Development of a Comprehensive Framework for the Efficiency Measurement of Road Maintenance Strategies using Data Envelopment Analysis

by

Mehmet Egemen Ozbek

Dissertation Submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Civil Engineering

Submitted to:
Dr. Jesus M. de la Garza, Chair
Dr. Michael C. Vorster
Dr. Anthony D. Songer
Dr. Konstantinos Triantis
Dr. Eileen M. Van Aken

September 19, 2007
Blacksburg, Virginia

Keywords: Road Maintenance, Asset Management, Performance Measurement, Efficiency Measurement, Data Envelopment Analysis, Performance-Based Contracts

Development of a Comprehensive Framework for the Efficiency Measurement of Road Maintenance Strategies using Data Envelopment Analysis

Mehmet Egemen Ozbek

ABSTRACT

For the last two decades, the road maintenance concept has been gaining tremendous attention. This has brought about new institutional changes, predominant of which is the challenge for maintenance managers to achieve maximum performance from the existing road system. Such challenge makes it imperative to implement comprehensive systems that measure road maintenance performance. However, the road maintenance performance measurement systems developed and implemented by researchers and state departments of transportation (DOTs) mainly focus on the effectiveness measures, e.g., the level-of-service. Such measurement systems do not sufficiently elaborate on the efficiency concept, e.g., the amount of resources utilized to achieve such level-of-service. Not knowing how “efficient” state DOTs are in being “effective” can lead to excessive and unrealistic maintenance budget expectations. This issue indicates the need for a performance measurement approach that can take the efficiency concept into account.

Another important concept that is not investigated in the current road maintenance performance measurement systems is the effect of the environmental factors (e.g., climate, location, and etc.) and operational factors (e.g., traffic, load, design-construction adequacy, and etc.) on the performance of the road maintenance process. This issue, again, indicates the need for a performance measurement approach that can take such external and uncontrollable factors into account.

The purpose of this research is to develop and implement a comprehensive framework that can measure the relative efficiency of different road maintenance strategies given the (i) multiple inputs and outputs that characterize the road maintenance process and (ii) uncontrollable factors (e.g., climate, traffic, etc.) that affect the performance of such process. It is challenging to measure the overall efficiency of a process when such process is a multiple input-multiple output process and when such process is affected by multiple factors. To address this challenge, an

innovative approach to efficiency measurement, Data Envelopment Analysis, is used in this research.

It is believed that this research, by taking the efficiency concept into account, will significantly improve the ways that are currently used to model and measure the performance of road maintenance. The findings of this research will contribute new knowledge to the asset management field in the road maintenance domain by providing a framework that is able to differentiate effective and efficient maintenance strategies from effective and inefficient ones.

DEDICATION

To the memory of my both grandfathers: **Mehmet Ertekin** and **Riza Ozbek**

ACKNOWLEDGMENTS

I would like to start by stating my sincere appreciation to **Dr. Jesus M. de la Garza**, the chairman of my advisory committee. Under his supervision for the last 5 years, I have learned more lessons than I did or can learn in any 5-year time span of my life, past or future. These lessons helped me to progress not only towards my academic goals but also towards becoming a mature individual (even though I do not claim to be "there" yet). He has been a great example for me as an individual who is detail-oriented and on top of the big picture at the same time (which may sound as an oxymoron but which, I think, is the key to be successful). He has been the main inspiration for me in deciding to pursue a PhD degree after my M.S. degree three and a half years ago and now to pursue an academic career. He has taught me the importance of keeping a freezer next to the printer (so that the print-outs can cool faster before I hand them to him) and the moral of the "Napoleon Bonaparte Story". Above all, he has shown me how to get so much excited and interested in every single task that I have undertaken as a part of my graduate studies. As I told him earlier, it was truly an "honor" to be a graduate student of his. I hope I can be as great of an advisor as he is.

In addition to having the "great advisor", I was also very lucky to have the great "advisory committee" (or as I would like to refer to it as the "synergy committee") which I would highly recommend to any fellow PhD degree pursuer. I owe each of my committee members a number of sections of this dissertation. It was their thought-provoking questions and pointing out the overlooked issues that made this research meet its objectives. I would like to extend my gratitude to **Dr. Michael Vorster** for bringing up the issues that I have missed, for providing some real life examples which helped me to understand the issues that I was struggling with, for telling me anecdotes from his own graduate school experience that I will make sure to pass on to the next generations by quoting him, and for assuring me that "*the numbers will change if I keep on looking at the computer screen*". I am grateful to **Dr. Konstantinos Triantis** for teaching me what Data Envelopment Analysis (DEA) is all about, for giving a whole new direction to my research at the initial stage, for always asking challenging questions for my own benefit, for making me produce papers and a proposal, for hosting very *productive* (pun intended) meetings in his office in Northern Virginia, and due to all of the abovementioned matters for being like a co-advisor to me. I would like to thank **Dr. Eileen Van Aken** for introducing me to the concept

(DEA) that materialized this research, for providing me with papers that she authored even before they are published, and for making every effort to be available whenever I requested even though she has a very busy schedule with administrative duties. Last but not least, I would like to thank **Dr. Anthony Songer** for teaching me a very valuable lesson which basically states that *it is not the end product that matters, but the journey in reaching the PhD degree*. I cannot tell him how many times this little lesson helped me to address the problems I have encountered as I knew that those were the parts of the journey that I was within and thus I had to overcome them to deserve the PhD degree.

Even though he was not in my advisory committee, **Dr. Richard Groesbeck** has been very helpful just like my committee members. I would like to thank him for being very patient with me during the numerous meetings that we had at the initial stage of this research. Special thanks go to all past and present members of the infamous A-Team, specifically to **Juan Pinero**, **Adrian Burde**, **Nikhil Ambani**, **Emily Prince**, **Walter Fedrowitz**, and **Sercan Akyildiz**.

I would like to acknowledge the **Virginia Department of Transportation** (**VDOT**) for providing the financial support to make this research possible and specifically **Dr. James Bryant** and **Mr. Clinton Simpson** for making available the data used in this research.

Of course, the **family** is above all. "Thanks for everything" goes to my mom, **Tulay Ozbek**, my dad, **Ahmet Ozbek**, my sister, **Burcu Akinci**, and my second family's members **Ayla Omur**, **Ilhami Omur**, **Mehmet Akinci**, and **Ece Omur**.

Finally, my dear wife- soon to be "Dr." **Pinar Omur-Ozbek**: Since the time you jokingly indicated that my thanking you in the last paragraph of the Acknowledgments section of my M.S. Thesis was *unfair*, I have gone through countless theses and dissertations. In each of them, sweethearts (Number 1s) were always left to the last. I am not violating this academic tradition and once again acknowledging you the last; as you are really the first of everything in my life. There is no way to thank you for all the things that you have done for me for over a decade now. I cannot think of the place I would be if you were not with me. Therefore, I think this one sentence says it all: *Thank you for being with me in the past, present, and future*.

TABLE OF CONTENTS

LIST OF FIGURES ..... **XI**

LIST OF TABLES ..... **XII**

CHAPTER 1- INTRODUCTION **1**

1.1 BACKGROUND 1
1.2 PATH LEADING TO THIS RESEARCH 3
1.3 MOTIVATION FOR THIS RESEARCH AND PROBLEM STATEMENT 6
1.4 PURPOSE, OBJECTIVES, AND HYPOTHESES 8
1.5 SCOPE 13
1.6 SPECIFIC STEPS TO ACHIEVE THE PURPOSE 14
1.7 OVERVIEW OF DATA ENVELOPMENT ANALYSIS 16
1.8 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE 18
1.8.1 Contributions to the Body of Knowledge in the Highway Maintenance Domain 18
1.8.2 Contributions to the Body of Knowledge in the Performance Measurement Domain 19
1.9 ORGANIZATION OF THE DISSERTATION 20

CHAPTER 2- LITERATURE REVIEW **22**

2.1 PERFORMANCE MEASUREMENT IN GENERAL 22
2.2 PREVIOSULY DEVELOPED PERFORMANCE MEASUREMENT FRAMEWORKS AND METHODS 25
2.2.1 Previously Developed Performance Measurement Frameworks 26
2.2.1.1 Kaplan and Norton's Balanced Scorecard Approach 26
2.2.1.2 Mark Graham Brown's Scorecard Approach 27
2.2.1.3 Performance Prism Approach 27
2.2.1.4 Baldrige 2006 Criteria for Performance Excellence 28
2.2.1.5 Department of Energy Performance Measurement Program 28
2.2.2 Previously Developed Performance Measurement Methods 29
2.3 PERFORMANCE MEASUREMENT OF HIGHWAY MAINTENANCE IN USA 30
2.3.1 Current State of Highway Maintenance in USA 30
2.3.2 Asset Management in USA 32
2.3.3 NCHRP 14- 12: Highway Maintenance Quality Assurance Program 33
2.4 HIGHWAY MAINTENANCE PERFORMANCE MEASUREMENT PROGRAMS USED BY VDOT 37
2.5 DATA ENVELOPMENT ANALYSIS (DEA) 39
2.5.1 Overview of the Productivity Theory 40
2.5.2 Basic DEA Models and Formulations 42
2.5.2.1 Primal CCR Models 46
2.5.2.2 Dual CCR Models 55
2.5.2.3 Returns to Scale Issue and BCC Models 60
2.5.3 Issues Related to DEA 64
2.5.3.1 General Notes on DEA 64
2.5.3.2 Major Phases of DEA 66
2.5.3.3 Strengths and Limitations of DEA 73
2.5.3.4 Computer Support for DEA 74
2.6 EARLIER WORK POSSESSING APPLICATION OF DEA TO HIGHWAY MAINTENANCE 75
2.6.1 Measurement and Monitoring of Relative Efficiency of Highway Maintenance Patrols using DEA- by Cook et al. (1990 and 1994) 75
2.6.2 Measuring Highway Maintenance Performance using DEA- by Rouse et al. (1997) 79
2.7 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE 81
2.7.1 Contributions to the Body of Knowledge in the Performance Measurement and DEA Area 81
2.7.2 Contributions to the Body of Knowledge in the Highway Maintenance Area 83
2.8 THE POTENTIAL OF THE SYSTEM DYNAMICS APPROACH TO BE UTILIZED IN THIS RESEARCH 84

CHAPTER 3- METHODOLOGY **91**

3.1 OVERVIEW OF THE HIGHWAY MAINTENANCE PROCESS IN GENERAL 92

3.1.1 Definition of Highway Maintenance Process and Types of Highway Maintenance 92
3.1.2 Deferred Highway Maintenance 96
3.2 OVERVIEW OF THE PROCESSES PERFORMED FOR THE LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS...97
3.3 THE APPROACH UTILIZED TO DEFINE CONTROLLABLE VARIABLES TO BE USED FOR THE LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS...101
3.4 THE APPROACH UTILIZED TO DEFINE UNCONTROLLABLE FACTORS TO BE USED FOR THE LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS...104
3.5 THE COMPREHENSIVE LIST OF CONTROLLABLE VARIABLES AND UNCONTROLLABLE FACTORS FOR LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS.......................106
3.6 THE APPROACH UTILIZED TO REFINE THE COMPREHENSIVE LISTS OF CONTROLLABLE VARIABLES AND UNCONTROLLABLE FACTORS...114
3.6.1 Approaches that can be utilized to Refine the Comprehensive List of Variables...................................115
3.6.1.1 Judgmental Process 115
3.6.1.2 Quantitative Methods 119
3.6.1.3 DEA Based Analyses 124
3.6.2 Applicability of the Approaches to Refine the List of Variables established for the Comprehensive Highway Maintenance Efficiency Measurement Framework 127
3.7 THE APPROACH UTILIZED TO DEAL WITH UNCONTROLLABLE FACTORS..................................129
3.7.1 Approaches that can be utilized to Deal with Uncontrollable Factors within a DEA Study..................130
3.7.1.1 One Stage Approaches 131
3.7.1.1.1 Uncontrollable Factors treated as Controllable Variables in the DEA Model.......................... 131
3.7.1.1.2 Uncontrollable Factors treated as Uncontrollable Variables in the DEA Model...................... 131
3.7.1.1.3 Uncontrollable Factors used to Develop Categories of DMUs to be included in the DEA Models 134
3.7.1.1.4 Continuous Uncontrollable Factors used to Restrict the Peer Reference Set 135
3.7.1.2 Multi Stage Approaches.. 136
3.7.1.2.1 Uncontrollable Factors used to Perform Regression Analysis over the Obtained Efficiency Scores........ 136
3.7.1.2.2 Parameters Obtained by the Regression Analysis used to Build an Overall Environmental Harshness Index 138
3.7.1.2.3 Uncontrollable Factors used to Perform Bootstrapped Regression Analysis over the Obtained Efficiency Scores 140
3.7.2 Applicability of the Approaches to Deal with the Uncontrollable Factors Identified for the Comprehensive Highway Maintenance Efficiency Measurement Framework...142
3.8 THE APPROACH UTILIZED TO CHOOSE THE TYPE OF DEA MODELS TO BE RUN.........................145
3.9 THE USE OF DEA IN THIS RESEARCH VERSUS COMMON DEA STUDIES 147
3.10 THE UTILIZATION OF COST VERSUS PRICE FOR THE DEA MODELS OF THE CONTRACTOR WORKING UNDER PERFORMANCE-BASED MAINTENANCE 148
3.11 THE ISSUE OF COST ADJUSTMENTS FOR THE DEA ANALYSES INCLUDING DIFFERENT PERIODS AND DIFFERENT GEOGRAPHIC LOCATIONS 151
3.11.1 Cost Adjustments to Address Different Periods 151
3.11.2 Cost Adjustments to Address Different Geographic Locations..154
3.12 SUMMARY AND OVERVIEW OF THE DEVELOPED FRAMEWORK 155

CHAPTER 4- HYPOTHESIS TESTING: IMPLEMENTATION OF THE FRAMEWORK 157

4.0 SOURCES OF DATA...157
4.0.1 Level-of-Service Data..157
4.0.2 Cost Data 160
4.1 APPLICATION OF THE FRAMEWORK TO THE “BRIDGES” ELEMENT OF THE LEVEL-OF-SERVICE COMPONENT FOR THE MAINTENANCE PERFORMED BY TRADITIONAL METHODS........................161
4.1.1 Comprehensive Lists of Variables and DMUs 161
4.1.1.1 Comprehensive List of Variables.. 162
4.1.1.2 Comprehensive List of DMUs 164
4.1.2 Final Lists of Variables and DMUs to be included in the DEA Model 165
4.1.2.1 Final List of Variables to be included in the DEA Model.. 165
4.1.2.2 Final List of DMUs to be included in the DEA Model 170
4.1.3 Data Preparation Process...171
4.1.3.1 Step 1- Data Gathering.. 171

4.1.3.2 Step 2- Data Mining ... 173
4.1.3.3 Step 3- Data Cleaning ... 174
4.1.3.4 Step 4- Data Conversion/Rearrangement ... 176
4.1.3.4.1 Converting the "Bridge Cost Data" to Represent the Variable "Cost for Maintaining the Bridges" ... 176
4.1.3.4.1.1 Problems with Obtaining the Complete Cost Data ... 176
4.1.3.4.1.2 Remedies and Assumptions to Resolve the Cost Data Issue ... 178
4.1.3.4.2 Rearranging the "Bridge Condition Data" to Represent the Variable "Change in Overall Bridge Condition" ... 179
4.1.4 DEA Model Selection, Final Refinements in Data and Results of DEA ... 183
4.1.5 Conclusions ... 188
4.1.6 Findings Gathered from the Further Analyses ... 189
4.1.6.1 Reducing the Number of Variables ... 189
4.1.6.2 Increasing the Number of DMUs ... 191
4.1.6.3 Excluding the DMUs that Belong to the Roanoke County from the Analysis ... 200
4.1.7 Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency ... 204
4.2 APPLICATION OF THE FRAMEWORK TO THE "PAVED LANES" ELEMENT OF THE LEVEL-OF-SERVICE COMPONENT FOR THE MAINTENANCE PERFORMED BY TRADITIONAL METHODS ... 209
4.2.1 Comprehensive Lists of Variables and DMUs ... 210
4.2.1.1 Comprehensive List of Variables ... 210
4.2.1.2 Comprehensive List of DMUs ... 212
4.2.2 Final Lists of Variables and DMUs to be included in the DEA Model ... 213
4.2.2.1 Final List of Variables to be included in the DEA Model ... 213
4.2.2.2 Final List of DMUs to be included in the DEA Model ... 216
4.2.3 Data Preparation Process ... 217
4.2.3.1 Step 1- Data Gathering ... 217
4.2.3.2 Step 2- Data Mining ... 219
4.2.3.3 Step 3- Data Cleaning ... 221
4.2.3.4 Step 4- Data Conversion/Rearrangement ... 222
4.2.3.4.1 Converting the "Paved Lanes Cost Data" to Represent the Variable "Cost for Maintaining the Paved Lanes" ... 222
4.2.3.4.2 Rearranging the Interstate ADT Data ... 222
4.2.3.4.3 Rearranging the "Paved Lanes Condition Data" to Represent the Variables "Change in CCI" and "Change in IRI" ... 224
4.2.4 DEA Model Selection, Final Refinements in Data and Results of DEA ... 227
4.2.5 Conclusions ... 233
4.2.6 Analysis Excluding the "Modified Change in CCI" Output Variable ... 237
4.2.7 Comparison of the Results of the 2 DEA Models for the Paved Lanes and Overall Conclusions ... 245
4.2.8 Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency ... 247
4.3 APPLICATION OF THE FRAMEWORK TO THE "FENCE TO FENCE ASSET GROUPS" ELEMENT OF THE LEVEL-OF-SERVICE COMPONENT FOR THE MAINTENANCE PERFORMED BY TRADITIONAL METHODS ... 253
4.3.1 Comprehensive Lists of Variables and DMUs ... 253
4.3.1.1 Comprehensive List of Variables ... 254
4.3.1.2 Comprehensive List of DMUs ... 255
4.3.2 Final Lists of Variables and DMUs to be included in the DEA Model ... 256
4.3.2.1 Final List of Variables to be included in the DEA Model ... 256
4.3.2.2 Final List of DMUs to be included in the DEA Model ... 259
4.3.3 Data Preparation Process ... 261
4.3.3.1 Step 1- Data Gathering ... 261
4.3.3.2 Step 2- Data Mining ... 265
4.3.3.3 Step 3- Data Cleaning ... 268
4.3.3.4 Step 4- Data Conversion/Rearrangement ... 269
4.3.3.4.1 Converting the "Asset Groups Cost Data" to Represent the Variable "Cost for Maintaining the Asset Groups" ... 269
4.3.3.4.2 Rearranging the "County Precipitation Data" to Represent the Variable "Climate-Precipitation Amount" ... 270
4.3.3.4.3 Rearranging the "Interstate ADT Data" to Represent the Variable "Traffic-Count" ... 272
4.3.3.4.4 Rearranging the "Asset Groups Condition Data" to Represent the Variable "Change in LOS Rating Percentage" ... 273
4.3.4 DEA Model Selection, Final Refinements in Data and Results of DEA ... 277
4.3.5 Conclusions ... 282

4.3.6 Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency.............................*285*

CHAPTER 5- CONCLUDING REMARKS 291

5.1 SUMMARY OF THE RESEARCH 291
5.2 FINDINGS OF THE RESEARCH 293
5.3 DATA AVAILABILITY ISSUES THAT PREVENTED THE FURTHER IMPLEMENTATION OF THE FRAMEWORK TO DIFFERENT CASES 298
5.4 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE AND THE OVERALL IMPORTANCE OF THE STUDY 299
5.4.1 Contributions to the Body of Knowledge *299*
5.4.1.1 Contributions to the Body of Knowledge in the Highway Maintenance Domain 299
5.4.1.2 Contributions to the Body of Knowledge in the Performance Measurement Domain...................... 301
5.4.2 Overall Importance of the Study *302*
5.5 RECOMMENDATIONS 305
5.5.1 Recommendations for Using the Results Obtained through Implementation of the Framework *305*
5.5.2 Recommendations for a Better Cost Data Collection and Recording System that would accommodate the needs of the Framework..*306*
5.5.3 Recommendations to Address the Issue of Uncontrollable Factors..*307*
5.6 POSSIBLE FUTURE RESEARCH AREAS..308
5.6.1 Developing Modules for the Highway Maintenance Efficiency Measurement Framework....................*308*
5.6.2 Collecting Data and Implementing the Framework to Other Cases..*309*
5.6.3 Collecting Data and Implementing the Framework for the Timeliness of Response Component...........*310*
5.6.4 Using Quality of Service as the Output of the Highway Maintenance Process *311*
5.6.5 Using the Efficiency and Effectiveness Results Simultaneously for Decision-Making............................*311*
5.6.6 Using Iso-Output Curves to Identify the Effect of Cost on Efficiency *314*
5.6.7 Including Undesirable Outputs in the DEA Models..*316*
5.6.8 Ranking Efficient Units among Themselves *317*
5.6.9 Combining Statistics with DEA..*317*
5.6.10 Imprecise Data Envelopment Analysis (IDEA) and Fuzzy DEA *318*
5.6.11 Tools to Deal with the Dynamic Nature of the Highway Maintenance Process *318*

BIBLIOGRAPHY..320

VITA 333

LIST OF FIGURES

Figure 1.1: Key Components of the Framework for Performance Evaluation (Piñero 2003, p. 47)....................5
Figure 1.2: Relationship between the Motivation, Problem Statement, Purpose, and Contribution to BOK...12
Figure 1.3: Components of Piñero's Framework that are in the Scope of this Research....................................14
Figure 1.4: DEA Model with Single Input and Single Output (de la Garza et al. 2005)......................................17
Figure 2.1: Input Isoquant illustrating the Efficient Frontier 41
Figure 2.2: Plot to Solve the Example LP Graphically...50
Figure 2.3: Normalized Inputs of the DMUs 52
Figure 2.4: Efficient Frontier as defined in DEA 53
Figure 2.5: Efficient Frontier when DMUs are Experiencing Constant Returns to Scale 61
Figure 2.6: Efficient Frontier when DMUs are Experiencing Variable Returns to Scale 62
Figure 2.7: A Preliminary System Dynamics Model of Highway (Pavement) Maintenance (Adopted From Burde et al. (Burde et al. 2005, p.69)) 86
Figure 3.1: Highway Maintenance Process Performed through MMS...94
Figure 3.2: Highway Maintenance Process and its Relation to the Level-of-Service and Timeliness of Response Components 98
Figure 3.3: Effects of Various Phenomena on the Level-of-Service Component 98
Figure 3.4: Effects of Various Phenomena on the Timeliness of Response Component....................................99
Figure 3.5: Process for Maintaining Paved Lanes 101
Figure 3.6: Metrics to be used in the DEA Model- Technical Efficiency 102
Figure 3.7: Metrics to be used in the DEA Model- Cost Efficiency..103
Figure 3.8: Groups of Uncontrollable Factors for the Level-of-Service Component..105
Figure 3.9: Groups of Uncontrollable Factors for the Timeliness of Response Component............................105
Figure 3.10: Flowchart for Reaching a Well-Refined List of Variables (Partially adopted from Golany and Roll (Golany and Roll 1989, p.240))...126
Figure 3.11: Depiction of the DEA Model with Uncontrollable Input 134
Figure 3.12: The Approach to be Followed to Choose the Type of DEA Models to be Run 147
Figure 3.13: Typical Breakdown of Cost to the state DOT for the Highway Maintenance 150
Figure 3.14: Components of the Road Maintenance Efficiency Measurement Framework 156
Figure 4.1: Environmental Regions of Virginia (Dadson 2001, p.30) 167
Figure 4.2: Typical Breakdown of Cost to VDOT for Routine Maintenance Activities for the Maintenance of the "Bridges" Element 176
Figure 4.3: Frontier Analyst Data Loading Step Screenshot...187
Figure 4.4: Frontier Analyst Results of the Model Screenshot..187
Figure 4.5: Peer Relationships of the DMUs for "Bridges" 197
Figure 4.6: Frontier Analyst Data Loading Step Screenshot-Paved Lanes 231
Figure 4.7: Peer Relationships of the DMUs for "Paved Lanes"...234
Figure 4.8: Frontier Analyst Data Loading Step Screenshot-Paved Lanes without "Modified Change in CCI" Variable...238
Figure 4.9: Peer Relationships of the DMUs for "Paved Lanes" without "Modified Change in CCI" Variable 241
Figure 4.10: Peer Relationships of the DMUs for "Asset Groups" 283
Figure 5.1: Combining Effectiveness and Efficiency Results...312
Figure 5.2: Input-Output Relationship for the Rockbridge and Spotsylvania Counties...................................315
Figure 5.3: Iso-Output Curves...316

LIST OF TABLES

Table 1.1: Level-of-Service Evaluation Elements and Details 4
Table 2.1: Input-Output Values for the Data Set...48
Table 2.2: Results of the Example DEA Problem obtained using the Primal CCR Formulation 51
Table 2.3: Inputs Normalized by the Output 51
Table 2.4: Summary of Multiplier and Envelopment Models 56
Table 2.5: Input-Output Values for 5 DMUs 61
Table 3.1: List of Asset Groups and Asset Items to be maintained by the Contractor and VDOT.................100
Table 3.2: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Level-of-Service Component...108
Table 3.2: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Level-of-Service Component (CONTINUED)...109
Table 3.2: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Level-of-Service Component (CONTINUED)...110
Table 3.3: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Timeliness of Response Component..111
Table 3.3: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Timeliness of Response Component (CONTINUED)...112
Table 3.4: Scale of Importance as utilized in AHP (Saaty 1980, p.54))..117
Table 3.5: Pairwise Comparison Matrix for the Highway Maintenance Input Variables 118
Table 3.6: Data for Public Utilities (Example Dataset within the *XLMiner Demo Edition 3.0.0* (QuantLink 2005))..121
Table 3.7: Results of the Application of PCA (Example Dataset within the *XLMiner Demo Edition 3.0.0* (QuantLink 2005))...122
Table 3.8: Specifics of the Cost and Price of the Maintenance Activities performed by the Transportation Agency and the Contractor 149
Table 3.9: FHWA Composite Bid Price Index for Highway Construction- National Level (FHWA 2006).....154
Table 4.0: Sources of the Level-of-Service Data for Asset Items...158
Table 4.1: The Comprehensive List of Input and Output Variables for the DEA Model of the Maintenance of the “Bridges” Element of the Level-of Service Component 163
Table 4.2: The Comprehensive List of DMUs for the DEA Model of the Maintenance of the “Bridges” Element of the Level-of-Service Component 165
Table 4.3: Effect of Environmental Region on the Deterioration of the Concrete Decks.................................168
Table 4.4: Final List of Variables to be used in the DEA Model for Bridges 170
Table 4.5: Final List of DMUs to be included in the DEA Model for Bridges..171
Table 4.6: Fauquier County’s Bridge Condition Data for Fiscal Year 2002 174
Table 4.7: Fauquier County’s Cost Data with respect to Bridges 174
Table 4.8: Fauquier County’s Bridge Condition Data for Combined Fiscal Years 2002 and 2003.................180
Table 4.9: The Condition Ratings and ADT for the Bridges within the Fauquier County at the County Level......181
Table 4.10: Bridge Weighting Scheme developed by Virginia Tech 181
Table 4.11: Overall Bridge Condition for the Fauquier County 181
Table 4.12: Change in Overall Bridge Condition for the Fauquier County...182
Table 4.13: Input and Output Variables’ Data for the Combined Fiscal Years of 2004 and 2005..................183
Table 4.14: Data to be used in the Input Oriented BCC Model for “Bridges” 186
Table 4.15: Detailed Results of the Input Oriented BCC Model (as Extracted from the Frontier Analyst) ...188
Table 4.16: Detailed Results of the Input Oriented BCC Model without the DMU $_{TAS}$ Variable.....................190
Table 4.17: Detailed Results of the Input Oriented BCC Model without the DMU $_{REGIONAL\ EFFECT}$ Variable...........190
Table 4.18.A: Data to be used in the DEA Model with DMUs as Counties of Individual Fiscal Years 194
Table 4.19: Detailed Results of the DEA Model with DMUs as Counties of Individual Fiscal Years (as Extracted from the Frontier Analyst) 195
Table 4.20: Overall Efficiency Scores of the Counties...195
Table 4.21.A: Detailed Results of the DEA Model with DMUs as Counties of Individual Fiscal Years (as Extracted from the Frontier Analyst) Excluding Roanoke County from the Analysis...........................203

Table 4.22.A: Overall Efficiency Scores of the Counties Excluding Roanoke County from the Analysis 203
Table 4.18.B: Data to be used in the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency 205
Table 4.21.B: Detailed Results of the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency 206
Table 4.22.B: Overall Efficiency Scores of the Counties for the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency 206
Table 4.21.C: Efficiency Scores of the DMUs obtained from both DEA Models for Bridges 207
Table 4.22.C: Overall Efficiency Scores of the Counties obtained from both DEA Models for Bridges 207
Table 4.23: The Comprehensive List of Input and Output Variables for the DEA Model of the Maintenance of the "Paved Lanes" Element of the Level-of Service Component 211
Table 4.24: The Comprehensive List of DMUs for the DEA Model of the Maintenance of the "Paved Lanes" Element of the Level-of-Service Component 213
Table 4.25: Final List of Variables to be used in the DEA Model for Paved Lanes 216
Table 4.26: Final List of DMUs to be included in the DEA Model for Paved Lanes 217
Table 4.27: Fauquier County's Paved Lanes Condition Data (for CCI) for Fiscal Year 2002 220
Table 4.28: Fauquier County's Paved Lanes Condition Data (for IRI) for Fiscal Year 2002 220
Table 4.29: Fauquier County's ADT information for Interstate 66 (I-66) 221
Table 4.30: Fauquier County's Cost Data with respect to Paved Lanes 221
Table 4.31: Fauquier County's Overall ADT for Interstate 66 (I-66) for Calendar Years 223
Table 4.32: Fauquier County's Overall ADT for Interstate 66 (I-66) for Fiscal Years 223
Table 4.33: The condition ratings (CCI and IRI) for the Paved Lanes within the Fauquier County at the County Level 224
Table 4.34: Change in Paved Lanes Condition for the Fauquier County 225
Table 4.35: Original and Adjusted "Change in IRI" Variable for the Fauquier County 226
Table 4.36: Input and Output Variables' Data for the Fiscal Years of 2003, 2004 and 2005 for Paved Lanes 227
Table 4.37.A: Data to be used in the Input Oriented BCC Model for "Paved Lanes" 230
Table 4.38: Detailed Results of the Input Oriented BCC Model for "Paved Lanes" (as Extracted from the Frontier Analyst) 232
Table 4.39: Overall Efficiency Scores of the Counties for "Paved Lanes" 232
Table 4.40.A: Detailed Results of the Input Oriented BCC Model for "Paved Lanes" without "Modified Change in CCI" Variable (as Extracted from the Frontier Analyst) 239
Table 4.41.A: Overall Efficiency Scores of the Counties for "Paved Lanes" without "Modified Change in CCI" Variable 239
Table 4.37.B: Data to be used in the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency 249
Table 4.40.B: Detailed Results of the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency 250
Table 4.41.B: Overall Efficiency Scores of the Counties for the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency 250
Table 4.40.C: Efficiency Scores of the DMUs obtained from both DEA Models for Paved Lanes 251
Table 4.41.C: Overall Efficiency Scores of the Counties obtained from both DEA Models for Paved Lanes 251
Table 4.42: The Comprehensive List of Input and Output Variables for the DEA Model of the Maintenance of the "Asset Groups" Element of the Level-of Service Component 254
Table 4.43: The Comprehensive List of DMUs for the DEA Model of the Maintenance of the "Asset Groups" Element of the Level-of-Service Component 256
Table 4.44: Final List of Variables to be used in the DEA Model for Asset Groups 259
Table 4.45: Final List of DMUs to be included in the DEA Model for Asset Groups 260
Table 4.46: Rockbridge County's Asset Groups Condition Data for Fiscal Year 2005 266
Table 4.47: Rockbridge County's Asset Density Database as updated in 2007 267
Table 4.48: Rockbridge County's ADT information for Interstate 64 (I-64) 267
Table 4.49: Rockbridge County's Cost Data with respect to Asset Groups 267
Table 4.50: List of the Weather Stations Used and Discarded 269
Table 4.51: Precipitation Data for Stations that belong to Rockbridge County 271

Table 4.52: Overall Precipitation Amounts for Stations that belong to Rockbridge County for Fiscal Years 2003, 2004, and 2005 271
Table 4.53: Overall Precipitation Amounts for Rockbridge County for Fiscal Years 2003, 2004, and 2005 271
Table 4.54: Rockbridge County's Overall ADT for Interstate 64 (I-64) for Calendar Years....272
Table 4.55: Rockbridge County's Overall ADT for Interstate 64 (I-64) for Fiscal Years....272
Table 4.56: The Condition Ratings at the Asset Item Level for the Rockbridge County for Fiscal Year 2005....274
Table 4.57: Asset Items and Groups Weighting Scheme Implemented by Virginia Tech....275
Table 4.58: The Level-of-Service Rating for the Rockbridge County for Fiscal Years 2002, 2003, 2004, and 2005 275
Table 4.59: Change in LOS Rating (for the asset groups) for the Rockbridge County....276
Table 4.60: Input and Output Variables' Data for the Fiscal Years of 2003, 2004 and 2005 for Asset Groups....277
Table 4.61.A: Data to be used in the Input Oriented BCC Model for "Asset Groups"....279
Table 4.62.A: Detailed Results of the Input Oriented BCC Model for "Asset Groups" (as Extracted from the Frontier Analyst)....281
Table 4.63.A: Overall Efficiency Scores of the Counties for "Asset Groups"....281
Table 4.61.B: Data to be used in the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency....287
Table 4.62.B: Detailed Results of the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency....288
Table 4.63.B: Overall Efficiency Scores of the Counties for the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency 288
Table 4.62.C: Efficiency Scores of the DMUs obtained from both DEA Models for Asset Groups 289
Table 4.63.C: Overall Efficiency Scores of the Counties obtained from both DEA Models for Asset Groups 289
Table 5.1: Overall Efficiency Scores for Each County and Each Model 294
Table 5.2: Overall Efficiency Scores for Each County and Each Model- Effects of Uncontrollable Factors.... 295
Table 5.3: Summary of the Results from the Relevant Models 297

CHAPTER 1- INTRODUCTION

This chapter starts off with the brief **background** presenting the establishment and the type of the highway maintenance contract which is the departure point of this research. Afterwards, it presents the **path leading to this research** in an effort to introduce the **motivation** behind the research and the **problem statement**. After this, the research's **hypothesis, scope, purpose** and **specific steps to achieve such purpose** are introduced. This is followed by an **overview of Data Envelopment Analysis**, the technique that is used in this research to address the stated problem. After that, this research's **contributions to the body of knowledge** are discussed. This chapter is concluded by the section presenting the **organization of this dissertation**.

1.1 BACKGROUND

In July 1995, the **Public-Private Transportation Act** (PPTA) of Virginia was passed. This act authorized the Commonwealth of Virginia (responsible public entity) to establish contracts with private entities to acquire, construct, improve, maintain, and/or operate one or more transportation facilities within the state of Virginia. PPTA further states that this approach of privatization may result in the availability of such transportation facilities to the public in a **more timely** or **less costly** fashion (Code of Virginia 56-558 A-3).

Three months after PPTA was passed, in October 1995, a private contractor, Virginia Maintenance Services (VMS) submitted an unsolicited proposal to Virginia Department of Transportation (VDOT) for the maintenance of assets within a portion of the interstate highway system of Virginia. After an intensive evaluation of this proposal by VDOT (including the phases of a detailed proposal re-submittal by VMS and negotiations), in December 1996, the contract, "*Comprehensive Agreement for Interstate Highway Asset Management Services*", was signed. The contract required VMS to administer and maintain all assets and carry out incident management and snow removal facilities on 250 miles of Virginia's interstate highways (I-81, I-77, I-95, and I-381). By this contract, a total of 20% of Virginia's interstate highways were covered. The contract was a fixed-fee (lump-sum) 5.5 year contract with an option of renewal for one more term and with a total fee of $131.6 million. Furthermore, the contract was renewed in

June 2001 for 5 more years (contract term to commence in July 2002 and end in July 2007) at a fixed-fee of $162 million with contract provisions (other than the fee) remaining exactly the same as the previous term's.

A very important aspect of the contract between VDOT and VMS is its **performance-based nature**. A performance-based contract is very different from a method based contract (traditional contract type which is common in the construction industry) in one large sense. A performance-based contract, as the name implies, sets forth the performance expected from the end product of a project rather than directing the contractor with the methods to achieve that end product. In other words, a performance-based contract specifies the desired outcomes rather than the desired processes to reach those outcomes. A performance-based contract leaves the contractor free, in any sense, to choose and apply the construction methods he wishes to carry out. This nature of performance-based contracts leads to two significant results. First, it imposes the risk of deficient design on the contractor due to the fact that the design component is performed by the contractor under the terms of performance-based contracting. Thus, it is beneficial for the owners to use performance-based contracts for their projects. Second, it often makes the contractor seek innovative construction methods (Hardy 2001; Porter 2001; Zietlow 2002). That is why the term "performance-based contracting" is used interchangeably with the term "innovative contracting".

Another important aspect of the VDOT- VMS contract is it being an **asset management** contract. As Falls, Haas, McNeil, and Tighe (2001) assert, asset management is "*a systematic process of maintaining, upgrading, and operating physical assets* ***cost-effectively***" (Falls et al. 2001, p.2). Asset management is a comprehensive and well-structured approach to the long-term management of assets to provide **effective** and **efficient services** to the community. Asset management does not elaborate on a singular system within the highway (i.e. pavement, bridges, etc.) but examines all components to allow **effective management of resources**, to make **effective investments**, and to **decrease overall costs** (JLARC 2002). Along the lines of these definitions, current VDOT-VMS contract makes the contractor in charge of maintaining all assets between VDOT's right-of-way fences within the sections of the interstate highway system covered by the contract (JLARC 2001). This includes all road surfaces, roadside, drainage, and traffic assets. Moreover, the contractor is responsible to provide snow and ice removal services.

1.2 PATH LEADING TO THIS RESEARCH

Being a performance-based asset management contract, the current VDOT-VMS contract is very different from other highway maintenance contracts issued in Virginia as well as in other states. As a matter of fact, VDOT has been one of the first state agencies that took the initiative of using a performance-based asset management contract for the maintenance of a portion of its interstate highway system (Ozbek 2004). Hence, this contract acts as a pilot project for VDOT as well as other states' departments of transportation. Findings of a **comprehensive analysis of this pilot project** can be used to assess whether the use of performance-based asset management contracting for highway maintenance is of value or not. VDOT has already made the decision to use performance-based asset management contracting for the maintenance of its interstate system under the initiative called Turnkey Asset Maintenance Services. Such initiative calls for a gradual transition to the use of performance-based asset management for the maintenance of the interstate system within Virginia. As a matter of fact, it has been decided to finalize this transition and thus to use performance-based asset management for the maintenance of the complete interstate system by the end of fiscal year 2009 (Simpson 2006). Given this, there is an emerging need to assess whether the use of performance-based asset management contracting for highway maintenance is of value or not to be able to inform VDOT (and any other transportation agency) of the value it receives by using performance-based asset management contracting.

As Otto and Ariaratnam asserts, outsourcing should be accompanied by a well-structured system of **performance measurement** (Otto and Ariaratnam 1999). Moreover, as Secretary for Transportation of New Mexico, Rahn, states "*… the will to innovate must be matched by a willingness to **evaluate***" (AASHTO 2000, p.8). In concurrence with these statements, since the inception of the current VDOT-VMS pilot project, VDOT has investigated the ways to evaluate the contractor's performance. However, a study conducted by Joint Legislative Audit and Review Commission of the Virginia General Assembly (JLARC) in 2000 concluded that VDOT had not been able to develop a solid measurement system as far as the contractor's performance and the contract's cost-effectiveness are concerned. Furthermore, JLARC recommended the hiring of an independent party for the evaluation of sub-sequent performance-based highway maintenance projects (JLARC 2001).

Considering the findings and recommendations of the JLARC study, VDOT took the initiative of partnering with the Vecellio Construction Engineering and Management Program

(VCEMP) at Virginia Tech which would act as the independent party to evaluate the VDOT-VMS pilot project for the term 2001-2007. With this partnering, the Highway Maintenance Monitoring Program (HMMP) was initiated.

After the establishment of HMMP, Piñero developed a framework that would enable transportation agencies to evaluate the performance-based road maintenance projects with respect to the following five components (Piñero 2003):

i. **Level-of-Service Effectiveness**: This component investigates how well the highway within the right-of-way fences is maintained by using the performance criteria that are defined for each element existing within the right-of-way fences of a highway system. Level-of-Service for the VDOT-VMS contract is investigated for three different elements that are defined to exist within such right-of-way fences, evaluation details of which are shown within **Table 1.1**.

Table 1.1: Level-of-Service Evaluation Elements and Details

Level-of-Service Element	Sub-elements	Evaluation Method	Range (from Worst Condition to Best Condition)
Fence to Fence Asset Groups	- Shoulders - Roadside Asset Items - Drainage Asset Items - Traffic Asset Items	Grading on a Percentage Scale	0%-100%
Paved Lanes		Load-Related Distress Index (LDR)	0-100
		Non Load-Related Distress Index (NDR)	0-100
		Critical Composite Index (CCI)	0-100
		International Roughness Index (IRI)	No Theoretical Limit for the Worst Condition-0
Bridges	- Deck - Superstructure - Substructure - Slope/Channel Protection	Grading on a Number Scale	0-9

ii. **Timeliness of Response**: This component investigates whether the contractor meets the timeliness requirements as defined in the contract to repair certain damaged asset items such as pavement segments with large potholes and to respond to certain emergency incidents such as accidents for the sake of safety and for enabling the free-flow of traffic.

iii. **Safety procedures**: This component investigates whether the contractor's employees follow the safety guidelines and meet the safety requirements required by the contract.

iv. **Quality of Service**: This component measures the overall satisfaction of the people and agencies directly affected by the services of the contractor. Some of the parties whose satisfaction is measured by this component can be listed as: State Police, VDOT, business and casual users of the highway.

v. **Cost Efficiency**: This component investigates the amount of savings, if any, accrued by VDOT using the performance-based contract for the maintenance of its highways.

As shown in **Figure 1.1**, this framework breaks down the overall performance of the contractor into the abovementioned components and investigates each component at a time. Previously, three components of this framework, level-of-service effectiveness, timeliness of response, and cost-efficiency, were implemented to the VDOT-VMS pilot project to evaluate the maintenance performance of the contractor and to compare it with VDOT's maintenance (carried out by in-house forces and traditional ways of contracting- both of which are referred to as "traditional maintenance" henceforth) performance. Currently, Virginia Tech uses only two components, level-of-service effectiveness and timeliness of response, due to data availability issues.

