Research Record 1272*, Transportation Research Board, Washington, DC., pp. 65-79.

Markow, M. (1990). "Life-Cycle Evaluation of the Effects of Pavement Maintenance.", *Transportation Research Record 1276*, Transportation Research Board, Washington, DC., pp. 37-47.

Micro PAVER (1994). *Micro PAVER Pavement Management System. User's Guide Version 3.21.* Software Developed by US Army Construction Engineering Research Laboratory. University of Illinois at Urbana-Champaign.

Millet, I. and Harker, P. T. (1990). "Globally Effective Questioning in The Analytic Hierarchy Process." *European Journal of Operational Research.* No. 48. North Holland, pp. 88-98.

ML Aviation (1983). ML Mu-Meter Instruction and Servicing Manual. ML Aviation Company. Berkshire, U.K.

MOC (1986). *User Manual - Interim Pavement Evaluation System: Condition Survey.* Unpublished Report. Ministry of Communication, Riyadh, Saudi Arabia.

MOC (1992). Dhahran-Abqaiq Road Improvement. Final Report prepared by Ahmad Al-Rashed Al-Humaid Consulting Engineers.

MOC (1995). *MOC Road Information System Overview.* Ministry of Communication, Maintenance Department and SweRoad Technical Cooperation, February, 1995.

Montgomery, D. C. (1984). *Design and Analysis of Experiment.* Second Edition. John Wiley & Sons, New York, USA.

Ningyuan, L., and Haas, R. (1994). "Special Implementation of Pavement Management for Large Highway Network in Developing Countries.", *Proceedings of The Third International Conference on Managing Pavements.* Transportation Research Board, Texas., Vol. 1, pp. 179-190.

Noureldin, A. S, and Al-Dhalaan, M. (1993). "Performance of Laboratory Identified Rut Resistant Pavement Mixtures on Dhahran Abqiq Roadway Sections.", *Proceeding of the 12th IRF World Meeting.* Madrid, Spain, pp. 1-20

Nunnally, J. C. (1967). *Psychometric Theory*. McGraw-Hill, Inc. USA.

Osmani, A., Haas, C., and Hudson, W. R. (1994). "Evaluation of Road Maintenance Automation." *Journal of Transportation Engineering*. Vol. 122, No. 1, pp. 50-58.

Pajagobal, A. S., and George, K. P. (1990). "Pavement Maintenance Effectiveness.", *Transportation Research Record 1276*, Transportation Research Board, Washington, DC., pp. 62-68.

Peattie, K. R. (1978). "Flexible Pavement Design." *Development in Highway Pavement Engineering - 1*. Editor Pell, P. S. Applied Science Publisher Ltd. London.

Personal Communication (1996). Personal Consultation with Drs. H. I. Al-Abdul Wahhab, I. A. Al-Dubabe, and S. H. Al-Swailmi.

Philips, S. (1994). "Development of United Kingdom Pavement Management System.", *Proceedings of The Third International Conference on Managing Pavements*. Transportation Research Board, Texas., Vol. 1, pp. 227-239.

Pignataro, L. J. (1973). *Traffic Engineering - Theory and Practice*. Prentice-Hall, Inc., Englewool Cliffs. N.J., USA.

Rainhart 1972. *Mays Ride Meter Booklet*. 3rd Edition. Rainhart Company Testing Equipment. USA

Ramadhan, R. H. (1988). *Rut Depth Prediction from Laboratory Characterization tests*. MS Thesis, Civil Engineering Department. King Fahd University of Petroleum and Minerals.

Ramadhan, R. H. (1996). "Understanding Pavement Distress." *Proceedings of the Highway and Bridge Maintenance Forum*. Institute for International Research (IIR). Dubai, UAE.

Ramadhan, R. H., Al-Abdul Wahhab, H. I., Dubabe, I. M., and Asi, I. M. (1995). "Evaluation of Arabian Asphalt Binder for Low-Temperature Cracking Behavior.",

Proceedings of The Second ASCE-SAS Regional Conference, Beirut, Lebanon, pp. 871-890.

Ratrout, N. T., (1994). *Speed Study on KFUPM Road Network.* Unpublished Report. KFUPM, Civil Engineering Department.

Ratrout, N. T., (1996). *Traffic Count Study on KFUPM Road Network.* Unpublished Report. KFUPM, Civil Engineering Department.

Rilett, L. R., Hutchinson, B. G., and Haas, R. C. G. (1989). "Cost Allocation Implication of Flexible Pavement Deterioration Models.", *Transportation Research Record 1215*, Transportation Research Board, Washington, DC., pp. 31-42.

Roohanirad, A. (1994). "PMS for Low-Volume and Built-up Roads.", *Public Works*, pp. 44, January Issue.

RTAC (1977). *Pavement Management Guide*. Road and Transportation Association of Canada. Ottawa, Canada.

Saaty, T. L. (1990). *The Analytic Hierarchy Process*. RWS Publications. Second Edition, Pittsburgh, USA.

Saaty, T. L. (1982). *Decision Making for Leaders*. Kluwere Nijhoff Publishing, Lifetime Learning Publications, California, USA.

Saaty, T. L. (1986). "Axiomatic Foundation of The Analytical Hierarchy Process." *Management Sciences*, Vol. 32. No. 7. pp. 841-855.

Saaty, T. L. and Vargas, L. G. (1982). *Logic of Priorities*. Kluwere Nijhoff Publishing, Boston, USA.

Saleem, F. (1985). *Structural Evaluation on In-Service Asphalt Pavement by Deflection Measurement*. MS Thesis, Civil Engineering Department. King Fahd University of Petroleum and Minerals.

Sekiguchi, M., Fujita, E., Inagaki, M., and McGregor (1993). "Objective-Oriented Approach to Fulfilling the Need for PMS Pavement Structure Survey Data in

Japan.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 39-44.

Shahin, M. Y. and Kohn, S. D. (1981). *Pavement Maintenance Management for Roads and Parking Lots*. US Corps of Engineers, Technical Report M-294.

Shahin, M. Y., and Walter (1990). *Pavement Maintenance Management for Roads and Streets Using PAVER system*. US Army Corps of Engineers, Construction Engineering Research Laboratory (USACERL). Technical Report M-90/05.

Sharaf, E. (1991). "Simple Procedure for Selecting Best Maintenance Alternatives in Developing Countries.", *Transportation Research Record 1304*, Transportation Research Board, Washington, DC., pp. 38-47.

Sharaf, E. (1993). "Ranking Versus Simple Optimization in Setting Pavement Maintenance Priorities: A Case Study from Egypt.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 34-38.

Sharaf, E. A., Shahin, M. Y., and Mustafa, M. T. (1988). "Consequences of Delaying Pavement Maintenance Alternatives.", *Proceedings of The Third International Road Federation Middle East Regional Meeting*, Riyadh, Saudi Arabia, pp. 1.139-1.168.

