A GIS-ENABLED MULTI-YEAR PAVEMENT REHABILITATION NEEDS ANALYSIS SYSTEM

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy in Civil Engineering

Georgia Institute of Technology
August 2004

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A GIS-ENABLED MULTI-YEAR PAVEMENT REHABILITATION NEEDS ANALYSIS SYSTEM

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To my parents

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and sincere thanks to my advisors, Dr. James S. Lai and Dr. Yichang (James) Tsai, whose guidance and endless efforts to keep me motivated. I am also appreciative of the many suggestions that I received from the members of my advisory committee – Dr. David Frost, Dr. Adjo Amekudzi, Dr. Glenn Rix, and Dr. Xiaoming Huo.

I can never express my thanks enough to my family for their endless support. I must thank my wife, Dongmei Yang, for encouraging me and giving me the strength through the hardest times. I can never repay the sacrifices my parents have made over the years for me to pursue my degree.

I would also like to thank my friends, Ruiting, Xiaodong, Xiaofeng, Tianfei, Liang, and Fang, for sharing my disappointments and frustrations during the hardest times. Special thanks are also due to my colleagues – Yiching, Mingzhan, Lixiang, Zhaohua, Sheng-Te, Tina, and Jianping, for the brainstorm that we had during the past few years.

I would like to take this opportunity to thank the Georgia Department of Transportation, especially engineers in the Office of Maintenance, for their help and cooperation in obtaining the data used for this study. The views presented in this dissertation are those of the author and do not necessarily represent those of the Georgia Department of Transportation.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ..... **iv**

TABLE OF CONTENTS ..... **v**

LIST OF FIGURES ..... **ix**

LIST OF ABBREVIATIONS ..... **xiii**

SUMMARY ..... **xvi**

CHAPTER 1 INTRODUCTION **1**
1.1 Problem Description 1
1.2 Thesis Objective 3
1.3 Thesis Organization 5

CHAPTER 2 LITERATURE REVIEW OF NETWORK-LEVEL REHABILITATION NEEDS ANALYSIS SYSTEM **8**
2.1 Introduction 8
2.2 Historical Development of Pavement Management Systems 10
2.3 Review of Methodologies for Developing a Network-Level Rehabilitation Needs Analysis System 15
2.3.1 Prioritization Approach 15
2.3.2 Network Optimization Approach 18
2.4 Review of Implementation of Network-Level Rehabilitation Needs Analysis ... 24
2.4.1 Summary of Network-Level Rehabilitation Needs Analysis Implementation Status 24
2.4.2 Examples of Needs Analysis Systems Used by Highway Agencies 28
2.5 Improvement needs for Network-Level Rehabilitation Needs Analysis 38

CHAPTER 3 REVIEW OF GDOT PAVEMENT REHABILITATION NEEDS ANALYSIS PRACTICE **41**
3.1 Current Pavement Rehabilitation Needs analysis Practice at GDOT 42
3.2 GDOT Pavement Condition Survey Database 43
3.3 Historical Pavement Condition Data Filtering and Processing 49

CHAPTER 4 A FRAMEWORK FOR A GIS-ENABLED MULTI-YEAR PAVEMENT REHABILITATION NEEDS ANALYSIS SYSTEM FOR GDOT **55**
4.1 Needs for Developing a Pavement Rehabilitation Needs Analysis System 55
4.2 A Framework for a Pavement Rehabilitation Needs Analysis System 60

CHAPTER 5 DEVELOPMENT OF PROJECT-LEVEL ANALYSIS MODULE .. **65**
5.1 Overview of Project-level Analysis Module 65

5.2 Pavement Performance Forecasting Functions 68
5.2.1 A Function for Forecasting Project-level Pavement Performance Ratings 70
5.2.2 Function for Determining Deterioration Rates after Rehabilitation Treatments 75
5.2.3 Project-level Pavement Distress deduct value Forecast Function 80
5.3 Develop Rehabilitation Treatment Method and Costs Determination Function . 85
5.4 Life cycle Cost Effectiveness Analysis Functions 91
5.5 Interaction Between Project-level Analysis Module and Network-level Analysis Module 100
5.6 Approach to Reduce Computing Time in Project-level Analysis Module 102

CHAPTER 6 DEVELOPMENT OF NETWORK-LEVEL ANALYSIS MODULE 105
6.1 Overview of Network-Level Analysis Module 105
6.2 Justifications for Choosing a Single-Year Prioritization Approach for Developing Network-level Analysis Module 109
6.2.1 Optimization Approaches versus Prioritization Approaches 109
6.2.2 Single-year versus Multi-year Approaches 112
6.3 Scope and Capability of Network-Level Rehabilitation Needs Analysis 115
6.4 Algorithms for Multi-Year Network-level Pavement Rehabilitation Needs Analysis 121
6.4.1 General Algorithms for Multi-Year Network-level Pavement Rehabilitation Needs Analysis 121
6.4.2 Detailed Analysis Flow 126
6.4.3 Issues Regarding Associating Pavement Projects with State Congressional Districts 129
6.5 Approaches to Reduce Computing Time in Network Level Analyses 130

CHAPTER 7 DEVELOPMENT OF GIS MODULE 134
7.1 Review of GIS Integration with Pavement Needs Analysis Practice 134
7.2 Overview of GIS Module 135
7.3 Common Linear Reference System and Base Map Preparation 138
7.3.1 MDS Process for Linear Features 139
7.3.2 “Addrelate” Method for Polygon Features 142
7.3.3 Data 145
7.4 GIS Spatial Analysis and Visualization 147
7.4.1 GIS Spatial Analysis 147
7.4.2 Visualization 153
7.5 Interactive Map-based Multi-year What-if Pavement Scenario Analysis 161

CHAPTER 8 DEVELOPMENT OF NEEDAS PROGRAM 174
8.1 Overview of NEEDAS Program 175
8.2 Launch NEEDAS Program and Open/Save Database 181
8.3 Set and Select Input Parameters 185
8.3.1 Set Needs analysis Parameters 186
8.3.2 Update Treatment Criteria 198
8.4 Perform Needs Analysis 206

8.5 View and Output Needs Analysis Results 215
8.6 Online Help and User's Manual 230

CHAPTER 9 CASE STUDIES USING THE NEEDAS PROGRAM 232
9.1 Data Set Used for Case Studies 233
9.2 Study 1: Funding Required to Maintain Different Pavement Performance Levels 234
9.3 Study 2: Manual Adjustment of Pavement Performance Rating 239
9.4 Study 3: Need Analysis with Balancing Constraints 241

CHAPTER 10 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS ... 245
10.1 Summary and Conclusions 245
10.2 Recommendations for Future Research 249

APPENDIX A FORMULATION OF ADOT'S NEEDS ANALYSIS OPTIMIZATION MODEL 252

REFERENCE 260

VITA 269

LIST OF TABLES

Table 2 - 1 Network Project Selection Practices 25

Table 2 - 2 Prioritization Methods Survey Results (Tsai, 2003) 26

Table 2 - 3 Prioritization Criteria Survey Results (Tsai, 2003) 27

Table 2 - 4 Software Used Survey Results (Tsai, 2003)..... 28

Table 5 - 1 Linear Empirical Model Provided by GDOT 71

Table 5 - 2 Simplified Pavement Deterioration Model..... 72

Table 5 - 3 Example of Pavement Distress deduct values versus Project Rating..... 81

Table 5 - 4 Default Treatment Methods..... 89

Table 5 - 5 Descriptions of the Distress deduct value Array 104

Table 6 - 1 Example of Type II Analysis Results..... 118

Table 6 - 2 Refinement of Type II Analysis Results Using Type III Analysis Results. 119

Table 6 - 3 GDOT District-Level Analysis Results..... 131

Table 8 - 1 Fields in tblNeedAnalysisResults Table (Project-Level Results) 208

Table 8 - 2 Values in tblSetting Table 209

Table 9 - 1 Network-Level Composite Rating in Fiscal Year 2003 234

Table 9 - 2 Annual Funding Required to Maintain Different SCR..... 235

Table 9 - 3 Annual Funding Required to Maintain Different SCR..... 236

Table 9 - 4 Results of Alternate Funding Schedules on SCR 240

Table 9 - 5 Comparison of Funding Needs to Meet SCR Requirement 242

LIST OF FIGURES

Figure 2 - 1 A Conceptual IT-based Network-level Pavement Rehabilitation Needs Analysis System and Its Associated Components (Tsai & Lai, 2002) 14

Figure 3 - 1 Project Level Information Entry Form (Source: Tsai & Lai, 2001) 45

Figure 3 - 2 Segment Level Information Entry Form (Source: Tsai & Lai, 2001)..... 46

Figure 3 - 3 Error Sources and Data Filtering Results of Historical Pavement Data 52

Figure 4 - 1 Framework of NEEDAS 61

Figure 4 - 2 Flow of NEEDAS 64

Figure 5 - 1 Flow Chart of Project-level Analysis Module 67

Figure 5 - 2 Various Types of Deterioration Curves (Livneh, 1998) 73

Figure 5 - 3 Pavement Rating Prediction Model 77

Figure 5 - 4 Future Improved Method for Determining Effective Deterioration Rate 78

Figure 5 - 5 Decision Tree of Project Rehabilitation Treatment Methods 88

Figure 5 - 6 Illustration of Residual Value 96

Figure 5 - 7 Concept of Determining Rehabilitation Treatment Benefit 99

Figure 6 - 1 Flow Chart of Network-level Analysis Module..... 108

Figure 6 - 2 Analysis Performed in the Network-level Analysis Module 122

Figure 6 - 3 Analysis Flow of A Selected Scenario..... 127

Figure 7 - 1 Flow Chart of GIS Module 137

Figure 7 - 2 Example of Common Linear Reference System..... 140

Figure 7 - 3 Example of AddRelate Method..... 144

Figure 7 - 4 GIS Base Map 146

Figure 7 - 5 Illustration of Spatial Analysis..... 149

Figure 7 - 6 Lane Miles and Percentages of Projects with Rating ≤ 70 among GDOT Districts in Fiscal Year 2003 151

Figure 7 - 7 Example of Spatial Selection 152

Figure 7 - 8 Visualize Spatial and Temporal Treatment Information 155

Figure 7 - 9 Visualize Project-level Pavement Condition in Year 2003 157

Figure 7 - 10 Visualize Project-level Historical Data 159

Figure 7 - 11 Monitor Routes Not Considered in the Needs Analysis 160

Figure 7 - 12 Algorithm of Interactive Map-based Multi-Year What-if Pavement Scenario Analysis 163

Figure 7 - 13 Example of Interactive Analysis 171

Figure 7 - 14 Impact Analysis of Project-Level Distress Deduct Value (Load Cracking) 172

Figure 7 - 15 Impact Analysis of Network-Level Composite Rating 173

Figure 8 - 1 Main Screen of the NEEDAS 177

Figure 8 - 2 Procedures for Performing Pavement Rehabilitation Needs analysis 180

Figure 8 - 3 Login Form for NEEDAS System 182

Figure 8 - 4 Set Analysis Years and Budget Form 188

Figure 8 - 5 Set Needs analysis Criteria Form 189

Figure 8 - 6 Set Pavement Performance Constraint Form 190

Figure 8 - 7 Set Annual Traffic Increase Rate Form 191

Figure 8 - 8 Set Annual Interest Rate Form 191

Figure 8 - 9 Select Pavement Performance Model 193

Figure 8 - 10 Illustration of Incorporation New Models in the Future 194

Figure 8 - 11 Select Pavement Distress Model 196

Figure 8 - 12 Global Distress Deduct Values Prediction Model 196

Figure 8 - 13 Interface of Selecting Treatment Priority Criteria 197

Figure 8 - 14 Set Ratios of Unit Costs between Interstate and State Highway 198

Figure 8 - 15 Pavement Service Life Model 200

Figure 8 - 16 Update Treatment Method Form 201

Figure 8 - 17 Update Regular Treatment Criteria Form 204

Figure 8 - 18 Default Treatment Criteria Form 205

Figure 8 - 19 Needs Analysis Results 213

Figure 8 - 20 Performing Needs analysis 214

Figure 8 - 21 Georgia State Route Distribution 217

Figure 8 - 22 Project Survey Information DB Grid 218

Figure 8 - 23 Detail COPACES Project Survey Information 219

Figure 8 - 24 View Detail Project Results 223

Figure 8 - 25 View Results by Different Jurisdictions 226

Figure 8 - 26 View Results by Different Jurisdictions 228

Figure 8 - 27 Interface of GIS Map 229

Figure 8 - 28 About NEEDAS 230

Figure 8 - 29 Online Help and User's Manual 231

Figure 9 - 1 Yearly Rehabilitation Cost Corresponding to Different Performance Levels 237

Figure 9 - 2 GDOT District Composite Rating Distribution for Case 3-1 243

Figure 9 - 3 GDOT District Composite Rating Distribution for Case 3-2 243

Figure 9 - 4 GDOT District Rehabilitation Cost Distribution for Case 3-1 244

Figure 9 - 5 GDOT District Rehabilitation Cost Distribution for Case 3-2 244

Figure A - 1 Illustration of the Markov Chain Pavement Performance Model for PCR=98 in the first year 253

Figure A - 2 Example of Transition Probability Matrix 254

LIST OF ABBREVIATIONS

- AADT: Annual average daily traffic
- AASHO: American Association of State Highway Officials
- AASHTO: American Association of State Highway and Transportation Officials
- ADOT: Arizona Department of Transportation
- Caltrans: California Department of Transportation
- COPACES: Computerized Pavement Condition Evaluation System for GDOT
- DOT: Department of Transportation
- FHWA: Federal Highway Administration
- GA: Generic Algorithm
- GASB: Government Accountant Standard Board
- GASB 34: Government Accountant Standard Board Statement 34
- GDOT: Georgia Department of Transportation
- HCM: Highway Cost Model
- HDM: Highway Development and Management Standards Model
- HERS-ST: Highway Economic Requirements System-State Version
- HOV: High Occupied Vehicles
- GIS: Geographic Information System
- InDOT: Indiana Department of Transportation
- IPMS: Indiana Pavement Management System
- IRI: International Roughness Index

- ISTEA: Intermodal Surface Transportation Efficiency Act
- IT: Information technology
- LCPC: Laboratoire Central des Ponts et Chaussees
- LRS: Linear Reference System
- MIT: Massachusetts Institute of Technology
- MnDOT: Minnesota Department of Transportation
- MS: Microsoft Corporate
- MDS: Modified dynamic segmentation
- NCHRP: National Cooperative Highway Research Program
- NEEDAS: GIS-enabled multi-year pavement needs analysis system for GDOT
- NHS: National Highway System
- NOS: Network Optimization System for ADOT
- PACES: Pavement Condition Evaluation System for GDOT
- PCR: Pavement Condition Rating
- PMS: Pavement management system
- PQI: Pavement Quality Index
- PSI: Pavement Serviceability Index
- RAM: Random access memory
- RCLink: Road Characteristics Link
- RRS: Roadway Referencing System for InDOT
- TRRL: Transport and Road Research Laboratory
- VDOT: Virginia Department of Transportation

- VMT: Vehicle Miles Traveled
- VOC: Vehicle operation cost
- WDOT: Washington State Department of Transportation

SUMMARY

This dissertation presents the algorithm, methodology, modeling, and system development of a GIS-enabled multi-year pavement rehabilitation needs analysis system which can perform multi-year network-level pavement rehabilitation needs analysis subject to funding availability, minimum performance requirements, and balancing constraints. The system links network-level analysis results directly with project-level maintenance plans and, therefore, can generate not only network-level results but also detailed project-level rehabilitation plans, such as when to treat, where to treat and what treatment method to use.

The system first utilizes the current and historical project level pavement condition evaluation information stored in the central Oracle database to forecast future project performance ratings and distresses, to determine appropriate treatment methods and costs, and to calculate life-cycle cost effectiveness ratios for all the projects in the pavement network. Based on this information, a methodology was developed to perform various network-level analyses to determine multi-year funding requirements to meet various prescribed pavement performance requirements and to determine optimum pavement rehabilitation plans subject to funding availability and other requirements, such as balancing funding distribution or future pavement performance among Georgia Department of Transportation (GDOT) Engineering Districts or State Congressional Districts. The system integrates graphical information on GIS maps with information in the central Oracle database and the needs analysis results seamlessly so that engineers can perform interactive map-based multi-year what-if needs analysis directly on the maps

using the framework and methodology presented in this dissertation. Several case studies using the actual historical pavement condition evaluation data from the GDOT are presented to illustrate the capabilities of the system. The dissertation concludes with a summary of major conclusions and recommendations for future research.

Besides linking network-level analysis results directly with project-level maintenance plans, the following major advantages of the system are also recognized: GIS technology is fully utilized in the system. The system is one of the first pavement needs analysis systems that allows an engineer to perform interactive map-based what-if scenario analyses on multi-year pavement needs analysis. The system allows the rehabilitation plans to balance pavement rehabilitation costs and performances among different political jurisdictions. The system can perform various types of analyses to develop multi-year rehabilitation plans subject to various budget and performance constraints together with the balancing constraints. Although the system was developed for GDOT, with slight modifications, the system can be used by engineers in other transportation agencies to perform the same analyses.

CHAPTER 1

INTRODUCTION

1.1 Problem Description

Maintaining a pavement system at an acceptable level of service with limited budgets is always a challenge for every transportation agency. A pavement rehabilitation needs analysis system provides a valuable tool for achieving better and more cost-effective management of network pavement performance. The term of rehabilitation used in this thesis includes maintenance, repair and rehabilitations.

Much has been written in the past about the development of pavement rehabilitation needs analysis systems. However, even with several decades of implementation records, the state of pavement rehabilitation needs analysis systems still has much need for improvement. Several important issues related to pavement needs analysis remain to be explored, and some new trends in the development of pavement needs analysis systems, as briefly described below, have recently emerged (Kulkarni & Miller, 2003). Although almost every State Department of Transportation in the USA has certain types of pavement rehabilitation needs analysis systems, not many systems are fully implemented due to institutional and technical issues. It is believed that pavement rehabilitation needs analysis systems would be more widely implemented if those issues could be properly addressed.

Institutional Issues: According to NCHRP research projects, transportation agencies are usually unwilling to change their existing pavement management practices and accept results provided by pavement rehabilitation needs analysis systems without

understanding what is going on in the systems. Unfortunately, some pavement needs analysis systems with very advanced optimization models are difficult to understand. The potential user is afraid of such "Black Box" systems.

Technical Issues: Pavement rehabilitation needs analysis systems are invariably very complex, and incorporation of the new developments in Information Technology (IT), such as database technology and increased computing power, has the potential to greatly enhance the performance of pavement rehabilitation needs analysis systems. Incorporating Geographic Information System (GIS) visualization and spatial analysis capability would be very desirable. Recent advances in IT and GIS should make it very feasible to incorporate those technologies into pavement rehabilitation needs analysis systems. Very few pavement needs analysis systems have the capability to develop rehabilitation plans that can achieve balancing the rehabilitation needs of different jurisdictions within the network. The capability to balance the workload among different engineering districts, or to balance the pavement performance or fund among different political jurisdictions within the network system is very desirable and can foster the implementation of the system (Smith, 2000). During past decades, large amounts of pavement performance data have been collected, and the ability to incorporate those data into system could greatly improve the accuracy of the system. At the present time, very few systems have the capability to do so. Until now, most of the systems could perform either project-level analyses or network-level analyses. The capability to link the project-level analysis results with the network-level analysis results is very important in developing network rehabilitation plans. Also, the ability for the decision makers to perform "what-if" scenario analyses to evaluate the impact of different multi-year

rehabilitation strategies on the network's pavement performance conditions over time would be very useful. These are the technical issues in the development and implementation of pavement rehabilitation needs analysis systems.

Besides the issues pointed out above, the need for developing a pavement needs analysis system also comes from the changing of the accounting standards. In June, 1999, the Government Accountant Standard Board (GASB) published Statement 34 (GASB 34), which required that state and local governments begin reporting the value of their infrastructure assets, including roads, bridges, water and sewer facilities, and dams, etc., in their annual financial reports (Maze, 2000). Since pavement is one of the important components of infrastructure assets and since maintaining pavement assets efficiently and effectively is highly desired, pavement needs analyses systems have attracted more and more attention due to GASB 34. Today, many states have some form of pavement needs analysis programs in place or under development, and the need to improve the system is even more urgent.

1.2 Thesis Objective

The objective of this thesis is to present a system for determining future pavement rehabilitation needs and budget planning. The system developed in this thesis is a part of the research project for developing IT-based pavement management system for the Georgia Department of Transportation (GDOT). The system is intended to improve current GDOT practice of performing the annual rehabilitation planning and programming. Detailed information about GDOT's practice will be introduced in Chapter 3.

The system presented in this thesis is expected to incorporate functions to address the various issues mentioned above. Although the system has been developed specifically for GDOT's use in developing multi-year rehabilitation plans, it is general enough that with slight modifications the system can be used by other transportation agencies. The following were considerations in the design of the systems:

(1) Compatibility with the current practices used by GDOT to minimize the efforts of migrating from the current practice to the new system.

(2) Direct linkage between network-level analysis results and project-level maintenance plans.

(3) Capability for balancing needs among GDOT Districts and among Georgia State Congressional Districts.

(4) Flexibility for modifying existing pavement performance models, treatment methods, and the GDOT districts and congressional districts boundaries.

(5) Adaptability for incorporating new developments, such as pavement performance models and new treatment method decision criteria into the system.

(6) Capability to perform "What If" analyses so that decision makers could compare results of different scenarios.

(7) Capability for utilizing powerful GIS function in visualizing, analyzing, and interacting with needs analysis results dynamically.

(8) Capability for utilizing historical pavement condition survey data.

1.3 Thesis Organization

This thesis focuses on the development of a GIS-enabled multi-year pavement needs analysis system (NEEDAS) for the GDOT Office of Maintenance as a planning tool to perform multi-year pavement rehabilitation needs analysis to meet various network-level and project-level performance requirements based on pavement condition evaluation data. The entire development process, including the development of the various analysis models and functions, and the integration of entire system is discussed in the thesis.

Specifically, Chapter 2 first presents a review of historical development of pavement management systems. Then, different methodologies for developing network-level pavement rehabilitation needs analysis systems are reviewed. Various network-level rehabilitation needs analysis systems based on these methodologies are described. The limitations of these systems are identified, and improvement needs for network-level rehabilitation needs analysis systems are proposed.

Chapter 3 describes current GDOT pavement rehabilitation needs analysis practice. Also presented in this chapter is the GDOT pavement condition survey database, as well as the processes for sanitizing the historical data. The GDOT historical pavement condition survey database is the foundation for the NEEDAS program, as most of pavement performance forecasting models, pavement deterioration models, and the pavement rehabilitation treatment models are developed using the historical pavement condition survey data.

Chapters 4-7 present detailed system development of the NEEDAS program. Chapter 4 identifies needs for developing the system based on the desirable features and

needs identified in Chapter 1 to 3. The NEEDAS program consists of three modules: the Project-level Analysis Module, the Network-level Analysis Module, and the GIS Module. The pavement rehabilitation needs analysis is performed through interaction between the Project-level Analysis Module and the Network-level Analysis Module, and the GIS Module is used as a supplemental decision-making tool to help refine the needs analysis results. Chapter 5 describes the main components of the Project-level Analysis Module, which includes the functions for determining rehabilitation treatment methods and costs and forecasting future project performance and calculating life cycle cost effectiveness ratios for each pavement project within the network. Chapter 6 presents the detailed information of how the Network-level Analysis Module was developed and the challenging issues involved in the development of the Network-level Analysis Module. Chapter 7 first reviews the GIS integration into pavement needs analyses practice and then focuses on the integration of the GIS technology with multi-year pavement needs analysis modeling, including the Common Linear Reference System (LRS) and GIS Base Map Preparation Function, Spatial Analysis and Visualization Function, and Interactive Map-based Multi-year Pavement Scenario Analysis Function. It is worth pointing out that the NEEDAS program is one of the first pavement needs analyses systems that allows users to interact dynamically with pavement needs analyses through GIS maps.

Chapter 8 describes the NEEDAS computer program. Considerations for the flexibility and scalability of the system in the course of the program development to allow for ease of modifications of the program are presented. Various interfaces and design features are incorporated into the NEEDAS program development to make the computer program more user friendly and easier to implement.

Chapter 9 presents several case studies to illustrate the versatility and flexibility of the NEEDAS computer program in performing multi-year rehabilitation needs analysis. The cases presented include multi-year rehabilitation needs analysis results under different scenarios, such as varying annual rehabilitation funding amounts, different pavement performance constraints, and balancing constraints. Actual pavement condition evaluation data from GDOT were used for all the analyses presented in this chapter.

Finally, Chapter 10 summarizes the important conclusions and major contributions based on the current research and presents recommendations for future improvements and validations of the NEEDAS program.

CHAPTER 2

LITERATURE REVIEW OF

NETWORK-LEVEL REHABILITATION NEEDS ANALYSIS SYSTEM

2.1 Introduction

The literature review presented in this chapter covers the following four topics:

1. Historical development of pavement management systems
2. Review of methodologies for developing network-level pavement rehabilitation needs analysis systems
3. Overview of implementation of network-level rehabilitation needs analysis systems
4. Improvement needs for network-level rehabilitation needs analysis systems

The highway system is the economic artery in the USA. According to the highway statistics published by the Federal Highway Administration (FHWA) in 2002, there are 46,715 miles of Interstate highways, 114,706 miles of other national highways, 700,013 miles of other Federal-aided highways, and 3,002,830 miles of non-Federal-aid highways in the USA. More than 70% of the total statewide shipments in term of ton-miles were carried over interstate highway, and nearly 55% of the value of the commodities was transported by truck in 1993 (Chin et al., 1998). Americans took about 505 million long-distance, personal-use vehicle trips, traveling over 280 billion vehicle miles on the nation's highways in 1995 (U.S. DOT et al., 1997).

Every year in the USA, huge amounts of money are spent on the highways by the Federal agencies, states, counties, and municipalities. In 2001, Federal, state, and local governments invested about 130 billion dollars on various highway-related activities, such as capital outlay, maintenance, traffic services, administration, research, safety, etc. More than 30 billion dollars were spent on highway maintenance alone (FHWA, 2002a). Even with such huge amounts of money spent on the highway system, more than half of all roads in the USA are still rated as only fair, mediocre, or in poor condition (Smith et al., 2000). Therefore, there is a need to spend highway money effectively and efficiently. A pavement management system (PMS) provides such a tool to meet this need.

A pavement management system (PMS) is a set of tools or methods that assists decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time (AASHTO, 1990). A good PMS is designed to improve the efficiency of pavement management, expand its scope, provide feedback as to the consequences of decisions, and ensure the consistency of decisions made at different levels within the same organization (Haas et al., 1994). The primary objectives of a PMS are to answer the following questions (Peterson, 1987):

- What needs to be done for a given pavement project? A pavement project is a length of roadway with a common pavement section, similar structural conditions, and logical beginning and ending points.
- When are rehabilitation treatments needed?
- Which and in what order should pavement projects be treated?

A PMS has the capability of performing the following functions:

- Managing large amounts of pavement related data, such as inventory data and condition data,
- Evaluating the effectiveness of various rehabilitation strategies,
- Performing economic analyses of various rehabilitation strategies,
- Prioritizing rehabilitation pavement projects within the available funding constraints,
- Projecting funding needs to achieve certain level of pavement performance, and
- Supporting fund requests and justifying rehabilitation programs.

A PMS with all these capabilities could play a crucial role in managing the pavement system for a transportation agency.

2.2 Historical Development of Pavement Management Systems

The concept of a pavement management system can be traced back to 1966, when the American Association of State Highway Officials (AASHO) studied extending the results of the AASHO road test through the National Cooperative Highway Research Program (NCHRP) (Haas, 1994). Since then, in the late 1960s and early 1970s, several research groups began researching pavement management systems.

In 1970, FHWA and the Highway Research Board (now the Transportation Research Board) sponsored a workshop to discuss structural design of asphalt concrete

pavement systems. It was the fist national-level workshop in which the concept and the framework for pavement management systems were presented (Finn, 1997). Also in 1970, Haas and Hutchinson published a study on a highway pavement management system to the Australian Road Research Board (Haas et al., 1994). It was the first time the term "pavement management system" was used. In 1978, the first book on pavement management systems was published (Haas and Hudson, 1978).

The first project-level pavement management system was implemented by the Washington State Department of Transportation (WDOT) in 1974. The system identified rehabilitation treatment methods for the projects in its highway network. By 1980, only five states, Arizona, California, Idaho, Utah, and Washington, were reported to be in various stages of development of systematic procedures for managing their pavement systems (Finn, 1997). The first network-level PMS with optimization model was implemented by the Arizona Department of Transportation (ADOT) in 1982 (Golabi et al., 1982).

The Intermodal Surface Transportation Efficiency Act (ISTEA), passed into law by the Congress in 1991, mandated the development of pavement management system for each state Department of Transportation (DOT) and thus boosted the development and implementation of PMSs (U.S.DOT, 1997). As a result of ISTEA, the concept of pavement management had been built deeply into every transportation agency's operation systems. In June 1999, GASB published GASB 34, which required that state and local governments begin reporting the value of their infrastructure assets, including roads, bridges, water and sewer facilities, and dams, etc., in their annual financial reports (Maze, 2000). Since pavement is one of the important components of infrastructure assets, in

order to maintain pavement assets efficiently and effectively, PMS has attracted more and more attention due to the requirements stipulated by GASB 34. Today, all 50 states have some form of pavement management programs in place or under development.

Generally, PMS is developed and used in two levels: project level and network level (Cook and Lytton, 1987; Haas et al., 1994; Smith et al., 2000). Project-level PMS determines the most cost-effective strategy in the pavement design, establishes rehabilitation plans, or develops reconstruction strategy for a selected pavement project within available funds limitations and other constraints. Thus, the project-level PMS is primarily used by engineers involved in developing detailed design, construction, and maintenance for an individual project or a group of pavement projects at the local level. Network-level PMS primarily deals with financial planning and program planning at the network level for the entire pavement projects within a transportation agency's jurisdiction and usually covers an analysis period of several years. The objective of a network-level PMS for financial planning is to determine the amount of funds needed to maintain or achieve a certain level of performance for the pavements in the network. The purpose of the network-level PMS for program planning is to determine which projects are to be treated, when they are to be treated, and what treatment methods are to be used within available budgets and other constraints. All these network-level PMSs are referred to as network-level needs analysis systems. Since the objective of this thesis is to develop a network-level rehabilitation needs analysis system for GDOT, the discussion presented in the remainder of this chapter will concentrate on network-level rehabilitation needs analysis systems.

A conceptual IT-based network-level pavement rehabilitation needs analysis system framework and its associated components for GDOT, as shown in Figure 2-1, were proposed by Tsai and Lai (Tsai&Lai, 2002). The framework consists of three main components: data and database, operation, and decision support. The data and database component includes various databases for supporting field operations and decision-making processes. The operation component includes the modules to be used for routine and daily field operations. The decision support component includes various modules for analyzing, processing, and determining rehabilitation needs for the network. The essential information needed to ensure integration of all the modules in the framework is the spatial information and temporal information for the pavement projects in the network. Spatial information utilizes the Linear Reference System (LRS) and includes milepost-from and milepost-to information of the projects; the temporal information includes time stamp.

Some of the modules listed above have already been implemented. For example, the Computerized Pavement Condition Evaluation System (COPACES) (Tsai & Lai, 2001) has been fully implemented by the GDOT for the annual pavement condition evaluation program. Other modules that have been developed and implemented by GDOT include the Pavement Profile and Coring module (Tsai & Wu, 2003), the Historical Data Quality Control and Conversion module, the KBS module (a expert system for diagnosis of asphalt pavement distresses), and the rehabilitation Treatment module. Other modules listed above are either in the evaluation stage or in the development stage. Some of the modules in the development stage before the research started, including the Pavement Project Deterioration module, the Project Prioritization

module, the Network-level Needs Analysis module, and the GIS spatial analysis module, are the main components of this dissertation. The main focus of this thesis is to develop the network-level pavement rehabilitation needs analysis system and those modules related to it.

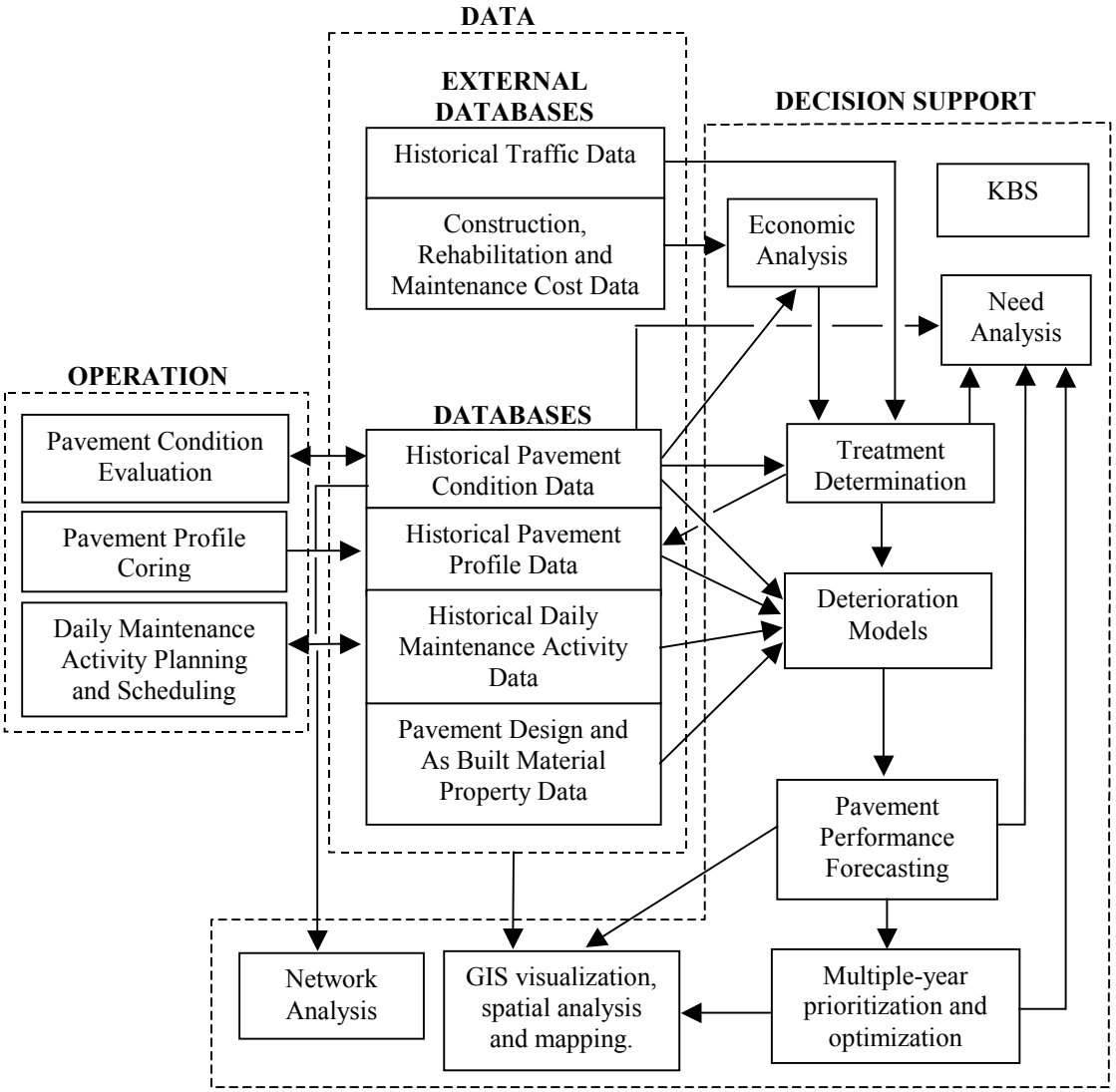


Figure 2 - 1 A Conceptual IT-based Network-level Pavement Rehabilitation Needs Analysis System and Its Associated Components (Tsai & Lai, 2002)

The review of the subjects related to the network-level needs analysis, including the methodologies for developing pavement network-level needs analysis, assessing the existing multi-year pavement needs analysis systems, and identifying the desirable features and needs for developing the network-level pavement rehabilitation needs analysis system, are presented in the sections below.

2.3 Review of Methodologies for Developing a Network-Level Rehabilitation Needs Analysis System

There are various types of methodologies used in formulating and developing network-level pavement rehabilitation needs analysis systems (Cook and Lytton, 1987; Haas et al., 1994; Zimmerman et al., 1995; FHWA, 1997; Smith et al., 2000). Basically, these methodologies can be divided into two approaches: the prioritization approach and the optimization approach. Both approaches can be used for network-level needs analysis. These two approaches for developing a network-level pavement rehabilitation needs analysis system are reviewed below.

2.3.1 Prioritization Approach

The prioritization approach is a sequential process for determining the rehabilitation prioritization order for pavement projects in a network system based on certain prioritization criteria, including subjective engineering judgments and/or objective parameters. This approach is generally used for program planning purposes to select certain pavement projects for rehabilitation in the network system subject to budgets or fund availability constraints. The prioritization criteria can include any one or a

combination of the parameters listed below (Cook and Lytton, 1987; Haas et al., 1994; Zimmerman et al., 1995; FHWA, 1997; Smith et al., 2000):

- Pavement performance index or pavement conditions
- Initial rehabilitation costs
- Life cycle costs
- Benefit/cost ratios
- Cost effectiveness ratios
- Traffic volume
- Safety concerns

The prioritization approach can be divided into two categories: single year prioritization method and multi-year prioritization method. The single-year prioritization method can be further divided into simple ranking method and single-year prioritization method. Essentially, these two methods have no significant differences except that the simple ranking method prioritizes projects based on the current pavement conditions, while the single-year prioritization method considers not only the current pavement conditions but also the treatment costs and/or benefits.

Single-Year Prioritization Method: The single-year prioritization method ranks projects for rehabilitation treatment priority in each year of the analysis period based on one or a combination of the prioritization factors, such as pavement conditions, initial costs, life cycle costs, or benefit/cost ratios. Pavements are then prioritized for rehabilitation treatment in each year based on these prioritization factors. If the

performance (or deterioration) of pavements can be forecasted using certain pavement performance models or pavement deterioration models, the single-year prioritization method can be used recurrently to develop a multi-year network pavement rehabilitation prioritization plan. This can be considered as the yearly multi-year prioritization method. The example of using such a method by the California Department of Transportation (Caltrans) is presented in the next section (Caltrans, 1978; Massey, 2001). Due to its simplicity and clarity in the logic and ease of understanding by non-engineers, this method is often used by the maintenance engineers to justify expenditures to managers and legislatures (FHWA, 1997). However, there are several drawbacks of using this method one must understand. First, no alternative treatment timings for individual pavement projects are considered, and, therefore, the long-term impacts of the rehabilitation plan made in each year are not assessed. Second, agencies using this method to address the rehabilitation needs are mostly based on the worst-conditions-first approach, which may not be the most cost-effective approach.

Multi-year prioritization method: This method uses cost-effectiveness, benefit-cost ratios, or other measures to compare different rehabilitation treatments to be applied at different times within the analysis period to all the pavement projects in the network system to achieve the highest benefit for the network. The benefits can be measured in terms of the highest network-wide pavement performance at a prescribed funding level or the lowest funding required to achieve a prescribed global pavement performance. The concept of cost effectiveness and the benefit-cost ratios will be further described in Chapter 5. The multi-year prioritization approach will identify treatment methods and timing with the highest benefit/cost ratio (or cost effectiveness) or the highest incremental

benefit/cost ratio (or cost effectiveness) as the best treatment methods and timing for all the pavement projects in the network system.

The main difference between the true multi-year prioritization method and the yearly multi-year prioritization method is that the latter lacks the considerations of treatments in alternate years in addition to the consideration of alternate treatment methods. However, the algorithms for the true multi-year network-level prioritization method are much more complex than those of the single-year prioritization method. They invariably result in a much more complex problem, and the problem size is usually very large for a network-level analysis (Fwa et al., 1988; Andres et al., 1994; Chan et al., 1994; George et al., 1994; FHWA, 1997). Even a small pavement network with a relatively small number of pavement projects would still require a large amount of computer storage space and computing time. Usually, some simplifications have to be made to reduce the problem size. An example of using such methods by the Indiana Department of Transportation is presented in the next section.

2.3.2 Network Optimization Approach

The optimization approach uses optimization models to study network-level pavement needs analysis problems. An optimization model is composed of objective functions and constraints. Both objective functions and constrains are formulated using the decision variables and known parameters. The ultimate goal of an optimization model is to find the values of decision variables that satisfy the constraints and bring the best results of the objective functions. It was initially used in the petroleum refining industry to determine the best way to refine petroleum so that maximum profits could be

achieved (Rardin, 2000). In 1970s, the concept of optimization models was introduced to the network-level pavement needs analysis system (Golabi et al., 1982).

In a network-level needs analysis, generally there are two types of objective functions: minimizing rehabilitation costs (or user costs, depending on an agency's interests) and maximizing pavement performance (or benefits). The possible constraints include budget constraints, performance constraints, treatment constraints, etc. The decision variables usually indicate when, where, and what to treat for various pavement projects in a pavement network. The network-level needs analysis system developed by the Arizona Department of Transportation (ADOT), presented in the next section, was one of the earliest and most successful network-level PMSs utilizing such models (Golabi et al., 1982).

There are many optimization techniques available, such as linear programming, non-linear programming, integer programming, etc. (Winston, 1995; Rardin, 2000). Integer programming and linear programming are two more commonly used optimization techniques for developing rehabilitation needs analysis for network-level pavement management systems. The following briefly describes these two methods. More details of these methods can be found in many articles, such as Golabi et al. (1982), Davis and Van Dine (1989), Haas et al. (1994), Winston (1995), Fwa et al. (1988, 1994, 1996), and Rardin (2000).

Integer Programming

An integer-programming model is an optimization model in which all decision variables can only have the values of integers. For a network-level needs analysis model,

they usually must have a value of 0 or 1 with the meanings described as follows: x_{ijt} is a decision variable, where i refers to pavement projects, j refers to rehabilitation treatment methods, and t refers to the future year. Thus: (Cook and Lytton, 1987; Smith, 2000):

$$x_{ijt} = \begin{cases} 1 & \text{If MR \& R strategy j is applied to pavement project i in Year t.} \\ 0 & \text{otherwise} \end{cases}$$

The ultimate goal for performing the network-level needs analysis under the integer programming method is to determine a set of X_{ijt} with the value of 1, a set of specific pavement projects i with specific rehabilitation treatment methods j to be applied in year t in the network-level to achieve optimum results. The integer programming is also called combinatorial optimization, because the model is concerned with finding answers to questions such as "Does a particular arrangement exist?" or "How many arrangements of some set of discrete objects exist to satisfy certain constraints?"

The concepts of integer-programming models are quite simple and easily understood by the engineers involved in developing rehabilitation needs analysis, as the decisions facing most transportation agencies are typically either to apply a treatment or not to apply a treatment. However, the difficulty is how to solve such a model, especially when the variables of i, j, and t are large. Two major technical issues further increase the difficulties of solving an integer-programming model (Fwa et al., 1994). First, the decision variables are integers that restrict the methods to those that can only deal with integer variables. Second is what is called the "combinatorial explosion" of the possible solutions. For example, a pavement network has 2,000 projects (which is very common in Georgia), and each project can have 4 rehabilitation treatment alternatives (such as

minor maintenance, major maintenance, rehabilitation, and do nothing); then, for an analysis period of 5 years, there are $(4^{2000})^5=3.98\times10^{6020}$ possible solutions. It will take a very high-speed computer many years to obtain the solutions.

Due to these difficulties, heuristic methods are often used to solve such models. Heuristic methods are approximations of true optimization techniques. The solutions obtained by heuristic methods are feasible solutions derived from certain searching methods that are not guaranteed to yield an exact optimum. The following is a short description of how heuristic methods work. Detailed algorithms can be found in standard texts on operations research, such as Rardin (2000).

One of the simplest heuristic methods is the improving-search heuristics method. This method begins with an initial feasible solution, then starts to iterate. Each iteration considers neighbors of current solution and tries to advance to one that is feasible and better in objective value. Through this process, a local optimum and heuristic solution is found. Although the improving-search algorithm of this method can be quite effective, the solution obtained is very likely to be local optima instead of true optima. To reduce the chance of reaching a local optimal solution that may significantly deviate from that of the true optima for a specific problem, many other methods have been explored to produce more robust algorithms for obtaining local optima, which is closer to its true optima.

Generic Algorithm (GA) is one of such methods used by some researchers in network-level PMS to solve an integer-programming model (Chan et al., 1994; Fwa et al., 1996; Ferreira et al., 2001). GA was first proposed by Holland (1975). The method begins with two feasible solutions. During each iteration, the new solution is created by

combining pairs of previous solutions. Thus, this method attempts to parallel the process of natural selection to find better solutions. There are many variations of GA methods. The differences are primarily based on how to select pairs of current solutions or how to produce new ones via combinations. That is, the differences are really about how to decide which new and/or old solutions will survive in the next population and how to maintain diversity in the population as the search advances from generation to generation. Although the method is very promising, the solution obtained is still a heuristic solution, and it loses the advantage of finding a true optimum solution with increasing complexity of a problem.

Besides GA, another method is to relax the constraint that decision variables must be integers. Thus, the problem can be solved using the traditional linear programming methods. In the Ontario Model, PARS (Cook & Lytton, 1987), traditional linear programming method was used to solve network pavement rehabilitation optimization problems.

In addition to the heuristic methods that have been briefly described above, there are many other heuristic methods (Rardin, 2000). They will not be presented here. All of these different heuristic methods are based on the notion that using the integer programming approach to obtain a true optimum solution of a large-scale problem is computational impossible, and, therefore, are attempting to obtain a heuristic solution without the guarantee that a true optimal solution will be obtained.

Linear Programming

A linear program is an optimization model in which the objective function and all constraint functions are linear in the decision variables. In a linear program for a network-level needs analysis, Markov Chain is usually used as pavement performance model to forecast future pavement performance. ADOT's pavement needs analysis system using this method is presented in the next section and Appendix A.

In the prioritization approaches, a treatment method is selected for a pavement project, and then the treatment method selected to that project is compared to the treatments selected for other projects, and all the pavement projects with the predetermined treatment methods are prioritized based on certain prioritization parameters. In the optimization approach, several different treatments can be considered for each project at the same time. The treatment that results in the most benefit for the network will be selected as the optimum solution. Compared with the prioritization approach, the optimization approach has the capability to evaluate different rehabilitation policies and select the optimal policy to treat a pavement in an optimum way.

Despite the advantages of finding optimum solution for optimization approaches, there are some drawbacks other than just the problems of facing the complexity of solving the optimization problem. Some agencies found that elected officials and upper management had difficulty comprehending and, therefore, were suspicious of the results of the rehabilitation plans generated by the optimization methods. That makes it much more difficult to defend such plans (and the funding requested) than the plans generated by a ranking approach (Zimmerman, 1995). Also, because the results generated by the optimization method are often complex and not easily understood, some agencies have

been reluctant to use this method for fear of losing control in their programming and scheduling processes (FHWA, 1997). An example of the optimization approach by Arizona Department of Transportation is presented in the next section and in Appendix A to illustrate the complexity of such method.

2.4 Review of Implementation of Network-Level Rehabilitation Needs Analysis

2.4.1 Summary of Network-Level Rehabilitation Needs Analysis Implementation Status

As presented previously, network-level needs analysis has been studied for several decades, and many methodologies have been developed. This section summarizes the implementation status of network-level needs analysis practice by various transportation agencies. The summary presented in this section is primarily based on the NCHRP Synthesis 222 (Zimmerman, 1995) and a recent survey on the practices of using pavement needs analysis in State Departments of Transportation in this country by Tsai (2003).

NCHRP Synthesis 222 investigated the network-level pavement project selection systems used by highway agencies in the United States, Puerto Rico, and the twelve Canadian provinces. Forty-six out of the 52 surveys sent to the State Departments of Highway/Transportation in the United States and its territories and 10 out of 12 surveys sent to Canadian provinces transportation agencies were returned. Table 2-1 presents the survey results.

Of all 62 responses, 29 agencies (47 percent) indicated that pavement condition ranking analysis systems were used and these systems perform network-level single-year prioritization (ranking) based solely on pavement conditions, such as pavement condition

rating (PCR), rut, cracking, etc. Twenty-four agencies included other factors, such as benefit-cost, life cycle cost and initial cost, in the network-level prioritization method. Most of the methods used by these agencies can perform multi-year prioritization. Twelve agencies (19 percent) used network optimization models, which are similar to Case 3 presented in the next section. Of all 12 agencies that used network optimization models, linear programming models were most often used. No agencies responding indicated using integer programming. One or more constraints were usually considered in the optimization models. The common constraints were limits on the budget levels and limits on the overall network pavement conditions. Other constraints used include network pavement deterioration rates, remaining network pavement service life, or benefit.

Table 2 - 1 Network Project Selection Practices

Method	Number of Responses	Percentages of All Responses
Ranking based on Pavement Conditions	29	47
Benefit-cost (or incremental benefit/cost)	12	19
Life cycle costs	6	10
Costs and timing	4	6
Initial costs	4	6
Network optimization models	12	19
Other	1	2

(Source: NCHRP Synthesis 222, 1995)

The total number of responses in the analysis methods are greater than 62 because some agencies selected more than one analysis method. Either their needs analysis used more than one method or that their current analyses used one method while different methods were to be used in their future revisions. Most agencies indicated that their pavement needs analysis systems have considered multi-year analysis. Fourteen agencies indicated using a 3-to-5-year analysis period, 12 agencies used 6 to 10 years, 8 agencies used 11 or more, and only 7 used single-year analysis.

Compared with NCHRP Synthesis 222, the survey performed by Tsai concentrated on network-level needs analysis methods used by the state DOTs in the USA. The survey by Tsai was sent to 50 state DOTs, and 22 states responded. Nine questions in the survey were related to the organization, prioritization, and planning of network-level needs analysis. In the questionnaire, agencies were asked to identify the approach that best described the prioritization criteria used. Multi-year cost effectiveness was the most common approach (10 out of 22) as shown in Figure 2-2. Four agencies reported using worst-first approach; one reported using an optimization model. Similar to the NCHRP Synthesis, some agencies indicated more than one approach was used.

Table 2 - 2 Prioritization Methods Survey Results (Tsai, 2003)

Prioritization Methods	Number of Responses
Worst First	4
Multi-year Prioritization	10
Optimization	1
Others	7

Most of the agencies responding to the survey indicated that they considered multiple years in the needs analysis. Seven agencies used a 2-to-5-year analysis period, 7

agencies used 6 to 10 years, and 5 agencies used 11 and more years. Many agencies use different periods for performing needs analysis and for funding allocation. Usually, a fund allocation period is shorter than the needs analysis period. No agency used more than 12 years in fund allocation. Mississippi and Virginia are the only two agencies that indicated using one year as the analysis period. Among all agencies that responded, 5 agencies reported using individual-year composite ratings (average pavement condition weighted by traffic and/or pavement project length) to define network-level performance requirements; two agencies used a multiple-year composite rating; three agencies used minimum individual project ratings or a condition index; three agencies did not use any index; and 9 indicated other measurements were used.

Regarding the criteria used for selecting pavement projects for rehabilitation, the most common factor used was surface distresses, followed by International Roughness Index (IRI) and skid resistance (see Table 2-3). The other physical factors mentioned included ride quality, structural integrity, age, time of last rehabilitation treatment, etc. Traffic and capacity improvement were reported by five and seven agencies, respectively. Six agencies considered safety in determining multi-year funding, and five agencies included user costs in determining multi-year funding.

Table 2 - 3 Prioritization Criteria Survey Results (Tsai, 2003)

Physical				Functional			Safety		
Surface Distress	IRI	Skid	Others	Traffic	Capacity Improve	Others	Safety	User Cost	Others
20	14	9	7	5	7	3	6	5	1

Most of the agencies, except Illinois and Mississippi, indicated that some kind of software was used to conduct pavement rehabilitation needs analysis and project selection. Ten agencies used customized applications; thirteen agencies used products from Deighton, Stantec, TRDI software, or Cambridge Systematics, as shown in Table 2-4.

Table 2 - 4 Software Used Survey Results (Tsai, 2003)

Software Types	Number of States
Customized Software	10
Commercial Product	13
dROAD/dTIMS by Deighton	6
HPMA by Stantec	3
TRDI Software	3
Cambridge Systematics	1

2.4.2 Examples of Needs Analysis Systems Used by Highway Agencies

To further understand network-level needs analysis, the following four cases present needs analysis systems used by highway agencies. These cases cover most types of network-level needs analysis. Of these four cases, Case 1 (Caltrans system) used the pavement condition single-year prioritization method; Case 2 (InDOT system) used the multi-year prioritization method; Case 3 (ADOT system) used traditional probabilistic network optimization model; and Case 4 (HDM System) is one of the most popular systems used by countries other than USA. For each case, the background and possible

reasons of network-level needs analysis are presented first; then the main objectives, methodology, and capabilities of the needs analysis system are introduced; in the last part of each case, implementation status, advantages and disadvantages are discussed.

In 2000, FHWA also published a system called Highway Economic Requirements System-State Version (HERS-ST). The system can be used for state DOTs to select projects. HERS-ST is an engineer-economic model that attaches each rehabilitation treatment to a dollar value, and then prioritizes projects based on benefit-cost analysis. HERS-ST is similar to the programme analysis, one of the three analyses of HDM-4, so it will not be presented here. Detailed information can be found in (FHWA, 2002b).

Case 1: Caltrans Needs Analysis System

Since the late 1970s, the California Department of Transportation (Caltrans) has been using a needs analysis system, primarily based on pavement distress conditions, for performing its pavement rehabilitation needs analysis for managing 15,000 centerline (47,000 lane) miles of highways (Caltrans, 1978; Zimmerman, 1995; Massey, 2001). The objective of Caltrans' pavement needs analysis system is to develop a list of candidate pavement projects with associated repair strategies for rehabilitation. The rehabilitation plan is developed solely based on the current year's pavement conditions. Use of the system allows Caltrans to quantify and justify pavement rehabilitation needs to the public and to the elected officials.

The Caltrans' needs analysis system consists of a pavement condition rating system and a pavement condition evaluation system. The pavement condition rating system is used by Caltrans to collects pavement condition information for its entire

highway network on a 2-year cycle. The rating system identifies the severity and extent for each of six pavement problems on flexible pavements and eight problems for rigid problems. Ride information is also collected. With these data, the pavement condition evaluation system is used by the central office to correlate pavement problems for feasible repair strategies based on a series of decision trees for each of the distresses collected. Trigger values are established for each severity/extent combination of each distress type to identify the time at which various rehabilitation strategies should be selected. Once all triggered strategies for various distresses of a pavement project are identified, the dominant rehabilitation strategy is selected based on the consideration that it could best address all the problems identified for that project. Using this system, Caltrans' central office identifies and issues a list of problem pavement locations, recommended dominant repair strategies, anticipated service life, and estimated project costs to each of the district. The districts review the list and select a final prioritized program based on field review, funding constraints, or level of service. The districts can also change the estimated project costs, if necessary (Zimmerman, 1995).