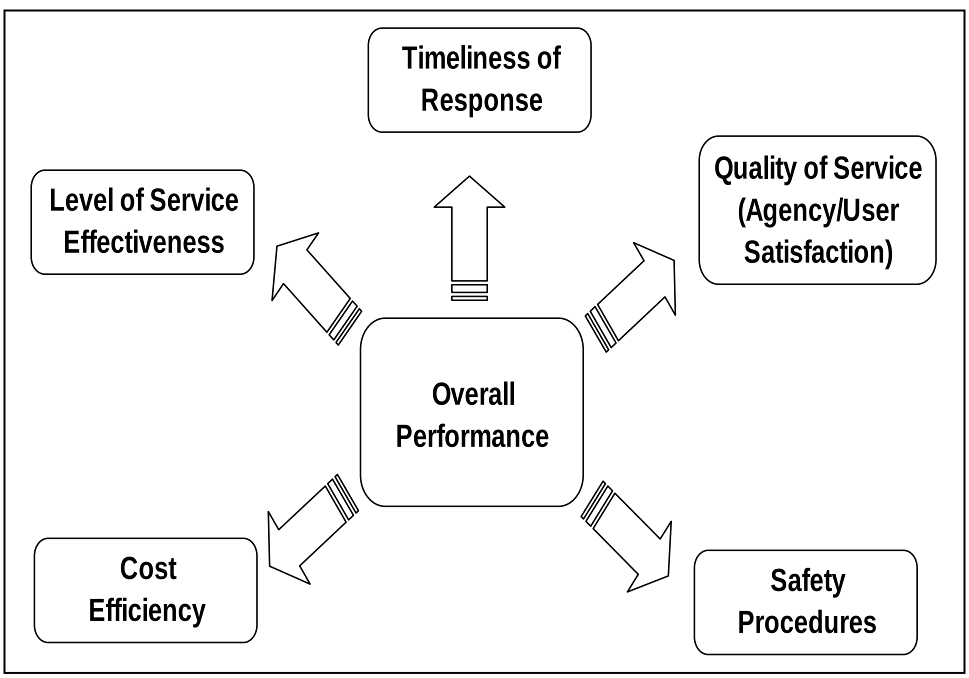


Figure 1.1: Key Components of the Framework for Performance Evaluation (Piñero 2003, p. 47)

1.3 MOTIVATION FOR THIS RESEARCH AND PROBLEM STATEMENT

When the VDOT-VMS pilot project ends in 2007, an assessment needs to be made to determine whether the use of performance-based asset management to maintain the Commonwealth of Virginia's interstate highways is of value or not. Therefore, there is an emerging need to implement a comprehensive system to measure and compare the overall performance of different approaches to highway maintenance inherent in a fair manner. Highway maintenance performance is difficult to measure given the presence of many variables affecting it (de la Garza et al. 2005). However, the performance measurement framework currently being utilized for the VDOT-VMS pilot project provides a comprehensive set of measurements gathered from a large number of highway segments. Nonetheless, that framework can further be enhanced by addressing the issues that accompany such framework as outlined below:

1. **Lack of a Performance Measurement Tool which takes the Efficiency Concept into Account**: The framework developed by Piñero focuses on the **effectiveness** measure (with respect to five components) only. The framework does not elaborate on the **efficiency** concept which is also a very essential performance measurement dimension. As a matter of fact, Sink and Morris defines performance as an "*integrated relationship among seven dimensions: effectiveness, efficiency …*" (Sink and Morris 1995, p.12). Road users expect not only a **well-maintained** highway system but also require it to be **efficiently** maintained (Dunlop 1999). Moreover, given the fact that the contract in hand is an asset management contract which calls for the delivery of **effective** and **efficient services** to the community (JLARC 2002), measuring only effectiveness and disregarding efficiency may be an incomplete (yet still valid) approach to performance assessment. As Barnard states, an action is effective when it results in a specific desired end or the right thing. When the unsought consequences or secondary desires are attained, then the action is efficient (Barnard 1938). Effectiveness can be defined as the degree to which an output (product/service) conforms to the requirements. Efficiency, on the other hand, is the degree to which the process produces the output (product/service) at a minimum resource level (Piñero 2003). Obviously, in a highway maintenance concept, everybody would want the actions (maintenance) to be effective, i.e. result in safe, travelable, good quality, etc. highways. But it is also reasonable to assume that efficiency, i.e. spending less

money, less time, etc., also possesses importance and thus needs to be accounted for. Not knowing how "efficient" state DOTs are in being "effective" can lead to excessive and unrealistic maintenance budget expectations. This issue indicates the need for a performance measurement approach that can also take the efficiency concept into account.

2. **Lack of a Performance Measurement Tool which acknowledges the External Factors Affecting the Performance**: Another shortcoming of the framework developed by Piñero is the fact that such framework, by focusing only on the effectiveness measure and making a comparison between performance-based highway maintenance and traditional highway maintenance using only the effectiveness results, is disregarding the environmental (i.e. climate, location etc…) and operational (i.e. traffic, load, design-construction adequacy, etc…) factors that highly affect the effectiveness of the highway maintenance process. Disregarding such external and uncontrollable factors and using pure effectiveness results may lead to unfair comparisons in which one maintenance approach may look better than the other just because it is being performed in a highway portion which is easier to maintain due to its advantageous location as far as such external factors are concerned. This issue, again, indicates the need for a performance measurement approach that can also take the external and uncontrollable factors into account.

In order to implement a comprehensive system to measure and compare the overall performance of different approaches to highway maintenance in a fair manner, the issues listed above, i.e. lack of a performance measurement tool which takes the efficiency concept into account and the lack of a performance measurement tool which acknowledges the external factors affecting the performance, need to be addressed.

Given the discussion above, there is a need to develop and implement a comprehensive framework that can measure the overall efficiency of road maintenance operations and that can also consider the effects of environmental and operational factors (both of which are beyond the control of the decision-maker, i.e., the maintenance manager) on such overall efficiency. This efficiency measurement framework, when implemented, should be able to address the following issues and questions:

1. How does the overall road maintenance efficiency of a "unit" compare to another similar type of unit? Within the context of this question, a unit can be any focal point of interest to the decision-makers. In other words, the comparison can be made across multiple state DOTs, across multiple districts within a state DOT, or across multiple maintenance crews of a state DOT. A unit can also represent the approach used for the maintenance of roads (e.g., traditional method-based maintenance approach versus performance-based maintenance approach).
2. If there are efficiency differences between the units of comparison, what are the reasons such efficiency differences could be attributed to?
3. How do the environmental and operational factors affect the maintenance efficiency of the units?
4. What should the decision-makers of the inefficient units do to be able to improve such units' efficiencies?
5. Which are the units that can act as benchmarks (peers) for the inefficient units?
6. What are the best practices that can be used by the inefficient units?
7. What are the fundamental relationships between the maintenance levels of service and the budget requirements?

It is important to note that the last two questions, i.e., 6 and 7, as listed above relate to the maintenance management issues identified by the Transportation Research Board as "*in need of comprehensive investigation*" in 2006 (TRB 2006).

1.4 PURPOSE, OBJECTIVES, AND HYPOTHESES

The purpose of this research is to develop a **comprehensive highway maintenance efficiency measurement framework** by utilizing an approach called Data Envelopment Analysis (DEA) (Charnes et al. 1978) to be able to address the issues and questions presented in the preceding section.

Given the fact that there are many inputs utilized by- and outputs obtained as a result of- the road maintenance process, such framework needs to incorporate all inputs and outputs to be able to identify the overall efficiency of a given unit's road maintenance process. Also, since there are many external and uncontrollable factors that affect the road maintenance performance, such framework needs to incorporate all factors to provide leveled comparison for different units trying to maintain roads facing different circumstances. However, it is challenging to measure the overall efficiency of a process when such process is a multiple input-multiple output process and when such process is affected by multiple factors.

To be able to develop the efficiency measurement framework, a number of approaches have been identified as possible candidates that may address both of the issues identified above. However, as will be discussed in the next chapter, all but one approach have fallen short of addressing the challenges of this research as well as tackling the complex nature of the process (i.e., highway maintenance) that is scrutinized in this research. Thus, the only remaining approach, DEA, has been chosen as the approach to utilize to develop the maintenance efficiency measurement framework as proposed by this research.

The developed comprehensive efficiency measurement framework will utilize the concept of DEA as DEA has the potential to address both of the issues discussed in **Section 1.3**. DEA is a procedure to measure the **efficiency** in situations where there are **multiple inputs** and **outputs** and there is no objective way of combining these inputs and outputs into an index of overall efficiency (Sexton 1986). DEA can help break down each component of the framework developed by Piñero into inputs and outputs and then derive an overall efficiency index for each component. This addresses the first issue that is identified in **Section 1.3**. In utilizing the DEA technique, external and uncontrollable factors (i.e. environmental and operational) are also taken into consideration (as will be expanded in **Chapter 3**). This addresses the second issue that is identified in **Section 1.3**. Hence, if developed and applied properly, DEA technique (which will be introduced in **Section 1.7** and expanded in **Chapter 2**) can address both of the issues discussed in **Section 1.3**.

After the framework is established, it will be applied to the current VDOT-VMS performance-based pilot project (to the extent the data to perform this task is made available to Virginia Tech) in an effort to evaluate and compare the efficiency of different approaches to highway maintenance. As discussed earlier, the starting point of this research is the performance-based highway maintenance contract that is in effect between VMS and VDOT and the main motivation behind this research is to measure and compare performance-based and traditional highway maintenance approaches inherent in VMS and VDOT respectively in a fair manner. As underlined in **Section 1.3,** this requires some enhancements to be made to the highway maintenance performance measurement framework that is already developed by Piñero and implemented to the VDOT-VMS pilot project to evaluate the maintenance performance of the contractor and to compare it with VDOT's maintenance performance. This research proposes that such enhancements be made by the introduction of the efficiency concept. However, this research aims to develop such efficiency concept at a framework level. Thus, even though the main motive is to measure and compare performance-based and traditional highway maintenance approaches inherent in VMS' and VDOT's maintenance respectively, this research will not explore the full implementation of such a comparison. Rather, this research will develop a comprehensive highway maintenance efficiency measurement framework, one use of which can be to compare the efficiencies of different approaches to highway maintenance and then will present an example application of this framework to VDOT-VMS case in a limited manner, mainly due to data availability issues.

In summary, the **purpose** of this research is to develop a replicable, generic, and comprehensive highway maintenance efficiency measurement framework by utilizing the DEA approach and to present an example application of this framework so as to illustrate the full implementation of such framework.

The specific **objectives** of this research are, through the use of real data, to:

1. Identify the relative efficiency of different units in performing road maintenance services.
2. Identify the reasons of the efficiency differences between units.
3. Identify the effects of the environmental and operational factors on the road maintenance efficiency of units.
4. Identify the benchmarks (peers) and best practices that pertain to the inefficient units in an effort to inform the decision-makers within such units of possible efficiency improvements than can be secured in the future.

The **hypotheses** of this research, which will be tested through the implementation of the developed framework, are as follows:

1. Within the state of Virginia, some counties are more efficient than others in performing highway maintenance operations.
2. Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties.

The findings of the research outlined herein will **contribute new knowledge to the asset management field** in the road maintenance domain by providing a framework that is able to differentiate effective and efficient maintenance strategies from effective and inefficient ones; as such, the impact of such framework will be broad, significant, and relevant to all transportation agencies. The main **contribution** of this research to the **body of knowledge** will be at the framework level as opposed to being at the implementation level.

Figure 1.2 illustrates the relationship between the motivation behind-, problems addressed by-, purpose of-, and the main contribution of- this research.

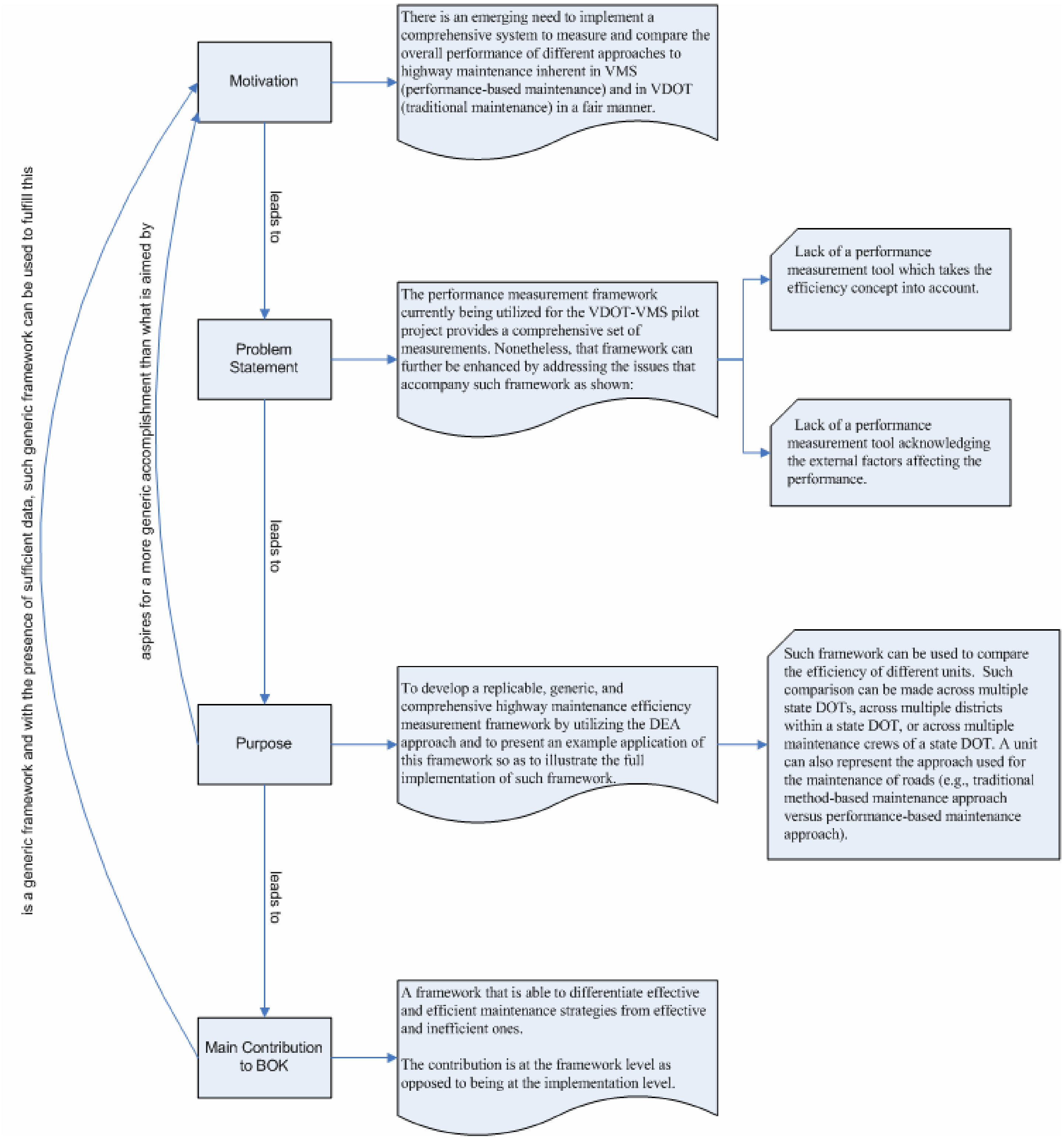


Figure 1.2: Relationship between the Motivation, Problem Statement, Purpose, and Contribution to BOK

1.5 SCOPE

As mentioned in the previous section, DEA can help break down each component of the framework developed by Piñero into inputs and outputs and then derive an overall efficiency index for each component. Constructing such an index includes difficult and challenging tasks, especially when each component under consideration is defined by inputs and outputs that have different units. DEA, also called as Frontier Analysis, addresses this complication by generalizing the well-known scientific and engineering efficiency valuation of a single input, single output system as the ratio of output to input (e.g. energy) to multi-input, multi-output systems when there is no same measure for all inputs and outputs (Charnes and Cooper 1990). However, performing such a task of investigating and modeling each of the five components as separate multi-item indices in an effort to utilize DEA models for deriving an overall efficiency index for each component is not within the scope of this research.

This research will focus only on the **level-of-service effectiveness**, **timeliness of response** and **cost efficiency** components. The third component, which has mainly something to do with the expenditures for highway maintenance will actually be the major input variable for the other two components. In the context of DEA, we are measuring "efficiency" so obviously cost is going to be incorporated into our DEA model in one way or another. So, as opposed to Piñero's framework which treated cost as a component, our DEA model will not treat cost efficiency as a component but will utilize cost as the major input variable for the other aforementioned two components (level-of-service effectiveness and timeliness of response). This will be discussed in detail within **Chapter 3.** The reason that the **quality of service** component is chosen to be out of the scope of the research is the fact that such component is believed to be interrelated with the abovementioned components (level-of-service effectiveness and timeliness of response). In other words, quality of service is assessed to be the end result (impact/effect) of delivering the outputs of the processes within such components to users/consumers. This makes the quality of service an outcome of those two components, making it redundant to develop an efficiency measurement framework for it. The reason that the **safety procedures** component is chosen to be out of the scope of the research is the fact that the availability of data with respect to this component is believed to be very scarce. Thus, even though this research is set to develop a generic and comprehensive highway maintenance efficiency measurement framework which then can be populated with data for implementation purposes, the researcher deemed it to be very unlikely for the safety procedures component to ever have an actual implementation. That being noted, it is believed that the development of a generic framework for safety procedures component does not add much value to the body of knowledge and hence the scope limit for such component. **Figure 1.3** illustrates, in green color, the components of the performance measurement framework (which is developed by Piñero) that are chosen to be within the scope of this research.

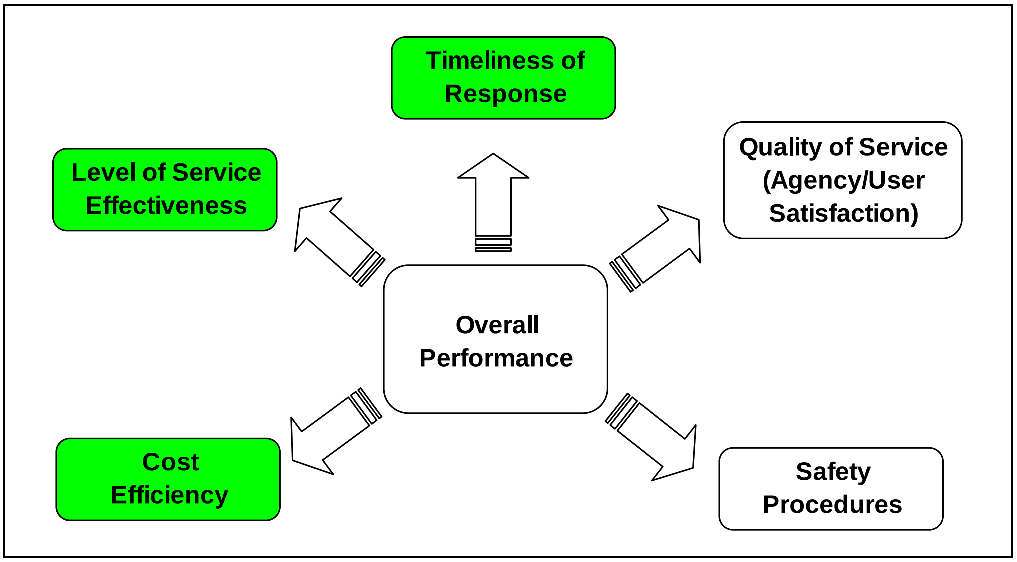


Figure 1.3: Components of Piñero's Framework that are in the Scope of this Research

1.6 SPECIFIC STEPS TO ACHIEVE THE PURPOSE

To achieve the **purpose** of this research, there are **ten steps** (which are linked to each other) that need to be completed. Each step is taken into consideration in the given order. When a satisfactory result is achieved in one step, the next step becomes the one which is to be performed. Once the results for all the steps are achieved, so is the **purpose** of the research. These specific steps are as follows:

1. To define the highway maintenance process in general.

2. To define the processes of the components for which the comprehensive highway maintenance efficiency measurement framework is to be developed (i.e. level-of-service and timeliness of response).

3. To identify the approach to develop the comprehensive set of controllable variables, a subset of which (obtained through the refinement process performed in **Step 5**) is to be utilized in the selected DEA model development (as expanded in **Step 7**) of the level-of-service and timeliness of response components. The controllable variables used in the DEA models must include key inputs as well as key outputs pertinent to the each process identified by **Step 2**.

4. To identify the approach to develop the comprehensive set of external and uncontrollable factors such as environmental (i.e. climate, location etc…) and operational (i.e. traffic, load, design-construction adequacy, etc…) factors that affect the effectiveness of the abovementioned components. Such factors need to be pertinent to the each process identified by **Step 2**. Such factors are to be added to the list of controllable variables identified by **Step 3** to be refined in **Step 5** in order to be included in the DEA models identified by **Step 7**.

5. To identify the approach to refine the comprehensive sets of controllable variables and uncontrollable factors identified in **Step 3** and **Step 4** respectively to be included in the DEA models identified by **Step 7**.

6. To identify the approach to deal with the uncontrollable factors (as finalized in **Step 5**) in the development of the DEA models identified by **Step 7**.

7. To identify the approach to choose the type of the DEA models (as expanded in **Chapter 2**) to be run by utilizing the sets of controllable variables and uncontrollable factors identified by **Step 5**. By the conclusion of this step, the main purpose of this research, i.e. developing a comprehensive highway maintenance efficiency measurement framework, will have been achieved.

8. To apply this comprehensive highway maintenance efficiency measurement framework to the current VDOT-VMS performance-based pilot project to the extent the data to perform this task is made available to Virginia Tech. Depending on the availability and quality of data, the application may focus on both VMS and VDOT (to compare the efficiency of different approaches to highway maintenance- i.e. performance-based approach vs. traditional approach), or the application may focus on either VDOT or VMS only (to compare the efficiency of different units possessing the same approach to

highway maintenance- i.e. unit 1 with traditional approach vs. unit 2 with traditional approach).

9. To identify the efficiency score, peers, and targets (as expanded in **Chapter 2**) of each of the units of comparison as used in the application of the framework performed in **Step 8**.

10. To derive overall conclusions that would help the decision making process.

1.7 OVERVIEW OF DATA ENVELOPMENT ANALYSIS

DEA is a mathematical method based on the principles of linear programming theory and application. It enables one to assess how efficiently a firm, organization, agency, or such other unit uses the resources available (inputs) to generate a set of outputs relative to other units in the data set (Ramanathan 2003; Silkman 1986). Within the context of DEA, such units are called Decision Making Units (DMUs). A DMU is said to be efficient if the ratio of its weighted outputs to its weighted inputs is larger than the similar ratio for every other DMU in the sample (Silkman 1986). The weights used are DMU-specific and during the application of DEA they are chosen by each DMU to maximize its own efficiency rating. The selection of the weights is only subject to limitations that they should be non-negative and they cannot result in an efficiency score larger than 100% (Sexton 1986; Thanassoulis 2001). The weights for the inputs and outputs do not need to be identified by the analyzer and instead they are determined by the DEA model in the best interest of DMUs (Thanassoulis 2001). The major advantage of DEA is that each input and output can be measured in its natural physical units. DEA can be performed to assess the relative efficiency of DMUs in a group within a single period or in sequence of periods (Golany and Roll 1989).

To be able to perform DEA, the analyzer needs to choose DMUs that use a variety of identical inputs to produce a variety of identical outputs. Calculated efficiencies are relative to the best performing DMU (or DMUs if there is more than one best performing DMU). The best performing DMU is given an efficiency score of 100 percent, and the efficiencies of other DMUs vary, between 0 and 100 percent, relative to this best performance (Ramanathan 2003).

Figure 1.4 presents the application of DEA in a single input, single output system case. The DMUs, shown in diamonds, are plotted on an x-y plane by using the values for their inputs and outputs. Then, the efficient frontier, representing the DMUs with 100 percent efficiency score (relative to the other DMUs in the data set), is drawn. Hence, relative to each other, gray DMUs have an efficiency of 100 percent and red DMUs have efficiencies varying between 0 and 100 percent. The efficiency of DMU labeled as "1" can be stated by two ways. First, DMU 1 could have produced the same level of output by spending less input, as DMU 2 does; therefore DMU 1 is less efficient than DMU 2. Second, DMU 1, spending same amount of input, could have produced more output, as DMU 3 does; therefore DMU 1 is less efficient than DMU 3. Relative efficiencies of each DMU can be stated in comparison to the efficient frontier in a similar manner and then the relative efficiency scores can be calculated. As can be understood, DEA is a relative efficiency calculation technique as efficient frontier is not absolute but determined by the data set under investigation.

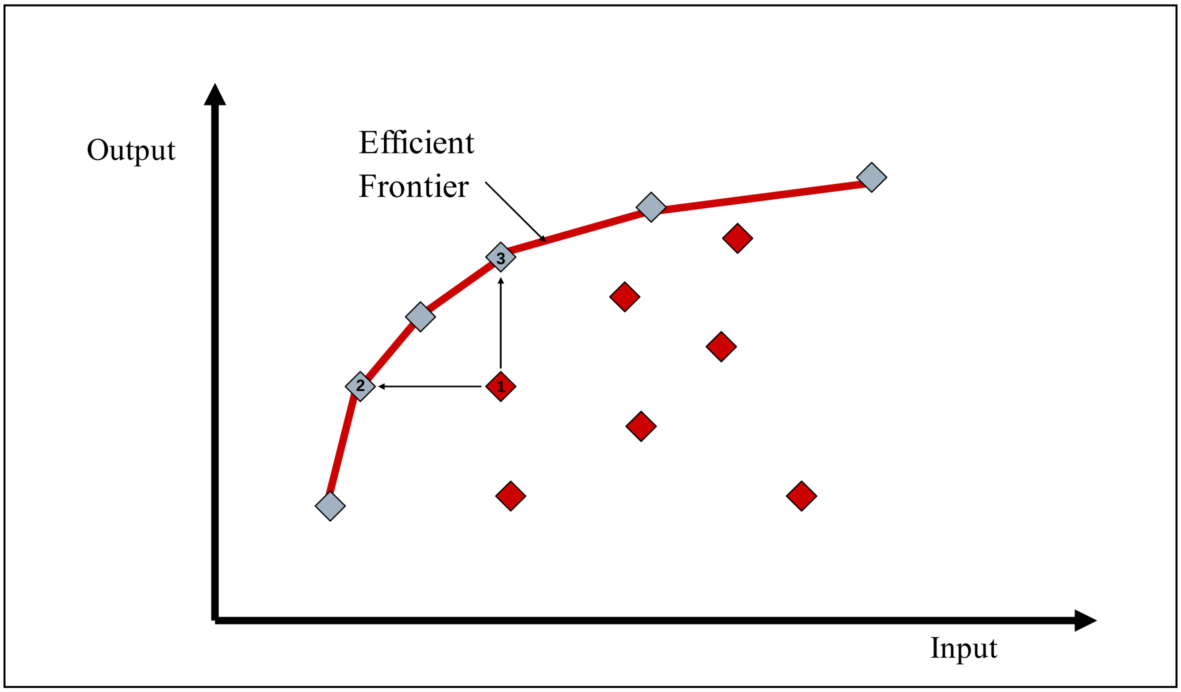


Figure 1.4: DEA Model with Single Input and Single Output (de la Garza et al. 2005)

The single input, single output case presented above is certainly not the case for highway maintenance in which there can be numerous inputs and outputs. DEA has the capability of dealing with multi-input, multi-output scenarios and thus is proved to be a very strong technique for developing a comprehensive efficiency measurement system.

1.8 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE

The contributions of this research to the body of knowledge are believed to be with respect to two different areas of literature: (i) highway maintenance and (ii) performance measurement (specifically DEA). A more detailed section which discusses the overall importance of this study is presented in **Section 5.4**.

1.8.1 Contributions to the Body of Knowledge in the Highway Maintenance Domain

Highway maintenance has not been the focus of basic and applied research as topics such as road design, construction, and traffic flow have. Research in the highway arena has traditionally been related to topics like geometric and structural design, selection of materials, specification of sufficient capacity, safety devices, location of intersections and interchanges; and location and characteristics of signs and signals. Comparatively little research has been performed in the areas of highway maintenance and highway maintenance performance (TRB 2006). TRB (2006) identified that some topics related to maintenance management need more examination. This research addresses, to a certain extent, two of such topics as listed below (TRB 2006):

- Fundamental relationships between highway maintenance levels of service and budget and labor utilizations.
- Best practices in specifying maintenance and operations performance, as used in contracting for these services.

As identified by and underlined throughout this write-up, efficiency is a very important dimension of overall performance and thus should be considered as an indispensable element of the concept of "performance measurement". Nonetheless, none of the performance measurement systems developed for highway maintenance in USA elaborates on the efficiency concept in an effort to measure the efficiency of the highway maintenance process. It is believed that this research, by taking the efficiency concept into account, improves the ways that are currently used to measure and model the performance of highway maintenance.

This research is built on the research already performed at Virginia Tech. As a matter of fact, DEA was identified and recommended as a possible future research area to be explored, by

Piñero (Piñero 2003). This research addresses the two short-comings of the already developed five component framework for monitoring performance-based road maintenance by developing a comprehensive highway maintenance efficiency measurement framework, i.e., such framework investigates the efficiency of the highway maintenance process and considers the external and uncontrollable factors that affect the performance of such process in investigating its efficiency. This is believed to substantially improve the framework (for monitoring performance-based road maintenance) that is already developed and in use by Virginia Tech.

This research contributes new knowledge to the asset management field in the highway maintenance domain by providing a framework that is able to differentiate effective and efficient maintenance strategies from effective and inefficient ones; as such, the impact of such framework is believed to be broad, significant, and relevant to all transportation agencies as it can easily be utilized by any transportation agency that is desiring to measure the efficiency of its highway maintenance operations in an effort to improve its performance.

1.8.2 Contributions to the Body of Knowledge in the Performance Measurement Domain

As Rouse (1997) pointed out, the performance measurement concept has been the subject of research in many disciplines such as operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management, and public administration (Rouse 1997). Engineering, on the other hand, is not a discipline in which research about performance measurement is performed as much as it is performed in these other disciplines. Specifically in the DEA arena, even though there have been many studies presenting the application of DEA to real-world situations in other disciplines, there has been limited amount of research that uses DEA in the engineering discipline. Such under-utilization of DEA in the engineering discipline can be attributed to many reasons such as the lack of understanding of the role of DEA in evaluating and improving design decisions, the inability to define the transformation process and thus inputs and outputs of a system, and unavailability/inaccessibility of reliable production and engineering data (Triantis 2004). This research is believed to contribute to the literature of performance measurement (specifically DEA) by developing a replicable generic framework that is based on engineering principles. Thus, this research can be labeled as an application of DEA within the engineering discipline.

1.9 ORGANIZATION OF THE DISSERTATION

This dissertation is organized in the following manner:

Chapter 1- Introduction: This chapter acts as an introductory chapter in which the background as well as the motivation behind the research is presented. Also, the hypothesis, scope, and purpose of the research are stated in this chapter. Furthermore, a brief overview of the methodology to be used in this research, i.e. Data Envelopment Analysis (DEA), is presented. Finally, contributions of this research to the body of knowledge are discussed.

Chapter 2- Literature Review: This chapter presents a literature review pertaining to the performance measurement (i) in general, (ii) in relation to previously developed frameworks and methods, (iii) related to highway maintenance in USA, and (iv) related to VDOT's highway maintenance practices. This chapter also contains a general literature review about the main technique to be used in this research, DEA. This is followed by a literature review presenting the previous work that is highly related to this research which can be cited as the main literature pertaining to this research, i.e. earlier work possessing application of DEA to highway maintenance. This is followed by a section discussing the body of knowledge that will be affected by this research as well as how this research is different from the previous work. This chapter concludes with a section investigating the potential of the System Dynamics approach to be utilized in this research.

Chapter 3- Methodology and the Development of the Comprehensive Highway Maintenance Efficiency Measurement Framework: This chapter presents the full and detailed methodology of the research. By the conclusion of this chapter, the main purpose of this research, i.e. developing a comprehensive highway maintenance efficiency measurement framework, will have been achieved.

Chapter 4- Hypothesis Testing: Implementation of the Framework: This is the chapter in which the framework developed in **Chapter 3** is applied to the current VDOT-VMS performance-based pilot project to the extent the data to perform this task is made available to Virginia Tech; and the results are obtained. Along with the discussion of the results, the hypotheses tests are also presented. This chapter also presents the conclusions derived as a result of the implementation of the framework to a number of scenarios. By the conclusion of this chapter, the specific objectives of this research as listed in **Section 1.4** will have been achieved.

Chapter 5- Concluding Remarks: This chapter contains an overall assessment of the research presented herein. Within such context, first a summary of the research is presented. Then, specific findings as they relate to the hypotheses and objectives of this research are discussed. After that, data availability issues that prevented the further implementation of the framework to different cases are discussed. Then, the contributions of this research to the body of knowledge are presented along with the overall importance of the study. After that, recommendations are provided for the prospective users of the framework developed by this research. This chapter is finalized by the section discussing some possible future research areas as identified to be related to this study.

CHAPTER 2- LITERATURE REVIEW

This chapter presents a literature review pertaining to the performance measurement (i) in general, (ii) in relation to previously developed frameworks and methods, (iii) related to highway maintenance in USA, and (iv) related to VDOT's highway maintenance practices. This chapter also contains a general literature review about the main technique to be used in this research, DEA. This is followed by a literature review presenting the previous work that is highly related to this research which can be cited as the main literature pertaining to this research, i.e. earlier work possessing application of DEA to highway maintenance. This is followed by a section discussing the body of knowledge that will be affected by this research as well as how this research is different from the previous work. This chapter concludes with a section investigating the potential of the System Dynamics approach to be utilized in this research.

2.1 PERFORMANCE MEASUREMENT IN GENERAL

NPR (1997) defines performance measurement as: "*a process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources (inputs) are transformed into goods and services (outputs), the quality of those outputs (how well they are delivered to clients and the extent to which clients are satisfied), and outcomes (the results of a program activity compared to its intended purpose)…*" (NPR 1997, p.7).

Performance measurement, as stated in such definition, is composed of measuring both **effectiveness** and **efficiency** of organizational **processes**. As a matter of fact, Sharman (1995) asserts that the performance of an organization is equal to the sum of the performance of its processes. Thus, to be able to develop and implement performance measurement in an organization, one need to clearly define processes, sub-processes, and relationship between the processes within that organization (Sharman 1995). Kennerley and Neely (2000) established a similar performance measurement framework, primary step of which is to quantify efficiency and effectiveness of processes (Kennerley and Neely 2000). Rouse and Putterill (2003) indicate that 40 years of research has proven that it is impossible to create one single framework for performance measurement. The performance measurement framework that they developed focuses on the processes of an organization. They assert that each process can be regarded as a group of activities converting inputs to outputs and then form the framework around effectiveness and efficiency of such processes (Rouse and Putterill 2003).

Altman (1979) divides the performance measurement into three elements (Altman 1979):

i. Data component that collects and processes data
ii. Analysis component that translates data into information
iii. Action component for the decision-makers' use of such information

It can be stated that the organizations measure their performance due to statutory and contractual requirements dictating the organizations to provide information on their performance to their owners and/or to the government. Government Performance and Results Act of 1993 (GPRA) was signed into law with the main motivation that all organizations, whether they are public or private, should develop and implement effective performance measurement and management systems. GPRA dictated such concept be institutionalized at the public agency level. Former President, William J. Clinton, on signing the GPRA, has underlined the importance of the performance measurement concept as: "*… chart a course for every endeavor that we take the people's money for, see how well we are progressing, tell the public how we are doing, stop the things that don't work, and never stop improving the things that we think are worth investing in*" (NPR 1997, p.2).

Nonetheless, many organizations implement performance measurement systems that go far beyond what is required by such regulations. The main reason for that is that performance measurement is the prominent, if not only, means for them to monitor how well they are performing which then enables them to seek improvements in the areas that they are not performing well. Performance measurement enables an organization to evaluate whether it is capable of meeting its objectives or not (Dickinson et al. 2002). Pioneering organizations, whether public or private, implement performance measurement to arrive conclusions about the efficiency and effectiveness of their processes (NPR 1997).

Performance measurement is a part of an overall program designed not only to make sure that prescribed performance is achieved by the existing processes but also to seek ways to improve the performance achieved by such processes (Miller 1989). As MacLean suggests: "*If* *you cannot measure it, you cannot improve upon it; if you do not measure it, you will not even try to improve upon it*" (MacLean 1993; TRB 1997, p.120).

Regardless of size, sector, or specialization, organizations divide overall performance into components (all of which are defined by processes) such as (NPR 1997):

i. Financial component
ii. Customer satisfaction component
iii. Employee satisfaction component
iv. Business operations component

Performance measurement is a challenging task because overall performance is the result of the interaction of many variables, some of which are controllable and some of which are not, some of which can be measured and some of which cannot (Dickinson et al. 2002). Given this fact, deciding on for which variable the data should be collected and how such data is to be collected has always been a subject that is under scrutiny. NPR (1997) states the following principles to be followed in deciding on which variables to use and in gathering the data for such variables (NPR 1997):

i. The number of variables that are chosen to be associated to a performance component should be minimized. Defining a few number of basic variables representing the component (for which performance measurement is executed) significantly is better than defining a large number of complex variables for which data gathering may be an issue.
ii. Only the data for the selected variables should be collected. Collecting the extra data that will not be included in the performance measurement means unnecessary use of resources.
iii. Data should be collected from a variety of resources to make sure that it is accurate.
iv. A set of agreed-upon definitions should be established for the data so that it is understood the same way by all involved in the performance measurement process.

According to NPR (1997), the issues that should be taken into consideration while designing and implementing a performance measurement system are as follows (NPR 1997):

i. Initially, a comprehensive and conceptual framework should be developed.
ii. During the design stages of a performance measurement system, continuous and effective communication with internal parties (employees and process designers) and external parties (customers and stakeholders) should be established. It is of utmost importance that design of a performance measurement system be executed with as much input from such parties as possible.
iii. A performance measurement system should produce timely and easy to understand reports at a reasonable cost.
iv. A performance measurement system should not just compile data but provide information to the decision-makers. Such information should be used by the decision-makers to improve organizational performance.
v. Results of a performance measurement system should be shared with employees, process designers, customers, and stakeholders.

Given the abovementioned discussion, it takes a lot of resources to design, implement, and perfect an effective performance measurement system. It, in fact, requires an iterative process where there is always room for continuous revision, update, and improvement.

Once the results of a performance measurement implementation are gathered, they can be used for many purposes (all of which are intended to improve organizational performance) such as (NPR 1997):

i. Making resource allocation decisions
ii. Making management and employee evaluations
iii. Determining gaps between reality and targets and the reasons for such gaps
iv. Establishing internal and external benchmarks (peers)
v. Making decisions to improve and/or change organizational processes

2.2 PREVIOSULY DEVELOPED PERFORMANCE MEASUREMENT FRAMEWORKS AND METHODS

The performance measurement concept has been the subject of research in many disciplines such as operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management, and public administration (Rouse 1997). Therefore, there is a large amount of literature related to the performance measurement issue and thus it has been the topic of an abundant number of publications. Within these publications, certain guidelines, integrated frameworks, methods, and models are presented with respect to measuring and monitoring performance. This section is divided into two parts to present the reader the most significant of such frameworks and methods: (i) Previously Developed Performance Measurement Frameworks and (ii) Previously Developed Performance Measurement Methods.

2.2.1 Previously Developed Performance Measurement Frameworks

The following five frameworks are chosen to be the literature pertaining to the previously developed performance measurement frameworks due to their impact in the research area: (i) Kaplan and Norton's Balanced Scorecard Approach, (ii) Mark Graham Brown's Scorecard Approach, (iii) Performance Prism Approach, (iv) Baldrige 2006 Criteria for Performance Excellence, and (v) Department of Energy Performance Measurement Program.

2.2.1.1 Kaplan and Norton's Balanced Scorecard Approach

The Balanced Scorecard concept was developed by Kaplan and Norton in 1992. According to Kaplan and Norton, this concept is a means for measuring and improving an organization's performance (Kaplan and Norton 1996). The Balanced Scorecard suggests that to implement a comprehensive performance measurement system, the following four organizational perspectives need to be measured: (i) financial, (ii) customer, (iii) internal business process, and (iv) innovation and learning, which was later renamed as learning and growth (Piñero 2003; Rouse and Putterill 2003). First two perspectives include measures as sales, profitability, and customer satisfaction. Third perspective, which focuses on the efficiency of internal business process, includes measures as cycle time, yield rate, and unit cost. Last perspective investigates the ability of an organization to improve and grow in an effort to create value for its customers and stakeholders. The Balanced Scorecard has been extensively used since its development (Rouse and Putterill 2003).

2.2.1.2 Mark Graham Brown's Scorecard Approach

In 1996, a model similar to the Balanced Scorecard was developed by Mark Graham Brown. Brown introduced a process model that is composed of inputs, processing system, outputs, outcomes, and goals (Brown 1996; Rouse and Putterill 2003). Brown identified five categories and developed a Scorecard Approach that can be used as a performance measurement system. The five categories considered in Brown's framework are listed and briefly discussed below (Piñero 2003):

1. **Financial Performance**: The organizations need to measure not only the cost of providing their products/services but also whether they are providing those products/services at a reasonable cost compared to their competitors or actual benchmarks.
2. **Process/Operational Performance**: According to Brown's Scorecard Approach, for an organization to improve its operational performance, it should be able to measure and interpret the quality of its products/services.
3. **Customer Satisfaction**: This category underlines that in order to be able to measure the customer satisfaction, the organization needs to collect data frequently, and implement statistical methods to analyze such data.
4. **Employee Satisfaction**: Organizations should measure the health and well being of their employees to inform management.
5. **Community/Stakeholder Satisfaction**: It is important to preserve good relations with the community and stakeholders and such should be measured.

2.2.1.3 Performance Prism Approach

This is a framework aimed to measure and improve organizational performance. This is achieved by seeking the answers to the questions posed within each of the following interrelated perspectives (Neely et al. 2002):

1. **Stakeholder Satisfaction**: Who are the organization's significant stakeholders and what do they want?

2. **Stakeholder Contribution**: In return, what does the organization want from such stakeholders?
3. **Strategies**: What strategies does the organization need to implement to address the desires of the stakeholders while satisfying its own requirements as well?
4. **Processes**: What processes does the organization need to implement to enable itself to execute such strategies?
5. **Capabilities**: What capabilities does the organization need to implement to enable itself to operate such processes?

2.2.1.4 Baldrige 2006 Criteria for Performance Excellence

This is a framework designed to (i) serve as a tool to understand the details of organizational performance, (ii) provide sharing of best practices between U.S. organizations, and (iii) improve organizational performance by implementing such best practices. The framework possesses a systems perspective and is composed of the following concepts: (i) leadership, (ii) strategic planning, (iii) customer and market focus, (iv) measurement, analysis, and knowledge management, (v) human resources focus, (vi) process management, and (vii) results. The framework measures the organizational performance by focusing on different categories of performance, which are structured in a similar manner to Mark Graham Brown's Scorecard Approach. The categories scrutinized in Balridge's framework are (i) product and service outcomes, (ii) customer-focused outcomes, (iii) financial and market outcomes, (iv) human resource outcomes, (v) organizational effectiveness outcomes, including key internal operational performance measures, and (vi) leadership and social responsibility outcomes (NIST 2006).

2.2.1.5 Department of Energy Performance Measurement Program

To promote the use of performance based management and effective implementation of GPRA, the U.S. Department of Energy (DOE) and DOE contractors funded the Performance-Based Management Special Interest Group (PBM SIG). The PBM SIG has developed a performance measurement model and published this in the document titled *Performance-Based Management Handbook* (Piñero 2003). The handbook emphasizes six main dimensions that need to be considered when developing a performance measurement model, two of which are of particular importance for this research as discussed in **Chapter 1**:

1. **Effectiveness**: This dimension measures whether the outputs (product/service) conform to predetermined requirements.
2. **Efficiency**: This dimension measures whether the processes produce the required outputs (product/service) by utilization of minimum inputs (resources).

2.2.2 Previously Developed Performance Measurement Methods

In the previous section, a number of general frameworks developed for measuring organizational performance are discussed. This section lists and briefly discusses the specific methods applied to measure organizational performance. Such methods are the tools within those frameworks and have practical applications (Rouse 1997):

1. **Ratio Analysis**: This tool investigates the financial performance of an organization using a series of ratios. This is an excellent tool used for comparison and benchmarking purposes.
2. **Systems of Weighted Measures**: When there is more than one measure/ratio that is required to be identified by the performance measurement framework, different measures/ratios may provide conflicting results. This can be prevented by using weights to obtain one composite measure of performance. Although the weights are established by the organization's management according to the organizational priorities, it is often difficult to obtain a complete agreement in the establishment of such weights.
3. **Statistical Methods**: Regression models are commonly utilized tools for performance measurement. They explain variations in measures of a dependent variable of interest with respect to the behavior(s) of one or more independent variable(s).
4. **Geographic Information Systems (GIS)**: GIS is a tool which makes it possible to spatially present the results that are obtained through the implementation of a performance measurement framework.

2.3 PERFORMANCE MEASUREMENT OF HIGHWAY MAINTENANCE IN USA

This section is divided into three parts. First part introduces the reader the current state of highway maintenance in USA. Second part briefly discusses the asset management concept as implemented in USA. Last part presents an important piece of literature pertaining to the highway maintenance quality assurance and performance measurement programs developed specifically for the state DOTs within USA.

2.3.1 Current State of Highway Maintenance in USA

For the last two decades, the highway maintenance concept has been gaining tremendous attention. The main reason for this is the fact that with the Interstate system construction essentially completed, the focus of transportation programs has been moving from capital investment to maintenance and operation. As the infrastructure building is slowing down, the maintenance of the existing infrastructure is becoming much more critical. From the early 1990s, federal government implemented a program of preservation, maintenance, and restoration. The Intermodal Surface Transportation Efficiency Act of 1991 established the Interstate Maintenance Program which called for pavement, bridge, and other management systems to be implemented by the state DOTs in an effort to preserve the current system and improve its efficiency. Funding for the construction of new highways similar to the Interstate program is unlikely to be allocated in the near future. As the funding shifts from construction to maintenance, maintenance organizations (such as state DOTs) become more accountable to the public, administrators, legislators, and politicians for a safe, accessible, efficient, and convenient transportation network. Maintenance is also regarded as the vital element to protect the nation's multibillion-dollar investment on highways (TRB 2006).