SHRP (1993). *Distress Identification Manual for Long-Term Pavement Performance Project*. Strategic Highway Research Program. SHRP-P-338. National Research Council, Washington DC.

Smith, H. A., Stephanson, P. J., Rada, G. R., Schwartz, C. W., and Casanova, L. (1993). "Development of Delaware Department of Transportation Pavement Management System.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 55-62.

Sood, V. K., Shamra, B. K., Kanchan, P.K., and Sitaramanjaneyulu, K. (1994). "Pavement Deterioration Modeling for India.", *Proceedings of The Third*

International Conference on Managing Pavements, Texas, Transportation Research Board, National Research Council, Vol. 1, pp. 47-54.

Sprent, P. (1989). *Applied Nonparametric Statistical Methods*. Chapman and Hall Ltd. New York, USA.

STATISTICA (1995). STATISTICA for WINDOWS Manual. StatSoft, USA.

Stevens, L. B. (1985). *Road Surface Management for Local Governments: Resource Notebook*. US Department of Transportation. Office of Highway Planning, Federal Highway Administration. Washington, D. C.

Still, P. B., Burtwell, M. H., and Young, J. C. (1983). *Evaluation of A Microprocessor System for Bump Integrators*. Transport and Road Research Laboratory TRRL Laboratory Report 1083. Crowthorne, Berkshire, U.K.

Stopher, R. S., and Meyburg, A. H. (1979). Survey Sampling and Multivariate Analysis for Social Scientists and Engineers. Lexington Books, Toronto, Canada.

Stylianopoulus, L. C. (1988). "Value Engineering and Road Performance in Saudi Arbaia.", *Proceedings of the Third International Road Federation Middle East Regional Meeting*, Riyadh, Saudi Arabia, Vol. 4, pp. 4.308-4.322.

Tabachnick, B. G. and Fidell, L. S. (1983). *Using Multivariate Statistics*. Harper and Row, Publishers, New York.

Taha, H. A. (1992). *Operation Research: An Introduction*. Fifth Edition. Macmillan Publishing Company. Singapore.

The World Bank (1989). *The Highway Design and Maintenance Standards Model (HDM3) User Guide*. The International Bank for Reconstruction and Development, Washington, DC.

TRRL (1986). *Operation Handbook - The ABAY Beam*, An Instrument for Calibrating and Standardizing Road Roughness Measurements made with Response Type

Instruments and Systems. Transport Road Research Laboratory, Crowthorne, England.

Ullidtz, P. (1987). *Pavement Analysis*, Elsevier Science Publisher, Amsterdam, The Netherlands, 1987.

USACERL (1993). *MicroPAVER Pavement Management System*, User's Guide Version 3.21, U. S. Army Construction Engineering Research Laboratory. University of Illinois at Urbana-Champaign.

Vargas, L. G. (1990). "An Overview of The Analytical Hierarchy Process and Its Applications." *European Journal of Operational Research*. No. 48. North Holland, pp. 2-8.

Walpole, R. E. and Myers, R. H. (1978). *Probability and Statistics for Engineers and Scientists*. Macmillan Publishing Co., Inc. USA.

Weisberg, S. (1985). Applied Linear Regression. Second Edition. John Wiley and Sons. USA.

Wood L. E. (1995) "The Importance of Relating Field Performance to Laboratory Measured Properties." *Proceedings of The Second International Conference of Road and Airfield Pavement Technology*. Singapore. pp. 94-102.

Zaghloul, S., Al-Tayer, M., and Saeed, N. (1996). "Advanced Technology in Pavement Evaluation". *Proceedings of Highway and Bridge Maintenance Forum*. Institute for International Research (IIR). Dubai , UAE.

Zhang, Z., Singh, N., and Hudson, W. R. (1993). "Comprehensive Ranking Index for Flexible Pavement Using Fuzzy Sets Model.", *Transportation Research Record 1397*, Transportation Research Board, Washington, DC., pp. 96-102.

APPENDIX - A

بسم الله الرحمن الرحيم

Ministry of Higher Education
King Fahd University of Petroleum & Minerals
COLLEGE OF ENGINEERING SCIENCES
CIVIL ENGINEERING DEPARTMENT

وزارة التعليم العالي
جامعة الملك فهد للبترول والمعادن
كلية العلوم الهندسية
قسم الهندسة المدنية

عزيزي المدير/المهندس/الأكاديمي/المراقب/أخصائي الصيانة المحترم.

يقوم قسم الهندسة المدنية بإجراء مشروع بحث (رسالة دكتوراه) حول استحداث وتطوير نمذجة إدارة الرصفات في الطرق، وكجزء من هذا البحث يعتبر تحديد أولويات أعمال الصيانة والإصلاح في مقاطع الطرق من الأجزاء المهمة لأي نظام إدارة صيانة الرصفات، حيث يتم معرفة أي المقاطع التي تحتاج الى إجراءات الصيانة قبل غيرها. ويتم عادة تحديد هذه الأولوية بناءً على عوامل متعددة. لذا نرجو من شخصكم الكريم التفضل بمساعدتنا في إجراء هذه الدراسة بإعطاء رأيكم والذي سيكون محل احترامنا وتقديرنا.. شاكرين لكم حسن مساعدتكم وتعاونكم.

الجزء الأول: في الجدول التالي، يرجى تقدير أهمية كل عامل من العوامل بإعطاء النسبة المئوية في الخانة المناسبة وذلك من واقع خبرتكم ووجهة نظركم حول موضوع تحديد أولويات الصيانة في رصفات الطرق، بحيث يكون المجموع الكلي ١٠٠٪.

الرقم	نوع الطريق	الشرح	النسبة المئوية للأهمية
١.	نوع الطريق	رئيسي/فرعي أو تجاري/سكني	
٢.	حالة سطح الطريق	من حيث وجود التشوهات والتقييات ومداها وكثافتها مثل التشققات والحفر والهبوطات.	
٣.	حجم المرور العامل على الطريق	من حيث أعداد المركبات العاملة على الطريق والذي يعطي مؤشراً لمدى استعمال هذا الطريق من قبل المجتمع.	
٤.	جودة القيادة على الطريق	من حيث وجود الهبوطات الطولية والمناسيب الوعرة بحيث ينتج عنها إجهادات مختلفة للمركبات وقيادة غير مريحة للسائقين والركاب	
٥.	نعومة سطح الطريق ونواحي السلامة فيه	من حيث صعوبة استعمال الفرامل بطريقة مناسبة وفعالة خلال المسافة المطلوبة قبل حدوث التصادم مع السيارات الأخرى او المشاة او الشواخص الثابتة والمتحركة	
٦.	تكاليف الصيانة وتوابعها	والتي تشمل تكاليف الصيانة والإغلاق والمشاكل المرادفة	
٧.	أهمية الطريق بالنسبة للمجتمع	مروره قرب مناطق خدمات هامة مثل المستشفيات ومراكز الدفاع المدني والمدارس وغيرها. كما هو موضح في الجزء الثاني.	