The Caltrans needs analysis system is fully implemented and has been used throughout the agency. The following benefits are recognized by Caltrans:

1) Meaningful pavement condition data for each lane throughout the entire state highway system is collected
2) Reduced lane miles of rough pavement
3) A structured process for evaluating pavement conditions and identifying the appropriate level of repair commensurate with the assigned level of service

4) The priorities are established in conjunction with legislative, fiscal, and other controls that are imposed on the agency
5) Pavement condition evaluation system has aided in improved communications between the districts, headquarters, and FHWA
6) Pavement condition evaluation system has improved the consistency in decision-making within the agency and in making tradeoffs of within and between districts of candidate projects for rehabilitation

Despite of the benefits recognized above, Caltrans also recognizes that there are some limitations of the system, such as lack of predictive capabilities, no explicit prioritization or optimization programming, and no pavement performance model involved. The system cannot perform multi-year needs analysis. Caltrans is currently enhancing its system by adding predictive capabilities, benefit/cost analysis capabilities, and prioritization algorithms (Zimmerman, 1995; Massey, 2001; Caltrans, 2001a; Caltrans, 2001b) and is expected to replace the existing system in the next few years.

Case 2: InDOT Network-level Pavement Needs Analysis

The Indiana Department of Transportation (InDOT) manages 11,200 miles of state-maintained highways, including approximately 3,500 miles of National Highway System (NHS) roadways. It started to develop a pavement management system in 1991 with an objective of maintaining its existing pavement network at a certain specified level of service for the least possible cost. The Indiana Pavement Management System (IPMS) included a roadway referencing system (RRS), a database for storage and retrieval of

pavement condition and inventory data, and a software program dROAD/dTIMS developed by Deighton Associates for developing the rehabilitation plans. Pavement condition data collected by InDOT included International Roughness Index (IRI), Rutting, PCR, and Pavement Quality Index (Flora, 2001). The PCR is a composite rating incorporating various pavement distresses, excluding rutting. The Pavement Quality Index (PQI) is a composite index based on IRI, PCR, and Rutting. The RRS database resides on a mainframe computer to store roadway inventory information and pavement condition data for all the roadways in InDOT network. The dROAD/dTIMS program was developed by Deighton Associates and has been used also by 17 other US State DOTs (Deighton, 2004). The dROAD/dTIMS program consists of two programs: the dROAD program and the dTIMS program, both residing in the personal computer in the Pavement Management Section. The dROAD program is used to download and store relevant information for the identification of rehabilitation projects and treatments. The dTIMS program is used as the analysis tool for developing the pavement rehabilitation plans. The dTIMS program uses an incremental benefit/cost analysis based on selected pavement deterioration models, and the current and forecast pavement condition levels to prioritize all rehabilitation projects over a 5-year period. The prioritized candidate project list obtained from dTIMS is then used as the first-cut list to be evaluated by the field committee.

IPMS was implemented in two phases. In Phase 1, the system was first implemented on the Interstate highway rehabilitation project selection process. This phase has been completed by 2001, and the Interstate highway conditions have improved

since the implementation of the program (Flora, 2001). Phase 2 will involve all non-interstate routes. This phase is currently being developed.

InDOT feels that one of the greatest benefits provided by the needs analysis has been an increase in efficiency within the Department in developing and execution of the annual pavement rehabilitation program. However, InDOT also realizes that several issues need to be addressed in the future (FHWA, 1997):

- Very limited analyses have been performed on the system outputs to evaluate the reliability of the multi-year analysis results
- The system in Phase 1 covers only Interstate highway and principal arterial highways. Adding the rest of the highway network into the pavement management system is very complicated, because districts control most of the rehabilitation work on the non-interstate highway network

Case 3: Arizona Network-Level Needs Analysis System

The Arizona Department of Transportation (ADOT) maintains 2,200 miles of Interstate and 5,200 miles of non-interstate highways. The primary objective of the ADOT needs analysis system was to find the least cost that would maintain pavement network at certain specified service level. The core of ADOT system is the Network Optimization System (NOS). Two interrelated models are included in NOS, a long-term model and a short-term model. The Markov Chain process is one of the main components of these two models. Detailed information about ADOT's models and the Markov Chain process is presented in Appendix A.

The long-term model seeks to minimize the annual rehabilitation costs while maintaining long-term pavement performance standards. It is used to determine the steady-state optimal policy. The policy is independent of the initial conditions of the pavements in the network. That is, if the optimal policy is followed, after certain unspecified years, the steady-state conditions will be achieved, and the proportion of roads in each pavement condition state and the expected budget required to maintain the corresponding pavement conditions will remain constant.

Under certain circumstances, ADOT might not be able to follow steady-state policies in a particular year, such as if a large proportion of roads needed immediate repair but was not recommended by the steady-state policies. Therefore the short-term model was developed to solve such problems and to allow the network to be upgraded to the long-term standards after T-years while using the rehabilitation plans developed by the short-term model during the first T-years. The short-term model is also formulated as another linear programming and is presented in Appendix A. The system first solves the steady-state problem using the long-term model. Then, it solves the short-term model to find the final solution based on the optimal solution of the long-term model (the steady-state solution).

The system was implemented in 1981 and has changed the pavement management decision process in ADOT from subjective and non-quantitative to a system integrating policy decisions and engineering inputs through an optimization system. The system achieves great success and has inspired many transportation agencies to develop similar pavement needs analysis systems (Davis and Van Dine, 1989; Alviti et al., 1994; Butt et al., 1994; Gaspar, 1994; Wang et al., 1994). However, the implementation of the system

by ADOT encountered certain difficulties. The system is very complex, which requires sophisticated computer equipment and system analysts who understand the program and particularly the Markov Chain process well. The results generated by the system are difficult to understand for those not familiar with the program. Another major drawback of the system is that the results generated from the model contain only the percentages of the pavements for each of the pavement categories to be treated by different rehabilitation actions. Specific pavement projects requiring specific rehabilitation treatments are not identified. For these reasons, ADOT is in the process of changing the pavement needs analysis system after using the original system for about 20 years. The changes include not using Markov chain models and incorporating certain capabilities to allow the results generated from network optimization analysis to be connected with specific pavement projects for specific rehabilitation treatments (Delton, 2003).

Case 4: Highway Development and Management Standards Model (HDM)

The development of the HDM Model can be traced back to 1968. The first model was produced in response to a highway design study initiated by the World Bank in conjunction with the Transport and Road Research Laboratory (TRRL) and the Laboratoire Central des Ponts et Chaussees (LCPC). Subsequently, the World Bank funded the Massachusetts Institute of Technology (MIT) to continue the study and the Highway Cost Model (HCM) was developed from the study. This model was used to study the relationship between roadwork costs and vehicle operating costs. In 1976, based on a study in Kenya done by TRRL in collaboration with the World Bank to investigate the deterioration of paved and unpaved roads as well as the factors affecting

vehicle-operating costs in a developing country, the first version of the HDM was produced at MIT. Further work resulted in releasing the RTIM2 model in 1982 and HDM-III in 1987 (Kerali & Mannisto, 1999; Kannemeyer & Kerali, 2001). The development of the improved version, HDM-4, was started in 1993. The first version of HDM-4 was released in 2000, and the development is still continuing. The features contained in the first version of HDM-4 are described below.

HDM-4 utilizes a prioritization method based on the concept of benefit cost analysis over the pavement life cycle. Pavement network performance is predicted as a function of traffic volumes, wheel loads, pavement structural strength, maintenance standards, and environments in the network. Benefits are quantified from savings in vehicle operation cost (VOC), reduced road user travel times, a decreased number of accidents, and improved environmental effects. Using these concepts above, HDM-4 can perform three levels of analyses: strategy analysis, programme analysis, and project analysis.

Strategy analysis is used to determine funding needs and/or to predict future performance under budget constraints of an entire road network. A pavement network is first divided into different categories, such as bituminous, unsealed, concrete, and block. For each pavement category, representative traffic volume and loading and rehabilitation standards are defined. Then benefits are calculated for each corresponding rehabilitation treatment to be used. Finally, long-term funding needs and/or future performance under budget constrains are determined based on prioritization of benefit/cost ratio of the pavements in the network. The output of the strategic analysis includes funding

requirements and long-term performance trends, such as average network conditions and performance indicators.

The objective of programme analysis is to prioritize candidate road projects in each year for a single or multi-year period within annual budget constraint obtained from strategic maintenance plan. Similar to the strategy analysis, prioritization of benefit/cost ratio is used to select projects in each year within the analysis period. A list of feasible projects within budget period is provided as the results of programme analysis.

Project analysis of HDM-4 is concerned with the evaluation of one or more road projects or investment options. Different treatment and investment alternatives are evaluated for one or more road projects based on road-user costs and benefits, life cycle predictions of road deterioration, road works effects and costs, etc.

According to Robertson (2001), more than 100 countries have shown interest in HDM-4. About two-thirds of the countries are developing countries. One of the major advantages of the HDM-4 model is that it combines engineering practice and economic concepts together. Every rehabilitation action is associated with not only the construction cost, but also the user cost and benefits. Thus every rehabilitation action is associated with a dollar value. However, several issues limit its implementation. First, since most highway agencies are government organizations and are not paid by the users of the pavement network for their work, any attempt to attach a dollar value to highway agencies' pavement rehabilitation activities would be speculative since there is little or no supportive data available (VDOT, 2003). Second, the HDM-4 model tends to assign benefits to most indirect costs, such as reduced accident costs, VOC, live costs, and economic benefit to agencies. Thus, the results of economic models tend to be unstable

and lack credibility. Small changes in the values of input parameters often lead to significant changes in the optimal maintenance program (Smith et al., 2000). Third, although HDM-4 does have several levels of analysis as presented above, it does not link them dynamically. For example, although the budget determined based on strategic analysis can be use in programme analysis to select projects; however, the effects of project selection process in programme analysis on network performance cannot be evaluated.

2.5 Improvement needs for Network-Level Rehabilitation Needs Analysis

The review and discussions presented in this chapter indicate that various network-level pavement rehabilitation needs analysis systems have been developed and implemented in the past. However, there are still a significant number of challenges and opportunities for improving the network-level needs analysis practice, as pointed out by various researchers (Zimmerman et al., 2000; Zimmerman et al., 2003; Kulkarni, 2003). The major improvement needs in the development and implementation of network-level needs analysis systems are summarized below:

Linking Network-Level Results with Project-Level Results

The traditional probability-based network-level rehabilitation needs analysis systems mostly generate percentages of pavements in each pavement categories to be treated by different rehabilitation treatment methods, such as the system used by ADOT. Results of the specific pavement projects in the pavement network in which the treatments are to be applied are not identified. It is often difficult to translate network

goals into project-specific objectives. The capability for a system to provide a macro network-level rehabilitation plan and link that with detailed project-level plan is very desirable. However, developing such a system is very challenging. Several studies (Fwa et al., 1994; Ferreira et al., 2001; Wang et al., 2003) have pointed out that a needs analysis model which has the capability of linking project-level results with network-level analysis is usually a very complex model for which current technology cannot find the exact solution when the model size is relatively large, which is very common for network-level needs analysis problems. Research on this subject will continue.

Balancing Rehabilitation Needs of Different Jurisdictions within the Network

Very few pavement needs analysis systems consider balancing rehabilitation needs of different jurisdictions within the network. However, most transportation agencies making their pavement maintenance decisions often consider not only the entire network needs but also the needs among the various jurisdictions within the network system. It may be desirable for state DOTs to balance the annual pavement rehabilitation workloads among their maintenance districts. Balancing annual pavement rehabilitation workloads and/or funding among the political jurisdictions (Congressional districts, state senate districts, etc.) could be of important consideration in developing statewide rehabilitation plans. A common approach used by most transportation agencies is to divide the rehabilitation workloads or funding based on the relative values from a formula using a combination of total lane miles, traffic volumes, or other parameters among the jurisdictions (Smith, 2000). Perhaps a more sensible approach would be for a system to have the flexibility to allocate funding and/or workloads based on achieving

comparable pavement performance among the jurisdictions in addition to other balancing criteria.

Feedback and Validation of Network-Level Needs Analysis Systems

Validating a system is very important. It is often difficult to validate a network-level Needs Analysis System in the early implementation stages due to the lack of available historical data. Without validations and proper calibrations, applicability and accuracy of the system cannot be ascertained. With the improvement of IT and the accumulation of sufficient historical pavement performance data and rehabilitation records, it is feasible now to validate the systems. Some researchers have started to validate pavement performance models using historical data (Hudson et al., 1994; Hall et al., 1994; Kuo et al., 2003; Pierce et al., 2003). Many of these validations concentrate mostly on pavement performance models. Beyond that, validations of other models still are facing many challenging issues. Another related issue is concerned with how to effectively utilize the huge amount of pavement condition survey data and rehabilitation records available in the system to provide feedback for further improving an existing needs analysis system.

CHAPTER 3

REVIEW OF GDOT PAVEMENT REHABILITATION NEEDS ANALYSIS PRACTICE

The NEEDAS program presented in this thesis is developed specifically for GDOT for performing the multi-year, long-term pavement rehabilitation needs analysis for the Georgia state highway system, although, with slight modifications, the program can be used by the engineer in other transportation agencies to perform the same analysis. Since the system and the computer program are developed for GDOT to maintain its flexible pavements in its state highway network, it is appropriate in this chapter to first identify issues related to the development of the system pertinent to GDOT. Although the issues presented in this chapter are specific for GDOT, it is believed the issues presented here will be of some value for other transportation agencies developing similar systems.

This chapter is organized as follows: the current pavement rehabilitation needs analysis practice used by GDOT is first introduced in Section 3.1. In Section 3.2, the GDOT pavement condition survey database, the foundation for developing the new rehabilitation needs analysis system, and the various issues related to the database are presented. Section 3.3 presents the procedures for sanitizing the pre-1998 pavement condition evaluation data to ensure the accuracy of the data stored in the database.

3.1 Current Pavement Rehabilitation Needs analysis Practice at GDOT

The GDOT has been maintaining its 18,000-centerline-mile highway pavement system using the pavement rehabilitation needs analysis procedures described below.

1) Pavement condition evaluations are performed annually using the Pavement Condition Evaluation System (PACES), developed by GDOT, from 1986 to 1997, and using the Computerized Pavement Condition Evaluation System (COPACES), implemented since 1998. PACES and COPACES were designed to evaluate the severity and extent of various types of pavement surface distresses at the time the survey was performed. Pavement performance ratings based on the distress conditions were then calculated. More detailed information about PACES and COPACES is presented in the next section.
2) Projects with unacceptable conditions (low performance ratings) are prioritized for rehabilitation treatments. Each of the seven GDOT District offices is responsible for making the initial selections of projects to be treated. Suitable rehabilitation treatment methods for the candidate projects are determined by the engineers based on the pavement distress conditions, performance ratings, and traffic conditions. Results of the preliminary pavement rehabilitation plans prepared by each GDOT District office are submitted to the Central Office (Office of Maintenance of GDOT).
3) The Central Office collects the lists of the plans submitted from all seven GDOT District offices and develops a statewide, yearly pavement rehabilitation program. The total number of projects to be treated is determined based on funding

availability and other considerations, such as balancing funding distribution among different GDOT Districts and State Congressional Districts.

The procedure described above has been used by GDOT since the late 1980s for managing the state highway system with reasonably good results. However, GDOT is aware of certain inherent deficiencies of the current practices and the need for improvements, particularly with the advent of information and computer technologies, as discussed in next chapter.

3.2 GDOT Pavement Condition Survey Database

Consistent and accurate field pavement condition survey data is an essential component for building a reliable pavement rehabilitation needs analysis system. Many important features in a needs analysis system, such as forecasting future pavement performance, developing rehabilitation strategies, and allocating budgets, depend on having reliable and complete pavement condition data. Therefore, the GDOT pavement condition survey database and issues related to the database are presented in this section.

GDOT has performed pavement condition evaluations annually for its 18,000 centerline-mile highway system except 858 center-line concrete pavement since 1986 using the PACES developed by GDOT (GDOT, 1996). PACES was designed to record the severity and extent of various types of surface distress of asphalt pavements. The system standardizes the terminology for the types of distresses found on asphalt pavements in Georgia and defines various levels of severity for these distresses. The following are the distress types recognized by PACES:

Rut Depth	Raveling
Load Cracking	Edge Distress
Block Cracking	Bleeding/Flushing
Reflection Cracking	Corrugations/Pushing
Patches and Potholes	Loss of Section

In PACES, three levels of spatial units are used to manage the data: sampling section, segment, and project. A project is a length of roadway with similar pavement geometries, structural conditions, and logical beginning and ending points. Normally, a project is divided into one-mile segments for rating purposes. Exceptions to this are the beginning and ending segments of a project, which can be less than one mile, or when drastic changes in pavement conditions occur within that one-mile interval. In this case, shorter rating segments are used to obtain a more representative rating of pavement conditions for that portion of the pavement. All project-related information is recorded in the field by the rater using the project form as shown in Figure 3-1. A representative 100-ft section is selected within each segment by the rater during the field survey. A rater first drives through the entire one-mile segment to assess the general pavement conditions and identifies the representative 100-ft sample section. The rater then conducts the detailed distress condition evaluation on this identified representative 100-ft sampling section. Results of the distress survey of this 100-ft section represent the average distress conditions of that segment. The results are recorded by the rater in the field in a segment form, as shown in Figure 3-2. The distresses recorded for all the segments of a project are then averaged and the deduct values for each distress type and

severity level are calculated by the rater. The project rating is then determined by subtracting all the deduct values from 100, and both the project rating and the averaged deduct values for a project are recorded in the project form (Figure 3-1) by the rater. Thus, a pavement with a higher rating indicates the pavement is in a better condition (less distresses observed) and vice versa. The pavement rating is used to represent the overall performance conditions of a pavement project. For GDOT, a rating over 90 is considered to be very good, while a rating of below 70 is considered to be poor.

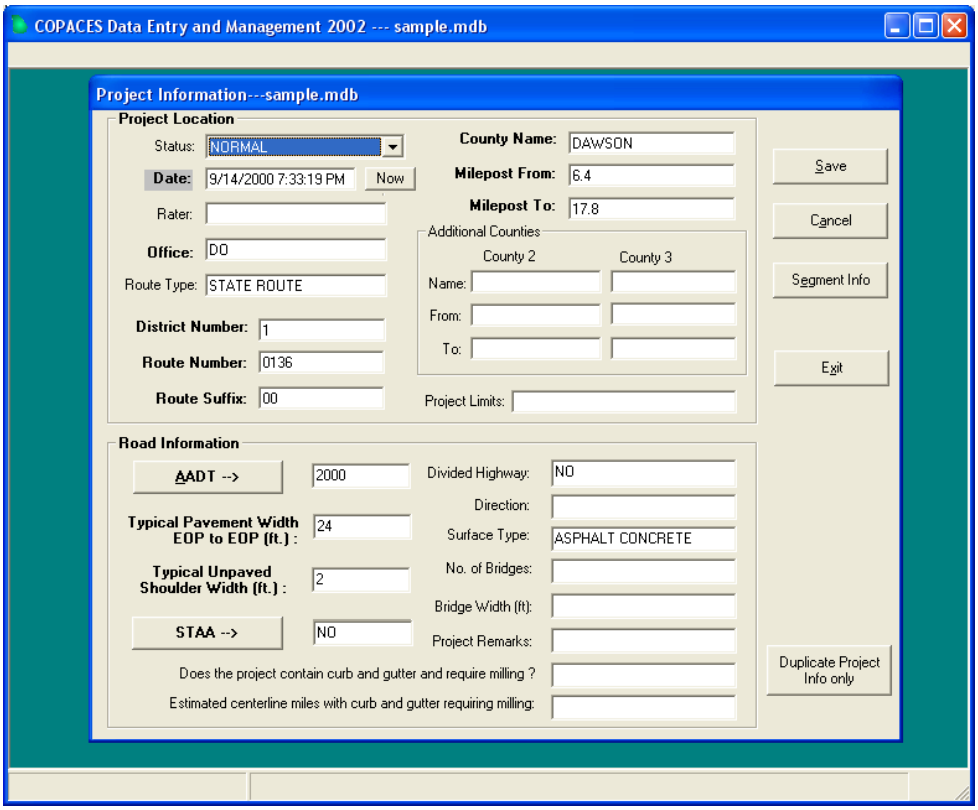


Figure 3 - 1 Project Level Information Entry Form (Source: Tsai & Lai, 2001)

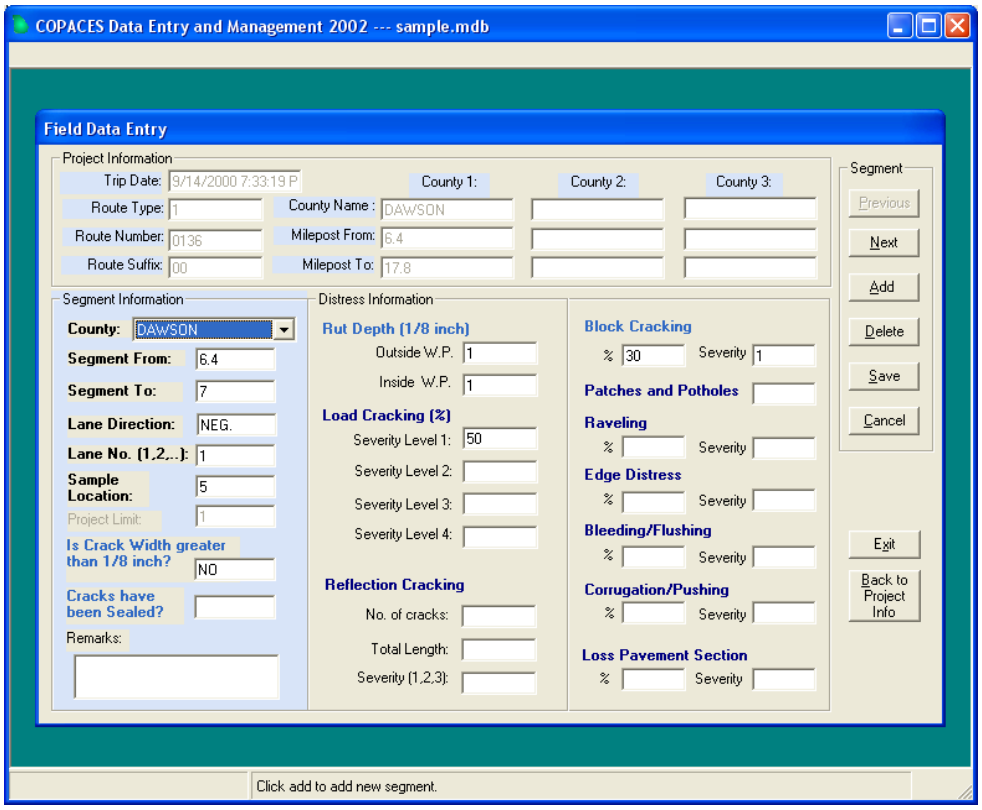


Figure 3 - 2 Segment Level Information Entry Form (Source: Tsai & Lai, 2001)

More detailed explanations of each item in the project form and the segment form are presented in the PACES manual (GDOT, 1996). The data recorded in the field are then keyed into a mainframe computer and transmitted from an Area Office to the District Office (a GDOT district office has several area officers located within its jurisdiction). Based on the survey done by the Area Office, the engineer in the District Office conducts a second PACES survey for projects with ratings less than 70 to confirm the survey results done by the Area Office. Field PACES survey data from each District Office are then transmitted to the Central Office (Office of Maintenance). The engineer

in the Central Office performs additional field surveys for the projects with ratings less than 70 and for the projects requiring further confirmation of the survey results. The ratings for all the projects within the state pavement network are used by the Office of Maintenance as one of the important factors for developing the annual statewide pavement rehabilitation program and for allocating the rehabilitation budget for the coming year.

Although the annual PACES survey has provided vital data for establishing the annual rehabilitation plans for the state's highway network, GDOT did recognize certain areas in the PACES that could be improved, particularly with the advent of IT. In particular, the lack of an automatic data error checking capability and a data integrity verification process due to the manual operation process used by PACES has affected the accuracy and reliability of the survey data, which, in turn, has affected the annual rehabilitation plans generated based on those data.

In response to the needs for improving the existing PACES, a Computerized Pavement Condition Evaluation System (COPACES) was developed by Georgia Tech and implemented by GDOT in 1998 to replace the PACES for performing the annual pavement condition evaluation exercise. Implementation of the COPACES has significantly improved the data acquisition productivity and data quality (Tsai and Lai, 2001). The COPACES program has various built-in data-error and data-integrity detection features, and it has significantly improved the data quality over the quality of data acquired under the PACES program. In addition, the program has a pavement condition survey training module to train the rater to gain proficiency in correctly identifying the type, extent, and severity level of the various distresses. Since 1998, the

pavement condition survey data has been stored in a central ORACLE database (referred to as COPACES database).

The PACES data from 1986 to 1997 (referred to as pre-COPACES data) were converted into the COPACES format and stored in the COPACES database. In order to have a reliable historical database to develop pavement performance models, an intensive data filtering and processing was performed on the pre-COPACES data to ensure the data quality before the data was allowed to be merged into the COPACES database. The data filtering and processing procedures are presented in Section 3.3.

Both pre-COPACES database and COPACES database contain the same types of pavement condition survey data. The database includes two tables: a project table and a segment table. The project table is for recording information and data pertaining to pavement projects and is linked with the segment tables for the segments associated with the projects. The segment table is for recording pavement condition survey data for the segments.

The data included in the project table, see Figure 3-1, can be divided into three types:

- Spatial/time information for a project, includes: Starting survey time (TripDate), Route number (RouteNo), Route suffix, Route type, County number (CountyNo), MilepostFrom, and MilepostTo.
- Roadway information for a project, includes: AADT (Annual Average Daily Traffic), Surface Type, Divided Highway (whether the route is a divided

highway or not), Direction, Typical pavement width, Typical shoulder width, Number of bridges in the project, and Bridge width.

- Pavement condition information for a project, includes project rating and deduct values of various distresses.

The TripDate and RouteNo, combined together, form the primary key used to distinguish different projects. Based on the pavement condition survey operation procedures, more than one project with a specific combination of TripDate and RouteNo should not exist because there should be only one survey being performed at a specific RouteNo at a given time. Pavement condition information for a project, including the project rating, and the various distress deduct values, are computed from the pavement condition survey data recorded in all of the segments associate with the project.

The Segment table contains the detailed pavement condition survey results, including the severity levels and extents of the various distresses for a specific segment and the spatial/time and location information for the segment (see Figure 3-2).

3.3 Historical Pavement Condition Data Filtering and Processing

The pre-COPACES database contains various errors because the data were manually entered into the database and there were no on-site data integrity and quality control functions available to alert the rater in time to correct the errors in the field. As a result, various data errors may be introduced into the pre-COPACES database. The following are major error sources found when filtering and processing the PACES historical data:

- **Invalid Project Rating:** A project rating has a value between 0 and 100. Due to data entry errors, some records contain project rating values outside this range, and, therefore, are invalid.
- **CountyNo does not exist:** The county name is not correct, or the county name does not exist.
- **Invalid RouteNo:** The route number for a state highway in Georgia should be four digits. The projects with incorrect route numbers are invalid.
- **Inconsistent CountyNo2 and CountyNo3:** In the GDOT, a project can cover up to three counties, which are represented by the fields of CountyNo1, CountyNo2, and CountyNo3 in the historical database. Each one is associated with a MilePostFrom and a MilePostTo. Sometimes, the MilePostFrom and MilePostTo are improperly recorded.
- **Same MilePostFrom and MilePostTo:** Due to data entry errors, MilePostFrom and MilePostTo have the same value.
- **No segment data:** When a project rating is ≤ 99, segment data must exist.
- **Projects with duplicated survey in 1 year**
- **Both TripDate and RouteNo are the same**: Since TripDate and RouteNo, combined together, are used as the primary key for the database for identifying a project, when two projects have the same TripDate and RouteNo, it means that these two projects are the same project in the database. However, the other fields of the two projects are different. This means that only one of them could be correct. Since it is impossible to determine which one is correct, these projects are deleted from the database.

- **Invalid Rut-depth Project:** Rut depth is one of the distress attributes. The value of rut-depth should be within certain reasonable ranges, so projects having unreasonable rut depth values should be rejected.

The errors listed above affect the integrity of the pre-COPACES data, and data error correction and filtering were performed to correct the data. A program was created to automatically query and filter out projects containing irregularities/errors data (Tsai et al., 2004). Some of the irregularities/errors were automatically corrected or filtered out, while others were identified and required manual actions to correct or delete them. The procedure and corresponding results are shown in Figure 3-3. The original pre-COPACES data contained 47,519 projects. About 22.6% (10,733 out of 47,519 projects) of the whole PACES data from 1986 to 1999 were removed from the original survey data (note that COPACES was implemented in 1998; since it was the first year in which the system was implemented, the data surveyed in 1999 using COPACES was also included in the data filtering process). Most of the erroneous data come from duplicate data in the same survey year (3,977 out of 47,519 projects), the same TripDate and RouteNo (3,353 projects), and the No segment data (2,241 + 2,412).

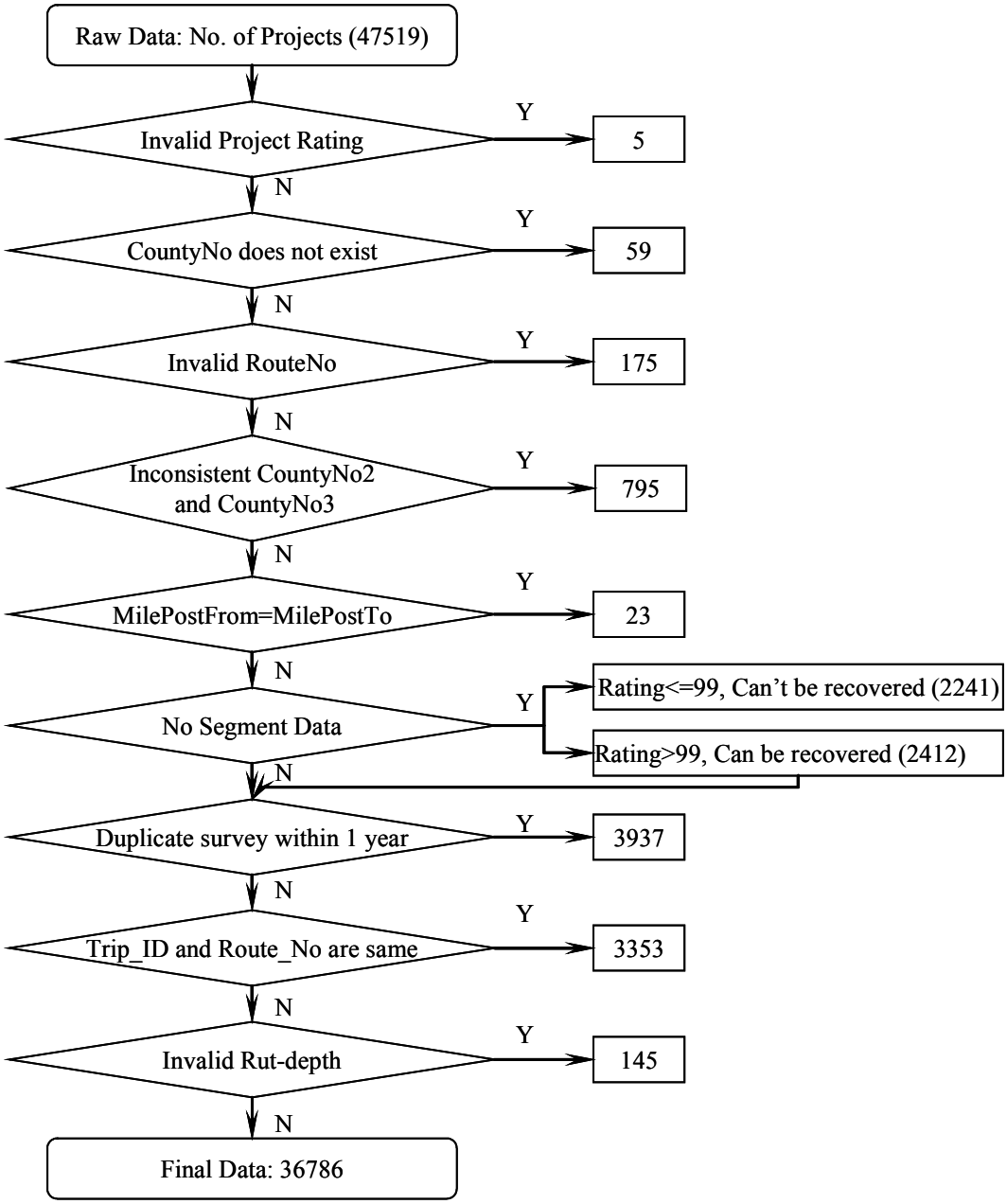


Figure 3 - 3 Error Sources and Data Filtering Results of Historical Pavement Data

With the implementation of the COPACES program, most of the errors associated with the spatially related data in the project level, as discussed above, have been avoided. This is because many of the spatial data required are acquired by the program from other databases and entered into the program automatically. However, errors in the pavement distress related data could not be entirely eliminated, although they have been minimized because the built-in error detection features can detect out-of-range or missing data and alert the rater in time to correct the errors. The errors that cannot be eliminated entirely are those of the inaccurate field condition survey data entered by the rater in the segment table; in particular, they are comprised of the errors due to the inconsistency of the subjective judgments of the raters. It is entirely possible that a rater can rate the pavement conditions differently on the same project when performing the rating at a different time; the problem is compounded when surveys are performed by different raters.

One idea for minimizing this type of error is to place the previous years' COPACES data into the COPACES program. When the rater enters the segment distress data and before the program allows the data to be recorded into the database, the program can compare the current data with the past data for the same pavement segment to intelligently detect inconsistencies in the data and alert the rater to confirm or reenter the data. Another idea that can minimize the error is to identify the parameters from the database that most likely could influence the rater's judgments and, thus, contribute to the subjective errors, whether it is due to the misjudgment of distress severity level or extent or whether it is due to the selections of different sample locations. After the parameters are identified, more effective training during the annual pre-survey refresh training

sessions or modification of the training module in the COPACES program can reduce the occurrence of such errors in the future.

CHAPTER 4

A FRAMEWORK FOR A GIS-ENABLED MULTI-YEAR PAVEMENT REHABILITATION NEEDS ANALYSIS SYSTEM FOR GDOT

The NEEDAS program was developed based on the needs and desirable features for multi-year pavement rehabilitation needs analysis systems identified in Chapter 2, and the requirements to conform with the current procedures used by GDOT and with the existing GDOT's pavement condition evaluation database (COPACES Database) presented in Chapter 3. This chapter presents the needs and the desirable features to be included in the NEEDAS program and the general framework of the system. Detailed information regarding the development of the three main modules for the system is presented in Chapter 5, 6, and 7, and the development and use of the NEEDAS computer program are presented in Chapter 8.

4.1 Needs for Developing a Pavement Rehabilitation Needs Analysis System

The major improvements and desirable features in the development of network-level needs analysis systems have been identified as presented in Section 2.5 in Chapter 2. Those desirable features and improvements identified there, including linking network-level results with project-level results together, balancing needs among different jurisdictions in the network, and validation and feedback for improving the reliability of the system, are also applicable in developing of the network-level pavement rehabilitation needs analysis system for GDOT. Besides the issues identified in Chapter 2, the

following are additional requirements that should be incorporated into the development of the multi-year pavement rehabilitation needs analysis system for GDOT:

- Compatibility with the current practices used by GDOT to minimize the efforts of migrating from the current practice to the new system.
- Capability to balance funding allocations and performance among GDOT Districts and State Congressional Districts. GDOT has seven engineering districts (referred to as GDOT Districts below) and 11 State Congressional Districts (at the time the research project started). The locations of pavement projects are based on GDOT Districts and a pavement project could cross more than one State Congressional District. That makes it difficult to determine rehabilitation funding distributions among State Congressional Districts. The ability to determine rehabilitation funding distributions, and thus to be able to balance the funding distributions or pavement performance among State Congressional Districts, is important because the directors of the State Transportation Board, being elected to represent each State Congressional District, are often interested in knowing such information. Balancing the funding or projects distributions or performance among the seven GDOT Districts is also important. Therefore, the feature that maximizes the pavement performance at the network level while being subject to different balancing constraints, such as balancing funding or performance among different State Congressional Districts and/or GDOT Districts, would be very desirable.

- Integration of GIS into the NEEDAS program. GIS is an information technology that can retrieve, store, analyze, and visualize spatial and non-spatial data. It provides a tool for users to make rehabilitation changes as to when, where, and what to treat at the project level on the map interactively and readily, and it shows the impact of performance and cost at both project level and network level, which can be visualized and evaluated immediately after re-running the needs analysis modeling. It allows users to conduct what-if analyses to support their decision-making effectively. There is a need to integrate GIS with pavement needs analysis so that dynamic interactive analysis can be performed directly on the GIS map to support decision making.
- Utilization of historical pavement condition data. As presented in Chapter 3, GDOT has been performing pavement condition evaluations annually since 1986. All the historical pavement condition data from 1986 to 2004 is stored in COPACES Database. In the current GDOT practice for developing annual rehabilitation plans, only the current year pavement condition data is used. The historical data provides vital information about pavement performance, particularly about pavement performance trends, migration of pavement distresses, and performance of different pavement types subjected to different traffic volumes and in different geographical areas. A program that has the capability to utilize historical data when performing the rehabilitation needs analysis could greatly enhance the reliability of the results of the analysis.

- Capability to perform "what-if" scenarios analyses. Many needs analysis systems lack the capability to perform different scenarios analyses. For example, the ADOT system determines the least cost for rehabilitation that satisfies the statewide pavement network performance constraints (Golabi, 1982), and the only scenario analyses are limited to varying the statewide pavement network performance constraints. Similarly, the Connecticut DOT system can only perform analyses to minimize user costs subject to budgetary and other constraints (Davis and Van Dine, 1989). When a transportation agency determines the rehabilitation budget plans or funding allocation plans, usually it compares several options and evaluates the impact of each plan before making the final decisions. Various issues, such as pavement performance conditions under different levels of funding, impacts of different funding balancing criteria on pavement performance and funding requirements, can be explored through the "what-if" scenarios analyses. Also, it will be very persuasive to have the results and comparisons of different plans and quantify their effects when presenting the final budget plans to the legislators for the funding request. Therefore, the capability for performing and reporting "what-if" scenarios analyses is an important feature that needs to be incorporated in the development of the needs analysis system.
- Flexibility and scalability. A program should be designed to allow for the flexibility and scalability to modify and update the various functions and models, such as the pavement performance models and the pavement rehabilitation treatment methods in the program, and to incorporate new

developments into the system, such as new pavement performance models and new treatment method decision criteria. Also, the boundaries of State Congressional Districts could be subject to change from time to time, and, therefore, the network-level pavement rehabilitation needs analysis system should be flexible enough to accommodate re-districting of the State Congressional Districts without requiring a major change in the system.

- Needs to satisfy the changing requirement of accountability. In June, 1999, the GASB established new financial reporting standards that will fundamentally change the way state and local governments report their financial status. One of the provisions, GASB 34, requires that major infrastructure assets, acquired or having major conditions or improvements in fiscal years beginning after June 15, 1980, be capitalized in financial statements. In addition, the cost of using the assets must be reflected (U.S.DOT, 2000). Using pavement needs analysis system will help GDOT to justify its budget needs.

The concerns and needs for improvements of pavement rehabilitation needs analysis presented above clearly show that major improvements on the network rehabilitation needs analysis are necessary for GDOT. A GIS-enabled, multi-year pavement rehabilitation needs analysis system (NEEDAS) was proposed to provide effective decision support, to improve the operation efficiency, and to enhance the pavement management practices the proposed system has incorporated. The framework for the system is presented in the following section.

4.2 A Framework for a Pavement Rehabilitation Needs Analysis System

The NEEDAS program developed for GDOT has incorporated most of the desirable features described in the previous section. Figure 4-1 presents the framework of the NEEDAS program. Data from the Central Oracle Database (the COPACES database, as discussed in Chapter 3) is used as the basis for developing the NEEDAS program. Besides pavement condition data, the data necessary for pavement needs analysis such as traffic volume, rehabilitation treatment methods and costs, and special concerns, etc. are retrieved from other databases and used interactively.

The NEEDAS program has three modules: Project-level Analysis Module, Network-level Analysis Module, and GIS Module. The pavement rehabilitation needs analysis is performed through the interaction between the Project-level Analysis Module and the Network-level Analysis Module. The GIS module provides the capability for data/information visualization, spatial analyses, mapping, and interactive analysis. The GIS Module also makes graphical information in GIS maps integrate seamlessly with needs analysis modeling (performance forecasting, treatment determinations, etc.) to support effective decision-making. It readily provides a tool for users to make rehabilitation changes as to when, where, and what to treat at the project level on the map interactively, and it shows the impact of performance and cost at both project level and network level, which can be visualized and evaluated immediately after re-running the needs analysis modeling. It allows users to conduct "what-if" analyses to support the decision-making effectively.

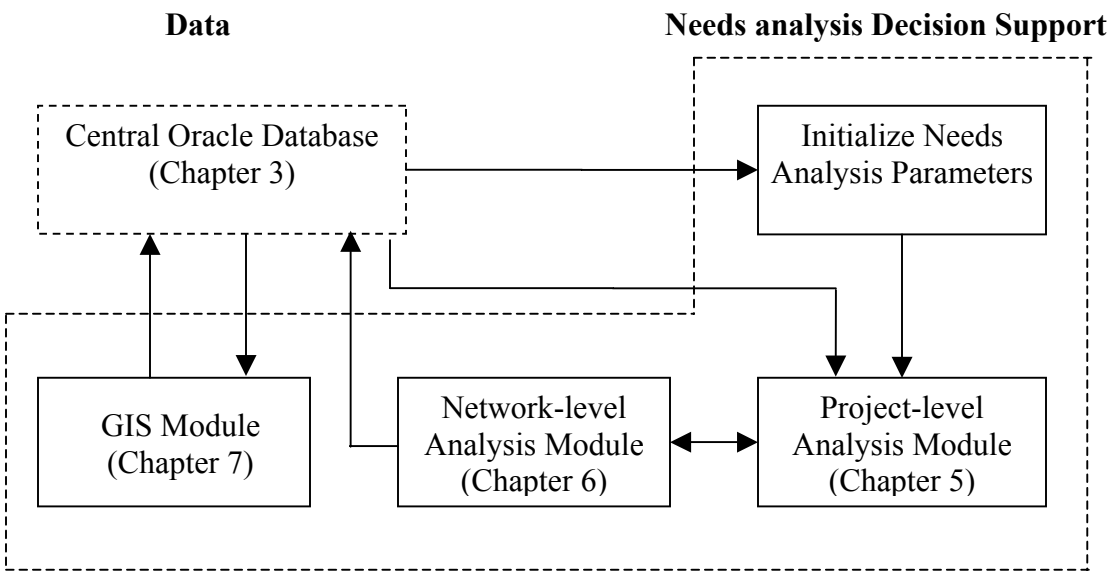


Figure 4 - 1 Framework of NEEDAS

Figure 4-2 presents the detailed steps and flow for conducting multi-year pavement needs analysis using the NEEDAS program. Based on the COPACES database information, including rehabilitation treatment methods and cost data, historical pavement condition data, historical traffic data, and historical maintenance activity data, the Project-level Analysis Module was developed to determine an appropriate rehabilitation treatment method and costs, predict future performance, and calculate life cycle cost effectiveness ratio for each pavement project within the network in each of the forecasted period (e.g. five years).

The results of the life cycle cost effectiveness ratios of all the pavement projects obtained from the Project-level Analysis Module are then forwarded to the Network-level Analysis Module. Using the results from the Project-level Analysis Module, the Network-level Analysis Module analyzes the information associated with each project

(life cycle cost effectiveness ratio, traffic, and others) and selects candidate projects to be treated subject to various network constraints, including budget availability constraint, network performance requirement constraints, and various balancing constraints.

The needs analysis results determined from the combination of these two modules include the results at both project level, such as when, where, what to treat in the forecasted period (e.g. five years), and network level, such as statewide and different jurisdictions' pavement performance and funding requirements in different years within the analysis period. These results can be uploaded to the COPACES database directly. Also, these results can be accessed, displayed, and analyzed using the GIS Module.

Using the GIS Module, the NEEDAS program allows the engineer not only to retrieve and display the network-level results according to different jurisdiction boundaries, such as the GDOT District-level pavement performance per year, State Congressional District-level rehabilitation cost per year, etc., but also to make the project-level changes as to when, where, and what to treat directly and dynamically on the map so that the corresponding impacts of future performance and cost at project and network levels can be evaluated and displayed dynamically. The users can then conduct "what-if" analyses readily to evaluate various future treatment strategies to support their final decision. Detailed information of these modules will be introduced in Chapter 5, 6, and 7.

The system is client/server-based, which allows GDOT District offices to communicate with the Central Office through the shared Central Database. Oracle 8i was used to develop the centralized database. The client/server communication is through TCP/IP protocol. MicroSoft (MS) Visual Basic 6.0 was used to develop the functions

and the user-friendly interfaces, and MS Excel 2000 was used to generate graphs and reports. ESRI MapObjects 2.1 was used to create functions for spatial analyses, mapping, and visualization for the GIS-enabled system. The system is running on Windows 95/98/ME/NT/2000/XP.

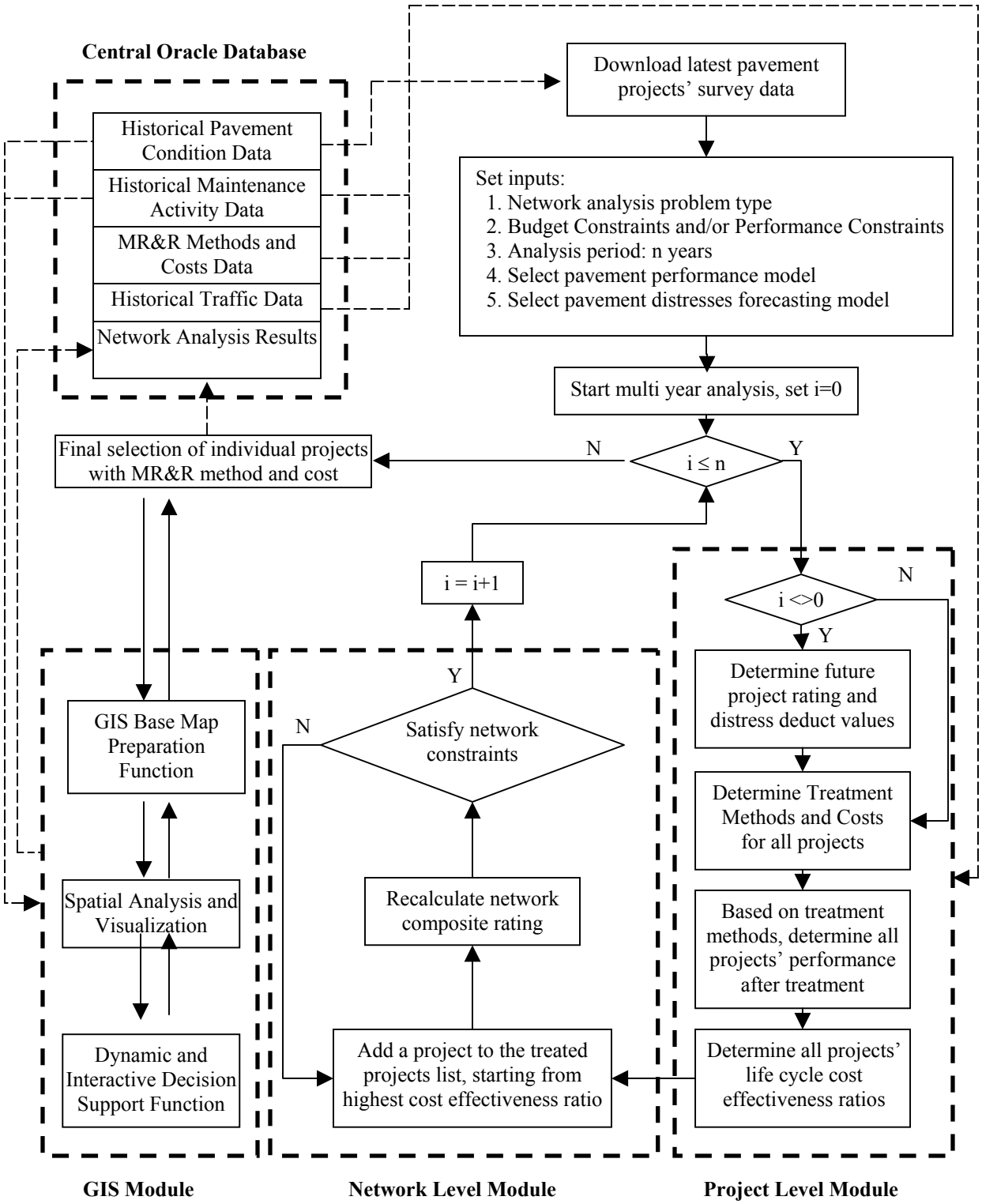


Figure 4 - 2 Flow of NEEDAS

CHAPTER 5

DEVELOPMENT OF PROJECT-LEVEL ANALYSIS MODULE

5.1 Overview of Project-level Analysis Module

As pointed out in Chapter 4, the Project-level Analysis Module would extract historical data, including past and current year pavement condition survey data for statewide highway pavements in the network and perform project-level analyses. The project-level analyses include determining appropriate rehabilitation treatments and costs, predicting future performance, and calculating life cycle cost effectiveness ratios for each pavement project within the network. Figure 5-1 shows the flow of the project-level analyses. Because the NEEDAS program uses a yearly-based prioritization approach in the Network-level Analysis Module as presented in Chapter 6 for selecting pavement rehabilitation projects, the project-level analyses are also performed on a yearly basis. The analyses performed in this module include the steps described below:

Step 1: Determine forecasted future project ratings and distress deduct values for each project based on the current and the historical pavement condition survey data.

Step 2: Determine viable rehabilitation treatment methods (including "Do Nothing") and costs for each project based on the project ratings and distress deduct values obtained in Step 1.

Step 3: Determine future rehabilitation ratings and deterioration rates for each project based on the rehabilitation treatment methods determined in Step 2

along with the corresponding traffic volume and the historical pavement performance of each project.

Step 4: Determine the life cycle cost effectiveness ratio for each project based on the improved ratings and the costs associated with the rehabilitation treatment determined in Step 2 and Step 3.

Three important functions have been developed in this module to facilitate the various analyses described above. These three functions are pavement performance forecasting functions, rehabilitation treatment methods and costs determination functions, and life cycle cost effectiveness analysis function. Detailed information on the development of these functions and the challenging issues encountered during the development of these functions are presented in the subsequent sections in this chapter. Section 5.2 describes the development of pavement performance forecasting analysis functions, which include the pavement rating forecasting function and the pavement distress deduct values forecasting function. These two functions are required for determining suitable rehabilitation treatment methods for a pavement project and for predicting future pavement performance for the project. Section 5.3 describes the development of the rehabilitation treatment methods and costs determination functions. Section 5.4 presents the detailed information of developing the life cycle cost effectiveness analysis function. This function is used to calculate the life cycle cost effectiveness ratio of each project, a parameter that is used in the Network-level Analysis Module for prioritizing projects in formulating the network needs analysis plans. Section 5.5 discusses the interaction between the Project-level Analysis Module and the Network-

level Analysis Module. Section 5.6 discusses the approaches to reduce the computing time in the Project-level Analysis Module.

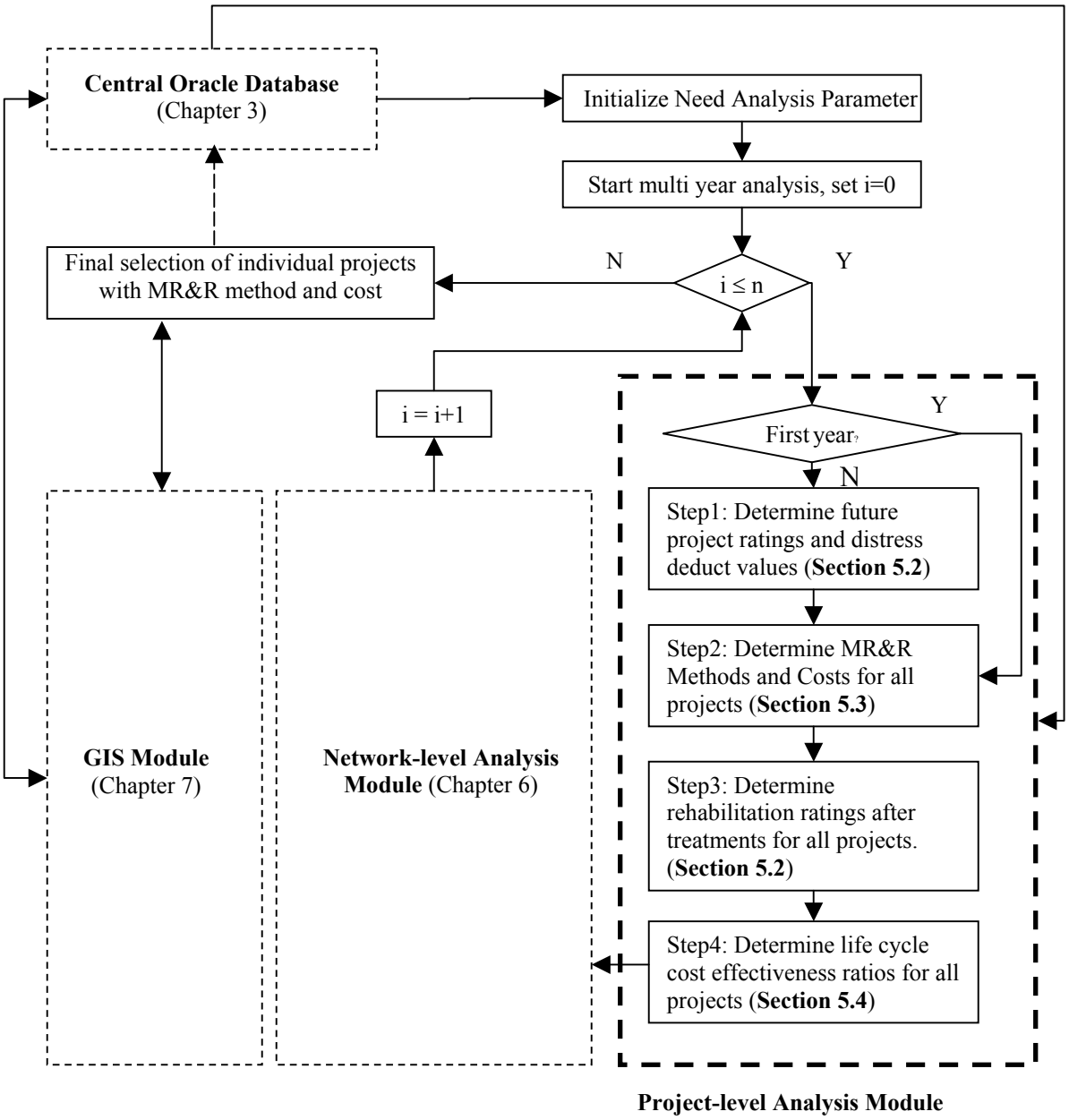


Figure 5 - 1 Flow Chart of Project-level Analysis Module

5.2 Pavement Performance Forecasting Functions

As mentioned in the previous chapters, GDOT has established a Central Oracle Database (the COPACES database) containing eighteen years (1986 to present) of pavement condition survey data for all the pavement projects in the GDOT pavement network. These data were utilized as the basis for developing the pavement performance forecasting functions.