This phenomenon brings about new institutional changes, predominant of which is the challenge for maintenance managers to achieve maximum performance from the existing system and improve the effectiveness and efficiency at the network and activity levels (TRB 2006).

Another institutional change that is aroused by the political climate is the call for a smaller government, resulting in fewer maintenance staff in state DOTs and increased use of private contractors. Almost all states have begun to outsource a portion of their maintenance program. Method based contracts have traditionally been the most common form of maintenance contracting. Nonetheless, some states such as Virginia, Florida, Texas, and Massachusetts have taken the traditional maintenance contracting a step further by innovative contracting approaches such as performance-based contracting. It is very likely that use of performance-based contracting is to increase in the future. This, again, imposes a challenge on the maintenance managers because regardless of the fact that the maintenance is contracted out, the ultimate responsibility for maintenance performance is on the maintenance manager and thus the maintenance managers need to make sure that such new approaches work (TRB 2006).

Such challenges make it imperative to implement solid systems to measure the maintenance performance, i.e. effectiveness and efficiency. Therefore, maintenance managers should be provided with means to measure and analyze the maintenance performance to assure that maximum performance is achieved and to make improvements, changes and decisions (such as choosing between private contractors and in-house forces to perform maintenance) if that is not the case (TRB 2006).

In USA, a product's quality has become the chief goal of the industry due to the public's perception that the goods produced in other countries are better than the domestic ones. Highway maintenance can be regarded as a product with consumers such as road users who pay taxes and user fees. Therefore, maintenance managers need to be as concerned as any other provider about the quality of their product, i.e. maintained highway (Miller 1989).

Given the discussion above, highway maintenance performance measurement has been a key element within the overall performance management approach. Florida Department of Transportation (FDOT) has been the pioneer for this, measuring its maintenance performance for the last 20 years. FDOT needs to maintain a specified level of performance with respect to the maintenance of its highways as directed by law. Other state DOTs are also implementing a variety of performance measurement systems focusing mainly on the effectiveness of the highway maintenance processes (TRB 2006).

Nonetheless, state DOTs need to and in fact seek to measure not only the effectiveness of their maintenance processes (i.e. how good their outputs and outcomes are) but also the efficiency of and value added through such processes as far as reduction in taxpayer costs, reduction in user costs (e.g. travel time and accidents), and reduction in undesirable outputs (i.e. air, noise, and water pollution) are concerned (TRB 2006). It is essential for the maintenance managers to investigate how all components present in a highway maintenance system combine to result in the most efficient infrastructure (Dunlop 1999).

2.3.2 Asset Management in USA

Asset management is "… *a comprehensive and structured approach to the long-term management of assets as tools for the efficient and effective delivery of community benefits*" (JLARC 2002, p.16). Within the context of transportation in USA, asset management is allocating resources to preserve, operate, and manage the nation's transportation infrastructure. Asset management calls for the utilization of management, engineering, and economic principles to help state DOTs in making decisions as to how resources should be allocated. It is the strategic allocation of resources that improves the system performance, maximizes the return on investment, and increases customer satisfaction (Geiger 2005). In response to the severe deterioration of the country's road systems, Federal Highway Administration (FHWA) endorsed asset management to be the future approach of highway maintenance for all state DOTs (JLARC 2002).

Asset management requires state DOTs to implement integrated systems which take environmental conditions, operational conditions, materials, labor, and equipment into account. The function of an asset management system is (i) to prepare an inventory of the transportation system, (ii) to collect, analyze, and summarize data, (iii) to identify performance measures and evaluate compliance with such measures, (iv) to identify needs, (v) to determine strategies to address such needs, and (vi) to evaluate the effectiveness of those strategies that are implemented (Venner 2005).

The key components and principles of an asset management system are as follows (Dornan 2002):

- A spatially referenced asset inventory
- Performance measures and targets
- Quantitative and qualitative condition assessment process
- Performance prediction models, i.e. deterioration models
- Asset disposal policies and procedures
- Asset management measurement and planning systems

As many state DOTs are now vigorously trying to implement the asset management concept, FHWA is promoting the development of management tools, measurement/analysis methods, and research topics that are needed to accompany such concept (Geiger 2005).

2.3.3 NCHRP 14- 12: Highway Maintenance Quality Assurance Program

In 1995, the National Cooperative Highway Research Program (NCHRP) conducted Project 14-12, Highway Maintenance Quality Assurance Program, objective of which was to evaluate existing highway maintenance quality assurance and performance measurement programs and to subsequently develop an up to date prototype maintenance quality assurance (QA) program (Stivers et al. 1997). This project resulted in the development of a model QA program that could be implemented by the state DOTs to measure and improve the performance of their highway maintenance processes (Piñero 2003). The prototype QA program was developed by performing a comprehensive literature review including a similar earlier study by Miller (1989) which contained the highway maintenance performance measurement practices executed by the Louisiana Department of Transportation, the Michigan Department of Transportation, the Ohio Department of Transportation, the California Department of Transportation, and the Iowa Department of Transportation; and surveying numerous other highway agencies such as the Florida Department of Transportation, the Maryland Department of Transportation, the Pennsylvania Department of Transportation, the Oregon Department of Transportation-Region 4, and the British Columbia Ministry of Transportation and adapting their practices. This section presents the findings of the Project 14-12 (Miller 1989; TRB 1997).

According to the Project 14-12, the essential requirements for a highway maintenance QA program are as follows:

- Presence of a maintenance management system
- Definition of quality standards
- Establishment of procedures to accomplish the defined work
- Presence of a quality control and performance measurement procedure
- Availability of sufficient resources

Project 14-12 identified the following reasons for the failure of QA programs in highway maintenance:

1. **The Need for a Substantial Amount of Resources**: Many state DOTs believe that they cannot afford the resources associated with the QA program depending on the fact that such resources would cut into the existing maintenance funds. This belief, while may be true, disregards the anticipated long term benefits of the QA program and performance measurement.
2. **Lack of Documented Benefits**: Maintenance managers are not informed and convinced of the benefits resulting from a QA program. As mentioned in the preceding sections of this write-up, performance measurement brings about improvements in the processes. Given this, maintenance managers should be informed that performance measurement is not only implemented just to measure the highway maintenance but it also results in improvements in highway maintenance and thus have benefits.
3. **Lack of Highway Users' Comprehension of the Importance of Maintenance**: In the cases where highway users do not comprehend the relative importance of maintenance for the overall quality of the highways, there is no public demand for improved maintenance efforts. This "no pressure" situation makes maintenance managers less interested in implementing QA programs which would improve the maintenance process.
4. **Fear of Change**: Some maintenance managers believe that a QA program is a short-term idea which will not last long. Therefore, they deem no need to change the ways that the maintenance process is performed and thus do not find any need to implement a QA program.
5. **Lack of Objective Staff**: Evaluators who are measuring the performance of the highway maintenance are often the state DOT's field supervisors. Thus, they may carry an inherent bias and their evaluations may not necessarily represent the real highway user's perception.

Project 14-12 identified that the existing highway maintenance quality and performance measurement programs have been following the procedures utilized by manufacturing industries in monitoring, assessing, and improving the overall performance of highway maintenance. The ultimate purpose of such programs is to increase the provided level-of-service while decreasing the overall maintenance costs, in other words improving the efficiency in performing the highway maintenance process. Such programs measure the performance at the activity, project, and network levels. These programs help identify the problems with respect to maintenance crews and districts, causes of such problems (i.e. lack of training, lack of sufficient expertise, poor management practices), and specific needs that should be addressed in order to improve the maintenance crew's and district's quality of work. Maintenance managers can improve the maintenance quality by planning, organizing, and directing procedures as they developed by taking such problems into account.

Project 14-12 develops the prototype QA program by considering eight key items. Following are the three of those as identified to be relevant to this research:

1. **Types of Data to be collected**: Report suggests that activity cost data (which is identified to be extremely important for the successful implementation of the prototype program), formal level-of-service inspection data as gathered from randomly selected short segments of the highway, and customer satisfaction data as gathered from periodic assessments be collected for the QA/ performance measurement program.
2. **Availability of Data from Other Management Information Systems**: Report suggests that availability of data in the existing management information systems should be investigated in an effort to minimize the amount of data collection efforts described above. Such data, being readily available and accessible through other information systems, may reduce the resources used for data gathering (which is a large component of the overall performance measurement system) drastically. For example, level-of-service data for the bridges can be gathered from National Bridge Inventory Program which is a data information system administered by FHWA and this can significantly reduce the amount of resources spent to be able to gather such data.
3. **Avoiding Bias in Data Collection and Analysis:** The quality of a performance measurement system is greatly incumbent on the collection of accurate data and use of unbiased analysis techniques. The bias and inaccuracy introduced by the data collectors should be minimized because otherwise the credibility of the whole performance measurement system is very likely to be challenged. The foremost way of ensuring the

data accuracy is through the implementation of formal level-of-service training programs. Such programs familiarize the data collectors with the rating process and provide a good estimate of the unavoidable variability among different data collectors once an agreeable level of consistency is reached through training. Although such variability is unavoidable, it should be kept within acceptable limits. The ultimate objective of a training program is to ensure that data collectors reach the same basic conclusions in evaluating the condition of highway elements. Developing a good description of when a highway component meets or exceeds the specified performance criteria is a key factor for the accomplishment of a training program.

Project 14-12 identifies the advantages of implementing the prototype QA/performance measurement program. Following is a list of those as identified to be relevant to this research:

- It results in a highway maintenance process that exceeds the expectations of the travelers.
- It provides the maintenance managers with information to accomplish the highway maintenance process in an efficient manner.
- It enables maintenance managers to monitor the level-of-service attained at the activity, project, and/or network level.
- It enables maintenance managers to identify locations that have extra resources (i.e. labor, equipment, and resources) and locations that are short of resources in order to attain the prescribed level-of-service.
- It enables maintenance managers to make budget allocations required to upgrade the level-of-service from the existing condition to the required conditions.

Project 14-12 also identifies the disadvantages of implementing the prototype QA/performance measurement program. The one major disadvantage as identified to be relevant to this research is the cost of developing and implementing such a program.

Project 14-12 concludes by underlining that measuring performance to improve performance and continuously seeking better and more efficient processes are acknowledged as better means of conducting the business of highway maintenance. Therefore, there is an emerging need to implement a comprehensive performance measurement system in the arena of highway maintenance.

2.4 HIGHWAY MAINTENANCE PERFORMANCE MEASUREMENT PROGRAMS USED BY VDOT

Virginia has the third-largest State-maintained highway system in USA, behind North Carolina and Texas. VDOT is responsible for building, maintaining, and operating Virginia's roads, tunnels, and bridges. Virginia has 1118 centerline miles of 4 to 10 lane Interstates system that connects States and major cities; 8050 centerline miles of 2 to 6 lane Primary system that connects cities and towns with each other and with Interstate system; 47582 centerline miles of Secondary system consisting of local connector and county roads; and 333 miles of frontage roads (FHWA 2004).

State legislation requires VDOT to allocate funding to maintaining the current infrastructure of highways before planning or building new projects (FHWA 2004; VTrans2025 2005). As former VDOT Commissioner Philip Shucet (2003) suggested "…*maintenance remains a critical item- keeping what we have safe, reliable, and in good condition. In fact the Code of Virginia (§33.1-23.1) requires that the first allocation be "an amount deemed necessary for maintenance of roads*…*" In fact, in the current six year program, we have taken $420 million from construction to meet maintenance needs*…" (Shucet 2003), maintenance of the roadways is of chief importance to VDOT for which vast amount of money is spent. According to a study by VTrans2025 (2005), in years to come, more and more highway construction funds will be transferred to address maintenance needs. By the year 2018, no state funds will be available for construction. Starting with the year 2019, even the federal highway funds will have to be used for maintenance, further decreasing the funds available for construction (VTrans2025 2005). Maintenance costs are increasing by four percent a year as the highway system gets older (VTrans2025 2005). The Honorable Mark R. Warner, former governor of the Commonwealth of Virginia, has stated that "*There is three billion dollars in unmet needs for the maintenance of transportation system within Virginia*… *We should highly focus on maintenance*…" (Warner 2005). Abovementioned legislation and approach to maintenance have made it possible for VDOT to maintain its system in a relatively good condition making 80 percent of its Interstate and Primary systems to be in good condition (FHWA 2004)

As such importance is given to the highway maintenance concept in the Commonwealth of Virginia; it would be fair to assert that VDOT should be keeping the maintenance efforts, whether performed by in-house forces or private contractors, in close scrutiny. In other words, the importance given to maintenance should be accompanied by the measurement of the performance of such maintenance process. This is the prominent way for VDOT to get as much as it expects from the maintenance efforts and furthermore improve such maintenance efforts.

The most important and formal highway maintenance performance measurement program developed and implemented by VDOT until recently is called VDOT's "Maintenance Quality Evaluation Program" (MQE). This program was developed per the initiative of enhancing the efficiency and effectiveness of highway maintenance operations. It started to be implemented on July 1st 1989. This program was one of several that were developed to assist VDOT in meeting its mission of "providing safe, efficient, and effective transportation systems" (Kardian and Woodward 1990). The main objectives of such program were (Kardian and Woodward 1990):

- To monitor the overall quality of highway maintenance.
- To indicate areas of poor performance.
- To establish a formal process that would assure that consistent levels of service are attained statewide.

In 2002, the Virginia General Assembly introduced a legislation that requires VDOT to incorporate the principles of the asset management concept (as outlined in **Section 2.3.2**) into its maintenance practices and to submit biennial reports that present the actual condition of its highway system resulting from such maintenance practices. Virginia law defines asset management as "*a systematic process of operating and maintaining the system of highways by combining engineering practices and analysis with sound business practices and economic theory to achieve cost-effective outcomes*" (FHWA 2004). This legislation resulted in the recent establishment of a new division, Asset Management Division, within the organizational structure of VDOT. This division is currently responsible for operating and maintaining all of VDOT's assets. According to the project charter, the Asset Management System is to enable VDOT to more effectively and efficiently perform the maintenance of its roadway assets (FHWA 2004).

VDOT's asset management approach to maintenance is believed to provide a basis for measuring the performance of its highway maintenance process in an effort to monitor the condition of the existing transportation system as well as optimizing the maintenance process through cost effective methods. In order to successfully instigate asset management in an effort to efficiently and effectively performing its maintenance activities, VDOT needs to implement a comprehensive performance measurement system, major components of which are identifying its assets, determining the condition of those assets, and determining the efficiency with which such asset are maintained (JLARC 2002).

VDOT's current highway maintenance performance measurement program does not measure efficiency. VDOT's highway maintenance program should measure the efficiency of its maintenance process in a manner that enables comparisons across the State to be made. A lack of efficiency comparison, which is performed by measuring the amount of resources associated with the maintenance process, raises questions about whether such process is done efficiently. If VDOT measures the efficiency accurately, it can address inefficient maintenance practices by communicating efficient maintenance practices to areas with such inefficient maintenance practices. For example, results of a performance measurement system which takes the efficiency dimension into account can be used by maintenance managers to determine why a certain method of maintenance was able to address a certain function better than another method of maintenance (JLARC 2002).

2.5 DATA ENVELOPMENT ANALYSIS (DEA)

The DEA concept was introduced to the reader in **Section 1.7**. This section is divided into three parts to build on that introduction in an effort to present a complete literature review about DEA. First part briefly introduces the productivity theory, some basic concepts and definitions of which are used in DEA. Second part presents a description of the basic DEA models, mathematical formulations, an example DEA problem and the hand solution of that problem performed using those basic DEA models. In literature, many extensions have been made to the basic DEA models presented in this section in an effort to cover different issues pertinent to different applications. Although such extensive literature is acknowledged, DEA's coverage in this literature review is limited to a level that is sufficient to enable the reader to understand the basic theory that is underlying the DEA concept. Extensions and modifications to these basic

DEA models will need to be made to be able to address the issues identified by this research. Such extensions and modifications will be presented during the development of the methodology of this research (in **Chapter 3**) as they are made. Last part of this section presents a general literature review about DEA to cover the issues related to it.

2.5.1 Overview of the Productivity Theory

There are two schools of thoughts for the productivity theory. One assumes that all processes are efficient. The second one allows for the presence of inefficiency within the production, enabling the development of methods to measure such inefficiency (Rouse 1997). Within the context of the productivity theory, an **input** is any resource that contributes to the production of an output through a process, a **process** is the change in the form, appearance, condition, nature, function, character, capability of an input (such changes should add positive value to the inputs as determined by the users of the resulting outputs) which results in the output, and an **output** is a product that results from the transformation of the inputs through such processes. It is important to note that both inputs and outputs are usually described in terms of their quantity and quality (Triantis 2005e).

Being **technically efficient** refers to the production of maximum output for a given amount of input, or the production of a given amount of output using minimum input. Graphically, technical efficiency is represented by a locus (i.e. isoquant) of optimal combinations of inputs and outputs. Such curve is called as an efficient frontier. Depending on the orientation, the efficient frontier may be shown either as an output isoquant or an input isoquant.

Figure 2.1 presents an input isoquant as shown in green color (Rouse 1997). It is important to note that such efficient frontier is plotted by connecting efficient bundles of production instances in concordance with the assumptions made by Farrell (Farrell 1957) as follows: Efficient bundles are found by picking adjacent pairs of bundles and connecting them with a line segment. If the line segment has a non-positive slope and none of the other bundles (representing other production instances) lies between such line segment and the origin, the chosen bundles are stated to be efficient and otherwise they are stated to be inefficient (Triantis 2005c).

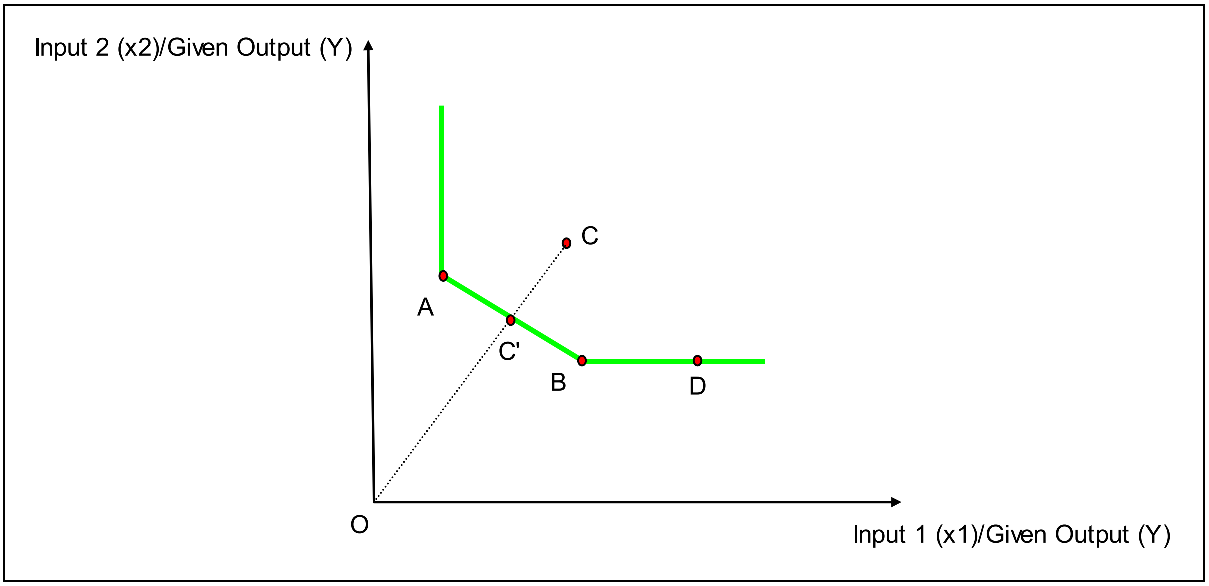


Figure 2.1: Input Isoquant illustrating the Efficient Frontier

This isoquant (efficient frontier) illustrates the efficient combinations of inputs for a given technology. In terms of the figure presented above, the **technology** refers to all the technical information about the combinations of input 1 and input 2 necessary for the production of output Y through the process. Technology includes all physical possibilities. With respect to the figure above, the technology may state that a single combination of input 1 and input 2 can be utilized in a number of different ways (Triantis 2005e). A **production function** is the mathematical expression of the relationship between the outputs(s) and the input(s) of a process (i.e. y=x1*x2). It describes the unconstrained technical possibilities of a technology with no limitation to any existing or realized production units (Rouse 1997). The production function differs from the technology in that it assumes technical efficiency and states the minimum amount of input needed to obtain a given amount of output or the maximum amount of output that can be obtained using a given amount of input (Triantis 2005e). An efficient frontier may be obtained by one of the following two ways (Rouse 1997):

1. By using the mathematical expression of the production function.
2. By specification of the technology from which the production function may be defined. The efficient frontier shown in **Figure 2.1** was obtained using this approach.

In **Figure 2.1**, production instances "A" and "B" are technically efficient as they are located on the efficient frontier. On the other hand, production instance "C" is not technically efficient as it is located above the isoquant depicting the efficient frontier. The main reason for "C" not to be on the efficient frontier is the fact that it consumes more of input 1 and input 2 to produce a given output level (Y) compared to the other production instances located on the efficient frontier. **Technical efficiency** of such a production instance can be measured in terms of its relative distance from the efficient frontier. This can be illustrated on the ray passing through O, C′, and C as (Rouse 1997):

$$Q = \frac{|OC'|}{|OC|}$$

It is important to note that Q refers to the proportional reduction to be made in the inputs of "C" that is needed to place C on the efficient frontier (C′). Q, in literature, is referred to as the radial contraction (Rouse 1997).

The abovementioned definition of being technically efficient furthermore asserts that a production instance, being on the efficient frontier, is technically efficient if a reduction in any input necessitates an increase in at least one other input (at a given output level) or a reduction in at least one output and if an increase in any output necessitates a reduction in at least one other output (at a given input level) or an increase in at least one input (Rouse 1997). The production instance "D" (even though is on the efficient frontier), does not satisfy this criterion of being technically efficient as a reduction in input 1 is possible without increasing input 2 or reducing the given output level, Y. Such production instances located on the flat portion of the efficient frontier are referred to as being **weak efficient** (Rouse 1997). This concept will be explained in more detail within **Section 2.5.2** as basic DEA models and formulations are introduced.

2.5.2 Basic DEA Models and Formulations

A commonly used measure of efficiency is (Cooper et al. 1999):

$$\text{Efficiency} = \frac{Output}{Input}$$ **Expression (2.1)**

For the systems/processes in which there are multiple inputs and/or outputs such as the highway maintenance process, the abovementioned expression is referred to as "partial efficiency measure". This terminology is intended to distinguish such measure from "total factor efficiency measure", a concept which produces an output-to-input measure that takes into account all of the inputs and outputs. Traditionally, there have been three approaches to measure and compare the efficiencies of systems/processes with multiple inputs and/or outputs:

i. **Partial Efficiency Measure Approach**: This approach requires investigating and calculating the single output to single input ratio shown in **Expression (2.1)** one at a time for each relevant input and output (e.g. # of lane miles overlaid with asphalt/labor time spent in such operation and # of lane miles overlaid with asphalt/amount of asphalt spent in such operation) (Sexton 1986). One major drawback of this approach is its potential to result in serious misunderstandings about the overall efficiency of a process. This can be explained by the following example: An entity (e.g. a contractor) decides to use a higher quality raw material that drastically reduces the labor time needed for processing such material but which also necessitates an increased amount of other raw materials to be used to produce the same product/service. In such a situation, a partial efficiency measure that only investigates the efficiency from the "labor time" point of view would determine substantial (but artificial) efficiency increases in the process. As can be grasped from the discussion above, such efficiency increase is not necessarily the case; as within a process with multiple inputs, such inputs are very likely to interact with and thus affect each other and the overall efficiency of that process. Therefore, using just one partial efficiency measure to determine the overall efficiency of a process can be misleading (Craig and Harris 1973). Nonetheless, even if all partial efficiency measures are computed for a process, it is very challenging to reach solid conclusions about the overall efficiency of that process especially when such measures are used to compare the efficiencies of different units of comparison or different periods of performance of a single unit of comparison. This is mainly because one partial efficiency measure may suggest that one unit of comparison is performing better than the other and another partial efficiency measure may suggest just the opposite, preventing the analyzer to arrive in solid conclusions about the overall performance. In conclusion, Partial Efficiency Measure Approach can pinpoint extremely good and extremely bad performing units but does not provide good and clear results for the units in between (Sexton 1986). As one of the main goals of this research is to be able compare the overall efficiency of performance-based and traditional highway maintenance, Partial Efficiency Measure Approach proves to be an insufficient approach to handle the complex and multi-variable process (highway maintenance process) investigated within this research.

ii. **Parametric Approach**: This approach overcomes the problem identified in (i) by modeling the output (dependent variable) level of a unit as a function of the various input (independent variables) levels. This average relationship (which can be used to calculate the expected output level of a unit given its input levels) is assumed to apply to each unit that is compared within the data set. Units that are relatively efficient lie above this relationship (as they produce more output than what the model predicts) and units that are relatively inefficient lie below this relationship (as they produce less output than what the model predicts). However this requires the parametric specification of the system/process to be made through the use of a mathematical form presenting how inputs are combined to produce the outputs. This, in essence, is to provide the equation of the production function of the system/process, which can be a very challenging task for large systems/processes. Given the fact that the highway maintenance process is a complex process with many variables, deriving the equation of the production function of such a process is out of the question, rendering the Parametric Approach to be of no value for the purposes of this research. Moreover, this approach measures the efficiency with respect to average performance of a unit, not the best performance (Charnes et al. 1994; Sexton 1986).

iii. **Total Factor Efficiency Measure Approach**: This approach derives an output-to-input measure that takes into account all of the inputs and outputs at one time. Even though total factor efficiency measure is essential to cover all variables (inputs and outputs) that are associated with a system/process at one time (overcoming the problem identified in (i)) and does not need a parametric specification of the production function (overcoming the problem identified in (ii)), it comes with one major drawback. It makes the analyzer prescribe weights to be assigned to each individual input and output variable to obtain a ratio that reduces to a form like the one in **Expression (2.1)** (Cooper et al. 1999). Since this is a task that could result in different weights to be chosen by different individuals (i.e. decision makers), it is very likely to create subjectivity in the efficiency measurement process. Prescription of weights can be avoided if and only if all inputs and outputs that are considered in the calculation of the total factor efficiency measure can be represented in the common measurement unit of monetary terms (which intrinsically posses such weights) such as the dollar value of each input and output (Craig and Harris 1973). Even though this may be possible for processes whose outputs are products (e.g. car, toaster, and etc.), it is not always possible to represent all inputs and outputs by their dollar values when the output of a process is a service as opposed to a product. For this research, in which the process whose efficiency is under investigation is the highway maintenance, it is impossible to assign a monetary value to the output (i.e. maintained highway). This fact makes the Total Factor Efficiency Measure Approach inapplicable to this research.

Data Envelopment Analysis (DEA), which was initially proposed by Charnes et al. in their 1978 seminal paper (Charnes et al. 1978), is an approach that can deal with systems/processes that have multiple inputs and/or multiple outputs and yet does not possess the shortcomings of any of the abovementioned approaches. DEA is a mathematical method based on the principles of linear programming theory and application. It enables one to assess how efficiently a firm, organization, agency, or such other unit uses the resources available (inputs) to generate a set of outputs relative to other units in the data set (Ramanathan 2003; Silkman 1986). Within the context of DEA, such units are called Decision Making Units (DMUs). The efficiency score of any DMU, as proposed by Charnes et al. (1978), is calculated as the maximum of a ratio of the weighted outputs to weighted inputs subject to the constraints that (i) the similar ratio for every DMU in the data set be less than or equal to unity using the same set of weights and (ii) such weights be non-negative (Charnes et al. 1978). Calculated efficiencies are relative to the best performing DMU (or DMUs if there is more than one best performing DMU).

2.5.2.1 Primal CCR Models

Input Oriented Primal CCR Model

The formulation developed by Charnes et al. (1978) uses linear programming to extend Farrell's (1957) single output/single input technical efficiency measure (Farrell 1957) to the multi-output/multi-input case. The focus is to optimize the ratio of outputs to inputs by solving for a group of weights that satisfy a system of linear equations (Rouse 1997). A mathematical formulation of such an optimization/linear programming problem is presented below in the format of a fractional program (**FP$_0$**):

(**FP$_0$**): maximize $Q = \dfrac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{i0}}$

subject to:

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \; ; \qquad j = 1,\ldots\ldots,n \qquad r = 1,\ldots\ldots,s \qquad i = 1,\ldots\ldots,m$$

$$u_r, v_i \geq 0$$

where n: number of DMUs in the data set

s: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$u_r, v_i \geq 0$: the variables' (inputs' and outputs') weights to be determined by the solution of this optimization problem.

This fractional program (**FP_0**) can be replaced by the following linear program (**LP_0**). It is important to note that such formulation is commonly referred to as the primal CCR model in the literature:

Formulation 2.1

(**LP_0**): maximize $Q = \sum_{r=1}^{s} u_r y_{r0}$

subject to:

$$\sum_{i=1}^{m} v_i x_{i0} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} \le \sum_{i=1}^{m} v_i x_{ij} \; ; \qquad j = 1,\ldots\ldots,n \qquad r = 1,\ldots\ldots,s \qquad i = 1,\ldots\ldots,m$$

$$u_r, v_i \ge 0$$

where n: number of DMUs in the data set

s: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$u_r, v_i \ge 0$: the variables' (inputs' and outputs') weights to be determined by the solution of this optimization problem.

The model presented above, in essence, seeks the weights (v_i) for each input and (u_r) for each output of the DMU under investigation which maximize the efficiency score of that DMU, subject to the constraint that such weights, when applied to the output to input ratios for all other DMUs in the data set (including the DMU under investigation), result in an efficiency score which is equal to or less than 1. The efficiency score and the weights of the input and output variables for each DMU can be calculated by solving the linear program (LP) formulation presented above for each DMU in the data set. The weights calculated are DMU-specific and due to the optimization structure of the LP formulation as described above, such weights are not assigned to the DMUs by people (who may possess subjectivity) but are chosen by each DMU (as allowed by the constraints) to maximize its own efficiency rating.

Following is an example of the application of the primal CCR model to a DEA problem with three variables (two inputs and one output) and 6 DMUs. The hand solution for one of the DMUs is presented in the example to illustrate the mechanism of the primal CCR model.

This example presents the hand solution for calculation of the efficiency score and weights of the input and output variables for a DMU. The DMU selected to be under investigation is DMU B. **Table 2.1** presents the input and output values of each DMU in the data set. The LP set up for DMU B and the graphical solution of such LP follows. The example is adopted from Cooper et al. (Cooper et al. 1999, p.28).

Table 2.1: Input-Output Values for the Data Set

	DMU	A	B	C	D	E	F
Inputs	x_1	4	7	8	4	2	10
	x_2	3	3	1	2	4	1
Output	y	1	1	1	1	1	1

The linear program for DMU B, as set up using the primal CCR formulation, is:

(**DMU B**): maximize Q= 1*u

subject to:

$$7v_1 + 3v_2 = 1$$

$$1u \le 4v_1 + 3v_2 \quad \text{(A)}$$

$$1u \le 7v_1 + 3v_2 \quad \text{(B)}$$

$$1u \le 8v_1 + 1v_2 \quad \text{(C)}$$

$$1u \le 4v_1 + 2v_2 \quad \text{(D)}$$

$$1u \le 2v_1 + 4v_2 \quad \text{(E)}$$

$$1u \le 10v_1 + 1v_2 \quad \text{(F)}$$

$$u, v_1, v_2 \ge 0$$

Using the first constraint and thus substituting $v_2 = \dfrac{1-7v_1}{3}$ in (A), (B), (C), (D) (E), and (F):

(**DMU B**): maximize Q= u

subject to:

$7v_1 + 3v_2 = 1$

$u + 3v_1 \leq 1$ (A)

$u \leq 1$ (B)

$3u - 17v_1 \leq 1$ (C)

$3u + 2v_1 \leq 2$ (D)

$3u + 22v_1 \leq 4$ (E)

$3u - 23v_1 \leq 1$ (F)

$u, v_1, v_2 \geq 0$

In order to be able to hand-solve this LP graphically, the constraints represented by 6 inequalities are plotted on a u-v_1 plane graph as can be seen in **Figure 2.2** and then the feasible region that is satisfying all the constraints is obtained (feasible region in the graph is the region which is NOT shaded). As the feasible region is obtained, the number which serves our objective function of maximizing "u" is calculated. It is the maximum point of the feasible region and has the coordinates (0.0526, 0.6316) as shown on the plot.

The solution of the primal CCR model set up for DMU B gives us the efficiency score of DMU B as well as the weights associated with the inputs and output of DMU B. The values for these, as obtained by hand-solving the primal CCR model, are as follows:

- Weight of input 1 = $v_1 = 0.0526$
- Substituting $v_1 = 0.0526$ into $7v_1 + 3v_2 = 1$, weight of input 2, v_2, can be calculated as 0.2105
- Weight of the output which also happens to be the efficiency score for this particular problem, $u = Q = 0.6316$

One can double check the results shown above by calculating the efficiency score, Q, using the common efficiency equation of (Total Weighted Outputs)/(Total Weighted Inputs) as used in the primal CCR formulation:

$$Q = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{i0}} = \frac{0.6316 * 1}{0.0526 * 7 + 0.2105 * 3} = 0.6316 \ \surd$$

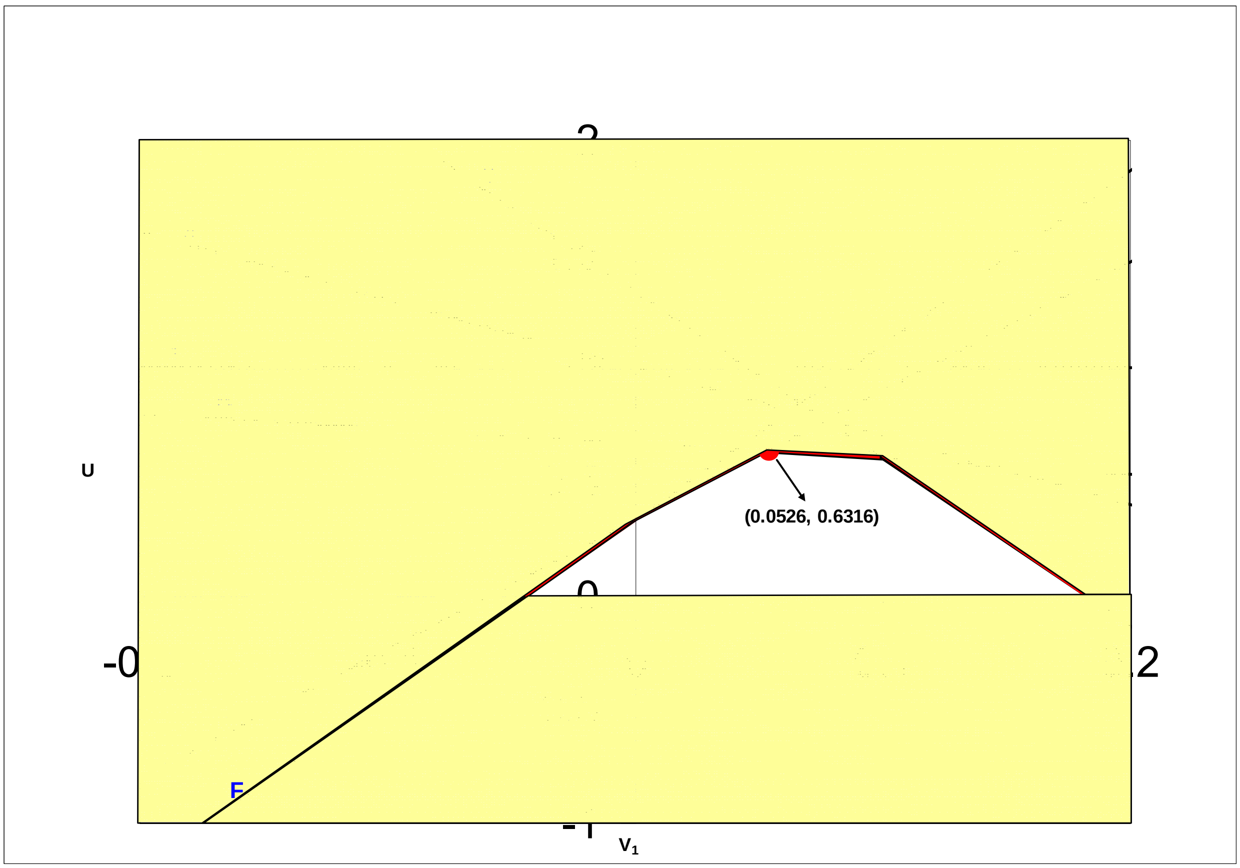


Figure 2.2: Plot to Solve the Example LP Graphically

To complete the solution of this example DEA problem, primal CCR formulation can be set for the remaining DMUs in the data set in a similar manner. Similar graphical hand-solution approach can be used to obtain the efficiency scores of other DMUs in the data set as well as the weights associated with the inputs and outputs of such DMUs. For the purposes of this write-up, such task will not be performed but rather the results will be shown in **Table 2.2**. After the presentation of the results, this example is further elaborated on with the presentation of some graphs and introduction of new concepts to make the reader much more familiarized with DEA.

Table 2.2: Results of the Example DEA Problem obtained using the Primal CCR Formulation

DMU	Input 1 (x_1)	Input 2 (x_2)	Output (y)	CCR Efficiency Score (Q)	Weight of Input 1 (v_1)	Weight of Input 2 (v_2)	Weight of the Output (u)
A	4	3	1	0.8571	0.1429	0.1429	0.8571
B	7	3	1	0.6316	0.0526	0.2105	0.6316
C	8	1	1	1	0.0833	0.3333	1
D	4	2	1	1	0.1667	0.1667	1
E	2	4	1	1	0.2143	0.1429	1
F	10	1	1	1	0	1	1

The example presented above illustrated the application of the primal CCR formulation to a single output-two input case in an effort to familiarize the reader with the basic formulation that the DEA concept is based on. Since this is an example with a few number of input-output variables, it allows us to draw a plot on which the efficient frontier and efficiency (Q) can be shown and through the help of which the term "data envelopment" can be made clear.

Let's normalize both input 1 (x_1) and input 2 (x_2) with the single output (y). Such normalization process gives us the results presented in **Table 2.3**.

Table 2.3: Inputs Normalized by the Output

DMU	A	B	C	D	E	F
x_1/y	4	7	8	4	2	10
x_2/y	3	3	1	2	4	1

Using such normalized input results, a graph showing the input relationships of all 6 DMUs can be plotted. **Figure 2.3** is the plot showing the normalized inputs of all 6 DMUs.

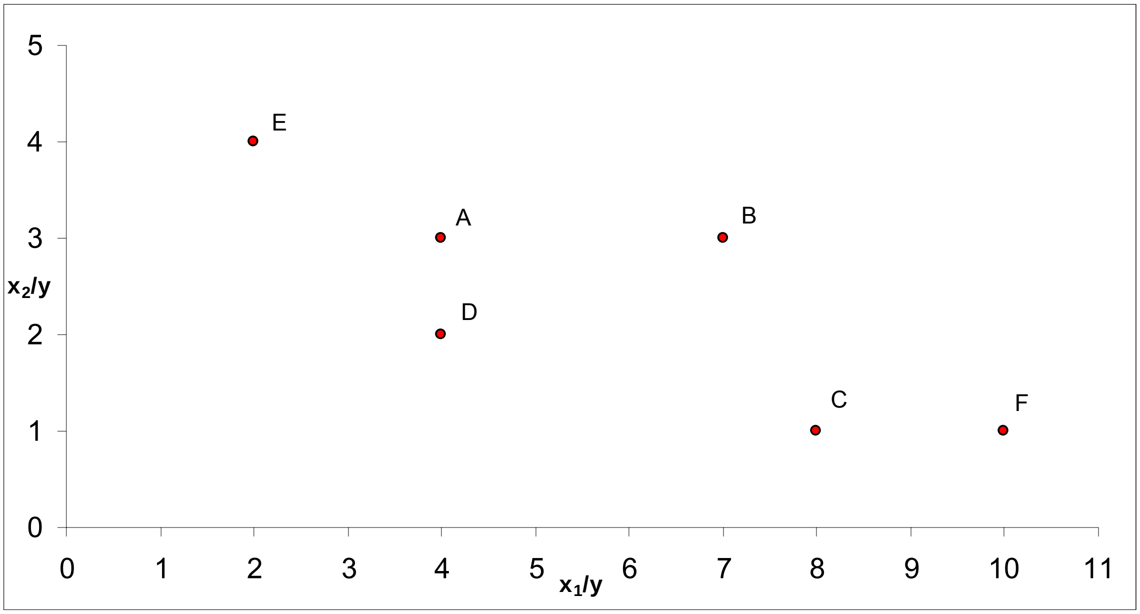


Figure 2.3: Normalized Inputs of the DMUs

It was described and illustrated in **Section 2.5.1** that efficient bundles (as identified in concordance with Farrell's (1957) assumptions) can be connected to form the efficient frontier composed of production instances gathered from the technology of a single process. In this case, similar approach can be utilized to obtain the efficient frontier, with the only difference that this time, each unit to be bundled represents a DMU as opposed to a production instance gathered from the technology of a single process. This, in fact, is the essence of the DEA model proposed by Charnes et al. (1978) in which a frontier is constructed from the identified efficient DMUs which "envelop" the data, hence the name Data Envelopment Analysis. Such frontier is constructed using actual observations of DMUs within the data set and thus it is an empirical frontier representing achieved performance (Rouse 1997). The efficient frontier for this example is shown (in green color) in **Figure 2.4**.

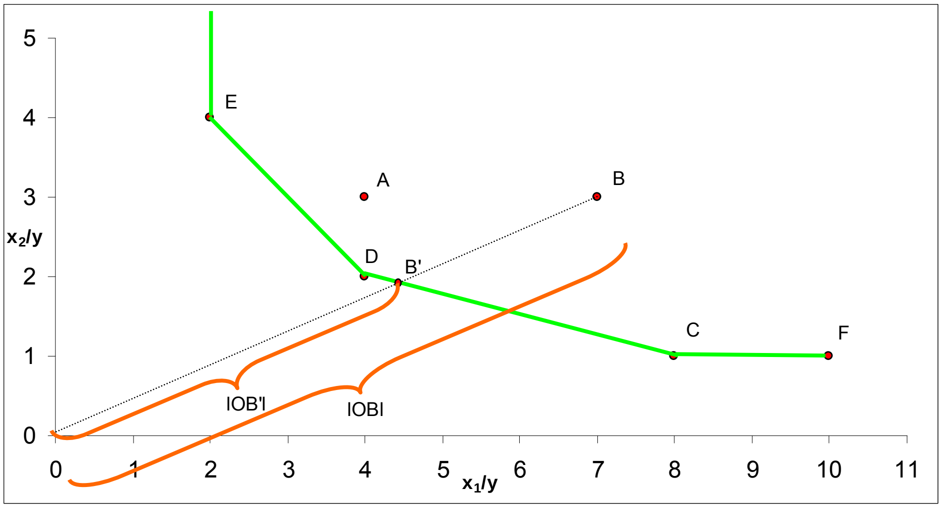


Figure 2.4: Efficient Frontier as defined in DEA

Efficiency score of DMU B, which was calculated to be 0.6316 using the primal CCR formulation, is in fact the technical efficiency of DMU B as discussed in **Section 2.5.1**. Thus, it can be represented by the ratio presented in that section as:

$$Q = \frac{|OB'|}{|OB|} = 0.6316$$

By using the plot shown above, this ratio and thus the efficiency score of DMU B can be calculated as 0.6316. This is exactly the same as what was found using the primal CCR formulation. Using this "relative distance from the efficient frontier" approach, the efficiency score of each of the remaining DMUs can be calculated to be the same as what was found by the primal CCR formulation (as presented in **Table 2.2**). Obviously with such an approach, each DMU that is on the efficient frontier (i.e. DMU C, DMU D, DMU E, and DMU F) gets the same efficiency score of 1 which is the same as what the primal CCR formulation calculated as presented in **Table 2.2**.

The technical efficiency mentioned above is called the *input reducing technical efficiency* within the context of DEA. It indicates the level by which the inputs utilized by a DMU can be reduced without changing the level of outputs produced by such DMU. Using the efficiency score that is obtained through the solution of the primal CCR model, one can establish the projection of any DMU (that is not technically efficient) on the efficient frontier. In the example presented above, the projection of DMU B on the efficient frontier is point B′ as shown in **Figure 2.4**. As discussed in **Section 2.5.1**, such projection is obtained by radial contraction of the inputs of DMU B, i.e. by the same ratio of Q, as calculated for DMU B. So, the projection of DMU B on the efficient frontier is the point B′ whose input 1 and input 2 are 4.4212 (=7*0.6316) and 1.8948 (=3*0.6316) respectively and whose output is 1 (left unchanged as we are dealing with the input reducing technical efficiency).