المجموع: ١٠٠٪

الجزء الثاني: العامل السابع "أهمية الطريق" في الجزء السابق عامل مهم ولكنه يحتاج الى أن يكون من الاشياء المقاسة لا التخمينية. والمطلوب إعطاء نسبة مئوية لأهمية كل عامل فرعي من العوامل الفرعية الموضحة في الجدول التالي، بحيث يكون المجموع الكلي ١٠٠٪:

الرقم	نوع الطريق	الشرح	النسبة المئوية للأهمية
١.	نوع الطريق	رئيسي/فرعي أو تجاري/سكني	
٢.	بعد الطريق أو قربه من مركز المدينة	مركز المدينة: وسط المدينة وأماكن تجمع الأسواق والخدمات العامة	
٣.	مرور الطريق من مناطق رسمية	مثل مركز الإمارة أو استخدامه للمواكب الرسمية وكبار الزوار	
٤.	حجم المرور المستخدم لهذا الطريق	حيث أن حجم المرور يؤدي إلى زيادة الأولوية في الصيانة	
٥.	وجود طريق أو طرق بديلة في حالة الصيانة	حيث يؤثر هذا على أولوية الصيانة لهذا الطريق	
٦.	مروره أو قربه من مراكز المجتمع الأخرى	مثل مباني الدفاع المدني والمساجد وأماكن الترفيه والمتنزهات العامة.	

المجموع: ١٠٠٪

الجزء الثالث: إضافة أيّ عوامل أخرى ترى أهميتها وضرورتها في تحديد أولويات الصيانة

١. .....

٢. .....

٣. .....

الجزء الرابع: الرجاء تحديد طبيعة عملك أو مركزك العملي:

١. أكاديمي في تخصص النقل أو الرصفات ( )
٢. إداري مسئول في قسم إدارة الرصفات ( )
٣. مهندس مرور أو نقل أو رصفات ( )
٤. مراقب أو فني صيانة رصفات ( )
٥. فني مؤهل في غير مجال الرصف ( )
٦. مستخدم عام للطرق ( )

الجزء الخامس: الرجاء كتابة الاسم والعنوان ورقم الهاتف الفاكس (إختياري) .....

وأخيراً نشكرك على تعاونك معنا راجين أن توفق في الاستفادة من خبرتك ومعلوماتك القيمة. يرجاء إرسال مساهمتك في هذا الاستبيان الى العنوان التالي: جامعة الملك فهد للبترول والمعادن ص. ب. (٥٠١) الظهران ٣١٢٦١ أو على فاكس رقم ٠٣-٨٦٠٣٩٩٦ عناية /م. رمضان

بسم الله الرحمن الرحيم

وزارة التعليم العالي
جامعة الملك فهد للبترول والمعادن
كلية العلوم الهندسية
قسم الهندسة المدنية

Ministry of Higher Education
King Fahd University of Petroleum & Minerals
COLLEGE OF ENGINEERING SCIENCES
CIVIL ENGINEERING DEPARTMENT

عزيزي المدير، المهندس، الاكاديمي، أخصائي الصيانة، مستخدم الطريق المحترم

يقوم قسم الهندسة المدنية بإجراء مشروع بحث (رسالة دكتوراه) حول استحداث وتطوير نمذجة إدارة الرصفات في الطرق، وكجزء من هذا البحث يعتبر تحديد اولويات أعمال الصيانة والاصلاح في مقاطع الطرق من الأجزاء المهمة لأي نظام إدارة صيانة الرصفات، حيث يتم معرفة أي المقاطع التي تحتاج الى إجراءات الصيانة قبل غيرها. ويتم عادة تحديد هذه الاولوية بناءً على عوامل متعددة. لذا نرجو من شخصكم الكريم التفضل بمساعدتنا في إجراء هذه الدراسة بإعطاء رأيكم والذي سيكون محل إحترامنا وتقديرنا.. شاكرين لكم حسن مساعدتكم وتعاونكم.

عملية التحليل التسلسلي **(Analytical Hierarchy Process - AHP)** واحدة من الطرق الحديثة المستخدمة في تحديد الأولويات وإيجاد مقدار الأهمية لكل عامل من العوامل التي تدخل في تحديد الأولويات. ففي هذه الطريقة يقوم المتخصصون المشاركون في الاستبيان بإعطاء مقارنة زوجية ثنائية لكل عاملين من العوامل حسب أهميتهما في عملية تحديد الأولوية أو في أية عملية تحت الدراسة ، وذلك باستخدام مقياس جُهز لهذا الغرض مبنيّ على المقاييس السيكولوجية. وهذا المقياس ثبتت مصداقيته ووثوقيته من خلال العديد من التطبيقات في مجالات علمية متعددة.

والمطلوب في هذه الدراسة، هو إجراء مقارنة ثنائية لأهم العوامل التي تؤثر في تحديد أولويات صيانة الرصفات والموضحة في **الجدول رقم ١**. وذلك بملء الفراغات في **الجدول رقم ٣** . والمقصود في المقارنات الزوجية (أو الثنائية) هو تقدير نسبة أهمية العامل الاول الى العامل الثاني على مقياس AHP المكون من ٩ نقاط، فمثلاً نسبة أهمية نوع الطريق الى حالة سطح الطريق ٦ الى ١ بمعنى أن نوع الطريق أهم ٦ مرات من سطح الطريق في تحديد أولوية الصيانة.

وبنفس الطريقة استخدام الشرح الموجود في **الجدول رقم ٢** في إجراء المقارنات الزوجية لفئات الأشخاص المشاركين في هذه الاستبانة في **الجدول رقم ٤**

شاكرين ومقدرين لمشاركتكم معنا في هذا الاستبيان الذي سيؤدي (بإذن الله) الى نتائج هامّة. مما يساعد في استحداث نماذج لتحديد الطريقة العلمية المثلى في تحديد أولوية إجراءات أعمال صيانة رصفات شبكات الطرق

الرجاء تحديد طبيعة عملك أو مركزك العملي:

١. أكاديمي في تخصص النقل أو الرصفات ( ) ٢. إداري مسئول في قسم إدارة الرصفات ( ) ٣. مهندس مرور أو رصفات ( )

٤. مراقب أو فنّي صيانة رصفات ( ) ٥. مؤهل في غير مجال الرصف ( ) ٦. مستخدم عام للطرق ( )

الاسم / العنوان / أورقم الهاتف والفاكس (إختياري) .....

واخيراً نشكرك على تعاونك معنا راجين أن نُوفق في الاستفادة من خبراتك ومعلوماتك القيمة. برجاء إرسال مساهمتك في هذا الاستبيان الى العنوان التالي:

جامعة الملك فهد للبترول والمعادن ص. ب. (٥٠١) الظهران ٣١٢٦١ أو على فاكس رقم ٨٦٠٣٩٩٦-٠٣ عناية / م. رزق الله رمضان

الجدول رقم ١. بيان للعوامل التي تؤثر في عملية تحديد أولويات الصيانة.