The pavement performance forecasting functions described in this section are used for predicting future pavement ratings and pavement distresses conditions. As presented in Chapter 3, pavement ratings are the primary indicator for assessing pavement performance. To be presented in Chapter 6, pavement ratings are also used for establishing pavement performance constraints at both the network level and the project level. Pavement distress conditions, as expressed in terms of deduct values for different types of distresses, together with pavement ratings, are used for determining rehabilitation treatment methods. Therefore, the development of pavement performance functions is essential for the NEEDAS system.

According to GDOT's PACES manual, the performance rating of a pavement project is calculated as 100 minus the deduct values from all the distresses determined from the pavement condition survey on the project (GDOT, 1990). Therefore, the first thought for developing the pavement performance forecasting functions was to develop a pavement distress deduct value forecasting model for each type of distress. Once all the deduct values for a pavement project are determined from the model, the corresponding pavement ratings can be calculated from the pavement distress deduct values. Unfortunately certain inherent characteristics of pavement distresses and the

corresponding distress deduct values cause irregular changes of these values and, thus, make such an approach impractical. The reason that changes of individual pavement distresses, and, therefore, the distress deduct values, are much less regular is that the extent of a specific severity level of a pavement distress type could become a different severity level of the same distress type or even change to other distress types between two consecutive survey years. For example, a high extent of load cracking severity level one distress in one year could become a medium extent of severity level one plus a low-to-medium severity level two load cracking in the following year, as a portion of the severity level one load cracking could further deteriorate and become severity level two load cracking. Based on the PACES manual (GDOT, 1990), the deduct value of load cracking is determined by the highest deduct value of each severity level. Therefore, it is possible that although the overall severity of load cracking of a project is increased (worsened), the deduct value of the load cracking may not be increased accordingly.

Because of these reasons, use of regression analysis approaches for developing forecasting models for deduct values of different pavement distress types at different severity levels for each pavement project would not work. Therefore, separate approaches were used to develop models forecasting pavement performance ratings and pavement distress deduct values. Three pavement performance forecasting functions, (1) a function for forecasting project-level pavement performance ratings, (2) a function for determining deterioration rates after rehabilitation treatments, and (3) a function for forecasting pavement distress deduct values, are presented in the following three subsections.

5.2.1 A Function for Forecasting Project-level Pavement Performance Ratings

This function is developed for forecasting the next year's performance rating of a pavement project before a rehabilitation treatment is applied to the project. Two models are developed for the function: GDOT Empirical Model and Project Specific Dynamic Linear Regression Model.

GDOT Empirical Model

Table 5-1 shows the performance model developed by the GDOT Office of Maintenance for pavements using different types of rehabilitation treatments. In this table, *MaxRating* is the pavement rating immediately after a specific rehabilitation treatment is applied on the pavement; *MinRating* is the expected pavement rating at the end of the defined pavement service year for a specific rehabilitation treatment method. The defined pavement service year is the service life of a specific rehabilitation treatment. The service life for each type of treatment method is categorized based on the traffic conditions in terms of AADT and percent of truck traffic. The average deterioration rate for a pavement with a specific treatment can be calculated as shown below, assuming linear decay:

$$\text{Deterioration rate per year} = \{[\text{Max. Rating}] - [\text{Min. Rating}]\} / [\text{Service Years}] \quad (5\text{-}1)$$

Unfortunately, this model cannot be used directly for forecasting pavement performance rating for the following two reasons. First, the pavement condition survey in the past did not record pavement surface types according to those specified in Table 5-

1. Instead, the pavement surface types were recorded in terms of "A" for all hot-mix asphalt surface types, "B" for bituminous treated surface types, and "S" for Slurry Seal or Micro Seal. The surface types described according to that specified in Table 5-1 are not readily available in any GDOT databases, although GDOT is contemplating generating such information. The second reason is that the COPACES database has AADT information but no percent of truck traffic information. It is conceivable that this information could be added into the COPACES database, although it would take a fair amount of effort to do so. For the time being, a simplified performance model as shown in Table 5-2 was adopted by GDOT. This model utilizes the pavement surface types ("A", "B" and "S") and traffic information in terms of AADT, the information currently available in the COPACES database.

Table 5 - 1 Linear Empirical Model Provided by GDOT

Treatment Method	Max. Rating	Min. Rating	Service Years		
			CLASS 1	CLASS 2	CLASS 3
Level and Resurface	100	70	12	10	9
Level	100	70	6	6	5
Mill and Micro Seal	90	70	6	5	4
Mill and Resurface	100	70	12	10	9
Mill, Level and Resurface	100	70	12	10	9
Mill	85	70	3	2	1
Surface Treatment and Resurface	100	70	12	10	9
Resurface	100	70	12	10	9
Slurry Seal	90	70	7	6	5
Surface Treatment	100	70	9	6	5
Micro Seal	90	70	6	5	4

Note:

CLASS 1: AADT <5,000 and % Truck <5%

CLASS 2: AADT <10,000 and % Truck <7%

CLASS 3: AADT >10,000 and % Truck >7%

Table 5 - 2 Simplified Pavement Deterioration Model

Surface Type	Minimum AADT	Maximum AADT	Deterioration Rate
A	0	5000	2.50
A	5000	10000	3.00
A	10000	50000000	3.33
B	0	5000	3.33
B	5000	10000	5.00
B	10000	50000000	6.00
S	0	5000	2.85
S	5000	10000	3.33
S	10000	50000000	4.00

Project Specific Dynamic Linear Regression Model

The project specific dynamic linear regression model utilizes the historical pavement performance ratings of a project in the COPACES database to develop a linear regression equation and uses that to forecast the next year's performance rating for the project.

Before the decision was made to use the linear regression model, nonlinear models were also considered. Many nonlinear regression models for pavement performance index have been used before (Turner et al. 1986; Smith et al., 1987; Chen et al., 1995; Livneh, 1998; Robinson, 2003). Figure 5-2 represents four typical nonlinear regression relationships for predicting pavement performance index. However, the current COPACES database does not provide sufficient information, such as rehabilitation treatment history, pavement design parameters, etc., to allow for identifying which one of the nonlinear relationships would be more suitable for a given pavement project. If the performance ratings of a project were supposed to follow Curve "A" as

shown in Figure 5-2, using a wrong type of nonlinear relationship, such as Curve "B," could generate a much larger bias than using a linear regression model. Because of this concern, the use of nonlinear models was not considered.

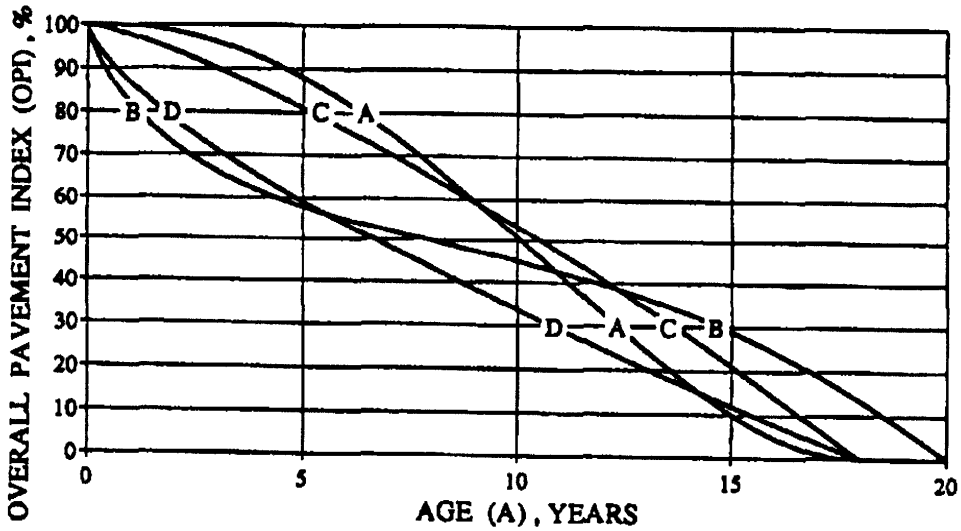


Figure 5 - 2 Various Types of Deterioration Curves (Livneh, 1998)

During the selection of pavement performance models, another major concern had to do with the quality of the historical survey data stored in the COPACES database. Errors from any one of the rating data could potentially introduce a significant bias on the forecasting. However, errors in pavement performance rating data could not be entirely eliminated, even though extensive efforts had been made to eliminate errors from the

pavement condition evaluation database, including the use of the COPACES built-in error-checking functions.

Another challenging issue is that the rating in a certain year in the historical data is abruptly increased, although the ratings should be trending downward if no rehabilitation treatment action is applied on the pavement. The program would need to be able to automatically decide if the increasing in the rating is due to rehabilitation treatment actions applied on the pavement or due to errors in the field condition survey. The COPACES database does not contain information on when pavement rehabilitation treatment actions were applied and, therefore, the decision as to whether the abrupt increase in the rating is due to a rehabilitation treatment action or not has to be determined by logic. The NEEDAS program has included an algorithm to perform such logic determinations on whether an abrupt increase in the rating between two successive years is due to a rehabilitation treatment action that occurred between these two successive years or due to reasonable variation in the field condition survey. If the abrupt increase in the rating is deemed to be due to reasonable variation, the linear regression analysis will proceed to include both years' data to determine the linear regression equation. On the other hand, if the abrupt increase in the rating is deemed to be due to a new rehabilitation treatment applied on the pavement between the two years, the program will automatically stop extracting rating data from the database and use the data after the first year in the two successive years to determine the linear regression equation.

Although the linear regression model is used for this needs analysis system, the NEEDAS computer program developed for the system has the built-in flexibility to allow for incorporating any nonlinear regression model. In the future, if a nonlinear regression

model is developed, it can be easily incorporated into the system without requiring modifications of other functions and modules in the program.

Comparison with the GDOT empirical model, the project specific dynamic linear regression model has the advantage of considering the specific characteristics of each individual project in forecasting its future year pavement deterioration rates. Also, the model automatically incorporates the most recently available performance rating data for the project as they are available from the pavement condition survey for developing the regression equation. Limitations of the model do exist. Not every project has valid historical performance ratings. Some projects had invalid PACES historical survey data and were deleted from the database during the data sanitizing process before uploading to the COPACES database, as described in Chapter 3. Obviously, the linear regression model cannot be used to forecast project rating without the historical performance ratings. For those projects without historically surveyed data, GDOT's empirical model has to be used to forecast future performance ratings.

5.2.2 Function for Determining Deterioration Rates after Rehabilitation Treatments

This function is for forecasting the next year's performance rating and the deterioration rate of a pavement project after a specific rehabilitation treatment has been applied on the pavement.

As shown in Table 5-1, the GDOT Office of Maintenance has established general pavement performance properties for different rehabilitation treatment methods under different AADT and truck traffic conditions. Besides the specific rehabilitation treatment methods that could affect the future pavement performance, shown in Table 5-1, the

opinions from the maintenance engineers of GDOT strongly indicate that the historical pavement performance of a pavement project prior to the application of a rehabilitation treatment could also affect the future pavement performance after a treatment has been applied. This opinion has also been shared by maintenance engineers from the other State DOTs (FHWA, 1997). Although this important finding has not been incorporated formally into the rehabilitation planning decision process in the past, the concept of "effective deterioration rate" is introduced here in an attempt to address this issue. The effective deterioration rate of a pavement project after application of a specific treatment method considers both the effects of a specific rehabilitation treatment method used and the existing pavement performance behavior prior to the application of the rehabilitation treatment. To quantify the effects on pavement performance influenced by both a rehabilitation treatment method and the prior pavement conditions would require a significant amount of effort, even if the required past pavement treatment records of all the pavement projects within the network were available in the COPACES database. After consultation with GDOT engineers, a simplified effective deterioration rate as described below was proposed. It is the average of the deterioration rates for a specific rehabilitation treatment method and the deterioration rate of a pavement prior to the rehabilitation treatment action's being applied. The deterioration rate of a pavement prior to the rehabilitation treatment action was obtained from the project specific dynamic linear regression model presented in the previous section. Figure 5-3 shows an example of how the effective deterioration rate of a pavement was determined after treatment was applied. In Figure 5-3, slurry seal was scheduled in Year 2003, and the deterioration rate for slurry seal under low AADT was 2.85 (based on Table 5-2). The deterioration rate

for the pavement project prior to the rehabilitation action was 4.0. Therefore, the effective deterioration rate of this pavement project after the application of a slurry seal treatment became (4+2.85)/2=3.43.

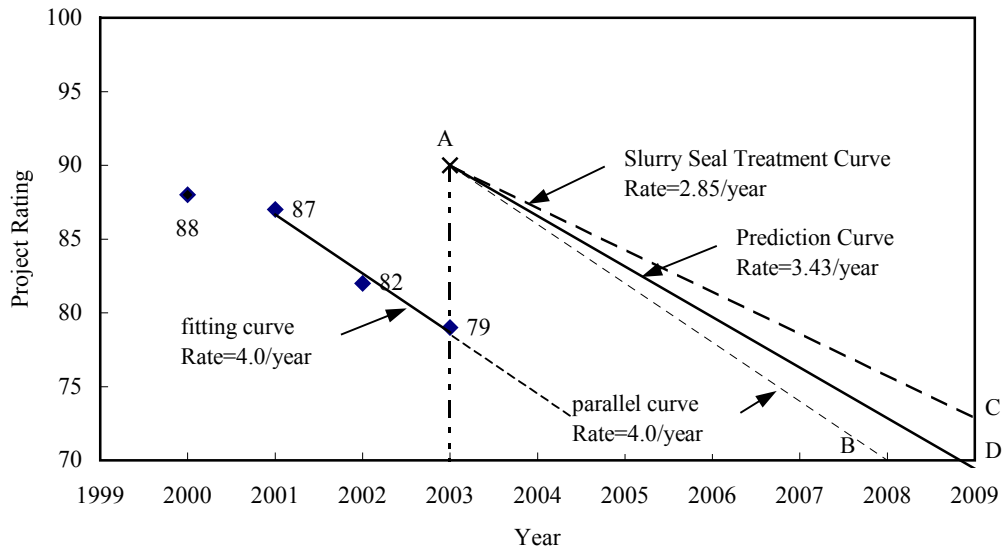


Figure 5 - 3 Pavement Rating Prediction Model

In the future, when historical treatment methods are accurately recorded in the database, the effective deterioration rate can be determined more accurately based on the adjustment of the difference between a typical deterioration rate obtained from Table 5-1 and the project-specific deterioration rate for a specific pavement project after different treatment actions are applied. Figure 5-4 illustrates the proposed concepts. The objective

of the example in Figure 5-4 is to illustrate the proposed concept of determining the effective deterioration rate after Treatment 2 is applied at year X_2. The first step is to determine the difference between the deterioration rate obtained from the historical surveyed ratings for the project and the deterioration rate obtained from the empirical model based on Treatment 1 for the project prior to year X_2. In the example, the deterioration rate of the empirical model and the actual surveyed averaged rating are 2.5 and 3.5, respectively. Therefore, the difference of the deterioration rates between the empirical model and the actual historical surveyed rating is 2.5-3.5 = -1.0. Then, several different approaches described below can be used to determine the effective deterioration rate after Treatment 2 is applied at year X_2 based on this difference.

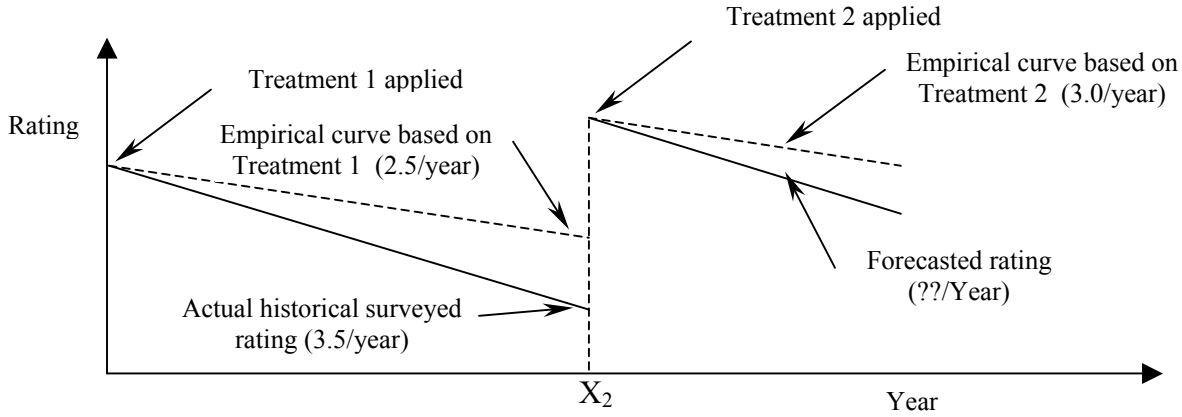


Figure 5 - 4 Future Improved Method for Determining Effective Deterioration Rate

(1) Adjust by absolute difference. This method is based on the assumption that the difference of the deterioration rates between the empirical model and the actual historical surveyed rating for a specific project after X_2 is the same as that prior to the application of Treatment 2 at X_2; that is, the difference is -1.0. In this case, if the deterioration rate of the empirical model after Treatment 2 is 3.0, then the effective deterioration rate of forecasted rating will become 3.0 – (-1.0) = 4.0 per year.

(2) Adjust by relative difference. This method assumes that the ratio between the actual deterioration rate and the deterioration rate determined by the GDOT Empirical Model for a specific project is constant. Thus, the forecasted deterioration rate after Treatment 2 is applied can be determined by multiplying the same ratio with the deterioration rate determined for Treatment 2 from Table 5.1. In the example above, the forecasted deterioration rate after Treatment 2 applied at year X_2 becomes 3 x (3.5/2.5) = 4.2.

At this point, it is difficult to say which method would yield a better forecast. However, further study can be performed once historical rehabilitation treatment data, including the treatment methods, are available.

5.2.3 Project-level Pavement Distress deduct value Forecast Function

To overcome the inherent variability of distress deduct values, as mentioned at the beginning of this section, the three different models presented below were developed to forecast the future distress deduct values for different pavement distress types and severity levels for a pavement project. All three models have been implemented in the system, and the user can select any one of the models for predicting distress deduct values. Although each model reflects certain engineering considerations, the accuracy of each model can only be established after extensive validation analyses have been performed using the historical COPACES data.

(A) Model I: Global Distress deduct values Prediction Model

This model uses the statistical results of pavement deduct values determined within a common class of pavement projects to represent the deduct values for any pavement projects within this common pavement class. Using historical pavement survey data, the model determines the statistical average deduct values for various pavement distress types and different severity levels versus pavement performance ratings for all the pavement projects within a common pavement class. The pavement classes are categorized according to GDOT Districts (1 to 7), traffic (high, medium and low AADT) and pavement surface types (A, B, and S). Table 5-3 illustrates the deduct values of different distress types versus performance ratings (100 to 1) for a specific pavement class (GDOT District 7, high AADT, and A-type pavement surface). When using this model to forecast distress deduct values, the NEEDAS system first determines

the forecasted performance rating of a project and then extracts the distress deduct values at the specific rating from the common pavement class this project belongs to.

Table 5 - 3 Example of Pavement Distress deduct values versus Project Rating

District	Traffic	Surface Type	Project Rating	Average Distress deduct values					Total Projects	Remark
				Rutting	Load Cracking	Block Cracking	…	Patches and Potholes		
7	H	A	100	0.00	0.00	0.00	…	0.00	201	
7	H	A	99	0.00	1.00	0.00	…	0.00	153	
7	H	A	98	1.64	0.18	0.00	…	0.00	160	
…	…	…	…	…	…	…	…	…	…	
7	H	A	47	3.20	26.4	16.0	…	5.00	153	
7	***H***	***A***	***46***	***2.60***	***28.2***	***17.0***	…	***5.00***	***160***	***Interp-olated***
7	H	A	45	2.00	30.0	18.0	…	5.00	160	
…	…	…	…	…	…	…	…	…	…	

Two factors have been carefully evaluated in the course of developing this model. These two factors are determination of common pavement classes and selection of the database. The model assumes that projects within a common pavement class will behave similarly and can be considered statistically as having the same distributions of distress deduct values. Therefore, common pavement classes should consider as much as possible the factors that could influence pavement rating and distresses. Taking into consideration the variables available in the COPACES database and the inputs from GDOT, common pavement classes are classified based on GDOT Districts (This reflects

the influences of geography, climate, and economy factors), traffic conditions (High, Medium, and Low AADT) and pavement surface types (Asphalt Concrete "A," Bituminous Surface Treatment and Seal Coats "B," and Slurry Seal "S"). Currently, truck traffic has not been considered in determining pavement classes because such information is not available in the COPACES database. Route type (Interstate versus State highway) has not been considered due to limited data available and large variation of traffic conditions in the Interstate highways.

Although GDOT has accumulated eighteen years of pavement condition survey data (1986 to present), the system utilized only the historical data from 1999 to 2002 to develop this model. There were two reasons for that. The first reason is that the quality of the pavement survey data has been significantly improved since the implementation of COPACES in 1999 because the COPACES program has many built-in error-checking and data-quality validation functions. The second reason is that some of the rehabilitation treatment methods have been developed and used more recently. For example, one of the more common rehabilitation treatment methods, that has been used by GDOT in the past few years, is Micro Seal (Micro-surfacing), and this method has been used on Georgia highways only since 1996.

In Table 5-3, two additional fields, "Total Projects" and "Remark" were created to track the model development process and can be used for future model improvement and validation purposes. The "Total Projects" field indicates the population of projects used to develop the model. The larger the number is, the more representative the average deduct values are. The "Remark" field is used to indicate whether the deduct values at that particular performance rating are determined from the actual data or through

interpolating the values from the adjacent values. Although it is very rare, some ratings have no project survey data. In those cases, the average deduct values for these ratings have to be interpolated from the adjacent values and an "Interpolated" note is placed in the "Remark" field.

The advantage of this model is that it is simple to develop and easy to use. The limitation of this model is that it does not consider the unique characteristics of each individual project.

(B) Model II: Project-Distinct Proportional Distress deduct values Forecast Model

This model utilizes current project rating, future project rating, and current distress deduct values of each individual project to forecast its future distress deduct values using the following formula:

$$\text{Future deduct values} = \frac{100 - \text{Future project rating}}{100 - \text{Current project rating}} \times \text{Current Deduct Values} \quad (5\text{-}2)$$

This model is based on the assumption that close relationships exist between the project rating and the distress deduct values of a pavement project. Since the project rating of a pavement project is calculated from the distress deduct values, it seems reasonable that the changes in the distress deduct values are proportional to the changes in the ratings. However, this model does encounter the inherent variability problems as pointed out before. There are two other limitations. First, if the current pavement project rating is 100, and, therefore, all the current deduct values are zero, the equation is unable to predict future distresses conditions. To overcome this limitation, a rule is set in the

program so that when a project rating is between 100 and 95, it uses Model I to determine distress deduct values. Second, if current deduct values of certain types of distresses are zero, these distress deduct values will remain zero during the entire future years covered in the analysis period. Model III was developed to overcome this limitation and to reduce the inherent variability,

When using this model, the current year distress deduct values for all the projects in the network have to be retrieved from the database, and the next year's distress deduct values calculated for all the projects to facilitate the determination of treatment methods and pass the information to the Network-level Analysis Module for rehabilitation projects selections. The information for next year's deduct values for all the projects will have to be written back to the database. These steps are repeated for each year and involve a significant amount of computer time in swapping data between the hard disk and the RAM and in computing updated distress deduct values. An alternative procedure was developed for processing the information, and it has significantly reduced the computing time. The details of the alternative procedure will be presented in Section 5.6.

(C) Model III: Network-Project Conjunction Distress Deduct Values Forecast Model

The development of this model comes from the need to overcome the limitations of Model II mentioned above and still be able to consider the project distinct performance and distress characteristics when forecasting distress deduct values for a pavement project. This model determines pavement distress deduct values by averaging distress deduct values determined from Model I and Model II. This model has the advantages of considering both the performance of the pavement from its common pavement class and

the individual project's distresses conditions. Further studies are needed to investigate whether there are better ways to combine Model I and Model II together than just simply averaging the results of these two models, and whether the results from Model III are better than Model I and II, and how much improvement is achieved by using Model III.

5.3 Develop Rehabilitation Treatment Method and Costs Determination Function

The Rehabilitation Treatment Method and Costs Determination Function was developed following the current GDOT practices. This function determines a suitable rehabilitation treatment method for a pavement project among the 9 treatment methods commonly used by GDOT. The determination of a suitable rehabilitation treatment method is based on three parameters: pavement performance rating, pavement distress conditions (in terms of distress deduct values), and traffic conditions (in terms of AADT). The decision tree for determining a suitable rehabilitation treatment method from these three treatment decision parameters is shown in Figure 5-5. The Rehabilitation Treatment Method Determination Function also considers whether the Curb and Gutter Milling (CGMIlling) operation is required during a rehabilitation operation. During the annual pavement condition survey, a rater is required to determine whether milling of curbs and gutters is required for a pavement project and then enter "Yes" or "No" in the "CGMilling" selection box in the COPACES field data entry form, shown in Figure 3-1. With a "Yes" in the "CGMilling" field, a milling operation should always be required in conjunction with the rehabilitation treatment method determined from Figure 5-5. For example, if based on Figure 5-5, a project is to be treated by "Overlay," and the field

"CGMilling" of the project is "YES," the correct treatment of this project should be "Milling and Inlay" (milling then overlay with hot mix asphalt mixtures).

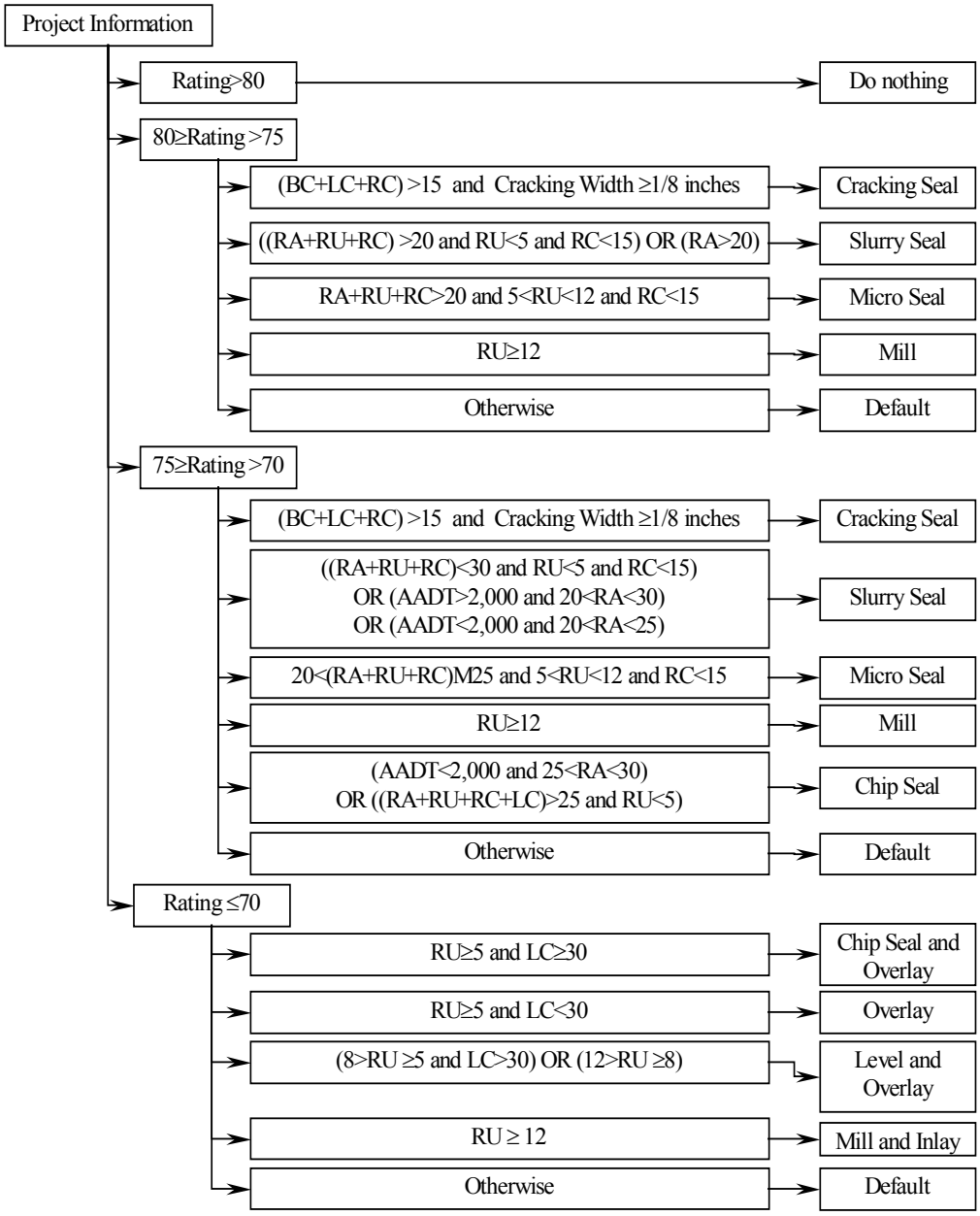
Although the flow of the rehabilitation treatment determination function, shown in Figure 5-5, is very clear, there are some issues that need to be addressed.

1) It is possible that more than one rehabilitation treatment method can satisfy the prevailing performance rating, distress conditions, and AADT parameters (treatment decision parameters) for a pavement project. Then, how to determine which treatment method should be selected?
2) The decision tree shown in Figure 5-5 may not cover all the possible combinations of the pavement treatment decision parameters. Under this circumstance, what treatment method should be used if none of the treatment methods shown in Figure 5-5 could meet the prevailing treatment decision parameters posted by a pavement project?
3) In Figure 5-5, treatment methods depend only on treatment decision parameters. No considerations are given to a project's treatment history. It is possible that a same treatment method may be recommended repeatedly by the treatment method determination function within a 2 to 3 years interval. This is highly possible, particularly for those lower-cost treatment methods, such as a slurry seal treatment. One of the reasons is that the pavement selection criteria (to be presented in Chapter 6) are based on cost-effectiveness ratios, and a project treated with those lower-cost treatment methods may result in having higher cost-effectiveness ratios within a 2 to 3 years interval after the first treatment and,

therefore, are being selected again for treatment. This is neither a good practice nor a practice commonly used by state DOTs for the following reasons. Repeated applications of a same treatment method, such as applying a slurry seal treatment on top of slurry seal, will result in a less effective performance of the treatment the second time. Also, frequent use of low-cost treatment methods on the same location may create negative public opinions that consider the project as time and money being wasted or causing inconvenience to the traveling public. Therefore, some rules have to be imposed on such issues to restrict the frequent, repeated use of the same treatment method.

To resolve the first issue, the following four prioritization criteria were developed, allowing the user to select one of the criteria for the program to select a treatment method for a pavement project if more than one candidate method meets the treatment decision criteria:

- Highest service year to cost ratio: Select the rehabilitation treatment with highest Service Year to Costs ratio as the preferred rehabilitation treatment for the project.
- Premium: Select a rehabilitation treatment with the highest unit cost.
- Economic: Select a rehabilitation treatment with the lowest unit cost.
- Longer Performance: Select a rehabilitation treatment with the longest "Service Year"



BC: Blocking cracking deduct value; LC: Load cracking deduct value;
RC: Reflective cracking deduct value; RA: Raveling deduct value; RU: Rutting deduct value

Figure 5 - 5 Decision Tree of Project Rehabilitation Treatment Methods

Regarding the second issue that none of the treatment methods shown in Figure 5-5 could meet the prevailing conditions posted by a pavement project, one way to overcome this problem is to assign default treatment methods to cover the gaps. As shown in Figure 5-5, different default treatment methods that represent the most conservative treatment methods within the corresponding performance rating ranges were included to cover the gaps in which no specific treatment method could be found under the combination of treatment decision parameters. Table 5-4 lists current default treatment methods. It covers all the rating range from 0 to 100. As the decision flow shown in Figure 5-5 improves in the future, the need for using defaults to determine appropriate treatment methods for pavement projects will decrease.

Table 5 - 4 Default Treatment Methods

Minimum Rating	Maximum Rating	Treatment Method
0	70	Level-Resurface
70	75	Level-Resurface
75	90	Micro Seal
90	100	Do Nothing

Regarding the third issue that appropriate treatment methods for pavement projects depend only on treatment decision parameters and no considerations is given to a project's treatment history, this could cause the same treatment method to be recommended by the treatment method determination function within a 2 to 3 year

interval. As mentioned above, this is neither a good practice nor a practice commonly used by state DOTs. It is a problem encountered in many needs analysis systems. A common approach to resolve this problem is to add rules that restrict or disallow the use of the same treatment method for a pavement project within a certain period.

Many needs analysis systems, such as that used by InDOT, Minnesota Department of Transportation (MnDOT) (FHWA, 1997), and ADOT (Golabi et al., 1983), impose restrictions that limit the number of treatment activities and/or the same type of treatment method that can be applied to a pavement project within a specific period. For example, InDOT allows only two treatment methods within a 20-year analysis period, and only one rehabilitation alternative can be applied to each pavement project. These same restrictions apply for MnDOT's pavement management system unless the rehabilitation alternative is a cyclic treatment (FHWA, 1997).

Compared with these systems, the system developed for GDOT, as described here, incorporates a logic constraint of limiting consecutive use of certain treatment methods instead of simply limiting the number of treatments within a specific period. When determining an appropriate treatment method for a pavement project, the system will check the previous treatment method used for the project. If both the previous treatment and the treatment to be applied for a project, as determined by the treatment determination function, are among the low-cost treatment methods (crack seal, slurry seal, micro-seal, mill and chip seal), an overlay treatment (more costly and higher quality treatment method) will be selected as the recommended treatment method instead of the treatment method determined from Figure 5-5 based on the treatment decision parameters. The life cycle cost effectiveness analysis of the project will be based on the

overlay treatment. This rule not only stops repeated use of low-cost treatment methods for a pavement project, but also can achieve more balanced rehabilitation treatment applied on all the projects in the network within an analysis period.

Once an appropriate rehabilitation method for a pavement project is determined, the associated treatment costs for the project can be calculated based on the unit cost of the selected method and the lane-mile of the project. The unit cost information for the various treatment methods is stored in the database and is updated annually based on the actual costs from the GDOT past year's construction cost database.

5.4 Life cycle Cost Effectiveness Analysis Functions

Decision makers often face the challenge that limited funding cannot meet the growing demand for pavement rehabilitation activities. Effective cost evaluation methods are needed to prioritize projects so that limited funding can be used more efficiently. According to AASHTO *Pavement Management Guide* (2000), the following criteria can be used to prioritize projects for rehabilitation actions:

- Prioritization by severity of various pavement distresses.
- Prioritization by certain performance index, such as pavement serviceability index (PSI), pavement condition rating (PCR), or other indices.
- Prioritization by weighted performance function, such as PSI, PCR, or other indices weighted by a usage value, such as vehicle miles traveled (VMT).
- Prioritization by composite criteria. In this method, pavement performance and distress conditions are combined with other data to develop a priority

score. For example, a distress index could be weighed 40 percent, traffic condition could be weighted 40 percent, and safety could be weighted 20 percent.

- Prioritization by initial rehabilitation treatment cost.
- Prioritization by least life cycle cost. This analysis identifies the projects that will provide the desired level of service at the minimum cost over a selected analysis period.
- Prioritization by Benefit/Cost Ratio or Cost-Effectiveness Ratio. Benefits are normally those benefits gained by the highway user, such as reduced traffic delay costs, reduced accident costs, reduced environmental costs, etc. The costs usually include the total costs incurred, including construction costs, maintenance costs, and future rehabilitation costs. The cost effectiveness uses the same concepts as that of the benefit/cost ratio except a surrogate is used in cost-effectiveness in place of monetary benefits in the benefit/cost ratio to reflect the benefits received.

There are pros and cons for using these different criteria for prioritizing pavement projects for developing rehabilitation plans. The advantages of using the first two criteria, prioritization by pavement distress and pavement performance functions, are that the parameters, whether the pavement distresses or pavement performance indices, are direct measurable quantities, and, therefore, are more readily available and easily understood. Prioritization using these two criteria is essentially a “worst first” approach, selecting projects starting with the worst conditions until the available funding is

exhausted. However, they fail to consider the benefits generated for the funds spent. If achieving an optimum network performance with limited funding is the goal, use of the worst first approach cannot achieve this goal. Prioritization by weighted performance function criterion also suffers the same drawbacks as that for the first two criteria mentioned above. In addition, prioritization by a usage-weighted performance function may skew the allocation of funds to certain pavement projects if such usage functions were not carefully and correctly defined and calibrated. Prioritization by least initial construction cost is too simplistic and does not consider the potential benefits of a specific treatment within its useful life. Prioritization by least life cycle cost makes it possible to develop a rehabilitation plan that not only can increase pavement performance and service life, but can also reduce long-term costs of pavements maintenance for the network. It has attracted more attention in pavement needs analysis practice (Geoffroy, 1996; Labi and Sinha, 2003; Hall et al., 2003; Ozbay et al., 2004). Although the concept of life cycle cost analysis has been in existence for quite a while, some issues still have not been adequately addressed in many existing pavement needs analysis systems, such as how to select an appropriate pavement life (or analysis period) and how to consider benefits (Hall et al., 2003). These issues will be addressed later in this section.

After evaluating the pros and cons of all the criteria listed above, the life cycle cost effectiveness ratio was chosen for prioritizing projects for the NEEDAS system, as this criterion can best achieve the objectives of the system. The choice of the cost effectiveness ratio over benefit/cost ratio as the prioritization criterion was for the following reasons. Although the research efforts on how to monetize benefits continue to grow and become more mature, there are still many uncertainties in monetizing these

costs (Ozbay et al., 2004). Also, State DOTs often tend to exclude user costs in their analysis, as user costs are not being perceived as the real costs. Therefore, after consulting with GDOT, cost effectiveness analysis instead of benefit/cost ratio was adopted.

As pointed out previously in this section, selection of an appropriate pavement life (or analysis period) and consideration of pavement residual value are two important issues that require special considerations when performing pavement life cycle analyses, using cost effectiveness ratio or benefit/cost ratio method, or least life cycle cost method. These two issues will be discussed in the following sections.

There are several approaches for determining or selecting an appropriate analysis period for comparison of rehabilitation treatment alternatives (Hall et al., 2003). These include (1) the least common multiple of the service lives of all the treatment alternatives; (2) the shortest service life among the alternatives; (3) the longest service life among the alternatives; and (4) others. Each option has its limitations. The use of the least common multiple of the service lives of all the treatment alternatives may result in an unrealistically long analysis period. For example, the service life of a slurry seal treatment under low traffic is 7 years, and an overlay has a service life of 12 years (see Table 5-2). Thus the common multiple of the service lives of these two alternatives is 84 years, which is unrealistically long. The use of the shortest service life as the analysis period does not fully consider the differences in the long-term performance among the alternatives and often can favor treatment alternatives with shorter service life because they are usually cheaper than the treatments with longer service life if their residual values are not correctly considered. Using the longest service life among the alternatives

usually assumes the treatment alternative with shorter service life is being applied repeatedly, which is not a common practice in reality, as discussed in the previous section.

When using a same-length analysis period to compare projects with different treatment methods that have different lengths of service lives, the residual value or salvage value for different treatment methods at the end of the analysis period should be considered. One common method to consider the residual value is to convert it into a cost item based on certain proportional relationship. For example, the FHWA's Interim Technical Bulletin on life cycle cost analysis recommends that the residual value be determined as the portion of the cost of the last rehabilitation equal to the portion of the remaining life of the last rehabilitation (Hall et al., 2003). This approach for assessing the residual value is simple and easy to understand, but is rather simplistic as it fails to recognize the benefits of different services provided by different treatment methods as illustrated in Figure 5-6. Assuming the service life of Project A and B are T1 and T2, respectively, and their construction costs are $A and $B, respectively. Assuming the analysis period is T1, then during the analysis period, the cost of Project A is $A, while that for Project B is $B x (T1/T2) (assume no interest rate or discount rate is considered). At the end of the analysis period, Project A has no residual value, while Project B has (T2 – T1) x $B/T2 residual value. If the initial construction costs $A for project A equals $B x (T1/T2), according to the least life cycle cost approach, both projects are rated equally. However, it is quite obvious that Project B is a better choice than Project A because Project B provides better performance during the analysis period. Therefore, there is a need to have a better way for prioritizing pavement projects, taking into consideration of

the costs, residual values, and performance. The "cost effectiveness concept" was applied for this purpose.

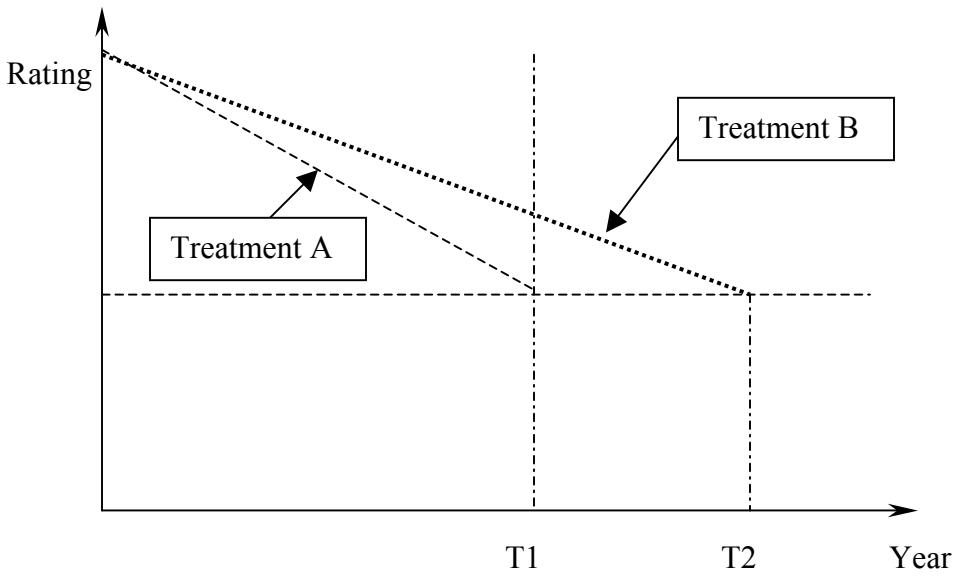


Figure 5 - 6 Illustration of Residual Value

The cost effectiveness ratio approach is proposed to consider life cycle cost and residual values for projects using different rehabilitation treatment alternatives. The approach utilizes the following concepts:

(1) Equivalent uniform annual cost (EUAC) is used to normalize the cost associated with each treatment and the service life each treatment can provide.

Service life is defined as the time period from the time a rehabilitation treatment is completed to the time the pavement reaches the performance rating of 70. One thing that should be pointed out is that the "service life" used here is not the same as the one listed in Table 5-1 or 5-2. It is determined based on the effective deterioration rate described in Section 5.2.2. The initial construction cost is converted to equivalent uniform annual costs (EUAC) using the EUAC formula:

If $r \neq 0$,

$$EUAC = \frac{PC \cdot r \cdot (1+r)^{LY}}{(1+r)^{LY} - 1} \tag{5-3}$$

Where,

LY: Service life of the treatment alternative, in years.

PC: Present value of initial construction cost.

r: The discount rate. It is used to determine the present value of all costs.

If $r = 0$,

$$EUAC = PC / LY \tag{5-4}$$

(2) Pavement performance improvement is used to measure the benefit of a treatment method. It is defined as the area between the pavement performance curve after a treatment is applied and the pavement deterioration curve without treatment (the shadow area shown in Figure 5-7). Traditionally,

rehabilitation benefits are calculated based on the area between the performance curve and the minimum performance line (Tilly, 1997). Pavement performance improvement as defined here is a better measure of treatment benefits since it considers the gain in performance ratings after treatment over the ratings if no treatment was done on the pavement. Incorporating traffic volume in determining the benefit can be done, although it is not incorporated in this function as suggested by GDOT. Although equivalent uniform annual benefit (EUAB) can be determined using the similar equation as EUAC, the benefit is difficult to be monetized accurately. For the time being, the EUAB is calculated as the following:

$$\text{EUAB} = \frac{\text{Total Benefit}}{\text{LY}} \tag{5-5}$$

In the future, if benefits could be evaluated in term of dollars, a similar concept to that used for calculating EUAC could be used for calculating EUAB.

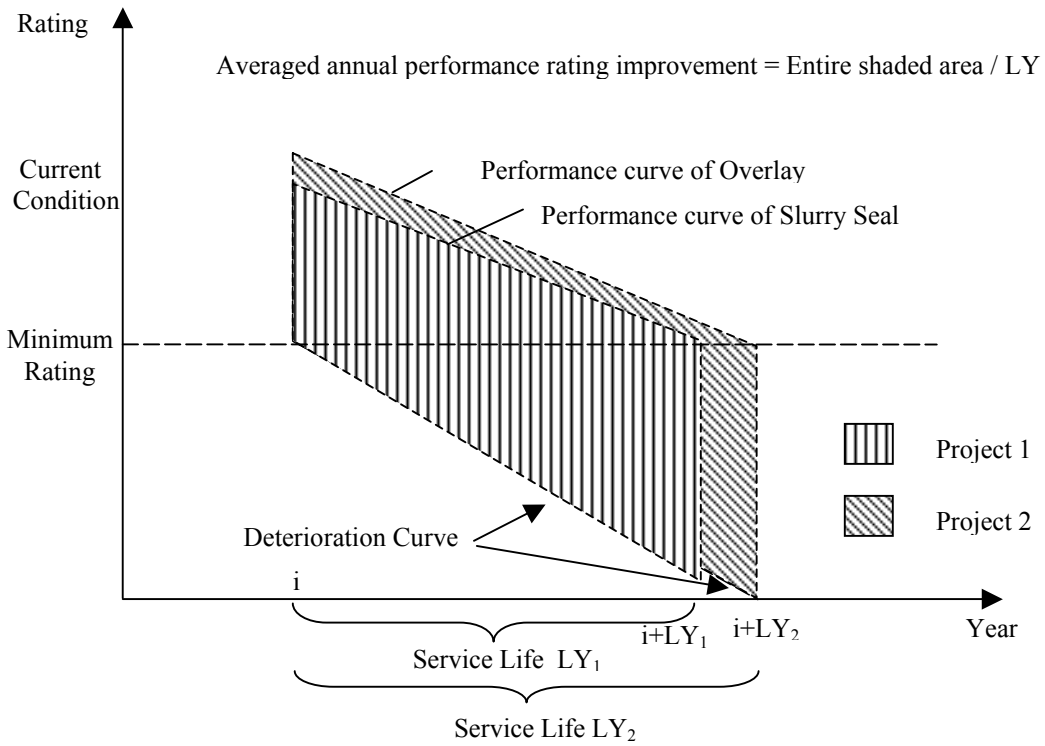


Figure 5 - 7 Concept of Determining Rehabilitation Treatment Benefit

(3) The equivalent annual cost effectiveness is defined as the ratio of EUAB over EUAC:

$$\text{Equivalent Annual Cost Effectiveness Ratio} = \frac{\text{EUAB}}{\text{EUAC}} \qquad (5\text{-}6)$$

The larger the cost effectiveness ratio is, the better the treatment alternative, as it provides more uniform annual rating improvement with the same amount of uniform annual cost.

The life cycle cost effectiveness analysis function utilized the concepts of service life to evaluate projects with different treatment methods. Since at the end of the service life of each treatment method the project ratings are all equal to 70, there is no residual value difference for different treatments based on the project rating. This is the advantage of using this approach.

Despite the advantages of using the rehabilitation treatment benefit concept and the service life concept for determining life cycle cost effectiveness as pointed out above, certain potential problems do exist with this approach. At the present time, linear deterioration beyond the minimum rating is used for a pavement project due to the reasons discussed in Section 5.2.1. A pavement could deteriorate more rapidly beyond certain stages of degradations. Since GDOT normally performs rehabilitation on pavements before the pavement ratings drop below 70, there is not enough data in the COPACES database for pavements with ratings below 70 to develop such nonlinear degradation relationships.

5.5 Interaction Between Project-level Analysis Module and Network-level Analysis Module

The various functions presented in this chapter can process the pavement condition evaluation data for all the pavement projects stored in the COPACES database

and forward the information to the network-level module for performing the yearly prioritization analysis. The interaction between the Project-level Analysis Module and the Network-level Analysis Module and the steps for performing the yearly optimization with the NEEDAS system are summarized below:

- Step 1: Extract the past and the current-year pavement condition evaluation data from the COPACES database for all the pavement projects in the network and forward the data to the Project-level Analysis Module.
- Step 2: The Project-level Analysis Module performs project-level analyses, such as determining future project ratings and distress deduct values, determining rehabilitation methods and costs, determining life cycle cost effectiveness ratios, as described in Section 5.1 to Section 5.4, to obtain the first year project-level information, and forwarding the information to the Network-level Analysis Module.
- Step 3: The Network-level Analysis Module performs the network-level analysis to optimize network performance and determine funding needs for the first year based on the selected analysis type and the constraints. A detailed description of the network-level analysis is presented in the next chapter.
- Step 4: Project-level information determined from the network-level analysis for the first year is looped back to the Project-level Analysis Module to perform the second-year project-level analysis.

- Step 5: Repeat Step 2, 3 and 4 until the analyses for all the years specified by the analysis period are completed.
- Step 6: All the project-level information and the network-level information determined in Step 3, 4, and 5 are forwarded to the GIS Module for further evaluation or analyses by engineers.

5.6 Approach to Reduce Computing Time in Project-level Analysis Module

As mentioned in Section 5.2.3, the processes to determine distress deduct values for all the projects using Model II or Model III would require a significant amount of computing time. Therefore, it is worth studying how to compute and store the future distress deduct values information efficiently.

The key question in dealing with distress deduct values is whether the predicted distress deduct values will be saved in a database permanently or not. If the distress deduct values are to be saved in the database, it will involve a large number of interactions between computer RAM (random access memory) and hard disk during the process and would take up a significant amount of computing time due to the following reason. RAM is the place in a computer where the operating system, application programs and the data currently used are kept so that they can be quickly reached by the computer's processor. RAM is much faster to read from and write to than the other kinds of storage devices in a computer, such as the hard disk, floppy disk, and CD-ROM. Because of this, programs involving large numbers of operations, which require access to the data that resides in the hard disk, will be performed much slower than programs involving RAM only. Therefore, if the analysis involves storing the analysis results, in

this case, the distress deduct values, in the database on the hard disk, it will be slowed down and require large amounts of hard disk space to save such information. Saving distress deduct values in the database does have the advantage of speeding up the subsequent manual adjustment process after the initial needs analysis has been completed by the computer program, as the engineer would need to access such information to help in making adjustments.

If the distress deduct values determined during the initial analysis are not saved in the database, the deduct values will have to be recalculated in the subsequent manual adjustment operations. However, large amounts of computing time during the initial needs analysis process can be saved.

Since computing time is a major concern, it has been decided that distress deduct values will not be saved in the database. Instead, an array variable is created to store the deduct values of all projects in a year during the needs analysis process. The following describes how it works. An array is a named collection of variables of the same data type. Each array element can be distinguished from other elements by one or more integer indexes. In the NEEDAS computer program, a two-dimension array, p_sngDeductValues (i =1 to total projects No., j = 0 to 11), is created. The descriptions of the array variables are presented in Table 5-5. During the yearly analysis, at the beginning of each year, the array contains the current year's distress deduct values of all projects. After the candidate rehabilitation treatment method is determined and projects for treatment in the year are selected by the Network-level Analysis Module, the system will calculate the next year's distress deduct values, and these values will be saved in the same array. Since the operation of array variables is done in RAM, the interaction

between RAM and hard disk is reduced greatly, which speeds up the needs analysis process greatly, as will be mentioned in Chapter 6.

Table 5 - 5 Descriptions of the Distress deduct value Array

Array elements	Descriptions
p_sngDeductValues(i, 0)	Project rating of the ith project
p_sngDeductValues(i, 1 to 10)	Distress deduct values of the ith project
p_sngDeductValues(i, 11)	Whether the crack width of the ith project is greater than 1/8 inch or not. = 0: Yes; = 1: No.

The limitations of using such a process do exist, as pointed out before. The data in the array variable stays in the RAM only as long as the NEEDAS computer program performing the specific analysis is not terminated. When the analysis process is terminated, the data in the array variable stored in the RAM will be lost, even though the NEEDAS program is still running other analyses. So, if the user wants to review the detailed distress deduct values information for a specific project of the previous analysis, the program will have to recalculate the distress deduct values of this specific project again. For a 5-year plan, it takes about 10 seconds to recalculate these values for a project. Considering that a user will be interested in the detailed information of only a limited number of projects, the effects of this drawback are very limited.

CHAPTER 6

DEVELOPMENT OF NETWORK-LEVEL ANALYSIS MODULE

6.1 Overview of Network-Level Analysis Module

The main function of the Network-level Analysis Module is to perform multi-year rehabilitation budget needs analysis and generate rehabilitation treatment plans at the network level based on the information provided from the Project-level Analysis Module. The module can perform four types of analyses subject to one of the five different balance constraints and two different performance constraints.

Figure 6-1 illustrates how the analyses are performed in the Network-level Analysis Module. The NEEDAS system utilizes the yearly-based multi-year prioritization approach to generate multi-year pavement rehabilitation plans. That is, the single-year prioritization processes using the project-level analyses described in Chapter 5 and the network-level analyses shown in Figure 6-1 are performed repeatedly to develop multi-year network pavement rehabilitation plans. The following steps are used by the NEEDAS computer program to perform the analyses and develop the plans. Details of the procedures used in each step are presented in Section 6.4.

Step1: The Network-level Analysis Module stores information generated from the Project-level Analysis Module in a Not-to-be-treated Projects list. At the same time, the module also creates a blank To-be-treated Projects list.

Step 2: The analysis proceeds by moving projects from the Not-to-be-treated Projects list to the To-be-treated Projects list one by one starting from the

project with the highest priority. The priorities of projects are determined based on individual project rating constraints, the life cycle cost effectiveness ratio, and balance constraints.

Step 3: Each time a project is added to the To-be-treated Projects list, the total rehabilitation treatment costs for all the projects in the To-be-treated Projects list and the composite ratings for all the projects both in the To-be treated Projects list and in the Not-to-be-treated Projects list are recalculated for the statewide network, GDOT District level network, and State Congressional District level network. The module checks to determine whether the network level constraints are satisfied. The process continues until the network level constraints (costs or performance rating constraint or both) are satisfied or no more projects in the Not-to-be-treated Projects list are left.

Step 4: When the network constraints are satisfied, the current year network-level analysis is completed and the updated information for all the projects, both in the To-be-treated list and the Not-to-be-treated list, are sent back to the Project-level Analysis Module for performing the project-level analysis for the following year.

The processes described in Step 1 to Step 4 continue until the specified multi-year analysis is completed.

Although the network-level analysis procedures described above are quite straightforward, the detailed algorithms for performing these analyses are quite complex,

especially when the constraints for balancing the funding or performance among the GDOT Districts or State Congressional Districts are imposed.