Output Oriented Primal CCR Model

In DEA, efficiency can be studied from an output point of view (orientation) as well as from an input point of view (orientation). Therefore, DEA also establishes the *output increasing technical efficiency*, which is defined as the level by which the outputs produced by a DMU can be increased without changing the level by which inputs are utilized by such DMU (Triantis 2005c).

The formulations, calculations, and graphs that are used in the example presented above were based on the input orientation. Same orientation will be used in the later parts of this chapter whenever such example is referred to. Nonetheless, for the sake of completeness, the formulations that are based on the output orientation will also be presented. The primal CCR formulation that is based on the output orientation is presented below:

Formulation 2.2

(LP_0): minimize $H_0 = \sum_{i=1}^{m} v_i x_{i0}$

subject to:

$$\sum_{r=1}^{s} u_r y_{r0} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} \le \sum_{i=1}^{m} v_i x_{ij} \; ; \qquad j = 1,\ldots\ldots,n \qquad r = 1,\ldots\ldots,s \qquad i = 1,\ldots\ldots,m$$

$$u_r, v_i \ge 0$$

where n: number of DMUs in the data set

s: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$u_r, v_i \ge 0$: the variables' (inputs' and outputs') weights to be determined by the solution of this optimization problem.

2.5.2.2 Dual CCR Models

Input Oriented Dual CCR Model

As presented in the example above, the solution to the primal CCR formulation gives the optimal set of weights (u_r, v_i) of the input-output variables that maximizes the technical efficiency of the DMU for which the formulation is solved (Djerdjouri 2005). The solution also gives the efficiency score and by using this efficiency score, the projection of a DMU on the efficient frontier can be calculated as illustrated above. This is the case regardless of the orientation of the formulation that is used (i.e. input oriented or output oriented). However, what are of interest to the decision-maker are not only the weights of the input-output variables and efficiency score of a DMU, but also the peer DMUs for that DMU. In the example presented above, by observing the plot shown in **Figure 2.4**, the peer DMUs for DMU B can be identified as DMU C and DMU D as the projection of DMU B on the efficient frontier, B′, is a weighted combination of such peer DMUs. Nonetheless, for the cases which can not be plotted (due to having a large number of input-output variables as opposed to the three as in this example) as this example was plotted, identifying such peers and the weights of such peers cannot be achieved using the primal CCR formulation presented earlier. Nonetheless, the dual of the linear program presented in primal CCR formulation can identify such peers and their weights easily.

Every LP problem has an associated LP problem that is called the dual. It is important to note that the original LP is called the primal. If in the primal LP, the objective is maximization; then in the dual LP, the objective is minimization (Reeb and Leavengood 2000). In the case of DEA, both primal and dual formulations identify the efficiency scores of DMUs. The main difference of the formulations (as far as what they compute is concerned) is that the primal formulation identifies the virtual set of weights of the input-output variables and the dual formulation identifies the peer DMUs of the DMU under investigation (Golany and Roll 1989). The dual formulation not only names such peers but also identifies the relative importance (i.e. weights) of the peers in forming the target of the DMU under investigation. The dual formulation, furthermore, identifies the target of the DMU under investigation. The term “target” is conceptually very similar to the term “projection on the efficient frontier” as described above. As a matter of fact, the projection of a DMU on the efficient frontier is in fact the target of such DMU in the cases where that DMU has no slacks associated with its inputs and outputs. The slack concept will be made clear as the dual formulation is presented. For the time being, it is sufficient to note that the dual formulation has the capability of identifying the slacks which are needed to be known to be able to identify the target of the DMU under investigation (Cooper et al. 1999). As will be described later on, both the "target" and "relative importance of peers in forming the target" concepts are very important concepts as far as the decision-making is concerned. Thus, the results that are obtained using the dual formulation (efficiency score, peers and their weights, and the target) can be asserted to be more important than the results obtained using the primal formulation (efficiency score, weights of the input-output variables, and projection on the efficient frontier).

In the literature, the DEA model that uses the primal formulation is named as the "multiplier model" and the one that uses the dual formulation is named as the "envelopment model" (Rouse 1997). **Table 2.4** summarizes the discussion presented in the preceding paragraph.

Table 2.4: Summary of Multiplier and Envelopment Models

		Items that are Obtained using the Model				
LP Formulation	**Model Name in DEA**	**Efficiency Score**	**Weights of the Input-Output Variables**	**Projection on the Efficient Frontier**	**Peers and their Weights**	**Target**
Primal	Multiplier Model	Yes	Yes	Yes	No	No
Dual	Envelopment Model	Yes	No	Yes	Yes	Yes

Below is the dual CCR LP formulation that is used in the envelopment model. It is important to note that such formulation is presented for the input orientation. The one for the output orientation will be presented at a later part of this section.

Formulation 2.3

minimize Q **Expression (2.2)**

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \le Q x_{i0} \quad \textbf{Expression (2.3)}$$

$$\sum_{j=1}^{n} z_j y_{rj} \ge y_{r0} \quad \textbf{Expression (2.4)}$$

j = 1,……,n r = 1,…….,t i = 1,…….,m

where n: the number of DMUs in the data set

t: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$z_j \ge 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

In the formulation presented above, Q is the measure of input reducing technical efficiency. The right hand side of **Expression 2.3** gives the potential input usage (target) of the DMU which is being investigated. If the investigated DMU turns out to be inefficient, Q will be less than 1, indicating that the target of such DMU should use a fraction of its actual input usage (Medina-Borja 2002; Triantis 2005c).

The left hand sides of **Expression 2.3** and **Expression 2.4** represent the hypothetical DMU (that is a combination of the peer DMUs to which the DMU that is under investigation is compared) formed by taking weighted averages of the real (and peer) DMUs for each input and output. The fact that the z_j s are the same in all of the constraints means that each of the inputs and outputs of the hypothetical DMU is the same weighted average of those of the real DMUs (Medina-Borja 2002; Triantis 2005c).

The first set of constraints (**Expression 2.3**) indicates that the weights will generally be chosen so that the hypothetical DMU uses the inputs in the same quantities as the target of the DMU which is under investigation uses. The inequality is to allow for the possibility that the investigated DMU (or the projection of an investigated DMU on the efficient frontier) is on the flat portion of the efficient frontier (as illustrated by D in **Figure 2.1**). In essence, that inequality is to allow for the possibility of the presence of a slack on the input side. A slack on the input side means that a DMU (or the projection of a DMU on the efficient frontier), even though located on the efficient frontier, is still using some excessive input which should be removed for it to be technically efficient (Medina-Borja 2002; Triantis 2005c).

The second set of constraints (**Expression 2.4**) indicates that the weights must be such so that the hypothetical DMU produces as much of output as the DMU which is under investigation produces. Again, the inequality is to allow for the possibility of the presence of a slack, this time as the presence of an amount of shortfall on the output side (Medina-Borja 2002; Triantis 2005c).

Exploring the input oriented envelopment model, one can understand that what the formulation tells is: A DMU is not efficient in using its inputs to produce given amount of outputs if it can be proved that another DMU or a combination of other DMUs can produce the same amount of outputs by using less of some inputs and no more of any other inputs. A DMU is efficient if this is not possible (Djerdjouri 2005).

When the formulation within the envelopment model is solved, the following results can be obtained and interpretations can be made (Rouse 1997):

- For an efficient DMU, Q=1 and there are no slacks; the DMU's own z=1 and all other DMUs' z=0
- For a weak efficient DMU, Q=1 but there are one or more slacks; some other efficient DMUs' z>0
- For an inefficient DMU, Q<1 and there may be one or more slacks; some other efficient DMUs' z>0

For the example presented earlier, the envelopment model would be formulated as follows to measure the input reducing technical efficiency of DMU B:

minimize Q

subject to:

$$4z_A + 7z_B + 8z_C + 4z_D + 2z_E + 10z_F \leq Q*7$$

$$3z_A + 3z_B + 1z_C + 2z_D + 4z_E + 1z_F \leq Q*3$$

$$z_A + z_B + z_C + z_D + z_E + z_F \geq 1$$

It is very cumbersome to compute the results of this optimization problem by hand. However, the efficient frontier of this particular DEA problem could be plotted (due to the presence of a few number of input-output variables) in **Figure 2.4**. When this figure is observed, it can be seen that DMU B needs to be projected on the efficient frontier on the spot B′ to be able to be technically efficient. Since such projection is not on the flat portion of the efficient frontier, it can be said that DMU B has no slacks associated with its inputs and output. In other words, the projection of DMU B on the efficient frontier is in fact the target of DMU B. In addition to this, it can be observed that such target is formed by a weighted combination of DMU C and DMU D. Given these pieces of information, the LP formulation presented above can be simplified to a series of linear equations such as:

$8z_C + 4z_D = Q*7$ **Expression (2.5)**

$1z_C + 2z_D = Q*3$ **Expression (2.6)**

$1z_C + 1z_D = 1$ **Expression (2.7)**

When **Expression (2.5)**, **Expression (2.6)**, and **Expression (2.7)** are solved simultaneously, following results can be obtained for DMU B:

- Efficiency score: $Q = 0.6316$
- Weight of the peer DMU C: $z_C = 0.1053$
- Weight of the peer DMU D: $z_D = 0.8947$

As can be seen from the results above, both the multiplier model (with primal formulation) and the envelopment model (with dual formulation) computed the efficiency score of DMU B the same, i.e. 0.6316. The multiplier model computed the weights of the inputs and output of DMU to reach that efficiency score. Envelopment model, on the other hand, identified the peers of DMU B as well as computing their relative importance (weights) in forming the target of DMU B.

Output Oriented Dual CCR Model

The formulation presented above is for input orientation. The dual CCR LP formulation for the output orientation is presented below:

Formulation 2.4

maximize Q

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \leq x_{i0}$$

$$\sum_{j=1}^{n} z_j y_{rj} \geq Q y_{r0}$$

j = 1,……,n   r = 1,…….,t   i = 1,…….,m

where n: the number of DMUs in the data set

t: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$z_j \geq 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

2.5.2.3 Returns to Scale Issue and BCC Models

Processes may be operating on two different returns to scale (Triantis 2005c):

1. **Constant Returns to Scale**: This is the operation mode in which a proportionately equal increase in all inputs leads to the same proportional increase in all outputs.
2. **Variable Returns to Scale**: This is the operation mode in which a proportionately equal increase in all inputs leads to a proportional greater or smaller increase in all outputs.

All of the DEA formulations presented till now assume that the DMUs are experiencing constant returns to scale. However, if the DMU is not operating under constant returns to scale, it is experiencing scale inefficiencies (Triantis 2005c). As underlined earlier, DEA is an approach designed to measure the technical efficiencies of DMUs and thus the formulations presented earlier need to be adjusted in the cases where DMUs are experiencing variable returns to scale, to be able to consider and remove the effect of scale inefficiency that is inherent in such operation mode. The concept of "scale inefficiency" within the context of DEA is presented below through the help of a single input-single output case. **Figure 2.5** illustrates the efficient frontier plotted for 5 DMUs (whose input and output values are shown in **Table 2.5**) when such DMUs are assumed to be experiencing constant returns to scale.

Table 2.5: Input-Output Values for 5 DMUs

DMU	M	L	N	O	P
Input	3	5	6	8	9
Output	7	2	9	5	10

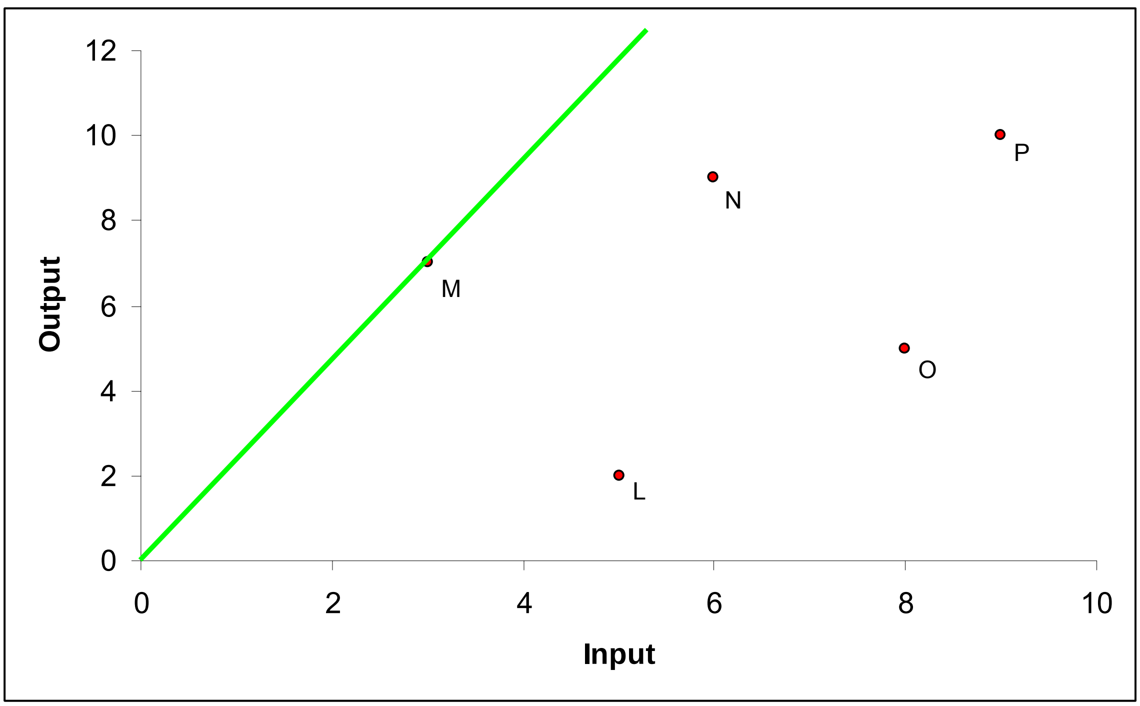


Figure 2.5: Efficient Frontier when DMUs are Experiencing Constant Returns to Scale

Figure 2.6, on the other hand, illustrates the efficient frontier plotted for the same 5 DMUs when such DMUs are assumed to be experiencing variable returns to scale.

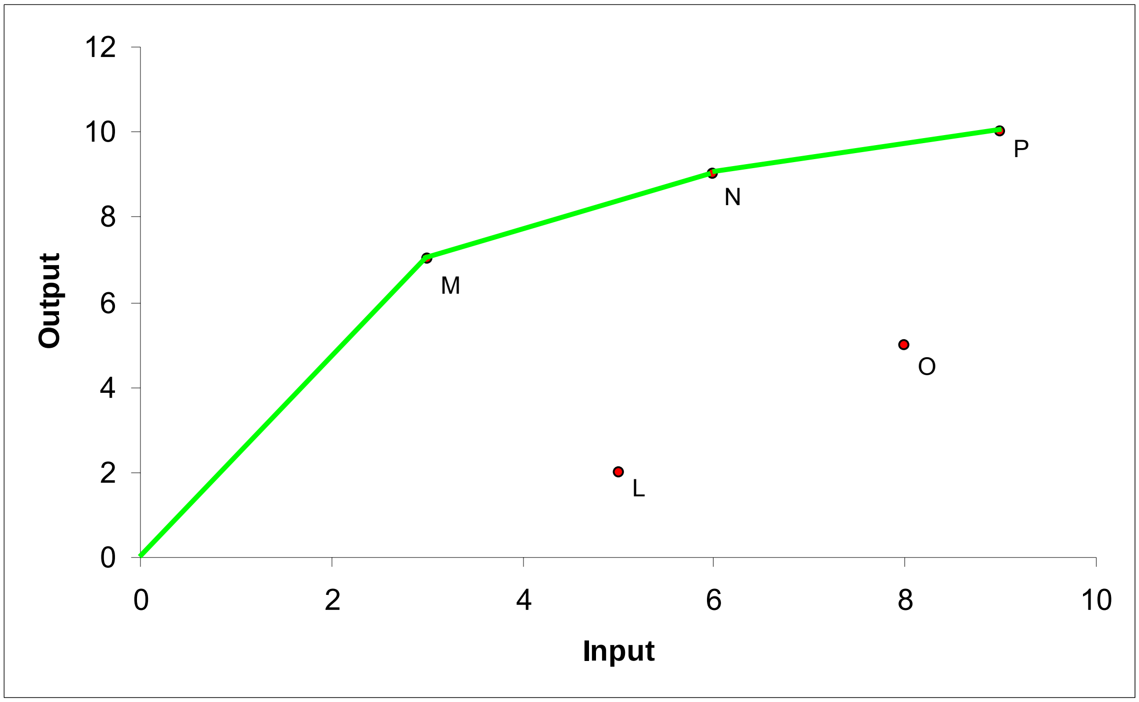


Figure 2.6: Efficient Frontier when DMUs are Experiencing Variable Returns to Scale

When **Figure 2.5** and **Figure 2.6** are compared, it can clearly be seen that DMU N and DMU P are not on the efficient frontier when they are assumed to be experiencing constant returns to scale and thus their DEA efficiency scores are less than 1. On the other hand, same DMUs are on the efficient frontier when they are assumed to be experiencing variable returns to scale and thus their DEA efficiency scores are equal to 1. Moreover efficiency scores of DMU L and DMU O are greater when they are assumed to be experiencing variable returns to scale than the case in which they are assumed to be experiencing constant returns to scale.

Given the discussions presented above, during the establishment of a DEA model, if it is known that the DMUs in the data set are experiencing variable returns to scale, a new formulation which takes care of their scale inefficiencies and thus results in a new efficient frontier and efficiency scores as presented above should be used. Such new formulation and DEA model, which was proposed by Banker et al (1984) is called the BCC model and is presented below (Banker et al. 1984):

Formulation 2.5

minimize Q

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \leq Q x_{i0}$$

$$\sum_{j=1}^{n} z_j y_{rj} \geq y_{r0}$$

$$\sum_{j=1}^{n} z_j = 1 \qquad \textbf{Expression (2.8)}$$

j = 1,……,n r = 1,…….,t i = 1,…….,m

where n: the number of DMUs in the data set

t: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$z_j \geq 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

The only difference of this formulation from **Formulation 2.3** is the presence of one extra constraint that is seen in **Expression (2.8)**. Within the BCC model, this constraint ensures that the hypothetical DMU (that is a combination of the peer DMUs to which the DMU that is under investigation is compared) is operating at a scale size similar to the one under which the DMU under investigation is operating (Triantis 2005c). In other words, the effect of this extra constraint (which is called the convexity constraint) that states that the sum of peer weights should be equal to unity is to restrict the peer comparison set to DMUs with comparable size or volume (Rouse 1997).

The formulation presented above is for the input orientation. The formulation for the output orientation is presented below:

Formulation 2.6

maximize Q

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \leq x_{i0}$$

$$\sum_{j=1}^{n} z_j y_{rj} \geq Q y_{r0}$$

$$\sum_{j=1}^{n} z_j = 1$$

j = 1,……,n   r = 1,…….,t   i = 1,…….,m

where n: the number of DMUs in the data set

t: number of outputs

m: number of inputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

$z_j \geq 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

2.5.3 Issues Related to DEA

2.5.3.1 General Notes on DEA

As indicated earlier, DEA is a linear programming based modeling technique that is used to convert multiple input and output measures into a single comprehensive measure representing technical efficiency (Epstein and Henderson 1989). It is based on the productivity theory and production technology assumptions. The six postulates that form the basis of DEA are (Medina-Borja 2002; Triantis 2005c):

1. Free production is not possible. In other words, one cannot have positive outputs without using some inputs.
2. Infinite production is not feasible. In other words, finite inputs cannot produce infinite outputs.

3. A proportional increases in inputs do not decrease outputs.
4. A proportional increase in outputs cannot be obtained if inputs are reduced.
5. The correspondence between inputs and outputs is closed. This assumption allows for the definition and the existence of an isoquant.
6. The isoquant is convex to the origin. In a two dimensional input space this indicates that if two input bundles can each produce one unit of output, then so can the weighted average of them.

DEA approach possesses the following characteristics (Charnes et al. 1994):

- It focuses on individual observation of DMUs in the data set as opposed to population averages of such DMUs.
- It produces a single aggregate measure for each DMU in the data set with respect to its usage of inputs to produce desired outputs.
- It can simultaneously deal with multiple outputs and multiple inputs each of which may be measured in different units.
- It can incorporate external and uncontrollable factors (such as environmental factors that affect the production) as variables into the model.
- It can incorporate categorical variables.
- It does not require the specification of a priori weights for the variables.
- It does not place any restriction on the functional form of the production relationship.
- It can accommodate judgment if desired.
- It produces the estimates for desired changes in inputs or outputs for projecting DMUs below (in output orientation) or above (in input orientation) the efficient frontier onto the efficient frontier.
- It focuses on the obtained best-practice frontiers rather than central tendency frontiers.

As can be seen in the primal CCR formulation, there is a great deal of flexibility of DMUs in choosing their variables' (inputs' and outputs') weights (v_i and u_r). As a result of this flexibility, some truly inefficient DMUs may appear efficient as a result of the DEA calculations by choosing the appropriate set of weights. This raises the question of whether the DMU calculated as efficient by the DEA model is truly technically efficient or it is efficient due to such flexibility it has in choosing the weights. On the other hand, if DEA calculates a DMU to be inefficient, it means that such DMU is truly inefficient as it turned out to be inefficient even by choosing the most favorable set of weights (Triantis 2005c).

The efficiency scores obtained from DEA provide a ranking of the inefficient DMUs. However, there is no such ranking for efficient DMUs as they all receive the rating of 100%, i.e. they all are best-performing DMUs (Thore 2002). Certain methods, prominent of which are by Andersen and Petersen (1993), Doyle and Green (1994), Tone (2001), and Jahanshahloo et al. (2006) (Andersen and Petersen 1993; Doyle and Green 1994; Jahanshahloo et al. 2006; Tone 2002), have been developed in an effort to enable the ranking of efficient units as well. Establishment of such a ranking is not within the scope of this research and thus those methods will not be utilized during the course of this research.

Some characteristics of DEA that distinguish it from other methods of efficiency analysis (such as regression) are as follows (Thore 2002):

- DEA is based on empirical relationships. In other words, it is a non-parametric method that does not need any assumption of a theoretical relationship between the inputs and outputs of a process.
- DEA results in a piecewise linear efficient frontier. This efficient frontier (“envelope” as used in DEA) is made of corner points that are representing the efficient observations and the adjoining linear facets.
- DEA is a one-sided estimation method in which all observations (“DMUs” as used in DEA) are located either on the efficient frontier itself or on one side of such frontier.

2.5.3.2 Major Phases of DEA

An efficiency study performed using DEA is composed of six major phases as listed and elaborated on below (Golany and Roll 1989; Ramanathan 2003):

1. **Phase 1- Definition and Selection of DMUs to be used in DEA**: DEA is a method to measure the relative efficiency of “comparable” units with an ultimate goal of improving their performance. Therefore, a homogenous set of units (DMUs) needs to be included in

the analysis. A homogenous set of units can be obtained by considering the following criteria (Dyson et al. 2001; Golany and Roll 1989):

i. The units should be performing the same tasks with similar objectives. It may also be an assumption that common technologies should be used among the units but there are instances in which DEA is used to compare different technologies.
ii. The input-output variables characterizing the process of the units in the data set should be identical except for the differences in their magnitude or values. In the cases when a different resource such as different equipment is used by different DMUs, DEA can still be applied if such resource is brought to a common denominator as an input such as cost.
iii. The units should be performing under the same market conditions.
iv. The units should be operating in similar environmental conditions as such conditions greatly affect the overall performance of units. Nonetheless, this criterion can rarely be met and to overcome this issue, some factors which reflect this environmental effect are brought into the analysis as variables to be added to the input-output set. This approach will be elaborated on within **Chapter 3**.

In the cases when the homogeneity across all of the units is not met, an approach is to cluster the units into homogenous sets and perform DEA within these different clusters (Dyson et al. 2001).

One other issue that needs to be considered during the selection of DMUs is determining the size of the data set. Such determination is accompanied by a trade-off. The larger the population of the data set, the larger the probability of capturing high performance DMUs that would form the efficient frontier. Furthermore, as the number of DMUs in the data set increases, it is possible to incorporate more variables into the analysis (due to the reasons explained in phase 2 below). On the other hand, the larger the population of the data set, the larger the probability of risking the homogeneity within such data set (Golany and Roll 1989).

DMUs to be included in the DEA models can be selected in two levels: (i) DMUs can actually represent different units/organizations or (ii) DMUs can represent the time periods for a single unit/organization. In the latter case, the analysis is time-based. Preferably, the time periods should be naturally broken and correspond to seasonal or fiscal cycles of budgeting or measuring periods. If the time period is chosen to be too long, it may obscure significant changes taking place within it. On the other hand, if it is chosen to be too short, it may give an incomplete picture of the DMU's process and activities (Golany and Roll 1989).

2. **Phase 2- Definition, Selection, and Measurement of Input and Output Variables**: As mentioned many times before, an important feature of DEA is its free functional form. DEA does not need any production function equation of a parametric form for the solution of the model specified within it. Therefore, any variable can be included in the model without the need to specify functional or parametric relationships. Even a variable that is neither an economic resource nor a product but just an attribute of the environment or of the production process can easily be included in the DEA model. Moreover, DEA does not make a priori distinction between the relative importance of any two input or two outputs. In other words, all variables that are included in the model have an equal opportunity to influence the calculated efficiency (Epstein and Henderson 1989). Given this, the initial list of variables used to assess the efficiency of a DMU tends to be and in fact should be as comprehensive as possible. This list should contain each relevant and suitable variable which affects the performance and efficiency of the DMU and which is strongly related with the objectives of the DMU. In other words, this list should contain each input and output variable that would be a part of the reasonable production function of the DMU (even though the equation of such production function is not needed to be stated explicitly in DEA). The variables within this list should be common to all DMUs. Such variables may either be controllable by the DMU or they may be external and uncontrollable factors such as environmental and operational effects. Some of the variables may be quantitative and others may be qualitative. Variables can be represented using one of the following four scale types: categorical, ordinal, interval, and ratio. Considering every variable that has an impact on the performance of the DMU is very likely to result in a list composed of a large number of variables. However, running the DEA model using a large number of variables would shift the compared DMUs towards the efficient frontier, resulting in a large number of DMUs to have high efficiency scores.

As DEA allows flexibility in the choice of input-output variables' weights, the greater the number of variables included in the analysis, the lower the level of discrimination. A DMU for which one particular ratio of an output to an input is the highest can allocate all of its weight to such ratio and become efficient. The total number of such ratios will be the product of the number of inputs and outputs. This product is a practical indicator of the minimum number of efficient units that will result from the implementation of DEA. Thus, in a case with 4 inputs and 4 outputs, DEA would result in at least 16 efficient DMUs. A suggested rule of thumb to achieve a reasonable level of discrimination is that the number of DMUs should be at least 2*m*t where m*t is the product of the number of inputs and number of outputs (Boussofiane et al. 1991; Dyson et al. 2001). Given this discussion, once the initial comprehensive list is developed, such list should be reinvestigated and refined to include only the most relevant and important variables. Such refinement can be performed in three ways as explained below (Golany and Roll 1989):

i. Judgmental Process: This process is composed of a critical examination of the variable list by expert decision makers (of the relevant field). Decision makers may identify some variables as repeating virtually the same information, some of them as conflicting or confusing. Decision makers may deem some variables to be not too crucial. This judgment process, as performed by the decision makers, generally results in the refinement of the list through the help of the answers given to the following questions (Golany and Roll 1989):

   - Is the variable related to one or more of the objectives set for the process?
   - Does the variable possess relevant information that is not included in the other variables?
   - Does the variable possess elements (i.e. price) that impedes with the concept of technical efficiency?
   - Is the data for the variable readily available or measurable, and sufficiently reliable?

ii. Quantitative Methods: There are certain quantitative methods to refine the list of variables. First one is related to reducing the number of variables. Some variables can be aggregated into one variable. A good example of this is the cost. Variables as “number of people”, “gallons of fuel”, “KWH of electricity” can be measured in terms of cost, resulting in the reduction of number of variables. Regression analyses which identify the correlations between variables and/or statistical analyses may also help eliminating redundancies and reducing the number of variables. Some variables (typically the uncontrollable ones) can be used to rescale all other variables in the analysis, again resulting in the reduction of total number of variables. Second method of quantitative refinement deals with the isotonicity issue. DEA requires that the input-output relations of a DMU be isotonic, i.e. an increase in any input should not result in a decrease in any output. To avoid this, the values of some variables may need to be inverted before they are used in DEA (the ways to deal with the isotonicity issue will be elaborated on in more detail within **Chapter 4**). Last method of quantitative refinement has something to do with qualitative variables. Such variables need to be assigned numerical values to be used in the mathematical evaluation of efficiency as used in DEA. The common practice to perform this is to find some measurable surrogate variable which possesses a known relation to the varying levels of the qualitative variable.

iii. DEA Based Methods: Variables which are remained in the list so far are used to run the CCR model. Variables which consistently get very small weights may be removed from the list as they have little impact on the efficiency scores. To test the discriminating power of different variables, the DEA model can be run with a series of combinations of these variables. Then some techniques can be used to group the DMUs based on the resulting efficiency scores. Observing the DMU groupings as established after each run of the model with different combinations of variables, one can identify the variables which have little discriminating power and then remove those from the list.

3. **Phase 3- Selection of the DEA Model and Formulation**: A number of DEA models and formulations are presented in the previous sections of this chapter. Such models can be

grouped as (i) the models for DMUs with constant returns to scale (CCR) or the models for DMUs with variable returns to scale (BCC), (ii) input oriented models or output oriented models, and (iii) multiplier (primal) models or envelopment (dual) models. To be able to select the right model to utilize, one needs to answer the following series of questions (Charnes et al. 1994; Ramanathan 2003):

i. Are the DMUs within the data set experiencing constant returns to scale or variable returns to scale?
ii. Are the decision makers more flexible and interested in changing (increasing/maximizing) the outputs of the DMUs or changing (reducing/minimizing) the inputs of the DMUs?
iii. Do the decision makers need to identify best practices within the data set, peers and targets of the DMUs or input and output weights of such DMUs?

The answer of the first question will help deciding on whether to use the CCR or the BCC model. Once such decision is made, the answer of the second question will identify whether to use an input oriented or output oriented model. The answer to the third question is not as critical as the first two as given enough resources (time, software, etc…), one can run both the primal and dual models to identify all possible information with respect to the DMUs (i.e. best practices within the data set, peers and targets of the DMUs, and input and output weights of DMUs).

4. **Phase 4- Application of DEA Models**: This is the phase in which the model(s) as identified in phase 3 are run by including the variables identified in phase 2 and DMUs identified in phase 1. Given the heavy computation requirements of the DEA models, usually this phase is performed with the help of appropriate computer codes and/or software that are specifically designed to solve DEA problems. Discussions about the usage of such software and some prominent software within the field will be presented in **Section 2.5.3.4**.
5. **Phase 5- Post-DEA Procedures**: One should always keep in mind that DEA measures the efficiency with respect to the DMUs and based on the variables selected. There is no guarantee that initial selection of such DMUs and variables are correct and serves the best

purpose of the analysis. Therefore, the issues discussed in phase 1, phase 2, and phase 3 may require the application of DEA in an iterative fashion. Additionally, it may be useful to obtain more than one set of results as derived from different selection of DMUs, variables, and/or models/formulations (Golany and Roll 1989).

DEA results are very sensitive to even small errors within the input-output variables' data. Moreover, since DEA is a non-parametric method, it may not be possible to estimate the confidence (as used in statistics) with which DEA results are calculated. Thus, DEA results should be viewed with caution and should be used only after appropriate sensitivity analysis is conducted. Some of the possible sensitivity analyses that can be conducted are: Running the DEA model one more time after removing the efficient DMUs from the data set and running the DEA model one more time after removing some variables from the list of variables that was used in the initial run of the DEA model (Ramanathan 2003).

6. **Phase 6- Presentation and Analysis of Results**: DEA is a technique which does not directly pinpoint the underlying causes of inefficiencies of DMUs (Triantis 2005a). Nonetheless, the results of DEA can be utilized to direct decision makers' attention to developing a better understanding of the reasons why some DMUs are located on the efficient frontier and thus efficient and why others are inefficient. DEA may trigger decision makers to try to identify the differences in formal structures, operational practices (managerial practices, field practices etc…), or other organizational factors of the DMUs that may account for the observed efficiency differences in such DMUs. The overall objective of DEA is to assign organizational meaning to the observed efficiency differences and to determine the organizational changes that the inefficient DMUs will need to undertake and how to implement such changes. The common methods to be able to reach such objective are benchmarking and describing and documenting the best practice processes of the DMUs that are efficient (i.e. located on the efficient frontier) (Charnes et al. 1994).

   The DEA results are intended to be used as guides for managerial actions and policymaking as calculated targets for inputs and outputs indicate potential performance and efficiency increases for inefficient DMUs. However, such use of DEA results is often not appreciated in practice (Charnes et al. 1994). One of the major reasons of this fact may be the complex mathematical formulations and computations possessed by DEA and poor presentation of DEA results to the decision makers. To overcome this issue, DEA results should be presented in a very concise way, possibly with the use of some charts and easy-to-follow tables.

2.5.3.3 Strengths and Limitations of DEA

This section lists the strengths and limitations of DEA as identified through the literature review. Strengths are as follows (Ramanathan 2003; Rouse 1997):

i. The main strength of DEA is its objectivity. DEA provides efficiency scores based on the solution of some formulations that give the optimum input and output weights to the DMUs by using numerical data. Thus, such efficiency scores are not based on the subjective opinions of people.
ii. DEA can handle multiple inputs and multiple outputs each of which may be measured in different units.
iii. DEA identifies the efficient units that define the efficient frontier and it quantifies the inefficiency of each of the remaining units and also identifies such units' peers.
iv. Unlike other methods of statistical analysis, DEA is non-parametric and thus it does not require the specification of an explicit functional form relating inputs to outputs.
v. DEA can take the differences in scale of operations into account.
vi. DEA can incorporate external and uncontrollable factors (such as environmental factors that affect the production) as variables into the model.
vii. One can add as many constraints to the original formulation as desired such as assigning some bounds on the input and output weights that the DMUs can take.

Limitations of DEA are as follows (Ramanathan 2003; Rouse 1997):

i. Application of DEA requires a separate LP be solved for each DMU in the data set. When there are many DMUs, the computation can be cumbersome. Nonetheless, this limitation has been minimized with the development of computer codes and software that specifically deal with DEA problems (as will be presented in **Section 2.5.3.4**).

ii. Since DEA is a non-parametric method, statistical hypothesis tests are difficult to implement to assess the reliability of results.
iii. Since DEA is an extreme point technique, errors in measurement or recording of data for input-output variables may result in significant problems. Thus, utmost care should be given to assure that input-output data is accurate. This issue can also be addressed using sensitivity analysis as pointed out earlier.
iv. The flexibility given to the DMUs in selecting their input-output weights may lead to some input or output measurements to be completely ignored by the DMUs. This issue can be addressed by using some bounds on input-output weights as mentioned above.
v. As efficiency scores in DEA are obtained by running a series of LP formulations, it becomes intuitively difficult to explain the process of DEA to the non-technical audience and/or decision makers for the cases in which there are more than two inputs and outputs. An audience which does not have background in linear programming may not deem DEA as transparent and may find it difficult to comprehend the results. Nonetheless, this issue may be overcome by explaining the DEA process in simpler terms and by proper use of charts and tables to communicate the results.

2.5.3.4 Computer Support for DEA

As underlined many times, DEA is based on linear programming. Therefore, any software package that is designed to solve linear programming formulations can be used to solve DEA problems. However, one distinct character of DEA makes such software packages inadequate, necessitating specialized software to be used for DEA problems. Such characteristic is that DEA applications require solving separate linear programming problems for each DMU that is in the data set. Thus, if there are N DMUs in the data set, one must utilize the software package N times with each time modifying the objective function and constraints. This can become very tedious in the cases where there are a significant number of DMUs in the data set (Ramanathan 2003).

Various DEA formulations as presented in this write-up can be programmed using high-level programming languages to produce software. Such software is available from a number of developers including universities and commercial companies. With the progress of DEA within the academia, some varieties to original formulations are developed. DEA software developers followed this trend and kept pace with the academic developments by producing software that offers solution mechanisms to such advanced modeling formulations, graphical user interfaces, interoperability with other applications, and the ability to quickly solve DEA problems with a larger number of DMUs in the data set (Barr 2004). A review of the capabilities of such software resulted in the selection of *Frontier Analyst* (as it possesses the most professional user interface with the added benefit of numerous visual displays and enables the exporting of results to MS Excel) for the purposes of this research. Such software will be utilized during the application of the end product of this research (i.e. the comprehensive highway maintenance efficiency measurement framework) to the current VDOT-VMS performance-based pilot project within **Chapter 4** for the purposes of hypothesis testing.

2.6 EARLIER WORK POSSESSING APPLICATION OF DEA TO HIGHWAY MAINTENANCE

A thorough literature of review revealed two pieces of research that possess the application of DEA to highway maintenance, which is the case explored in this research. This section elaborates on each of them in an effort to provide the reader with the variables used, methodology and models utilized, and results achieved within each research.

2.6.1 Measurement and Monitoring of Relative Efficiency of Highway Maintenance Patrols using DEA- by Cook et al. (1990 and 1994)

Cook et al. (1990) set off to measure and compare the technical efficiencies of highway maintenance patrols within Ontario. In Ontario, each maintenance patrol is responsible for the maintenance activities associated with some fixed number of lane kilometers of highways. More than 100 different categories of such activities exist and they are grouped under the headings “surface”, “shoulder”, “right of way”, “median”, and “winter operations” (Cook et al. 1990).

Cook et al. (1990) establish the need for an efficiency measurement by stating that observed accomplishments of maintenance patrols influence budgetary decisions and thus a better understanding of their efficiency would give management a yardstick for measuring what accomplishments can be expected within a fixed budget limit. To them, some specific and important questions that are required to be answered are (Cook et al. 1990):

- Why are observed accomplishments different in one jurisdiction than in another?
- Are such observed differences an indication of patrols' performances or are they a function of environmental, traffic or similar other factors?
- What is the influence of the proportion of privatized work on a patrol's efficiency?
- How should the efficiency of a patrol be judged given the abovementioned considerations?

To answer such questions, Cook et al. (1990) decided to use DEA, mainly because it is capable of handling non-economic factors that form an important part of the picture for the highway maintenance such as environmental effects (i.e. climate, etc…) and operational effects (traffic intensity, age of pavement, accidents, etc…) and it allows for measurement of such factors within their own units. Their purpose was to test if DEA is a viable method that can measure the technical efficiencies of highway maintenance patrols (Cook et al. 1990).

Cook et al. (1990) underline that DEA is a good approach to measure the technical efficiencies of highway maintenance patrols as it does not require a priori allocation of weights to the input and output variables of such patrols and lets the patrols choose the most appropriate weights for themselves. This is particularly important in the highway maintenance setting because the importance of environmental factors (variables) to patrols in regions with harsh climates may be different than such to patrols in regions with calmer climates. In choosing weights for any patrol, DEA tries to put the patrol to its most favorable position. The weights assigned to input and output variables illustrate the relative importance of each variable in terms of its influence on a patrol's standing. By including and then excluding some variables within the analysis or by applying various levels of disaggregation, the significance of such variables on the efficiency of patrols can be evaluated (Cook et al. 1990).

In selecting the variables to be used in their analysis, Cook et al. (1990) assert that such selection should seek to find the effects of maintenance activities and the set of explanatory causal factors that enable one to create such effects. Outputs should measure the effectiveness of what maintenance patrols perform. In addition to the controllable variables, uncontrollable variables such as environmental variables that describe the circumstances in which a maintenance patrol is forced to operate and thus which may have strong influences on the maintenance process should also be selected. According to them, the selection of variables must also be guided by the very important considerations of data availability, measurability and reliability. Thus, existing data sources tend to dictate what can be selected as input and output variables to a great extent (Cook et al. 1990).

Cook et al. (1990) state that as soon as the variables which describe the cause and effect with respect to highway maintenance activities are selected, they need to be quantified. While it is true that DEA does not need variables to be reduced to a common unit, it requires each variable to be quantified on some scale. For example, if “safety” is selected as a variable, some reasonable method of capturing and quantifying “safety” (i.e. number of traffic accidents, number of fatal traffic accidents) needs to be found (Cook et al. 1990).

Cook et al. (1990) assert that once the variables are selected, quantified and thus a comprehensive list of variables is prepared, grouping of some variables into overall composite variables should take place to decrease the total number of variables that go into the analysis for the sake of discriminating power of DEA. For example, environmental variables such as the amount of snowfall and the amount of freeze and thaw cycles should be combined into one composite variable which may be called as the climate variable (Cook et al. 1990).

The final list of input variables selected by Cook et al. (1994) to be included in their DEA model is as follows (Cook et al. 1994):

i. Maintenance Expenditures: This variable represents the total expenditures that are linked directly to maintenance patrols. Such expenditures include the expenditures resulting from both in-house work and the maintenance activities performed by private contractors.
ii. Capital Expenditures: This variable represents the total capital expenditures made toward improving the highway conditions existing within the jurisdiction of each maintenance patrol. Five year average figures are used for this variable. Such capital expenditures include resurfacing, shoulder paving, and similar items that complement maintenance efforts.
iii. Climatic Factor: This is a combined variable which takes four climatic variables into account. It is a weighted combination of the effects of snowfall amount, rainfall amount, amount of major temperature cycles, and amount of minor temperature cycles. It is important to note that the weights are chosen such that the issue of differences in numerical scales of each of the factors (i.e. the snowfall numbers are much greater in size than the major temperature cycle numbers) is taken into account. Moreover, the weights

are chosen such that the computation results in a Climatic Factor variable which is in the same order of magnitude as the other variables selected to be used in the DEA model.

The final list of output variables selected by Cook et al. (1994) to be included in their DEA model is as follows (Cook et al. 1994):

i. Area Served Factor: This variable is chosen to measure the extent of the work load for which the maintenance patrol has responsibility. It considers the length, width, shoulder width, surface type and other similar characteristics of the highway section that is under the jurisdiction of each maintenance patrol.
ii. Average Traffic Served: This variable is chosen to represent the overall benefit of the maintained highway to users. This variable is mainly based on the "Annual Average Daily Traffic" (AADT[1]) concept.
iii. Pavement Rating Change Factor: This variable is a measure of the actual change in the pavement condition within a time period relative to a standard (expected) change for the same time period. This variable, intrinsically, takes the age of the pavement into consideration as an element affecting its condition change.
iv. Accident Prevention Factor: This is a variable that is calculated using the ratio of traffic level within the jurisdiction of a maintenance patrol to amount of accidents that occurred due to the maintenance problems within the same jurisdiction.

Of these seven different variables that are chosen to be used, only for one variable (Maintenance Expenditures), it is possible to use the observed data in its raw form. All other factors need to be modified in one way or another, or obtained from combinations of a set of observed data (Cook et al. 1994).

Cook et al. (1990) ran an initial unbounded DEA model first. Then they assigned some bounds on the input and output weights that the DMUs can take and recalculated the efficiency scores of highway maintenance patrols by running another DEA model. Finally, they tried to

[1] AADT is determined by dividing a count of the total yearly traffic volume by 365. Its unit is "vehicles per day" (UIdaho 2006).

answer the set of questions that they developed at the beginning of their research by running different DEA models with three different clustering schemes. They clustered the patrols (i) of similar privatization percentage, (ii) maintaining the highway portions of similar traffic volume, and (iii) maintaining the highway portions of similar importance (i.e. main traffic artery vs. not a main traffic artery) into groups and ran separate DEA models for each group. At the end of their study, they compared the efficiency scores obtained from each run of the DEA models and tried to draw some conclusions about the reasons of inefficiencies (Cook et al. 1990). Of their major findings were that there is no conclusive evidence that privatization affects efficiency, and there appears to be no effect of the traffic volume on the highway maintenance patrols' performance. It is important to note that a total of 62 DMUs (highway maintenance patrols) were included in their analysis (Cook et al. 1994).

2.6.2 Measuring Highway Maintenance Performance using DEA- by Rouse et al. (1997)

Rouse et al. (1997) applied DEA to measure the performance of highway maintenance activities of New Zealand territorial local authorities (TLAs) by using the inputs and outputs measured and reported by such TLAs. They state that TLAs tend to have plenty of data and measures but they lack systematic, consistent, and objective methods of data analysis. TLAs need reliable methods of performance measurement and data analysis to make budgetary and resource allocation decisions as well as to achieve continuous improvement by identifying peers. Such data analysis methods should be able to accommodate the multi dimensional and complex nature of organization activities (Rouse et al. 1997b).