العامل	الشرح
نوع الطريق	رئيسي/فرعي أو تجاري/سكني أو سريع مع طريق للخدمة أو بدون طريق للخدمة
حالة سطح الطريق	من حيث وجود التشوهات والتلفيات ومداها وكثافتها مثل التشققات والحفر والهبوطات. أو سوء تصريف المياه
حجم المرورالعامل على الطريق	من حيث أعداد المركبات العاملة على الطريق والذي يعطي مؤشراً لمدى استعمال هذا الطريق من قبل المجتمع.
جودة القيادة على الطريق	من حيث وجود التموجات الطولية والمناسيب الوعرة بحيث ينتج عنها إجهادات مختلفة للمركبات وقيادة غير مريحة للسائقين والركاب
نعومة سطح الطريق ونواحي السلامة فيه	من حيث صعوبة استعمال الفرامل بطريقة مناسبة وفعالة خلال المسافة المطلوبة قبل حدوث التصادم مع السيارت الاخرى او المشاة او الشواخص الثابتة
تكاليف الصيانة وتوابعها	والتي تشمل تكاليف الصيانة والاغلاق والمشاكل المرادفة
أهمية الطريق بالنسبة للمجتمع	مروره قرب مناطق خدمات هامّة مثل المستشفيات ومراكز الدفاع المدني والمدارس وغيرها. أو مروره قرب مبانٍ رسمية مثل الإمارة أو البلدية. أو استخدام هذا الطريق من قبل كبار الزوار.

الجدول رقم ٣ بيان لفئات الأشخاص المشاركين في الاستبيان

المجموعة أو الفئة	الشرح
الاكاديميين	المتخصصين في الاقسام الاكاديمية للطرق والمرور والرصفات في الجامعات والمعاهد العلمية
المدراء	العاملين في إدارات المرور والرصفات في المؤسسات الحكومية والخاصة ممن تصدر عنهم قرارت الصيانة وأولوياتها
المهندسين	مثل مهندسي المرور والرصف العاملين في التصميم والاشراف والتنفيذ لرصفات الطرق وصيانتها
المراقبين والفنيين	المراقبين والفنيين العاملين في مجال إنشاء رصفات الطرق ومشاريع صيانتها
المتخصصين في غير موضوع الرصف	الاشخاص المؤهلين في تخصصات غير مجال الطرق والرصف مثل الصحفيين والتجار والاقتصاديين والمدرسين وما شابه ذلك
المستخدم العادي للطريق	أي مستخدم للطريق من غير الفئات السابقة الذكر

الجدول رقم ٣ استبيان المقارنة الزوجية الثنائية لعوامل أولوية الصيانة

العامل الاول	العامل الثاني	١/١	١/٢	١/٣	١/٤	١/٥	١/٦	١/٧	١/٨	١/٩	٢/١	٣/١	٤/١	٥/١	٦/١	٧/١	٨/١	٩/١
نوع الطريق	حالة سطح الطريق																	
نوع الطريق	حجم المرور العامل على الطريق																	
نوع الطريق	جودة القيادة على الطريق																	
نوع الطريق	نعومة سطح الطريق ونواحي السلامة																	
نوع الطريق	تكاليف الصيانة وتوابعها																	
نوع الطريق	أهمية الطريق بالنسبة للمجتمع																	
حالة سطح الطريق	حجم المرور العامل على الطريق																	
حالة سطح الطريق	جودة القيادة على الطريق																	
حالة سطح الطريق	نعومة سطح الطريق ونواحي السلامة																	
حالة سطح الطريق	تكاليف الصيانة وتوابعها																	
حالة سطح الطريق	أهمية الطريق بالنسبة للمجتمع																	
حجم المرور العامل على الطريق	جودة القيادة على الطريق																	
حجم المرور العامل على الطريق	نعومة سطح الطريق ونواحي السلامة																	
حجم المرور العامل على الطريق	تكاليف الصيانة وتوابعها																	
حجم المرور العامل على الطريق	أهمية الطريق بالنسبة للمجتمع																	
جودة القيادة على الطريق	نعومة سطح الطريق ونواحي السلامة																	
جودة القيادة على الطريق	تكاليف الصيانة وتوابعها																	
جودة القيادة على الطريق	أهمية الطريق بالنسبة للمجتمع																	
نعومة سطح الطريق ونواحي السلامة	تكاليف الصيانة وتوابعها																	
نعومة سطح الطريق ونواحي السلامة	أهمية الطريق بالنسبة للمجتمع																	
تكاليف الصيانة وتوابعها	أهمية الطريق بالنسبة للمجتمع																	

المطلوب: ضع إشارة (×) في المربع الذي يمثل نسبة أهمية العامل الاول الى الثاني في تقدير أولويات الصيانة. مثال: العامل الاول الى الثاني تمثل نسبة ٥ : ١ أي أن العامل الاول يؤثر في أولويات الصيانة خمسة أضعاف العامل الثاني. إذن نضع اشارة (×) تحت رقم ١/٥

الجدول رقم ٤. استبيان المقارنة الزوجيّة الثنائية للأشخاص المشاركين في الاستبيان

الفئة الاولى	الفئة الثانية	١	٢	٣	٤	٥	٦	٧	٨	٩	٢/١	٣/١	٤/١	٥/١	٦/١	٧/١	٨/١	٩/١
الأكاديميين	المدراء																	
الأكاديميين	المهندسين																	
الأكاديميين	المراقبين والفنيين																	
الأكاديميين	المتخصصين في غير مجال الرصف																	
الأكاديميين	مستخدمي الطرق العاديين																	
المدراء	المهندسين																	
المدراء	المراقبين والفنيين																	
المدراء	المتخصصين في غير مجال الرصف																	
المدراء	مستخدمي الطرق العاديين																	
المهندسين	المراقبين والفنيين																	
المهندسين	المتخصصين في غير مجال الرصف																	
المهندسين	مستخدمي الطرق العاديين																	
المراقبين والفنيين	المتخصصين في غير مجال الرصف																	
المراقبين والفنيين	مستخدمي الطرق العاديين																	
المتخصصين في غير مجال الرصف	مستخدمي الطرق العاديين																	

المطلوب: ضع إشارة (×) في المربع الذي يمثل نسبة أهمية الفئة الاولى الى الثانية في تقدير أهمية عوامل أولويات الصيانة. مثال: الفئة الاولى الى الثانية تمثل نسبة ٥ : ١ أي أن الفئة الاولى تستطيع تقدير أولويات الصيانة خمسة أضعاف الفئة الثانية. إذن نضع اشارة (×) تحت رقم ٥.