This chapter presents detailed information on how the Network-level Analysis Module is developed and the challenging issues involved in the development. The chapter is organized as follows. Justifications for using the yearly-based multi-year prioritization approach to perform multi-year rehabilitation needs analyses are presented in Section 6.2. Section 6.3 presents the scope of the network-level rehabilitation needs analysis, including types of analyses, balance constraints, and performance constraints. The method for determining network-level composite ratings is also presented in this section. Detailed algorithms for performing the network-level needs analysis are discussed in Section 6.4. Section 6.5 discusses the approaches used to reduce computing time when performing the network-level analyses.

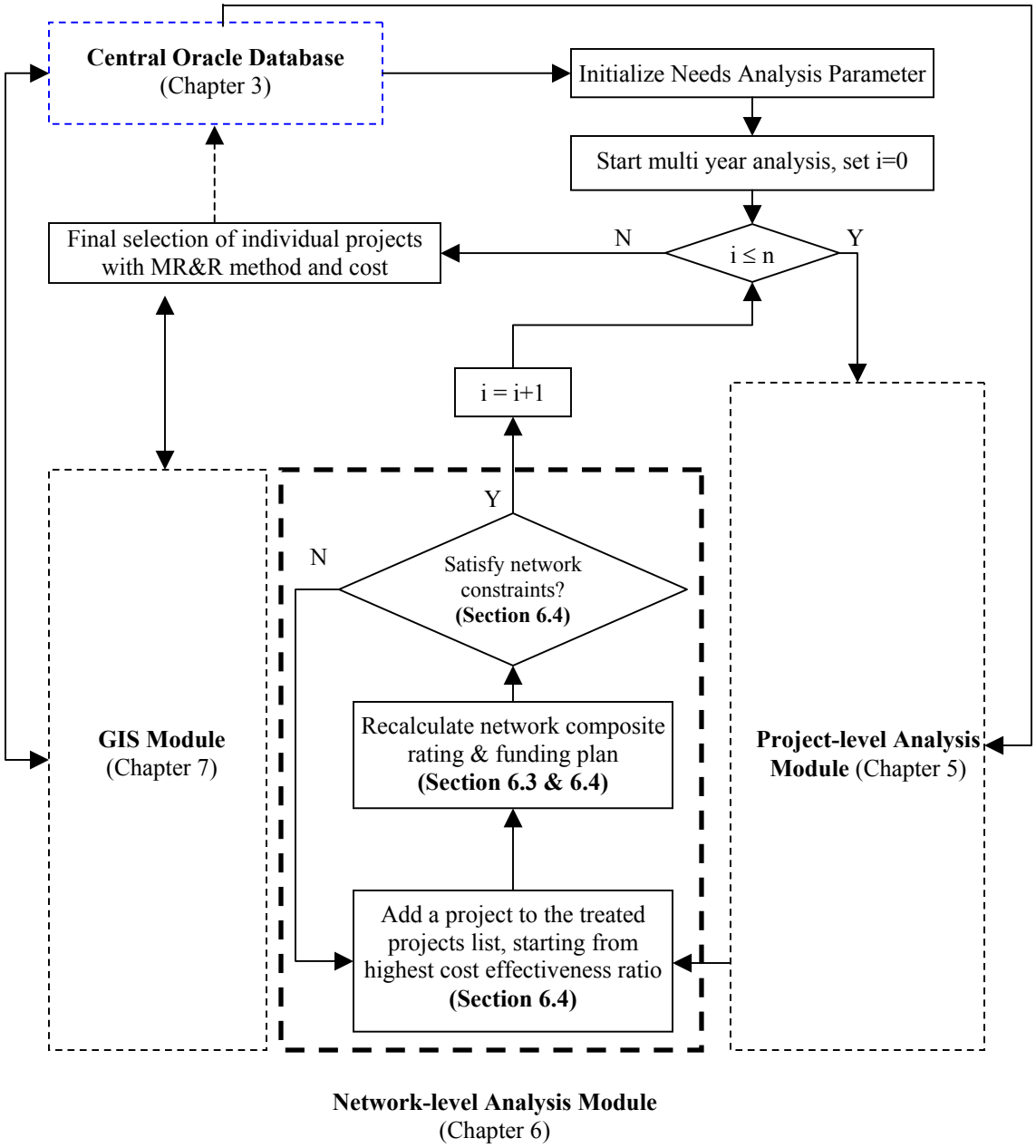


Figure 6 - 1 Flow Chart of Network-level Analysis Module

6.2 Justifications for Choosing a Single-Year Prioritization Approach for Developing Network-level Analysis Module

The issues and the pros and cons for using the various approaches, including the single-year and multi-year prioritization approaches and the integer programming and linear program optimization approaches, for developing network-level rehabilitation needs analysis systems have been reviewed in Section 2.3 of Chapter 2. Based on the review of these different approaches, together with the needs identified for developing an immediately implementable rehabilitation needs analysis system for GDOT, it was determined the best option was using the single-year prioritization approach to develop such a system (yearly-based multi-year prioritization approach). The following are the reasons for selecting this approach.

6.2.1 Optimization Approaches versus Prioritization Approaches

The pros and cons of using the optimization approaches and the prioritization approaches for developing pavement rehabilitation needs analysis systems have been presented in detail in Section 2.3. The optimization approaches have the capability to evaluate different rehabilitation methods and select an optimal method to treat a pavement and incorporate that into the network-wide optimization schemes. For the optimization approach, several different treatments are considered for each project at the same time, and the one that yields the most benefits for the network is selected as the optimum treatment method for a specific project. The network-level optimization is then performed to obtain an optimal pavement rehabilitation plan for the network. In the prioritization approaches, whether the single-year or the multi-year prioritization

approach, all the pavement projects within the network are prioritized based on certain prioritization parameters. The results obtained from the prioritization approaches may not be the optimal pavement rehabilitation plan for the network. This is the advantage of using the optimization approaches over the prioritization approaches.

Despite the advantage mentioned above, there are several reasons why optimization approaches were not selected for this module. From the technical point of view, algorithms for finding optimum solutions using various optimization approaches, whether the linear programming, nonlinear programming or integral programming, are all very complex. Also the traditional Markov Chain-based linear programming model provides only the percentage of the roads in the network to be treated in each pavement category for each year of the planning analysis period. The method cannot identify specific projects in each pavement category where specific treatments are to be applied (Ferreira et al., 2002; Wang et al., 2003). The ability to identify specific treatment methods for individual pavement projects is one of the GDOT requirements identified in Section 4.1. Although integer programming has the capability for identifying specific projects in the pavement network where specific treatment methods are to be applied, it is computationally impossible to obtain a real optimization solution for a large-size integer programming. In a study done by Ferreira (2001), it took 1987 minutes (30 hours) to obtain an optimization solution for a small network-level needs analysis integer program consisting of only 27 pavement projects in a 4-year analysis period. Considering that computational time increases exponentially with the number of projects and analysis years, the computation time required for using the integer programming method to perform an analysis for the GDOT pavement network (containing more than 2000

projects and a 5-year analysis period) would be prohibitively long. Although some heuristic methods can be used to solve such integer programming to obtain near-optimization solutions with reduced computing time, it is difficult to ascertain the accuracy of the solutions because the heuristic methods cannot provide accurate estimations of the differences between the near-optimization solution and the real optimization solution.

Besides the technical complexities mentioned above, there are also some other drawbacks related to the institutional issues. Because the results generated by the optimization approaches are often complex and not easily understood, transportation agencies were often reluctant to use this approach for afraid of losing control of generating pavement rehabilitation plans when using such complex and hard-to-understand programming and scheduling processes (FHWA, 1997). Some agencies found that elected officials and upper management had difficulty comprehending the results of the rehabilitation plans generated by the optimization approaches and, therefore, were suspicious of the viability of the results. That makes it much more difficult to defend such plans (and the funding requested) than the plans generated by a simpler and easier-to-understand prioritization approach (Zimmerman, 1995). Several studies have confirmed this observation. NCHRP Synthesis 222 reported that it was easier to defend projects and treatments selected through a prioritization process than through an optimization approach (Zimmerman, 1995). In Tsai's latest survey (Tsai, 2003), the result indicated that optimization approaches to perform needs analysis were used only by one out of twenty-two States DOTs. All of these arguments are relevant to

the needs identified for developing the GDOT rehabilitation needs analysis program presented in Section 4.1.

6.2.2 Single-year versus Multi-year Approaches

The pros and cons of using the multi-year prioritization approaches and the single-year prioritization approaches for developing pavement rehabilitation needs analysis have also been presented in Section 2.3. The multi-year prioritization approach uses cost-effectiveness ratios and/or other parameters to compare and select pavement projects in the network system within the entire analysis period to develop the network rehabilitation treatment plan to achieve the highest benefit for the network. The multi-year prioritization approach identifies treatment methods and timing with the highest cost- effectiveness ratio as the best treatment methods and the best timing within the analysis period for all the pavement projects in the network system. On the other hand, the yearly-based multi-year prioritization method identifies projects for rehabilitation treatments only for a specific analysis year in the analysis period by comparing only the cost-effectiveness ratios and/or other prioritization parameters of all the projects in the network in the specific analysis year. It is highly possible that the projects selected for rehabilitation treatment in any specific year in the analysis period using the yearly-based prioritization method may not achieve the best benefits for the network within the entire analysis period.

However, the algorithms for a true multi-year network-level prioritization method are much more complex than those of the single-year prioritization method. The algorithms for a true multi-year network-level prioritization method invariably result in a

much more complex problem (Fwa et al., 1988; Andres et al., 1994; Chan et al., 1994; George et al., 1994; FHWA, 1997). Even a small pavement network with a relatively small number of pavement projects would still require a large amount of computer storage space and lengthy computing time, and, invariably, some simplifications will have to be made to make the solution tractable. To explore the complexity of the method, a sample problem consisted of only 13 pavement projects was studied to identify the issues involved and explore the techniques and algorithms for solving the problem using the multi-year prioritization method. The 13 projects were randomly selected from the pavement projects in GDOT District 1. For a three-year analysis period, there are 294,912 possible treatment combinations for the 13 projects, as one project usually has 2 to 6 treatment alternatives within the three-year period, and the treatment combinations of the 13 projects are the product of each project's treatment alternatives. To prioritize these treatment combinations would require 1M bytes of space. A computer can solve this problem within 1 minute. For a problem containing 200 projects, the required storage space would be more than 2G bytes, which is the maximum size a Microsoft Access database file allows (Microsoft, 2000a). Considering that computing time and the storage space increases exponentially with the number of projects and analysis years, the computing time and the storage space required for using the multi-year prioritization approach to perform an analysis for GDOT's pavement network (containing more than 2000 projects) would be prohibitive. Because of this issue, many multi-year prioritization needs analysis systems have to make certain simplifications during the needs analysis (FHWA, 1997).

After the decision was made to use single-year approach for the NEEDAS system, efforts were made to enhance the traditional single-year analysis approach to make it more versatile in performing the need analyses. The following points briefly describe the enhancements developed in the NEEDAS program.

(1) The computer program developed for the NEEDAS system (referred to as NEEDAS program) can perform four types of need analyses, which allows the user to perform various "What-If" analyses.

(2) The GIS module presented in Chapter 7 incorporates powerful, dynamic interactive analysis capabilities, which allow the user to manually adjust the timing for individual pavement projects, and the impact of such adjustments will be displayed in the GIS map immediately and dynamically.

(3) Incorporating life cycle cost effectiveness analysis in the Project-level Analysis Module makes it possible to assess the long-term impacts, rather than just a one-year impact, of the rehabilitation treatment for an individual pavement project.

With these addition features incorporated into the program, the yearly-based prioritization method proposed for this system could meet all the needs identified in Section 4.1 for the pavement rehabilitation needs analysis system for GDOT.

6.3 Scope and Capability of Network-Level Rehabilitation Needs Analysis

This module performs multi-year rehabilitation needs analysis and determines optimum rehabilitation treatment plans to achieve a prescribed level of statewide pavement performance or to meet the available rehabilitation budget, or both. In addition, this module has the capability to develop rehabilitation treatment plans, which can achieve balancing performance or rehabilitation funding among GDOT Districts or State Congressional Districts. The scope and the capability of the Network-level rehabilitation Needs Analysis Module are presented below.

Composite Ratings

As presented in Chapter 3, a performance rating is used in COPACES to describe the performance of an individual pavement project. A pavement performance composite rating (referred to as composite rating) is developed to describe the performance of all the pavement projects in the network level (statewide network level, GDOT District level, or State Congressional District level). The composite rating is an average rating weighted by the project length in lane-miles of all the pavement projects within the specified network boundary and is calculated using the following formula:

$$\text{Composite Rating} = \frac{\sum_{i=1}^{\text{Total No. of Projects}} (\text{Project Length in LaneMile})_i \cdot \text{Project Rating}_i}{\sum_{i=1}^{\text{Total No. of Projects}} (\text{Project Length in LaneMile})_i} \qquad (6\text{-}1)$$

Where, "Total No. of Projects" refers to the total number of projects within the specified network boundary.

Although arguments could be made for incorporating traffic conditions (such as AADT) as a weighting factor in calculating composite ratings (FHWA, 1997), extreme variations of AADT from over 200,000 to less than 2,000 in Georgia's highway network could seriously distort the network composite performance ratings. After consulting with GDOT, traffic was not included in computing the composite ratings.

Types of Analyses

The following four types of analyses can be performed by the NEEDAS program:

- Type I: Determine optimum pavement rehabilitation plans with minimum costs subject to future pavement performance requirements.
- Type II: Determine optimum pavement rehabilitation plans subject to available rehabilitation budgets.
- Type III: Determine optimum pavement rehabilitation plans controlled by pavement performance constraints. The plan will be subject to both pavement performance constraints and budget availability constraints with pavement performance constraints taking precedence over budget availability constraints. If the funding required to satisfy performance constraints is less than the available budget, the program will determine optimum rehabilitation plans until the available budget is exhausted. In this case, the performance determined by the plans will exceed the level set by the performance constraints. On the other hand, if the funding required to satisfy the performance constraint exceeds the available budget, the program will

determine optimum rehabilitation plans to meet the performance constraints and report the additional funding required over the specified available budget.

- Type IV: Determine optimum pavement rehabilitation plans controlled by budget availability. The plan will be subject to both pavement performance constraints and budget availability constraints with budget availability taking precedence over pavement performance constraints. If the funding required to satisfy performance constraints is less than the available budget, the program will determine optimum rehabilitation plans based on performance constraints and report the budget left under this scenario. On the other hand, if the funding required for the optimum rehabilitation plans to meet the performance constraints exceeds the available budget, the program will determine the optimum plans to meet the budget constraints and report the network pavement performance under this scenario, which obviously could not meet the specified pavement performance constraints.

The reasons for having these four types of analyses are due to the following considerations. First, to simulate actual practice used by GDOT, such as Type I and Type II. Second, to compensate for the limitations of using yearly-based prioritization analysis. The Type III and IV analyses allow the user to study different pavement rehabilitation schemes that cannot be achieved directly by the Type I and Type II analyses. Thus, these two analyses can be used to further refine the results obtained from Type I and Type II analyses.

Table 6-1 shows an example of how Type II Analysis can be used. Suppose the user performs the Type II Analysis with a prescribed amount of annual rehabilitation budgets, and the resulting composite ratings for each year are shown in Table 6-1. If a minimum composite rating of 86 is required as being the agency's policy, the funding plan cannot meet that requirement as the 5th year's statewide composite rating (85.81) is less than 86. The user will have to generate an alternate funding plan to meet the minimum composite rating requirement. Using the Type II analysis, the user will have to adjust the budget in the 5th year and re-run the analyses. It may take several iterations to achieve the expected results. However, by performing the Type III analysis and simply specifying 86 for statewide pavement performance constraint in addition to the original budget scheme, the analysis will automatically compute the funding required to achieve the 86 performance rating constraint in the 5th year. As shown in Table 6-2, with the Type III analysis, the composite rating in each year satisfies the performance constraint and the rehabilitation funding needed to improve the 5th year's composite rating to over 86 is also determined automatically by the program (108 million dollars).

Detailed descriptions and development of each analysis type are presented in Section 6.4.

Table 6 - 1 Example of Type II Analysis Results

Future Year	Yearly Specified Budget	Yearly Statewide Composite Rating Achieved
1st	100 Million Dollars	87.79
2nd	100 Million Dollars	87.64
3rd	100 Million Dollars	87.18
4th	100 Million Dollars	86.56
5th	**100 Million Dollars**	**85.81**

Table 6 - 2 Refinement of Type II Analysis Results Using Type III Analysis Results

Future Year	Yearly Specified Budget	Yearly Statewide Composite Rating Achieved
1st	100 Million Dollars	87.79
2nd	100 Million Dollars	87.64
3rd	100 Million Dollars	87.18
4th	100 Million Dollars	86.56
5th	**108 Million Dollars**	**86.00**

Balance Constraints

One of the unique features of the NEEDAS program is the capability of the program to generate rehabilitation treatment plans, which can also meet various balance constraint requirements. Five different balance constraints can be imposed in conjunction with any one of the analyses listed above. These five balancing constraints are

- balance pavement performance among GDOT Districts,
- balance pavement performance among State Congressional Districts,
- balance rehabilitation costs among GDOT Districts,
- balance rehabilitation costs among State Congressional Districts, and
- no balance constraints.

One interesting question related to balance constraints is how to define "balance." Balance, or equality of funding distributions among different districts, could be based on the total route length in each district, the traffic volume, or other parameters. It is conceivable that using various parameters as the weighting factor for determining a fair

balance criterion would create all sorts of problems. Each GDOT District or State Congressional District is of equal importance, and it is difficult to justify why certain districts are more important than the other districts just because of certain weighting factors. After consulting with GDOT, it was decided that no weighting factors would be used. Thus, balance costs means evenly distributing the costs among the districts and balance performance means achieving the same performance rating among different districts.

Statewide versus Individual Pavement Performance Constraints

There are two pavement performance constraints used in this module. One is the statewide pavement performance requirement based on the statewide pavement performance composite rating, and the other is the individual project performance rating. For Analysis Type I, III and IV, the analyses are always subject to a prescribed statewide composite rating requirement. The individual project performance requirement can be imposed as an additional requirement for any one of these four types of analyses. Incorporating individual project rating constraints in this module is intended to mimic the current GDOT practice, as GDOT normally will initiate rehabilitation actions on any pavement before its rating drops below 70. When the optional individual project rating requirement is imposed, all the pavement projects with ratings less than the specified minimum individual project rating requirement will be selected for rehabilitation actions first, regardless of their priority rankings in the network.

Based on the types of the analyses, balance constraints, and performance constraints described above, forty "What-If" scenarios can be performed by different combinations of needs analysis types, balance constraints and performance constraints. It should be pointed out that these scenarios do not include scenarios with different budget amounts and different levels of performance requirements in which the NEEDAS program does allow the user to change these values manually.

6.4 Algorithms for Multi-Year Network-level Pavement Rehabilitation Needs Analysis

The necessary algorithms to facilitate the analyses and to generate the results were developed for the program. This section first presents the general algorithms used by the NEEDAS computer program to perform the analyses and develop the rehabilitation plans. Then, a specific scenario is used to further illustrate the detailed analysis flow of the network-level needs analysis. In the last part of this section, a special issue regarding associating pavement projects with State Congressional Districts is discussed.

6.4.1 General Algorithms for Multi-Year Network-level Pavement Rehabilitation Needs Analysis

The Network-level Analysis Module follows the algorithms described below to perform the analyses and develop the rehabilitation plans.

<u>Step 1: Initialize Information Obtained from the Project-level Analysis Module</u>

The module stores the information generated from the Project-level Analysis Module for all the projects in the network in a Not-to-be-treated Projects list, as shown in Figure 6-2. At the same time, the module also creates a blank To-be-treated Projects list.

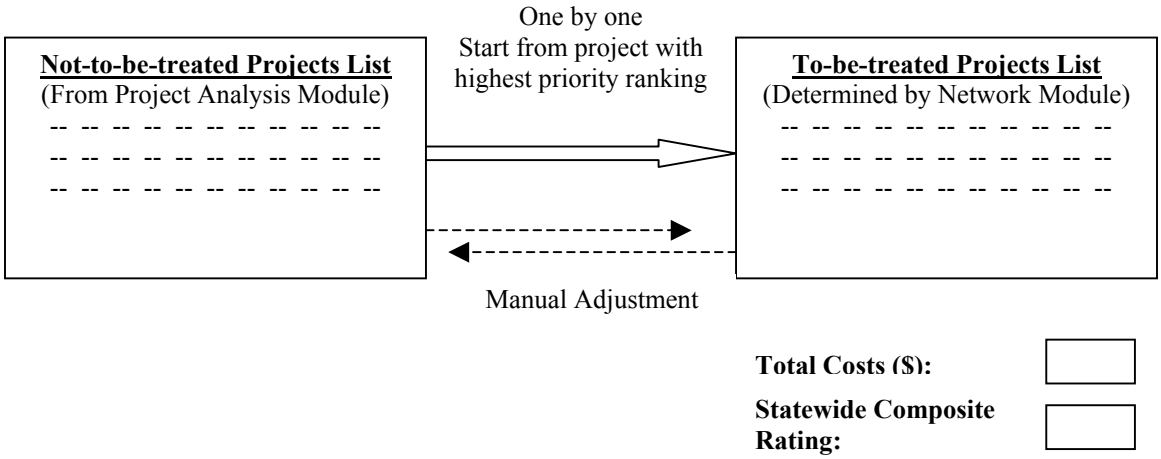


Figure 6 - 2 Analysis Performed in the Network-level Analysis Module

Step 2: Add Project One-By-One from the Not-to-be-treated Projects List to the To-be-treated Projects List

The analysis proceeds by moving projects from the Not-to-be-treated Projects list to the To-be-treated Projects list one by one starting from the project with the highest priority. Each time a project is added to the To-be-treated Projects list, the total rehabilitation treatment costs for all the projects in the To-be-treated Projects list and the composite rating for all the projects include in the To-be-treated Projects list and in the Not-to-be-treated Projects list are computed, and the results are displayed on the "Total

Costs ($)" box and the "Statewide Composite Rating" box as shown in Figure 6.2. The priorities for selecting projects from the Not-to-be-treated Projects list to the To-be-treated Projects list are determined based on whether the individual project rating constraint is imposed, the life cycle cost effectiveness ratios of the projects, and the type of balance constraints is imposed. The following describes the criteria used to select and move projects from the Not-to-be-treated Projects list to the To-be-treated Projects list:

(1) When the individual pavement rating constraint together with the threshold value are set, the analysis will search from the Not-to-be-treated Projects list for all the projects with ratings less than the threshold value and move these projects to the To-be-treated Projects list.

(2) If the individual pavement rating constraint is not set, or after (1) above has been done, the analysis will perform the following:

   a. If no balance constraint is set, the analysis just simply adds the project one by one starting from the project with the highest cost-effectiveness ratio from the Not-to-be-treated Projects list to the To-be-treated Projects list;

   b. If the balance performance constraint is set (for example, balancing GDOT Districts performance), the analysis will calculate the composite ratings for each GDOT District, including projects in the To-be-treated Projects list and in the Not-to-be-treated Projects list, in addition to the total costs and the statewide composite rating. The analysis will then select the project with the highest cost-effectiveness ratio belonging to the district having the worst district-level composite rating from the Not-to-be-treated Projects list and

add it to the To-be treated Projects list. The analysis will then update the composite ratings and the rehabilitation costs for each GDOT District, the total costs, and the statewide composite rating. Then, repeat the same process to add projects one-by-one.

c. If the balance rehabilitation cost constraint is set (for example, balancing State Congressional Districts rehabilitation cost), the analysis will calculate the total rehabilitation cost in each State Congressional District for all the projects already on the To-be-treated Projects list. The analysis will also calculate the total costs for all the statewide projects on the To-be-treated Projects list and the statewide composite rating including all projects on the To-be-treated Projects list and on the Not-to-be-treated Projects list. The analysis will then select the project with the highest cost-effectiveness ratio belonging to the district having the least district-level rehabilitation funding from the Not-to-be-treated Projects list and add it to the To-be treated Projects list. The analysis will then update the rehabilitation costs and the composite ratings for each State Congressional District, the total costs for the network, and the statewide composite rating. Then, repeat the same process to add projects one-by-one.

d. The same concepts are applied for performing project selections when other balancing constraints are set.

e. If several projects have the same cost effectiveness ratio, they are prioritized by their forecast project ratings in the future year and the AADT. The

project with lower forecast project rating and higher AADT will be selected and added to the To-be-treated list first.

Step 3: Evaluate Network Constraints

Each time a project is added to the To-be-treated Projects list, the analysis will check to determine whether the network level constraints are satisfied or not. The process continues until the imposed network level constraints (costs or performance rating constraint or both) are satisfied or no projects are left in the Not-to-be-treated Projects list. The following are different network level constraints corresponding to different types of analyses:

(1) Type I Analysis: Pavement performance constraint must be satisfied

(2) Type II Analysis: The total rehabilitation costs must reach the preset amount

(3) Type III Analysis: Both conditions below must be satisfied:

   i. Performance constraints are satisfied, and

   ii. The total rehabilitation Cost of the To-be-treated projects is equal to or greater than the total budget available

(4) Type IV Analysis: Either condition below must be satisfied:

   i Performance constraints are satisfied and the total rehabilitation cost of the To-be-treated projects is less than or equal to the total budget available, or

   ii Performance constraints are not satisfied, but budget is reached.

Step 4: Continue to Next Year until the End of the Analysis Period

After the completion of the year-one analysis, the analysis saves the results of the network related information (composite rating, costs, etc.) in a database and forwards the project-specific information back to the Project-level Analysis Module for it to proceed to the second-year analysis cycle. This process continues until the specified multi-year analysis is completed.

These steps involve significant amount of computing time for recalculating the statewide network level as well as GDOT Districts and Congressional Districts network level composite ratings and costs. A special approach to significantly reduce the computing time for calculating these parameters was developed and will be presented in Section 6.5.

6.4.2 Detailed Analysis Flow

This subsection utilizes a specific scenario to illustrate the detailed analysis flow of the network-level needs analysis. The scenario is for performing a Type II analysis (determine optimum pavement rehabilitation plans subject to budget constraints) and further subject to balancing performance among GDOT Districts.

Figure 6-3 presents the detailed analysis flow of the scenario described above. Step 1 and 4 are the same for performing any types of analyses. However, Step 2 and Step 3 require different algorithms to process different project selection criteria and network constraints criteria. Therefore, during the system development for the program, the concept of object-oriented programming was used. In an object-oriented programming language, applications are written by creating objects that communicate by sending messages to other objects (Microsoft, 2000b). Using this concept, independent

modules were written for Step 2 and Step 3 so that if new network-level analysis criteria are to be developed, the Network-level Analysis Module will not be impacted greatly.

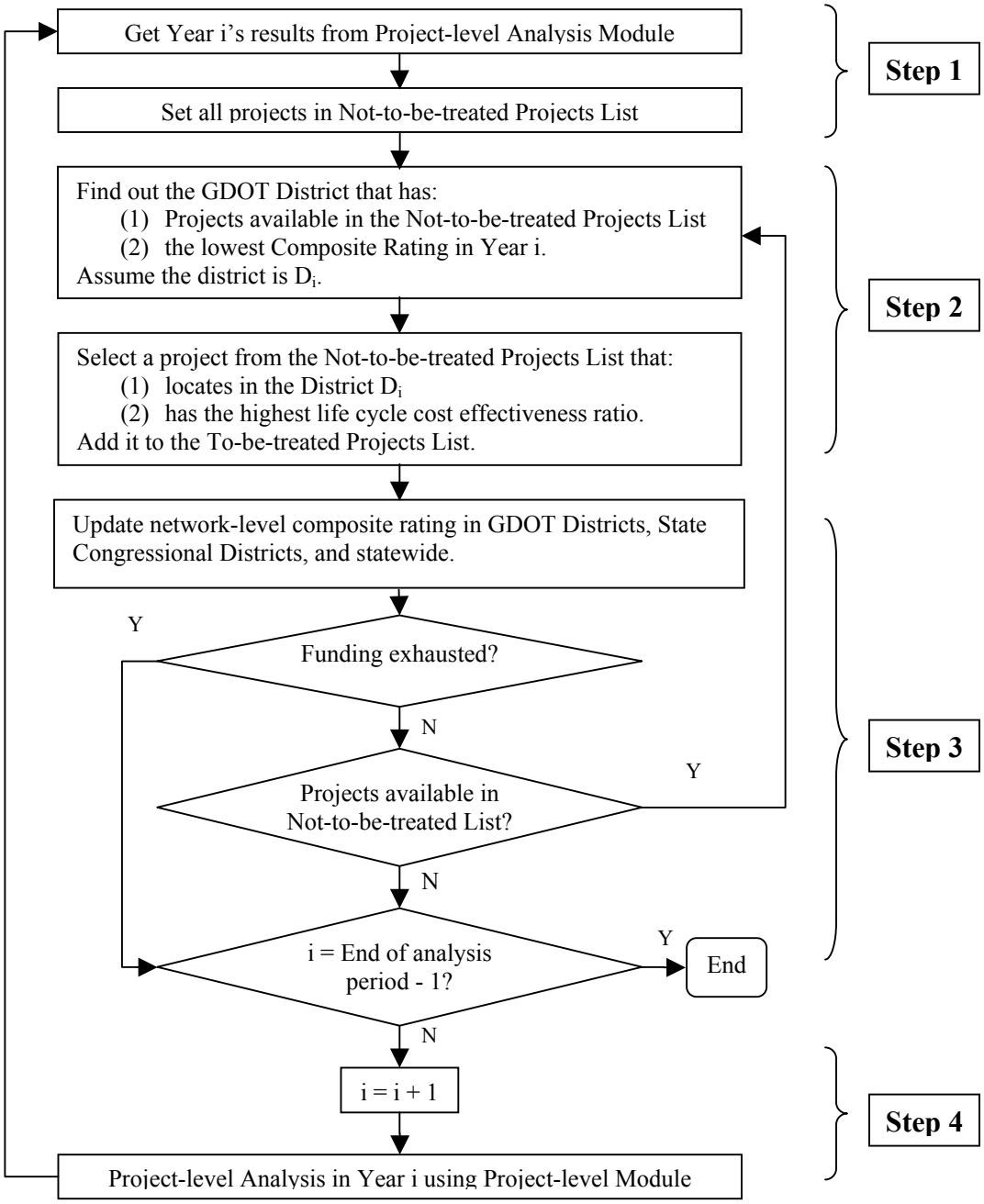


Figure 6 - 3 Analysis Flow of A Selected Scenario

In this scenario, a project is selected from the GDOT District with the lowest composite rating and moved from the Not-to-be-treated Projects list to the To-be-treated Projects list, as shown in Step 2 of Figure 6-3. The project selection process in each year continues until the rehabilitation funding is exhausted or there are no projects available in the Not-to-be-treated Projects list. Once the analysis is finished, different GDOT Districts will have relatively balanced composite ratings, as Case 3-2, presented in Chapter 9, shows.

Output Results of the Scenario

The output from the analysis described above consists of the following:

1. Costs and composite ratings for various jurisdictions, including GDOT Districts, State Congressional Districts and entire state, per year;
2. Detailed project-level rehabilitation plans per year in the analysis period. The plans provide the detailed information, such as when to treat, where to treat and what treatment methods to be used, for each candidate project included in the annual rehabilitation plans.

A case study will be presented in Chapter 8 to show the procedures for performing the analysis, the output results, and the various graphs and forms for displaying and reporting the results.

6.4.3 Issues Regarding Associating Pavement Projects with State Congressional Districts

Current GDOT's pavement survey does not provide information in which State Congressional District a project is located. Thus, before performing the analysis, the spatial location of pavement projects associated with State Congressional Districts has to be determined first using the State Congressional Districts information provided by GDOT. Each pavement project is located completely in a GDOT District; however, it is possible that a project may cross more than one State Congressional District. It is possible to divide such project into several projects so that each individual project locates completely within a State Congressional District. However, this would create difficulties in maintaining and recording the historical and on-going pavement survey data, and it will require large amount of additional works to modify existing GDOT practices and the database. For example, the current COPACES database uses "TripDate" and "RouteNo" as the primary keys to identify each project. When a project is separated into two projects, one of these two fields must be changed for the newly created projects, or another field must be combined with these two fields to work as a primary key to uniquely identify a project because a database does not allow projects to have duplicate primary keys. Such modifications will significantly impact the current GDOT practice and the COPACES database structure. After studying the actual data, it was realized that very few projects are located in more than one State Congressional District. For example, out of 2,472 projects identified in the 2003 Georgia State highway network, only 121 projects (4.9%) cross more than one State Congressional Districts, and most of these projects have their major portions of projects located in one district. Therefore, it was decided that if a project is associated with more than one State Congressional

District, the project is assigned entirely to a State Congressional District that has the larger portion of the project in it.

6.5 Approaches to Reduce Computing Time in Network Level Analyses

The procedures described in Section 6.4 and the algorithms developed to accomplish the analyses involve significant amount of computing time for recalculating the statewide as well as GDOT Districts and State Congressional Districts network level composite ratings and costs each time when a project is added to the To-be-treated Projects list. This is an important issue. After careful considerations of various options for reducing the computing time for the analyses, the following approach was adopted. Instead of saving the composite ratings directly for all the projects statewide, the program would save the total "Rating*Length" of all projects in the statewide and in each GDOT District and State Congressional District. Table 6-3 shows how the GDOT District-level analysis results are recorded in the database. A similar approach was used to save the State Congressional District and statewide composite ratings. The information shown in Table 6-3 represents the most current analysis results for each GDOT District for each year in the analysis period. Each time a new project is added to the To-be-treated Projects list or a project is removed from the To-be-treated Projects list, which affects the specific GDOT District, the fields of "Total Project No. to be Treated," "Total Treated Miles," "Total Rating*Length," and "Total Cost" will be updated quickly by merely adding (when a project is added) or subtracting (when a project is removed) the information pertinent to the effected project to these fields. Then, the "Composite Rating" field can be updated using the following equation:

Updated Composite Rating =

[Updated Total Rating*Length] / [updated Total Miles] (6-2)

The computing time required to obtain the updated composite rating is much less than if the program were to save the composite rating directly without saving the information of "Total Rating*Length." In the latter, the program has to recalculate the total rating*Length each time a project is added or removed from the To-be-treated list. It will be very time consuming.

Table 6 - 3 GDOT District-Level Analysis Results

GDOT Dist.	Total Miles in the Dist.	Total Project No. to be treated	Total Treated Miles	Total Rating*Length	Composite Rating	Total Cost (Dollar)	Fiscal Year
1	4071.65	142	1689.16	360050.8	88.43	26513654	2004
1	4071.65	109	1185.52	361494.44	88.78	15664030	2005
1	4071.65	174	1977.54	362617.75	89.06	24169521	2006
1	4071.65	179	2004.43	360922.2	88.64	24498181	2007
1	4071.65	216	2540.26	360749.6	88.60	31047086	2008
…	…	…	…	…	…	…	…
7	4635.74	61	638.74	392141.5	84.59	13585763	2004
7	4635.74	51	631.27	389812.4	84.09	11660014	2005
7	4635.74	65	939.99	392924.4	84.76	17636554	2006
7	4635.74	84	1349.16	398214	85.90	18447326	2007
7	4635.74	103	1516.93	400526	86.40	20366775	2008

The following two processes would be involved in requiring recalculation of updated composite ratings.

(1) In the Network-level Analysis Module. The program automatically processes and selects projects for the yearly treatment plans subject to various constraints as mentioned in Section 6.4. Typically, more than 200 projects are selected for the yearly treatment plans. It will be very time consuming to calculate the total rating*Length of all the projects in the To-be-treated list each time a project is added.

(2) The dynamic interactive analysis process will be described in Chapter 7. After the yearly rehabilitation treatment plans are generated by the Project-level Analysis Module and the Network-level Analysis Module, the user can utilize the GIS Module (presented in Chapter 7) to perform the dynamic interactive analysis for adding, removing, and/or combining certain projects in the treatment plans. Using the approach described above can speed up the process so that the updated results can be displayed immediately, allowing the user to decide whether to accept the changes or make further adjustments.

With this approach incorporated into the network analysis algorithms, together with the approaches adopted for speeding up the computing time in the Project-level Analysis Module, a complete analysis of the GDOT five-year rehabilitation plan now takes no more than 10 to 15 minutes. The program allows the user to interact with the needs analysis results obtained from the Project-level Analysis Module and the Network-

level Analysis Module, such as selecting or de-selecting certain projects for rehabilitation activities, or changing the rehabilitation treatment methods and/or costs for certain pavement projects, and performing the what-if analyses under different scenarios. The results of a typical dynamic interactive analysis will take just a few seconds.

CHAPTER 7

DEVELOPMENT OF GIS MODULE

7.1 Review of GIS Integration with Pavement Needs Analysis Practice

GIS is an information technology used to retrieve, store, analyze, and visualize spatial and non-spatial data. GIS provides the capability of combining tabular information from databases and graphic information represented by spatial maps. This capability allows people to comprehend and absorb information from maps more quickly and effectively than from a list of records in a tabular format.

Starting from 1990s, with the advent of computer technology and GIS technology, integration of GIS in pavement needs analysis systems has received much attention. Several network-level pavement needs analysis systems have incorporated GIS capabilities (Guo et al., 1995; Tsai et al., 2000; Bham et al., 2001; Ferreira et al., 2001; Massey, 2001; Shahin, 2001; FHWA, 2002b; Rodriguez, 2002; Ozbay et al., 2003; Quiroga et al., 2003). Their uses of GIS have been primarily for displaying results and for generating reports. However, GIS functions have not yet been fully integrated into network-level needs analysis to take advantage of the full potential of GIS for pavement needs analysis systems. For example, the pavement needs analysis systems cited above do not provide dynamic integration between GIS visualization and multi-year pavement needs analysis modeling, including pavement performance forecasting, treatment determination, and project prioritization. In addition, most of them do not utilize the spatial analysis function. Dynamic integration between GIS visualization at the project-level and network-level of multi-year needs analysis modeling allows engineers to

conduct what-if analysis and to explore different pavement rehabilitation management practices effectively and practically. Therefore, a pavement multi-year needs analysis system with the above capability was developed.

7.2 Overview of GIS Module

In the course of developing the pavement needs analysis system for GDOT presented in this thesis, a GIS module containing various functionalities was developed. Many developed GIS functionalities presented in this chapter have not yet been implemented in most of the pavement needs analysis systems mentioned above. The developed GIS module is fully integrated with the Project-level Analysis Module and the Network-level Analysis Module presented in Chapter 5 and 6 and contains many features in addition to the graphic displaying and report generating functions. The functions developed for the GIS module include the following capabilities:

(1) integrating needs analysis results and the graphic information in GIS maps dynamically,
(2) allowing engineers to perform map-based what-if analysis to explore various alternatives and combinations that are either difficult to conduct or unfeasible to perform without GIS maps,
(3) allowing engineers to make changes on the year, location and treatment method intuitively and directly on the map, and,
(4) presenting the project-level and network-level impacts with the modifications by engineers on the map.

As shown in Figure 7-1, Common Linear Reference System (LRS) and GIS Base Map Preparation Function, Spatial Analysis and Visualization Function, and Interactive Map-based Multi-year What-if Pavement Scenario Analysis Function are three important functions that have been developed in the GIS module. Section 7.3 presents the Common Linear Reference System and Base Map Preparation Function. This function is for creating GIS base maps with each map layer linked dynamically with certain results obtained from the Project-level Analysis Module and the Network-level Analysis Module. This section also introduces the LRS designed for GDOT and the dynamic segmentation function. Section 7.4 presents the development of Spatial Analysis and Visualization Function, which allows engineers to specify desired features to be displayed on GIS maps using a simple query form, and the function will automatically generate the GIS map containing the specified data created by the Common LRS and GIS Base Map Preparation Function. Finally, Section 7.5 presents the Interactive Map-based Multi-year What-if Scenario Analysis Function that allows engineers to change different scenarios easily, such as changing treatment year and treatment methods on the map based on the initial project level multi-year needs analysis results.

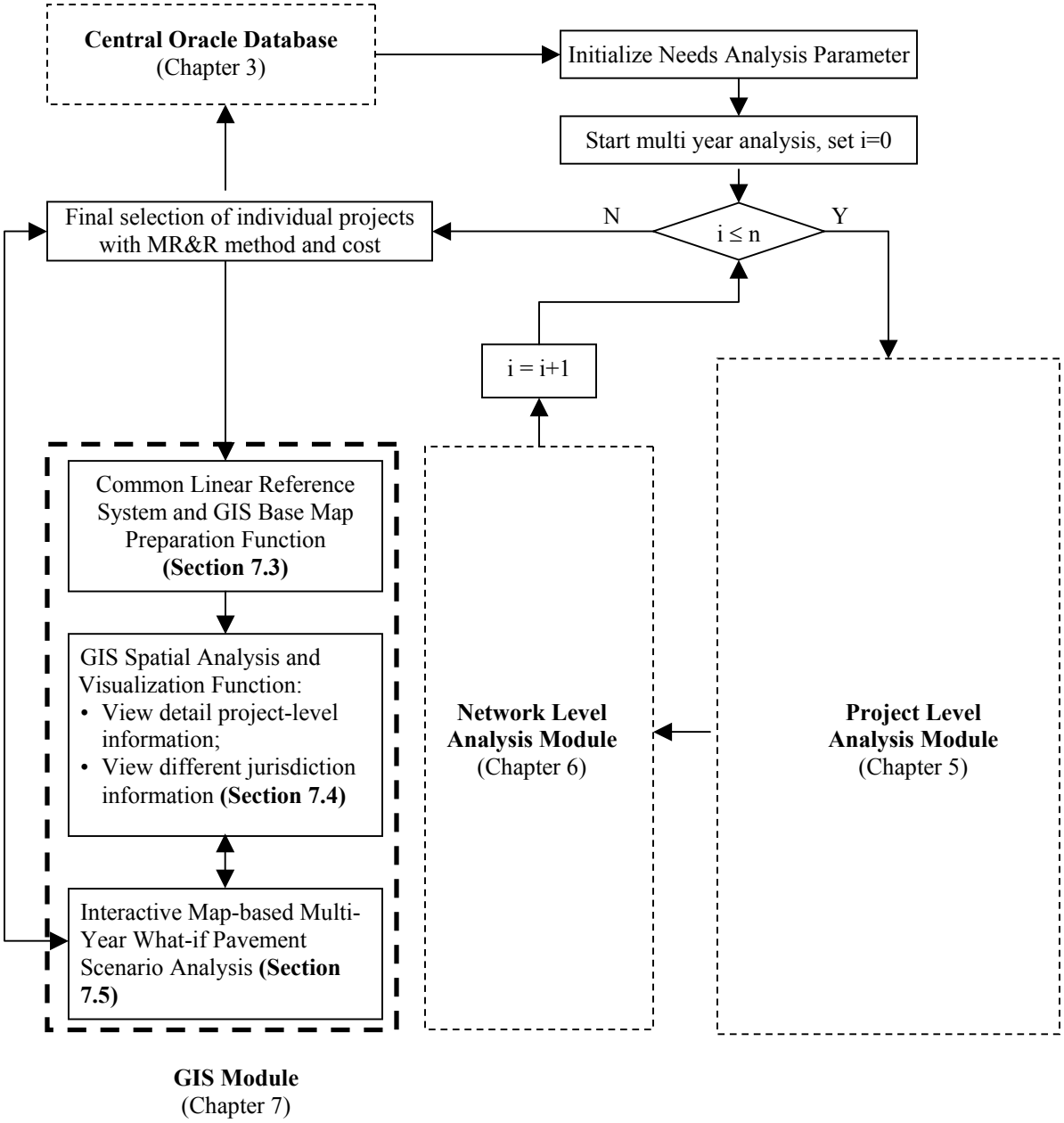


Figure 7 - 1 Flow Chart of GIS Module

A GIS map typically contains multiple layers of information. Each map layer represents a set of attributes of some real world objects. In this GIS module, some basic GIS map layers are provided by GDOT. These map layers include state routes, state boundary and various jurisdiction boundaries, such as GDOT Districts, State Congressional Districts, and counties in the state of Georgia. These basic map layers contain graphical information of highways and different jurisdiction boundaries, but they do not contain results generated from the Project-level Analysis Module and the Network-level Analysis Module. Integration of graphical information on GIS map layers with the COPACES database and needs analysis results provides an effective way of analyzing the results and allows engineers to visually verify and make modifications.

Although GIS software programs, such as ESRI ArcView and ArcInfo, provide some of the general functions, they are not designed specifically for use in pavement management and, thus, it is not easy to use these GIS software for pavement management without the in depth GIS and database training. One of the contributions in the developed GIS module is its capability to analyze different levels of needs analysis results (project-level and network-level) by associating different levels of needs analysis results automatically and linking them dynamically with the map layers.

7.3 Common Linear Reference System and Base Map Preparation

The Common LRS and GIS Base Map Preparation Function presented in this section are used to integrate the pavement needs analysis results obtained from the Project-level Analysis Module and the Network-level Analysis Module with the graphic information in the GIS maps. The Modified Dynamic Segmentation (MDS) technology

was developed to create new map layers based on the state route map layer and the results obtained from the Project-level Analysis Module using common LRS. The "Addrelate" method was used to link the network-level analysis results, including GDOT District-level and State Congressional District-level results with the corresponding map layers provided by GDOT. The MDS and the "Addrelate" method developed for this function, and the data that can be displayed on the GIS maps are presented in the following sub-sections.

7.3.1 MDS Process for Linear Features

A standard common location identification system based on a common LRS was used to facilitate the data integration between the project-level results and the graphic information provided by the statewide route map layer. Figure 7.2 illustrates how a common LRS works. In order to be able to uniquely differentiate a route spatially, a unique identification called RCLink (Road Characteristics Link) was designed. It has 10 characters containing 3 digits for county number, 1 digit for route type, 4 digits for route number, and 2 digits for route suffix type as defined by GDOT (1999). Route type includes state route, county road, city street, private road, public road, ramp, etc. Route suffix includes bypass connector, business dual, connector, loop, etc. Any projects or segments of the projects on a route need to have a RCLink plus the beginning and ending mileposts to uniquely identify them. In Figure 7-2(a), the thin black line represents a state route in the GIS "stateroute" map layer and the route is identified by its unique RCLink of "2811000200" (type 1 state route in "Towns" County with county number 281 and a route number of 0002 and no specific route suffix with suffix code of 00). The

beginning and ending mileposts of the route are 0.0 and 20.0, respectively. Figure 7-2(b) is the tabular project-level results obtained from the needs analysis modeling results for the projects on this route. As shown in Figure 7-2(b), Project 1 and 2 on this route have the same RCLinks as the route in Figure 7-2(a), but have different beginning and ending mileposts, 2.0 to 5.0 and 10.0 to 12.0, respectively for Project 1 and Project 2. According to LRS, Project 1 and Project 2 are spatially located on the route shown in Figure 7-2(a) based on their RCLinks and the beginning and ending mileposts, and the results are shown in Figure 7-2(c). Thus, the tabular project-level needs analysis results become the attributes of the corresponding map features and can be queried and displayed on the GIS map. To integrate the project-level needs analysis results shown in Figure 7-2(b) with the graphic information in Figure 7-2(a), a dynamic segmentation has to be used.

+

Project ID	RCLink	Milepost From	Milepost To	Treatment	Cost ($)	…
1	2811000200	2.0	5.0	Slurry Seal	232,218	…
2	2811000200	10.0	12.0	Overlay	572,890	…
…	…	…	…	…	…	…

(b)

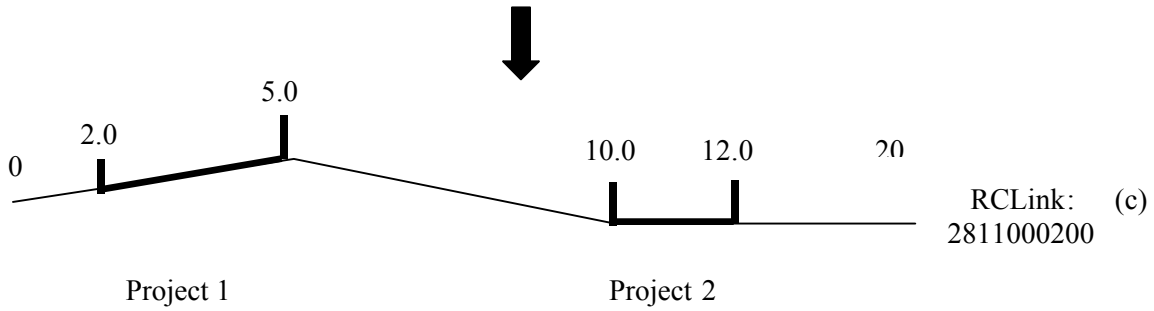


Figure 7 - 2 Example of Common Linear Reference System

A dynamic segmentation is the process of transforming the tabular linearly referenced data known as events into map features that can be displayed and analyzed on a map. The events include point event, such as traffic accident, and linear event, such as traffic volume (AADT) and pavement projects, that have been stored in a database. This process is very useful in pavement needs analysis system for two reasons. The first reason is that a pavement project (e.g., milepost from 2.0 to 5.0 and 10.0 to 12.0, as shown in Figure 7-2) usually contains only a portion of a highway route in the "stateroute" map layer (e.g. milepost from 0 to 20) provided by GDOT, and, therefore, the project-level needs analysis results for that project cannot be associated directly with the entire highway route in the "stateroute" map layer. Secondly, the beginning and ending mileposts of a project may be changed over different pavement survey years. Using dynamic segmentation, a pavement project can be located dynamically on the map without changing the fundamental "stateroute" map layer. The project-level needs analysis results and the project's pavement condition survey results can be associated using the same fundamental "stateroute" map layer.

Although dynamic segmentation provides a dynamic method to link map features with linear referenced data, one major drawback of implementing dynamic segmentation is that the process is extremely slow when using the existing GIS techniques, even in simple mapping operations, such as Zoom In/Zoom Out a statewide map. An example of using the actual GDOT GIS map and the pavement projects information to assess the computing time required by dynamic segmentation was performed. For the GDOT stateroute map containing about 2,500 pavement projects and 18,000 center-line state

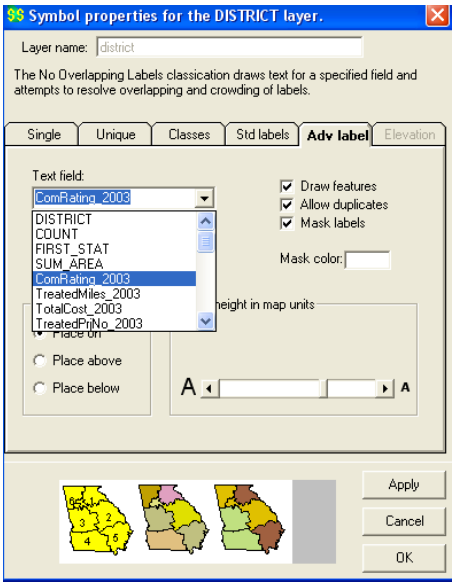
routes, it would take about 2 minutes to perform a Zoom In/Zoom Out using a Pentium IV, 1.7GHz laptop computer, which is impractical for using this function.

The MDS method was developed to overcome the technical challenges discussed above. First, a new project-based GIS shape file for a given year was generated using the base "stateroute" map and dynamic segmentation. Then, a new map layer with the attributes associated with all the results from the Project-level Analysis Module and the graphic information from the new project-based GIS shape file is generated in the local computer. Using this method, it will still take 1 to 2 minutes to create the GIS map layer at the first time. However, once the new map layer is generated, it only takes a few seconds to perform map operations. This method is proven to be working effectively.

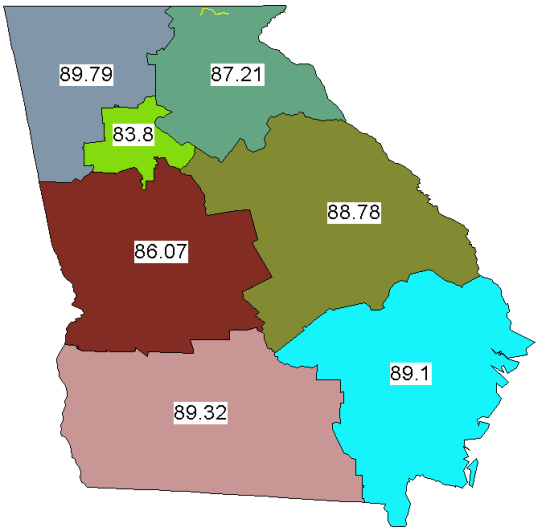
7.3.2 "Addrelate" Method for Polygon Features

The AddRelate method provided by ESRI GIS Component is available for displaying polygon map features. This method creates a relationship between the graphic information in a map layer and the recordsets generated from needs analysis results. Figure 7-3 shows that the year 2003 averaged performance ratings results in seven GDOT Districts can be associated with a polygon map and displayed using AddRelate method. The engineer can query needs analysis performance rating results (attribute) by clicking on the map. The GIS Base Map Preparation Function then automatically extracts the performance ratings of all the pavement projects associated with each GDOT District, computes the averaged performance ratings for each GDOT District, and creates "Composite Rating in Year xxxx" field on the table shown on the right side of Figure 7-3b. It also automatically creates a GDOT District map layer table, shown on the left side

of Figure 7-3b. There is a common "District" field on both of the recordsets tables. This field uniquely identifies each recordset on the map layer and the results table. The AddRelate method uses this common field to create a join between the map layer and the results table and creates a new recordset, which contains all the records (7 GDOT Districts) from the map layer together with all attributes from the analysis results table. Thus, the district-level analysis results will be able to display on the GIS map as shown in Figure 7-3c.



(a)



(c)

Join

District	SUM_AREA
1	5748.0804
2	11464.5854
3	10103.2151
4	12708.7351
5	10969.5517
6	5993.2049
7	1641.8240

Original Recordset
Associated with a Map Layer

District	Composite Rating in 2003	Treated Miles in 2003	…	Total Center Miles
1	87.21	0	…	2656.08
2	88,78	0	…	3638.18
3	86.07	0	…	3639.45
4	89.32	0	…	3900.08
5	89.10	0	…	2954.56
6	89.79	0	…	2179.93
7	83.80	0	…	1257.04

Recordset of District-Level
Analysis Results

(b)

Figure 7 - 3 Example of AddRelate Method

7.3.3 Data

The six basic map layers below are used in the GIS module.

(1) ANALYSIS RESULTS: contains detailed project-level results, including project ratings in each future analysis year, treatment methods and costs, AADT, and spatial location information, such as RouteNo, RouteSuffix, CountyNo, MilePostFrom and MilePostTo, District, Office, etc. It is created by the MDS method.

(2) STATEROUTE: This layer is provided by GDOT. After data integration, the layer contains the complete information on state highway routes in Georgia.

(3) COUNTY: Contains the detailed county information of Georgia.

(4) CONGRESS: Contains the State Congressional District boundary information and the State Congressional District-level needs analysis results, such as network-level composite ratings, total rehabilitation funding allocation, total lane-miles to be treated and total number of projects to be treated in each year.

(5) DISTRICT: Contains the GDOT District boundary information and the GDOT District-level needs analysis results.

(6) STATEBOUNDARY: Contains the state boundary information and the statewide network-level needs analysis results.