Rouse et al. (1997) state that the combination of multiple inputs and outputs into one single measure of efficiency enables managers to easily assess a unit's overall performance. This requires the development of a weighting scheme for those inputs and outputs. However, appropriate choice of weights by TLA managers possesses subjectivity and may result in the disagreement between different parties who make such choices. DEA has the capability of addressing this problem in addition to having the capability of incorporating non-economic factors (i.e. external and uncontrollable factors), which are very common in a highway maintenance setting, into the efficiency calculations. Moreover, DEA does not require the specification of a full functional relationship between inputs and outputs of the highway maintenance process. This is particularly important in highway maintenance given the complexity of the highway maintenance process and the number of variables influencing such process. Given all of these, DEA is a valuable method that can be used for the efficiency measurement of TLAs (Rouse et al. 1997b).

Rouse et al. (1997) assert that the key to a successful implementation of DEA for highway maintenance efficiency measurement is a detailed understanding of the highway maintenance process. This is essential to be able to identify the input and output variables that are to be used in the DEA model (Rouse et al. 1997b).

Rouse et al. (1997) give particular importance to the environmental variables that need to be used in the DEA model. They state that the research about the impact of geological factors on national highway maintenance costs identified such factors to be the significant drivers of the cost of maintenance activity. Therefore, environmental variables such as geological factors (and others) should be a part of the DEA model of highway maintenance performance (Rouse et al. 1997b).

The final list of variables selected by Rouse et al. (1997) to be included in their DEA model is as follows (Rouse et al. 1997b):

i. Total expenditure on reseals, rehabilitation, and general maintenance (input)
ii. Kilometers of highway resealed (output)
iii. Kilometers of highway rehabilitated (output)
iv. General maintenance as measured by an index of highway surface defects (output)
v. Level of service as measured by annual vehicle kilometers (output)
vi. Roughness measures combined for urban and rural highways (output)
vii. An assessment of environmental difficulty faced by each TLA (categorical variable with 8 categories)

Rouse et al. (1997) ran both CCR and BCC models for 52 DMUs by including the first six variables presented above. However, it is important to note that they have clustered these 52 DMUs based on the category that they belong to as mentioned in the seventh variable and ran the DEA models for each category. However, this posed a problem in relation to the results. Clustering DMUs based on the category significantly reduced the number of DMUs that are evaluated in the DEA models of each category. This, in turn, led to very high efficiency scores to appear in each category and each category ended up having most of the DMUs within to be efficient. This overestimation of efficiency scores is mainly due to the fact that the discriminating power of DEA reduced significantly due to the presence of a few number of DMUs (compared to the high number of input-output variables) to be included in each model. This obviously undermined the whole purpose of DEA which is to discriminate between the DMUs. In conclusion, although it seems fair to evaluate specific DMUs only against those facing similar or more challenging environmental conditions, the results of such an evaluation may not be satisfactory. To overcome this issue, Rouse et al. (1997) ran another model which was a two stage model in which the slacks from the first stage DEA run (incorporating only the controllable variables) are regressed against the environmental factors to adjust inputs and outputs which are subsequently utilized in a second DEA run. This time, DEA models were run with the inclusion of all 52 DMUs in the same model (Rouse et al. 1997b).

The major conclusion of Rouse et al. (1997) is that the identification, measurement, and evaluation of environmental factors are of critical importance during the implementation of DEA in highway maintenance arena because such factors not only provide major explanations for performance variability but they also are major cost drivers. They need to be incorporated into DEA models one way or another to provide a "leveled playing field" for performance analysis. Failure to acknowledge and incorporate environmental factors in performance measurement weakens the overall efficiency evaluation significantly (Rouse et al. 1997b).

2.7 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE

The contribution of this research to the body of knowledge is believed to be with respect to two different areas of literature: (i) performance measurement (specifically DEA), and (ii) highway maintenance. Following sections explain how this research will differ from the current research that is being performed within each of these two areas.

2.7.1 Contributions to the Body of Knowledge in the Performance Measurement and DEA Area

As Rouse (1997) pointed out, the performance measurement concept has been the subject of research in many disciplines such as operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management, and public administration (Rouse 1997). Engineering, on the other hand, is not a discipline in which research about performance measurement is performed as much as it is performed in these other disciplines. Specifically in the DEA arena, even though there have been many studies presenting the application of DEA to real-world situations in other disciplines, there has been limited amount of research that uses DEA in the engineering discipline. Such under-utilization of DEA in the engineering discipline can be attributed to many reasons such as the lack of understanding of the role of DEA in evaluating and improving design decisions, the inability to define the transformation process and thus inputs and outputs of a system, and unavailability/inaccessibility of reliable production and engineering data (Triantis 2004). This research is believed to contribute to the literature of performance measurement (specifically DEA) by developing a replicable generic framework that is based on engineering principles. Thus, this research can be labeled as an application of DEA within the engineering discipline.

As far as the application of DEA to highway maintenance is concerned, a thorough literature review revealed that there has been a very few number of studies that utilized this method in performance and efficiency measurement of highway maintenance operations. As presented in the previous sections, the only pieces of literature dealing with this subject are the two studies by Rouse et al. (1997) and Cook et al. (1990, 1994) (Cook et al. 1994; Cook et al. 1990; Rouse et al. 1997b). This research is believed to be more comprehensive than both of these studies. This is mainly because this research takes all elements of level of service (fence to fence asset groups, paved lanes, and bridges as listed in **Table 1.1**) into account, which was not the case in the abovementioned studies. Moreover, this research investigates the timeliness of response component, which was not investigated by those studies at all. Finally, this research is aimed to develop a more systematic approach in defining and refining the list of the input and output variables (to be used in the DEA models) affecting the performance and efficiency of the highway maintenance process than both of the abovementioned studies.

As a final note, the thorough literature review has not come across any DEA study that is used to compare different highway maintenance approaches (performance-based versus traditional approach) in the transportation arena. This research will address this issue and try to evaluate DEA as a potential technique to develop a comprehensive highway maintenance efficiency measurement framework which later can be utilized to evaluate different approaches to highway maintenance given the availability of data.

2.7.2 Contributions to the Body of Knowledge in the Highway Maintenance Area

Highway maintenance has not been the focus of basic and applied research as topics such as road design, construction, and traffic flow have. Research in the highway arena has traditionally been related to topics like geometric and structural design, selection of materials, specification of sufficient capacity, safety devices, location of intersections and interchanges; and location and characteristics of signs and signals. Comparatively little research has been performed in the areas of highway maintenance and highway maintenance performance (TRB 2006). TRB (2006) identified that some topics related to maintenance management need more examination. This research addresses, to a certain extent, two of such topics as listed below (TRB 2006):

- Fundamental relationships between highway maintenance levels of service and budget and labor utilizations.
- Best practices in specifying maintenance and operations performance, as used in contracting for these services.

As identified by and underlined throughout the literature review, efficiency is a very important dimension of overall performance and thus should be considered as an indispensable element of the concept of "performance measurement". Nonetheless, none of the performance measurement systems developed for highway maintenance in USA elaborates on the efficiency concept in an effort to measure the efficiency of the highway maintenance process. It is believed that this research, by taking the efficiency concept into account, will improve the ways that are currently used to measure and model the performance of highway maintenance.

This research will build on the research already performed at Virginia Tech. As a matter of fact, DEA was identified and recommended as a possible future research area to be explored, by Piñero (Piñero 2003). As mentioned earlier, this research will address the two short-comings of the already developed five component framework for monitoring performance-based road maintenance by developing a comprehensive highway maintenance efficiency measurement framework. Such framework will investigate the efficiency of the highway maintenance process and consider the external and uncontrollable factors that affect the performance of such process in investigating its efficiency. This is believed to substantially improve the framework (for monitoring performance-based road maintenance) that is already developed and in use by Virginia Tech.

2.8 THE POTENTIAL OF THE SYSTEM DYNAMICS APPROACH TO BE UTILIZED IN THIS RESEARCH

System Dynamics is an approach to understand, model and simulate the dynamic behavior of complex systems/processes which usually possess many variables that strongly interact with each other. This approach models a system by depicting the dynamic relationships (which can be circular, interconnecting, or time-delayed relationships) among its variables. This approach acknowledges that: (i) small events can cause large changes in the system due to the presence of many relationships between the variables, (ii) a change in one variable of a system can affect a totally different variable of the same system, and (iii) systems are vastly affected by the environment in which they exist. System Dynamics approach relies on computer software to simulate the depicted model of the system/process that is being investigated. Such simulations allow decision makers to run "what if" scenarios to test certain policies and to understand how the system/process changes over time (Sterman 1999).

A System Dynamics model is composed of stocks and flows which illustrate how a system is connected by feedback loops (Sterman 1999). Such loops, which can either be positive or negative, determine the dynamic behavior. Positive loops are demonstrated by systems that possess exponential growth or decaying behavior. The variable in this type of loop feeds on itself to provide continuous growth or decline. Negative loops seek an equilibrium state. This loop counteracts any deviation from an equilibrium state trying to self regulate the variable (Chasey et al. 1997).

In the System Dynamics approach, the first step is to develop a verbal model. Such model is developed by using the input gathered from experienced individuals familiar with the system and decision makers. Verbal model includes the variables of the system and how actions affect those variables (either increasing or decreasing them). Such verbal model, then, is converted to a causal diagram that depicts the impact of variables on each other. Then, mathematical formulations of all causal relationships are determined. This allows the formal quantification of the dynamic relationships to be made (Chasey et al. 1997). Defining explicit mathematical relationships between the variables is, in fact, the most challenging step of the whole process. Such mathematical relationships can only be defined by using a substantial amount of historical data, consulting with the experienced individuals familiar with the system and decision makers alike. As can be grasped, for the System Dynamics approach, the input from knowledgeable individuals and decision makers in the form of verification, validation, comments, suggestions, and criticism is of critical importance to be able to structure the verbal model and to define the mathematical formulations as close to reality of the system as possible.

Figure 2.7 displays a preliminary model developed for the System Dynamics approach to the highway (particularly the pavement) maintenance efficiency measurement, i.e. a part of the issue investigated in this research.

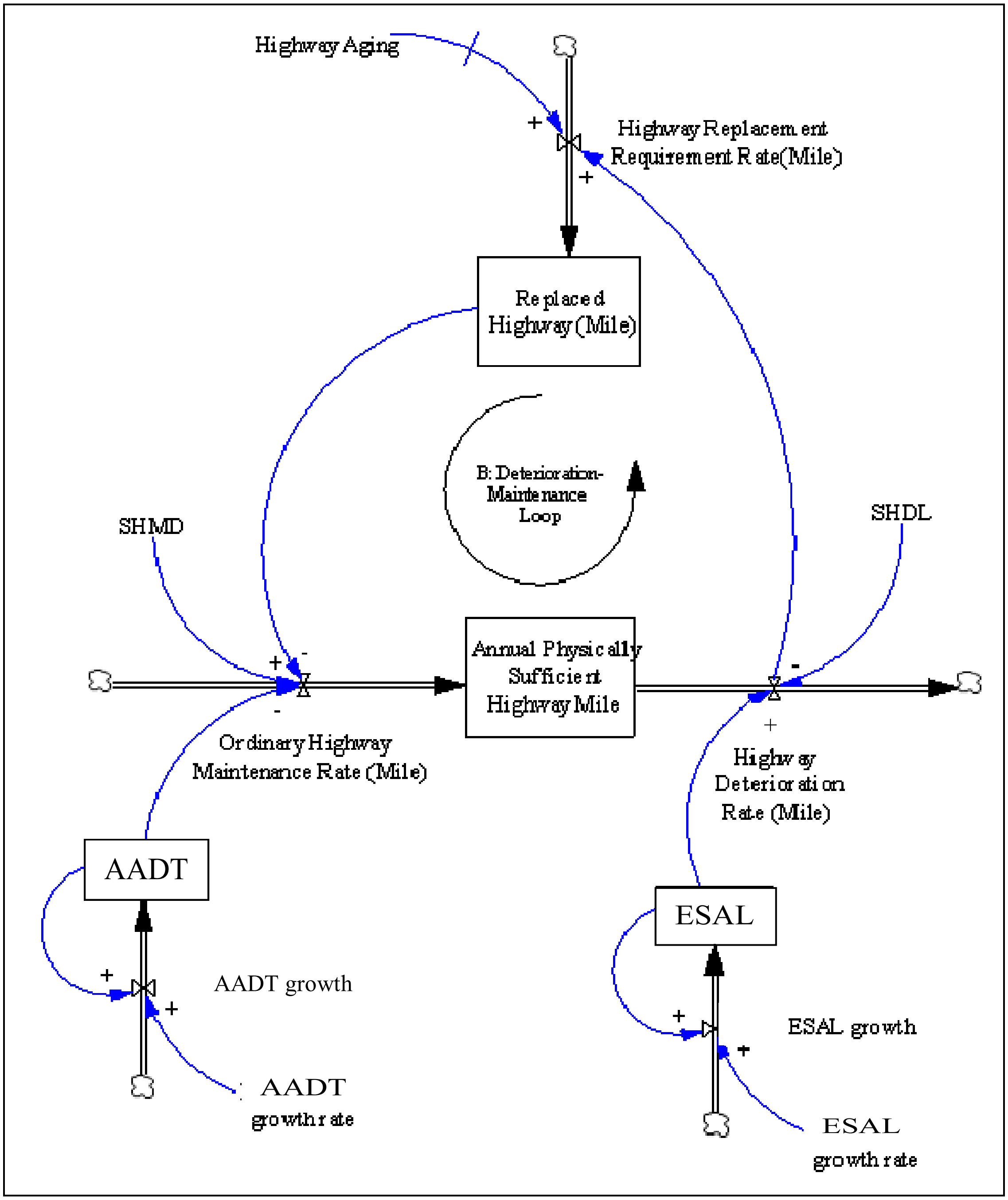


Figure 2.7: A Preliminary System Dynamics Model of Highway (Pavement) Maintenance (Adopted From Burde et al. (Burde et al. 2005, p.69))

The model includes four stocks (Replaced Highway (Mile), AADT, ESAL, and Annual Physically Sufficient Highway Mile) and five flows (Highway Replacement Requirement Rate, Ordinary Highway Maintenance Rate, AADT growth, ESAL growth, and Highway Deterioration Rate). The model has a single balancing loop, Deterioration-Maintenance Loop, between the flows of Highway Deterioration Rate and Ordinary Highway Maintenance Rate. Simply, an increase in the total number of deteriorated highway mile decreases the total highway miles ordinarily maintained by maintenance crews. The highway maintenance crew is responsible for replacing old and deteriorated highway sections as well as performing ordinary maintenance over the unit of time.

In the System Dynamics model depicted in **Figure 2.7**, it is assumed that SHMD[2] (Scaled Highway Maintenance Difficulty- A categorically scaled and unitless maintenance difficulty level based on the effects of climate on the performance of the maintenance crews) impacts only the Ordinary Highway Maintenance Rate flow, while SHDL[3] (Scaled Highway Deterioration Level- A categorically scaled and unitless deterioration level based on the effects of climate on the deterioration of the pavement) impacts only the Highway Deterioration Rate outflow. Similarly, AADT[4] (Annual Average Daily Traffic- The total annual traffic estimate divided by the number of days in the year) impacts only the Ordinary Highway Maintenance Rate flow and the ESAL[5] (Equivalent Single Axle Load- A measure of the load demand placed on a pavement by an 18,000 pound axle) impacts only the Highway Deterioration Rate outflow.

The Highway Deterioration Rate (Mile) outflow is defined as the total number of deteriorated highway miles over the time unit. It is inversely related with SHDL. For example, a higher numerical value of SHDL indicates a lower impact on pavement deterioration. Therefore, a higher numerical value of SHDL means less deteriorated highway miles over a unit of time. Conversely, an increase in the numerical value of ESAL indicates a higher impact on pavement deterioration, resulting in more deteriorated highway miles over a unit of time.

The Ordinary Highway Maintenance Rate (Mile) is the total number of highway miles that a maintenance crew is able to perform ordinary maintenance over the time unit. If the maintenance crew is busy with replacing old and deteriorated highway sections, it puts less time

---

[2] The higher this number, the easier it is for the crews to perform maintenance.
[3] The higher this number, the lower the impact of climate on the deterioration of pavement is.
[4] The higher this number, the harder it is for the crews to perform maintenance.
[5] The higher this number, the higher the impact of traffic load on the deterioration of pavement is.

and effort on ordinary highway maintenance, and thus the ordinary highway maintenance rate drops. The higher the numerical value of SHMD, the easier it is for the crews to perform maintenance, and thus the higher the total number of highway miles that a maintenance crew can perform ordinary maintenance over the time unit. Conversely, the higher the numerical value of AADT, the harder it is for the crews to perform maintenance, and thus the less the total number of highway miles that a maintenance crew can perform ordinary maintenance over the time unit.

The Annual Physically Sufficient Highway Mile stock is computed based on the difference between the total number of deteriorated highway miles and the total number of highway miles ordinarily maintained.

The Replaced Highway (Mile) displays the total highway miles that the maintenance crew has to completely replace due to aging and deterioration. As it increases with increasing number of deteriorated highway miles (positively proportional relationship), aging of the highway can be attributed to the increasing deteriorated highway miles as well. Even at the absence of deterioration, the second relationship shows that a maintenance crew has to replace some miles of highway due to aging after a certain time unit. This is incorporated in the model as a delay function.

Finally in the model, both AADT and ESAL stocks increase exponentially. Such exponential increase is controlled by the growth rates and the values of stocks at a given time as depicted in **Figure 2.7**. The model simulates how the Annual Physically Sufficient Highway Mile changes when the values of AADT and ESAL increase, in other words when the traffic and the load increase.

The causal diagram illustrated in **Figure 2.7** and the verbal model issues as discussed below that figure constitute the first two steps of a preliminary System Dynamics approach to highway maintenance. However, the most important step, defining mathematical relationships between the variables depicted in **Figure 2.7**, has not been performed as neither historical data nor input from the decision makers for the depicted system is available. Had this final step been completed, the model could provide very valuable and insightful information about the system behavior for the decision makers. For example, many different what if scenarios could be simulated by modifying the variables (such as SHMD, SHDL, AADT, ESAL, and Replaced Highway Mile) simultaneously or separately.

As can be grasped from the discussion presented herein, the System Dynamics approach is as good as the DEA approach as far as its usability in measuring the performance of different approaches to highway maintenance (performance-based approach and traditional approach) is concerned. It can even be stated that the System Dynamics approach is better in certain aspects due to the reasons discussed below.

The efficiency literature has primarily been interested in the performance of the processes as opposed to causes of such performance (Triantis 2005b). DEA approach is able to identify the efficiencies of complex systems but it cannot pinpoint the underlying causes of inefficiencies of DMUs directly (Triantis 2005a). In order to be able to figure out the causes of inefficiencies, some thorough analyses including comparisons of the inefficient units to their peers (best practice units in the data set) need to be performed. Only through investigating the means by which the process is carried out by such peers and making sufficient amount of comparisons, the analyzer can identify the causes of inefficiency in a particular DMU. On the other hand, the System Dynamics approach is able to point out the causes of inefficiencies within a system rather quickly as it investigates the whole system of inputs, processes, outputs and their interactions instead of investigating a system in terms of its input(s) and output(s) only, as is done in the case of DEA approach (Sterman 1999).

Another major advantage of System Dynamics approach is its ability to integrate the temporal aspect of any decision. Instead of investigating the performance at the discrete points in time, this approach enables one to see change of the performance as a continuous process especially through the usage of time-delayed relationships (Sterman 1999). In other words, while all other approaches measure the efficiency of a system at a given time by investigating the inputs and outputs of that system at such time, System Dynamics approach is able to explore how change of inputs at the current time would affect the performance of a system later on, i.e. 2 years down the road. This allows decision makers to evaluate the future consequences of present decisions (Chasey et al. 1997). In a highway maintenance setting, it is especially beneficial for decision makers to anticipate the system behavior over time, which can not be provided by the DEA approach.

Given these advantages, it can be stated that, with the support of rigorous analyses, the System Dynamics model presented above can be enhanced (especially by the addition of the "cost" variable into the model) and used as an alternative highway maintenance performance measurement approach. As well as a single DMU can be analyzed under a variety of conditions and relationships over a certain time period, different DMUs can be compared based on their overall performances (Annual Physically Sufficient Highway Mile) under similar conditions. Comparing the "Annual Physically Sufficient Highway Mile" of DMUs would be a deviation from the major goal of this research (i.e. measuring and comparing the **efficiency** of DMUs) as "Annual Physically Sufficient Highway Mile" is not the efficiency of the highway maintenance process but just an indicator of efficiency. Nonetheless, the results of this comparison could still provide valuable information which can be used to compare performance-based and traditional approaches to highway maintenance.

The main disadvantage of this approach (as far as its applicability to this research is concerned) is the fact that it requires the definition of the structure (physical, decision-making, and organizational) of the maintenance process. To do so presupposes the ability to define the mathematical relationships between key variables. For a complex process with many variables (like the road maintenance process), obtaining the requisite mathematical relationships is most challenging and requires a significant amount of participation from the decision-makers of the process that is being modeled. Thus, for this research, <u>DEA is a better approach than the System Dynamics approach</u> as it does not require one to define the relationships between inputs and outputs of a system and it also directly investigates the efficiency of processes (which is the major goal of this research). Nonetheless, the System Dynamics approach is still a valid approach that can be used to compare the overall performance (not the efficiency) of performance-based and traditional approaches to highway maintenance. Thus, if the obstacles (i.e. defining mathematical relationships) encountered in this research are overcome, the System Dynamics approach can be used for future studies of similar nature. As a matter of fact, the System Dynamics approach can be used in conjunction with DEA in the future studies of similar nature. The reasons of the inefficiencies that are obtained through DEA models can be more precisely and easily explained if System Dynamics models are utilized in conjunction with DEA models than if DEA models were used alone to try to explain the reasons of such inefficiencies.

CHAPTER 3- METHODOLOGY

This chapter presents the full and detailed methodology of the research. By the conclusion of this chapter, the main purpose of this research, i.e. developing a comprehensive highway maintenance efficiency measurement framework, will have been achieved. In an effort to achieve that, the steps detailed in **Section 1.6** need to be fulfilled. Within this context, this chapter starts by defining the highway maintenance process in general. Afterwards, it focuses on the components for which the comprehensive highway maintenance efficiency measurement framework is to be developed (level-of-service and timeliness of response) to be able to identify the comprehensive list of controllable variables and external/uncontrollable factors to be utilized in the DEA model development. As presented in **Section 1.6**, once (i) the highway maintenance process in general is defined, (ii) the processes for the level-of-service and timeliness of response components are detailed, and (iii) the comprehensive sets of controllable variables and uncontrollable factors for such components are identified, the methodology of this research calls for (i) the refinement of the comprehensive sets of controllable variables and uncontrollable factors, (ii) dealing with the uncontrollable factors, and (iii) choosing the type of the DEA models to be run. These three items constitute an important part of the DEA literature and thus regarded as being the issues that are pertinent to the comprehensive highway maintenance efficiency measurement framework that is aimed to be developed in this research. Therefore, such issues are discussed in depth within this chapter by reviewing literature. It is believed that once these issues are resolved, an important part of the methodology of this research will have been completed. This chapter continues with three sections that discuss important concepts (i.e. cost efficiency vs. technical efficiency, cost vs. price, and cost adjustments) that also pertain to the methodology of this research. The chapter is concluded by presenting a summary of the components of the framework.

This chapter, by developing the comprehensive highway maintenance efficiency measurement framework, provides conclusive suggestions that can be used as guidance during the implementation stage of such framework which is presented in **Chapter 4**.

3.1 OVERVIEW OF THE HIGHWAY MAINTENANCE PROCESS IN GENERAL

3.1.1 Definition of Highway Maintenance Process and Types of Highway Maintenance

Greitzer defines the highway maintenance as "*the act of preserving and keeping a highway, including all of its elements, in condition as close as is practical to its originally constructed condition, or its subsequently improved condition; and the operation of a highway facility and services incidental thereto, to provide safe, convenient, and economical highway transportation.*" Greitzer divides the highway maintenance into two main activities as physical maintenance and traffic services/operations (Greitzer 1976). Maintenance is defined in a very similar manner within the California Streets and Highways Code and divided into the following three groups: (i) preservation of the right-of-way, (ii) operation of special safety devices, and (iii) special or emergency maintenance to address the unexpected or unusual damage resulting from accidents or act of God (Caltrans 1998).

Highway maintenance involves actions performed for preserving and enhancing the safety, integrity, and serviceability of highways. Such actions should be performed timely and cost-effectively to be able to successfully interfere with the continuous deterioration (Rouse and Putterill 2000). There are four essential maintenance objectives (TRB 1997):

- Safety of the road users (i.e. traveling public)
- Preservation of the investment
- Comfort and convenience of the road users
- Aesthetics

In USA, starting in 1960s, maintenance staff has evolved from solely being common laborers to being maintenance technicians and maintenance engineers. With this evolution, a disciplined and sophisticated process has been developed for the maintenance. Such approach is known as the Maintenance Management System (MMS). This system consists of the management tools such as organization, planning, scheduling, budgeting, performance measurement, control, and reporting. The reporting is aimed at performance improvement through feedback provided to the MMS (Greitzer 1976). MMS is a systematic approach to maintenance and it is aimed at achieving desired level-of-service in the least costly fashion. MMS enables the maintenance managers to (TRB 1997):

- Identify and quantify maintenance needs
- Identify the necessary resources to meet such needs
- Determine standards to be able to measure accomplishments and set priorities
- Evaluate performance
- Perform program, budget, and expenditure controls to improve performance

The highway maintenance process performed through MMS is presented as a work flow diagram as depicted in **Figure 3.1** (Caltrans 1998; TRB 1997; Venner 2005).

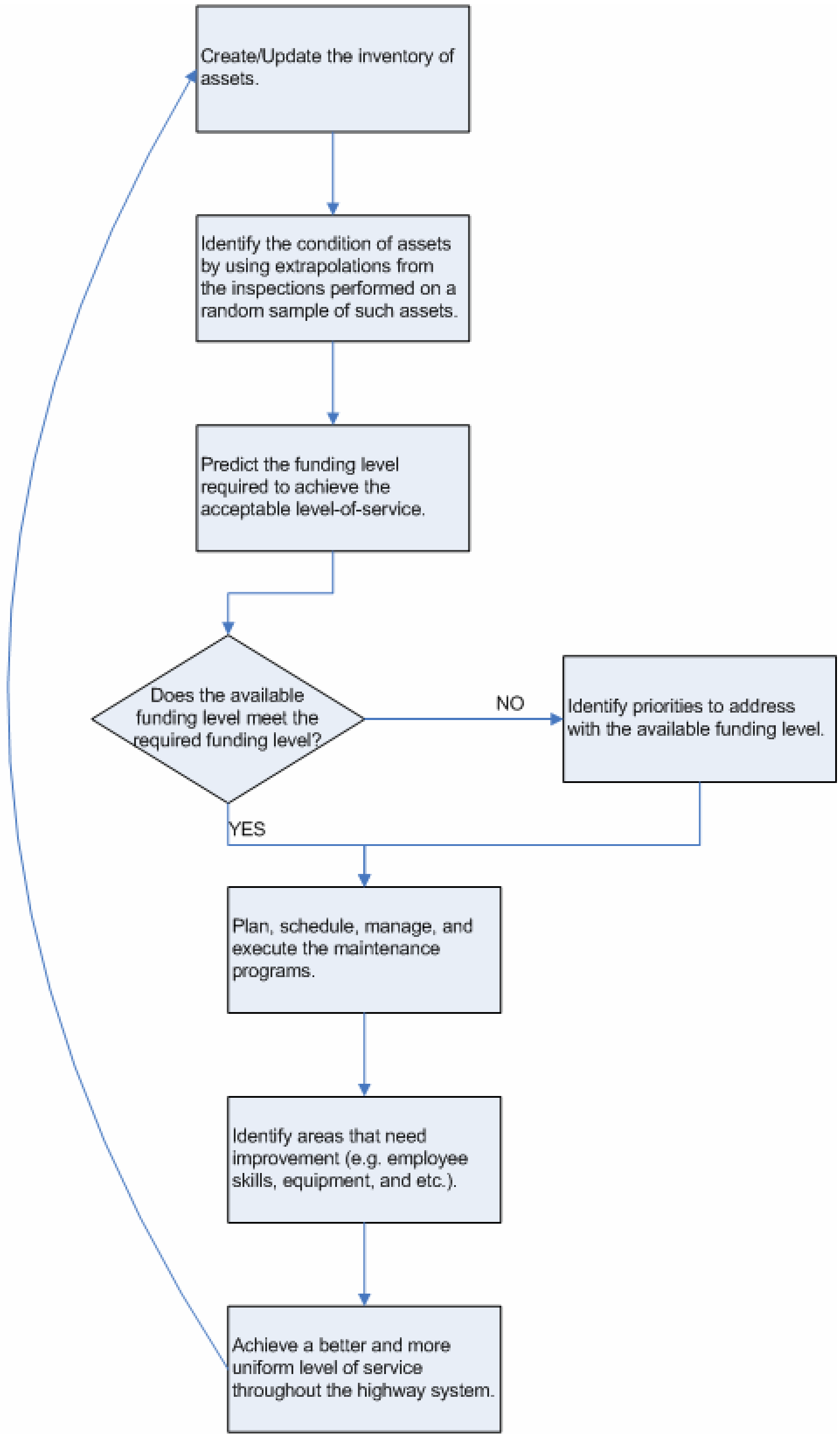


Figure 3.1: Highway Maintenance Process Performed through MMS

There are three types of maintenance (JLARC 2002; Ozbek 2004; VDOT 2005b):

- **Preventive Maintenance**: This type of maintenance consists of activities that are performed to extend the life of newly-constructed asset items. Such activities are performed in a planned fashion and in advance of a need for repairs and in advance of substantial deterioration of the asset items to be able to avoid such occurrences, to decrease the deterioration rate of such asset items, to increase the time in which they become defective, and to maintain or improve the overall functional condition of the highway system without enhancing the structural capacity. Preventive maintenance is: (i) planned, (ii) cyclical, (iii) not condition-based, and (iv) does not add structural capacity (where applicable, e.g. pavement).
- **Restorative (Reactive) Maintenance**: This type of maintenance consists of activities that are performed to return an asset items as close as to its original condition. This requires minor repairs and replacement of certain components. Such maintenance is performed on asset items that are still functioning and structurally sound but which have minor defects such as section loss, cracking, and etc.
- **Rehabilitative Maintenance**: This type of maintenance consists of major repairs and replacements. Such efforts are regarded as reconstructions which are much more expensive than the abovementioned two types of maintenance.

It is important to note that there is an additional type of maintenance which is not listed within the types of maintenance discussed above but which is intrinsic to the definition of highway maintenance presented above. This type of maintenance is called the **incident response** and is aimed at responding to emergency incidents such as traffic accidents, heavy traffic conditions, hazardous material spills, the presence of debris and roadkill on the traveled lanes, and adverse weather conditions like rain, fog, snow, ice, and flooding in an effort to maintain the free flow of traffic (VDOT 1996).

VDOT combines Preventive Maintenance and Restorative Maintenance under the heading Routine/Ordinary Maintenance. It is important to note that Rehabilitative Maintenance is disregarded within this research as it is more like a construction than maintenance. As a matter of fact, the performance-based highway maintenance contracts issued by VDOT require the contractors to perform only Routine/Ordinary Maintenance. In other words, VDOT does not expect the contractors to perform Rehabilitative Maintenance (VDOT 2005b).

3.1.2 Deferred Highway Maintenance

It is important to discuss the **deferred maintenance** concept as it relates to the highway maintenance process as well. Deferred maintenance, as the name implies, is making the decision to postpone the maintenance to a later time in an effort to address the funding limitations (as depicted in the decision box within **Figure 3.1**). Within the context of highway maintenance, generally such decision is made for the asset items whose maintenance needs are thought to be non-essential at the time when such decision is made; nonetheless this is not always the case. Deferred maintenance results in faster deterioration; and generally, results in increased cost of future maintenance (Chasey 1995). A study by Sharaf et al. sought to identify the effect of deferring the maintenance of pavement through life cycle cost assessment (Chasey 1995). Their finding was that the cost of the maintenance of the pavement in good condition is one–fourth of that of the pavement in poor condition. Utah Department of Transportation determined a three-fold cost increase if the maintenance of the pavement is deferred until the stage where rehabilitative maintenance is required (Chasey 1995). Similarly, for pavement, California Department of Transportation (Caltrans) determined that for every $1 spent on preventive maintenance, $3-$20 is saved if such maintenance is performed at the right time before it deteriorates into the state which can only be addressed by rehabilitative maintenance (Venner 2005). In another study, it was determined that in 85 countries that received assistance from the World Bank during the 1980s, deferred maintenance resulted in the erosion of 15% of the capital invested in the construction of main roads (Heggie 2003). As pointed out by FHWA, "*…some of the highway deficiencies that currently exist could be addressed relatively inexpensively in the short term, but will become much more expensive to correct if they are deferred…*" (Dornan 2002).

In summary, different types of maintenance greatly differ in their costs and in their impacts on the time required until the next maintenance or reconstruction for any given asset item. Preventive and restorative maintenance activities are less costly, performed more frequently, and keep the asset items at a better quality level for a longer period. Deferring the maintenance, on the other hand, results in rehabilitative type of maintenance activities which are performed at much higher costs (Chasey 1995). This phenomenon indicates the need for measuring the efficiency of highway maintenance operations over a period of time by using multiple years of data as opposed to a single year's data. This is mainly because if a unit of comparison chooses to defer maintenance and thus consumes a minimal amount of resources in a given year; such unit may seem to be more efficient than other units of comparison for that year. Nonetheless, when multiple years of data are considered, the adverse effect of deferred maintenance on such unit becomes apparent as it will need to utilize a very large amount of resources to be able to address the substantial amount of deterioration that will surface in the subsequent years. This would be reflected in the efficiency scores of such a unit in consecutive periods and would bring the other units of comparison above this unit as far as their relative efficiency scores are concerned. As will be seen in the implementation stage of this research (within **Chapter 4**), this research uses multiple years of data in an effort to address the issue of impact of deferred maintenance on the efficiency scores calculated by DEA.

3.2 OVERVIEW OF THE PROCESSES PERFORMED FOR THE LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS

According to Otto and Ariaratnam, maintenance of highways includes: (i) preserving the capital investment and (ii) maintaining the free flow of traffic by keeping the right-of-way in safe operation conditions (Otto and Ariaratnam 1999). By using the discussion presented within the preceding section, and referring to Otto and Ariaratnam's simplistic approach for the definition of highway maintenance, the highway maintenance process and its relation to the level-of-service and timeliness of response components for VDOT's case can be summarized as depicted in **Figure 3.2**.

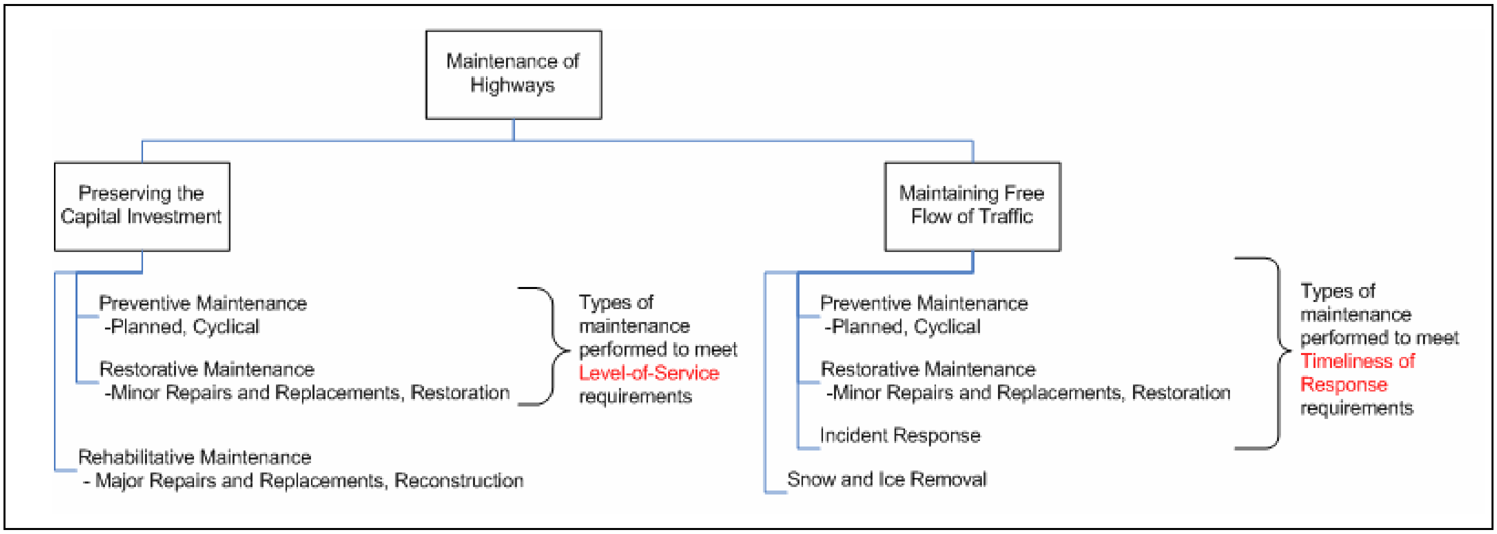


Figure 3.2: Highway Maintenance Process and its Relation to the Level-of-Service and Timeliness of Response Components

By referring to the diagram presented above to identify the types of maintenance activities performed for level-of-service and timeliness of response components, and by using the definitions of such maintenance activities as discussed within the preceding section, one can identify the effects of various phenomena on the level-of-service and timeliness of response components. These relationships are shown in **Figure 3.3** and **Figure 3.4** for the level-of-service and timeliness of response components respectively.

Figure 3.3: Effects of Various Phenomena on the Level-of-Service Component

Figure 3.4: Effects of Various Phenomena on the Timeliness of Response Component

In VDOT's case, the private contractor and VDOT are responsible for maintaining all assets items within the highway right-of-way. This is also known as fence-to-fence maintenance (in clear reference to the physical limits of the facilities). The contractor and VDOT are not only responsible for meeting the level-of-service requirements for all asset items, but also need to meet timeliness of response requirements established for some of the asset items. A complete list of asset groups and asset items that should be maintained by the contractor (through performance-based maintenance) and VDOT (through traditional maintenance) is provided in **Table 3.1**. The asset items marked with (**) have timeliness of response requirements in addition to the level-of-service requirements.

Table 3.1: List of Asset Groups and Asset Items to be maintained by the Contractor and VDOT

Asset Group	Asset Item
Shoulders	Shoulders- Hard Surfaced
	Shoulders- Non-hard Surfaced
Roadside	Grass
	Debris and Roadkill
	Litter
	Landscaping
	Brush and Tree Control
	Concrete Barrier
	Sound Barrier
	Slopes
	Fence
Drainage	Paved Ditches
	Unpaved Ditches
	Pipes
	Box Culverts
	Under/Edge Drains
	Storm Drains/Drop Inlets
	Curb and Gutter
	Sidewalks
	Storm Water Management Ponds
Traffic	Signals**
	Pavement Messages
	Pavement Striping
	Pavement Markers
	Delineators/Object Markers
	Glare Foils
	Regulatory Signs**
	Other Signs**
	Luminaries**
	Guardrail**
	Impact Attenuators**
	Truck Ramps**
	Cross Overs
	Rumble Strips
Roadway	Paved Lanes**
Bridges	Deck**
	Superstructure**
	Substructure**
	Slope/Channel Protection**

For the purposes of this dissertation, these are called as "Fence to fence asset groups". (Shoulders through Traffic)

For the purposes of this dissertation, these are called as "Fence to fence asset items". (Shoulders- Hard Surfaced through Rumble Strips)

3.3 THE APPROACH UTILIZED TO DEFINE CONTROLLABLE VARIABLES TO BE USED FOR THE LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS

For the sake of explanation, the discussion presented within this section is limited to the level-of-service component (and the paved lanes element within that component) but it is important to note that the very same discussion applies to the other elements within the level-of-service component as well as the timeliness of response component. **Figure 3.5**, as presented below, depicts a portion of the highway maintenance process that is performed by the contractor and the transportation agency to meet the level-of-service requirements for the paved lanes (traveled portion of the pavement).

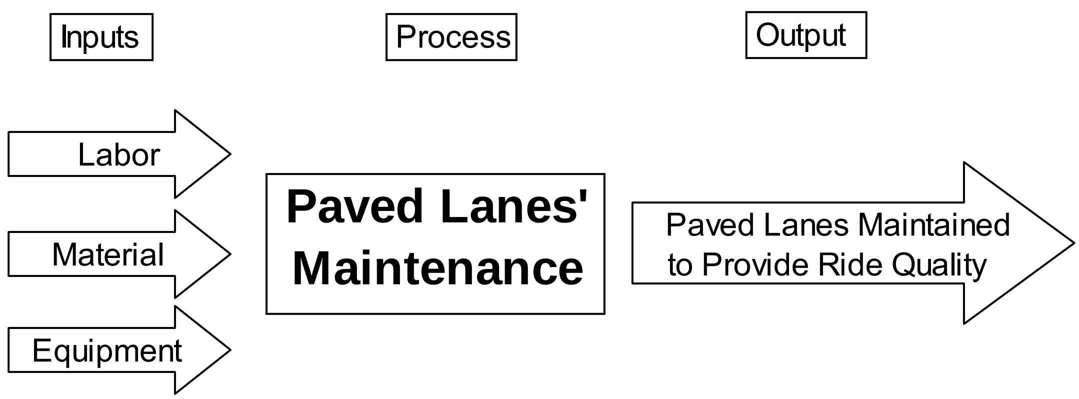


Figure 3.5: Process for Maintaining Paved Lanes

It is important to note that **Figure 3.5** depicts only the variables (inputs and output) that are controllable by the parties. DEA technique, by its nature, is able to take uncontrollable factors (as will be discussed in the **Section 3.4** and listed in **Section 3.5**) which are not shown in **Figure 3.5** into its modeling structure. This indeed ensures a fair comparison to be made as uncontrollable and external factors such as environmental (i.e. climate, location, and etc.) and operational (i.e. traffic, load, design-construction adequacy, and etc.) factors highly affect the maintenance efforts performed for the paved lanes as well as the deterioration of the paved lanes. Nonetheless, for the purposes of this section, such uncontrollable factors are not shown in **Figure 3.5** and will not be a part of the discussion presented hereafter within this section.

DEA technique relies on quantifiable measures to be able to model efficient frontiers. **Figure 3.6** illustrates the metrics that can be used to quantify each of the variables presented in **Figure 3.5**.

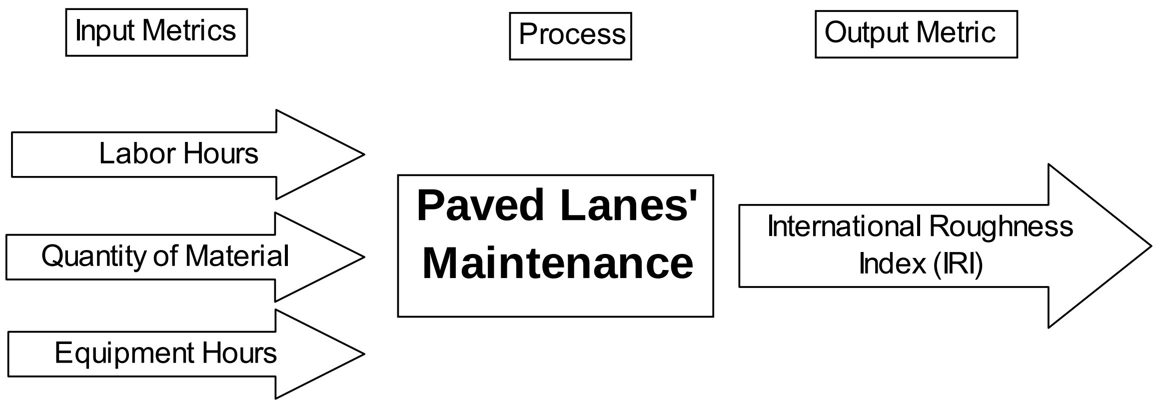


Figure 3.6: Metrics to be used in the DEA Model- Technical Efficiency

If the metrics presented in **Figure 3.6** were chosen to be utilized, the DEA models would calculate and compare the **technical efficiency** of the Contractor and the transportation agency. However from a transportation agency (e.g. VDOT) point of view (which is the point of view taken in this research as this research is aiming to provide VDOT and other transportation agencies with a decision-making tool to identify whether to use traditional or performance-based approach to highway maintenance), a more important concept is the **cost efficiency**. Thus, within the context of this research, all of the input metrics presented in **Figure 3.6** can and should be replaced with the cost figures associated with them. Such cost figures then can be summed to a final cost figure as shown in **Figure 3.7**. Given this discussion, it can be said that in order to be able to reach conclusive results through this research, it is essential to use cost variable as opposed to other variables (such as labor hours, and etc.) as the controllable input variable for both the level-of-service and timeliness of response components.