بسم الله الرحمن الرحيم

Ministry of Higher Education
King Fahd University of Petroleum & Minerals
COLLEGE OF ENGINEERING SCIENCES
CIVIL ENGINEERING DEPARTMENT

وزارة التعليم العالي
جامعة الملك فهد للبترول والمعادن
كلية العلوم الهندسية
قسم الهندسة المدنية

Dear Manager, Engineer, Technician, Supervisor, Pavement Specialist, and Road User;

Civil Engineering Department is undertaking a research project on the development of pavement management modeling (Ph.D. Research Work). A part of this project is a modeling of maintenance priority ranking. This modeling is considered a major part of any Pavement Management System (PMS) since it determines the order of urgency or importance of pavement sections in need of maintenance and repair. Many factors affect this determination. Therefore, we are seeking your help in sharing with your experience by filling out this questionnaire about your opinion and practice in carrying out the priority ranking. Your contribution will be very helpful and valuable to us. Thank you very much for your cooperation and help.

Part I: In the following table, please fill out the blank column by the approximate percentage of importance of the corresponding factor in determining the priority for maintenance:

Factor	Description	Importance Weight (%)
1. Road Class	Major/Minor Road; Arterial, Collector, or Local; Commercial or Residential	
2. Pavement Condition	Existence of pavement defects in the road surface such as cracking, rutting, potholes, settlements, and others.	
5. Operating Traffic	Operating traffic volume detemines the extent of road utilization by the public.	
4. Safety Conditions	Smoothness of the road surface that causes safety hazards to vehicle stopping and braking; Low skid resistance or surface friction; High accident rates (rear-end type).	
6. Maintenance Cost	The overall maintenance cost for the road section in need of maintenance, this includes closing and detouring costs.	
7. Importance to Community	Overall importance to community determined by its distance from official buildings or important locations such as hospital, schools, mosques, etc. See Part II.	
	OVERALL	100%

Part II: The importance to community factor (No. 7 in Part I) can be measured by different sub-factors; a list is shown in the following table. In order to quantify the weight of this factor in priority ranking, you are requested to give your estimated weight for each of these sub-factors, based on your experience and common sense of maintenance priority ranking practices:

Factor	Description	Importance Weight (%)
1. Road Class	Major/Minor road; arterial, collector, or local; Commercial or Residential	
2. Distance from CBD	The distance from down-town or City Business Center determines the importance of the road section.	
3. Distance from official buildings	If the road section under consideration passing through an official complex may call for higher priority.	
4. Operating Traffic	Higher traffic volume roads calls for higher priority	
5. Availabilirty of alternative roads	availability of alternative roads affcets the priority of maintenance for the road in question	
6. Distance from other important buildings	Other buildings such as Civil Defense, Hospitals, Schools, etc. may call for higher maintenance priority	
	OVERALL	100%

Part III: Any other factors that may affect the maintenance priority ranking in your opinion:

1. .....
2. .....
3. .....

Part IV: Your position and/or qualification (check please):

1. Highway Pavement/Traffic Management Academician ..... ( )
2. Pavement Management Department Official ..... ( )
3. Highway Pavement/Traffic Engineer ..... ( )
4. Pavement Maintenance Supervisor/Texhnician..... ..... ( )
5. Qualified Non-Pavement Specialist ..... ( )
6. Ordinary Road User ..... ( )

Part V: Your Name, Tel/Fax, and Address (Optional): .....

Finally, We would like to thank you for your cooperation which will be very helpful to us.
Please send back your response to KFUPM Box 501 Dhahran 31261, KSA or Fax it to (03) 860 3996. Attn. Mr. Ramadhan

بسم الله الرحمن الرحيم

Ministry of Higher Education
King Fahd University of Petroleum & Minerals
COLLEGE OF ENGINEERING SCIENCES
CIVIL ENGINEERING DEPARTMENT

وزارة التعليم العالي
جامعة الملك فهد للبترول والمعادن
كلية العلوم الهندسية
قسم الهندسة المدنية

Dear Manager, Engineer, Technician, Supervisor, Pavement Specialist, and Road User;

Civil Engineering Department is undertaking a research project on the development of pavement management modeling (Ph.D. Research Work). A part of this project is a modeling of maintenance priority ranking. This modeling is considered a major part of any Pavement Management System (PMS) since it determines the order of urgency or importance of pavement sections in need of maintenance and repair.

The Analytical Hierarchy Process (AHP) is a new technique for priority assessment. In this method, the weight of importance of the different factors, considered in the priority ranking process, is determined by pair-wise comparison between these factors. This comparison is done according to an established scale. Experienced people of the matter under study are asked to give this comparison. In this study, different groups of people are considered (i.e. all groups that may have an opinion in the road maintenance priority). What is required is to give an estimate ratio of the importance for each pair of factors that affect the maintenance priority ranking process. **Table 1** below details the factors that are mostly affect the priority ranking.

You are kindly requested to fill out the pair-wise comparison Table 3 by checking the appropriate ratio of importance for each pair of factors.

Similarly, **Table 4** has to be filled using the information in **Table 2** about the pair-wise comparison of the importance of the individuals participated in this questionnaire.

Your position and/or qualification (check please):

1. Highway Pavement/Traffic Management Academician ( )
2. Pavement Management Department Official ( )
3. Highway Pavement/Traffic Engineer ( )
4. Pavement Maintenance Supervisor/Technician ( )
5. Qualified Non-Pavement Specialist ( )
6. Ordinary Road User ( )

Finally, We would like to thank you for your cooperation which will be very helpful to us.

Your Name, Tel/Fax, and Address (Optional):.....

Please send back your response to KFUPM Box 501 Dhahran 31261, KSA or Fax it to (03) 860 3996, Attn. Mr. Ramadhan

Table 1. Factors Considered in the Pavement Maintenance Priority Ranking.

Factor	Explanation
1. Road Class	Major/Minor Road; Arterial, Collector, or Local; Commercial or Residential
2. Pavement Condition	Existence of pavement defects in the road surface such as cracking, rutting, potholes, settlements, and others.
3. Riding Quality	Existence of longitudinal corrugation, potholes, and unevenness in the road surface that cause high stresses to vehicles and discomfort to the road users (drivers and passengers); High road roughness.
4. Safety Conditions	Smoothness of the road surface that causes safety hazards to vehicle stopping and braking; Low skid resistance or surface friction; High accident rates (rear-end type).
5. Operating Traffic	Operating traffic volume determines the extent of road utilization by the public.
6. Maintenance Cost	The overall maintenance cost for the road section in need of maintenance, this includes closing and detouring costs.
7. Importance to Community	Overall importance to community determined by its utilization by official people or VIPs, distance from official buildings or important locations such as hospital, schools, mosques, etc.