These six basic map layers include most of the information generated from the needs analysis results that can be displayed on GIS maps. Results from the Project-level Analysis Module related to individual project information are displayed on the ANALYSIS RESULTS layer, see Figure 7-4. Results from the Network-Level Analysis Module related to State Congressional Districts, GDOT Districts, and statewide are displayed respectively on the CONGRESS, DISTRICT, and STATEBOUNDARY map layers.

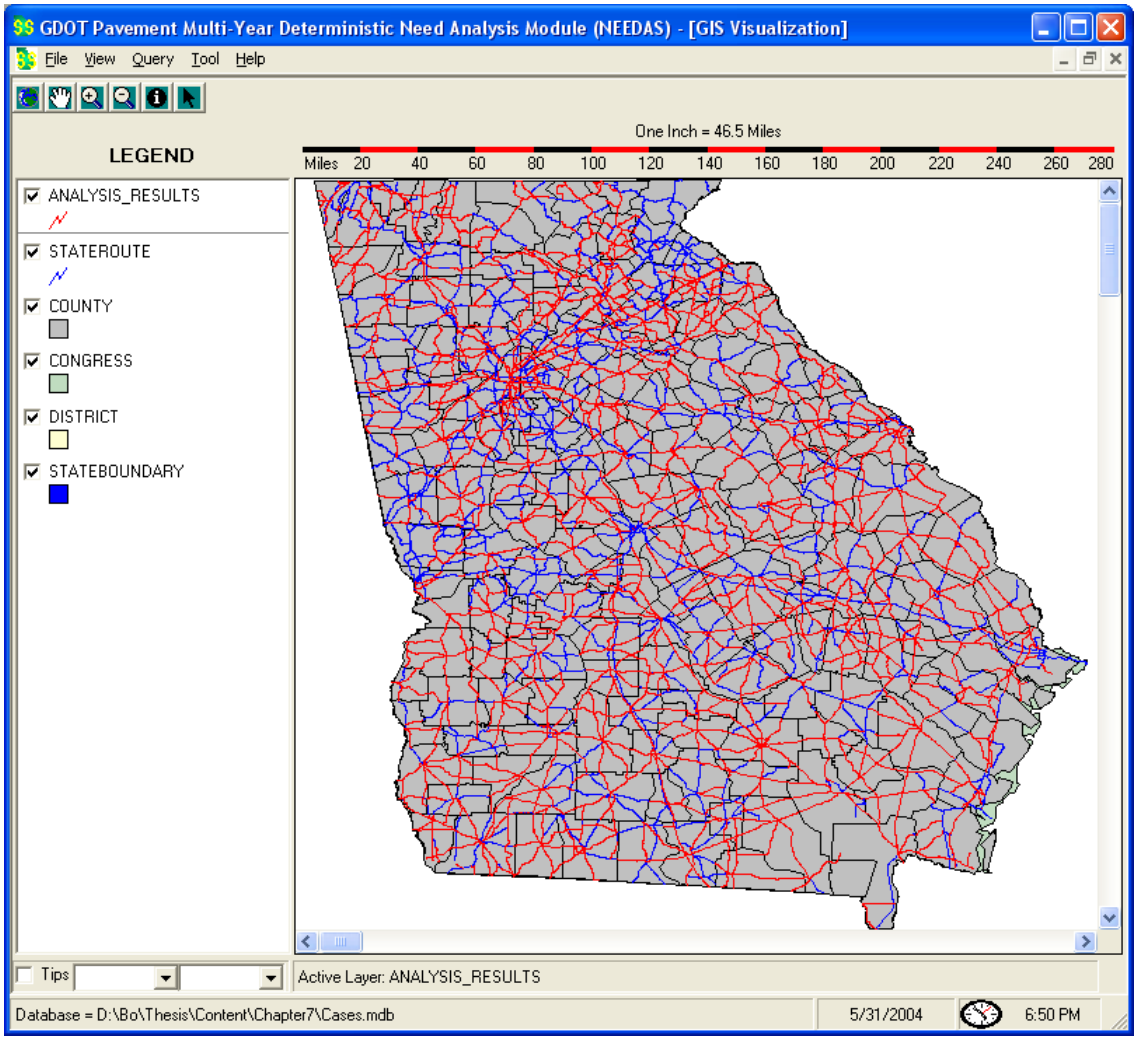


Figure 7 - 4 GIS Base Map

7.4 GIS Spatial Analysis and Visualization

GIS provides a powerful capability for conducting spatial analysis and data visualization. The GIS Spatial Analysis and Visualization Function was developed to support the results generated from the GDOT multi-year needs analysis. Various analysis results can be analyzed spatially and displayed on GIS maps directly and dynamically using the Spatial Analysis and Visualization Function. Several examples are presented below to illustrate the integrations and benefits of using the GIS functions developed in the GIS module for pavement needs analysis.

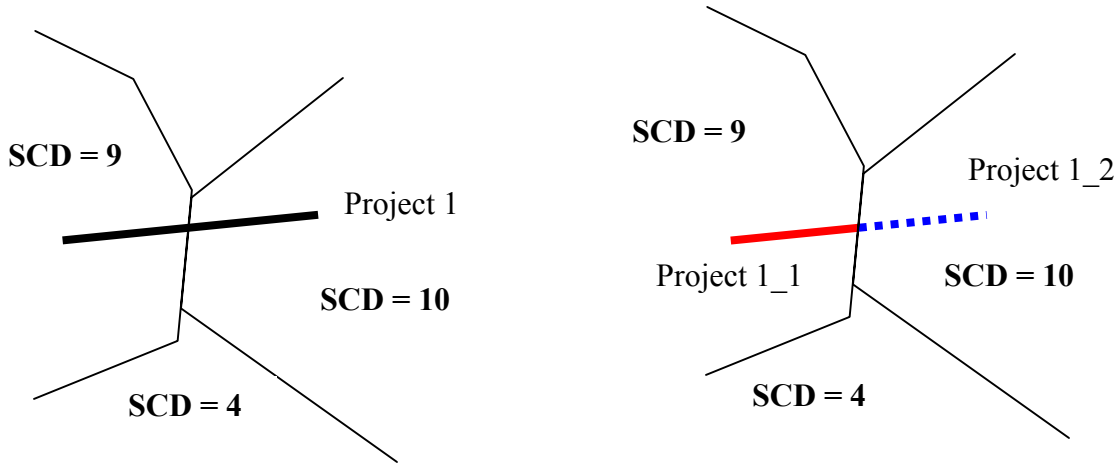
7.4.1 GIS Spatial Analysis

GIS Spatial Analysis is the process of extracting or creating new information about a set of geographic features (ESRI, Inc., 2001). The spatial analysis is crucial for GDOT's multi-year needs analysis. For example, it would be useful and informative to present the results of multi-year project-level forecasted pavement conditions and the corresponding future funding requirements based on GDOT Districts and State Congressional Districts. As pointed out in Chapter 4, a pavement project is always located within a GDOT District, while it could cross several State Congressional Districts. This creates a challenge to distribute the attributes of a pavement project when a project is located in more than one State Congressional District. In addition, the State Congressional District boundaries change from time to time due to changes of the population and political considerations. Fortunately, GIS spatial analysis function provides a powerful capability to proportionally divide miles/funding through State Congressional District boundaries when a route or a project runs through more than one

district. The function can aggregate the funding of the divided projects based on jurisdiction boundaries from a project located in more than one districts. Figure 7-5 illustrates how spatial analysis works. In Figure 7-5(a), a project with "Project_ID"=1 crosses State Congressional District 9 and 10. The total funding of the project is $10,000. Figure 7-5(b) shows the results after conducting spatial analysis. Using spatial analysis, the funding of the project is now distributed to State Congressional District 9 and 10 proportionally based on the spatial length of the project between these two districts, which makes it possible to accurately determine rehabilitation funding distributions among different State Congressional Districts. The developed system is using the major portion of State Congressional District for funding balance as indicated in Section 6.4.3, because there are only a few projects (4.9%) cross more than one State Congressional Districts. However, it is possible in the future to incorporate a more accurate project State Congressional District disaggregation using GIS spatial analysis, as illustrated in this section.

Engineers can obtain the total miles of routes with project rating less than 70 (the threshold value of pavement project rating currently used by GDOT) for each GDOT District or State Congressional District. Routes with the project ratings less than or equal to 70 indicate the pavements are in poor conditions. Figure 7-6 shows the pavement performance in 2003 among 7 GDOT Districts. The number outside the brackets indicates the total center-lane miles of projects with ratings less than or equal to 70. The number inside the brackets indicates the percentage of projects with ratings less than or equal to 70 to the total projects in each district. As shown in Figure 7-6, District 7 has the highest percentage (7.7%) of projects with poor pavement conditions, which is

reasonable because more projects in this district (around Metro Atlanta area) are subject to heavy traffic, thus, causing more damage to the pavements. The spatial data presentation allows the user to integrate with other spatial information such as traffic.



Project ID	Funding ($)	GDOT District	…
1	10,000	1	…

(a)

Project ID	Funding ($)	GDOT District	State Congressional District (SCD)	…
1_1	4,800	1	9	…
1_2	5,200	1	10	

(b)

Figure 7 - 5 Illustration of Spatial Analysis

The spatial selection capability of the GIS Spatial Analysis Function provides a useful tool to allow engineers to extract a specified set of projects and their attributes within any GDOT District, State Congressional District, County, or even a specific route.

An example to demonstrate this capability is shown in Figure 7-7. Figure 7-7(a) is the spatial selection query form. It allows engineers to specify any one or all of GDOT Districts, State Congressional Districts, or counties, or select a specific route. In this case, the user selects GDOT District 4 by selecting "4" from the *District* selection box. Immediately, the information of all projects within GDOT District 4 was queried out using the spatial selection function, and a new map layer is created, as shown in Figure 7-7(b). Different colors on this map indicate different treatment years. The text next to each route indicates the rehabilitation method to be applied. This new map layer can be sent to GDOT District 4 for confirmation or adjustment of the analysis results, as district offices may possess more detailed information related to the projects than Central Office does.

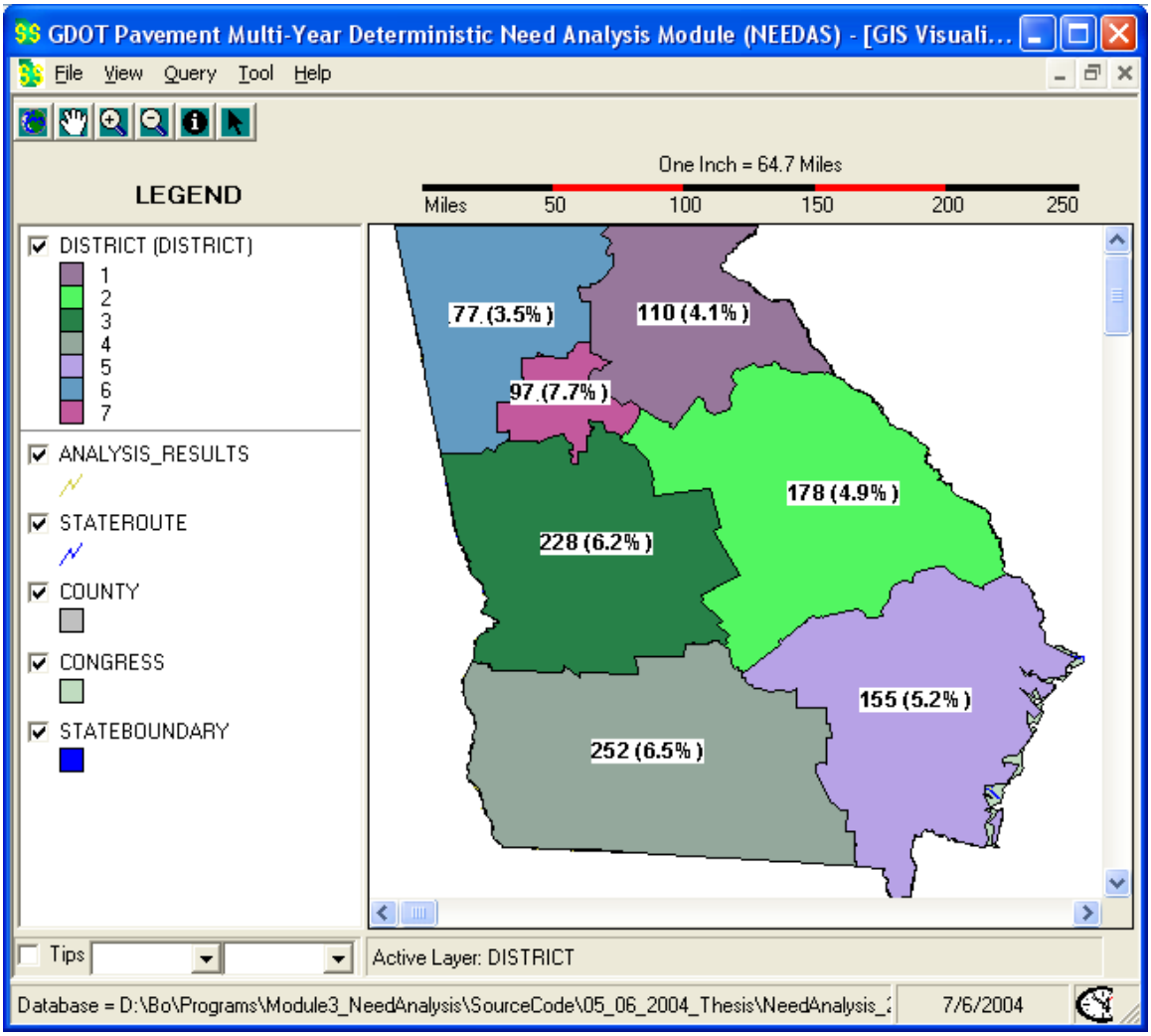
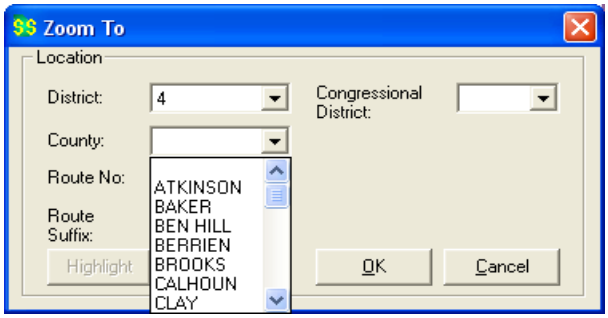
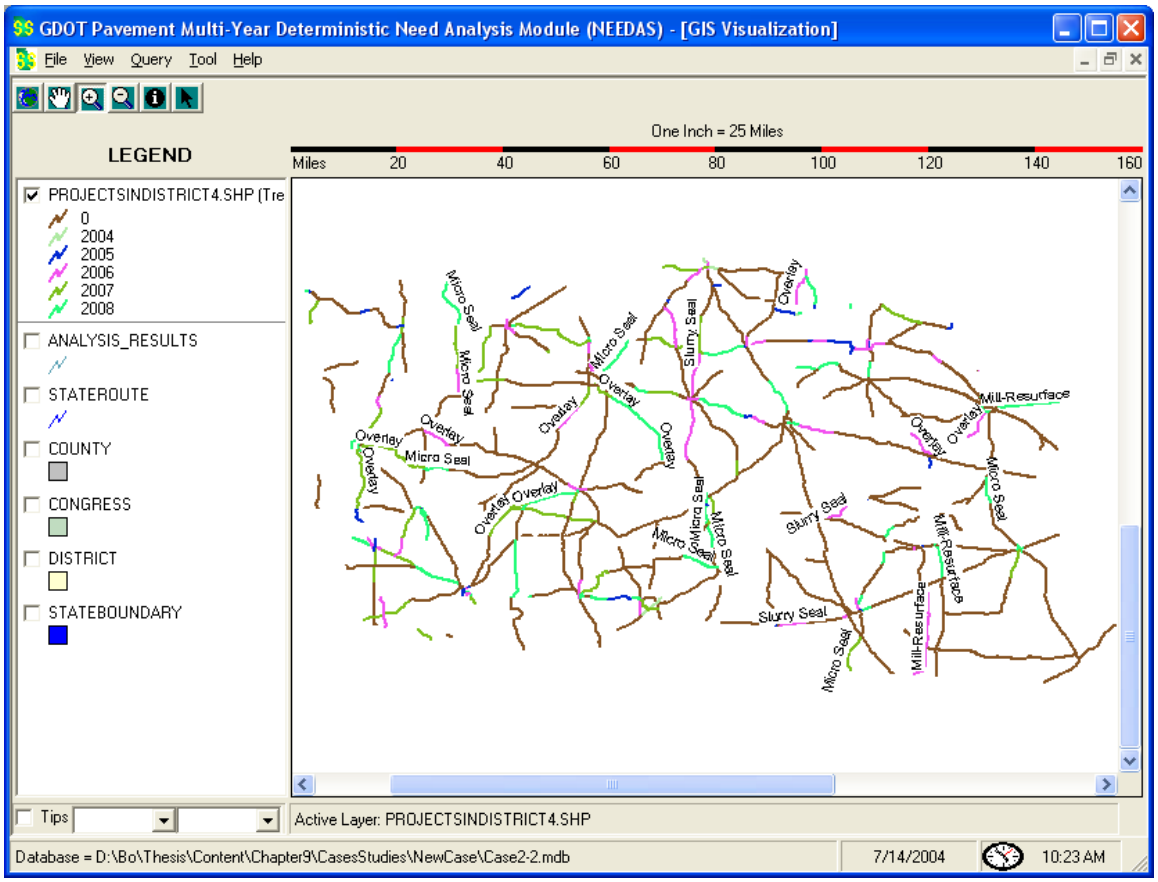


Figure 7 - 6 Lane Miles and Percentages of Projects with Rating ≤ 70 among GDOT Districts in Fiscal Year 2003



(a) Chose GDOT District 4



(b) Visualize Projects Information in GDOT District 4

Figure 7 - 7 Example of Spatial Selection

7.4.2 Visualization

GIS provides a powerful visualization and mapping capability, which is useful for pavement rehabilitation needs analysis. In order to facilitate the decision support on multi-year rehabilitation needs analysis, several advanced functions have been developed. The design concept of these functions is to facilitate pavement rehabilitation needs analysis using GIS visualization. The potential uses of the visualization and mapping functions are described below:

- Visualize spatial and temporal treatment strategies on one map.
- Identify projects with abnormal pavement conditions.
- Investigate detailed historical information and needs analysis results of the interested project dynamically and interactively.
- Make comparison among different jurisdictions.
- Monitor routes not surveyed.

Several potential GIS applications are presented in the following to demonstrate the potential uses of these functions to facilitate the decision-making for planning pavement rehabilitation needs activities.

<u>Case 1: Visualize spatial and temporal treatment strategy on one map</u>

The multi-year needs analysis results include not only the spatial information, such as where to treat, but also the temporal information, such as when to treat. GIS visualization provides the capability to visualize both spatial and temporal treatment

information on one map. As shown in Figure 7-8, the project-level multi-year needs analysis result, obtained from the Project-level Analysis Module and the Network-level Analysis Module, are displayed on the map. Different colors on the map indicate different years a rehabilitation treatment is to be applied and the text along a route indicates the suggested treatment method. With this information, engineers can grasp the suggested multi-year, statewide pavement treatment strategy effectively, as the information presented on the map allows the engineers to absorb the information much more quickly than that from a tabular format. Besides the efficiency gained for decision makers, there are some engineering implications allowing the engineers to explore new alternatives or new strategies using this powerful tool. For example, in Figure 7-8 the two adjacent projects circled are to be treated using the same "Micro Seal" treatment method. However, the different colors of these two projects clearly indicate that one project is to be treated in Year 2006 while the other project in Year 2004. Using this visual information, the engineers can decide whether it would be more beneficial to treat these two projects at the same time. Using this GIS-unique visualization functionality, engineers can scan through the maps to check for consistency and compatibility of the rehabilitation treatment plans and make proper adjustments. The next section will further illustrate how the changes can be easily made through a GIS map and how they impacts the needs analysis results.

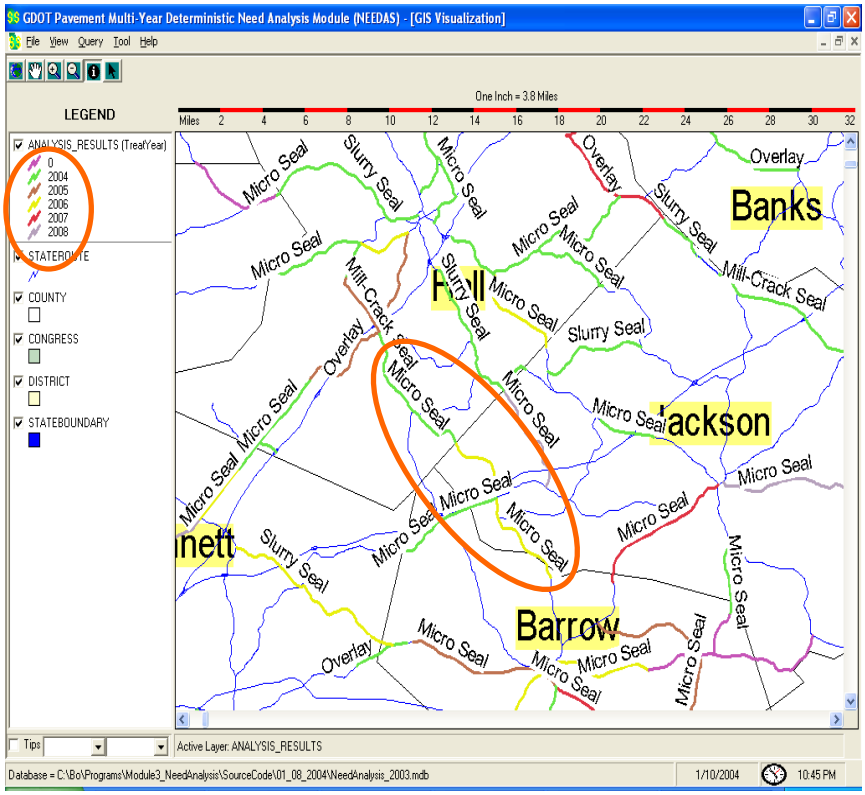
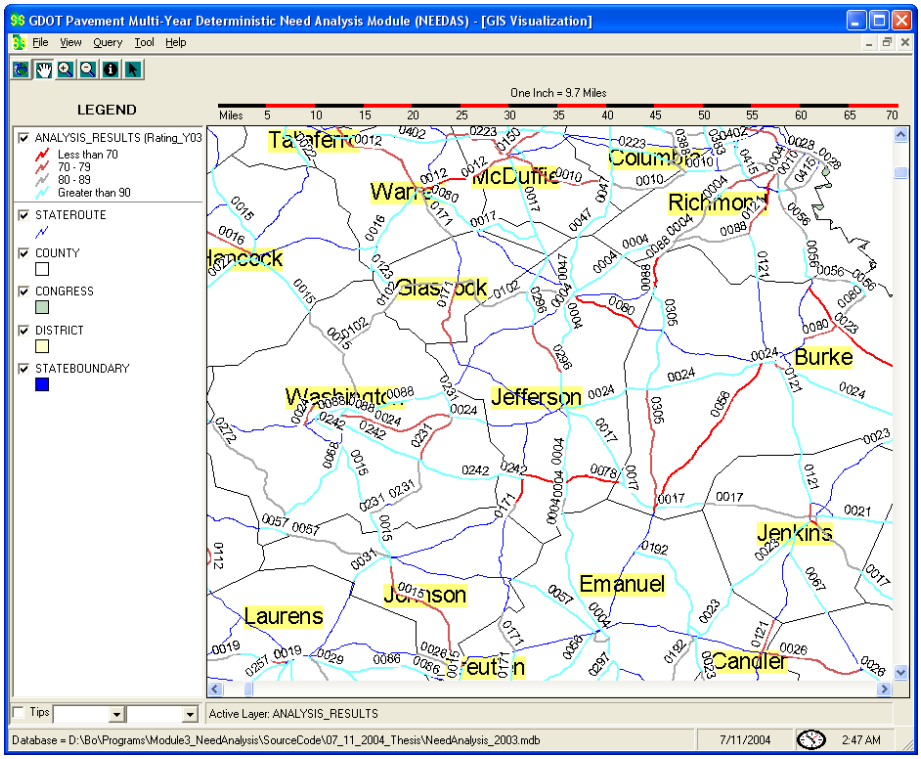


Figure 7 - 8 Visualize Spatial and Temporal Treatment Information

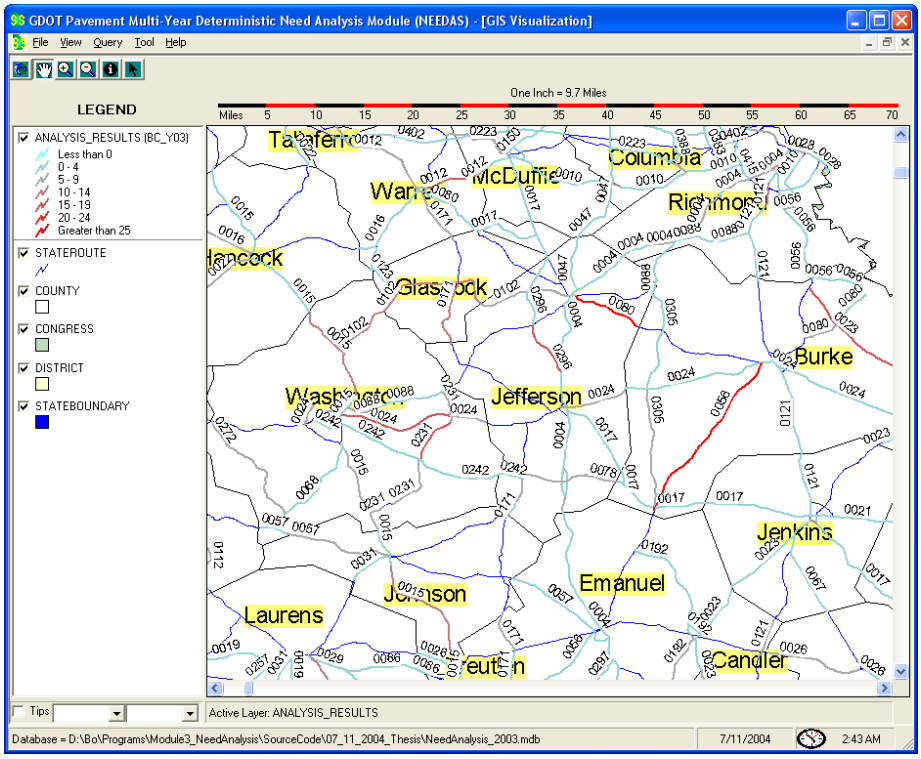
<u>Case 2: Identify projects with abnormal pavement conditions</u>

The engineers in the Central Office can query and view the pavement conditions in a particular year and use them to identify projects with abnormal pavement conditions and then make proper adjustments directly on the map for the results generated from the NEEDAS program. As shown in Figure 7-9, the projects with different pavement conditions in fiscal year 2003, including project ratings and different distress deduct values, are displayed in different colors. Figure 7-9 (a) shows the distribution of the project ratings, while Figure 7-9 (b) shows the distribution of the deduct values for block cracking. Figures showing deduct values of other types of distresses can also be

generated. In both Figure 7-9 (a) and (b), the number next to each project indicates the "RouteNo" of each project. The engineer can easily identify projects with relatively low ratings (projects with red color) in Figure 7-9(a), and also can easily identify projects with relatively high deduct values of block cracking (projects with red color) from Figure 7-9(b). Also, through the comparison between Figure 7-9(a) and Figure 7-9(b), and with other companion figures showing deduct values of other types of distresses, engineers can easily relate projects with lower ratings to the predominate distresses causing the low ratings. Engineers can further explore the project's information, such as historical distresses condition, traffic volumes, etc., as will be shown in the next Case.



(a) Project Rating

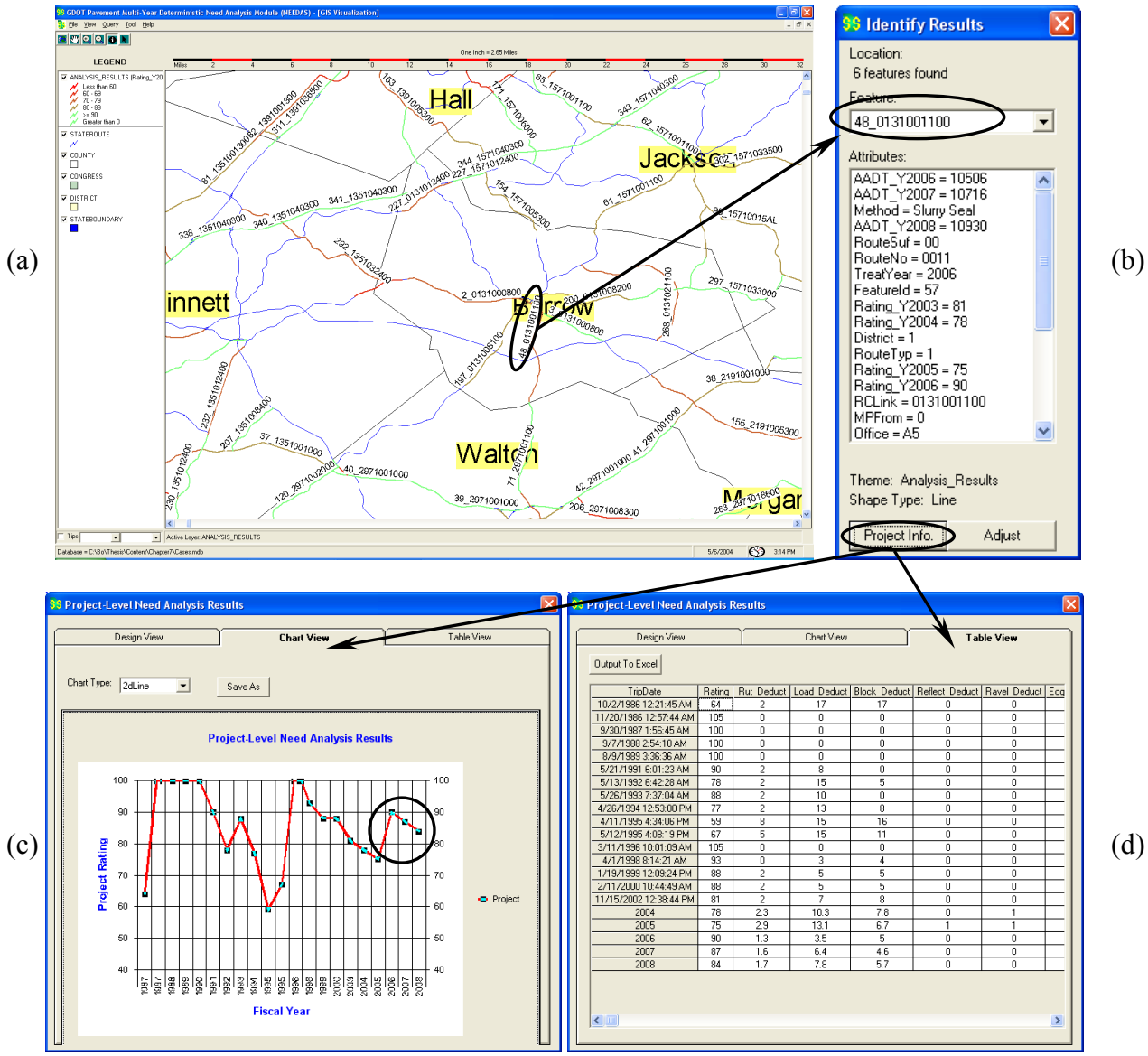


(b) Block Cracking

Figure 7 - 9 Visualize Project-level Pavement Condition in Year 2003

Case 3: Investigate detailed historical information and rehabilitation needs analysis results

Historical information of a pavement project, as it reveals not only the pavement conditions in the past, but also the rehabilitation history (when such information is available in the future), is of great importance in helping engineers make proper judgments of pavement rehabilitation plans. The GIS module integrates the graphical information seamlessly with the COPACES database, and the needs analysis results. Engineers can retrieve historical information through the GIS map dynamically. Figure 7-10 shows an example for doing that. Engineers can select a specific project on the GIS map, as shown in Figure 7-10(a). The detailed information, including AADT, treatment year, ratings, treatment methods, etc., of the selected project is displayed on a table as shown in Figure 7-10(b). By clicking the "Project Info." Button, shown in Figure 7-10 (b), various historical project information of the selected project, such as project rating, different distress deduct values, and AADT, can be retrieved from the COPACES database, and the corresponding forecasted project information, determined from the needs analysis results and stored in the database, can also be retrieved and displayed in a chart format or a tabular format, as shown in Figure 7-10 (c) and (d).



TripDate	Rating	Rut_Deduct	Load_Deduct	Block_Deduct	Reflect_Deduct	Ravel_Deduct	Edg
10/22/1986 12:21:45 AM	64	2	17	17	0	0	
11/20/1986 12:57:44 AM	105	0	0	0	0	0	
9/30/1987 1:56:45 AM	100	0	0	0	0	0	
9/7/1988 2:54:10 AM	100	0	0	0	0	0	
8/9/1989 3:36:36 AM	100	0	0	0	0	0	
5/21/1991 6:01:23 AM	90	2	8	0	0	0	
5/13/1992 6:42:28 AM	78	2	15	5	0	0	
5/26/1993 7:37:04 AM	88	2	10	0	0	0	
4/26/1994 12:53:00 PM	77	2	13	8	0	0	
4/11/1995 4:34:06 PM	59	8	15	16	0	0	
5/12/1995 4:08:19 PM	67	5	15	11	0	0	
3/11/1996 10:01:09 AM	105	0	0	0	0	0	
4/1/1998 8:14:21 AM	93	0	3	4	0	0	
1/19/1999 12:09:24 PM	88	2	5	5	0	0	
2/11/2000 10:44:49 AM	88	2	5	5	0	0	
11/15/2002 12:38:44 PM	81	2	7	8	0	0	
2004	78	2.3	10.3	7.8	0	1	
2005	75	2.9	13.1	6.7	1	1	
2006	90	1.3	3.5	5	0	0	
2007	87	1.6	6.4	4.6	0	0	
2008	84	1.7	7.8	5.7	0	0	

Figure 7 - 10 Visualize Project-level Historical Data

Case 4: Monitor routes not surveyed

The analysis performed by the NEEDAS program uses the projects that have been surveyed and stored in the COPACES database. Those projects that have not been surveyed or have not been uploaded to the COPACES database are not considered during the rehabilitation needs analysis. As shown in Figure 7-11, the routes that have been surveyed are colored in green in the state highway network, and the remaining routes are shown in blue. Such routes can be identified easily from the GIS map, and detailed information of these routes can also be queried.

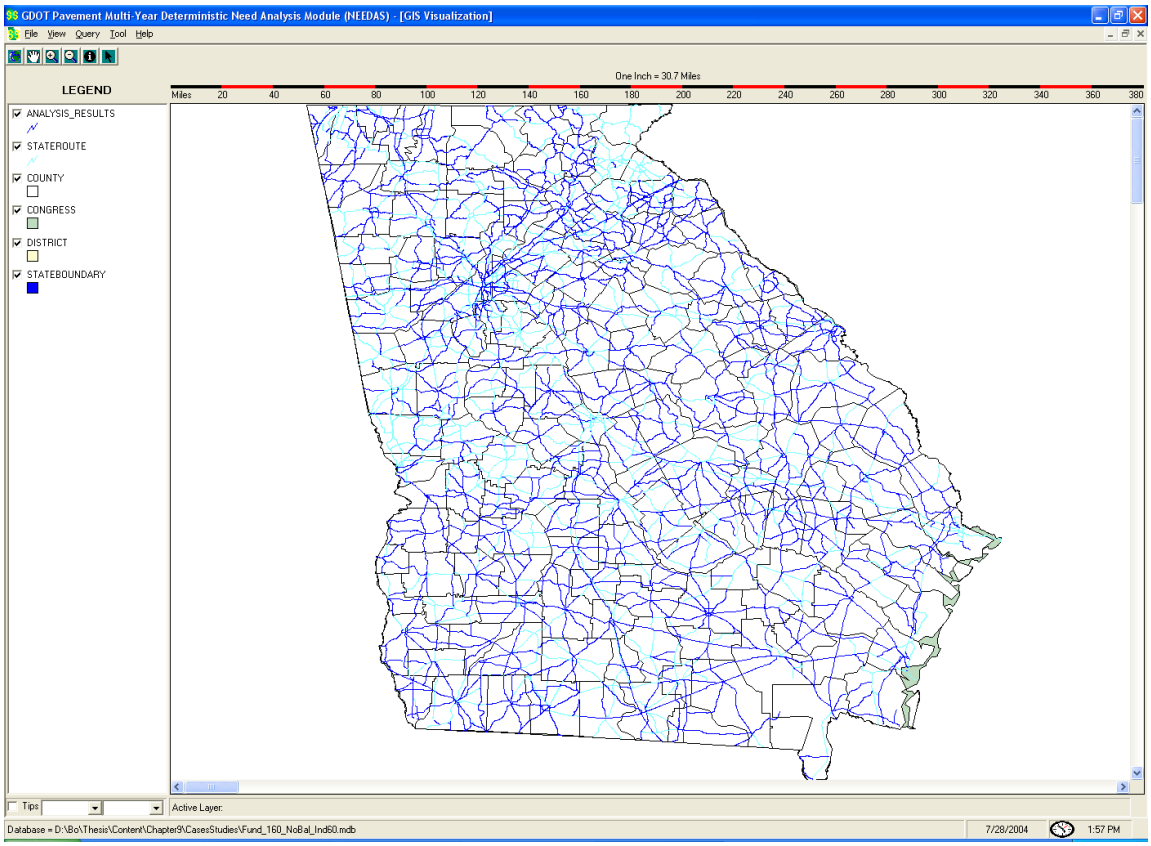


Figure 7 - 11 Monitor Routes Not Considered in the Needs Analysis
(Blue: Surveyed Routes; Green: Not-surveyed Routes)

7.5 Interactive Map-based Multi-year What-if Pavement Scenario Analysis

In order to facilitate the decision support on multi-year needs analysis, the framework and methodology of a GIS-enabled multi-year what-if scenario analysis to fine-tune the initial rehabilitation needs analysis results generated from the NEEDAS program were developed. The GIS-enabled multi-year scenario analysis framework integrates GIS capabilities, including visualization, identification, and spatial analysis, with multi-year needs analysis modeling including project-level pavement distresses and performance forecasting, treatment determination and project prioritization. The Interactive Map-based Multi-year What-if Scenario Analysis Function was developed to enable decision makers to develop and evaluate different treatment scenarios intuitively and directly on a GIS map. The development of this capability was motivated by the following reasons.

First, engineers can grasp the project-level multi-year needs analysis results easily by looking at them directly on a map. It is more difficult to evaluate the project-level needs analysis results on a tabular format. To go over more than 2,000 treatment strategies per year in a tabular format is not easy. It is even more difficult to look at more than 10,000 treatment strategies in a 5-year analysis period and to associate space and time relationships of the analysis results. On the contrary, the GIS map can display clearly the project-level needs analysis results, including using different colors to represent treatment actions taken in different years and the texts labeling the treatment actions recommended by the program, as shown in Figure 7-8.

Secondly, engineers can incorporate additional data and then better utilize their engineering knowledge through the map-based interactive analysis. This allows

engineers to incorporate their engineering knowledge, and other related data, such as future plans for High Occupied Vehicles (HOV) lane, flood concerns, future bridge replacements, etc., to fine-tune the decision on project-level pavement rehabilitation strategies.

Thus, it is necessary to develop an Interactive Map-based Multi-year What-if Pavement Scenario Analysis Function to facilitate the performance of what-if analysis. This section presents the framework and methodology for developing such a function. However, to develop such a function is not easy due to the following reasons:

(1) Changing the treatment method or treatment year of a project could impact the network performance and the costs during the entire analysis period.
(2) Changing the treatment method or treatment year of a project could trigger the changes of the treatment method or treatment year of other projects in the network.
(3) After changing the treatment method or treatment years, the ratings, distresses, and treatment methods of the project in the subsequent years need to be recalculated.

Figure 7-12 illustrates the algorithms for performing an interactive, map-based, multi-year what-if pavement scenario analysis. The algorithms used in each step to perform the analysis are presented below.

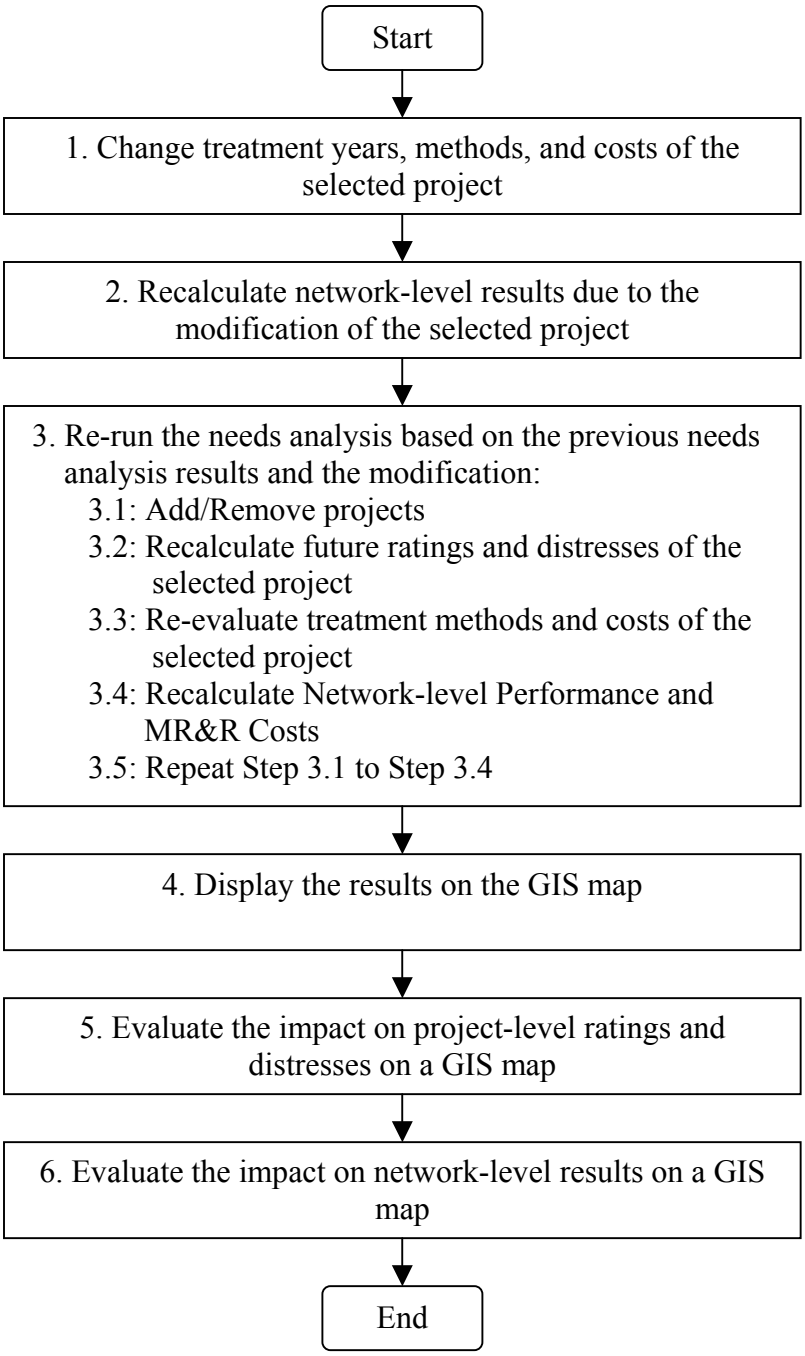


Figure 7 - 12 Algorithm of Interactive Map-based Multi-Year What-if Pavement Scenario Analysis

Step 1: Change treatment years, methods, and costs of a selected project

First, the changes of the treatment years, methods, and costs of a selected project are decided by engineers. Then, the performance of the selected project is updated. The updated performance rating and the deterioration rate after the application of the new treatment designated by the engineers are calculated based on the new treatment method and taking into consideration of the early rehabilitation action (early rehabilitation action should enhance the performance rating and reduce the future deterioration rate).

A linear performance model, similar to the one discussed in Chapter 5, Section 5.2, is used except two factors are used to consider the changes of the performance rating and the deterioration rate right after the treatment. Equations (7-1) and (7-2) describe how the factors are used:

$$[\text{Performance Rating}]_{\text{Adj_Treat}} = [\text{Performance Rating}]_{\text{Ori_Treat}} + \text{Factor}_1 \quad (7\text{-}1)$$

$$\text{Slope}_{\text{Adj_Treat}} = \text{Slope}_{\text{Ori_Treat}} + \text{Factor}_2 \quad (7\text{-}2)$$

Where:

$[\text{Performance Rating}]_{\text{Ori_Treat}}$: Rating after treatment, obtained from Table 5-2

$[\text{Performance Rating}]_{\text{Adj_Treat}}$: Rating after treatment due to interactive adjustment

$\text{Slope}_{\text{Ori_Treat}}$: Deterioration rate of a treatment, if the treatment is determined based on GDOT's decision tree

$\text{Slope}_{\text{Adj_Treat}}$: Predicted deterioration rate of treatment, if the treatment is determined based on the interactive adjustment

$Factor_1$, $Factor_2$: Parameters used to modify performance model due to interactive adjustment, which depends on the change of initial pavement conditions, treatment methods, traffic condition, etc.

The determination of $Factor_1$ and $Factor_2$ requires statistical analysis using the historical treatment data. Because most of the historical treatment data are not available, and therefore appropriate values for these two factors cannot be determined. For the time being both factors are set as 0. However, these two factors are already incorporated in the system and appropriate values other than 0 can be assigned when such values are available.

Step 2: Recalculate network-level results

This step recalculates the network performance, costs, number of treated projects, and treated length, in GDOT District-level, State Congressional District-level and entire state due to the changes made on the selected project.

Step 3: Re-run the needs analysis

Due to the adjustment of the selected project, the network constraints may not be satisfied anymore. Therefore, it is necessary to reevaluate the network constraints and re-run the needs analysis. The following recalculations start from the earliest year in which the treatment method, or rehabilitation cost of the selected project has been changed.

Step 3.1: Add/remove a project

When network constraints are not satisfied due to interactive adjustment of the selected project, a project will be added or removed based on the cost-effectiveness ratios from the previous needs analysis results. To add a project, the function will select a project with the highest cost-effectiveness ratio from the Not-to-be-treated Project lists. To remove a project, the function will select a project with the lowest cost-effectiveness ratio from the To-be-treated Project lists. To prevent the project selected by engineers that has been added or removed during the interactive analysis, a "Criteria" field is used, as shown in Table 8-1 in the next Chapter. If a project is adjusted by engineers, the value of the field is set as "Manual." During the automatic selection of a project performed by the program, any project with "Manual" marked in the "Criteria" field will not be considered, since the treatment methods of the project have been reviewed and accepted by engineers.

Step 3.2: Recalculate future ratings and distresses of the selected project

Once a new project is added or removed in a year by the program, the "Treatment" field for the added/removed project will be set as "Do Nothing" first in the subsequent years because previous treatments of the project may not be qualified any more. Then, the future ratings and distresses of the project will be re-calculated based on the pavement performance model presented in Chapter 5.

Step 3.3: Re-evaluate treatment methods and costs of the selected project

The candidate treatment methods and the associated costs of the project have to be re-assessed based on the project ratings and distresses conditions obtained in the previous step.

Step 3.4: Recalculate network-level performance and rehabilitation costs

The network-level performance and rehabilitation costs are updated based upon the modification of the project added to or removed from the To-be-treated Projects list.

Step 3.5: Repeat Step 3.1 to Step 3.4

Step 3.1 to Step 3.4 are repeated until the network-level constraints in the adjusted year is satisfied or there are no projects to be added/removed. Then, the NEEDAS system will repeat the entire Step 3 processes year after year until the end of the analysis period.

Step 4: Display the results on the GIS map

Once Step 3 is completed, the GIS map will be refreshed immediately to reflect the project-level analysis results after the interactive analysis.

Step 5: Evaluate the impact on project-level ratings and distresses on a GIS map

To help engineers make proper judgments, project-level results after the interactive analysis, including project ratings and distress deduct values in the analysis

period, can be generated for engineers to compare with the corresponding results before the interactive analysis.

Step 6: Evaluate the impact on network-level results on a GIS map

The network-level results, including performance (composite rating), costs, treated miles, and treated project numbers, can also be generated for engineers to compare with the corresponding results before the interactive analysis.

The following example illustrates the use of an interactive map-based multi-year what-if pavement scenario analysis.

After the NEEDAS program has completed the initial multi-year pavement needs analysis, the program generates the project-level results, including the treatment years, the locations, and the treatment methods of the projects to be treated. Besides storing the project level results in a table, the results can also be presented in a GIS map, as shown in Figure 7-13(a). The engineers can incorporate their engineering knowledge to refine the treatment strategies determined by the NEEDAS program. Figure 7-13 shows two adjacent projects to be treated with the same treatment method in 2 years apart. Based on the engineer's judgment, these two projects can be combined to be treated in 2004 because they are adjacent, and the original scheduled treatment years are not that far apart and require using the same treatment method. This refined decision can reduce the project mobilization cost and traffic congestion caused by constructing two projects in separate years, and even can reduce the total construction cost.

Figure 7-13(a) shows the GIS map before the interactive analysis. Figure 7-13(c) and (d) describe the interfaces that allow engineers to perform the interactive analysis. During the interactive analysis, the treatment year of the selected project, was changed from Year 2006 (in yellow color) to Year 2004 (in green color), as shown in Figure 7-13 (a). Figure 7-13(b) shows the GIS map immediately after the interactive analysis. As shown in Figure 7-13(b), after the interactive analysis, the two adjacent projects have the same green color, which indicates that they will be treated in the same year (2004).

Figure 7-14 and 7-15 shows the effects on the project-level and network-level analysis results due to the interactive adjustment made in Figure 7-13. Figure 7-14 shows the comparison of the deduct values for load cracking of the selected project (in yellow color in Figure 7-13(a)) before and after the manual changes of the treatment strategy. From Figure 7-14, it can be seen that the deduct value for load cracking in the last year increased from 4 to 8 due to the interactive adjustment. Figure 7-15 shows the impact on the network-level composite rating (GDOT District-level) due to the interactive adjustment of the project. According to Figure 7-15(a) and (b), the GDOT District-level composite ratings in 2004 and 2005 after the interactive adjustment are higher than that before the interactive adjustment (87.13 and 87.1 versus 87.02 and 86.99, respectively). Although the GDOT District-level composite ratings in 2006 to 2008 after the interactive adjustment are less than that before the interactive adjustment (86.91, 86.97, and 87.12 versus 86.94, 87.01, and 87.15, respectively), the average GDOT District-level composite rating in the entire analysis period after the interactive analysis is slightly higher than that before the interactive analysis (87.05 versus 87.02). The results of this network-level

impact analysis will make engineers feel comfortable about the interactive analysis made in Figure 7-13.

To summarize, the following benefits are achieved by developing the Interactive Map-based Multi-Year What-if Pavement Scenario Analysis Function:

1) Engineers can make changes intuitively and readily on the map by changing the treatment method and the time to perform treatment. It is a more effective and intuitive decision-making process.
2) The multi-year needs analysis model will run behind the scenes to show the effect of the changes at the project and network levels immediately and effectively on the map, and to display the detailed results in graphs and in tables.
3) Engineers can perform what-if analysis to explore various alternatives and combinations, which is otherwise difficult to conduct or unfeasible to perform. This may lead to new knowledge discovery and to new pavement management philosophies and practices.