To define the controllable output variables for the level-of-service and timeliness of response components, it is essential to identify what is expected from the maintenance process as far as such components are concerned (e.g. paved lanes maintained to provide ride quality in accordance with the performance criteria and performance targets- as shown in **Figure 3.5**).

Once that is completed, one needs to assign metrics which enable the analyzer to quantify such controllable output variables (e.g. IRI- as shown in **Figure 3.6** and **Figure 3.7**).

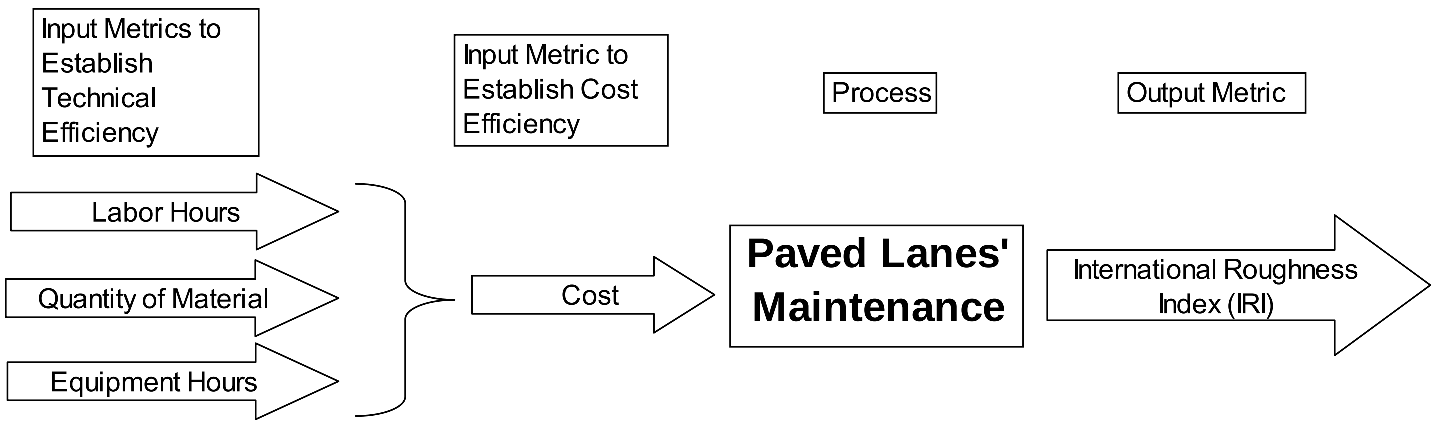


Figure 3.7: Metrics to be used in the DEA Model- Cost Efficiency

It is important to note that many references focusing on the highway maintenance process also cite a number of outputs resulting from the highway maintenance process which are referred in the DEA literature as another group of outputs: Undesirable Outputs (Amirteimoori et al. 2006; Scheel 2001; Seiford and Zhu 2002). Such output variables for the highway maintenance process are air pollution, water pollution, and noise pollution (Fitch et al. 2005; TRB 2006; Venner 2005; Williams and Stensland 2006). As the "Undesirable Outputs" name implies, such outputs are not produced as a goal of the highway maintenance process but rather produced as by-products which are not desired to be produced at all. They are different from the common concept of the output of a process as their production is tried to be avoided or minimized at best as opposed to being maximized as desirable outputs. In other words, the less of the undesirable outputs, the better off the process is. From an efficiency point of view, the inclusion of them in the DEA model is not critical but nonetheless given the availability of data, they should be included in the model. It is important to note that modeling and including undesirable outputs in DEA is a rather new concept in the DEA literature.

This section described the approach utilized to define controllable variables**.** The comprehensive list of controllable variables (and their metrics) will be presented in **Section 3.5** for both the level-of-service component and timeliness of response component.

3.4 THE APPROACH UTILIZED TO DEFINE UNCONTROLLABLE FACTORS TO BE USED FOR THE LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS

Highway maintenance is a process that is greatly affected by the uncontrollable factors. The reviewed literature lists the major of these uncontrollable factors as: (i) climatic conditions, (ii) traffic density ,(iii) characteristic of the traffic that travels on the highway, (iv) geographic location, (v) terrain, (vi) age of the highway, (vii) type or class of the highway (e.g. pavement types), (viii) the highway's surrounding environment, (ix) highway design (e.g. type of materials, thickness, and etc.), (x) highway construction (e.g. quality of materials and workmanship, conditions during the construction phase, and etc.), (xi) subsurface conditions, and (xii) amount of snow and ice treatment applied to the highway (Caltrans 1998; de la Garza et al. 1998; Greitzer 1976; JLARC 2002; TRB 1997).

All of the uncontrollable factors (listed above), as agreed upon to be the major factors affecting the highway maintenance process by different references, may not necessarily be applicable for the level-of-service and timeliness of response components of such process. Moreover, there can be some other uncontrollable factors affecting such components in particular. This research develops a systematic approach to be able to identify most, if not all, of the uncontrollable factors for both the level-of-service and timeliness of response components of the highway maintenance process. Such approach is developed in an effort to instigate a thought process to be able to identify such factors rather than completely depending on the previous literature to do that. By this way, such literature can even be enhanced through the identification of factors that had not been previously identified in the literature. Such thought process is explained below.

For any of the abovementioned components of the highway maintenance process, it is essential to identify the primary goal of the process to be able to figure out the uncontrollable factors affecting the process. Once such goal is identified, the phenomena that work in the favor of and against such goal need to be listed as shown in **Figure 3.3** and **Figure 3.4**. Each of these phenomena can be affected by some factors that are beyond the immediate control of the decision maker. Thus, by focusing on the already identified phenomena and invoking a thought process, one can identify the uncontrollable factors that belong to each phenomenon. Applications of such approach for level-of-service and timeliness of response are provided below.

For the level-of-service component, the primary goal of the process is to maintain each asset item listed in **Table 3.1** to meet the level-of-service requirements. **Figure 3.3** lists the two phenomena that work in the favor of and against such goal. Thus, there are two groups of uncontrollable factors for the level-of-service component as depicted in **Figure 3.8**.

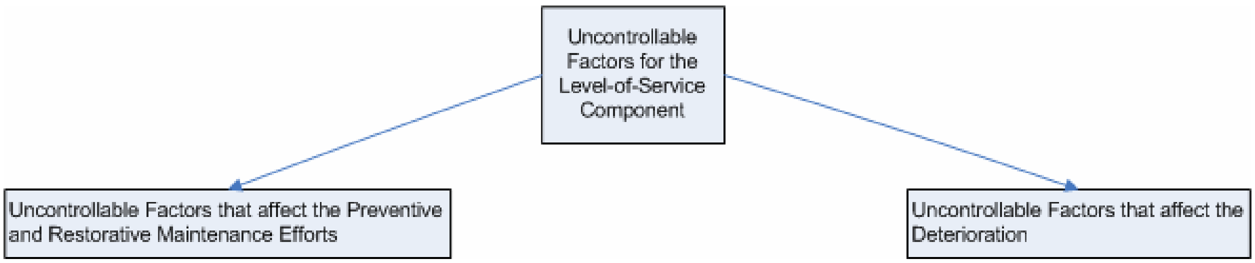


Figure 3.8: Groups of Uncontrollable Factors for the Level-of-Service Component

For the timeliness of response component, the primary goals of the process are to be able to meet the timeliness requirements: (i) to repair certain damaged asset items (as marked with (**) in **Table 3.1**) and (ii) to respond to certain emergency incidents as discussed in **Section 3.1.1**. **Figure 3.4** lists the four phenomena that work in the favor of and against such goals. As a matter of fact, two of these phenomena are related to first goal of the timeliness of response component and the other two are related to second goal. Thus, there are four groups of uncontrollable factors for the timeliness of response component as depicted in **Figure 3.9**.

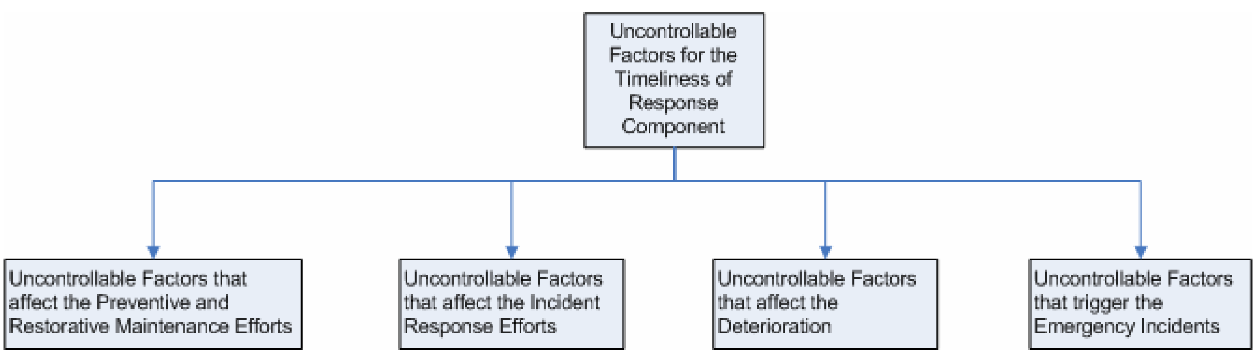


Figure 3.9: Groups of Uncontrollable Factors for the Timeliness of Response Component

This section described the approach utilized to define uncontrollable factors**.** The comprehensive list of uncontrollable factors (and their metrics) will be presented in **Section 3.5** for both the level-of-service component and timeliness of response component.

3.5 THE COMPREHENSIVE LIST OF CONTROLLABLE VARIABLES AND UNCONTROLLABLE FACTORS FOR LEVEL-OF-SERVICE AND TIMELINESS OF RESPONSE COMPONENTS

Within the DEA literature, inputs of a process can be defined as the resources used by the DMUs or conditions affecting the performance of the DMUs. Outputs, on the other hand, are the benefits made as a result of the process undertaken by the DMUs (Ramanathan 2003).One of the most important features of DEA is its free functional form. DEA does not need any production function equation of a parametric form for the solution of the model specified within it. Therefore, any variable (i.e. input and output) can be included in the model without the need to specify functional or parametric relationships. Even a factor that is neither an economic resource nor a product but just an attribute of the environment or of the production process (i.e. uncontrollable factor) can easily be included as an input variable in the DEA model. Moreover, DEA does not make a priori distinction between the relative importance of any two inputs or two outputs. In other words, all variables that are included in the model have an equal opportunity to influence the calculated efficiency (Epstein and Henderson 1989). Given this, the initial list of controllable variables and uncontrollable factors used to assess the efficiency of a DMU tends to be, and in fact, should be as comprehensive as possible. This list should contain each relevant and suitable controllable variable and uncontrollable factor which affects the efficiency of the DMU and which is strongly related with the objectives of the DMU. In other words, this list should contain each controllable variable and uncontrollable factor that would be a part of the reasonable production function of the DMU (even though the equation of such production function is not needed to be stated explicitly in DEA). The variables within this list should be common to all DMUs. Some of the variables may be quantitative and others may be qualitative. Variables can be represented using one of the following four scale types: categorical, ordinal, interval, and ratio (Boussofiane et al. 1991; Dyson et al. 2001).

In order to be able to develop the comprehensive list of controllable variables and uncontrollable factors, the process whose efficiency is measured has to be taken under close scrutiny. Specifically, the answers to the questions: “What does this process do?”, “How does this process do that?”, “What outputs do this process produce?”, “What inputs does this process use to produce those outputs?”, and “What internal and external uncontrollable factors affect this process?” should continuously be sought during the development of this list. Since the DEA concept is based on the "production function" theory, a DEA model can only be meaningful for one specific process (production function). Thus, ultimate care should be given in selecting the controllable variables and uncontrollable factors for a specific process to make sure that such process is responsible for the utilization of all of the selected controllable input variables and the production of all of the selected controllable output variables and affected by all of the selected uncontrollable factors.

As discussed in **Section 3.2, Section 3.3, and Section 3.4**, even though both the level-of-service and timeliness of response components are parts of the same overall process (i.e. "Highway Maintenance" process as described in **Section 3.1.1**), they have different primary goals and they are affected differently by different phenomena (as depicted in **Figure 3.3** and **Figure 3.4**). Given these, it can be asserted that they possess different production functions. Thus, a different set of comprehensive list of controllable variables and uncontrollable factors is produced for each component as presented in **Table 3.2** and **Table 3.3**. **Table 3.2** presents the comprehensive list of controllable variables and uncontrollable factors for the process performed to meet the level-of-service requirements. **Table 3.3** presents the comprehensive list of controllable variables and uncontrollable factors for the process performed to meet the timeliness of response requirements. Separate DEA models are to be run for each component based on such separate lists.

For the same reason stated in the preceding paragraph, timeliness of response component is furthermore divided into two elements as can be seen in **Table 3.3**: (i) timeliness in repairing damaged asset items and (ii) timeliness in responding to emergency incidents. Each element has a different primary goal and affected differently by different phenomena and thus possesses a different production function. Therefore, separate DEA models are to be run for each element of the timeliness of response component.

Furthermore, as can be seen in **Table 3.2**, the level-of-service component is divided into three elements, each of which has its own comprehensive list of controllable variables and uncontrollable factors: (i) level-of-service for the fence to fence asset items, (ii) level-of-service for the paved lanes, and (iii) level-of-service for the bridges. Even though such elements possess the same production function, such a grouping is necessitated for the purposes of disaggregating the analysis. By doing so, one can perform much more specific analysis and identify the efficiency problems based on the maintenance of a certain element (e.g. bridges) and thus much easily identify the reasons for the inefficiency as opposed to the general analysis (including all level-of-service elements) in which the inefficiency can be attributed to any, some, or all of the level-of-service elements. Such disaggregation is also beneficial in the sense that it results in three separate DEA models to be run for the abovementioned three separate elements and thus enables one to include a much smaller number of variables in separate DEA models as opposed to a large number of variables to be included in one single aggregate model (had the level-of-service component been not disaggregated into three elements). The problems with having a large number of variables within a DEA model were discussed in **Section 2.5.3.2** and will be recaptured in **Section 3.6**.

The comprehensive lists of controllable variables and uncontrollable factors for the level-of-service and timeliness of response components are developed by following both of the approaches presented in **Section 3.3** and **Section 3.4** and by reviewing the literature related to the subject matter (Caltrans 1998; Cook et al. 1994; Cook et al. 1990; de la Garza et al. 1998; Fitch et al. 2005; Flintsch 2004; Greitzer 1976; JLARC 2002; Misra and Das 2003; Rouse et al. 1997b; Simpson et al. 2006; TRB 1997; TRB 2006; Venner 2005; Williams and Stensland 2006) It is important to note that the explanations and/or metrics for each of the controllable variables and uncontrollable factors are also presented in **Table 3.2** and **Table 3.3**.

Table 3.2: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Level-of-Service Component

Component	Element	Variable Name		Variable Explanation and/or Metric	DEA Model
Level of Service	Fence to Fence Asset Groups	Controllable Input Variables and Uncontrollable Factors	(1) Cost for maintaining the asset items	$	DEA Model 1
			(2) Climate- Effect on deterioration of the asset items	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles	
			(3) Climate- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity- availability of crews)	Yearly precipitation amounts (inches)	
			(4) Traffic- Effect on deterioration of the asset items	Equivalent Single Axle Load (ESAL)	
			(5) Traffic- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity- availability of crews)	Average Daily Traffic (ADT)	
			(6) Speed limit- Effect on deterioration of the asset items	miles/hr	
			(7) Accidents damaging asset items- Effect on deterioration of the asset items	count (of accidents damaging asset items)/year	
			(8) Subsurface conditions- Effect on deterioration of the asset items	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)	
			(9) Age of asset items- Effect on deterioration of the asset items	Years	
			(10) Terrain- Effect on deterioration of the asset items	Slope, Elevation, and Orientation	
			(11) Terrain- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity of crews)	Slope, Elevation, and Orientation	
			(12) Total Area Served- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity of crews)	Asset density (number of assets to maintain)	
		Controllable Output Variables	(13) Change in the condition of Asset Items (which are maintained to meet the Level of Service requirements)	$\%LOS_{t1}-\%LOS_{t0}$	
			(14) Air Pollution	Emission amounts	
			(15) Water Pollution	Emission amounts	
			(16) Noise Pollution	Emission amounts	

Table 3.2: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Level-of-Service Component (CONTINUED)

Component	Element	Variable Name		Variable Explanation and/or Metric	DEA Model
Level of Service	Paved Lanes (Traveled portion of the Pavement)	Controllable Input Variables and Uncontrollable Factors	(17) Cost for maintaining the paved lanes	$	DEA Model 2
			(18) Climate- Effect on deterioration of the paved lanes	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles	
			(19) Climate- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity- availability of crews)	Yearly precipitation amounts (inches)	
			(20) Traffic- Effect on deterioration of the paved lanes	Equivalent Single Axle Load (ESAL)	
			(21) Traffic- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity- availability of crews)	Average Daily Traffic (ADT)	
			(22) Snow treatment- Effect on deterioration of the paved lanes	count (of chloride applications)	
			(23) Speed limit- Effect on deterioration of the paved lanes	miles/hr	
			(24) Accidents damaging paved lanes- Effect on deterioration of the paved lanes	count (of accidents damaging paved lanes)/year	
			(25) Subsurface conditions- Effect on deterioration of the paved lanes	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)	
			(26) Subgrade-- Effect on deterioration of the paved lanes	Compaction etc…	
			(27) Base- Effect on deterioration of the paved lanes	Aggregate mix etc…	
			(28) Thickness of the different layers of the paved lanes- Effect on deterioration of the paved lanes	Inches	
			(29) Type of paved lanes-Effect on deterioration of the paved lanes)	Concrete, Asphalt (give a grade based on the effect)	
			(30) Type of paved lanes- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity of crews)	Concrete, Asphalt (give a grade based on the effect)	
			(31) Age of paved lanes- Effect on deterioration of the paved lanes	Years	
			(32) Terrain- Effect on deterioration of the paved lanes	Slope, Elevation, and Orientation	
			(33) Terrain- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity of crews)	Slope, Elevation, and Orientation	
			(34) Total Area Served- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity of crews)	Sum of the area (lane miles*lane width) of all of the paved lanes within the DMU	
		Controllable Output Variables	(35) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to load-related damages)	LDR_{t1}-LDR_{t0}	
			(36) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to non load-related damages)	NDR_{t1}-NDR_{t0}	
			(37) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to ride quality)	IRI_{t1}-IRI_{t0}	
			(38) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to rutting, skid index etc…)	$\%LOSp_{t1}$-$\%LOSp_{t0}$	
			(39) Air Pollution	Emission amounts	
			(40) Water Pollution	Emission amounts	
			(41) Noise Pollution	Emission amounts	

Table 3.2: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Level-of-Service Component (CONTINUED)

Component	Element	Variable Name		Variable Explanation and/or Metric	DEA Model
Level of Service	Bridges	Controllable Input Variables and Uncontrollable Factors	(42) Cost for maintaining the bridges	$	DEA Model 3
			(43) Climate- Effect on deterioration of the bridges	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles	
			(44) Climate- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity- availability of crews)	Yearly precipitation amounts (inches)	
			(45) Traffic- Effect on deterioration of the bridges	Equivalent Single Axle Load (ESAL)	
			(46) Traffic- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity- availability of crews)	Average Daily Traffic (ADT)	
			(47) Snow treatment- Effect on deterioration of the bridges	count (of chloride applications)	
			(48) Speed limit- Effect on deterioration of the bridges	miles/hr	
			(49) Accidents damaging bridges- Effect on deterioration of the bridges	count (of accidents damaging bridges)/year	
			(50) Subsurface conditions- Effect on deterioration of the bridges	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)	
			(51) Thickness of the deck- Effect on deterioration of the bridges	Inches	
			(52) Type of paved lanes-Effect on deterioration of the bridges	Concrete, Asphalt (give a grade based on the effect)	
			(53) Type of paved lanes- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Concrete, Asphalt (give a grade based on the effect)	
			(54) Span Information- Effect on deterioration of the bridges	Span length, span type etc…	
			(55) Age of bridges- Effect on deterioration of the bridges	Years	
			(56) Location- Effect on deterioration of the bridges	Above a creek, major river, highway, railroad etc… (give a grade based on effect)	
			(57) Location- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Above a creek, major river, highway, railroad etc… (give a grade based on effect)	
			(58) Terrain- Effect on deterioration of the bridges	Slope, Elevation, and Orientation	
			(59) Terrain- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Slope, Elevation, and Orientation	
			(60) Total Area Served- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Sum of the area (Deck Length * Deck Width) of all of the bridges within the DMU	
		Controllable Output Variables	(61) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Decks)	Deck $Rating_{t1}$-Deck $Rating_{t0}$	
			(62) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Superstructures)	Superstructure $Rating_{t1}$-Superstructure $Rating_{t0}$	
			(63) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Substructures)	Substructure $Rating_{t1}$-Substructure $Rating_{t0}$	
			(64) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Slope/Channel Protections)	Slope/Channel Protection $Rating_{t1}$-Slope/Channel Protection $Rating_{t0}$	
			(65) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their other parts such as joints, paint etc…)	X $Rating_{t1}$-X $Rating_{t0}$	
			(66) Air Pollution	Emission amounts	
			(67) Water Pollution	Emission amounts	
			(68) Noise Pollution	Emission amounts	

: The reason for computing the difference of ratings at time "t1" and "t0" will be explained in Chapter 4.

Table 3.3: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Timeliness of Response Component

Component	Element		Variable Name	Variable Explanation and/or Metric	DEA Model
Timeliness of Response	Repairing Damaged Asset Items	Controllable Input Variables and Uncontrollable Factors	(69) Cost for repairing damaged asset items to meet Timeliness requirements for the asset items with Timeliness requirements	$	DEA Model 4
			(70) Climate- Effect on deterioration of the asset items with Timeliness requirements	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles	
			(71) Climate- Effect on maintenance efforts performed for meeting Timeliness requirements for the asset items with Timeliness requirements (productivity- availability of crews)	Yearly precipitation amounts (inches)	
			(72) Climate- Effect on the time that it takes (within the DMU) for the maintenance crew(s) to reach to the areas in need of repair to perform maintenance on the asset items (which has Timeliness requirements) for meeting Timeliness requirements	Yearly data for fog, flooding, rain, snow, and ice	
			(73) Traffic- Effect on deterioration of the asset items with Timeliness requirements	Equivalent Single Axle Load (ESAL)	
			(74) Traffic- Effect on maintenance efforts performed for meeting Timeliness requirements for the asset items with Timeliness requirements (productivity- availability of crews)	Average Daily Traffic (ADT)	
			(75) Traffic- Effect on the time that it takes (within the DMU) for the maintenance crew(s) to reach to the areas in need of repair to perform maintenance on the asset items (which has Timeliness requirements) for meeting Timeliness requirements	Average Daily Traffic (ADT)	
			(76) Snow treatment- Effect on deterioration of the asset items with Timeliness requirements	count (of chloride applications)	
			(77) Speed limit- Effect on deterioration of the asset items with Timeliness requirements	miles/hr	
			(78) Accidents damaging asset items with Timeliness requirements- Effect on deterioration of the asset items with Timeliness requirements	count (of accidents damaging asset items with Timeliness requirements)/year	
			(79) Accidents- Effect on the time that it takes (within the DMU) for the maintenance crew(s) to reach to the areas in need of repair to perform maintenance on the asset items (which has Timeliness requirements) for meeting Timeliness requirements	count (of accidents adversely affecting traffic, i.e. creating congestion)/year	
			(80) Subsurface conditions- Effect on deterioration of the asset items with Timeliness requirements	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)	
			(81) Subgrade-- Effect on deterioration of the paved lanes	Compaction etc…	
			(82) Base- Effect on deterioration of the asset items with Timeliness requirements	Aggregate mix etc…	
			(83) Thickness- Effect on deterioration of the asset items with Timeliness requirements	Inches	
			(84) Type of paved lanes-Effect on deterioration of the asset items with Timeliness requirements	Concrete, Asphalt (give a grade based on the effect)	
			(85) Type of paved lanes- Effect on maintenance efforts performed for meeting Timeliness requirements for the asset items with Timeliness requirements (productivity of crews)	Concrete, Asphalt (give a grade based on the effect)	
			(86) Span Information- Effect on deterioration of the bridges	Span length, span type etc…	
			(87) Age of asset items- Effect on deterioration of the asset items with Timeliness requirements	Years	
			(88) Location- Effect on deterioration of the bridges	Above a creek, major river, highway, railroad etc… (give a grade based on effect)	
			(89) Location- Effect on maintenance efforts performed for meeting Timeliness requirements for the bridges (productivity of crews)	Above a creek, major river, highway, railroad etc… (give a grade based on effect)	
			(90) Terrain- Effect on deterioration of the asset items with Timeliness requirements	Slope, Elevation, and Orientation	
			(91) Terrain- Effect on maintenance efforts performed for meeting Timeliness requirements for the asset items with Timeliness requirements (productivity of crews)	Slope, Elevation, and Orientation	
			(92) Total Area Served- Effect on maintenance efforts performed for meeting Timeliness requirements for the asset items with Timeliness requirements (productivity of crews)	Asset density, number of lanes, area of the bridge	
		Controllable Output Variables	(93) Damaged asset items (with timeliness requirements) repaired to meet the Timeliness requirements	%Timeliness of Repair per 1 Fiscal Year	
			(94) Air Pollution	Emission amounts	
			(95) Water Pollution	Emission amounts	
			(96) Noise Pollution	Emission amounts	

Table 3.3: Comprehensive List of Controllable Variables and Uncontrollable Factors for the Timeliness of Response Component (CONTINUED)

Component	Element		Variable Name	Variable Explanation and/or Metric	DEA Model
Timeliness of Response	Incident Response (Heavy traffic conditions, traffic accidents, hazardous material spills, debris - roadkill and adverse weather conditions like rain, fog, snow, ice, and flooding- Excludes snow removal)	Controllable Input Variables and Uncontrollable Factors	(97) Cost for responding to incidents to meet Timeliness requirements	$	DEA Model 5
			(98) Climate- Effect on the frequency of incidents of adverse weather conditions	Yearly data for fog, flooding, rain, snow, and ice	
			(99) Climate- Effect on the efforts performed for meeting Timeliness requirements for the incidents with Timeliness requirements (productivity-availability of crews)	Yearly precipitation amounts (inches)	
			(100) Climate- Effect on the time that it takes (within the DMU) for the maintenance crew(s) to reach to the areas in need of incident response such as lane closures, wreck removals, installation and operation of portable message boards, and hazardous material spill removals (which has Timeliness requirements) for meeting Timeliness requirements	Yearly data for fog, flooding, rain, snow, and ice	
			(101) Climate- Effect on the frequency of incidents of debris and roadkill	Yearly data for wind, fog, flooding, rain, snow, and ice	
			(102) Traffic- Effect on the frequency of incidents of heavy traffic conditions	Average Daily Traffic (ADT)	
			(103) Traffic- Effect on the efforts performed for meeting Timeliness requirements for the incidents with Timeliness requirements (productivity-availability of crews)	Average Daily Traffic (ADT)	
			(104) Traffic- Effect on the time that it takes (within the DMU) for the maintenance crew(s) to reach to the areas in need of incident response such as lane closures, wreck removals, installation and operation of portable message boards, and hazardous material spill removals (which has Timeliness requirements) for meeting Timeliness requirements	Average Daily Traffic (ADT)	
			(105) Traffic- Effect on the frequency of incidents of debris and roadkill	Average Daily Traffic (ADT)	
			(106) Traffic type- Effect on the frequency of incidents of hazardous material spills	Equivalent Single Axle Load (ESAL)	
			(107) Traffic type- Effect on the frequency of incidents of debris and roadkill	Equivalent Single Axle Load (ESAL)	
			(108) Speed limit- Effect on the frequency of incidents of heavy traffic conditions	miles/hr	
			(109) Accidents- Effect on the frequency of incidents of traffic accidents	count (of accidents invoking incident response activities)/year	
			(110) Accidents- Effect on the time that it takes (within the DMU) for the maintenance crew(s) to reach to the areas in need of incident response such as lane closures, wreck removals, installation and operation of portable message boards, and hazardous material spill removals (which has Timeliness requirements) for meeting Timeliness requirements	count (of accidents adversely affecting traffic, i.e. creating congestion)/year	
			(111) Terrain- Effect on the frequency of incidents of hazardous material spills	Slope, Elevation, and Orientation	
			(112) Terrain- Effect on the frequency of incidents of debris and roadkill	Slope, Elevation, and Orientation	
			(113) Terrain- Effect on the efforts performed for meeting Timeliness requirements for the incidents with Timeliness requirements (productivity of crews)	Slope, Elevation, and Orientation	
			(114) Total Area Served- Effect on the efforts performed for meeting Timeliness requirements for the incidents with Timeliness requirements (productivity of crews)	Number of lanes	
		Controllable Output Variables	(115) Incidents responded to meet the Timeliness requirements	%Timeliness of Incident Response per 1 Fiscal Year	
			(116) Air Pollution	Emission amounts	
			(117) Water Pollution	Emission amounts	
			(118) Noise Pollution	Emission amounts	

This section presented the most comprehensive lists of controllable variables and uncontrollable factors that can be used in the DEA models for the level-of-service and timeliness of response components and the elements within such components as discussed above. Although such lists are the most comprehensive ones that are developed to date, they can further be modified by addition of more controllable variables and uncontrollable factors that relate to the processes under investigation. Nonetheless, the final lists to be used in the modeling stage should have a sufficiently minimum number of uncontrollable factors and controllable variables for the purposes of simplicity and to ensure the discriminating power of the utilized DEA models between the DMUs (as discussed in **Section 2.5.3.2** and will be recaptured in **Section 3.6**). These initial and comprehensive lists can be refined by removing some controllable variables and uncontrollable factors due to the following reasons:

(i) The inclusion of such controllable variables and uncontrollable factors in the DEA model is not much of a value (as deemed by the stakeholders) as they impact the process in negligible amounts.

(ii) Such controllable variables and uncontrollable factors are not related to the objectives of the process (e.g. performance measures, mission of the unit, and etc.) that is modeled using DEA.

(iii) Such controllable variables and uncontrollable factors possess information (about the DMUs) that is already captured by other controllable variables and uncontrollable factors.

(iv) The actual values of such controllable variables and uncontrollable factors do not differ materially from one DMU to another.

(v) The data for such controllable variables and uncontrollable factors is not readily available or measurable, and sufficiently reliable.

(vi) Such controllable variables and uncontrollable factors can be combined into new controllable variables and uncontrollable factors encompassing the issues represented by the original controllable variables and uncontrollable factors.

(vii) Such controllable variables and uncontrollable factors can be used to rescale the other controllable variables and uncontrollable factors.

(viii) Such controllable variables and uncontrollable factors are correlated to other controllable variables and uncontrollable factors in the list and thus taken care of with the usage of those other controllable variables and uncontrollable factors in the model.

A detailed discussion on the approaches that can be utilized to refine the comprehensive list of variables and uncontrollable factors and each's applicability to the highway maintenance case are presented within the next section.

3.6 THE APPROACH UTILIZED TO REFINE THE COMPREHENSIVE LISTS OF CONTROLLABLE VARIABLES AND UNCONTROLLABLE FACTORS

As presented in the preceding section, considering every controllable variable and uncontrollable factor (collectively called as "variables" hereafter within this section) that have an impact on the efficiency of the DMU resulted in lists which are composed of a large number of variables. However, running the DEA model using a large number of variables would (i) complicate the modeling process and (ii) shift the compared DMUs towards the efficient frontier, resulting in a large number of DMUs to have high efficiency scores. As DEA allows flexibility in the choice of input-output variables' weights, the greater the number of variables included in the analysis, the lower the level of discrimination. A DMU for which one particular ratio of an output to an input is the highest (of all DMUs for the same ratio) can allocate all of its weight to such ratio and become efficient. The total number of such ratios that is present in any DEA model can be as much as the product of the number of inputs and outputs included in such model. This product is a practical indicator of the minimum number of efficient units that will result from the implementation of DEA. Thus, in a case with 4 inputs and 4 outputs, DEA would very likely result in at least 16 efficient DMUs. A suggested rule of thumb to achieve a reasonable level of discrimination is that the number of DMUs should be at least 2*m*t where m is the number of inputs and t is the number of outputs (Boussofiane et al. 1991; Dyson et al. 2001). Given this discussion, once the initial comprehensive list is developed, such list should be reinvestigated and refined to include only the most relevant and important variables to be able to increase the discriminating power of DEA models.

It is important to note that an alternate approach to increase the discriminating power of DEA models is restricting the range of values that the input and output variables' weights can get. Discussion about such an approach is out of the scope of this research This is mainly because, even though it looks like a valid approach in serving its purpose, there has been much and unresolved discussion in literature about restricting the weights' values in a DEA study as such an action is likely to undermine the impartial nature of the DEA technique by introducing subjective opinions about the weights (i.e. importance) of input and output variables.

3.6.1 Approaches that can be utilized to Refine the Comprehensive List of Variables

A thorough review of literature identified the following approaches as being used in DEA studies to refine the initial and comprehensive list of variables.

3.6.1.1 Judgmental Process

This process is composed of a critical examination of the comprehensive variable list by expert decision makers (of the relevant field). Decision makers may identify some variables as repeating virtually the same information and some of them as conflicting or confusing. Moreover, decision makers may deem some variables to be not too crucial as far as their impacts on the process are concerned. This judgmental process, as performed by the decision makers, generally results in the refinement of the list through the help of the answers given to the following questions (Dyson et al. 2001; Golany and Roll 1989; Ramanathan 2003):

- Is the variable highly-related to one or more of the objectives (e.g. performance measures, mission of the unit, and etc.) set for the process?
- Does the variable possess relevant information about the DMUs that is not already captured by the other variables?
- Does the variable possess elements (i.e. price) that impedes with the concept of technical efficiency?
- Is the value of the variable materially different between the DMUs under investigation?
- Is the data for the variable readily available or measurable, and sufficiently reliable?

Forming a panel of experts to investigate the variables and to formalize the model is a systematic procedure to perform the judgmental process. Another systematic procedure that can be applied to expedite the judgmental process is the Analytic Hierarchy Process (AHP) (developed by Saaty (1980) (Saaty 1980)), which is discussed in detail below (Golany and Roll 1989; Ramanathan 2003).

The main purpose of AHP is to develop a vector of weights indicating the relative importance of the elements under investigation (Sinuany-Stern et al. 2000). In the case of refining the list of variables used in a DEA study, the elements can be those variables and AHP can develop an order of importance (as deemed by the decision maker) for such variables by assigning each one a weight through a systematic procedure. The variables that are assigned low weights, then, can be removed from the list of variables to be used in the DEA study. In such an application, AHP consists of the following steps: (i) structuring the elements (i.e. input and output variables in the DEA study) for evaluation; (ii) assessments made by the decision maker through pairwise comparisons of such elements; and (iii) using the eigenvector methodology to obtain weights (indicating the relative importance) for the elements. The critical step is the second step in which matrices of pairwise comparisons are formed. Usually, ratio scales (e.g. the integers 1-9 and their reciprocals) are utilized to represent the judgments of the decision maker in each pairwise comparison. Given the 2 elements i and j, if i is equally, weakly more, strongly more, very strongly more, or absolutely more important than j, an integer between 1 (indifference) and 9 (absolute importance) is assigned in such a pairwise comparison by the decision maker to express her/his preference. If i is less important than j with the abovementioned degrees, the reciprocals (i.e.1 to 1/9) are assigned (see **Table 3.4** below for the scale of importance defined by Saaty (1980) (Saaty 1980)). These pairwise comparisons are placed within a positive reciprocal matrix (i.e. $a_{ij} = 1/a_{ji}$). In such a matrix, only the upper part of the matrix needs to be filled as the remainder is assumed to reciprocal. The obtained matrix represents the judgments of the decision maker with respect to each element as far as its importance over another element is concerned. Once this matrix is formed, the principal eigenvector of the elements is calculated and then it is normalized to make the sum of entries in such eigenvector to be equal to 1. Such normalized values constitute the weights of the elements (i.e. their order of importance as judged by the decision maker) that are investigated (Saaty 1980; Shang and Sueyoshi 1995; Sinuany-Stern et al. 2000).

Table 3.4: Scale of Importance as utilized in AHP (Saaty 1980, p.54))

Intensity of Importance	Definition
1	Equally important as …
3	Weakly more important than…
5	Strongly more important than…
7	Very strongly more important than…
9	Absolutely more important than…
2, 4, 6, 8	Intermediate values between adjacent scale values
Reciprocals of above values	If element i has one of the above numbers assigned to it when compared to the element j (i.e. a_{ij}=1-9), then j has the reciprocal value when compared to the element i (i.e. a_{ji}=1-1/9)

As can be understood from the discussion presented above, the whole purpose of AHP is to reach a prioritized ranking that indicates the preference of the decision maker for each element that is investigated (Shang and Sueyoshi 1995). For its application to DEA, three separate AHP should be run; one for the controllable input variables, one for the controllable output variables, and one for the uncontrollable factors, as pairwise comparisons should be made within the same class of variables. A hypothetical example for the application of AHP to some of the uncontrollable factors that are included in the comprehensive list for the paved lanes element of the level-of-service component (as listed in **Table 3.2**) is presented below.

The uncontrollable factors (that are deemed to be affecting the paved lanes element of the level-of-service component) to be ranked by AHP are: (i) # of yearly chloride applications on the paved lanes (A), (ii) Average Daily Traffic (B), (iii) # of yearly freeze and thaw cycles (C), and (iv) yearly precipitation amounts (D). The decision maker performs the pairwise comparison for each pair by considering their degrees of importance and assigns a value (to be located in the appropriate cell of the matrix) by using the scale presented in **Table 3.4**. For example, as can be seen in cell (1,2), variable A (# of yearly chloride applications on the paved lanes) is deemed as strongly more important than variable B (Average Daily Traffic) and thus the value in the first row and second column of the matrix is 5. The final matrix obtained as a result of such pairwise comparisons is shown below in **Table 3.5**.

Table 3.5: Pairwise Comparison Matrix for the Highway Maintenance Input Variables

Importance of the Variable	A	B	C	D
A	1	5	6	7
B	1/5	1	4	6
C	1/6	1/4	1	4
D	1/7	1/6	1/4	1

The next step is to calculate the principal eigenvector of the matrix and normalize that to obtain the rank order of importance (named as "vector of priorities") for the variables A, B, C, and D. Saaty (1980) provides a number of methods that would result in the crude estimates for the vector of priorities in the absence of computing software to calculate such vector. The best estimate for the vector of priorities is to multiply the n elements in each row and take the n^{th} root and then to normalize the resulting numbers (Saaty 1980). The calculation for such an estimate is presented below:

Row 1: 1*5*6*7= 210→ $\sqrt[4]{210} = 3.807$

Row 2: (1/5)*1*4*6= 4.8→ $\sqrt[4]{4.8} = 1.480$

Row 3: (1/6)*(1/4)*1*4= 0.167→ $\sqrt[4]{0.167} = 0.639$

Row 4: (1/7)*(1/6)*(1/4)*1= 0.006→ $\sqrt[4]{0.006} = 0.278$

When the values obtained for each row is summed and then normalized with respect to the sum, the resulting estimate for the vector of priorities (i.e. rank order of importance of the elements) is as follows:

$$\begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = \begin{bmatrix} 0.61 \\ 0.24 \\ 0.10 \\ 0.05 \end{bmatrix}$$

It is important to note that the exact solution to this problem is obtained by raising the matrix to arbitrarily large numbers and dividing the sum of each row by the sum of elements of the matrix. For the example presented above, such a solution would yield to the same result as obtained above (Saaty 1980). Thus, the estimate presented above is a good approximation for the solution. For the exact solution methodology the reader is referred to Saaty (1980). Saaty (1980) also provides a detailed discussion on AHP including the intuitive justification of the AHP modeling and the scaling presented in **Table 3.4**. Commercial AHP application software packages are available to structure and solve AHP models (Shang and Sueyoshi 1995).

By using the rank order of importance presented above, the decision maker may decide to remove the two uncontrollable factors with the lowest weights (C and D) that make it to the end of the ranking from the list of variables to be included in the DEA study. Through such an approach, the number of DMUs to be compared in the study will be sufficiently larger than the number of variables used.

3.6.1.2 Quantitative Methods

There are four major quantitative methods that can be utilized to refine the list of variables. **First one** is the aggregation method which calls for the aggregation of different variables into one single variable that represents all such variables. For example, uncontrollable factors such as the amount of snowfall and the amount of freeze and thaw cycles can be combined into one composite factor which may be called as the climate factor (Cook et al. 1990). Another example of this is the cost variable. Variables as “number of people”, “gallons of fuel”, “KWH of electricity” can be measured in terms of their cost, resulting in the replacement of those variables with the cost variable, which in turn results in the reduction of number of variables. However, making such a replacement of input variables with the cost variable may contradict with the objective of a DEA study in the instances where such objective is to measure the pure technical efficiency. Inclusion of cost as an input variable to replace other input variables would yield to the measurement of cost efficiency as opposed to the technical efficiency. Thus such a replacement (i.e. aggregation of variables into one cost variable) should be made only if it matches the objectives of the analysis (Golany and Roll 1989).

Another quantitative method is rescaling. In this method, some variables (typically the uncontrollable factors) can be used to rescale other variables in the analysis and then can be excluded in the DEA models as they are accounted for in an indirect manner through such rescaling (Golany and Roll 1989).

Another possible quantitative method that can be utilized to refine the list of variables is the Principal Component Analysis (PCA) (Ruggiero 2003). PCA is a method that explains the variance structure of a matrix of data (with *n* units and *m* variables) through linear combinations of the variables. By this, PCA reduces the variables to a few principal components which generally describe 80-90% of the variance in the data. If most of the population variance in the data can be attributed to a few principal components, then such principal components can replace the original variables without much loss of information about the population (Adler and Golany 2001). These principal components are linear combinations of the original variables and they are derived in decreasing order of importance so that the first principal component accounts for as much as possible of the variance within the original data. In conclusion, the main purpose of PCA is to check whether the first few principal components (derived through the methodology of PCA) account for most (i.e. 80-90% - sufficiency to be determined for each individual analysis by the analyzer) of the variance in the original data. If that is the case, then it can be argued that the number of variables in the original data set can be reduced to the number of principal components providing such sufficiency, hence the reduction in the number of variables (Chatfield and Collins 1980).

As discussed above, PCA, by losing in the process as little information as possible, tries to reach to a few linear combinations of the original variables that can be used to summarize the data (Mardia et al. 1979). It is important to note that PCA transforms a set of correlated variables to another set of uncorrelated variables. Therefore, if the initial variables are uncorrelated, then PCA will yield to same set of variables without changing the initial data set. The major benefit of PCA is the fact that it enables one to assess the effective dimensionality of a set of data. If the results of a PCA run reveals that the first few principal components account for most of the variance in the original data, it is preferable to use just those first few principal component data (Chatfield and Collins 1980). The reader is referred to a number of text by Mardia et al. (1979), Chatfield and Collins (1980), Dunteman (1984), and Jolliffe (2002) for the detailed description of PCA, mathematical theory behind it, and relevant mathematical formulations. Commercial software packages, such as SAS, are available to solve PCA problems (Dunteman 1984). Presented below, are example data and the output obtained as a result of the application of PCA on such data, as performed by the *Microsoft Excel* add in *XLMiner* (QuantLink 2005). **Table 3.6** presents the data of 22 US public utilities for 8 variables (legend provided under **Table 3.6)** associated with such public utilities. Then, PCA is applied to this data and it is aimed to obtain a new data set with the smallest number of principal components possible that would explain the

90% of the variance in the original data set. When such criterion is entered into the software and it is run, the output is obtained with 6 principal components (as so many principal components were required to explain the 90% of the variance in the original data set) with new data as presented in **Table 3.7**. As can be seen in **Table 3.6** and **Table 3.7**, in this example, application of PCA on the original data resulted in the reduction of dimensionality from 8 variables (original data) to 6 principal components (data after the application of PCA).