Table 2. Persons involved in Priority Ranking Study

Person Group	Explanation
Academician	Highway Pavement/Traffic Management with experience in maintenance management
Managers	Pavement management department officials in ministries, municipalities, or road construction and maintenance companies
Engineers	Highway pavement or traffic engineer in highway departments or companies
Supervisors	Pavement maintenance supervisors or technicians working in pavement evaluation or maintenance firms or offices
Non-pavement Qualified	Qualified persons (not in pavement) such as journalists, education's staff, economists, businessmen, etc.
Others	Any ordinary road users other than the above

Table 3. Pair-wise Comparison of Factors Considered in the Priority Ranking Process.

Factor to be compared		Priority weight of importance pair-wise comparison *																
Factor 1	Factor 2	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
Road Class	Pavement Condition																	
Road Class	Riding Quality																	
Road Class	Safety Conditions																	
Road Class	Operating Traffic																	
Road Class	Maintenance Cost																	
Road Class	Importance to Community																	
Pavement Condition	Riding Quality																	
Pavement Condition	Safety Conditions																	
Pavement Condition	Operating Traffic																	
Pavement Condition	Maintenance Cost																	
Pavement Condition	Importance to Community																	
Riding Quality	Safety Conditions																	
Riding Quality	Operating Traffic																	
Riding Quality	Maintenance Cost																	
Riding Quality	Importance to Community																	
Safety Conditions	Operating Traffic																	
Safety Conditions	Maintenance Cost																	
Safety Conditions	Importance to Community																	
Operating Traffic	Maintenance Cost																	
Operating Traffic	Importance to Community																	
Maintenance Cost	Importance to Community																	

* Required: Please check the square by (X) for the ratio of importance of factor 1 to factor 2. Example Road Class to Pavement Condition importance ratio is 1:5 means that the pavement condition is five times more important in *priority ranking process* than road class. Therefore the box under the heading of 1/5 is to be checked.

Table 4. Pair-wise Comparison between individuals.

Groups to be compared		Priority weight of importance pair-wise comparison *																
Group 1	Group 2	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9
Academician	Managers																	
Academician	Engineers																	
Academician	Supervisors																	
Academician	Non-pavement Qualified																	
Academician	Others																	
Managers	Engineers																	
Managers	Supervisors																	
Managers	Non-pavement Qualified																	
Managers	Others																	
Engineers	Supervisors																	
Engineers	Non-pavement Qualified																	
Engineers	Others																	
Supervisors	Non-pavement Qualified																	
Supervisors	Others																	
Non-pavement Qualified	Others																	

* Required: Please check the square by (X) for the ratio of importance of Group 1 to Group 2. Example Engineers to supervisors importance ratio is 3:1 means that an engineer's opinion is three times more important in *priority ranking process* than that of a supervisor. Therefore the box under the heading of 3/1 is to be checked.

APPENDIX - B

Comparison between Saudi and UAE Experience

In order to extend this to the other Gulf countries, Part I and Part II of the priority ranking questionnaire were sent to the United Arab Emirates (UAE). The forms were distributed officially by the Road Department of Dubai Municipality to other pavement departments and contracting companies in UAE. A set of thirty forms were received back from UAE. Three forms were excluded since they were not completed, and a total of twenty-seven were considered. Tables B-1 and B-2 show a summary of the UAE data.

The collected data of UAE shown in Table B-1 were statistically compared with those collected in Saudi Arabia shown in Table 4.10, using the two-step technique. The results of these comparisons are shown in Table B-3. There is a clear difference between Saudi and UAE experiences or responses to the priority ranking factor weight determination. Road Class factor and Pavement Condition factor do not have equal statistical means in both countries. Therefore, in general, the perception of the maintenance priority ranking between the two countries is different. UAE participants ranked the Road Class as the most important factor and the Riding Quality as the least important factor, while Saudi participants ranked Pavement Condition as the most important factor and the Maintenance Cost as the least important factor. This difference may be attributed to the fact that the UAE pavement condition is (in general) better

Table B-1. Summary of main survey collected data of Part . I of UAE.

No.	Exp. Code	Factor 1, Road Class	Factor 2 Pavement Condition	Factor 3 Operating Traffic	Factor 4 Riding Quality	Factor 5 Safety Condition	Factor 6 Maint. Cost	Factor 7 Importance	Sum
1	1	20	15	15	10	10	20	10	100
2	1	20	10	10	5	30	15	10	100
3	2	25	25	10	15	10	5	10	100
4	2	20	25	15	10	5	10	15	100
5	3	15	15	15	10	25	10	10	100
6	3	10	5	10	5	40	20	10	100
7	3	5	16	20	16	19	8	16	100
8	3	20	10	15	10	10	30	5	100
9	3	20	10	10	10	20	10	20	100
10	3	10	10	25	10	20	10	15	100
11	3	15	10	15	15	20	15	10	100
12	3	15	20	10	20	15	10	10	100
13	3	15	20	10	10	20	15	10	100
14	3	5	15	10	15	25	20	10	100
15	3	30	5	10	10	20	5	20	100
16	3	25	5	5	15	25	5	20	100
17	3	20	20	15	5	5	5	30	100
18	3	20	10	15	10	10	30	5	100
19	3	10	15	20	25	5	5	20	100
20	3	20	9	14	9	20	14	14	100
21	3	20	12.5	15	5	20	15	12.5	100
22	3	30	20	10	5	25	5	5	100
23	6	21	5	31	5	21	11	6	100
24	6	20	8	15	10	15	6	26	100
25	6	20	15	15	15	10	10	15	100
26	6	4	50	20	8	6	5	7	100
27	6	19	12	6	13	16	16	18	100
Average		17.6	14.5	14.1	11.0	17.3	12.2	13.3	
Standard Dev.		6.8	9.1	5.6	4.9	8.4	7.1	6.4	

Table B-2. Summary of main survey collected data of Part II of UAE.

No.	Experience Code	Sub-Factor 1, Road Class	Sub-Factor 2 Dist. form CBD	Sub-Factor 3 Use of VIPs	Sub-Factor 4 Operating Traffic	Sub-Factor 5 Maint. Alternatives	Sub-Factor 6 Other Imp. Locations	Sum
1	1	25	10	10	25	20	10	100
2	1	20	5	15	10	20	30	100
3	2	50	10	10	8	10	12	100
4	2	25	20	15	15	10	15	100
5	3	10	15	15	25	15	20	100
6	3	5	5	5	30	20	35	100
7	3	10	16	16	30	10	18	100
8	3	25	20	5	20	30	0	100
9	3	30	10	10	20	20	10	100
10	3	20	10	15	30	10	15	100
11	3	25	10	5	25	10	25	100
12	3	20	20	15	25	10	10	100
13	3	20	15	10	25	15	15	100
14	3	10	25	15	15	15	20	100
15	3	15	20	20	15	20	10	100
16	3	20	15	15	20	25	5	100
17	3	30	20	20	15	5	10	100
18	3	25	20	5	20	30	0	100
19	3	20	15	10	30	10	15	100
20	3	14	20	14	20	16	16	100
21	3	20	5	15	20	10	30	100
22	3	35	5	5	20	25	10	100
23	6	40	10	10	20	10	10	100
24	6	20	10	20	25	10	15	100
25	6	25	25	5	15	20	10	100
26	6	5	30	5	30	20	10	100
27	6	15	12	15	18	25	15	100
Average		21.4	14.7	11.9	21.1	16.3	14.5	
Standard Dev.		10.1	6.7	5.0	6.2	6.9	8.3	

Table B-3. Summary of the comparison test for Saudi-UAE experience variation.