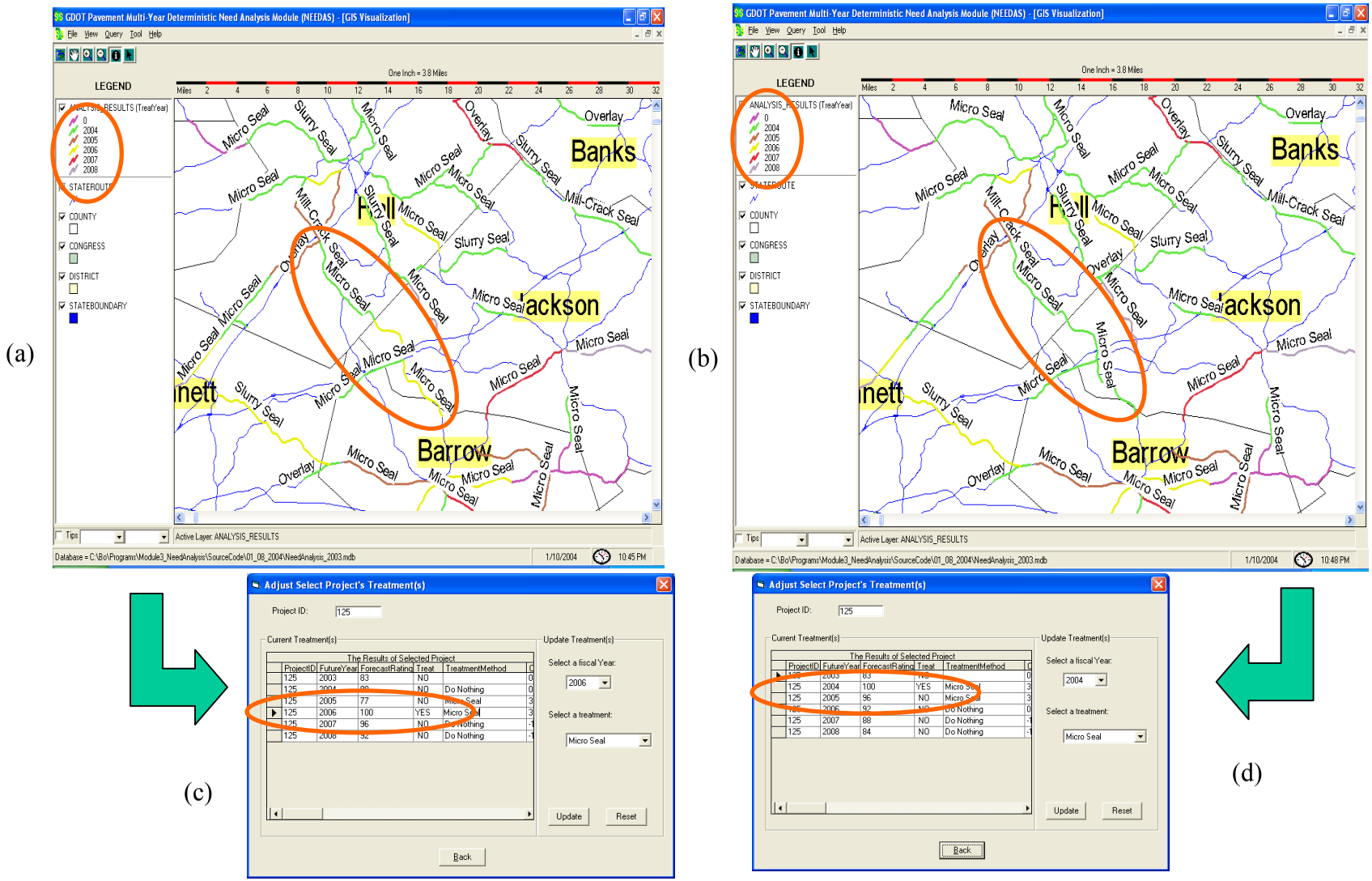


Figure 7 - 13 Example of Interactive Analysis

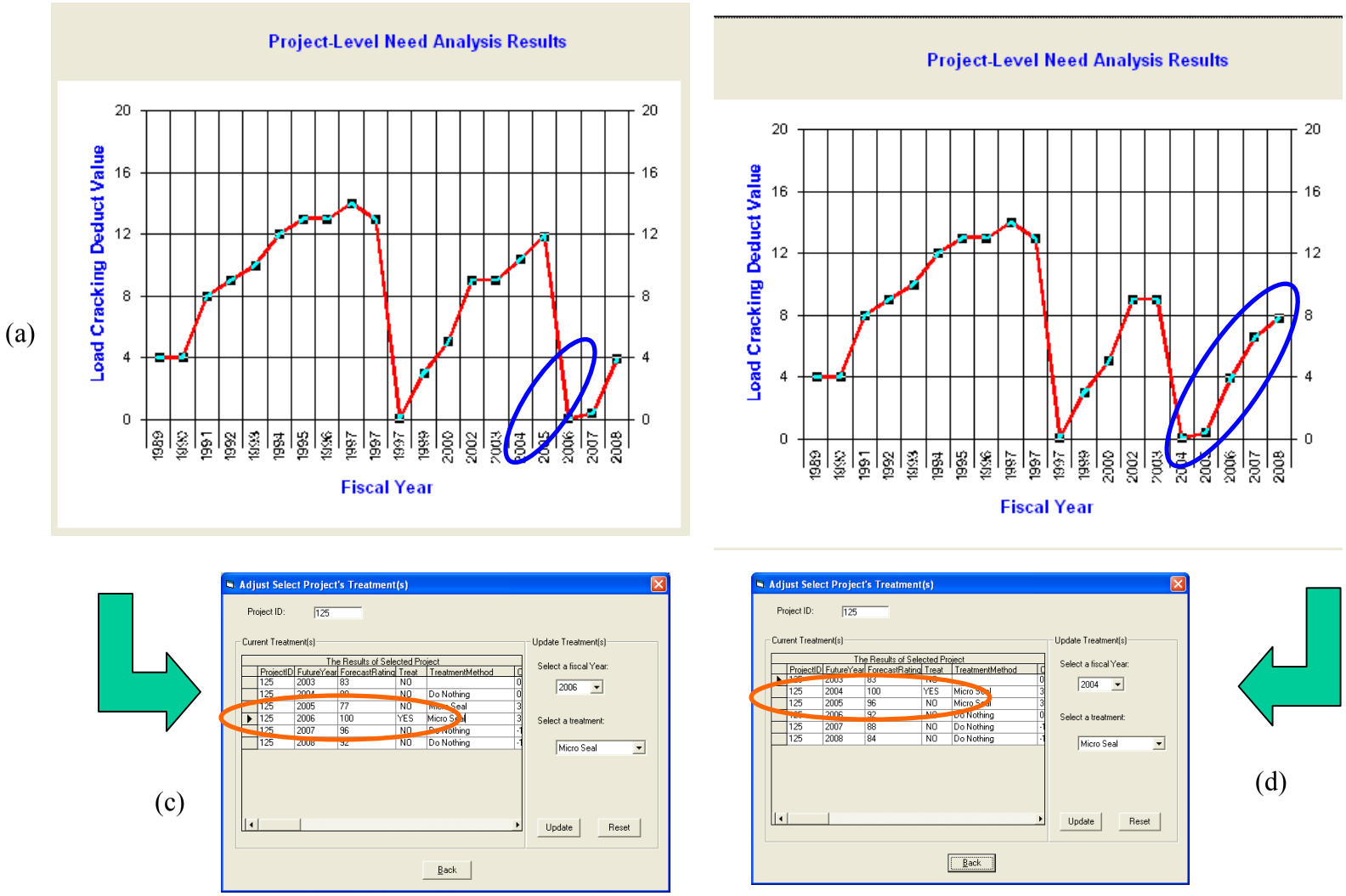


Figure 7 - 14 Impact Analysis of Project-Level Distress Deduct Value (Load Cracking)

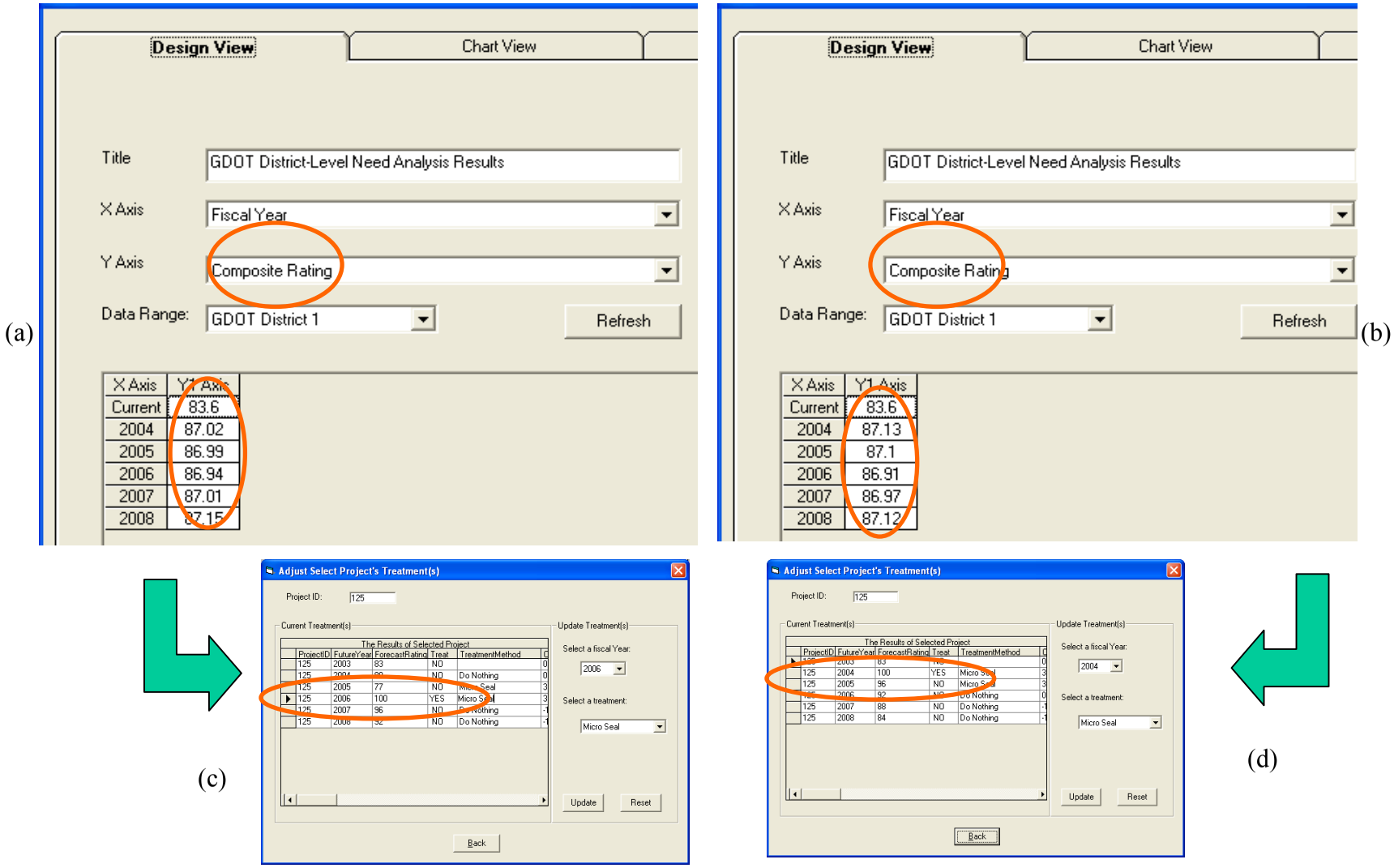


Figure 7 - 15 Impact Analysis of Network-Level Composite Rating

CHAPTER 8

DEVELOPMENT OF NEEDAS PROGRAM

Based on the concepts presented in previous chapters, a computer program for performing pavement rehabilitation funding needs analysis (NEEDAS program) was developed for the GDOT Office of Maintenance as a planning tool for performing multi-year pavement rehabilitation needs analysis to meet various network-level and project-level performance requirements. The analysis performed by this program utilizes the statewide pavement condition evaluation data stored in the COPACES database. More specifically, the program can perform the following tasks:

- Perform multi-year pavement rehabilitation funding needs analysis to meet prescribed network-level and project-level performance requirements.
- Determine optimum network pavement performance based on prescribed availability of annual rehabilitation funding for the network.
- Allocate funding to different jurisdictions to achieve balancing of funding allocation, or pavement performance among GDOT Districts or State Congressional Districts.

The objective of this chapter is to describe the NEEDAS computer program developed as a part of this thesis. Section 8.1 presents an overview of this program. Section 8.2 describes the components of this program for acquiring the data for performing the analysis and saving the database and the analysis results. Section 8.3

describes the development of components for setting, and modifying various input parameters. Section 8.4 describes the components for performing the actual analysis. Section 8.5 describes the functions for viewing and reporting the results. The Online Help function and the user manual developed for this program are presented in Section 8.6.

8.1 Overview of NEEDAS Program

The NEEDAS program is a PC-based computer program developed to perform multi-year pavement rehabilitation needs analysis for the Georgia state highway network. Figure 8-1 is the main screen of the NEEDAS program. The menu bar of the NEEDAS program has eight commands (**File, View, Setting, Treatment, Run, Output, Tool**, and **Help**). The "Output" command has not been developed, although all the results that can be displayed on the computer screen by the "View" command can be printed or exported in an Excel format for further processing as described in Section 8.5. The commands include the following sub-menu:

- File
  - New Analysis
  - Open Previous Analysis
  - Save As
  - Exit
- View
  - State Route Distribution
  - GIS Visualization
  - Project Survey Information (Enable after Run Needs analysis has been performed)
  - Project-Level Needs analysis Results (same as above)
  - Statewide Results (same as above)
  - Results by GDOT Districts (same as above)
  - Results by Congressional Districts (same as above)
  - Results by Funding Periods (same as above)
  - Results by Treatment Methods (same as above)

- Setting
  - Set Analysis Years and Budget
  - Set Needs analysis Criteria
  - Set Pavement Performance Constraints
  - Set Annual Traffic Increase Rate
  - Set Annual Interest Rate
  - Select Pavement Distress Model
  - Select Pavement Deterioration Model
  - Select Treatment Priority Criteria
  - Set Ratio of Unit Costs between Interstate and State Highway
- Treatment
  - Update Treatment Performance Model
  - Update Default Treatment Criteria
  - Update Regular Treatment Criteria
  - Update Treatment Methods
- Run
  - Needs analysis
- Tool
  - Change Background
- Help
  - Online Help
  - About NEEDAS

A total of 39 different interfaces were created in the NEEDAS program to facilitate the performance of needs analysis. The various commands and the details of each component of this program are presented in the subsequent sections in this chapter.

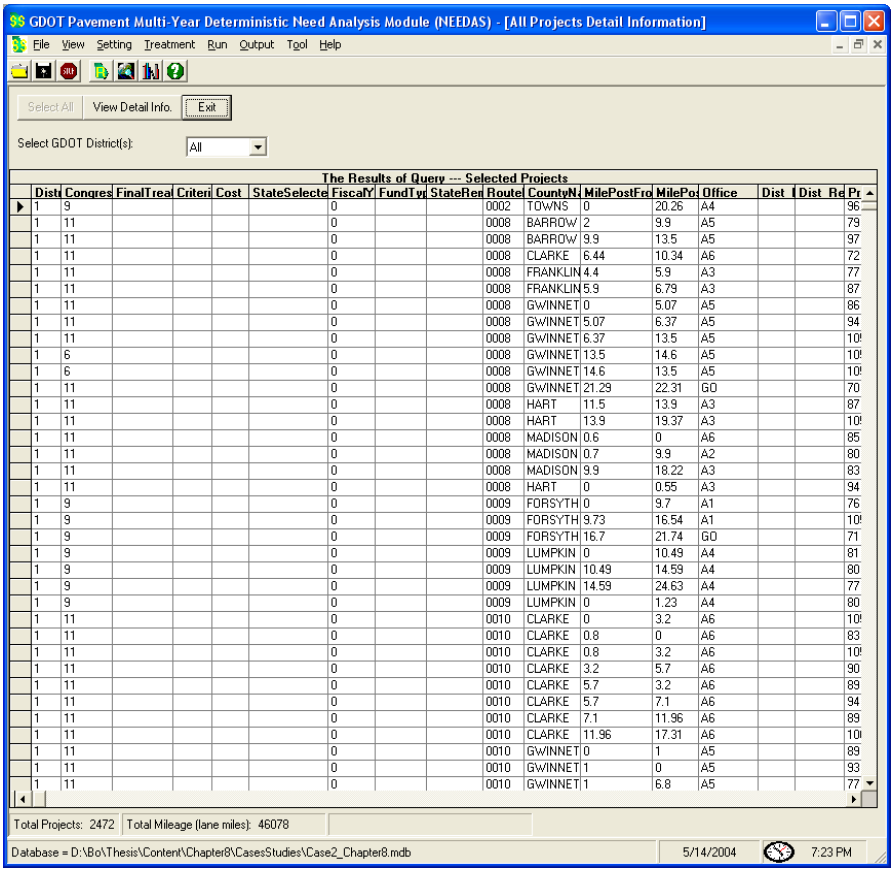


Figure 8 - 1 Main Screen of the NEEDAS

In addition to the needs identified in Chapter 4 for developing the multi-year rehabilitation needs analysis system for GDOT, the following design features were also incorporated to make the program more user friendly for ease of implementation of the program.

- **Simple But Effective Interface Design**. Efforts were devoted to make the interfaces simple and intuitive so that the user can easily perform the task with minimum training.

- **Effective Control of Input Parameters**. Performing the NEEDAS program requires the user to input many parameters. To reduce the efforts for entering such parameters, appropriate default values based on GDOT's current practices were set for various parameters in the program. Thus, the program can perform needs analysis based on the preset default values without requiring inputting essentially any parameters by the user. Of course, the user can modify any input parameters for conditions pertinent to a specific analysis. The preset default values for the parameters in the various interfaces also provide useful guides for the user to understand the meaning of the parameters and to reduce the errors in entering improper values. Furthermore, the program uses selection boxes for the user to select proper values for various parameters to minimize entering improper values. Also, the program has built-in error checking functions associated with various parameters to minimize improper or incorrect entering of the values. If an error is detected during the input, the program will pop up appropriate warning message to alert the user and provide suggestions for corrective actions.
- **Practical and Versatile Output Results**. Although the extensive results generated from the analysis can be exported in Excel format and thus allow the user to perform additional analyses and generate various reports using various Excel functions, this may take significant amount of user's effort and time and requiring the user to have sufficient knowledge in using Excel. Because of this, various bits of salient information from the

analysis cannot be viewed immediately at the end of an analysis. To overcome this deficiency, specific tables and graphs for displaying various salient information from the analysis are automatically generated by the program.

Figure 8-2 summarizes the general procedures for performing pavement rehabilitation needs analysis by this program. To run the program the user should (1) select a database, (2) set up the initial analysis parameters, and if necessary, modify the treatment criteria, (3) perform the analysis and (4) view various needs analysis results and output the results to Microsoft Excel sheet. The detailed information of developing and using these functions are presented in Section 8.2 to 8.5.

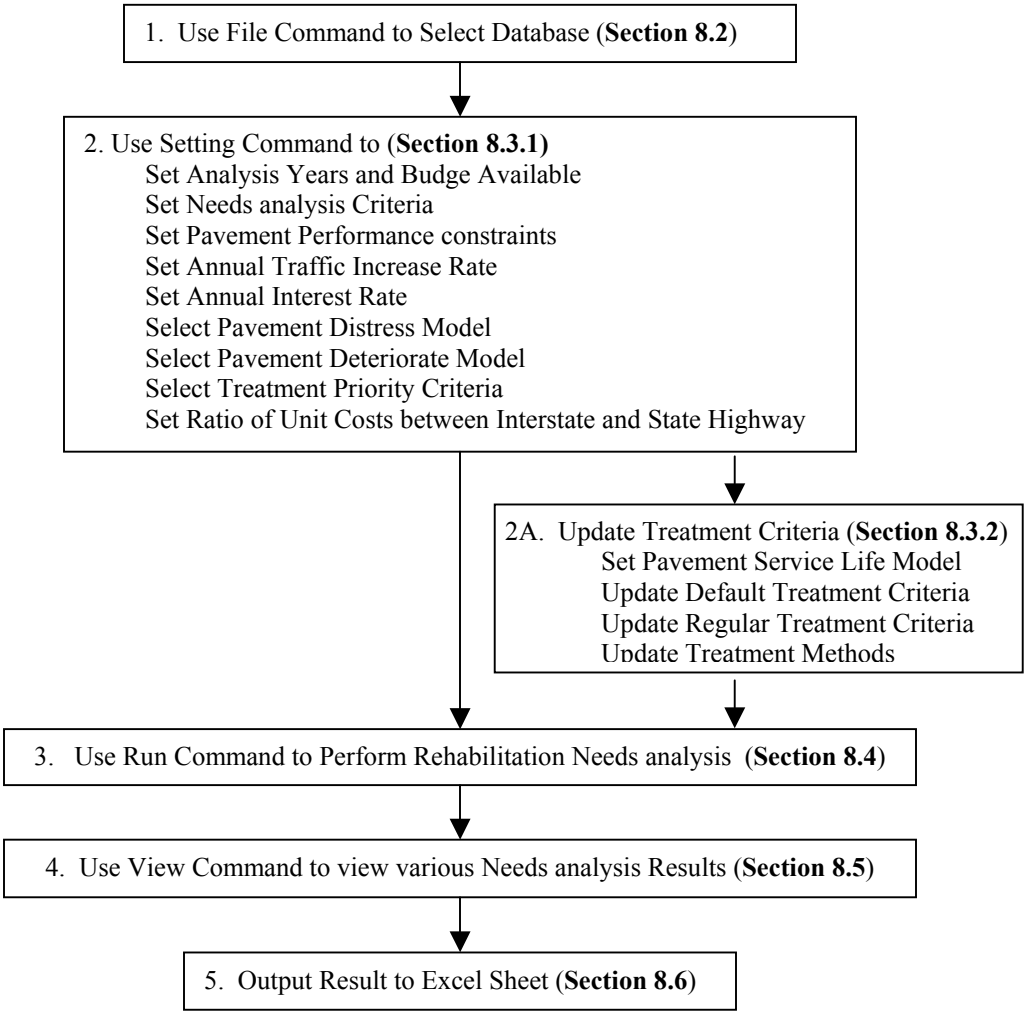


Figure 8 - 2 Procedures for Performing Pavement Rehabilitation Needs analysis

8.2 Launch NEEDAS Program and Open/Save Database

Figure 8.3 is the initial login form of the NEEDAS program. Security of accessing to the NEEDAS program and flexibility in selecting the database for analyses were two important considerations during the design of this form:

(1) **Security checking.** Once the NEEDAS program is opened, it allows the user to access and modify GDOT's COPACES database, including pavement condition survey data, the pavement rehabilitation treatment decision tree, cost estimation function, pavement performance forecasting function, etc. An unauthorized user can do great harm to the integrity of the COPACES database and other databases essential for developing GDOT's pavement management planning and programming functions. Therefore, proper security measures must be taken to prevent unauthorized personnel from gaining access to the NEEDAS program to guard against a possible security breach. The login form in Figure 8.3 requires the correct input of user name and password in order to use the NEEDAS program. The user name and password are to be set up and controlled strictly by GDOT Oracle Database Administrators.

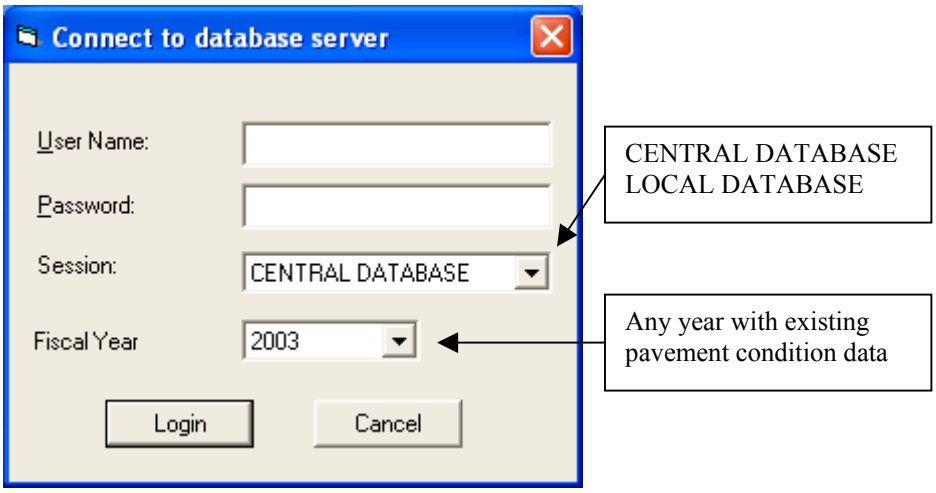


Figure 8 - 3 Login Form for NEEDAS System

(2) **Flexibility in selecting analysis database.** The NEEDAS program allows the user to select a database from CENTRAL DATABASE (the COPACES database) or from LOCAL DATABASE for performing a needs analysis.

(i) Select CENTRAL DATABASE from the *Session* selection box along with a specific year from the *Fiscal Year* selection box to download a specified year's pavement condition evaluation survey database from the COPACES database to the local computer via the GDOT Intranet. The user can then use the dataset to perform the analysis. The dataset downloaded from the COPACES database becomes the current dataset and is saved in a local folder.

Depending on the computer speed, it may take up to 10 minutes to download a dataset from the Central Database. Or,

(ii) Select LOCAL DATABASE from the *Session* selection box to use a dataset already stored in the local computer. When selecting the "LOCAL DATABASE" in Figure 8-3, a form will pop up allowing the user to access to the folder in the local computer where a specific dataset file is stored. Opening the local dataset allows the user to continue working on the analysis based on a dataset previously saved in the local computer. The user can then continue the unfinished analysis or change certain parameters and rerun the analysis. Opening a dataset from a local computer is much faster than downloading a dataset from the COPACES database.

When the user chooses to open the CENTRAL DATABASE, normally one would only select to open the current year dataset from the COPACES database to perform the future years' rehabilitation needs analysis. Indeed, the GDOT COPACES database administrators could limit the user to opening only the current year dataset from the ORACLE database. The privilege to open previous years' datasets would be on a needed base. By selecting a previous fiscal year's dataset and performing the needs analysis, the user can use the results generated from the NEEDAS program and compare them with the actual pavement rehabilitation practice for the same years for comparison and validation purposes. For example, if the user selects the dataset from fiscal year 1998 and performs a 5-year period needs analysis, the NEEDAS program will generate the rehabilitation

plans for fiscal years from 1999 to 2004. Then the user can compare the analysis results with the actual rehabilitation plans used by GDOT in these years. This is one of the recommendations suggested in this thesis (see Chapter 10) for validating and calibrating this program to ensure that the program can accurately reflect the practices used by GDOT.

After the program has started, and the NEEDAS main form as shown in Figure 8-1 appears, the user can use the sub-menu "New Analysis" from the **File** command to download an additional new dataset from the COPACES database or use the sub-menu "Open Previous Analysis" to open the dataset stored in a local folder. However, the program can have only one active dataset. When a new dataset, whether it is a new dataset extracted from the central database or a dataset stored in a local folder is opened, the program will automatically close and save the current dataset in a local folder. The "Save As" sub-menu from the **File** command allows the user to save the active dataset with a proper filename in a folder in the local computer.

The following error-checking functions are performed to ensure data integrity and correctness:

(1) To select a fiscal year to download data from the COPACES database, the program will check whether the data in the selected year is available and, also, whether all GDOT Districts have submitted their pavement condition survey data in that year to the central database. If either of these conditions is not satisfied, a warning message will pop up, and the specified dataset cannot be downloaded.

(2) To select a local database, the local database must be in the same NEEDAS program format. Otherwise, the database cannot be opened.

8.3 Set and Select Input Parameters

Chapter 4 identifies many desired features for the NEEDAS program, such as flexibility for modifying existing pavement performance models, pavement rehabilitation treatment methods, geographic boundaries of GDOT Districts and State Congressional Districts, compatibility with current GDOT practices, and scalability for future improvements, etc. These desirable features have been incorporated into the course of developing the various components of this program, particularly in the ability to update various input parameters and incorporate new models. Therefore, during the design of the interfaces for setting the needs analysis parameters, two important aspects are considered:

1. Flexibility to set values for different parameters. The interfaces have been designed to allow the user to set values for different parameters so that what-if analyses can be performed to compare the results under different scenarios.
2. Scalability to extend current models and treatment decision trees. The ability to incorporate new improvements must be considered during the interface design so that modifications or adding new models to the various settings can be easily incorporated in the program without requiring significant reprogramming efforts.

8.3.1 Set Needs analysis Parameters

The **Set** Command on the menu bar, shown in Figure 8-1, consists of the following nine needs analysis settings:

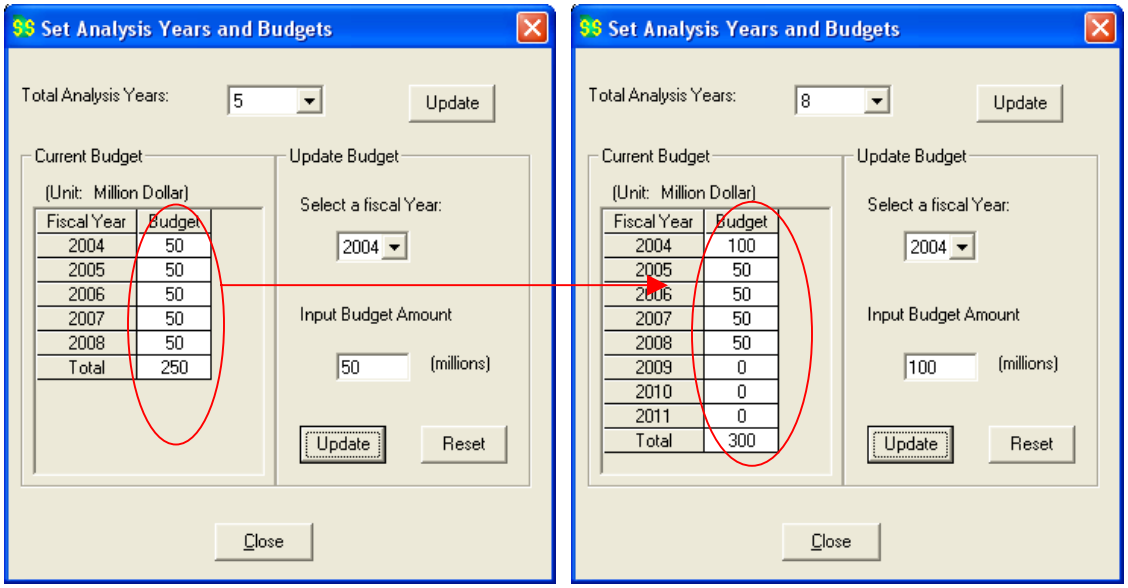
- Set Analysis Years and Budgets
- Set Needs analysis Criteria
- Set Pavement Performance Constraints
- Set Annual Traffic Increase Rate
- Set Annual Interest Rate
- Select Pavement Distress Model
- Select Project-level Pavement Performance Rating Forecast Model
- Select Treatment Priority Criteria
- Set Ratio of Unit Costs between Interstate and State Highway

The design and use of these parameters, as well as proper considerations for achieving flexibility and scalability during the design of the settings and the interfaces are as follows:

- **Set Analysis Years and Budget**: Figure 8-4(A) is the interface for setting analysis years and budgets. This interface has the flexibility to allow the user to make direct changes of analysis years and the annual budget in each year. The features shown on this interface are described as follows:
  - <u>Change Analysis Years</u>: In Figure 8-4(A), the default value for "Total Analysis Years" is 5 years and the default years start from one year after the

current year (the year the dataset is selected for the analysis), which is consistent with the current GDOT practice. The interface allows the user to change the total analysis years by selecting the years from the *Total Analysis Years* selection box and then clicking the **Update** button to effect the selection. This action will cause the table on the *Current Budget* pane to change in accordance to the total analysis years selected.

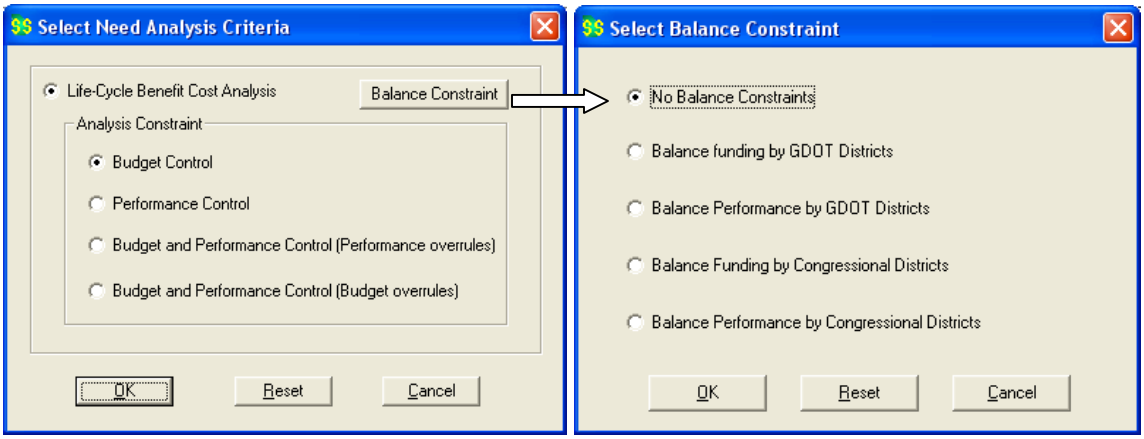
- Enter/Change Annual Budget: The *Current Budget* pane, shown on the left side of the form, displays the current or default annual budget for each year. The user can change the budget in any year by first selecting the year the budget is to be modified and then enter the revised amount on the *Update Budget* pane on the right side of the form. This updated budget for the selected year will be displayed on the table on the *Current Budget* pane immediately. For example, Figure 8-4(B) shows that the total analysis year has been changed from 5 to 8, and the table on *Current Year* pan has automatically added year 2009, 2010, and 2011 with zero budget for the user to enter the appropriate amount. Figure 8-4(B) also shows that the budget in 2004 has been modified from 50 to 100.



(A) (B)

Figure 8 - 4 Set Analysis Years and Budget Form

- **Set Needs Analysis Criteria:** As described in Chapter 6, Section 6.3, the network needs analysis can perform 4 types of analyses. Figure 8-5 (A) is the interface for the user to select an analysis from these 4 types of analyses: "Budget Control," "Performance Control," "Budget and Performance Control (Performance overrules)," and "Budget and Performance Control (Budget overrules)," shown on this interface corresponding to Type I, II, III, and IV analyses presented in Section 6.3. Since "Balance Constraint" is also one of the important factors during the needs analysis, clicking on the "Balance Constraint" button in Figure 8-5 (A) brings up the "Balance Constraint" interface, as shown in Figure 8-5 (B). The user can select any one of the five balance constraints on this interface.



(A) (B)

Figure 8 - 5 Set Needs analysis Criteria Form

- **Set Pavement Performance Constraints:** As pointed out in Chapter 6, two types of pavement performance constraints can be applied: annual statewide pavement performance constraint and individual pavement project rating constraint. Figure 8-6 is the interface for setting the minimum level of pavement performance at the network level and at the project level after the implementation of the rehabilitation plans. The individual project-level rating constraint is optional. The default setting for individual project rating is 60 but is not activated. It is important to check this box to activate the individual project minimum rating constraint and then enter an appropriate rating value if it is different from the default value, otherwise the minimum rating constraint for individual projects appears in the selecting box will not be activated. The program requires that the individual pavement project rating must be an integer number between 0 and 100. A selection box with integer numbers from 0 to

100 was created for entering the minimum individual project rating constraint to ensure that only a legitimate value can be entered.

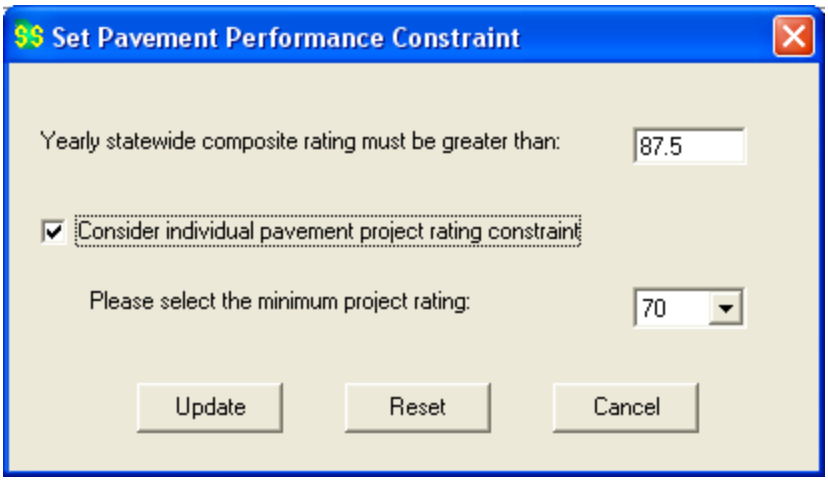


Figure 8 - 6 Set Pavement Performance Constraint Form

- **Set Annual Traffic Increasing Rate and Set Annual Interest Rate:** The interfaces for setting annual traffic increase rate and annual interest rate are similar because both of them are numbers, as shown in Figure 8-7 and Figure 8-8. An annual traffic increasing rate is used to allow for future traffic growth in the network. In the current version, a linear model is used for calculating future AADT growth. In the future, other models can be incorporated into the program. The object-oriented programming used in the program allows the other models to be incorporated in the program. In the NEEDAS program, the

computation of life-cycle costs incorporates annual interest rate, and, therefore, it also allows the user to enter an annual interest rate, as shown in Figure 8-8.

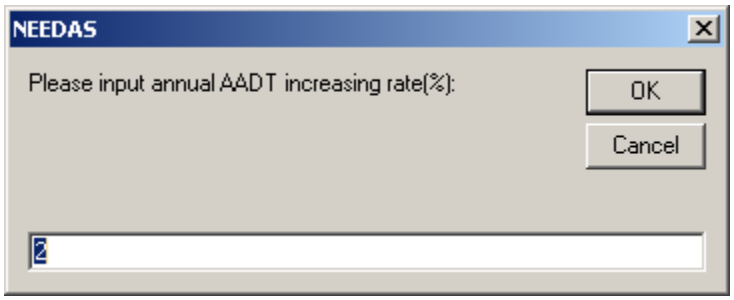


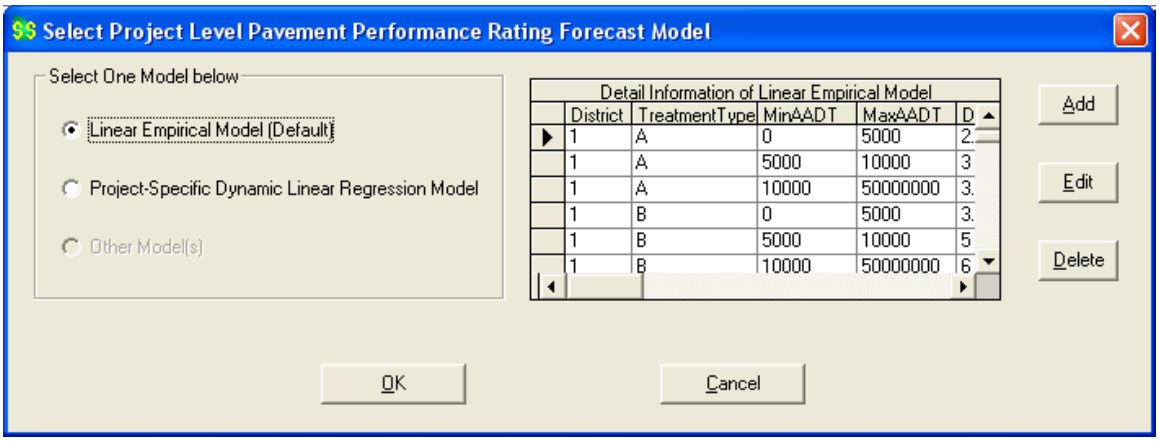
Figure 8 - 7 Set Annual Traffic Increase Rate Form

Figure 8 - 8 Set Annual Interest Rate Form

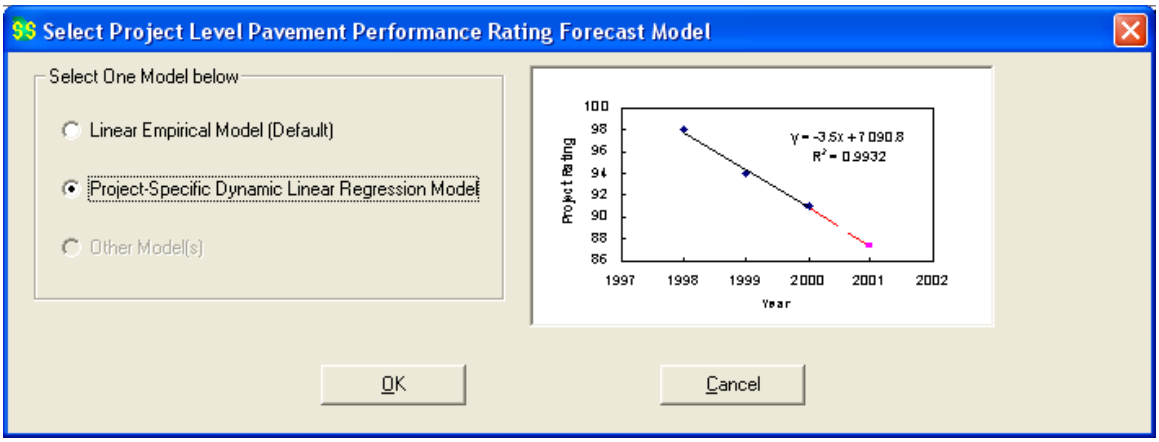
- **Select Project-level Pavement Performance Rating Forecast Model:** As presented in Chapter 5, an appropriate rehabilitation treatment method of a pavement project is determined based on the performance rating, the extents and severities of various types of pavement distresses expresses in terms of distress deduct values for the pavement, and the traffic volume expressed in

terms of the AADT. This "Select Project-level Pavement Performance Rating Forecast Model" sub-menu allows the user to select a model from the two models shown in Figure 8-9 to forecast future year's pavement ratings for projects in the current dataset if no treatment is to be applied on them. These two models are Linear Empirical Model and Project-specific Dynamic Linear Regression Model. The model for forecasting pavement rating and deterioration rate after a rehabilitation treatment has been applied on a pavement project will be presented in Section 8.5.2.

When the "Linear Empirical Model" is selected, a DBGrid summarizing the various deterioration rates and the corresponding parameters used for the currently linear empirical model appears on the right side of this form, as shown in Figure 8-9(A). Similar to that shown in Table 5-2, different deterioration rates have been assigned based on (i) Pavement Type (A for hot mix asphalt concrete surface, B for chip seal, and S for slurry seal), (ii) minimum and maximum AADT (less than 5,000, 5,000 to 10,000, and greater than 10,000) and (iii) GDOT Districts (1 to 7). The **Add**, **Edit**, and **Delete** buttons on the right of the DBGrid allow users to make changes of the criteria.



(A)



(B)

Figure 8 - 9 Select Pavement Performance Model

When the "Project Specific Dynamic Linear Regression Model" is selected, a chart displaying a linear regression line on it appears on the right side of this form, as shown in Figure 8-9(B), indicating regression analysis is utilized in the model. The project-specific dynamic linear regression model utilizes the historical pavement performance ratings of individual projects in the COPACES database to develop a linear regression equation and uses that to

forecast the next year's performance rating for the project. One of the advantages of this approach is that this model automatically incorporates the most recently available performance rating data for a project as they are available from the pavement condition survey toward developing the regression equation.

In order for the NEEDAS system to be adaptable and flexible to incorporate new performance rating forecast models in the future, the source code written for each model was following the object-oriented programming concept, illustrated in Figure 8-10, so that each model would use the same input data and data format (pavement condition data, traffic data, etc.), and the results generated from each model will have the same data and data format ready to be used for performing the analysis for the program. In this way, new models can be viewed as a "Black Box" and the computation process for each new model, from the input data to the output data, can be written into a "Black Box" ready to be plugged into the program to perform the analysis.

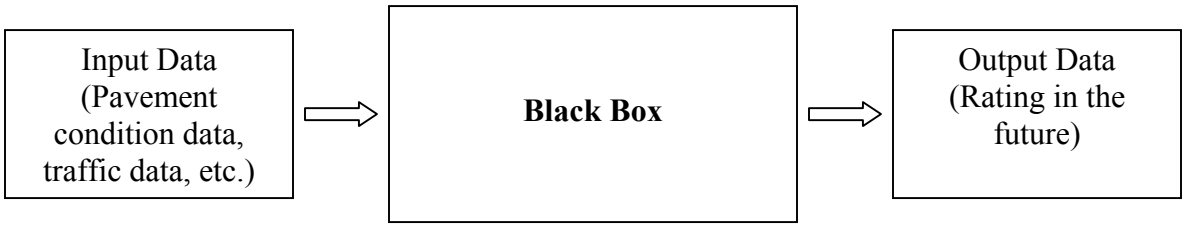


Figure 8 - 10 Illustration of Incorporation New Models in the Future

- **Select Pavement Distress Model:** The difficulty of forecasting the extents and severities of various types of pavement distresses and the corresponding distress deduct values directly from the pavement's historical distress data due to the inherent variability of distress deduct values was discussed in Chapter 5. Also presented in Chapter 5 (Section 5.2.3) are three different models that were developed to forecast a project's future distress deduct values for different pavement distress types and severity levels. As shown in Figure 8-11, all these three models have been implemented in this program and the user can select any one of the models for predicting distress deduct values of a pavement. Since the first and the third models require global distress deduct values prediction model, as described in Table 5-4, a "View" button is provided following each of these two models, which allows the user to view and output the predicted global distress deduct values versus rating information to a Microsoft Excel file. Clicking the "View" button, shown in Figure 8-11 and Figure 8-12, shows the estimated deduct values for pavements with different performance ratings. The specific values in Figure 8-12 can be modified by the COPACES database administrator.

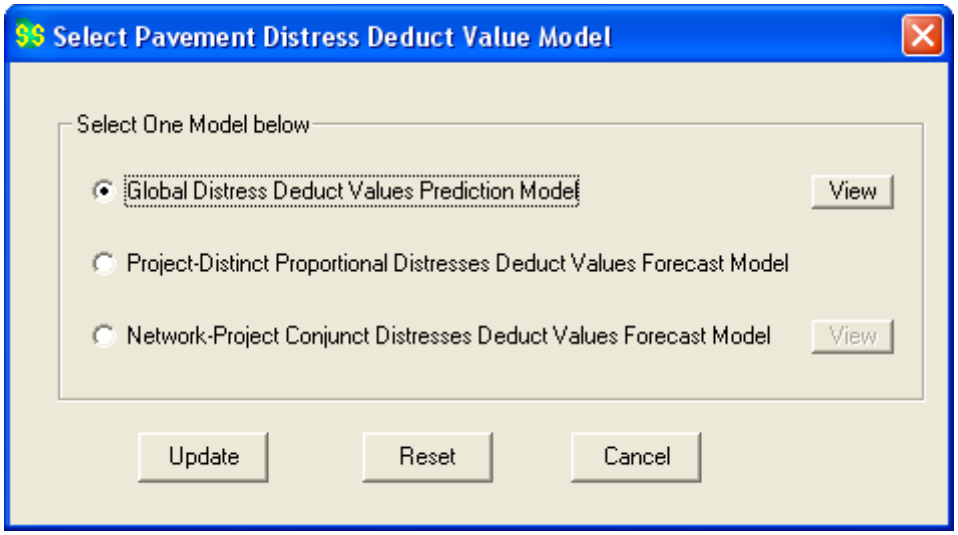
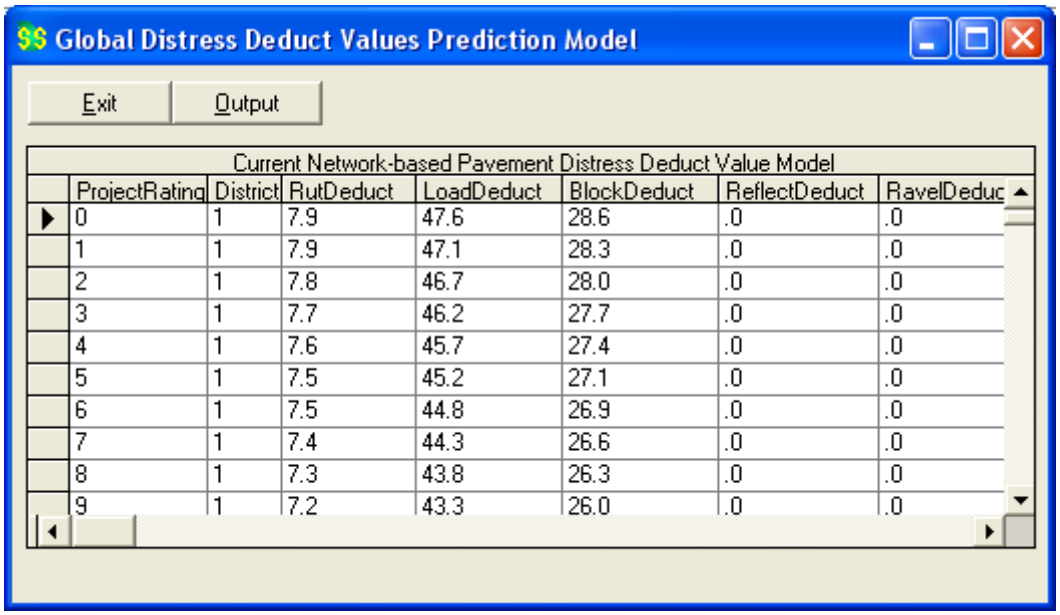


Figure 8 - 11 Select Pavement Distress Model



Current Network-based Pavement Distress Deduct Value Model

ProjectRating	District	RutDeduct	LoadDeduct	BlockDeduct	ReflectDeduct	RavelDeduc
0	1	7.9	47.6	28.6	.0	.0
1	1	7.9	47.1	28.3	.0	.0
2	1	7.8	46.7	28.0	.0	.0
3	1	7.7	46.2	27.7	.0	.0
4	1	7.6	45.7	27.4	.0	.0
5	1	7.5	45.2	27.1	.0	.0
6	1	7.5	44.8	26.9	.0	.0
7	1	7.4	44.3	26.6	.0	.0
8	1	7.3	43.8	26.3	.0	.0
9	1	7.2	43.3	26.0	.0	.0

Figure 8 - 12 Global Distress Deduct Values Prediction Model

Figure 8 - 13 Interface of Selecting Treatment Priority Criteria

- **Select Treatment Priority Criteria:** As mentioned in Chapter 5, Section 5.3, a treatment priority criterion should be selected in the NEEDAS program to determine the final treatment method when a project has more than one candidate rehabilitation treatment method. Clicking "Select Treatment Priority Criteria" from the **Set** menu brings up Figure 8-13. The user can select any one of the four criteria on the interface.

- **Set Ratio of Unit Costs between Interstate and State Highway**: When the COPACES database was constructed, the unit costs of maintaining state highways and Interstate highways were considered the same to simplify the development of treatment cost estimation function. However, in reality, the unit cost for resurfacing an Interstate highway is typically higher than a state route

because of the additional costs of vegetation removal, stripping, guardrailing, and others performed on Interstate highways. Therefore, for a rehabilitation treatment method, different unit costs should be recognized when applying to Interstate highways and state highways. Figure 8-14 allows the user to set the ratio of unit costs for treatment methods applied between Interstate and state highways. A default value of 1.35 is provided based on GDOT's experience.

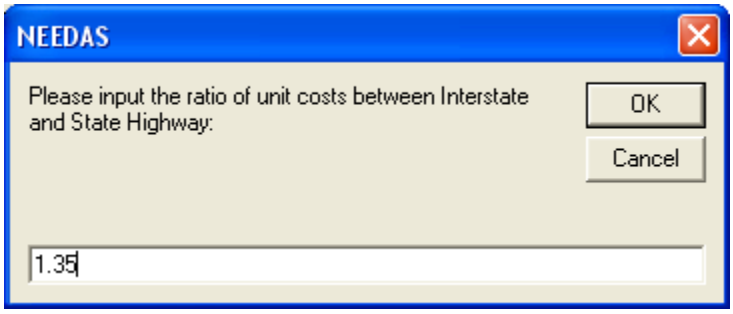


Figure 8 - 14 Set Ratios of Unit Costs between Interstate and State Highway

8.3.2 Update Treatment Criteria

Another special feature of the NEEDAS program is that the treatment criteria in the system can be readily updated by the user. This is very important as pavement rehabilitation treatment technologies are under constant development and improvement. The **Treatment** Command on the menu bar, shown in Figure 8-1, contains 4 sub-menus,

allowing the user to modify the treatment criteria under each of the sub-menu. At the present time, any user who can access to the program can make modifications of these criteria. The authority to modify these criteria can be easily restricted to only those at higher security access level. The 4 sub-menus are as follows:

- Update Treatment Performance Model
- Update Default Treatment Criteria
- Update Regular Treatment Criteria
- Update Treatment Methods

- **Update Treatment Performance Model (also called Pavement Service Life Model)**: The Treatment Performance Model determines the pavement rehabilitation ratings and deterioration rates after a project has been treated by a treatment method, as discussed in Chapter 5, Section 5.2.2. From Figure 8.1, the user selects this sub-menu from the **Treatment** command, and Figure 8-15 appears. To modify a performance criterion of a specific pavement category (pavement surface type and different AADT), the user first selects a row in Figure 8-15 corresponding to the treatment method and traffic condition, and, then, clicks the "Edit" button; this allows the user to change the service life of the selected pavement category. The user then clicks the "Refresh" button to effect the change.

Pavement Service Life Model

Add | Edit | Delete | Refresh | Output | Exit

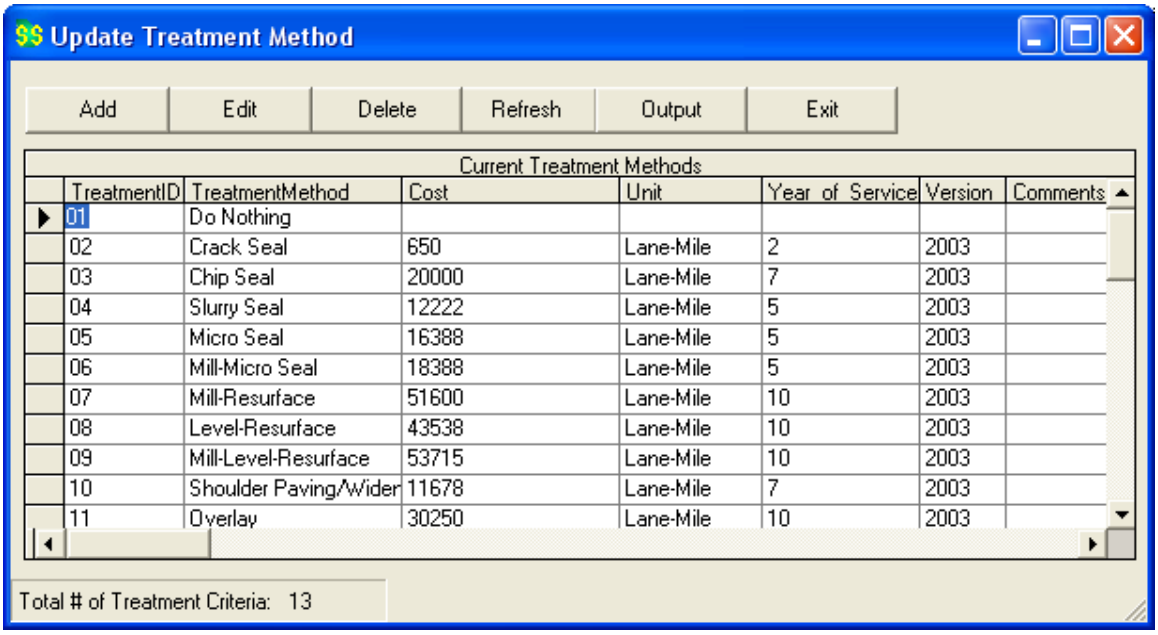
Current Pavement Treatment Performance Model

TreatmentMethod	TreatmentID	AADTMin	AADTMax	MaxRating	MinRating	LifeYear
Chip Seal	03	0	5000	100	70	9
Chip Seal	03	5000	10000	100	70	6
Chip Seal	03	10000	50000000	100	70	5
Slurry Seal	04	0	5000	90	70	7
Slurry Seal	04	5000	10000	90	70	6
Slurry Seal	04	10000	50000000	90	70	5
Micro Seal	05	0	5000	100	70	8
Micro Seal	05	5000	10000	100	70	7
Micro Seal	05	10000	50000000	100	70	6
Mill-Micro Seal	06	0	5000	90	70	6
Mill-Micro Seal	06	5000	10000	90	70	5

Total # of Treatment Performance Models: 30

Figure 8 - 15 Pavement Service Life Model

- **Update Treatment Decision Tree.** Updating the treatment decision tree is not easy, as it involves both the interface design and the database design. The following three functions combined together make it possible to update treatment decision tree in the NEEDAS program:
  - *Update Treatment Methods*. The first step to modify a treatment decision tree is to update treatment methods. Clicking the sub-menu, "Update Treatment Methods," from the **Treatment** command brings up Figure 8-16. It lists all available pavement rehabilitation treatment methods and the unit costs associated with each treatment method. The user can make changes on the information shown in this form using **Add**, **Edit**, and **Delete** buttons. The "TreatmentID" field on the DBGrid identifies different treatment methods uniquely. The data, shown in Figure 8-16, is saved in the "tblTreatmentMethod" table in the COPACES database.