Table 3.6: Data for Public Utilities (Example Dataset within the *XLMiner Demo Edition 3.0.0* (QuantLink 2005))

utility_name	utility	X1	X2	X3	X4	X5	X6	X7	X8
Arizona	1	1.06	9.2	151	54.4	1.6	9077	0	0.628
Boston	2	0.89	10.3	202	57.9	2.2	5088	25.3	1.555
Central	3	1.43	15.4	113	53	3.4	9212	0	1.058
Common	4	1.02	11.2	168	56	0.3	6423	34.3	0.7
Consolid	5	1.49	8.8	192	51.2	1	3300	15.6	2.044
Florida	6	1.32	13.5	111	60	-2.2	11127	22.5	1.241
Hawaiian	7	1.22	12.2	175	67.6	2.2	7642	0	1.652
Idaho	8	1.1	9.2	245	57	3.3	13082	0	0.309
Kentucky	9	1.34	13	168	60.4	7.2	8406	0	0.862
Madison	10	1.12	12.4	197	53	2.7	6455	39.2	0.623
Nevada	11	0.75	7.5	173	51.5	6.5	17441	0	0.768
NewEngla	12	1.13	10.9	178	62	3.7	6154	0	1.897
Northern	13	1.15	12.7	199	53.7	6.4	7179	50.2	0.527
Oklahoma	14	1.09	12	96	49.8	1.4	9673	0	0.588
Pacific	15	0.96	7.6	164	62.2	-0.1	6468	0.9	1.4
Puget	16	1.16	9.9	252	56	9.2	15991	0	0.62
SanDiego	17	0.76	6.4	136	61.9	9	5714	8.3	1.92
Southern	18	1.05	12.6	150	56.7	2.7	10140	0	1.108
Texas	19	1.16	11.7	104	54	-2.1	13507	0	0.636
Wisconsi	20	1.2	11.8	148	59.9	3.5	7287	41.1	0.702
United	21	1.04	8.6	204	61	3.5	6650	0	2.116
Virginia	22	1.07	9.3	174	54.3	5.9	10093	26.6	1.306

X1: Fixed-charge covering ratio (income/debt)
X2: Rate of return on capital
X3: Cost per KW capacity in place
X4: Annual Load Factor
X5: Peak KWH demand growth from 1974 to 1975
X6: Sales (KWH use per year)
X7: Percent Nuclear
X8: Total fuel costs (cents per KWH)

Table 3.7: Results of the Application of PCA (Example Dataset within the *XLMiner Demo Edition 3.0.0* (QuantLink 2005))

utility_name	utility	Principal Component1	Principal Component2	Principal Component3	Principal Component4	Principal Component5	Principal Component6
Arizona	1	0.14680855	-0.70668888	-0.75677061	-0.74634844	-0.4014447	0.27812439
Boston	2	-1.07771409	0.90181172	0.99761027	-0.90263563	0.10484068	0.43158054
Central	3	2.56794786	0.28825951	-0.76581848	1.06680882	-0.3701089	-1.29741466
Common	4	0.71929371	0.22586085	1.0541724	-1.26419866	0.42349446	0.69914985
Consolid	5	0.22515473	1.8523066	0.7835567	0.06194134	-2.90995908	-0.11569301
Florida	6	2.16410089	1.18942833	-0.85294658	-0.07549008	0.6818251	0.58680105
Hawaiian	7	-0.46976858	1.92928314	-0.81214392	1.47624409	0.99486291	0.62836438
Idaho	8	-0.6610496	-1.93031943	0.09715673	0.90812719	-0.29947528	1.59887278
Kentucky	9	0.46802694	0.13270581	-0.02153149	1.96017218	0.50696743	-0.75964105
Madison	10	1.03749263	-0.25631684	2.00106931	-0.52179921	-0.02076977	0.29224274
Nevada	11	-1.54902661	-3.25468898	-0.95496392	-0.85499084	-0.07517218	-0.35849735
NewEngla	12	-1.02220225	1.58694959	-0.45778888	0.74947989	0.01652738	-0.1470965
Northern	13	0.88136411	-0.64475149	2.79453492	-0.03680578	0.48660928	-0.41561717
Oklahoma	14	1.75141335	-0.87198108	-1.19805539	-1.12791932	-0.3572779	-0.82572198
Pacific	15	-1.42014563	1.11186957	-1.00230765	-0.88812333	0.10198388	1.00219798
Puget	16	-1.14856839	-2.67019272	0.4379189	2.10617328	-0.27088633	0.20017901
SanDiego	17	-3.24058604	0.73343951	-0.32994467	-0.97662145	0.7766698	-1.65977883
Southern	18	0.44847971	-0.16646586	-0.85349596	0.1182422	0.33069658	-0.20912193
Texas	19	1.93239129	-0.73060834	-1.9116739	-0.79767698	-0.0314763	0.52233469
Wisconsi	20	0.93864596	0.51465172	1.2934258	-0.22715119	1.1462853	-0.03438597
United	21	-2.08223939	1.32362068	-0.35397351	0.3387121	-0.56149328	0.23259456
Virginia	22	-0.60981947	-0.55817354	0.81197017	-0.36614031	-0.27269912	-0.64947331

There has been a very few number of studies which used PCA to reduce the number of variables to be included in the DEA models. A study by Adler and Golany (2001) to evaluate the efficiency of West European aviation industry used PCA to replace the original input data by principal components, reducing the number of input variables with minimum loss of information. However, to be able to use the principal component data instead of the original data, they needed to use a modified version of DEA formulation. As can be seen in **Table 3.7**, the results (the data of principal components) obtained through the application of PCA to the original variables can be negative. However, DEA requires all input and output data to be strictly positive. To overcome the issue of negative data, Adler and Golany (2001) increased each principal component's value by the most negative value in the data plus one (thus making each value strictly positive), counting on the fact that the DEA models they use are translation invariant (i.e. an affine transformation of data can be performed with no impact in the DEA efficiency results) (Adler and Golany 2001).

Adler and Berechman (2001), in measuring the relative efficiency of airports using DEA, utilized PCA to replace five output variables with three principal components that explain 82.2%

of the variance in the original data (Adler and Berechman 2001). Adler and Golany (2002) state that less than full information about the DMUs are used as a result of the application of PCA to original variable data. This leads to the loss of some explanatory powers of the data but in return improves the discriminatory power of the DEA models. They acknowledge the fact that, in applying PCA to input and output variable data, some information is lost. However, this is at a minimum amount compared to other variable reduction methods as PCA does not require the analyzers to remove the variables completely (leading to the complete loss of information drawn from those variables) as done in such other methods (Adler and Golany 2002).

Final and the least dependable quantitative method is the identification of correlations between the variables. For this method, correlation analyses can be used. Correlation analyses that identify strong relations between the variables may indicate that the information possessed by one variable is already represented by other variables, resulting in redundancies in data. However, such one at a time correlation analyses should not be regarded as reliable means of eliminating variables. Rather, results of such correlation analyses should only be utilized as indicators for a need to investigate some of the variables more closely (Golany and Roll 1989). The fact that solid conclusions should not be drawn from correlation analyses is also underlined by Dyson et al. (2001). They state that even though it is tempting to remove correlated variables in order to increase discrimination, such removal purely on the grounds of correlation should be avoided. In such situations, results of the correlation analyses should be used only as guidelines in the decision making process as opposed to sole indicator of the redundancy of a variable. This is mainly because, the choice of which variables to remove from a DEA study is very crucial as the results of efficiency evaluations can differ drastically between the removal of one variable and retainment of that. They furthermore state that, only if two variables are perfectly positively correlated and one is simply a multiple of other, removing one from the DEA study would be safe (Dyson et al. 2001). Just like the research mentioned so far, the research by Jenkins and Anderson (2003) points out that the actual interrelation between the variables that are partly correlated is not obvious. Furthermore, in a multi-variable case, the variable(s) that can be removed from the analysis with the least amount of loss of information cannot and should not be determined by just looking at the results of the correlation analyses. In other words, results of correlation analyses do not provide reliable information as to decide on which variable(s) to remove and which variable(s) to retain. Jenkins and Anderson (2003) tried to provide a reliable and analytic method to be able to use the results of correlation analyses in deciding on which variable(s) to remove. That method tried to identify the variable(s) to remove based on the least amount of loss of information resulting from the removal of such variable(s). However, in applying their method to different data sets, Jenkins and Andersen (2003) concluded that the results are erratic and not conclusive enough to validate such method. They, furthermore, concluded that DEA results can greatly differ according to which highly correlated variable(s) is/are removed or retained even when the scientific justification for the removal or retainment of such variable(s) is reasonable (Jenkins and Anderson 2003). Given all of the aforementioned issues with the usability of correlation analyses to identify the variables to remove from a DEA study, it can be stated that this quantitative method of identifying correlations between the variables should be avoided and the three other quantitative methods (aggregation, rescaling, and PCA) should be preferred over identifying correlations to the extent possible.

3.6.1.3 DEA Based Analyses

This procedure requires the analyzer to make trial runs of the appropriate DEA models (i.e. CCR and/or BCC model) by using the variable list in hand. To test the effects of different variables on the efficiency scores, the DEA model can be run with a series of combinations of these variables. Then some techniques can be used to group the DMUs based on the resulting efficiency scores. Observing the DMU groupings as established after each run of the model with different combinations of variables, one can identify the variables which have little effect on the efficiency scores (i.e. variables which do not alter such groupings significantly) and then remove those from the list (Golany and Roll 1989). This approach was first introduced in the paper by Farrell (1957) where a couple of efficiency scores were obtained for the units in the data set, by using a different combination of variables in each run. As a result of this, it was identified that the results of the model which included all variables did not differ significantly from the results of the model which included all but one variable. It was then concluded that such variable could be removed from the efficiency analysis (Farrell 1957). In conclusion, following a series of trial DEA model runs in which different combinations of variables are used, and then performing the abovementioned analysis, the final list of variables to be used in the formal DEA models can be obtained (Golany and Roll 1989).

It is important to note that, during the DEA study, the analyzer does not need to choose and apply only one of the approaches discussed in this section but can apply two or more suitable approaches in a step-by-step fashion to reach a well-refined list of variables as can be seen in **Figure 3.10** (Golany and Roll 1989).

As also can be seen in **Figure 3.10**, if this step-by-step process does not result in a list of variables which is sufficiently refined (i.e. the number of variables is far less than the number of DMUs in the data set as discussed at the beginning of **Section 3.6**), then the analyzer needs to go back to the list of DMUs and try to adjust it by disaggregating the DMUs into smaller units of comparison (based on data availability for such smaller units). This would result in an increase in the number of DMUs that are compared and thus would increase the discriminating power of DEA in the presence of a large number of input and output variables. As a matter of fact, the rule of thumb presented in the beginning of **Section 3.6** (the one that states that the number of DMUs should be at least 2*m*t where *m* is the number of inputs and *t* is the number of outputs) goes both ways; i.e., the number of DMUs included in the models should also be large enough to help the DEA models to discriminate between the DMUs. Therefore, every effort should be made to choose the size of the DMU such that the number of DMUs included in the models can be increased to the best extent possible while assigning a meaningful size to the DMU (i.e., it is indeed a unit for which decisions are made).

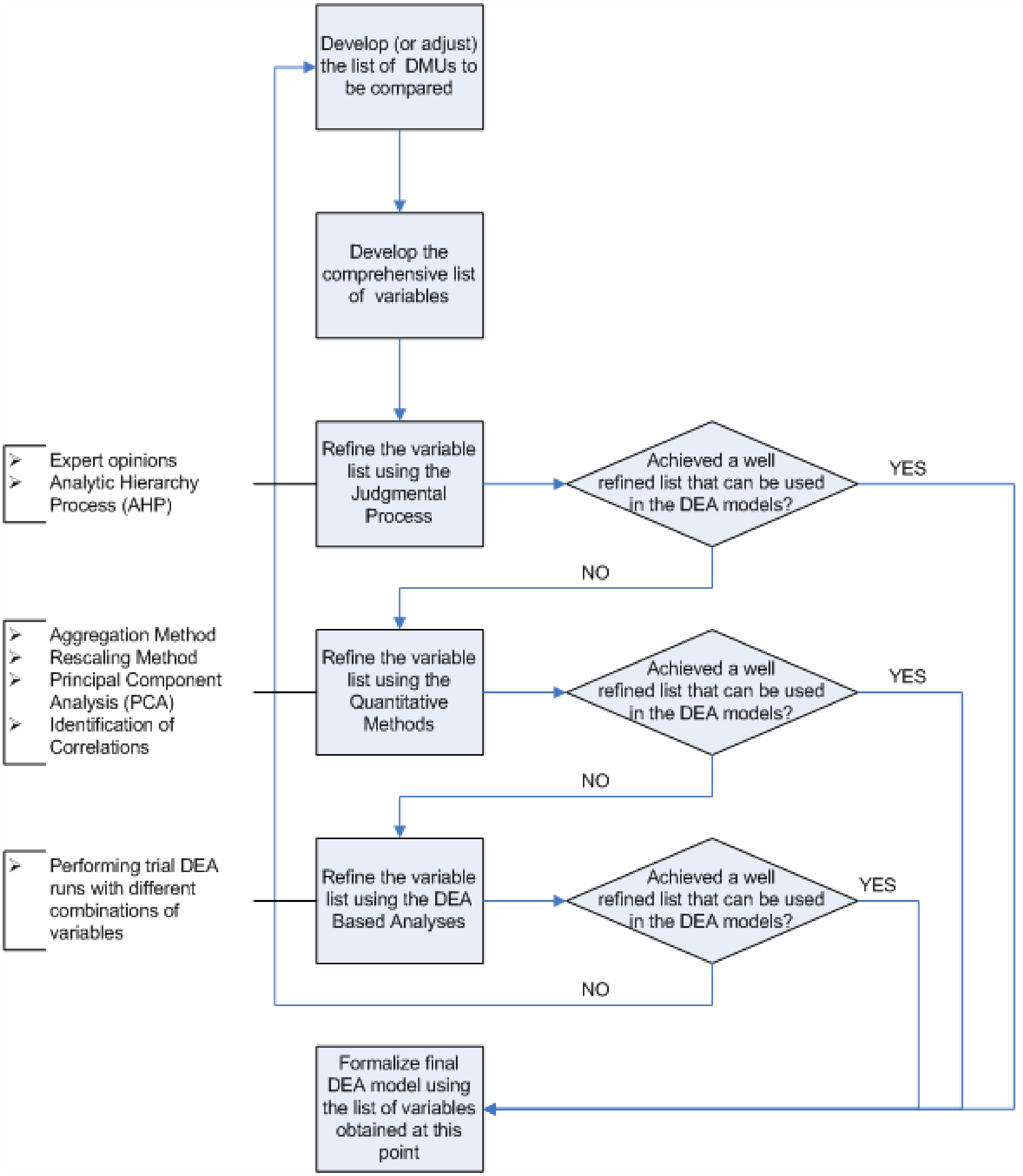


Figure 3.10: Flowchart for Reaching a Well-Refined List of Variables (Partially adopted from Golany and Roll (Golany and Roll 1989, p.240))

3.6.2 Applicability of the Approaches to Refine the List of Variables established for the Comprehensive Highway Maintenance Efficiency Measurement Framework

The previous section elaborated on each approach that can be used to refine the list of variables in a DEA study. This section discusses the applicability of each approach to the case investigated in this research, application of DEA to highway maintenance to develop a comprehensive highway maintenance efficiency measurement framework.

Judgmental process, whether it is performed informally by just using the expert opinions or using a more systematic procedure like AHP, greatly depends on the participation of key decision makers and experienced staff within the relevant field. Obviously, the collaboration with the decision makers (e.g. project sponsor or project stakeholders) who will use the end product of a DEA research to actually make decisions is very important for the success of any DEA study, especially at the stage of variable selection and refinement. Therefore, if such collaboration can be obtained at the later stages of this research, this approach is definitely the first approach to be used to refine the list of variables as depicted in **Figure 3.10**.

Of the **quantitative methods** presented, the aggregation method has some merits for its application to the highway maintenance research. As can be seen in **Table 3.2** and **Table 3.3**, highway maintenance is performed in a setting that is vastly affected by uncontrollable factors such as the climate and terrain (i.e. environmental factors). Such uncontrollable factors not only trigger the emergency incidents and affect the deterioration of the asset items maintained by the maintenance crews but also affect the maintenance efforts of such maintenance crews. In other words, there are many different uncontrollable factors that are associated with the environment that affect the efficiency of the highway maintenance process. Thus, just under the environment group, one can list many uncontrollable factors that need to be included in the DEA models to cover each uncontrollable factor's effect on the highway maintenance. Some of the uncontrollable factors (as defined in **Table 3.2** and **Table 3.3**) related to the environment can be listed as: (i) freeze and thaw cycles, (ii) rainfall, (iii) snowfall, (iv) wind, (v) yearly temperature cycles, (vi) flooding and (vii) terrain. By using the aggregation method, one can combine all of these uncontrollable factors into one single uncontrollable factor, the *environmental effect factor* namely. As a matter of fact, the Virginia State Climatology Office divided the state of Virginia into six environmental regions based on most of the environmental uncontrollable factors listed above (Dadson 2001). Thus, using the definitions for such environmental classification, one can develop the *environmental effect factor* which possesses a categorical scale (which may be converted to the ordinal or ratio scale if needed) based on the severity of environmental effects and then assign each DMU under investigation such *environmental effect factor* based on its location. This process would result in a significant amount of reduction in the number of uncontrollable factors as many environmental-related uncontrollable factors are aggregated into one single uncontrollable factor, the *environmental effect factor*. It is important to note that, Dadson et al. (2002), by using statistical one way ANOVAs and cluster analyses, were able to develop an environmental classification (low, moderate, or severe environment) to represent the effect of environment on the deterioration of bridges for the state of Virginia (Dadson et al. 2002).

Aggregations of similar nature can even be performed to combine different kinds of uncontrollable factors representing different effects. For example effects of operating practices and climatic exposure can be aggregated into one single uncontrollable factor representing both. A study by Wells (1994) aggregated three different uncontrollable factors affecting the deterioration of bridges (i.e. average daily truck traffic, chloride applications, and freeze/thaw cycles) into one uncontrollable factor by performing regression analyses on the responses of surveys sent to district bridge engineers in the state of Virginia. Through such an approach, Wells (1994) was able to derive an equation which combines the abovementioned three uncontrollable factors into one ordinal uncontrollable factor representing the effects of operating practices and climatic exposure on the deterioration of bridges with the following scale: 1- benign effect, 2- low effect, 3- moderate effect, and 4- severe effect (Wells 1994).

As was mentioned in **Section 3.6.1.2**, there has been a very few number of studies which used PCA to reduce the number of variables to be included in the DEA models. All of these studies used a modified version of common DEA formulations to be able to use the principal components instead of the original variables. This research aspires to use the common DEA formulations to the extent possible. Therefore, even though being an option, PCA method is not very likely to be used in this research to reduce the number of variables. Moreover, as PCA is a method which changes the values of variables in the original data to some other values (which may even be negative values) of principal components, it may be challenging to present the results of the DEA process to decision makers when they see such changed and negative values which they cannot attribute to the originally collected data for variables. Given these, for the purposes of this research, it is preferable to use the variable reduction methods other than PCA to the extent possible.

Other quantitative methods, rescaling method and identification of correlations, do not have any applications in the literature of DEA and thus they are not deemed as suitable to be applied to this research. Specifically the identification of correlations should be avoided due to the problems inherent in such methodology for the DEA applications as discussed in **Section 3.6.1.2**.

Finally, the third level of refinement approach, **DEA based analyses**, can be utilized in this research if needed, i.e. the other applicable approaches do not yield a well refined list that satisfies the need that the number of DMUs to be compared in a DEA study should be sufficiently larger than the number of input and output variables used.

3.7 THE APPROACH UTILIZED TO DEAL WITH UNCONTROLLABLE FACTORS

As mentioned earlier, within the DEA context, an uncontrollable factor (also referred to as non-discretionary, environmental, and exogenous factor in the DEA literature) is the factor that the DMU has no control or influence over. Nonetheless, it affects the transformation process as it may affect the ability of a DMU adversely in generating more of its outputs using a given amount of inputs or similarly it may preclude the DMU from reducing its inputs beyond a certain amount to produce a given amount of outputs. Given their effects on the efficiency of the transformation process that is investigated, all uncontrollable factors should be considered in the assessment of relative efficiencies among DMUs (Burley 2006; Golany and Roll 1993; Rouse et al. 1997a). Uncontrollable factors and their effects on the processes should be considered for the measurement of any kind of performance dimension (effectiveness, efficiency, productivity, and etc.). This should especially be the case in comparative performance measurement (such as DEA) of units as such uncontrollable factors may affect the performance of different units in different amounts. The process of benchmarking should acknowledge the fact that the best practices identified for a unit can be different in different environmental settings (Rouse et al. 1997a). However, traditional DEA formulations such as CCR and BCC assume that DMUs are encountering similar uncontrollable factors and do not consider the effects of the environment (in which the DMUs operate) on the performance of the DMUs (Dyson et al. 2001). This leads to the unfair comparison of DMUs in the presence of uncontrollable factors. Using traditional DEA formulations and approach, a DMU which operates in a more favorable environment and thus consumes less input (or uses the same amount of input as) than another one to produce the same amount of output (or to produce more output than) would be labeled as relatively more efficient than the other DMU which is operating in a less favorable environment that impacts its transformation process adversely. Thus, to be able to perform fair comparisons of units using DEA and to derive meaningful results that could be utilized by the decision makers to improve performance of such units, one needs to acknowledge the presence of uncontrollable factors that affect the performance of the units under scrutiny (if applicable) and consider such factors in one way or another in the DEA study.

The phenomenon of uncontrollable factor gains utmost importance in the engineering applications of DEA, specifically in the case that is investigated within this research: **Highway Maintenance**. Highway maintenance is a process that is greatly affected by the uncontrollable factors. As a matter of fact, it is not only affected by the uncontrollable factors of the environment that it is performed within (such as climate, terrain, location, and sub-surface conditions) but also by the uncontrollable factors representing the operational issues encountered by such process (such as design and construction adequacy, traffic and load, traffic accidents, aging, and area served). Abovementioned uncontrollable factors have a substantial effect on the highway maintenance process and its efficiency. Given this, it is essential to consider such uncontrollable factors in the DEA models of the highway maintenance process as they are very likely to explain majority of the efficiency differences that would otherwise be observed in the DEA model runs in which they are disregarded.

3.7.1 Approaches that can be utilized to Deal with Uncontrollable Factors within a DEA Study

A thorough review of literature identified the following approaches as being commonly used in the DEA studies to deal with uncontrollable factors.

3.7.1.1 One Stage Approaches

3.7.1.1.1 Uncontrollable Factors treated as Controllable Variables in the DEA Model

Early studies that acknowledged the presence of uncontrollable factors and their effects on the transformation process assumed such factors to be the variables (input or output) to be included in the DEA models. In other words, uncontrollable factors are treated the same way that the controllable input and output variables (also referred to as discretionary and endogenous variables in the DEA literature) are treated in the DEA models (Rouse et al. 1997a). Uncontrollable factors are quantified and included in the DEA models as either input or output variables. Even though this approach acknowledges the presence of uncontrollable factors, it possesses a major drawback as far as its practical implications are concerned. DEA is a method which not only provides the relative efficiency ratings for the DMUs but also the information about the extent to which inputs utilized by each DMU can be reduced without reducing any of its outputs (or the extent to which outputs produced may be increased without increasing the utilization of any of the inputs). Thus, when uncontrollable factors are included in the DEA models (as input or output variables) the same way the controllable variables are included, information about the extent to which such uncontrollable variables should be reduced or increased is not meaningful for the decision maker (Banker and Morey 1986a). As an example, if the uncontrollable factor is the climate effect and it is quantified and included as an input variable in the DEA model, the result of the DEA model which indicates that the adverse climate effect should be reduced for a DMU to be efficient does not have any applicability as the decision maker does not have any control over the climate.

3.7.1.1.2 Uncontrollable Factors treated as Uncontrollable Variables in the DEA Model

To overcome the drawback mentioned above, Banker and Morey (1986) modified the traditional DEA formulations such as CCR and BCC to be able to include uncontrollable factors as input or output variables in such formulations and derive meaningful results. By modifying the formulations, they were able to estimate the extent to which controllable inputs can be reduced (or controllable outputs can be increased) by the decision maker while keeping the uncontrollable variables at their given level (Banker and Morey 1986a). In essence, they addressed the question of "What would be the efficiency of a DMU given the uncontrollable factors it faces?" The modified formulation makes sure that the results of the DEA model will not suggest a change in the uncontrollable variables' values to project the inefficient DMUs on the efficient frontier. Such modified formulation for the input oriented model for the DMUs experiencing variable returns to scale is presented below as **Formulation 3.1** (Muniz et al. 2006). It is important to note that, to be able to apply this approach, one needs to know, a priori, the effects of the uncontrollable factors on the transformation process to be able to decide on whether to include such factors as input variables or output variables in the model (Daraio and Simar 2005).

Formulation 3.1

minimize Q

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \leq Q x_{i0} \qquad i = 1,\ldots\ldots,m \qquad \textbf{(Constraint 1)}$$

$$\sum_{j=1}^{n} z_j w_{kj} \leq w_{k0} \qquad k = 1,\ldots\ldots,s \qquad \textbf{(Constraint 2)}$$

$$\sum_{j=1}^{n} z_j y_{rj} \geq y_{r0} \qquad r = 1,\ldots\ldots,t \qquad \textbf{(Constraint 3)}$$

$$\sum_{j=1}^{n} z_j = 1 \qquad \textbf{(Constraint 4)}$$

j = 1,……,n

where n: the number of DMUs in the data set

m: number of controllable inputs

s: number of uncontrollable inputs

t: number of outputs (controllable and/or uncontrollable)

y_{rj}, x_{ij}, w_{kj} : known outputs and inputs of the jth DMU and they are all positive.

$z_j \geq 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

As can be seen, this formulation is very similar to the original input oriented BCC formulation with the exception of the constraint on the uncontrollable inputs. The radial efficiency measure, Q, is excluded from the right hand side of the constraint established for uncontrollable inputs. Thus, the uncontrollable inputs do not directly enter the efficiency measure (Q) that is being optimized. Nonetheless, they can affect the efficiency evaluations through their presence in the constraints (Cooper et al. 1999). In other words, even though uncontrollable inputs are excluded from the inputs subjected to radial contraction, they indirectly affect the efficiency scores through their influence on the intensity values, z_j (Rouse 1997; Rouse et al. 1997a). Golany and Roll (1993) explain the dynamics of **Formulation 3.1** as follows: "*While it is true that any DMU under evaluation has no control over its non-discretionary inputs, other DMUs may have an advantage (or disadvantage) from having at their disposal more (or less) of the same factor. These differences in the availability of resources (even though they are uncontrollable) should be reflected in the relative efficiency rating*" (Golany and Roll 1993). It is important to note that the technical efficiency scores calculated using **Formulation 3.1** are always less than or equal to the technical efficiency scores that are calculated in the models where the uncontrollable factors are treated as controllable variables (the approach discussed within the preceding section) (Rouse et al. 1997a).

Figure 3.11 illustrates the approach of including the uncontrollable factors as uncontrollable inputs in the DEA model and using the **Formulation 3.1** to compute relative efficiency scores. The traditional BCC formulation evaluates the efficiency of DMU C with respect to the point C′ that is located on the efficient frontier. This assumes a radial contraction resulting in the decrease of both inputs (X_d and X_n) along the path OC to establish the target for C as C′. However, since the input along the y-axis (X_n) is a non-discretionary one, the possible reduction along y-axis is not a meaningful reduction that could be used by the decision maker. Thus, the target for DMU C should be the point C″ which has the same quantity of non-discretionary input (X_n) but a smaller quantity of the discretionary input (X_d). As a matter of fact, the amount of reduction for the discretionary input can be stated as the distance $X_{dC} - X_{dA}$ and the efficiency of DMU C is equal to X_{dA}/X_{dC} (Banker and Morey 1986a).

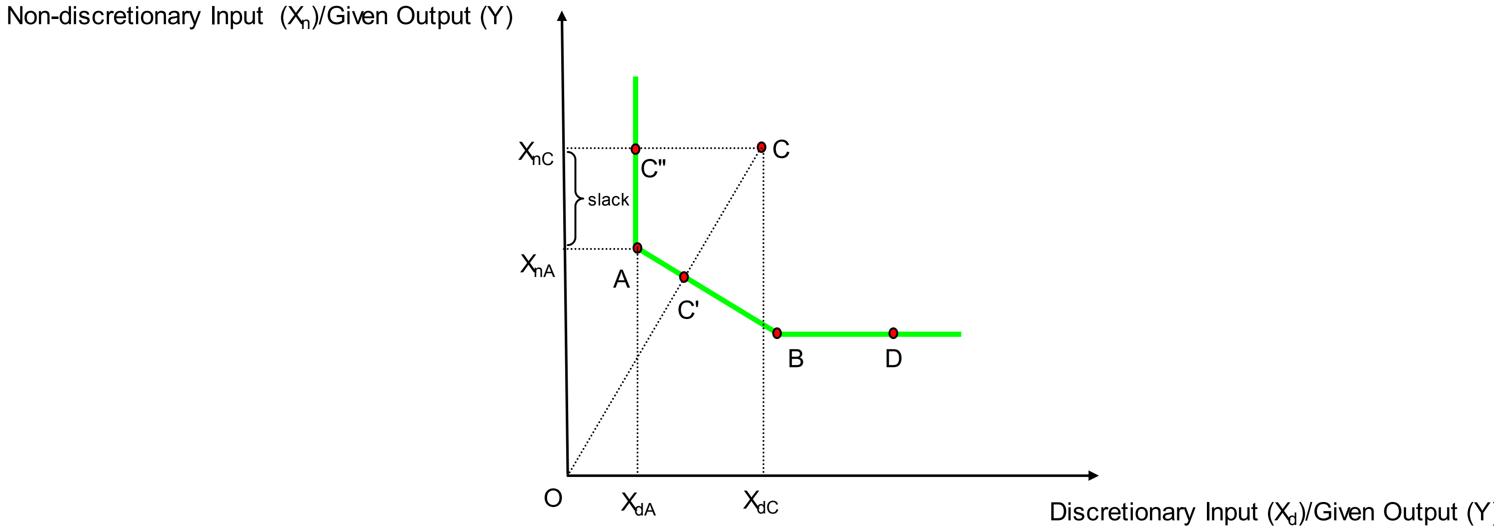


Figure 3.11: Depiction of the DEA Model with Uncontrollable Input

It is important to note that in **Constraint 2**, it is only required that the composite reference group consumes no more of the uncontrollable input than the DMU under consideration and not necessarily exactly the same amount. This may lead to the presence of slacks in the uncontrollable inputs as shown in **Figure 3.11**, but at the same time enriches the comparison set and guarantees that the formulation identifies a reference set for each DMU. However, **Formulation 3.1** would first identify the maximum reduction possible in the controllable input before identifying any slack in the uncontrollable input. The slack on the uncontrollable input represents the quantity of the uncontrollable input that cannot be replaced with any further reduction in the controllable input (Banker and Morey 1986a).

3.7.1.1.3 Uncontrollable Factors used to Develop Categories of DMUs to be included in the DEA Models

In this approach developed by Banker and Morey (Banker and Morey 1986b), the uncontrollable factors are used to define categories that represent the effect of such factors on the transformation process. Generally, each category is defined based on the harshness of the environment that the DMUs are operating within (i.e. mild, medium, or harsh). After each category is defined and each DMU is assigned to a category, DMUs that belong to successive categories are evaluated relative to their own category and to the categories of DMUs facing harsher environments. To achieve this, first the DEA model that includes the DMUs that are facing the harshest environment is run and the efficiency scores are obtained. After this, the DMUs from the next category (facing a milder environment than the previous one) are added and evaluated within the combined group, while not altering the efficiency scores of DMUs (belonging to the previous category) that were obtained in the previous DEA run. Such analysis is performed through successive stages in which the new (and milder) category's DMUs are added to the comparison set and the efficiency scores obtained at the previous stages are retained, till all categories are processed. The final stage of this process is the DEA run to determine the efficiency scores of the DMUs within the mildest category in which entire DMUs are included in the model. The main idea of this process is to keep the efficiencies of the DMUs belonging to the previous (harsher) categories the same, as DMUs representing successive (milder) categories are added to the evaluation. This approach has some similarity to the BCC model in the sense that it restricts the peer reference set for the investigated DMU to the DMUs that face similar or harsher environments (in BCC model, the peer reference set for a DMU is restricted to the DMUs operating on a similar scale). It is important to note that the efficiency scores obtained using this approach tend to be higher than those obtained in the traditional full discretionary approaches (due to the issues related to the discriminating power of DEA) especially for the DMUs that are in the harsher categories as the number of DMUs entering into the DEA model for harsh categories is low (Rouse 1997; Rouse et al. 1997a).

3.7.1.1.4 Continuous Uncontrollable Factors used to Restrict the Peer Reference Set

Ruggiero has extended the approach described above to allow for continuous uncontrollable factors (Ruggiero 1996). This approach's logic is the same as the approach described above in the sense that the DMU under investigation is compared only against the DMUs that are operating under the similar or harsher environments. However, this approach does not require categories to be defined beforehand based on the uncontrollable factors. Rather, this approach defines the following linear programming formulation (**Formulation 3.2**) for input oriented, variable returns to scale case which takes continuous uncontrollable factors into account within one of its constraints (**Constraint 3**) to restrict the peer reference set for the DMU that is under investigation to the DMUs that face similar or harsher environments (Muniz et al. 2006). This approach ensures that once the weights are assigned to the peer DMUs of the

DMU under investigation, such peers will only be composed of the DMUs that face at least as harsh an environment as the DMU under investigation (Triantis 2006).

Formulation 3.2

minimize Q

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \le Q x_{i0} \qquad i = 1,\ldots,m \qquad \textbf{(Constraint 1)}$$

$$\sum_{j=1}^{n} z_j y_{rj} \ge y_{r0} \qquad r = 1,\ldots,t \qquad \textbf{(Constraint 2)}$$

$$z_j = 0 \text{ if } w_{kj} > w_{ko} \qquad k = 1,\ldots,s \qquad \textbf{(Constraint 3)}$$

$$\sum_{j=1}^{n} z_j = 1 \qquad \textbf{(Constraint 4)}$$

j = 1,……,n

where n: the number of DMUs in the data set

m: number of controllable inputs

t: number of controllable outputs

s: number of uncontrollable factors

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

w_{kj} : Value of the uncontrollable factor representing the effect of the environment on the jth DMU. Larger the value, milder the environment in which the jth DMU operates.

$z_j \ge 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

3.7.1.2 Multi Stage Approaches

3.7.1.2.1 Uncontrollable Factors used to Perform Regression Analysis over the Obtained Efficiency Scores

In this approach developed by Ray (Ray 1991), there are two stages. In the first stage, the traditional DEA formulation (CCR or BCC) is utilized using only the controllable variables and thus disregarding the uncontrollable factors. This model results in the efficiency score that reflects not only the technical inefficiency of the DMU but also the inefficiency resulting from the effect of the environment (that the DMU is operating within) on the transformation process. Once the efficiency scores are obtained, regression analysis is performed in the second stage to point out the effect of the environment on the transformation process. For this, the efficiency scores observed in the first stage ($Q_{observed}$) are regressed on the fixed uncontrollable factors (Ruggiero 1998) to obtain the predicted efficiency scores ($Q_{predicted}$). The regression model is specified below in **Expression (3.1)**. It is important to note that once the regression analysis is performed, $Q_{predicted}$ is adjusted upward through the inclusion of a random disturbance term in the regression model to ensure that in no case, $Q_{predicted}$ falls below $Q_{observed}$ (Ray 1991; Rouse et al. 1997a).

$$Q_{predicted} = \alpha + \beta_1 w_1 + \beta_k w_k ... + \beta_S w_S \quad \textbf{Expression (3.1)}$$

where w_k : the kth uncontrollable factor and

β_k : the parameter derived from the regression analysis. If the positive change in w_k represents a milder (more favorable) environment, then β_k >0, otherwise β_k <0

Once the regression equation is obtained (as shown above) the technical efficiency of a DMU can be calculated by using the equation shown below in **Expression (3.2)** (Ray 1991). By this way, the effects of the environment which are disregarded in the first stage (as uncontrollable factors are not used in the first stage) and thus which introduce distortions to the efficiency scores are factored out through regression analysis (Ruggiero 1998).

$$Q_{TE} = 1 - (Q_{predicted} - Q_{observed})$$

$$\rightarrow Q_{TE} = 1 - (\alpha + \beta_1 w_1 + \beta_k w_k ... + \beta_S w_S - Q_{observed}) \quad \textbf{Expression (3.2)}$$

As can be understood from this approach, the main purpose of using a two stage model with regression is to explain the differences in efficiency scores in terms of the uncontrollable factors. For any DMU, the difference between the predicted efficiency score (which considers the effect of the environment in the transformation process) and the observed efficiency score reflects the technical inefficiency of the DMU in a given environment regardless of the environmental effects (Rouse et al. 1997a).

The parameters obtained as a result of the regression may yield to $Q_{predicted}$ values that are larger than 1 (maximum efficiency score that a DMU can get) for some DMUs. The inclusion of the random disturbance term in the regression model to adjust the value of $Q_{predicted}$ upward (as discussed above) intensifies the occurrence of this problem further (Ray 1991; Rouse et al. 1997a). Literature suggests the use of censored regression methods, such as the Tobit as opposed to the Ordinary Least Squares (OLS) regression method to overcome this problem (Afonso and St. Aubyn 2005; Rouse et al. 1997a).

3.7.1.2.2 Parameters Obtained by the Regression Analysis used to Build an Overall Environmental Harshness Index

As illustrated in the previous approach, the results of the regression analysis are used to factor out the effects of the environment on the transformation process and thus to obtain the technical efficiency of the DMUs. However, such approach does not provide any information about the peer reference set as the second stage is used just to modify the efficiency scores, not the reference set. To overcome this drawback of the abovementioned model, Ruggiero developed an approach which builds on the two stage approach developed by Ray (Ruggiero 1998). This approach depicts the parameters obtained within Ray's approach as a result of the regression analysis $(\beta_1,...,\beta_S)$ as indicating the importance of the uncontrollable factors that such parameters belong to. Therefore, using those parameters and the values of the uncontrollable factors, an overall environmental harshness index can be developed for each DMU by utilizing the following equation shown in **Expression (3.3)** (Ruggiero 1998):

$$w = \sum_{i=1}^{S} \beta_k w_k \quad \textbf{Expression (3.3)}$$

where: w_k : the kth uncontrollable factor and

β_k : the parameter derived from the regression analysis for the kth uncontrollable factor.

Once the overall environmental harshness index is calculated for each DMU, the following linear program formulation (**Formulation 3.3**) can be solved (for input oriented, variable returns to scale case) to obtain the efficiency score and reference peer set of each DMU (Ruggiero 1998). This approach, in fact, is a three stage approach and those stages can be summarized as follows:

1) **Stage 1**: The traditional DEA model (CCR or BCC) is run using only the controllable variables and thus disregarding the uncontrollable factors.
2) **Stage 2**: The obtained efficiency scores are regressed on the uncontrollable factors. Then for each DMU, an overall environmental harshness index is developed using the parameters obtained from the regression analysis as the weights of the uncontrollable factors.
3) **Stage 3**: The linear program shown in **Formulation 3.3** is solved using the controllable variables and considering the overall environmental harshness index in **Constraint 3**.

Formulation 3.3

minimize Q

subject to:

$$\sum_{j=1}^{n} z_j x_{ij} \leq Q x_{i0} \qquad i = 1,\ldots\ldots,m \qquad \textbf{(Constraint 1)}$$

$$\sum_{j=1}^{n} z_j y_{rj} \geq y_{r0} \qquad r = 1,\ldots\ldots,t \qquad \textbf{(Constraint 2)}$$

$$z_j = 0 \text{ if } w_j > w_0 \qquad \textbf{(Constraint 3)}$$

$$\sum_{j=1}^{n} z_j = 1 \qquad \textbf{(Constraint 4)}$$

j = 1,……,n

where n: the number of DMUs in the data set

m: number of controllable inputs

t: number of controllable outputs

y_{rj}, x_{ij} : known outputs and inputs of the jth DMU and they are all positive.

w_j : Value of the overall environmental harshness index representing the effect of the environment on the jth DMU. Larger the value, milder the environment in which the jth DMU operates.

$z_j \geq 0$: peer DMUs' weights to be determined by the solution of this optimization problem.

3.7.1.2.3 Uncontrollable Factors used to Perform Bootstrapped Regression Analysis over the Obtained Efficiency Scores

Both of the abovementioned multi stage approaches, which require the execution of regression analysis, possess a serious problem. The procedure utilized in the first two stages of such approaches violates a very important assumption required by regression analysis which states that the sample upon which regression is performed should be independent. In other words, in regression analysis, explained variables should be independent of each other. However, in the abovementioned two approaches, the explained variables (efficiency scores-$Q_{observed}$) used in the regression analysis are not independent from each other as they are the scores obtained in the first stage of such approaches through the application of DEA. The efficiency score obtained for a DMU through DEA is not an absolute but a relative value. This is because one needs to incorporate to the model all other DMUs in the data set to be able to calculate the efficiency score of a particular DMU (Wang et al. 2006; Xue and Harker 1999). As a matter of fact, if a single efficient DMU was to be removed from the analysis, efficiency scores of all inefficient DMUs which had the removed DMU in their peer set would change (Barth and Staat 2005). To be able to overcome this issue of not satisfying the independency requirement of regression analysis when performing regression analysis, Xue and Harker (1999) developed a bootstrapping approach in which the estimators in the direct regression analysis are replaced with the bootstrap regression estimators. Xue and Harker proposed that even though the efficiency scores calculated for DMUs are not independent, the bootstrapped regression analysis produces error-free results as it minimizes the bias resulting from the abovementioned dependency problem of efficiency scores (Wang et al. 2006; Xue and Harker 1999). Later on, Simar and Wilson (2003) expanded and enhanced the bootstrapped regression analysis approach developed by Xue and Harker by developing two new algorithms (Simar and Wilson 2003). For a general discussion on bootstrap, the reader is referred to Efron and Tibshirani (1993). For a detailed discussion on how to apply bootstrapped regression on the DEA scores, the reader is referred to Xue and Harker (1999) and Simar and Wilson (2003). For the purposes of this write-up, suffice it to say that this is still a two stage approach (just like the regular regression applied on the DEA efficiency scores) that is developed to overcome the independency problem that is inherent in the approach that utilize regular regression methods.

Even though they will not be presented in this write-up, it is important to cite the one stage approach developed the by Yang and Paradi (2003), two stage approach developed by Pastor (1994), and three stage approaches developed by Fried and Lovell (1996), and Muniz (2002) as other approaches that have been used in the DEA literature to deal with uncontrollable factors.

3.7.2 Applicability of the Approaches to Deal with the Uncontrollable Factors Identified for the Comprehensive Highway Maintenance Efficiency Measurement Framework

The previous section elaborated on each approach that can be used to deal with the issue of the presence of uncontrollable factors in a DEA study. This section discusses the applicability of each approach to the case investigated in this research, application of DEA to highway maintenance. As was discussed in **Section 3.7**, highway maintenance is a process that is greatly affected not only by the uncontrollable factors of the environment that it is performed within (such as climate, terrain, location, and sub-surface conditions) but also by the uncontrollable factors representing the operational issues encountered by such process (such as design and construction adequacy, traffic and load, traffic accidents, aging, and area served). Therefore, it is essential to choose and utilize the best approach(es) to consider such uncontrollable factors in the DEA models of the highway maintenance process.

The approach discussed in **Section 3.7.1.1.1**, while acknowledging the presence of uncontrollable factors, treats such uncontrollable factors as controllable variables to be included in the DEA models. Therefore it has no merits as far as its applicability to highway maintenance DEA model is concerned as it would not be meaningful to talk about input reductions where such inputs (such as climate, traffic, aging, traffic accidents, and etc.) are completely out of the control of the decision maker.

The approach presented in **Section 3.7.1.1.2** overcomes the drawback mentioned above by modifying the traditional DEA formulations and treating uncontrollable factors as uncontrollable variables to be included in the modified DEA models. The modified formulation makes sure that the results of the DEA model will not suggest a change in the uncontrollable variables' values. The formulation that is utilized (**Formulation 3.1**) is self-explanatory and easy to communicate to the decision maker. For the highway maintenance case, deciding on whether to include a particular uncontrollable factor as an input variable or an output variable in the formulation poses no challenge to the analyst as the effect of each uncontrollable factor on the transformation process is very clear. Given all of the positive features of this approach and its ease of application to the highway maintenance DEA case, this approach can be a viable approach to use in this research. However, Ruggiero (1996) showed that there can be some instances in which the frontier production possibility set obtained through the application of this approach is unfeasible.

This is mainly because through the use of **Formulation 3.1**, convexity is assumed to be the case for uncontrollable inputs as well as controllable inputs. Returns to scale can only be defined for controllable inputs and assuming convexity for the uncontrollable inputs may result in the improper restriction of the frontier production possibility set and inaccurate efficiency scores (Muniz et al. 2006; Ruggiero 1996; Ruggiero 1998).