Statistic	Factor 1		Factor 2		Factor 3		Factor 4		Factor 5		Factor 6		Factor 7	
	SA	UAE	SA	UAE	SA	UAE	SA	UAE	SA	UAE	SA	UAE	SA	UAE
Mean	13.45	17.56	19.64	14.54	13.19	14.11	12.38	10.96	15.46	17.30	10.59	12.22	15.29	13.31
Variance	40.97	46.03	130.36	83.48	41.42	31.41	30.65	24.04	55.53	70.83	36.73	50.56	63.48	40.64
Observations	65	27	65	27	65	27	65	27	65	27	65	27	65	27
F	1.123		1.562		1.319		1.275		1.275		1.377		1.562	
F Critical one-tail	0.557		1.796		1.796		1.796		0.557		0.557		1.796	
Conclusion 1	Reject Ho, Use t*-test		Accept Ho, Use t-test		Accept Ho, Use t-test		Accept Ho, Use t-test		Reject Ho, Use t*-test		Reject Ho, Use t*-test		Accept Ho, Use t-test	
t or t* statistic	-2.684		2.062		0.651		1.155		0-.985		-1.043		1.142	
t Critical two-tail	2.013		1.987		1.987		1.987		2.015		2.018		1.987	
Conclusion 2	Reject Ho		Reject Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho		Accept Ho	

compared to those in Saudi Arabia, therefore, the road pavement condition was considered as the most important factor with the highest priority weight as reported by Saudi respondents but not the UAE ones. On the hand, the riding quality, which is a derivative of the pavement condition, was rated as the least important factor by UAE respondents.

APPENDIX - C

FACTOR ANALYSIS

The basic idea of factor analysis is to combine the correlated variables in one factor for further analysis. The correlation among all the variables of a study are usually computed as the initial step in a factor analysis [Harman 1976].

In this study, the number of variables included in the priority modeling is not big (i.e. only seven). Factor analysis was performed according to principle component technique using STATISTICA package. This technique is the most widely used in factor analysis [Harman 1976]. There are number of criteria to determine the number of factors that are sufficient or adequate to the study. The most frequently used criteria are interpretability, reproducibility, and data fitting. eigenvalue of one. These criteria aim to limit the factors to those with eigenvalues greater than unity [Davison 1983].

In conducting the factor analysis, the solution of obtaining the number of factors (dimensions), should be interpretable. In other words, the factors obtained should be named sensibly and in such a way to convey information to both the analyst and the audience. [Stopher and Meyburg 1979]. A procedure that assists the interpretability is the rotation. The idea behind the rotation procedure is to simplify interpretation by rotating the factors about the origin to increase the larger variable loading and decrease the small

ones. The varimax rotation method is the most widely and is the one used in this study. Using the eigenvalue-one criteria, Figure C-1 shows a plot between the number of factors and the eigenvalue corresponding to each factor. As mentioned before, the addition of factors is stopped when the eigenvalue drops below unity. From the above figure, only three factors are sufficient or adequate to represent all variables.

The first step in factor analysis is to determine the correlation matrix. For this study, Table C-1 shows the correlation matrix of the seven factors considered. This matrix is used to generate the factor analysis results. STATISTICA package was used with the principle component method. The first eigenvalue ($\lambda 1 = 2.196$) which account for 31.37% of the total variance of the original variables and produce a set of coefficients shown in Table C-2.

The second step is to add as many factors as possible to the analysis. Only three additional factors were found as shown in Table C-3 with eigenvalues of $\lambda 1 = 2.196$, $\lambda 2 = 1.552$, and $\lambda 1 = 1.285$ that account for 71.9% of the total variations. In this table, it is difficult to group variables that are common or with high loadings to a specific factor. However, considering a minimum acceptable loading of 0.7, only one variable of each factor has loading above the acceptable level.

Varimax rotation was applied to the above factor analysis, in an attempt to improve its interpretability. The new factor loadings are shown in Table C-4, where Riding

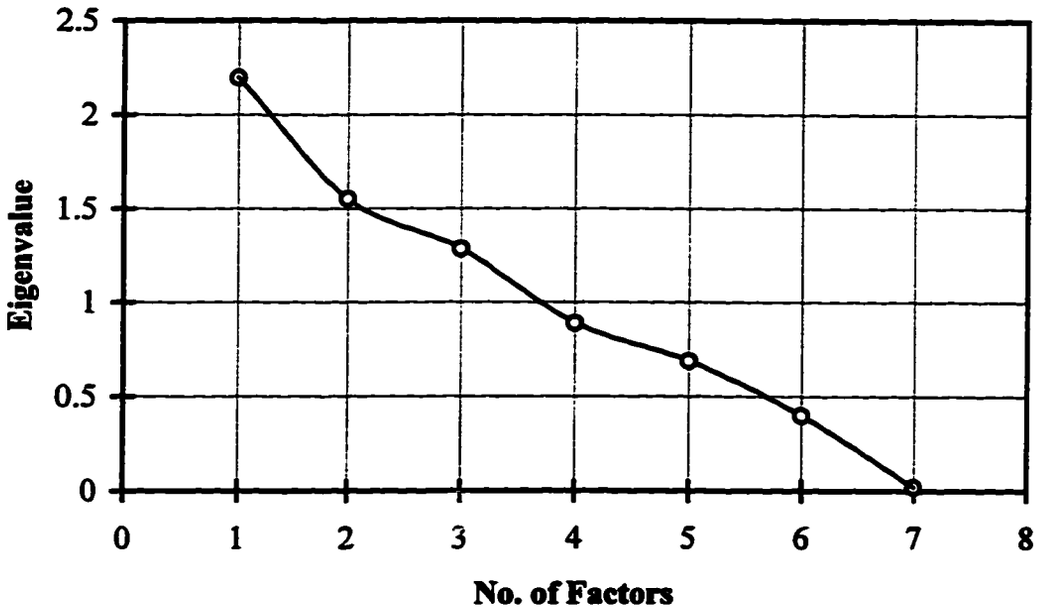


Figure C-1. Eigenvalue-one criteria plot.

Table C-1. Correlation matrix of the seven priority variables.