TreatmentID	TreatmentMethod	Cost	Unit	Year of Service	Version	Comments
01	Do Nothing					
02	Crack Seal	650	Lane-Mile	2	2003	
03	Chip Seal	20000	Lane-Mile	7	2003	
04	Slurry Seal	12222	Lane-Mile	5	2003	
05	Micro Seal	16388	Lane-Mile	5	2003	
06	Mill-Micro Seal	18388	Lane-Mile	5	2003	
07	Mill-Resurface	51600	Lane-Mile	10	2003	
08	Level-Resurface	43538	Lane-Mile	10	2003	
09	Mill-Level-Resurface	53715	Lane-Mile	10	2003	
10	Shoulder Paving/Wider	11678	Lane-Mile	7	2003	
11	Overlay	30250	Lane-Mile	10	2003	

Figure 8 - 16 Update Treatment Method Form

– *Update Regular Treatment Criteria*. The previous step shows how to update treatment methods. It is important to point out that certain regular treatment criteria have to be established before any treatment method listed in Figure 8-16 can be selected for a pavement project. Two tables, tblTreatmentCriteria1 and tblTreatmentCriteria2, combined together, define the regular treatment criteria--that is, under what conditions a treatment method can be used for a pavement project. The Table "tblTreatmentCriteria1" (Figure 8-17(A)) lists the treatment requirements for different combinations of ratings and traffic conditions (AADT), and the Table "tblTreatmentCriteria2" (Figure 8-17(C)) lists the treatment requirement for different distresses conditions. Figure 8-17 (B) and (D)

show how to modify these two tables. The solid lines in Figure 8-17 illustrate the procedures to activate these functions. Figure 8-17(A) appears when the user selects the "Update Regular Treatment Criteria" sub menu. Then, selecting a criterion in Figure 8-17(A) and clicking the "Edit" button in Figure 8-17(A) brings Figure 8-17(B). Figure 8-17(C) presents the detailed distress requirements corresponding to the regular treatment criterion selected in Figure 8-17(B). To modify the distress requirements listed in Figure 8-17(C), the user clicks the **Add** or **Edit** button on this figure and Figure 8-17(D) appears. The user can then make changes to the various deduct values for different distresses appear on this interface. To understand how to update regular treatment criteria, one needs to understand how the NEEDAS program determines a treatment method for a pavement project. For a given project, the NEEDAS program first identifies all the "TreatmentCriteriaID"s in Figure 8-17(A) that satisfy the project rating and AADT for the specific project. Each TreatmentCriteriaID corresponds to one row in the treatment decision tree shown in Figure 5-6. Thus, it is possible that more than one TreatmentCriteriaIDs are identified and each TreatmentCriteriaID has an associated TreatmentID (the sixth field in Figure 8-17(A)). Then, the NEEDAS program checks the distresses requirements (shown in Figure 8-17(C)) for each "TreatmentCriteriID." All rows in Figure 8-17(C) combined together form the distresses conditions for a specific TreatmentCriteriaID. Only when all the requirements, pavement performance rating, AADT, and distress deduct values in Figure 8-17 (A)

and (C) are satisfied will the “TreatmentID” corresponding to the “TreatmentCriteriaID” in Figure 8-17(A) be selected as the treatment method. For example, according to the three rows in Figure 8-17(C), the three distress requirements for “TreatmentCriteriaID”= 4 are: (1) Rutting (RU) + Reflective Cracking (RC) > 20; (2) RU<5; and (3) RC<15. Therefore, by modifying these two tables, the user can modify the existing treatment decision tree and introduce new treatment criteria. According to Figure 8-17(D), any combination of current distress conditions can be introduced into the treatment decision tree. No coding changes are needed to update or introduce a new treatment decision tree.

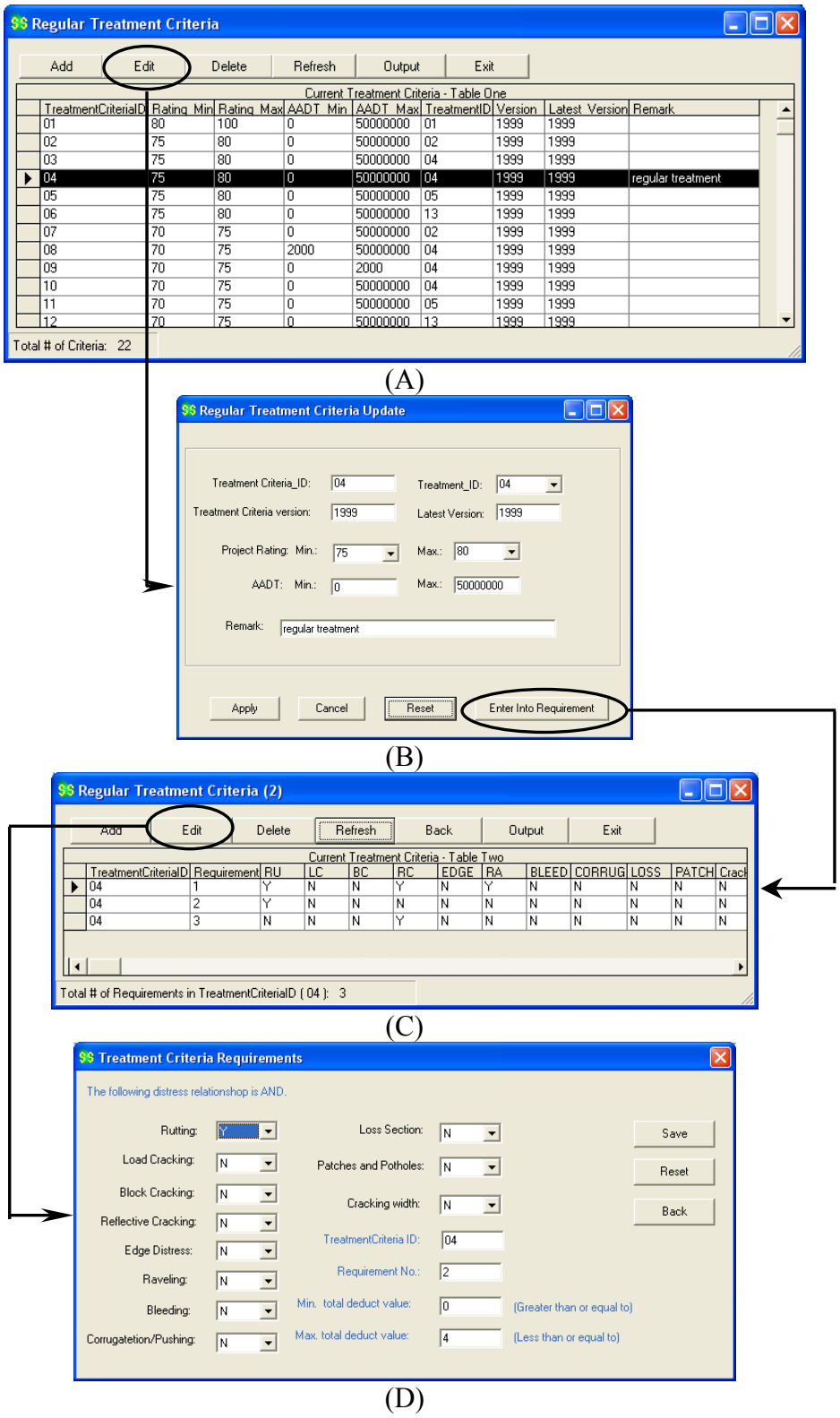
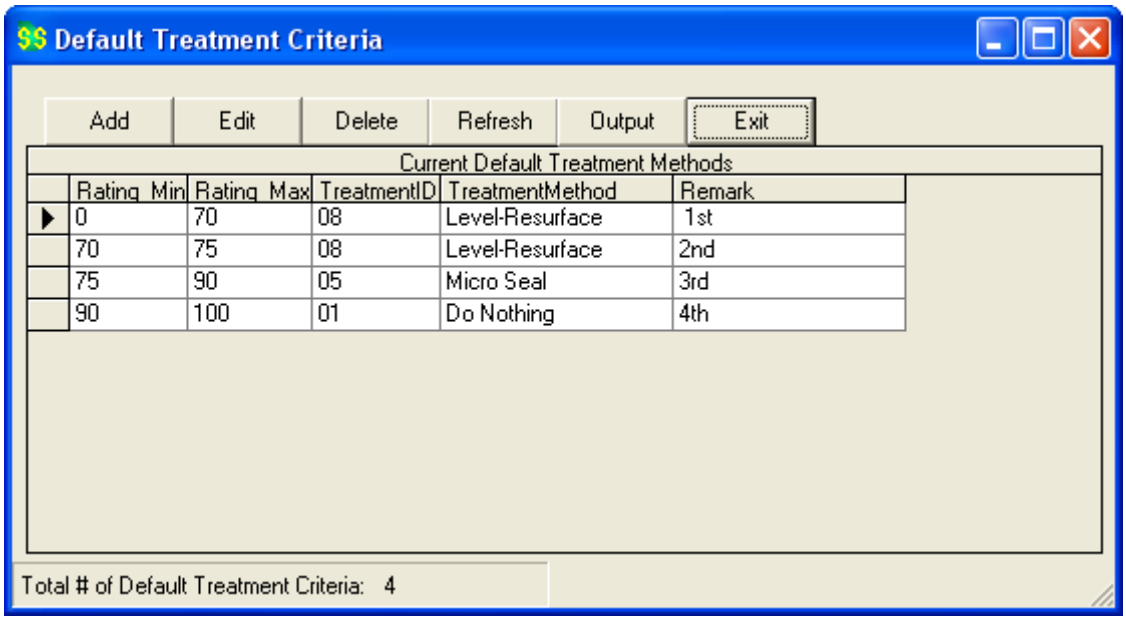


Figure 8 - 17 Update Regular Treatment Criteria Form

– *Update Default Treatment Criteria*. The default rehabilitation Treatment Criteria are developed to supplement the Regular rehabilitation Treatment Criteria to ensure that at least one treatment method can be assigned to a pavement project based on the project rating. Figure 8-18 appears by clicking the sub menu, "Update Default Treatment," from the **Treatment** Command. The NEEDAS program enforces the requirement that a default treatment method must be assigned for any rating from 0 to 100. Otherwise, certain error messages will pop up until any single rating value from 0 to 100 is covered by a unique default treatment method.



Rating_Min	Rating_Max	TreatmentID	TreatmentMethod	Remark
0	70	08	Level-Resurface	1st
70	75	08	Level-Resurface	2nd
75	90	05	Micro Seal	3rd
90	100	01	Do Nothing	4th

Figure 8 - 18 Default Treatment Criteria Form

8.4 Perform Needs Analysis

Select the **Run** command on the menu bar or the **Needs analysis** command on the toolbar (Figure 8-1) and the system will perform the rehabilitation needs analysis based on the various Set/Selection functions enacted as described in Section 8.3. Before committing to run the system, the user should check all the settings described in the previous sections to ensure that they are properly selected and that all the parameters are correctly entered.

The following example was created to perform the needs analysis program so that the results generated from the analysis can be used to describe and discuss the different features and effects more realistically due to the various settings used in this section and in the following sections.

- Dataset used: Year 2003 GDOT COPACES dataset
- Analysis Years and Budget: 5 years, $100 million dollars each year
- Needs Analysis Criteria: Life-cycle Cost Effectiveness Analysis – Performance Control
- Pavement Performance Constraints:

  Yearly Statewide Composite Rating ≥ 87.5

  Consider Individual Project Rating constraint: enables and minimum=70
- Balance Constraint: No balance constraint
- Annual Traffic Increase Rate: 2%
- Annual Interest Rate: 5%
- Pavement Distress Model: Global Distress Deduct Value Prediction Model

- Pavement Deterioration Model: Linear Empirical Model
- Treatment Priority Criteria: Select Longer performance

The following salient characteristics of Year 2003 Dataset should be pointed out here so that the results from the needs analysis can be assessed in a proper prospective.

- There were 2,472 projects surveyed in Year 2003.
- The total center-lane miles for asphalt pavements for the State highway network was 18,000 miles
- In the Year 2003 dataset a total of 5,020.12 center-lane miles was not surveyed, representing 24.8% of the total center-lane miles in the network, and, therefore, these pavement projects were not included in the year 2003 dataset.
- There were 858 center-lane miles of concrete pavements in the State highway network. Concrete pavement projects were not included in the dataset.
- The Statewide pavement composite rating was 87.92.

In Chapters 5 and 6, much has been discussed about the detailed models and functions associated with the Project-Level Analysis Module and the Network-Level Analysis Module. The following describes how these models and functions are integrated together dynamically to perform the analysis and generate the various results when the program receives the **Run** command from the user.

Step 1: A "tblNeedAnalysisResults" Table, as shown in Table 8-1, is generated, which stores project-level results in each future fiscal year. The "ProjectID" field in Table 8-1 is used to link with pavement survey data so that the project spatial location information does not need to be stored in this table. In the meantime, all the settings selected for this example are saved in a "tblSetting" Table, as shown in Table 8-2. This table has two fields: "ID" and "Value." "ID" indicates the types of parameters and "Value" indicates the values for the parameters selected by the user. For example, "ID" = 5 means this record is to set pavement distress model, and "Value" = 0 indicates that the "Global Distress Deduct Value Prediction Model" is selected for this example. Notice that there is a gap between "ID"=18 and "ID"=30. This gap is left on purpose so it can be used for future expansion to incorporate any new functions or models.

Table 8 - 1 Fields in tblNeedAnalysisResults Table (Project-Level Results)

Field Name	Description
ProjectID	A unique ID that is used to identify different projects uniquely.
FutureYear	Fiscal Year which the information of the record is related to.
ForecastRating	Forecasted project rating in the fiscal year
RehabRating	Rehabilitation rating if the treatment in the fiscal year is applied
DeteriorationRate	Deterioration rate of project rating since the fiscal year
TreatmentMethod	Recommended treatment method based on forecasted pavement condition and traffic information
Cost	Cost corresponding to the recommended treatment method
B_C_Ratio	Cost effectiveness ratio of the project in the fiscal year
ProjectLength	Total lane miles of the project
AADT	AADT in the fiscal year
YearlyPrior	Yearly priority index of the project
Treat	Whether the project is going to be treated or not
Criteria	What criterion is used to determine the treatment method
MinorTreatment	Whether minor treatment can be applied or not.

Table 8 - 2 Values in tblSetting Table

ID	Value	Description
1	2003	Survey year that will be used to pull out pavement condition survey data
2	5	Total No. of years to be analyzed
3	7	Total No. of GDOT Districts
4	11	Total No. of Congressional Districts
5	1	Indicator of Pavement Distress Model
6	0	Indicator of Project-level Pavement Performance Rating Forecast Model
7	3	Criteria to determine final treatment method
8	1	Whether the analysis has been performed or not
9	2	Type of Needs Analysis
10	95	Minimum percentage of Budget allowed (%)
11	105	Maximum percentage of Budget allowed (%)
12	5	Interest Rate per year (%)
13	87.5	Yearly allowable statewide composite rating
14	1	Indicator of whether individual project rating constraint is applied or not
15	70	Minimum allowable Individual Project Rating
16	2	Yearly AADT Increasing rate
17	0	Balance Constraint
18	1.35	Ratio of unit costs between Interstate Highway and State Highway
31	100	Estimated Budget of 1st Future Year (million dollars)
32	100	Estimated Budget of 2nd Future Year (million dollars)
33	100	Estimated Budget of 3rd Future Year (million dollars)
34	100	Estimated Budget of 4th Future Year (million dollars)
35	100	Estimated Budget of 5th Future Year (million dollars)

Step 2: Initialize current project information. The initial project information from the historical pavement condition survey data is retrieved from the appropriate sources. The data retrieved include initial project length (saved in "ProjectLenght" listed in Table 8-1), pavement rating (saved in the field of "ForecastRating" with Fiscal Year = current year, 2003 in this example), deterioration rate determined by selected pavement performance model (saved in the field of "DeteriorationRate" with Fiscal Year =2003),

traffic condition (saved in "AADT") and initial deduct values of various distresses. The information of various distress deduct values is saved in an array instead of a database file to reduce computation time and reduce database size.

Step 3: Once initial project information is retrieved, the program starts to perform the yearly prioritization and project selection process beginning in year one (year 2004, Year i = 1) following the procedures described briefly below:

a. First, assume no treatments are applied to any project and calculate the forecasted ratings and deduct values of various distresses and other parameters based on the information in the year 2003 dataset and store the forecasted values of rating ("ForecastRating"), deterioration rate ("DeteriorationRate"), and AADT ("AADT") for each project in the corresponding field in Table 8-1 with the fiscal year =1. The program also calculates the corresponding network-level composite ratings, including statewide, GDOT District-level and State Congressional District-Level composite ratings. The deduct values of various distresses of each project and the network-level composite ratings are saved in variables instead of database file to speed up the needs analysis process.

b. Based on the forecasted rating and distress deduct values and AADT for each project obtained in (a) above, determine rehabilitation treatment

methods, costs and performance rating after treatment for each project. The value of "TreatmentMethod," "Criteria," "Cost," and "RehabRating" are determined and saved in the database table shown in Table 8-1.

c. Calculate the cost effectiveness ratio based on the costs and the rating after the treatment for each project. The results of cost effectiveness ratios for all the projects are saved in the "B_C_Ratio" field in Table 8-1.

d. Determine yearly priority index for each project based on the cost effectiveness ratio, project rating, and AADT, and save the results in the "YearlyPrior" field.

e. Set the value of "Treat" field equals to "No" first (Not-to-be-treated), and then add projects to the To-be-treated Projects list one-by-one starting from the project having the highest priority index until network constraints are satisfied or no projects are left in the Not-to-be-treated Projects list using the algorithms presented in Chapter 6, Section 6.4. This is assuming no balancing constraint is set as the case in this example. Otherwise, a different algorithm will be used to select projects from the Not-to-be-treated Projects list in order to satisfy the balancing constraint.

f. Each time a project is added, the program will do the following:

(1) Change the value of the "Treat" field from "No" to "YES."

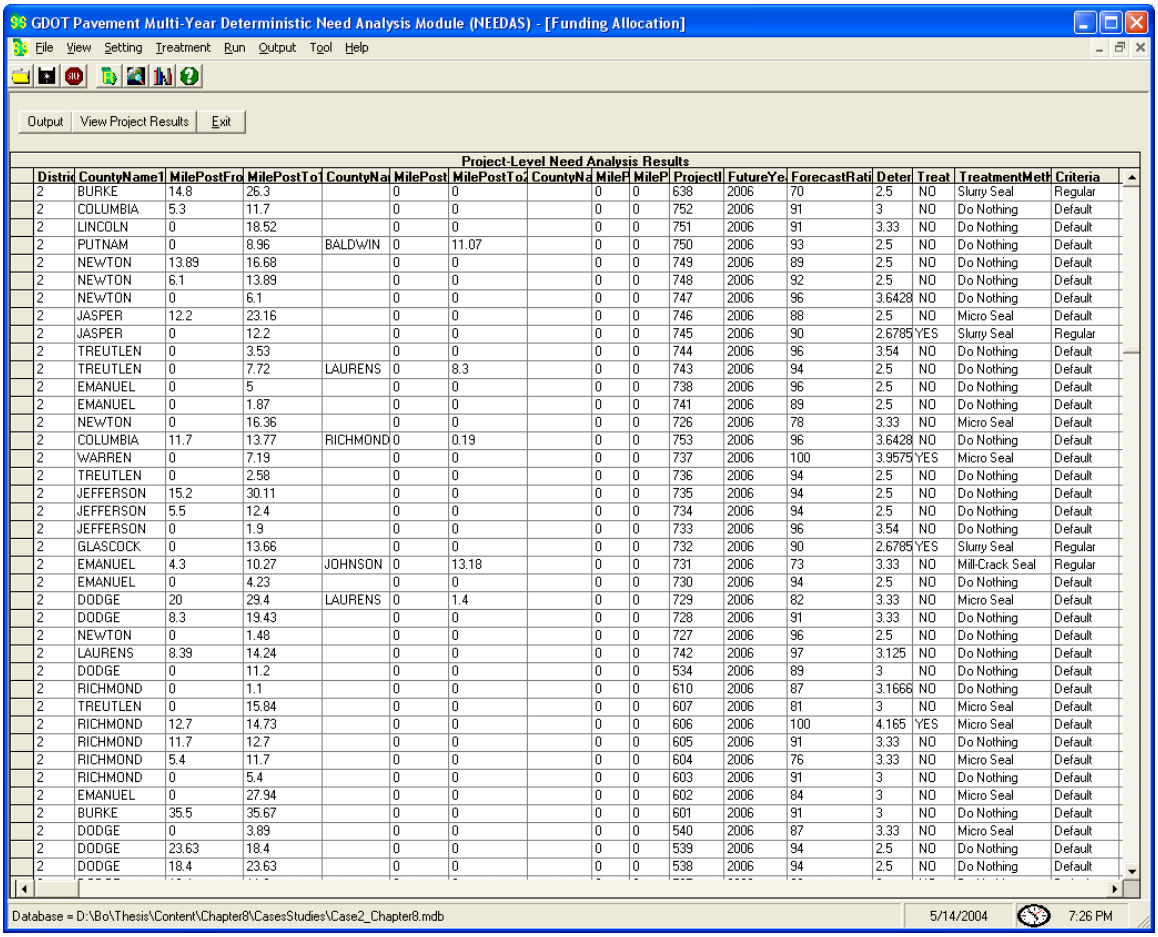
(2) Change the field of "ForecastRating"= "RehabRating," since the previous value of "ForecastRating" is forecasted by assuming no treatment is applied to the project and, with a specific treatment method assigned, the performance rating after treatment can be determined.

(3) Check whether the treatment to be applied is a minor treatment or not: if yes, then set "MinorTreatment"= "NO" (meaning the next treatment method cannot be a minor treatment); otherwise, set "MinorTreatment" = "YES," and

(4) Recalculate network-level composite rating and rehabilitation funding.

g. Based on "ForecastRating" and the historical data, calculate the corresponding deduct values of various distresses in year 1 (Year 2004). At this stage, Table tblNeedAnalysisResults should contain 2,472 entries (2,472 rows), with each entry represent the year 2004 analysis results for each project.

h. Repeat Step 3 to perform yearly analyses for year 2005, 2006, 2007, and 2008, the end of the analysis period. The tblNeedAnalysisResults Table should contain 5 x 2,472 entries as shown in Figure 8-19.



Distric	CountyName1	MilePostFro	MilePostTo	CountyNa	MilePost	MilePostTo	CountyNa	MileP	MileP	ProjectI	FutureYe	ForecastRati	Deter	Treat	TreatmentMeth	Criteria
2	BURKE	14.8	26.3		0	0		0	0	638	2006	70	2.5	NO	Slurry Seal	Regular
2	COLUMBIA	5.3	11.7		0	0		0	0	752	2006	91	3	NO	Do Nothing	Default
2	LINCOLN	0	18.52		0	0		0	0	751	2006	91	3.33	NO	Do Nothing	Default
2	PUTNAM	0	8.96	BALDWIN	0	11.07		0	0	750	2006	93	2.5	NO	Do Nothing	Default
2	NEWTON	13.89	16.68		0	0		0	0	749	2006	89	2.5	NO	Do Nothing	Default
2	NEWTON	6.1	13.89		0	0		0	0	748	2006	92	2.5	NO	Do Nothing	Default
2	NEWTON	0	6.1		0	0		0	0	747	2006	96	3.6428	NO	Do Nothing	Default
2	JASPER	12.2	23.16		0	0		0	0	746	2006	88	2.5	NO	Micro Seal	Default
2	JASPER	0	12.2		0	0		0	0	745	2006	90	2.6785	YES	Slurry Seal	Regular
2	TREUTLEN	0	3.53		0	0		0	0	744	2006	96	3.54	NO	Do Nothing	Default
2	TREUTLEN	0	7.72	LAURENS	0	8.3		0	0	743	2006	94	2.5	NO	Do Nothing	Default
2	EMANUEL	0	5		0	0		0	0	738	2006	96	2.5	NO	Do Nothing	Default
2	EMANUEL	0	1.87		0	0		0	0	741	2006	89	2.5	NO	Do Nothing	Default
2	NEWTON	0	16.36		0	0		0	0	726	2006	78	3.33	NO	Micro Seal	Default
2	COLUMBIA	11.7	13.77	RICHMOND	0	0.19		0	0	753	2006	96	3.6428	NO	Do Nothing	Default
2	WARREN	0	7.19		0	0		0	0	737	2006	100	3.9575	YES	Micro Seal	Default
2	TREUTLEN	0	2.58		0	0		0	0	736	2006	94	2.5	NO	Do Nothing	Default
2	JEFFERSON	15.2	30.11		0	0		0	0	735	2006	94	2.5	NO	Do Nothing	Default
2	JEFFERSON	5.5	12.4		0	0		0	0	734	2006	94	2.5	NO	Do Nothing	Default
2	JEFFERSON	0	1.9		0	0		0	0	733	2006	96	3.54	NO	Do Nothing	Default
2	GLASCOCK	0	13.66		0	0		0	0	732	2006	90	2.6785	YES	Slurry Seal	Regular
2	EMANUEL	4.3	10.27	JOHNSON	0	13.18		0	0	731	2006	73	3.33	NO	Mill-Crack Seal	Regular
2	EMANUEL	0	4.23		0	0		0	0	730	2006	94	2.5	NO	Do Nothing	Default
2	DODGE	20	29.4	LAURENS	0	1.4		0	0	729	2006	82	3.33	NO	Micro Seal	Default
2	DODGE	8.3	19.43		0	0		0	0	728	2006	91	3.33	NO	Do Nothing	Default
2	NEWTON	0	1.48		0	0		0	0	727	2006	96	2.5	NO	Do Nothing	Default
2	LAURENS	8.39	14.24		0	0		0	0	742	2006	97	3.125	NO	Do Nothing	Default
2	DODGE	0	11.2		0	0		0	0	534	2006	89	3	NO	Do Nothing	Default
2	RICHMOND	0	1.1		0	0		0	0	610	2006	87	3.1666	NO	Do Nothing	Default
2	TREUTLEN	0	15.84		0	0		0	0	607	2006	81	3	NO	Micro Seal	Default
2	RICHMOND	12.7	14.73		0	0		0	0	606	2006	100	4.165	YES	Micro Seal	Default
2	RICHMOND	11.7	12.7		0	0		0	0	605	2006	91	3.33	NO	Do Nothing	Default
2	RICHMOND	5.4	11.7		0	0		0	0	604	2006	76	3.33	NO	Micro Seal	Default
2	RICHMOND	0	5.4		0	0		0	0	603	2006	91	3	NO	Do Nothing	Default
2	EMANUEL	0	27.94		0	0		0	0	602	2006	84	3	NO	Micro Seal	Default
2	BURKE	35.5	35.67		0	0		0	0	601	2006	91	3	NO	Do Nothing	Default
2	DODGE	0	3.89		0	0		0	0	540	2006	87	3.33	NO	Micro Seal	Default
2	DODGE	23.63	18.4		0	0		0	0	539	2006	94	2.5	NO	Do Nothing	Default
2	DODGE	18.4	23.63		0	0		0	0	538	2006	94	2.5	NO	Do Nothing	Default

Figure 8 - 19 Needs Analysis Results

Step 4: Summarize network-Level needs analysis results and generate various tables and graphs described in Section 8.5 based on the results generated as presented in the Table tblNeedAnalysisResults.

Depending on the computer speed, it may take about 10 to 15 minutes for the system to perform this function. As the program starts to perform the analysis, the following form, shown in Figure 8-20, appears on the screen to show the progress. When the analysis is completed, the system will display a message indicating the analysis is

finished successfully and the screen will return to display the detailed project survey information. Use the various commands displayed on the **View** Command menu, described in next section, to display the results in different formats.

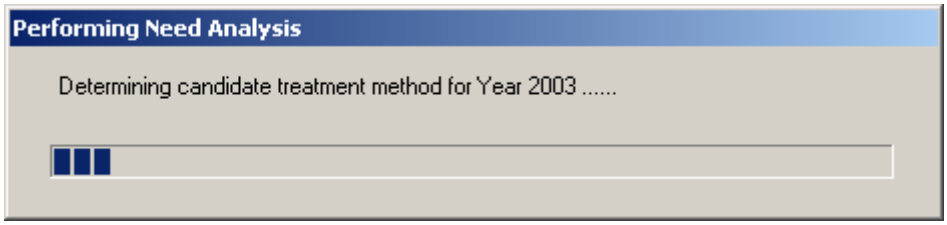


Figure 8 - 20 Performing Needs analysis

One thing that should be pointed out is that the total numbers and the boundaries of GDOT Districts and State Congressional Districts may be changed every few years due to political or other reasons. Thus, it is necessary for the NEEDAS program to reduce the impact of such changes. Two measures were taken to reduce the impact: (1) Two base tables, which contain the boundary information of GDOT Districts and State Congressional Districts, are created and stored in the database. (2) Two variables, g_intTotalGDOTDist and g_intTotalCongDist, are used to query out the total number of districts from the base table automatically. In this way, if GDOT Districts or State Congressional Districts are changed, new tables corresponding to the new district boundaries can be created and the existing tables can be easily replaced by the new

tables. This can be performed by the COPACES Database Administrator without affecting the other parts of the NEEDAS program.

8.5 View and Output Needs Analysis Results

Immediately after the needs analysis is completed, the user can use the **"View"** command on the menu bar from Figure 8-19 or Figure 8-1 to view and output various needs analysis results. Based on the objective and the desired features for the NEEDAS system identified in Chapter 4, the following results should be readily available and be presented in a clear and easily understandable format by the NEEDAS program to facilitate the planning and programming for multi-year rehabilitation needs for the Georgia state highway network:

- Results to facilitate the user in determining the budget needs and justifying funding allocation plans
- Results allowing the user to track and analyze both project-level and network-level rehabilitation maintenance activities
- Results allowing for monitoring future pavement performance and funding allocations in different jurisdictions
- Results allowing for future improvement and verifications of pavement needs analysis practice

Three different formats, MSChart (A Visual Basic Component provided by Microsoft to display data graphically), Microsoft Excel Sheet and GIS map, were used to

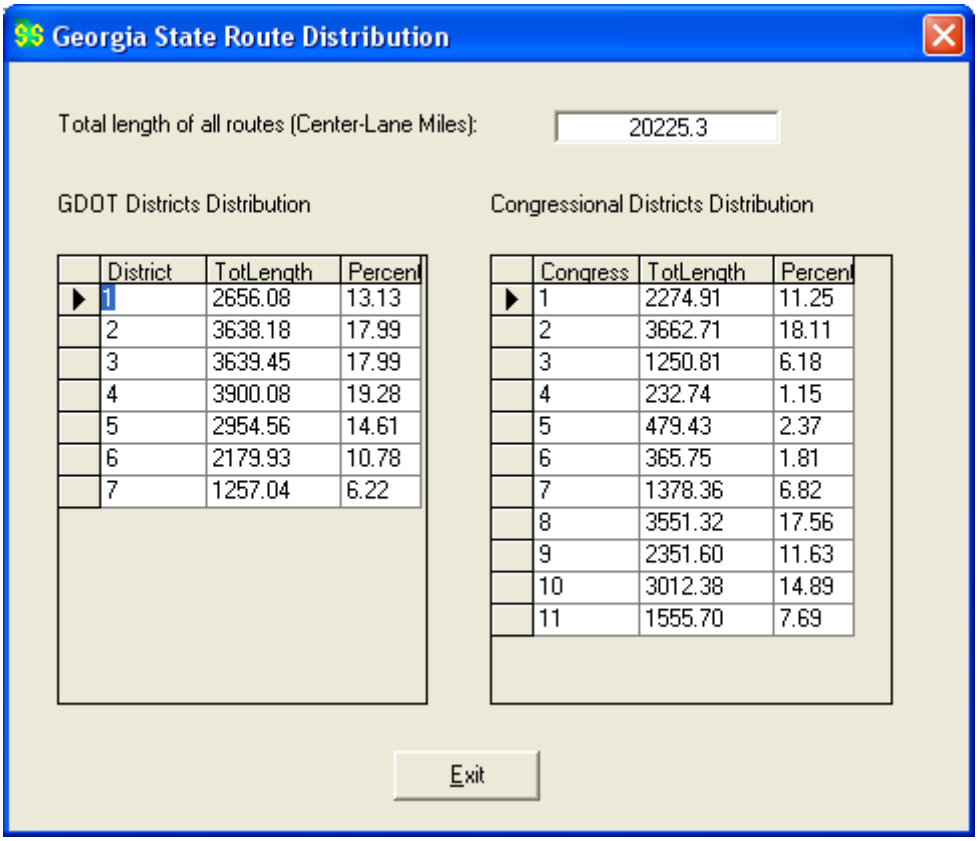
create many different types of tables and graphs to display the needs analysis results in various predefined formats. This is a part of the work performed by the NEEDAS program after the **Run** command is executed as mentioned in Step 4 in Section 8.4. So, immediately after the **Run** needs analysis is completed, the results expressed in various tables and graphs are ready to be reviewed through the various sub menus under the **View** command.

The **View** Command on the menu bar consists of the following nine sub menus:

- State Route Distribution
- Projects Survey Information
- Project-Level Needs Analysis Results (enabled after the **Run Needs Analysis** has been performed)
- Statewide Results (same as above)
- Results by GDOT Districts (same as above)
- Results by State Congressional Districts (same as above)
- Results by Funding Periods (same as above)
- Results by Treatment Methods (same as above)
- GIS Visualization (same as above)

- **State Route Distribution.** Select this sub menu command and the Georgia State Route Distribution form shown in Figure 8-21 appears. It provides the information of the total miles of the state routes in Georgia's state highway

network, the length and percentage of state routes in each GDOT District, and in each State Congressional District.



District	TotLength	Percent
1	2656.08	13.13
2	3638.18	17.99
3	3639.45	17.99
4	3900.08	19.28
5	2954.56	14.61
6	2179.93	10.78
7	1257.04	6.22

Congress	TotLength	Percent
1	2274.91	11.25
2	3662.71	18.11
3	1250.81	6.18
4	232.74	1.15
5	479.43	2.37
6	365.75	1.81
7	1378.36	6.82
8	3551.32	17.56
9	2351.60	11.63
10	3012.38	14.89
11	1555.70	7.69

Figure 8 - 21 Georgia State Route Distribution

- **Projects Survey Information:** Click “Projects Survey Information” sub menu command, and the detailed pavement project survey information for all the projects for the selected year are displayed on a DB grid as shown in Figure 8-22.

The *Select GDOT District* selection box located immediately above the DB grid allows the user to select **All** (all 7 Districts), or any one of the 7 GDOT Districts from this selection box. The program will respond by displaying the project information of the selected district on the DB grid.

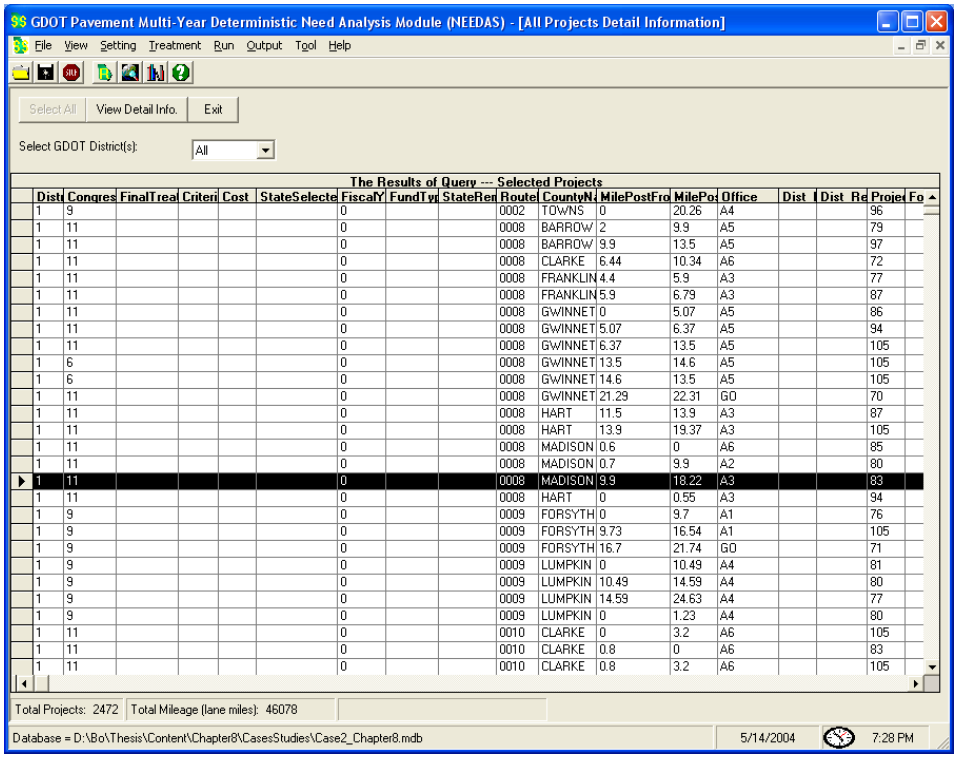
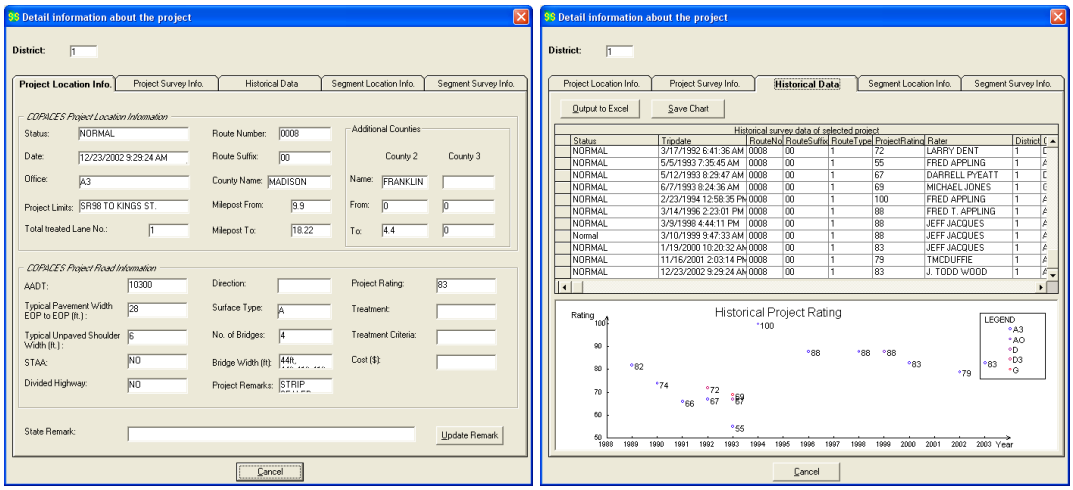


Figure 8 - 22 Project Survey Information DB Grid

The user can view detailed COPACES survey information for a selected project by selecting (highlighting) the project on the DB grid and clicking the "**View**

Detail Info." Button on Figure 8-22. The detailed COPACES survey information of the project selected in Figure 8-22 will be displayed, as shown in Figure 8-23 (A). There are 5 taps on this form (*Project Location Info*., *Project Survey Info*., *Historical Data*, *Segment Location Info*., and *Segment Survey Info*.). Figure 8-23 (A) displays the project location information for the selected project under the *Project Location Info*. Tap. Clicking any other taps will display different project information. For example, click the *Historical Data* tap and the historical project survey results are displayed in a DB grid, which shows all the survey data, including ratings, and all the distress deduct values, AADT, etc. for the selected project. Also, a graph, showing the project ratings versus survey years, is also displayed as shown in Figure 8-23 (B). The following are the additional features for the output shown in these two figures.



(A) (B)

Figure 8 - 23 Detail COPACES Project Survey Information

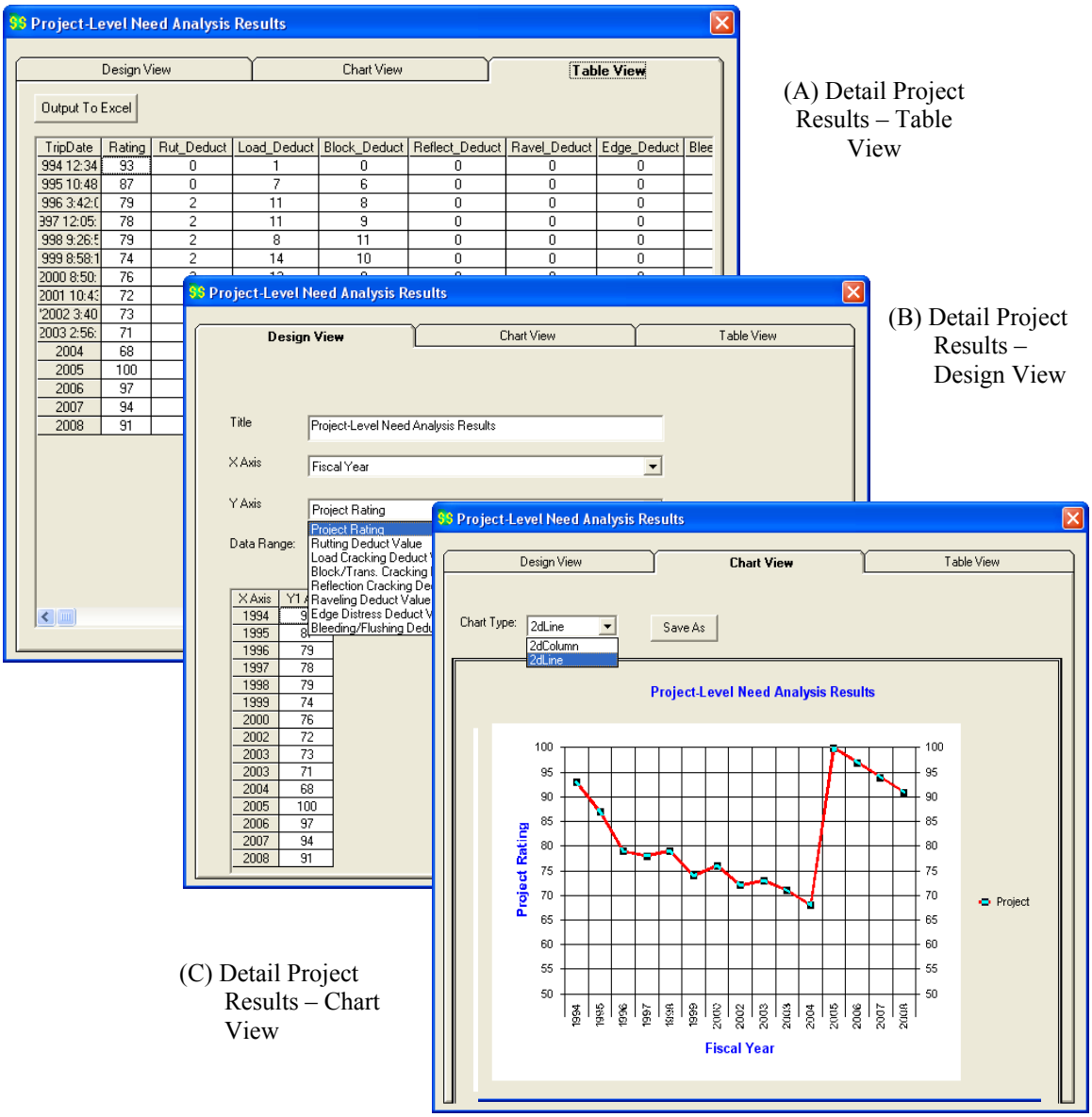
- On the “Project Location info.” form, shown in Figure 8-23 (A), the user can enter remarks for the project in the State Remark box located near the bottom of this form. These remarks can help the user to record any necessary comments related to this project during the needs analysis process.
- On the “Historical Data” form, shown in Figure 8-23 (B), all the historical COPACES survey information of the selected project are queried out from the COPACES database based on spatial location. The information can be output to an Excel file easily, which provides very useful information for the user to perform further analysis.

- **Project-Level Needs Analysis Results**. The results in Figure 8-19 present detailed project-by-project rehabilitation treatment analysis results, which include when, where, and which pavement projects are to be treated in the future. The user can click the **Output** button on this interface, and the entire results, shown on Figure 8-19, will be exported to an Excel file. In the example, shown in Figure 8-19, using the year 2003 COPACES data (see Section 8.4), the entire DB grid consists of 12360 (5x 2472 projects) rows by 17 columns! The DB grid of the project-level needs analysis results contains the following 17 types of project-level information:

  - GDOT District: 1 to 7;
  - County Name1, MilePostFrom1, MilePostTo1;

- County Name2, MilePostFrom2, MilePostTo2;
- County Name3, MilePostFrom3, MilePostTo3;
- ProjectID: A number assigned to each project to uniquely identify each project in each analysis year;
- Future Year: Year rehabilitation treatment is to be applied;
- Forecast Rating: Rating one year after the end of analysis year;
- Deterioration Rate: The annual performance rating deterioration rate
- Treat: YES or NO, indicating whether rehabilitation treatment is to be performed or not to be performed on the project. If it is NO, then the next 6 fields will be either zero or blank;
- Treatment Method: The rehabilitation treatment method to be used for this project;
- Criteria: Regular or Default, indicating whether the treatment method is determined by Regular Treatment Criteria or Default Treatment Criteria;
- Cost: Total rehabilitation treatment costs for the project;
- Rehabilitation Rating: Indicating the Rehabilitation Rating immediately after the selected treatment method is applied, i.e., Overlay = 100, Slurry Seal = 90;
- Yearly Priority: Annual statewide prioritization index;
- B C Ratio: Cost effectiveness ratio;
- ProjectLength: Total length of the project in lane-miles;
- AADT: The future year average annual daily traffic.

The detailed COPACES survey information of any project shown in this DB grid can also be obtained from Figure 8-19 by selecting (highlighting) a project on the DB grid and clicking the "**View Detail Info.**" Button. After selecting (highlighting) a project on the DB Grid and clicking the "View Project Results" button, Figure 8-24A, B, or C appears. There are 3 taps on this form, *Table* View (Figure 8-24 (A)), *Design View* (B) and, *Chart View* (C). *Table View* displays the summary of project ratings, deduct values for various distresses and other project information of the historical data, as well as the needs analysis results for the analysis periods of the selected project (see Figure 8-24 (A)). All the results in *Table View* can be exported to an Excel sheet by clicking the "Output to Excel" button on Figure 8-24(A). *Design View* allows the user to select one of the various attributes of the project, including project ratings and various distress deduct values from the Y-Axis selection box to be displayed, see Figure 8-24 (B). The attribute selected in the *Design View* will be displayed against fiscal year in a bar chart or XY line curve as shown in Figure 8-24 (C). Click the **Save As** button on Figure 8-24(C) allows the chart to be saved as a file in the local computer.



(A) Detail Project Results – Table View

(B) Detail Project Results – Design View

(C) Detail Project Results – Chart View

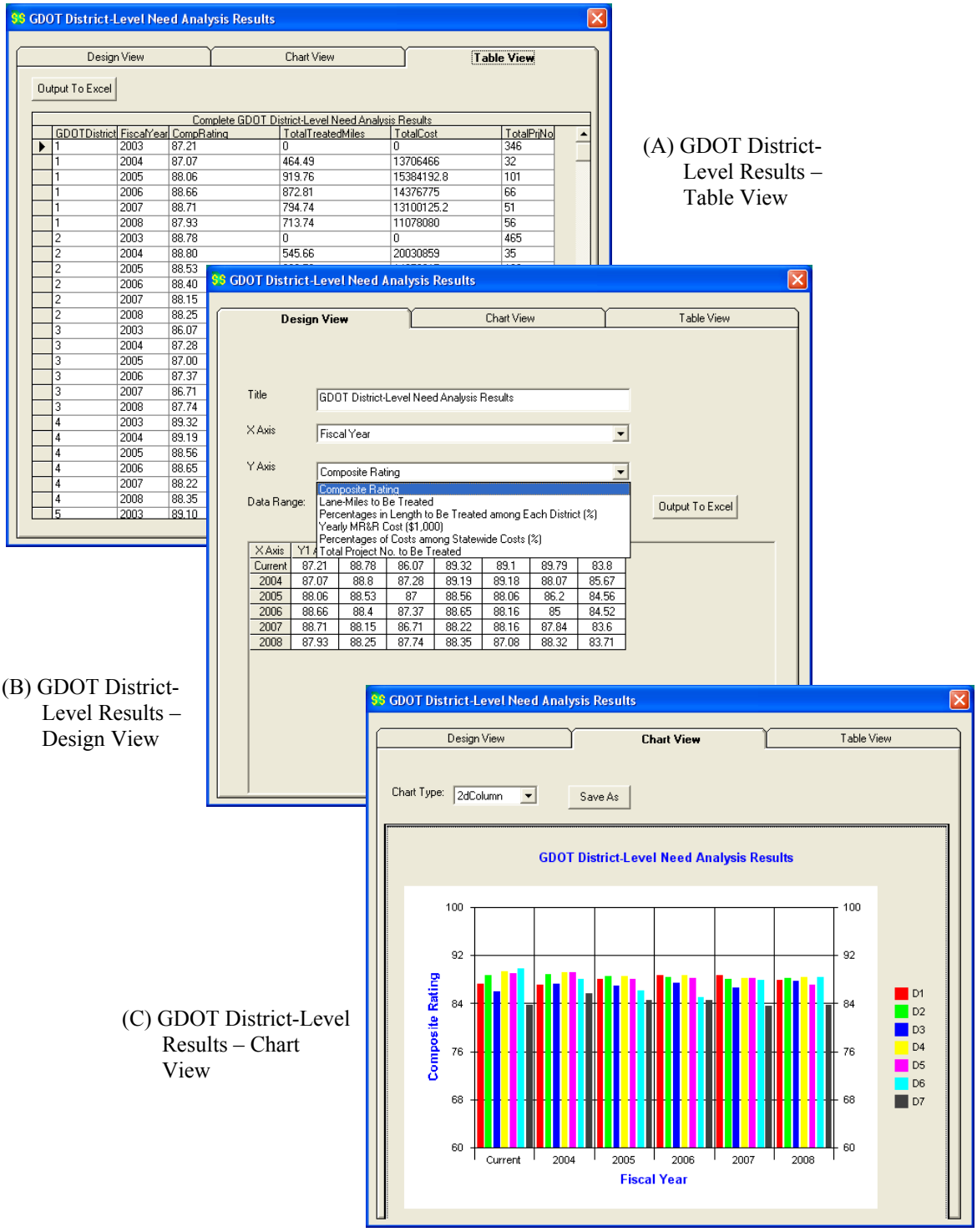
Figure 8 - 24 View Detail Project Results

These project-level needs analysis results and the various tables and graphs created to display the results make it easier for the user to assess whether the correct rehabilitation treatment methods are selected for a specific project. It also makes the comparison and validation of the needs analysis results with the actual rehabilitation treatment plans implemented by GDOT easier.

- **Results by Different Jurisdictions**. The three sub menus, "Statewide Results," "Results by GDOT Districts," and "Results by State Congressional Districts," display the network-level results by different jurisdictions. Under the "Statewide Results" sub menu, the network-level summary results of composite ratings, total miles treated, total costs, and total number of projects to be treated for each year in the analysis period for the entire statewide results are displayed. The "Results by GDOT Districts" sub menu and the "Results by Congressional Districts" sub menu display the corresponding statewide analysis results according to the GDOT Districts and Congressional Districts boundaries. For example, click the "Results by GDOT Districts" sub menu and the results shown in Figure 8-25 appear. Similar to that in Figure 8-24, the results are presented in 3 taps, *Design View, Chart View*, and *Table View*. *Table View* displays the summary results including the composite ratings, total miles treated, total costs and number of projects treated, for each of the seven GDOT Districts in each year from 1994 to 2008, see Figure 25 (A). Figure 8-25(B) and (C) show the GDOT District-level results in *Design View* and *Chart View*. Although the statewide composite ratings for each year is set at 87.5 for this

example, the composite ratings for GDOT District-level results vary greatly over the analysis period, as shown in Figure 8-25 (B) and (C). According to Figure 8-25 (B), the composite ratings among the GDOT districts over the analysis period varied from 83.6 to 89.2. If the constraint of balancing performance of GDOT Districts had been activated, the variation among the GDOT districts would have been much less. In the next chapter a case with balancing performance of GDOT Districts will be presented.

These summary results based on the jurisdiction boundaries allow the user to view and assess the analysis results in terms of pavement performance and rehabilitation cost allocations among different jurisdictions in the analysis period; therefore, the user can develop and compare alternate plans.



(A) GDOT District-Level Results – Table View

(B) GDOT District-Level Results – Design View

(C) GDOT District-Level Results – Chart View

Figure 8 - 25 View Results by Different Jurisdictions

- **Results by Funding Periods.** These results display the network-level summary results of the needs analysis by funding period. From the *Design View* interface, one can select different attributes in X-axis (State Congressional Districts or GDOT Districts) and different attributes in Y-axis (Composite Rating, Lane-mile to be treated, % Length to be treated, Costs, % of Statewide costs, and Number of projects to be treated), and different analysis years to generate the results expressed in table formats in *Design View* and graph formats in *Chart View*.

- **Results by Treatment Methods.** These results display the network-level results of different rehabilitation treatment methods. Three attributes, lane-miles to be treated, rehabilitation costs, and total No. of projects to be treated by different treatment methods, can be displayed for anyone or the entire analysis years. The results by treatment method allow the user to assess the rehabilitation treatment methods and evaluate various related issues. The related issues could include whether there is any single treatment method dominating the treatment plan developed by the program, whether use of this dominating method is in line with GDOT practice, with the national trend, and with emerging technical trend, and whether the construction industry has the adequate capability required to perform for the work.

- **GIS Visualization.** Click the "GIS Visualization" sub menu from the **View** Command and Figure 8-26 appears, indicating that the program is performing

the GIS analysis using the data generated from the needs analysis and is preparing the GIS layers. Once the process for generating GIS layers from the database is completed, the GIS main interface, shown in Figure 8-27, appears. Six maps (layers) are generated by the program using various GIS map preparation functions, such as modified dynamic segmentation process and "AddRelate" method, as described in Chapter 7.

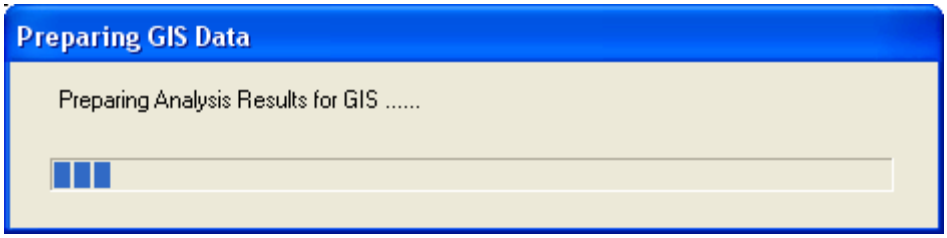


Figure 8 - 26 View Results by Different Jurisdictions

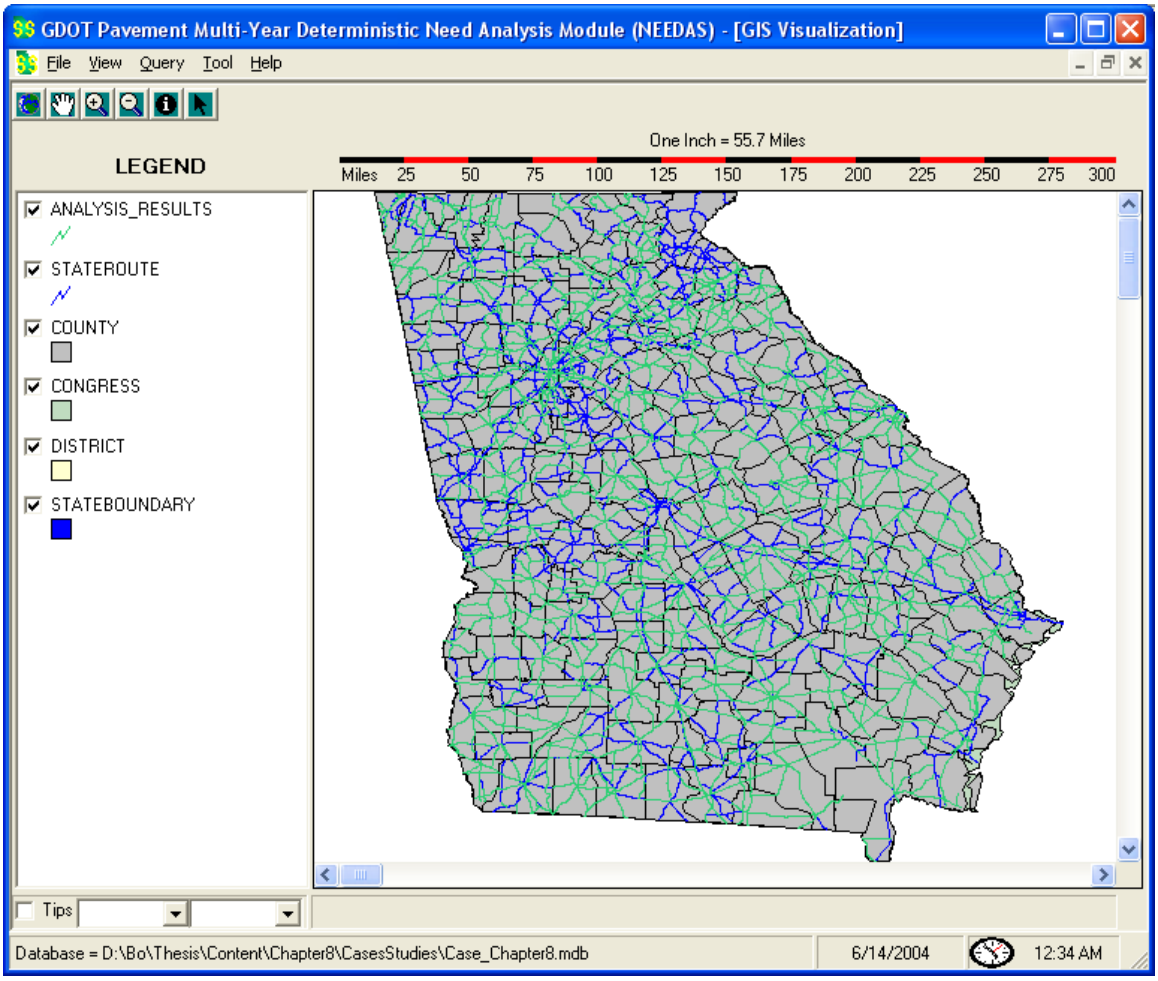


Figure 8 - 27 Interface of GIS Map

This six layers include most of the information generated from the needs analysis results that can be usefully and effectively displayed in GIS maps. As described in Chapter 7, the program has developed the capabilities to automatically link the needs analysis results obtained from this program directly to these 6 GIS maps. The names of these six layers are shown on the *Legend* pan on the left side of interface shown in Figure 8-27. To select any one of the layers to show the corresponding needs analysis results,

the user can use the mouse to move the selected layer to the top on the *legend pan*. The NEEDAS program also has the flexibility to create new layers (as presented in Chapter 7, Section 7.4) and add the newly created layer or additional layers provided by GDOT to the map simply by clicking the "Add Layer" from the **File** command shown in Figure 8-27.

Since the GIS features, their functionalities, and the use of GIS in the NEEDAS program have been presented in detailed in Chapter 7, they will not be repeated here.

8.6 Online Help and User's Manual

There are two items in the Help menu: Online Help and About NEEDAS.

Click the **About NEEDAS** sub menu and Figure 8-28 will appear, which displays information about the version, copyright, and release date of this program.

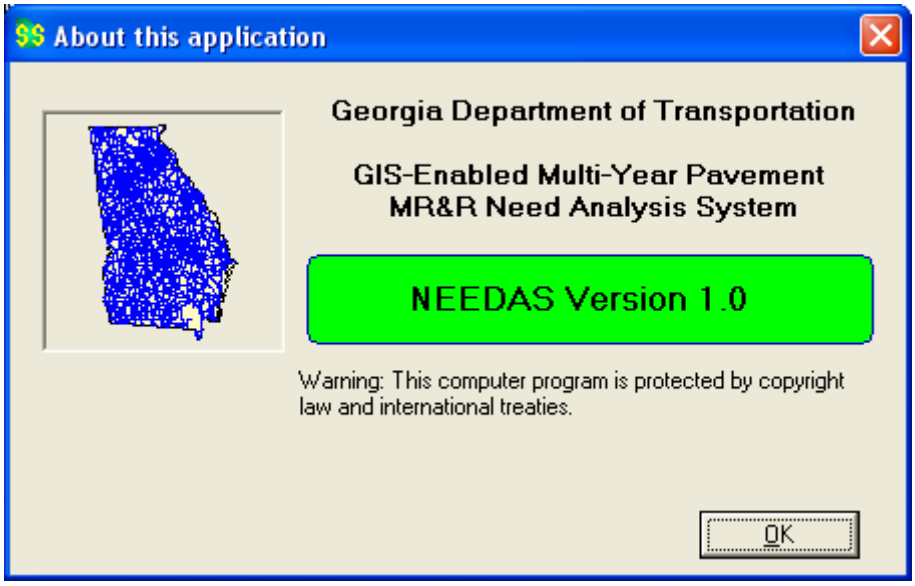


Figure 8 - 28 About NEEDAS

Clicking the **Online Help** sub menu will launch the online help document, as shown in Figure 8-29. This detailed user menu (95 pages long) contains detailed procedures for using this program.

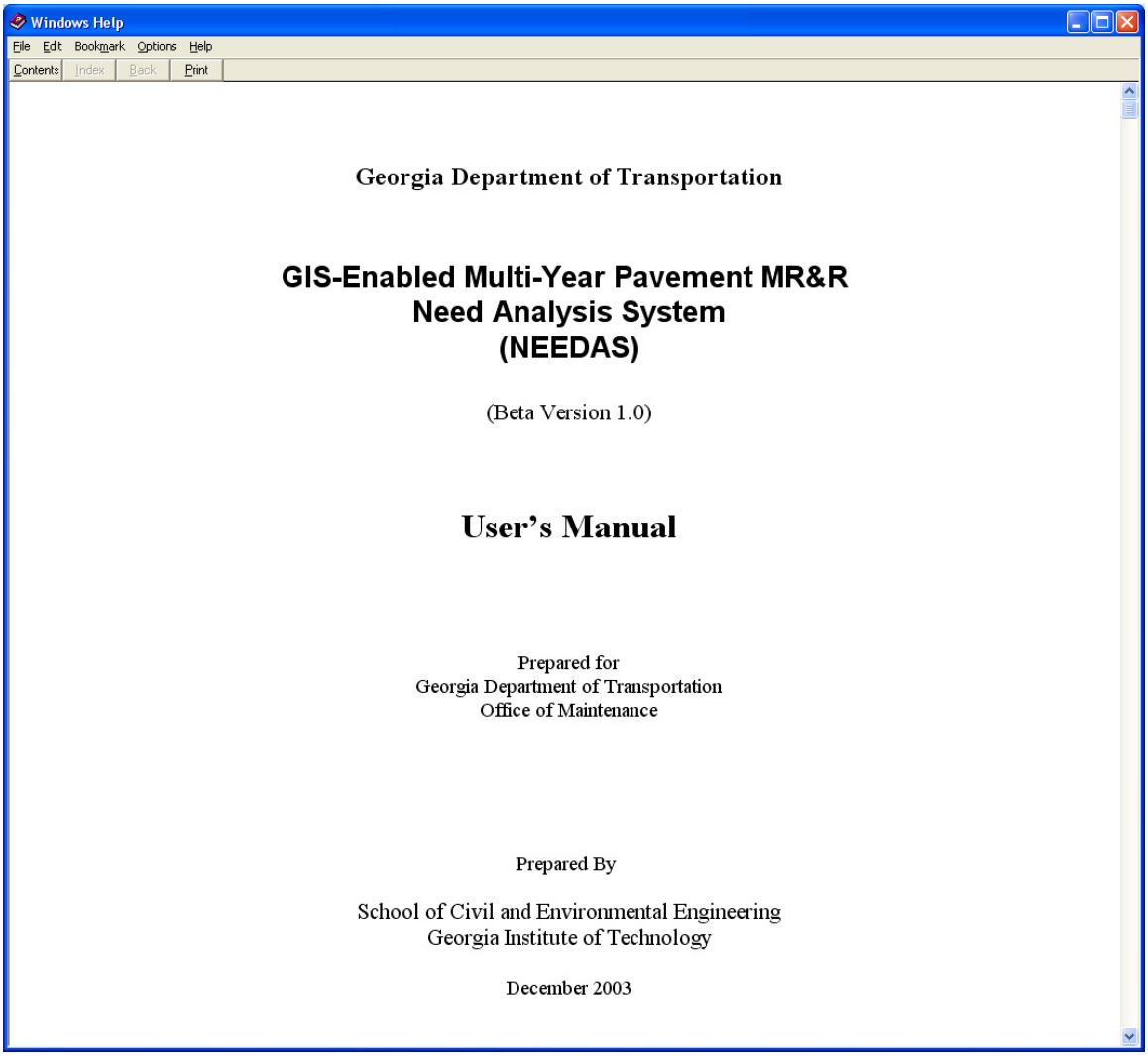


Figure 8 - 29 Online Help and User's Manual

CHAPTER 9

CASE STUDIES USING THE NEEDAS PROGRAM

The versatility and flexibility of the NEEDAS program allow pavement engineers in GDOT to perform and analyze multi-year rehabilitation needs for GDOT based on the current and the past pavement condition survey data of the pavement projects in the entire Georgia state highway network. Several cases using the program for evaluating multi-year rehabilitation plans are presented in this chapter to demonstrate the capabilities and the potential use of the program. The cases presented include different scenarios, such as varying the annual rehabilitation funding amount, different pavement performance constraints and balancing constraints. The actual pavement condition evaluation data from GDOT were used for all the analyses presented in this chapter. The analysis period is five years for all the cases presented in this chapter, which is the same period currently used by GDOT.

As demonstrated by the case studies presented in this chapter, this program is a powerful analytical tool allowing decision makers to determine the most cost-effective pavement rehabilitation strategies. However, before this program can be used for the actual rehabilitation planning, it needs to be fully validated, calibrated, and thoroughly tested to improve the accuracy of the results generated by the program. Therefore, the results, particularly the various funding figures, generated from the case studies presented in this chapter may not represent accurately the actual figures used by GDOT. However, the relative figures of the results from these case studies should be reasonably accurate.

This chapter is organized as follows: Section 9.1 describes the GDOT's data set used for case studies. Then three different studies are presented in the following sections: Section 9.2 presents the study of determining funding needed to maintain different performance levels. Section 9.3 discusses the manual optimization process. Section 9.4 compares the results of different balancing criteria.

9.1 Data Set Used for Case Studies

The COPACES database, which contains all the GDOT historical pavement condition evaluation data for asphalt pavements up to fiscal year 2003 data, was used for all the analyses presented in this chapter. The database contains only the information of the surveyed projects. The information of the not-surveyed routes was not included in the analyses. Also not included in the database were 858 center-lane miles of concrete pavements in the state highway network.

In fiscal year 2003, the COPACES database contained 2,472 surveyed projects with a total of 46,078 lane miles, representing 75.2% of the total asphalt pavements in the state highway network. The statewide pavement composite rating in fiscal year 2003 is 87.92, based on the surveyed asphalt pavements data. The composite ratings for each GDOT District and State Congressional District for 2003 are presented in Table 9-1. The district composite pavement performance ratings among GDOT Districts varied from 83.80 to 89.79; the composite ratings among State Congressional Districts varied from 85.01 to 89.37. It is worth it to point out that a one-point difference in the rating is quite significant, as it represents the difference of pavement performance rating by 1 point of the entire pavement network in the entire district. To increase one point of the statewide

composite rating would require an increase of over 10 million dollars for the annual rehabilitation funding (see Table 9-2).

Table 9 - 1 Network-Level Composite Rating in Fiscal Year 2003

Statewide Composite Rating = 87.92

GDOT Districts	Composite Rating	State Congressional Districts	Composite Rating
D 1	87.21	CD 1	89.37
D 2	88.78	CD 2	89.07
D 3	86.07	CD 3	85.76
D 4	89.32	CD 4	85.01
D 5	89.10	CD 5	84.61
D 6	89.79	CD 6	86.23
D 7	83.80	CD 7	86.45
		CD 8	87.38
		CD 9	88.98
		CD 10	88.57
		CD 11	87.42

9.2 Study 1: Funding Required to Maintain Different Pavement Performance Levels

The analyses presented in this section compare the annual rehabilitation funding required to maintain pavements in the statewide highway network at different statewide composite ratings (SCR) from 86 to 90. In these analyses, a constant SCR is used throughout the entire analysis period (2004 to 2008) under each scenario. In addition, the

minimum individual performance rating of 70 is set (for Case 1-1 to 1-5). The results of the analyses are summarized in Table 9-2.

The results shown in this table indicate that although the statewide pavement performance constraints are set as 86, 87, and 87.92, respectively for Case 1-1, 1-2 and 1-3, the actual SCR from the rehabilitation plans generated by the program for these cases is greater than that of the constraints (86.49, 87.22, and 87.96, respectively). This is due to the overwriting requirement that individual projects should have ratings equal to or greater than 70. Apparently, in the year 2003 survey data, there were a sufficient number of projects with ratings less than 70 that would require rehabilitation treatments in 2004 to bring the ratings up to 70. To confirm that, the same cases, except those without having individual project rating constraints, were run, and the results are presented in Table 9-3 and Figure 9-1. For the cases shown in Table 9-3, a smaller amount of funding is required in the first year for all the cases.

Table 9 - 2 Annual Funding Required to Maintain Different SCR

Year	Case 1-1		Case 1-2		Case 1-3		Case 1-4		Case 1-5	
	Cost	SCR	Cost	SCR	Cost	SCR	Cost	SCR	Cost	SCR
2003	0.0	87.92	0.0	87.92	0.0	87.92	0.0	87.92	0.0	87.92
2004	130.8	88.09	130.8	88.09	130.8	88.09	162.9	89.00	198.8	90.01
2005	44.9	86.37	66.1	87.00	97.10	87.92	103.5	89.00	107.6	90.01
2006	98.5	86.00	110.9	87.00	112.3	87.92	116.7	89.00	120.3	90.00
2007	112.1	86.01	114.2	87.01	114.6	87.92	121.6	89.00	128.3	90.01
2008	114.6	86.00	116.1	87.01	123.1	87.93	132.3	89.01	146.4	90.00
Average	**100.2**	**86.49**	**107.6**	**87.22**	**115.6**	**87.96**	**127.4**	**89.00**	**140.3**	**90.01**

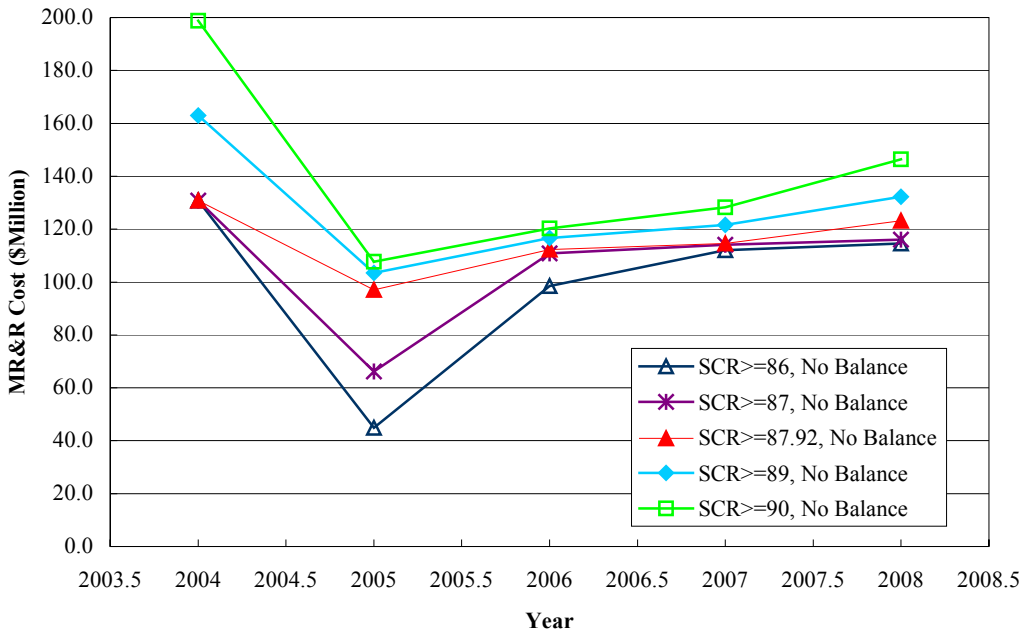
Note: Case 1-1 to 1-5 require individual project rating ≥ 70
No balance constraint for all the cases; Total funding in 5 years = 591.1
Cost in Million dollars.

Table 9 - 3 Annual Funding Required to Maintain Different SCR

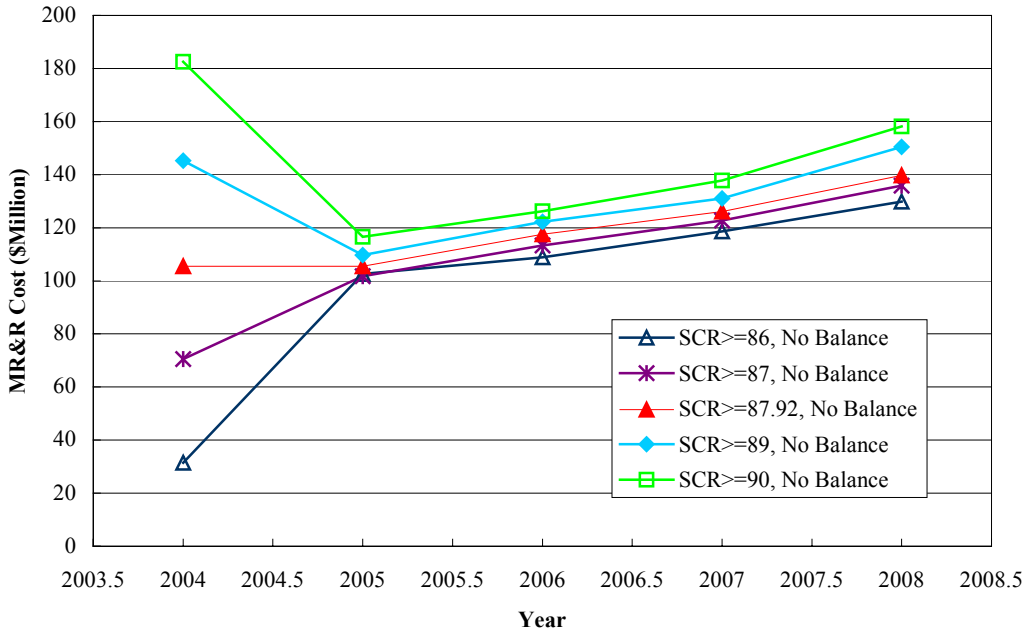
Year	Case 1-1A		Case 1-2A		Case 1-3A		Case 1-4A		Case 1-5A	
	Cost	SCR	Cost	SCR	Cost	SCR	Cost	SCR	Cost	SCR
2003	0	87.92	0	87.92	0	87.92	0	87.92	0	87.92
2004	31.41	86.00	70.5	87.00	105.4	87.92	145.3	89.01	182.6	90.02
2005	102.6	86.00	101.8	87.00	105.5	87.93	109.7	89.00	116.6	90.00
2006	108.9	86.00	113.3	87.02	117.5	87.93	122.2	89.01	126.2	90.00
2007	118.7	86.00	122.7	87.01	126.1	87.92	131.1	89.00	137.8	90.02
2008	129.8	86.01	135.9	87.01	139.7	87.93	150.4	89.01	158.2	90.06
Average	**98.3**	**86.00**	**108.9**	**87.01**	**118.9**	**87.93**	**131.7**	**89.01**	**144.3**	**90.02**

Notes: Case 1-1A to 1-5A require no individual project rating constraint;
No balance constraint for all the cases; Total funding in 5 years = 602.1
Cost in Million dollars.

Figure 9-1 shows the yearly rehabilitation funding distributions. Figure 9-1 (a) further confirms the observation above, as Case 1-1, 1-2, and 1-3 require the same amount of rehabilitation cost in the first year due to a sufficient number of projects with ratings less than or equal to 70. By performing rehabilitation treatments on these projects alone in Case 1-1, 1-2, and 1-3 would be sufficient to bring the SCR to meet the requirements. The trends for the funding requirements from 2004 to 2008 for Case 1-1, 1-2, and 1-3 with individual rating constraint versus Case 1-1A, 1-2A, and 1-3A without individual rating constraint are very different as shown in Table 9-2, 9-3, Figure 9-1 (a) and (b).



(a) With Individual Project Rating Constraint >=70



(b) Without Individual Project Rating Constraint

Figure 9 - 1 Yearly Rehabilitation Cost Corresponding to Different Performance Levels

There are many interesting conclusions that can be drawn from the results shown in Table 9-2, Table 9-3, and Figure 9-1 (a) and (b). One of the interesting observations is, perhaps, that the overall funding required in the five-year period for all cases, except for Case 1-1 versus Case 1-1A, are less, and the averaged SCR are higher for the cases with individual project rating constraints than that without (such as Case 1-2 vs. Case 1-2A to Case 1-5 vs. Case 1-5A). The total five-year averaged annual funding required for rehabilitation plans with individual rating constraints (Case 1-1 to Case 1-5) is 591.1 million dollars, while those without rating constraints (Case 1-1A to Case 1-5A) is 602.1 million dollars. The total averaged SCR for rehabilitation plans with individual rating constraint (Case 1-1 to Case 1-5) is about 0.14 higher than that without rating constraint, although intuition seems to expect the reverse, as more constraints would seem to require more costs or poor performance. This is not just a coincidence. Actually, there is an important implication related to pavement rehabilitation strategies. The message is that performing rehabilitation on pavements at their early stage of degradation (i.e. bringing individual pavements up to rating greater than 70) before reaching the state of serious degradation would, in the long run, cost less. One of the reasons that the overall pavement conditions in Georgia highways has been ranked the best in the United States is that GDOT has been able to perform pavement rehabilitation when pavements exhibit early stage of degradations before they are allowed to become badly damaged. This analysis seems to confirm the advantage of this practice.

Using a 1.7 GHz Pentium IV computer, it takes about 10 to 15 minutes to perform each case presented here. The 5 cases presented in Table 9-2 took less than 1.5 hours for the computer to complete the analyses.

9.3 Study 2: Manual Adjustment of Pavement Performance Rating

As discussed in Chapter 6, Section 6.2, the NEEDAS program utilizes single-year prioritization, and the program does not have the capability for automatically optimizing funding distributions to achieve the optimum pavement performance within the entire analysis period. Although the results obtained from the NEEDAS program are not a true optimization result, the user can use the results produced by the NEEDAS program as the starting point to perform "what-if" analyses based on the user's experiences and judgments to obtain improved results. Ease of modifying input parameters for the program coupled with the fast runtime makes it easier for the user to perform the manual optimization. The cases presented in this section illustrate the use of this manual process to achieve better network pavement performance under the same amount of total rehabilitation funding for the entire analysis period.

In the previous section, the results of Case 1-3A indicate that the annual rehabilitation funding required to achieve SCR of 87.92 throughout the entire analysis period varies from 105.4 to 139.7 million dollars from 2004 to 2008, and a total amount of 594.2 million dollars is needed for the five years period. These analysis results are shown in Table 9-4 as Case 2-1. Two alternate funding distributions in the analysis period with the total amount of 5 years remain the same were performed. In Case 2-2, the 594.2 million dollars are evenly distributed in the five-year period, while the funding distributions in Case 2-3 are the reverse of that in Case 2-1. The results of the SCR in the analysis period under these two alternate funding schedules, as summarized in Table 9-4, indicate that both alternate funding schemes can improve the pavement performance, in terms of the averaged SCR in the analysis period, to 88.29, and 88.69 respectively for

Case 2-2 and Case 2-3 versus 87.93 for Case 2-1. In these two cases, any single year SCR is higher than 87.92, except for Case 2-2 in 2008, which is 87.78, and for Case 2-3 in 2008, which is 87.67. The project-level results, in terms of "No. of projects to be treated" and "lane-mile to be treated," as shown in Table 9-3, also indicate that both alternative funding schedules can improve the pavement rehabilitation practice, as more projects and lane-mile can be treated for Case 2-2 (447 projects/year, 6508.7 lane-mile/year) and Case 2-3 (455 projects/year, 6696.0 lane-mile/year) versus that for Case 2-1 (443 projects/year, 6389.0 lane-mile/year).

Table 9 - 4 Results of Alternate Funding Schedules on SCR

Five years' total budget = 586.2 million dollars for all cases

Year	Case 2-1*				Case 2-2				Case 2-3			
	Cost	SCR	No. of Projects. treated	Lane-mile treated	Cost	SCR	No. of Projects. treated	Lane-mile treated	Cost	SCR	No. of Projects. treated	Lane-mile treated
2003	0	87.92	0	0	0	87.92	0	0	0	87.92	0	0
2004	105.4	87.92	602	5081.2	118.9	88.27	640	5719.2	139.9	88.85	711	6986.9
2005	105.5	87.93	399	5891.5	119.0	88.56	428	6683.2	126.7	89.28	439	7213.6
2006	117.5	87.93	375	6455.6	119.0	88.58	376	6707.8	117.5	89.14	372	6700.7
2007	126.1	87.92	353	6775.4	119.1	88.28	336	6484	106.7	88.53	316	6223.9
2008	139.7	87.93	485	7741.2	118.9	87.78	457	6949.5	105.8	87.67	437	6359.3
Average	**118.9**	**87.93**	**443**	**6389.0**	**119.0**	**88.29**	**447**	**6508.7**	**119.3**	**88.69**	**455**	**6696.9**

Note: Cost in Million dollars.

9.4 Study 3: Need Analysis with Balancing Constraints

The NEEDAS program allows the user to impose constraints for balancing funding distributions or pavement performance among GDOT Districts or State Congressional Districts when performing multi-year rehabilitation need analyses. In section 9.2, the results of Case 1-3A indicate that the annual rehabilitation funding required to achieve SCR of 87.92 from 2004 to 2008 varies from 105.4 to 139.7 million dollars. In the analyses performed in Case 1-3A, no balancing constraint was imposed. The results are shown in Table 9-5 again as Case 3-1. The Case 3-2 analysis is again to determine the annual funding required to maintain statewide composite rating of 87.92 throughout the entire analysis period with an additional constraint of balancing the pavement performance among the seven GDOT Districts. The results shown in Table 9-5 indicate that the total funding required in the analysis period for Case 3-2 is only slightly higher (about 0.4%) than that for Case 3-1. Also, the funding distributions for each year in the analysis period between these two cases are slightly different. However, the pavement performance rating distributions among the 7 GDOT Districts in the Case 3-1 and Case 3-2, as shown in Figure 9-2 and Figure 9-3, are very different. The largest composite rating difference among the seven GDOT Districts is about 12.0 for Case 3-1 (see Figure 9-2); while it is less than 0.7 under Case 3-2 (see Figure 9-3). The NEEDAS program is very effective in balancing pavement performance among different districts. The funding distributions among the seven GDOT Districts for Case 3-1 and Case 3-2 are shown in Figure 9-4 and Figure 9-5 and show that the rehabilitation cost per year in both cases is not balanced. In the future, the algorithm to balance both pavement performance and rehabilitation cost at the same time should be developed.

Both the composite rating distributions and the funding distributions from these two cases as shown in these four figures, as well as in tabulated forms, are automatically generated by the program and can be readily accessed through the "View" command as described in Chapter 8, section 8.5.

Table 9 - 5 Comparison of Funding Needs to Meet SCR Requirement

Year	Case 3-1*				Case 3-2			
	Cost	SCR	No. of Projects. treated	Lane-mile treated	Cost	SCR	No. of Projects. treated	Lane-mile treated
2003	0	87.92	0	0	0	87.92	0	0
2004	105.4	87.92	602	5081.2	110.3	87.93	561	5222.2
2005	105.5	87.93	399	5891.5	107.4	87.94	425	6042.7
2006	117.5	87.93	375	6455.6	111.0	87.93	370	6534.6
2007	126.1	87.92	353	6775.4	125.0	87.93	346	6696.1
2008	139.7	87.93	485	7741.2	143.5	87.92	452	7227.8
Average	**118.9**	**87.93**	**443**	**6389.0**	**119.4**	**87.93**	**431**	**6344.7**

Note: Case 3-1 same as Case 1-3 in Table 9-2
Case 3-1: No balance constraint
Case 3-2: Balance Performance among GDOT Districts
Cost in Million dollars

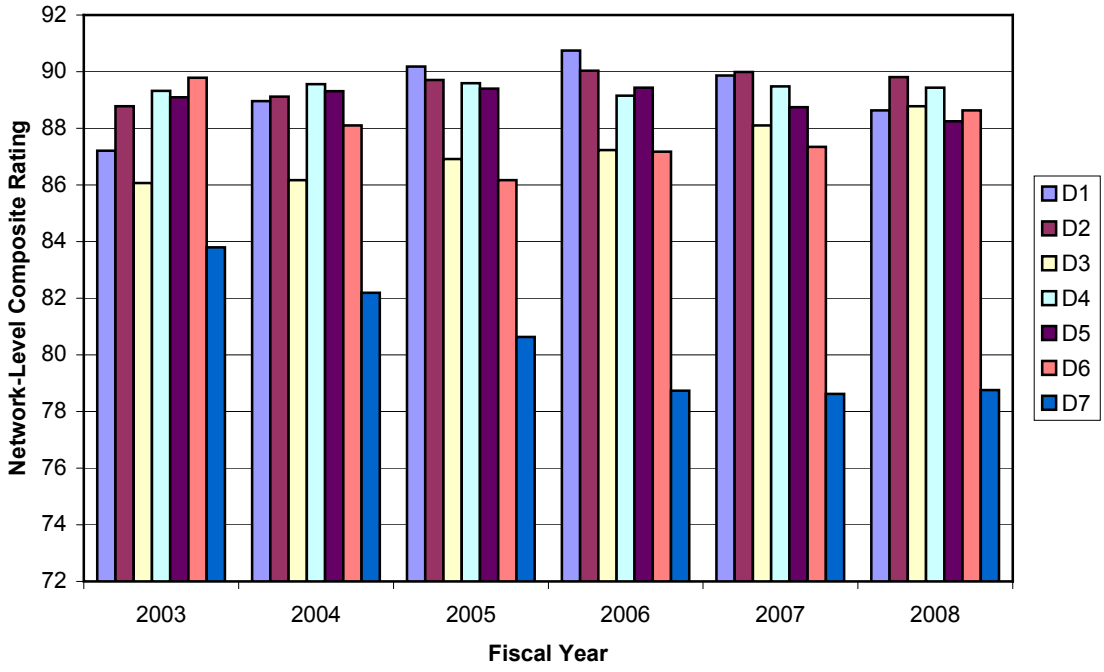


Figure 9 - 2 GDOT District Composite Rating Distribution for Case 3-1

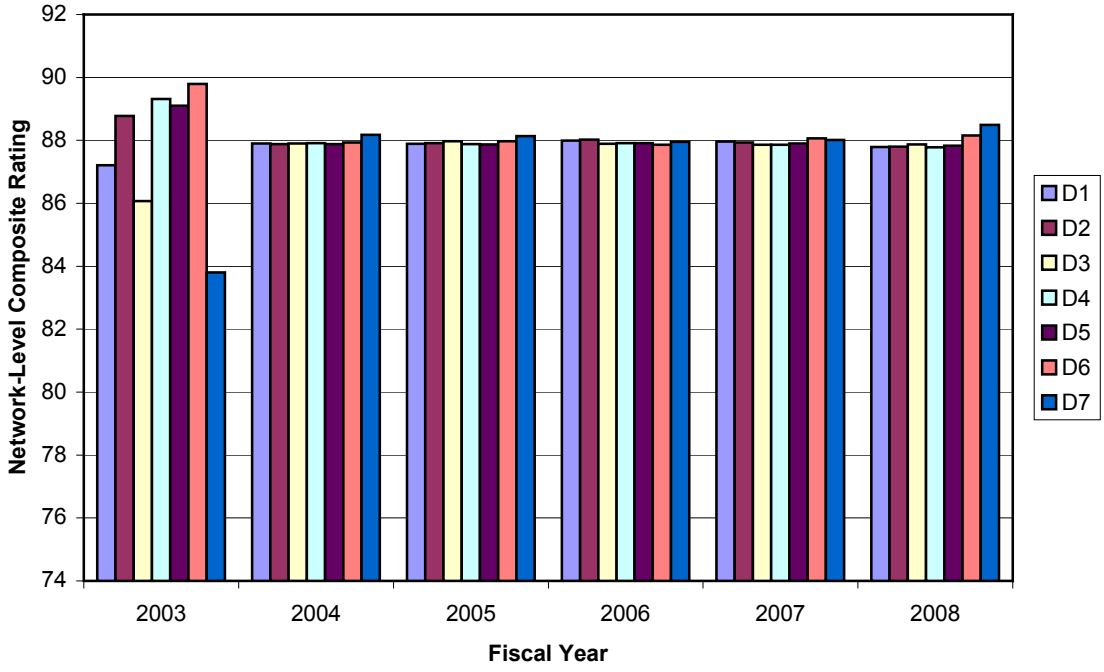


Figure 9 - 3 GDOT District Composite Rating Distribution for Case 3-2

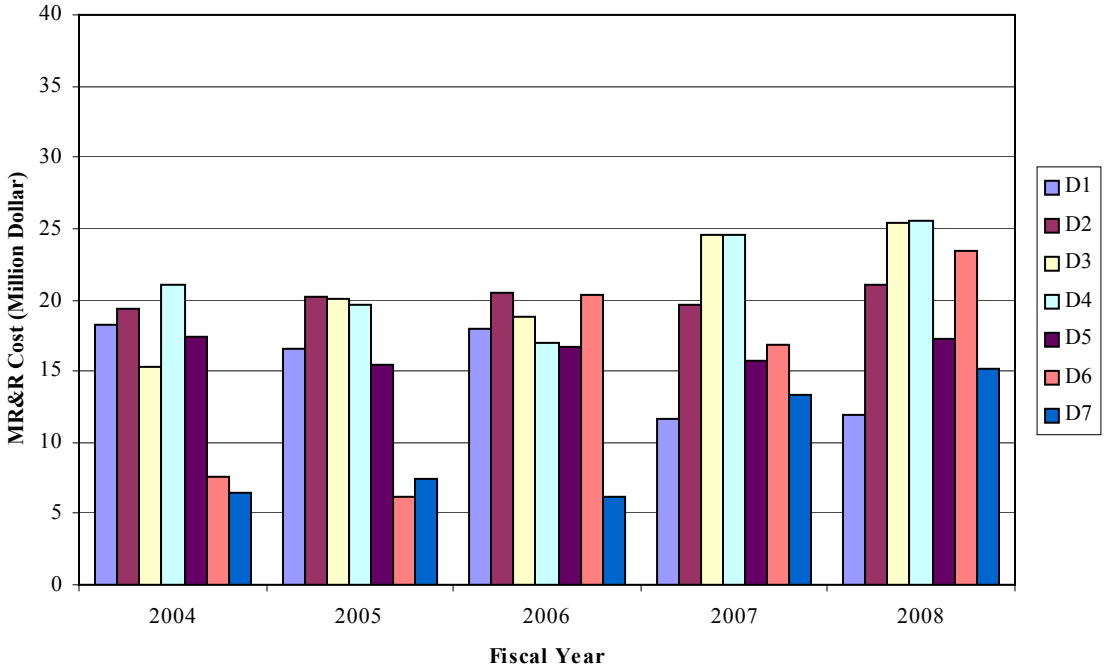


Figure 9 - 4 GDOT District Rehabilitation Cost Distribution for Case 3-1

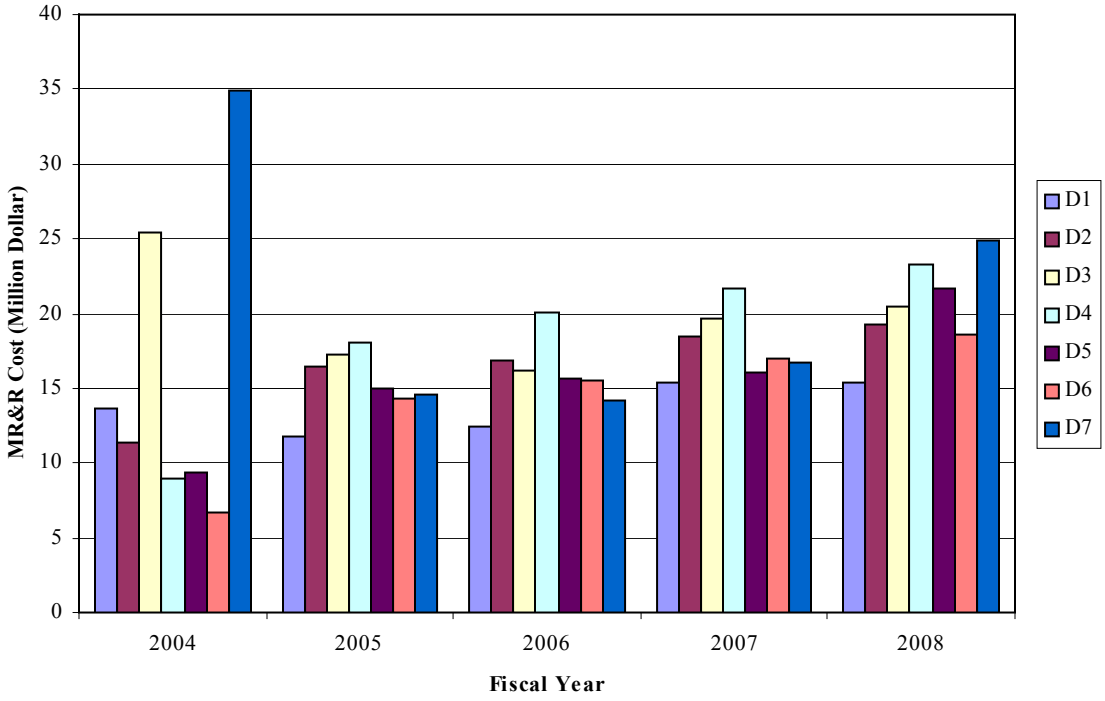


Figure 9 - 5 GDOT District Rehabilitation Cost Distribution for Case 3-2

CHAPTER 10

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter provides a summary and conclusions of the research work presented in this dissertation, and then proposes recommendations for future research.

10.1 Summary and Conclusions

This dissertation presented a GIS-enabled multi-year pavement rehabilitation needs analysis system and a companion computer program (NEEDAS Program) developed for GDOT. The program can perform multi-year, long-term pavement rehabilitation needs analysis for the Georgia state highway system subject to funding availability, performance requirements, and balancing constraints. The research performed includes a literature review of pavement needs analyses, formulation of the concept, development of the algorithm, and the system development and programming of the computer program.

The GDOT historical pavement condition survey data is the foundation for the NEEDAS program. Due to the importance of the historical pavement condition survey data, Chapter 3 presents the data sources and the detailed data error screening and data conversion processes. Chapters 4 to 7 present the detailed algorithm, methodology, modeling, and system development for the multi-year pavement rehabilitation needs analysis system developed specifically for GDOT. Chapter 4 describes the framework for the NEEDAS system. The system includes three modules: Project-level Analysis Module, Network-level Analysis Module and GIS Module. The pavement rehabilitation

needs analysis is performed through the interaction between the Project-level Analysis Module and the Network-level Analysis Module. Chapter 5 presents the main components of the Project-level Analysis Module, which includes developing the functions for determining rehabilitation treatment methods and costs and models for forecasting future project performance and calculating life cycle cost effectiveness ratios for each pavement project within the network. Chapter 6 presents the detailed algorithm for performing the network-level needs analysis. Chapter 7 presents the GIS Module, which integrates dynamically the graphic information in GIS maps and the needs analysis results obtained from both the Project-level Analysis Module and the Network-level Analysis Module seamlessly to support effective decision-making. The framework and methodology of interactive map-based what-if needs analysis using the GIS Module is also developed and presented in Chapter 7. Chapter 8 presents an overall picture of the NEEDAS computer program. Chapter 9 presents several case studies to illustrate the versatility and flexibility of the NEEDAS computer program in performing and analyzing multi-year rehabilitation needs.

Although further study is needed to verify and validate the models and functions in the system, the developed system provides a powerful tool for transportation agencies to develop multi-year pavement rehabilitation plans and has the potential of saving a significant amount of annual pavement rehabilitation budgets and achieving better pavement performance.

The following is a summary of the major advantages of the NEEDAS system developed over the other existing systems:

1. The system links network-level analysis results directly with project-level maintenance plans. The needs analysis system utilizes the historical pavement performance data of all the projects in the network and generates not only network-level results, such as rehabilitation costs and performance for statewide network, GDOT Districts, and State Congressional Districts, but also detailed project-level rehabilitation plans, such as when to treat, where to treat, and what treatment method to use.

2. GIS technology is fully utilized in the NEEDAS system. The GIS technology integrates graphical information in the GIS maps and the needs analysis results obtained from the Project-level Analysis Module and the Network-level Analysis Module seamlessly. The MDS technology developed in linking linear features on GIS maps with database information dynamically has proven to be very efficient and feasible.

3. The NEEDAS system is one of the first pavement needs analysis systems that allows an engineer to perform interactive map-based what-if scenario analyses on multi-year pavement needs analysis. Performance of what-if scenario analyses by changing the years, locations, and methods of treatment strategies on pavement projects directly on the maps can be performed more effectively and intuitively.

4. The system allows the rehabilitation plans to balance pavement rehabilitation costs and performances among different political jurisdictions, such as GDOT statewide, GDOT Districts, and State Congressional Districts.

5. The system can perform various types of analyses to develop multi-year rehabilitation plans subject to various budget and performance constraints together with the balancing constraints mentioned in (3) above.

6. Although the system was developed for GDOT, with slight modifications, the system can be used by engineers in other transportation agencies to perform the same analyses.

The following are the additional benefits for GDOT for implementing the NEEDAS system:

1. The system is compatible with the current practice used by GDOT and, thus, would minimize the efforts of migrating from the current practice of formulating multi-year rehabilitation plans to the new system.

2. Adaptability and flexibility in the system development and in the programming would allow for ease of updating and modifying the existing pavement performance models, treatment methods, and the State Congressional Districts

boundaries, and incorporating new treatment method and decision criteria into the system.

3. The design features, such as simple but effective interface design, effective control of input parameters, and practical and versatile output results, make the NEEDAS system more user friendly for ease of implementation. The efficient algorithms developed for the system result in the fast runtime, allowing the user to perform various scenarios for multi-year pavement needs analyses and to compare the results.

10.2 Recommendations for Future Research

The following research should be considered to further enhance the analysis and development of multi-year pavement rehabilitation plans.

1. The system and the various models incorporated into the system should be subject to rigorous calibration and validation to ensure that the models used in the system, such as the rehabilitation treatment method determination and the rehabilitation treatment costs, do accurately represent that the current GDOT practices and the results generated by the system are accurate. This would require a significant amount of effort as the validation and calibration would require using all the historical information on the actual rehabilitation plans and costs used by GDOT in the past.

2. Sensitivity analysis, such as AADT increasing rate, pavement rating forecasting models, pavement distress deduct values forecasting models, unit costs, etc, should be performed to identify the major factors that have greater impact on the needs analysis.

3. The present system uses a deterministic pavement performance/deterioration model. Incorporating a probabilistic pavement performance/deterioration model, such as Markov Chain model, in the system can be complementary to the existing system.

4. The current COPACES Database does not contain information on truck traffic. It is recommended that NEEDAS incorporates the truck traffic for establishing treatment determination criteria and pavement performance models.

5. The current system utilizes a prioritization method to perform the needs analysis. The alternate approach of using optimization methods can be investigated to evaluate the feasibility of incorporating these methods in the multi-year rehabilitation need analysis system.

6. In order to predict project rating after treatment, NEEDAS assumes all taken-treatment-actions are completed in one year. It is suggested that the actual durations of let projects can be incorporated.

7. The funding cycle for NEEDAS is currently yearly-based which is the one used by GDOT. Different funding cycles (e.g. six months) can be analyzed to evaluate their impacts on project selection, future performance, and costs after slightly modifying the current NEEDAS.

8. Improvements of the NEEDAS program to incorporate additional features and capabilities to the program could be needed. These could include:

    - Develop additional balancing constraints, such as balancing both pavement performance and costs among different jurisdictions.

    - Asphalt pavement shoulder widening is not considered in the NEEDAS system. It can be incorporated into NEEDAS system in the future.

    - The pavement needs analysis system developed in this dissertation focuses on only pavement physical condition, which is the core of pavement management. However, the analysis could be extended in the future to incorporate traffic volume, functional need, and user cost.

APPENDIX A

FORMULATION OF ADOT'S NEEDS ANALYSIS OPTIMIZATION MODEL

The optimization model of the ADOT needs analysis system was developed based on Markov Chain model. The Markov Chain was named after Andrei Andreyevich Markov (1856 – 1922). It was first used by Markov to model the alteration of vowels and consonants in Russian literary works (Gillispie, 1990). Since then, the model has been used widely in operations research to study probabilistic-related phenomena. The Markov Chain was introduced into ADOT's model in 1970s to forecast future pavement performance when considering many uncertainties affecting the pavement performance, such as traffic load, environmental conditions, difficulties in quantifying the factors or parameters that affect pavement deterioration, errors associated with measuring pavement conditions, bias from subjective evaluations of pavement conditions, etc.

Figure A-1 illustrates how the Markov Chain process works. The condition of a pavement project at any time is represented by "state." The total number of pavement states is defined based on pavement classifications. In Figure A-1, a PCR from 1 to 100 is used to define "state," with each rating increment representing a pavement state. Other factors, such as traffic volume, weather conditions, and environmental factors, can also be combined with pavement conditions to define pavement states. More information regarding defining pavement states for use of the Markov Chain for pavement rehabilitation needs analysis can be found in various references (Golabi et al., 1982; Davis and Van Dine, 1989; Alviti et al., 1994; Butt et al., 1994; Gaspar, 1994; Ferreira et al., 2002; Wang et al., 2003). The Markov Chain assumes that the distribution of future

states depends only on the present state and not on how the present state is derived. Therefore, the pavement conditions in the second year can be predicted from the pavement conditions in the first year and the corresponding probability, and the pavement conditions in the third year can be predicted from that of the second year, and so on. For example, in Figure A-1, for a pavement in a state with PCR = 98 in the 1st year, there is a probability of $P_{98,100}$ that the pavement will be at a state PCR=100 in the second year. Therefore, if the transition probabilities $P_{98,i}$ for the first year PCR at PCR=98 to have PCR=i in the second year are known, the expected pavement states in the 2nd year of a pavement project with current PCR=98 can be calculated as:

$$\text{Expected PCR in the 2nd year} = \sum_{i=1}^{100} i \cdot P_{98,i} \qquad \text{(A-1)}$$

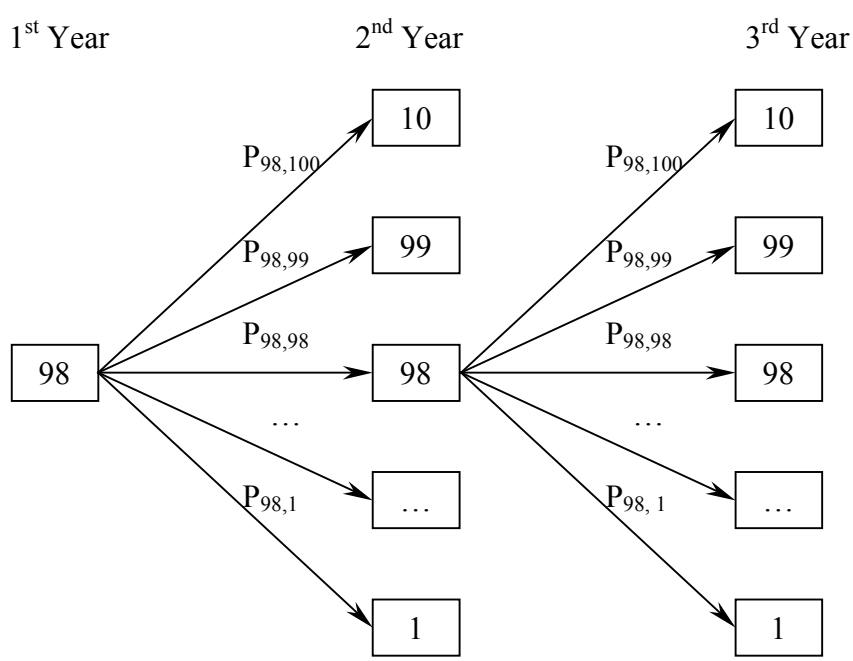


Figure A - 1 Illustration of the Markov Chain Pavement Performance Model for PCR=98 in the first year

Similar process can be repeated in the 3rd and succeeding years. Thus, the future pavement condition can be predicted.

All probabilities of transferring among different states are referred to as transition probabilities. So, the key for the Markov Chain model is to obtain the one-step transition probability matrix, as shown in Figure A-2. The transition probability matrix shown in Figure A-2 is for one distinct pavement category. Therefore, the total number of transition probability matrixes depends on the total number of rehabilitation treatment alternatives and pavement under different traffic categories. The more rehabilitation treatment alternatives and the more traffic categories, the more number of transition probability matrixes are needed.

		PCR in the next year				
		100	99	98	...	1
PCR in current year	100	$P_{100,100}$	$P_{100,99}$	$P_{100,98}$	...	$P_{100,1}$
	99	$P_{99,100}$	$P_{99,99}$	$P_{99,98}$	...	$P_{99,1}$
	98	$P_{98,100}$	$P_{98,99}$	$P_{98,98}$	...	$P_{98,1}$
	...	...	...	...	...	...
	1	$P_{1,100}$	$P_{1,99}$	$P_{1,98}$	...	$P_{1,1}$

Figure A - 2 Example of Transition Probability Matrix

Based on the Markov Chain, two interrelated models are built for ADOT's needs analysis system: the Long-Term Model and the Short-Term Model.

Long-Term Model

Equations (A-2) to (A-7) describe the details of the long-term model. Equation (A-2) is the objective function of the long-term model, which is to minimize the long-term rehabilitation costs. Equations (A-3) to (A-5) describe the properties of the Markov Chain model (w_{ia}) as discussed before. Equations (A-6) and (A-7) are annual performance constraints. Equation (A-6) indicates that if pavement condition in pavement category i is in a acceptable state, the proportion of pavements in pavement category i must be greater than a threshold value ε_i, a minimum of portion of pavements in this pavement category needs to be treated annually. Equation (A-7) indicates that if the pavement condition in pavement category i is unacceptable, the proportion of pavement road in pavement category i must be less than a threshold value γ_i. The long-term model is, therefore, to minimize (A-2) and satisfy (A-3) to (A-7). The solution of the long-term model will include not only the minimum budget (C) needed in the long term, but also the proportion of pavements in each pavement i to be treated by action a in the long term (denoted as w_{ia}^*).

Minimize $$\sum_i \sum_a w_{ia} c(i,a) \qquad \text{(A-2)}$$

Subject to

(1): Continuity constraints

$$w_{ia} \geq 0 \quad \text{for all i and a} \qquad \text{(A-3)}$$

$$\sum_i \sum_a w_{ia} = 1 \qquad \text{(A-4)}$$

$$\sum_a w_{ja} = \sum_i \sum_a w_{ia} p_{ij}(a) \text{ for all j} \tag{A-5}$$

(2): Annual performance constraints

$$\sum_a w_{ia} \geq \varepsilon_i \quad \text{if i is acceptable} \tag{A-6}$$

$$\sum_a w_{ia} \leq \gamma_i \quad \text{if i is unacceptable} \tag{A-7}$$

Where, i: a pavement road category;

a: pavement rehabilitation action

$w_{ia} = \lim_{n \to \infty} P[X_n = i, a_n = a]$: the limiting probability that the road will be in state i and action a will be chosen when policy π is followed

w_{ia}^*: the optimal steady-state decision variables, obtained from long-term model

c(i,a): the maintenance cost of a mile-segment when the road is in state i and maintenance action a is chosen

$p_{ij}(a)$: probability of moving from pavement state i to j in one year under rehabilitation action a

ε_i: minimum requirement of the proportion of roads in acceptable state i

γi: maximum allowance of the proportion of roads in unacceptable state i

Short-Term Model

Under certain circumstances, ADOT might not be able to follow steady-state policies in a particular year, such as if a large proportion of roads needed immediate repair but were not recommended by the steady-state policies. Therefore, the short-term

model was developed to solve such problem to allow the network to be upgraded to long-term standards after T years while using the rehabilitation plans developed by the short-term model during the first T-years. The short-term model is formulated as another linear programming by Equations (A-8) to (A-17). Equation (A-8) is the objective function, which is to minimize the total budget for the entire T years analysis period, in which α is used to consider the time value of budgets spent on different years. Equations (A-9) to (A-17) are constraints. Equations (A-9) to (A-11) are similar as Equations (A-3) to (A-5), which are used to describe the properties of the Markov Chain model. Equation (A-12) represents the initial pavement conditions. Equations (A-13) to (A-15) describe the budget constraints based on the results of the Long-Term Model. Equation (A-15) indicates that the budget requirement after T years should not be greater than certain ranges of steady-state budget requirements. Equations (A-16) and (A-17) limit the proportion of pavement categories after T years' analysis must be within certain ranges of the long-term pavement condition obtained from the Long-Term Model, similar to Equations (A-6) and (A-7).

$$\text{Minimize} \sum_{k=1}^{T} \sum_{i} \sum_{a} \alpha^{k} w_{ia}^{k} c(i,a) \tag{A-8}$$

Subject to

(1) Continuity constraints:

$$w_{ia}^{k} \geq 0 \quad \text{for all i, a, k=1, 2, …, T} \tag{A-9}$$

$$\sum_i \sum_a w_{ia}^k = 1 \quad \text{for all k=1, 2, …, T} \tag{A-10}$$

$$\sum_a w_{ja}^k = \sum_i \sum_a w_{ia}^{k-1} p_{ij}(a) \quad \text{for all j and k=1, 2, …, T} \tag{A-11}$$

$$\sum_a w_{ia}^1 = q_i^1 \quad \text{for all i} \tag{A-12}$$

(2) Maintenance cost constraints:

$$\sum_a w_{ja}^T \geq \sum_a w_{ia}^* (1-\phi) \quad \text{for all j} \tag{A-13}$$

$$\sum_a w_{ja}^T \leq \sum_a w_{ia}^* (1+\phi) \quad \text{for all j} \tag{A-14}$$

$$\sum_i \sum_a w_{ja}^T c(i,a) \leq C(1+\psi) \tag{A-15}$$

(3) Annual performance constraints:

$$\sum_a w_{ia}^k \geq \varepsilon_i' \quad \text{if i is acceptable, k=2, …, T-1} \tag{A-16}$$

$$\sum_a w_{ia}^k \leq \gamma_i' \quad \text{if i is unacceptable, k=2, …, T-1} \tag{A-17}$$

Where, α: a discount factor;

T: analysis period

$q^1{}_i$: the proportion of roads that is in state i in the beginning of the period, known

w_{ja}^* : the optimal steady-state decision variables, obtained from long-term model.

ϕ, ψ: the specified tolerance between calculated results and the steady-state results

C: the steady-state average cost

ε_i': minimum requirement of the proportion of roads in acceptable state i of the short-term model

γ_i': maximum allowance of the proportion of roads in unacceptable state i of the short-term model

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