	Road Class	Pavement Condition	Operating Traffic	Riding Quality	Safety Condition	Maint. Cost	Imp. to Community
Road Class	1.000	-0.124	0.170	-0.391	-0.292	0.053	-0.259
Pavement Condition	-0.124	1.000	-0.591	-0.008	-0.276	-0.363	-0.315
Operating Traffic	0.170	-0.591	1.000	-0.265	-0.294	0.184	0.221
Riding Quality	-0.391	-0.008	-0.265	1.000	0.375	-0.306	-0.272
Safety Condition	-0.292	-0.276	-0.294	0.375	1.000	-0.101	-0.251
Maintenance Cost	0.053	-0.363	0.184	-0.306	-0.101	1.000	-0.124
Importance to Community	-0.259	-0.315	0.221	-0.272	-0.251	-0.124	1.000

Table C-2. Initial loading (unrotated) for the first factor.

Priority Factor	Factor 1
Road Class	0.447
Pavement Condition	-0.551
Operating Traffic	0.760
Riding Quality	-0.684
Safety Condition	-0.507
Maintenance Cost	0.481
Importance to Community	0.401
Explained Variable	2.196
Proportion of Total Variance	0.314

Table C-3. Initial loading (unrotated) for the three factors.

Priority Factor	Factor 1	Factor 2	Factor 3
Road Class	0.447	-0.470	-0.487
Pavement Condition	-0.551	-0.768	0.183
Operating Traffic	0.760	0.291	0.032
Riding Quality	-0.684	0.424	-0.052
Safety Condition	-0.507	0.625	-0.327
Maintenance Cost	0.481	0.151	-0.488
Importance to Community	0.401	0.249	0.816
Explained Variable	2.196	1.552	1.285
Proportion of Total Variance	0.314	0.222	0.184

Table C-4. Rotated loading (varimax raw) for the three factors.

Priority Factor	Factor 1	Factor 2	Factor 3
Road Class	0.626	0.130	0.500
Pavement Condition	0.143	-0.945	0.119
Operating Traffic	0.347	0.696	-0.242
Riding Quality	-0.788	-0.155	0.067
Safety Condition	-0.813	0.185	0.246
Maintenance Cost	0.220	0.574	0.338
Importance to Community	0.153	0.186	-0.911
Explained Variable	1.886	1.815	1.332
Proportion of Total Variance	0.269	0.259	0.190

Quality and Safety Condition variables have high loadings in factor 1. This factor can easily be called 'Road User Perception' since these two variables are produced or measured by how the road user feel about the road pavement from riding comfort and safety. Pavement Condition variable has a high loading (0.945) in factor 2, therefore, this factor can be called as 'Pavement Condition'. Similarly, factor 3 can be called 'Importance to Community' factor since only this variable has a high loading (0.911) corresponding to it. Road Class, Operating Traffic, and Maintenance Cost variables did not have enough loading to be considered in any of the above three factors. It can be seen that the rotation process enhanced the interpretability of the results of the factor analysis.

From this factor analysis, it can be concluded that this study could be carried out by considering only three factors: Pavement Condition, Road User Perception, and Importance to Community, to account for the maintenance priority ranking modeling. However, since only about 72% of the variation could be captured by extracting these main factors, this analysis was not necessary.

VITA

Personal Data:

- **Name:** Rezqallah Hasan Fayyadh Ramadhan
- **Nationality:** Jordanian
- **Marital Status:** Married (Five Children)
- **Date of Birth:** 15 December 1957
- **Religion:** Islam

Academic History:

- **Ph.D. degree** in Transportation Engineering (Pavement) from Civil Engineering Department of King Fahd University of Petroleum and Minerals, Dhahran Saudi Arabia, Dhahran-Saudi Arabia. July 1997.
- **M.Sc. degree** in Transportation Engineering (Pavement) from Civil Engineering Department of King Fahd University of Petroleum and Minerals, Dhahran Saudi Arabia, Dhahran-Saudi Arabia. June 1988.
- **B.Sc. Degree (Honor)** in Civil Engineering from Civil Engineering Department of King Fahd University of Petroleum and Minerals, Dhahran Saudi Arabia, Dhahran-Saudi Arabia. June 1981.

Specialization:

- Transportation Engineering (Pavement and Traffic) of the road and airfield networks.

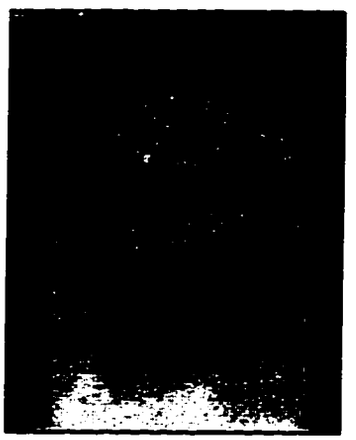
Employment History:

- Working at the Research Institute of King Fahd University of Petroleum and Minerals, Dhahran Saudi Arabia since 1981 as Pavement Engineer in the research areas of pavement design, pavement materials, pavement evaluation, and pavement maintenance management for road networks and airports.

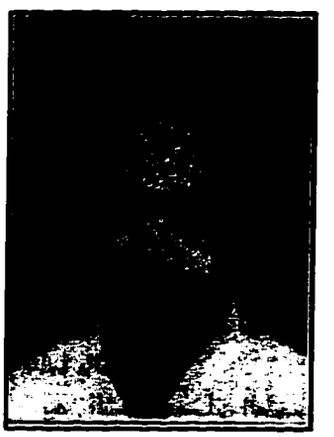
Research and Other Activities:

- The involvement and coordination of many funded and in-house research projects in the pavement area for several clients such as Presidency of Civil Aviation (PCA), Ministry of Communications (MOC), Royal Commission of Al-Jubail, Riyadh Municipality, Dammam Municipality, and other local companies and engineering firms.
- Author and co-author of several research technical papers presented in engineering local and international conferences or published in referred journals.
- An associate member of American Society Of Civil Engineers (ASCE) - Saudi Arabian Section.

Dissertation Committee

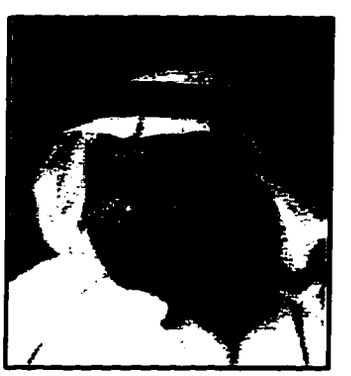


Dr. Hamad I. Al-AbdulWahhab
Associate Professor, CE
Dissertation Committee Chairman



Dr. Saleh O. Duffuaa
Professor, SE
Dissertation Committee Member

Dr. Nedhal T. Ratrout
Assistant Professor, CE
Dissertation Committee Member



Dr. Abdulaziz A. Bubshait
Associate Professor, CEM
Dissertation Committee Member

Dr. Walid S. Al-Sabah
Assistant Professor, MATH
Dissertation Committee Member

Dr. Khalaf A. Al-Ofi
Assistant Professor, CE
Dissertation Committee Member