Contrary to the approach discussed above, the approach presented in **Section 3.7.1.1.3** does not include uncontrollable factors as variables in the model but rather uses them to define categories that represent the effect of such factors on the transformation process. Thus, the convexity problem discussed above does not apply to this approach. One drawback of this approach is that it can consider only categorical uncontrollable factors (i.e. mild, medium, or harsh) to be able to define categories. Another drawback is that, due to the procedure employed in this approach, there should be a sufficient number of DMUs (especially in the harsher categories) for the DEA model to have discriminating power over the DMUs. Otherwise, the efficiency scores for the DMUs in the harsher categories would be overstated as the number of DMUs entering into the DEA model for harsher categories is lower than the other categories. In this research, the number of DMUs for which data are available does not satisfy this requirement. Therefore, even though this approach may be a viable approach that could be suggested at a framework level for the application of DEA to highway maintenance, it may have some problems for the implementation examples considered in this research.

The approach presented in **Section 3.7.1.1.4** overcomes the first drawback of the approach described above by allowing for continuous uncontrollable factors. However, it still possesses the second drawback, i.e. the issue with the discriminating power of the DEA model in the cases where number of DMUs is not sufficient. Moreover, the formulation used in this approach (**Formulation 3.2**) cannot weigh the effect of each uncontrollable factor on the transformation process. In this approach, when the number of uncontrollable factors increases, the probability of identifying a particular DMU as efficient increases. This is because once the DMU under investigation has one single uncontrollable factor that is worse than that of another DMU, that DMU is not included in the comparison set of the DMU under investigation even though at overall that DMU may be operating in a worse environment than the DMU under investigation. Thus, when the number of uncontrollable factors increases, this model tends to overstate the efficiency of DMUs (Muniz et al. 2006; Ruggiero 1998). Given all of these, even though this approach may be a viable approach that could be suggested at a framework level for the application of DEA to highway maintenance, it may have some problems for the implementation examples considered in this research.

The approach presented in **Section 3.7.1.2.1** does not possess the drawback related to the discriminating power of DEA (the case within the abovementioned two approaches) as it uses the uncontrollable factors just to perform regression analysis (either OLS or Tobit method) after the DEA model is run with the inclusion of only the controllable variables. However, as discussed in **Section 3.7.1.2.3** in detail, the dependency problem (i.e. efficiency scores which are obtained in the first stage and then used as the explained variables in the regression analysis are not independent from each other) inherent in this approach may result in completely inaccurate results. Moreover, this approach focuses on obtaining the efficiency scores and is unable to identify the peer reference set and thus the causes of inefficiency. One of the most important purposes of the highway maintenance DEA study is to provide the decision maker with the peer reference set of a particular DMU and the causes of inefficiency within such DMU. Given these drawbacks, this approach has also no merits as far as its applicability to highway maintenance DEA models is concerned.

The approach presented in **Section 3.7.1.2.2** is a combination of the approaches presented in **Section 3.7.1.1.4** and **Section 3.7.1.2.1**. It overcomes one of the issues identified for the approach presented in **Section 3.7.1.1.4** (the issue with respect to the overstatement of efficiency in the presence of many uncontrollable factors) as it calls for the calculation of a single weighted uncontrollable factor. Nonetheless it still possesses the discriminating power of DEA issue and the dependency problem inherent in the approach discussed in **Section 3.7.1.2.1** and thus its usage should be avoided in the highway maintenance DEA study.

The approach presented in **Section 3.7.1.2.3** overcomes the dependency problem inherent in the approaches that use regular regression analysis as their second stages. However, this approach also focuses on obtaining the efficiency scores and is unable to identify the peer reference set and thus the causes of inefficiency. Moreover, to be able to correctly utilize this two stage approach; one also needs to ensure that the controllable variables used in the first stage (DEA model run) should not be correlated to the uncontrollable factors used in the second stage (regression analysis) (Burley 2006; Wang et al. 2006). Finally, as asserted in two pieces of literature, the use of bootstrapped regression within DEA is based on some parametric assumptions that may be disputed (Afonso and St. Aubyn 2005; Daraio and Simar 2005). Given these drawbacks, this approach has also no merits as far as its applicability to highway maintenance DEA models is concerned.

In conclusion, as can be grasped from the discussion presented within this section, the best approaches that can be used to deal with the uncontrollable factors present in the highway maintenance DEA study seem to be the approach described in **Section 3.7.1.1.4** (i.e. restricting the peer reference set for the DMU that is under investigation to the DMUs that face similar or harsher environments) and the one described in **Section 3.7.1.1.2** (i.e. using a modified DEA formulation and treating uncontrollable factors as uncontrollable variables to be included in the modified DEA models). Specifically in the cases where there is a sufficient number of DMUs to address the discriminating power of DEA issue; and one can combine all uncontrollable factors into a single overall harshness index representing all of the uncontrollable factors for a given DMU, the approach described in **Section 3.7.1.1.4** proves to be the best approach. However, if the case in hand does not satisfy the abovementioned conditions (which is the case for the implementation examples considered in this research as will be seen in **Chapter 4**), then the approach described in **Section 3.7.1.1.2** is the best available approach to address the issue of uncontrollable factors even though it possesses a shortcoming that pertain to the frontier production possibility set (as discussed earlier) which may occur in some instances. It is important to note that the leading software in the DEA arena such as *Frontier Analyst* (the software that is used within this research), *OnFront*, and *DEAFrontier* use such approach as a part of their algorithms to solve the DEA problems with uncontrollable factors. It is also important to note that, a study identified by the literature review to be an important guide for this research (as it possesses the application of DEA to highway maintenance), treats uncontrollable factors as variables to be included within the DEA models (i.e. uses the approach described in **Section 3.7.1.1.2)** as presented in **Section 2.6.1** (Cook et al. 1994; Cook et al. 1990).

3.8 THE APPROACH UTILIZED TO CHOOSE THE TYPE OF DEA MODELS TO BE RUN

A number of DEA models and formulations are presented in **Chapter 2**. Such models can be mainly grouped as (i) the models for DMUs experiencing constant returns to scale (CCR) or the models for DMUs experiencing variable returns to scale (BCC), and (ii) input oriented models or output oriented models.

Given such groupings, first it is necessary for the analyzer to decide on the returns to scale that the DMUs under investigation are experiencing. Such a decision can be made only by investigating the process performed by such DMUs. The discussion presented in **Section 3.1**, **Section 3.2**, **Section 3.3**, and **Section 3.4** pertain to the decision of the returns to scale that the DMUs performing highway maintenance operations (specifically the level-of-service and timeliness of response components) experience as it focuses on the process of such components. Therefore such discussion can be utilized to choose either CCR or BCC formulation to be run for the highway maintenance DEA study.

It is also necessary for the analyzer to decide on the orientation (i.e. input oriented or output oriented) of the model once the abovementioned selection is made. This decision is made based on the dynamics of the process that is analyzed. If the decision makers are more flexible in modifying the outputs, the output oriented model should be chosen as it seeks, for the inefficient DMUs, the level by which the outputs produced can be increased without changing the levels by which inputs are utilized. If the decision makers are more flexible in modifying the inputs, the input oriented model should be chosen as it seeks, for the inefficient DMUs, the level by which the inputs utilized can be decreased without changing the levels by which outputs are produced (Triantis 2005c).

Given this discussion, to be able to choose the right model to utilize, one needs to follow the flowchart presented in **Figure 3.12** (Charnes et al. 1994; Ramanathan 2003). It is important to note that, based on the discussion presented in **Section 3.7**, it is quite possible to use slightly modified versions of the major formulations of the chosen models.

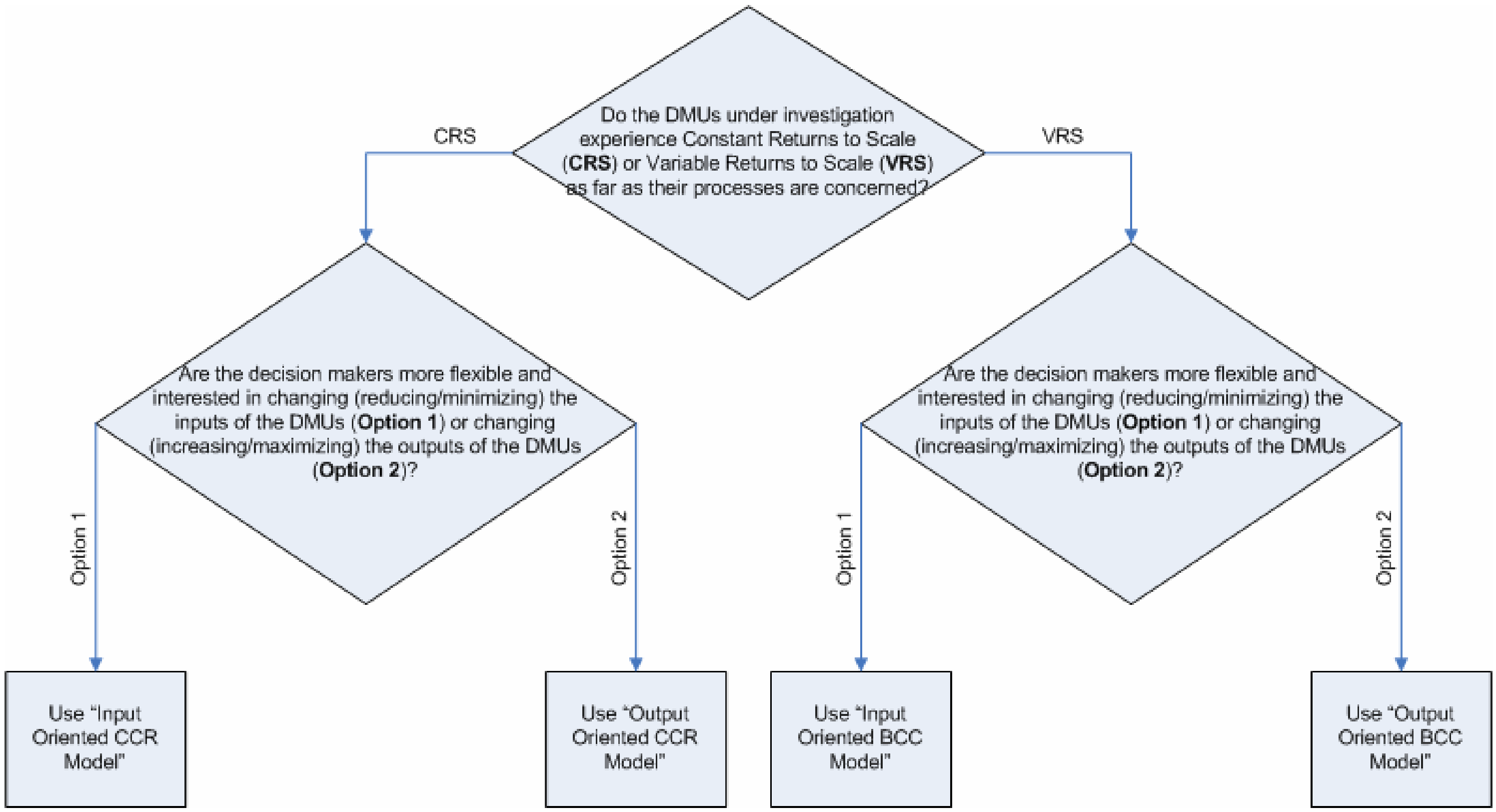


Figure 3.12: The Approach to be Followed to Choose the Type of DEA Models to be Run

3.9 THE USE OF DEA IN THIS RESEARCH VERSUS COMMON DEA STUDIES

The use of Data Envelopment Analysis (DEA) in this research is different from the traditional use of DEA as depicted in the DEA literature with respect to the measurement of efficiency. As discussed in detail within **Chapter 2**, DEA is commonly used in literature to measure the relative technical efficiency of units under investigation. Technical efficiency of the production process (e.g. highway maintenance) is calculated independently from the costs of inputs (e.g. labor, material, and equipment) and prices (e.g. highway tolls) of outputs (Golany and Roll 1989; Hussain and Brightman 2000). Therefore, a DEA model investigating the relative technical efficiency of units for performing the highway maintenance process should include the amounts of resources (labor, material, and equipment) used in such process as the input variables, as opposed to the cost of such resources (similarly, such model should include the amounts of benefits gained as a result of the highway maintenance process as the output variables, as opposed to the price of such benefits as incurred by the users of the highway). However, as can be seen in **Table 3.2** and **Table 3.3**, this research includes the cost of the resources used in the highway maintenance process as the major input variable to be used in the DEA model. In doing so, it seeks the relative cost efficiency of units for performing the highway maintenance process as opposed to their technical efficiency. This is done mainly due to the fact that from a transportation agency like VDOT's point of view (which is the point of view taken in this research as this research is aiming to provide VDOT and other transportation agencies with a decision-making tool to identify (i) whether to use traditional or performance-based approach to highway maintenance and (ii) which division (county, district, and etc.) of it is performing the highway maintenance in a more efficient way with the allocated funds), a more important concept is the cost efficiency due to limited funding.

Even though measuring technical efficiency is more common in the DEA literature, this research is not the only one that investigates the cost efficiency using DEA. As a matter of fact, both of the research (Cook et al. 1994; Cook et al. 1990; Rouse et al. 1997b) that were identified as the only applications of DEA to highway maintenance used the cost as an input variable and thus measured the cost efficiency of units as opposed to measuring their technical efficiency. As Golany and Roll (1989) underline, it is acceptable to use cost as the input variable in DEA but such an approach should be taken only if it matches the objectives of the analysis (i.e. measuring the cost efficiency as opposed to the technical efficiency) (Golany and Roll 1989).

3.10 THE UTILIZATION OF COST VERSUS PRICE FOR THE DEA MODELS OF THE CONTRACTOR WORKING UNDER PERFORMANCE-BASED MAINTENANCE

As can be seen in **Figure 3.7**, cost is the value of resources that are utilized to produce something, i.e. a product or service. For any entity, the **cost** can be defined as what such entity pays for the resources it uses. Price, on the other hand, is the compensation that is sought for the products or services. For an entity, the **price** can be defined as what the customers of the entity pay for its products or services. The specifics of the cost and price of the maintenance activities performed by the different entities (i.e. the transportation agency working under traditional maintenance and the contractor working under performance-based maintenance) that are investigated in this research are presented in **Table 3.8**.

Table 3.8: Specifics of the Cost and Price of the Maintenance Activities performed by the Transportation Agency and the Contractor

ENTITY	COST	PRICE	Used in the DEA models for the purposes of this research?
Contractor performing the performance-based highway maintenance work for the transportation agency	Labor Material Equipment	Contract Price paid to the Contractor by the transportation agency	No
The transportation agency when it uses the performance-based contract for the highway maintenance	Contract Price paid to the Contractor by the transportation agency	Car Licenses Gas Tax Tolls	Yes
The transportation agency when it uses the traditional ways for the highway maintenance (i.e. self-perform)	Labor Material Equipment	Car Licenses Gas Tax Tolls	Yes

The important thing to note in **Table 3.8** is the fact that the price up in the supply chain becomes the cost down in the same supply chain. In other words, the price of the Contractor becomes the cost of the transportation agency, when the transportation agency uses such Contractor under its performance-based contract. This phenomenon brings about the question of "Which item, cost or price of the Contractor, should be used within the DEA model that depicts the Contractor's performance?" The answer to this question depends on which of the following is tried to be accomplished with this research:

1. Comparing the transportation agency's efficiency with the Contractor's efficiency, or
2. Providing the decision-makers within the transportation agency with the answer to the question of whether the transportation agency is more efficient and thus better off in using traditional ways of maintenance or performance-based maintenance

As underlined within the previous section, the framework developed in this research is to be utilized by the transportation agencies as a decision-making tool to identify whether to use traditional or performance-based approach to highway maintenance and thus possesses transportation agency's point of view. This fact necessitates the use of the price of the Contractor (and hence the cost of the Contractor to the transportation agency) as the input variable within the DEA models.

In conclusion, to be able to evaluate and compare the overall efficiency of the performance-based and traditional approaches to highway maintenance, the total cost to the state DOT for each of the two cases (when the state DOT is using the performance-based contract and when the state DOT is using the traditional maintenance means) needs to be identified. **Figure 3.13** illustrates the typical cost breakdown for both of the cases for the maintenance of highways for any state DOT.

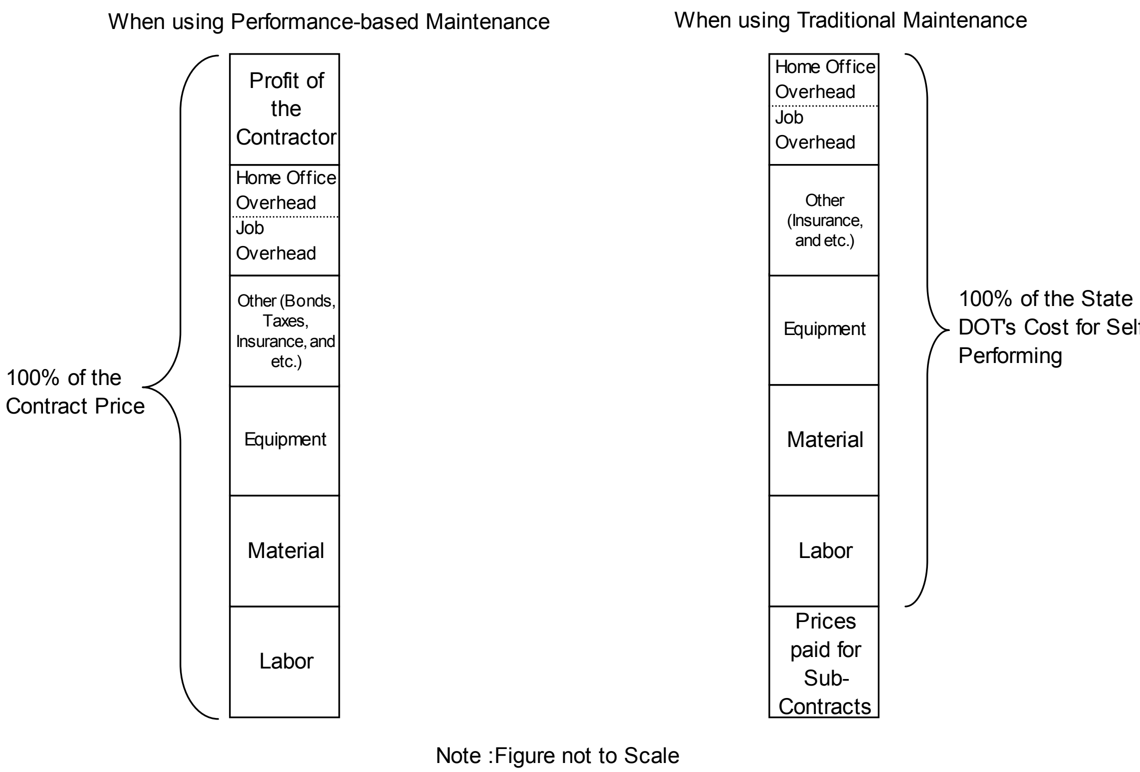


Figure 3.13: Typical Breakdown of Cost to the state DOT for the Highway Maintenance

3.11 THE ISSUE OF COST ADJUSTMENTS FOR THE DEA ANALYSES INCLUDING DIFFERENT PERIODS AND DIFFERENT GEOGRAPHIC LOCATIONS

3.11.1 Cost Adjustments to Address Different Periods

If the DEA is used to perform analysis by including the cost information of multiple periods for a DMU (which is going to be the case in this research as can be seen in **Chapter 4**), the effect of inflation/deflation[6] occurring along such periods should be considered. This is simply because inflation/deflation acts just like an uncontrollable factor which affects the cost of highway maintenance without the discretion of the decision maker. In other words, the money that is spent by the decision maker of a DMU to keep the level-of-service (similarly the timeliness of response) at a certain degree at a given year may not result in the same degree of level-of-service (or timeliness of response) in a subsequent year (assuming all of the remaining variables are kept the same). Such amount of money can only buy less amount of maintenance (to address the level-of-service and timeliness of response needs) if there is inflation present; and it can buy more amount of maintenance if deflation is present in the economy. Therefore, in order to be fair in the comparisons of DMUs representing different periods of time, the inflation/deflation phenomena associated with the cost variable should be acknowledged as an uncontrollable factor and treated accordingly. The best way to treat such uncontrollable factor is to use it to adjust the cost representing multiple (different) periods.

To remove the effects of inflation/deflation (as an uncontrollable factor) on the costs of the DMUs belonging to different time periods, a common denominator representing one time period should be chosen and the adjustment presented below should be applied to all of the DMUs belonging to other periods to bring their cost variables to the chosen period. Inflation/deflation rates can be used to adjust cost figures representing different time periods to bring such cost figures to a common denominator of the same time period. To perform such adjustment, **Expression (3.4)** is used (Piñero 2003):

$$IF_{FUTURE} = \left(1 + {}^{r}\!/_{c}\right)^{n} \qquad \textbf{Expression (3.4)}$$

[6] Inflation/deflation can be defined as the rise/drop in the general level of the costs of the commodities (Piñero 2003).

where:

IF_{FUTURE} : represents the inflation (deflation) factor used to carry cost figures to the future.

r: is the stated annual rate of inflation (if positive) or deflation (if negative).

c: is the number of times (compounds) the inflation (deflation) rate varies in one year.

n: is the number of times the inflation (deflation) rate changes over the entire time period considered in the analysis.

When the calculated IF_{FUTURE} is multiplied by the cost belonging to the original period, then such cost becomes adjusted by the inflation factor and be carried to a future time period (the chosen time period). It is important to note that a similar kind of adjustment can be performed to carry the cost values representing future periods to past by using the inflation factor calculated through **Expression (3.5)**.

$$IF_{PAST} = \frac{1}{\left(1+{}^{r}\!/_{c}\right)^{n}} \qquad \textbf{Expression (3.5)}$$

In addition to the method presented above, the adjustments can be made through the use of *cost indices* that are published for different type of industries. There are many references (most of which are published by government agencies) that could be used for this purpose. Some of the reliable references to locate such *cost indices* can be listed as: (i) FHWA Cost Indices, (ii) R.S. Means Collection of Cost Indices, and (iii) Engineering News Record Construction Cost Indices (Piñero 2003).

This research proposes the utilization of the indices prepared by FHWA as such indices are more specific than other published indices as far as their relation to the highway maintenance operations is concerned. A thorough literature review identified the following two indices published by FHWA: (i) *Highway Maintenance and Operations Cost Index* and (ii) *Composite Bid Price Index for Highway Construction*.

Of these two indices, the first one greatly relates to this research as the subject of this research is highway maintenance. However, the literature review identified that FHWA discontinued the use of it after the publication of a study exploring the feasibility of such index in 1990 (Markow et al. 1990).

Composite Bid Price Index for Highway Construction, as the name implies, is a price index developed for highway construction operations. It is composed of a market basket of six indicator items which are the major work items for highway construction projects and whose price changes are typical of the price changes of similar categories of work for highway construction projects (Mirack 1981). Such indicator items are combined into an overall index which shows the price trend for excavation, surfacing, and structural work (FHWA 2006). Thus, even though such index is not specific to highway maintenance as the one described above, it can still be a representative index as it is composed of items that are performed for highway maintenance as well. This index is prepared by compiling the data obtained from the contracts awarded by state DOTs. Thus, such index includes cost of materials, equipment, labor as well as overhead and profit; hence the name "price index". This index uses only the data for Federal-aid highway construction projects on the National Highway System with contract prices greater than $500,000 (FHWA 2006; Stern 1961). It has been stated that the prices on non-Federal-aid highway construction projects are essentially the same as the ones on Federal-aid projects and thus the index can be considered to be representative for all highway construction projects (Stern 1970). Furthermore, it has been stated that the projects with contract prices smaller than $500,000 have a negligible effect on the index so their elimination does not constitute a problem (Mirack 1981). This index is prepared at the state level as well as the national level (FHWA 2006).

Given all of the advantages as far as its relevancy to this research is concerned, *Composite Bid Price Index for Highway Construction* is chosen to be used in this research to address the issue of cost data belonging to different periods. As will be seen in the implementation examples presented in **Chapter 4**, such index will be used to make adjustments to the cost data belonging to the years 2003, 2004, and 2005. For such examples, the indices calculated at the **national level** are used as opposed to the ones calculated for the state of Virginia. This is mainly because the national index has a smoother trend line as it is an average of the indices that belong to all of the states within the country and thus is less susceptible to price spikes. **Table 3.9** lists the national indices for the years of 2003, 2004, and 2005.

Table 3.9: FHWA Composite Bid Price Index for Highway Construction- National Level (FHWA 2006)

Year	Price Index
2003	149.8
2004	154.4
2005	183.6

3.11.2 Cost Adjustments to Address Different Geographic Locations

If the DEA is used to perform analysis among the DMUs belonging to different geographic locations, a similar issue to the one discussed above arises. This time, such geographic location becomes an uncontrollable factor that affects the cost of highway maintenance as the costs of the commodities may vary depending on the geographic location. In other words, the money that is spent by the decision maker of a DMU that belongs to a particular geographic location to keep the level-of-service (similarly the timeliness of response) at a certain degree may not result in the same degree of level-of-service (or timeliness of response) within a DMU that belongs to a different geographic location (assuming all of the remaining variables are kept the same). For such cases, the cost of highway maintenance should be brought to a common denominator representing the geographic location of choice. There are *geographic location adjustment factors* for each geographic location that could be used for such conversion. The *geographic location adjustment factors* can be found in the abovementioned list of publications (Piñero 2003).

Of the abovementioned two adjustments, only the inflation/deflation adjustment will be performed during the implementation stage of this research. This is mainly because, it is believed that the effect of geographic location becomes irrelevant when such location is confined to a state, Virginia, as the cost of highway maintenance does not vary in significant amounts within the state of Virginia.

3.12 SUMMARY AND OVERVIEW OF THE DEVELOPED FRAMEWORK

This section presents a flowchart summarizing the comprehensive highway maintenance efficiency measurement framework developed in this chapter. Such flowchart lists the components of the developed framework. All of such components are discussed in detail (i.e. what to perform within a component, how to perform such, different approaches that can be chosen within a component, advantages and disadvantages of such approaches (where applicable), and guidelines for selecting one approach over another) throughout this chapter as well as in **Chapter 2** as a part of the DEA literature review. The components listed in **Figure 3.14** will be used to implement the framework developed in this chapter to the VDOT's case by using the real life data that is made available to Virginia Tech in **Chapter 4**.

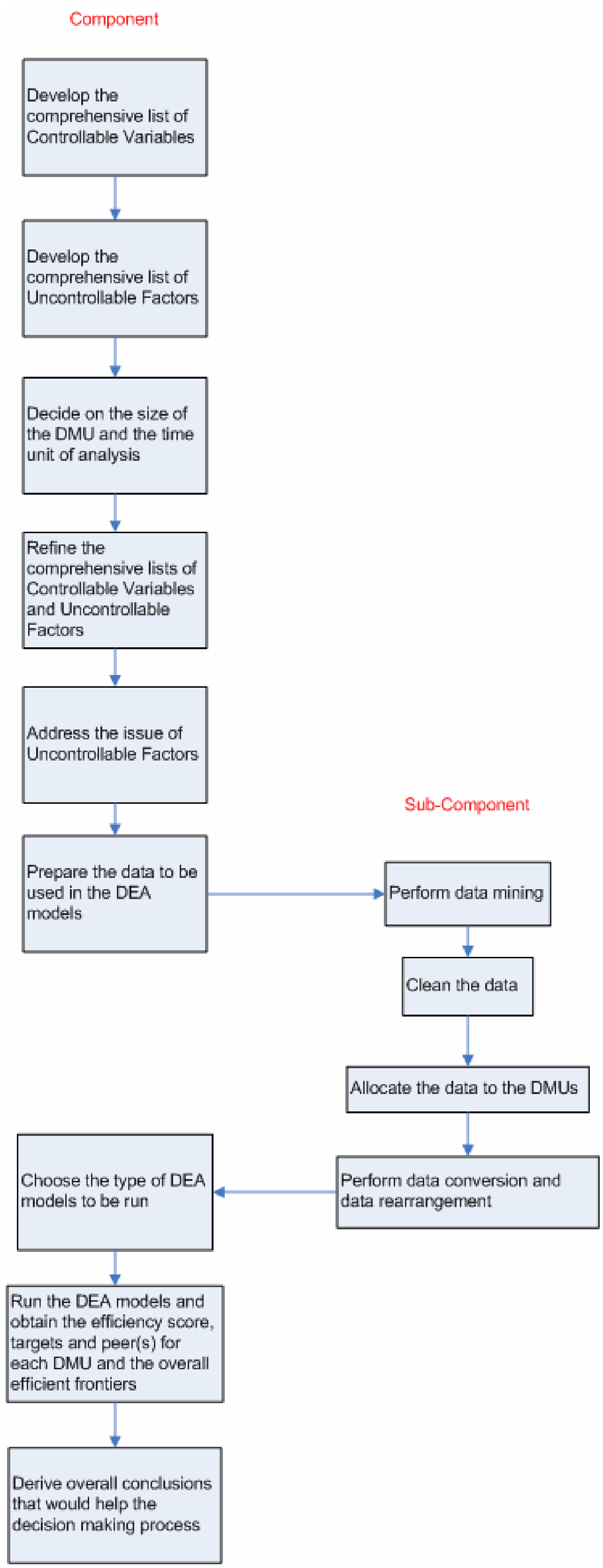


Figure 3.14: Components of the Road Maintenance Efficiency Measurement Framework

CHAPTER 4- HYPOTHESIS TESTING: IMPLEMENTATION OF THE FRAMEWORK

This is the chapter in which the framework developed in **Chapter 3** is applied to the current VDOT-VMS performance-based pilot project to the extent the data to perform this task is made available to Virginia Tech; and the results are obtained. Along with the discussion of the results, the hypotheses tests are also presented. This chapter also presents the conclusions derived as a result of the implementation of the framework to a number of scenarios. By the conclusion of this chapter, the specific objectives of this research as listed in **Section 1.4** will have been achieved.

4.0 SOURCES OF DATA

As this chapter presents the implementation of the framework developed in **Chapter 3**, a large amount of real life data is used throughout the chapter. Thus, it is essential to provide the reader with the sources of the data before illustrating the implementation examples that heavily depend on the utilization of such data. Within this context, this section elaborates on the two main sets of data that are used throughout this chapter: (i) Level-of-Service Data, and (ii) Cost Data.

4.0.1 Level-of-Service Data

As mentioned in **Chapter 3**, this research focuses on the fence-to-fence highway maintenance (in clear reference to the physical limits of the facilities) in which the contractor and VDOT are responsible for maintaining all assets items within the highway right-of-way. The contractor and VDOT are not only responsible for meeting the level-of-service requirements for all asset items, but also need to meet the timeliness of response requirements established for some of the asset items. A complete list of asset groups and asset items that should be maintained by the contractor (through performance-based maintenance) and VDOT (through traditional maintenance) was already presented in **Table 3.1**. **Table 4.0** presents the sources of the level-of-service data that is gathered for each of these asset items. It is important to note that, in **Chapter 3**, the comprehensive highway maintenance efficiency measurement framework was developed not only for the level-of-service component but also for the timeliness of response component. Nonetheless, such framework will not be implemented for the timeliness of response component due to data availability issues. Therefore, **Table 4.0** presents only the sources of the level-of-service data.

Table 4.0: Sources of the Level-of-Service Data for Asset Items

Asset Group	Asset Item	Source of Level-of-Service Data
Shoulders	Shoulders- Hard Surfaced	MRP Inspections
	Shoulders- Non-hard Surfaced	
Roadside	Grass	
	Debris and Roadkill	
	Litter	
	Landscaping	
	Brush and Tree Control	
	Concrete Barrier	
	Sound Barrier	
	Slopes	
	Fence	
Drainage	Paved Ditches	
	Unpaved Ditches	
	Pipes	
	Box Culverts	
	Under/Edge Drains	
	Storm Drains/Drop Inlets	
	Curb and Gutter	
	Sidewalks	
	Storm Water Management Ponds	
Traffic	Signals	
	Pavement Messages	
	Pavement Striping	
	Pavement Markers	
	Delineators/Object Markers	
	Glare Foils	
	Regulatory Signs	
	Other Signs	
	Luminaries	
	Guardrail	
	Impact Attenuators	
	Truck Ramps	
	Cross Overs	
	Rumble Strips	
Roadway	Paved Lanes	VDOT's Pavement Management System
Bridges	Deck	National Bridge Inventory Program
	Superstructure	
	Substructure	
	Slope/Channel Protection	

As can be seen in **Table 4.0**, there are three sources (detailed below) to obtain the data for the level-of-service component. It is important to note that the data obtained from all three sources is used by Virginia Tech to generate the yearly condition assessment reports submitted to VDOT as mentioned in **Section 1.2**.

1) **MRP Inspections**: These are the Maintenance Rating Program (MRP) inspections performed once in every year by the field crews hired by Virginia Tech. Such field crews are composed of experienced inspectors, majority of whom has been performing these inspections for a long time. Such field crews go through a well-structured training each year before being sent to the field. Furthermore, during the inspections these field crews are made subject to very strict quality assurance and quality control programs. It can be asserted that as a result of all of these efforts, the data gathered through MRP inspections is accurate and dependable. It is important to note that MRP does not call for the 100% inspection of the related highway sections but rather uses robust statistical techniques to sample the populations (by using 0.1 mile long segments) and to derive findings that can be generalized to the whole highway sections at 95% confidence level.

2) **VDOT's Pavement Management System**: This is the program that is used by VDOT to assess the condition of the paved lanes in a given year to be able to make budgetary decisions for the next years. As a part of this program, VDOT field crews travel through the state and collect data pertaining to the Load-Related Distress Rating (LDR), Non Load-Related Distress Rating (NDR), and International Roughness Index (IRI). Such information is provided to Virginia Tech for the highway sections that are used in the evaluations made by Virginia Tech. It can be asserted that such information is accurate and dependable as it is used by VDOT to generate budgets.

3) **National Bridge Inventory Program:** The data for bridges has consistently been provided to Virginia Tech by the personnel in VDOT's Asset Management Division (AMD). It has been acknowledged by VDOT's AMD that such data is gathered by VDOT as a part of the Federally-mandated NBI process and thus is well-documented. It can be asserted that the Bridge Condition Data is very reliable as it is provided to Federal Highway Administration and kept in its database to be used to establish investment requirements; to develop data summaries at the national level for reports to Congress, and to respond to inquiries from entities such as Congress, the National Transportation Safety Board, and others (ESRI 2004).

4.0.2 Cost Data

Cost Data has also been provided by VDOT's AMD. According to the statement made by Dennis Domayer from VDOT's AMD, "*The information was derived from FMS II using the VGLN50 reports Program 6040100 for the districts involved. Drills were run by route and then by county and then by activity. The original request was to extract the 7XXXX series of activity codes and omit all other activity codes*" (Domayer 2006). In further communication with the personnel from VDOT's AMD, the following information have been gathered about the Cost Data (Domayer 2006):

- The Cost Data includes only routine/ordinary maintenance (i.e. preventive maintenance and restorative maintenance) expenditures. No rehabilitative maintenance (i.e. reconstruction, and major repair/replacement) expenditure is included.
- No district or central office overhead is included in the Cost Data.
- Incident response expenditures are included in the Cost Data if such are coded to the activity codes that are extracted. Snow removal expenditures are captured in the 6XXXX series of activity codes and thus are not included in the Cost Data.
- All labor expenditures (including the labor burden) are included in the Cost Data if they are coded to the activity codes that are extracted.
- Costs of the private contracts (used by VDOT to perform maintenance) are included in the Cost Data if they are charged to county, route and asset but they are not included in the Cost Data if they are charged to a cost center, such as the Public- Private Transportation Act (PPTA) cost center which includes the VMS contract. Cost of maintenance performed by in-house forces (i.e. self-performed work) is included in the Cost Data.

4.1 APPLICATION OF THE FRAMEWORK TO THE "BRIDGES" ELEMENT OF THE LEVEL-OF-SERVICE COMPONENT FOR THE MAINTENANCE PERFORMED BY TRADITIONAL METHODS

This section presents the application of the framework developed in **Chapter 3** to the 215 miles of Virginia's Interstate where maintenance is performed on a traditional basis by VDOT (i.e. VDOT Control Sections for the Maintenance Rating Program (MRP) project). Such application of DEA is focused on the "Bridges" element of the level-of-service component, only for the years in which bridge condition and cost data are available. The approaches and concepts that are parts of the framework developed in **Chapter 3** are utilized for the purposes of this section. This section, first, presents the comprehensive lists of variables and DMUs that have initially been decided to be included in the DEA study. Then, it presents the final lists of variables and DMUs that are decided to be used in actual implementation of DEA and discusses the reasons behind the modification of the comprehensive lists to such final lists. After that, it illustrates the data preparation (gathering, mining, cleaning, and conversion/rearrangement) process performed to make such data ready to be used in the DEA model. Then, it discusses the reasons for the selection of the particular DEA model that is used in this study along with final data refinements and presents the results of the application of such model to the prepared data for the "Bridges" element (of the level-of-service component) for VDOT Control Sections. Finally, it presents the conclusions, findings gathered from the further analyses, and effects of uncontrollable factors on the bridge maintenance efficiency of units under investigation.

It is important to note that this section possesses a full implementation example (for the "Bridges" element of the level-of-service component) of the comprehensive highway maintenance efficiency framework developed in **Chapter 3**.

4.1.1 Comprehensive Lists of Variables and DMUs

This section is divided into two parts. First part presents the most comprehensive list of variables that can be used in the DEA model for the maintenance of the "Bridges" element of the level-of-service component. The second part presents the issues with the selection of DMUs to be included in such DEA model and presents the information for the identification/location of those DMUs.

4.1.1.1 Comprehensive List of Variables

Based on the discussion presented in **Section 3.7.2**, it is decided to utilize the Banker and Morey (1986) (Banker and Morey 1986a) approach as discussed in **Section 3.7.1.1.2** to deal with uncontrollable factors for the "Bridges" element of the level-of-service component as presented in **Table 3.2**. Therefore, such uncontrollable factors are decided to be treated as uncontrollable variables in the DEA models. Thus, the uncontrollable factors presented for the "Bridges" element in **Table 3.2** become uncontrollable input variables due to their effects on the maintenance of such element. **Table 4.1** presents the most comprehensive list of input and output variables that can be used in the DEA model for the maintenance of the "Bridges" element of the level-of-service component. It is important to note that such table is a subset of **Table 3.2** (with the sole difference that the uncontrollable factors in **Table 3.2** are now the uncontrollable input variables in **Table 4.1**) which was developed in **Chapter 3** by using the process definition and the approaches to develop the list of controllable variables and uncontrollable factors as presented in the same chapter.

Table 4.1: The Comprehensive List of Input and Output Variables for the DEA Model of the Maintenance of the "Bridges" Element of the Level-of Service Component

Component	Element	Variable Name		Variable Explanation and/or Metric
Level of Service	Bridges	INPUTS	(1) Cost for maintaining the bridges	$
			(2) Climate- Effect on deterioration of the bridges	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles
			(3) Climate- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity- availability of crews)	Yearly precipitation amounts (inches)
			(4) Traffic- Effect on deterioration of the bridges	Equivalent Single Axle Load (ESAL)
			(5) Traffic- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity- availability of crews)	Average Daily Traffic (ADT)
			(6) Snow treatment- Effect on deterioration of the bridges	count (of chloride applications)
			(7) Speed limit- Effect on deterioration of the bridges	miles/hr
			(8) Accidents damaging bridges- Effect on deterioration of the bridges	count (of accidents damaging bridges)/year
			(9) Subsurface conditions- Effect on deterioration of the bridges	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)
			(10) Thickness of the deck- Effect on deterioration of the bridges	Inches
			(11) Type of paved lanes-Effect on deterioration of the bridges	Concrete, Asphalt (give a grade based on the effect)
			(12) Type of paved lanes- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Concrete, Asphalt (give a grade based on the effect)
			(13) Span Information- Effect on deterioration of the bridges	Span length, span type etc…
			(14) Age of bridges- Effect on deterioration of the bridges	Years
			(15) Location- Effect on deterioration of the bridges	Above a creek, major river, highway, railroad etc… (give a grade based on effect)
			(16) Location- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Above a creek, major river, highway, railroad etc… (give a grade based on effect)
			(17) Terrain- Effect on deterioration of the bridges	Slope, Elevation, and Orientation
			(18) Terrain- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Slope, Elevation, and Orientation
			(19) Total Area Served- Effect on maintenance efforts performed for meeting Level of Service requirements for the bridges (productivity of crews)	Sum of the area (Deck Length * Deck Width) of all of the bridges within the DMU
		OUTPUTS	(20) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Decks)	Deck Rating_{t1}-Deck Rating_{t0}
			(21) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Superstructures)	Superstructure Rating_{t1}-Superstructure Rating_{t0}
			(22) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Substructures)	Substructure Rating_{t1}-Substructure Rating_{t0}
			(23) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their Slope/Channel Protections)	Slope/Channel Protection Rating_{t1}-Slope/Channel Protection Rating_{t0}
			(24) Change in the condition of the Bridges (which are maintained to meet the Level of Service requirements with respect to their other parts such as joints, paint etc…)	X Rating_{t1}-X Rating_{t0}
			(25) Air Pollution	Emission amounts
			(26) Water Pollution	Emission amounts
			(27) Noise Pollution	Emission amounts

: The reason for computing the difference of ratings at time "t1" and "t0" is explained in Section 4.1.3 of this chapter. (green-shaded cells, rows 20–24)

4.1.1.2 Comprehensive List of DMUs

Given the discussion presented in **Section 2.5.3.2** and **Section 3.6** with respect to the discriminating power of DEA, and given the fact that the DEA model will be applied for an approximately 430 directional miles of Interstate portion which is maintained on a traditional basis (the VDOT Control Sections for which condition data is available to Virginia Tech), initially it was decided to define the DMU as a 10-mile-long highway section of this 430 mile portion in an effort to maximize the number of DMUs while assigning a meaningful size to such DMUs as far as DEA is concerned. Such a definition would yield to 43 DMUs, which is likely to be a sufficient number (as far as the discriminating power of DEA is concerned) once the comprehensive list of variables is refined as discussed in **Section 3.6**. However, defining a DMU as a 10-mile-long highway section presented a major obstacle in the data gathering process. It was indicated by VDOT that the data for arguably the most important variable, the cost variable, cannot be gathered at a 10-mile-long highway section level as VDOT's financial management system (FMS II[7]) keeps track of the costs at the county level for each Interstate. Given this restriction, the definition of DMUs was changed to be the counties of Virginia (that encompass the portions of the interstate system that are under investigation), which is the minimum size of a DMU at which the cost data is available. **Table 4.2** presents the identification/location information of the counties that encompass the VDOT Control Sections.

As a final note, since the cost data that is provided by VDOT is in VDOT's fiscal years, all analysis will be performed on a fiscal year time frame basis. This means that all input-output data should be yearly data covering the time span of VDOT's fiscal years, i.e. July 1st of the previous year to June 30th of the current year.

---

[7] FMS II: is a relatively new financial management system that has the potential to provide cost data at levels of detail previously unavailable to VDOT (JLARC 2001).

Table 4.2: The Comprehensive List of DMUs for the DEA Model of the Maintenance of the "Bridges" Element of the Level-of-Service Component

MRP* Section	Route	County (DMU)	Route Relative		Closest County Relative	
			Begin Milemarker	End Milemarker	Begin Milemarker	End Milemarker
5-VDOT Control	I-95	Caroline	108.87	116.87	7.54	15.54
5-VDOT Control	I-95	Spotsylvania	116.87	132.40	0.00	15.53
6-VDOT Control	I-66	Fauquier	14.66	36.59	0.00	21.93
7-VDOT Control	I-64	Henrico	175.70	187.46	0.00	11.76
7-VDOT Control	I-64	Henrico	190.66	204.6[&]	14.96	28.90
8-VDOT Control	I-64	Alleghany	0.00	40.99	0.00	40.99
8-VDOT Control	I-64	Rockbridge	40.99	57.23	0.00	16.24
9-VDOT Control	I-64	Nelson	99.96	101.32	0.00	1.36
9-VDOT Control	I-64	Albemarle	101.32	131.16	0.00	29.84
10-VDOT Control	I-81	Roanoke	130.59	147.45	0.00	16.86
11-VDOT Control	I-581	Roanoke	0.00	6.64	0.00	6.64
12-VDOT Control	I-81	Augusta	206.04	237.51	0.00	31.47

*: MRP- Maintenance Rating Program- The program that is used by Virginia Tech to evaluate the Interstate maintenance performance in terms of effectiveness.
&: In January 2006, this Milemarker was changed to 200.9 as a private contractor started to undertake the maintenance of a portion of the Interstate beginning at milemarker 200.9.

4.1.2 Final Lists of Variables and DMUs to be included in the DEA Model

This section presents the final lists of variables and DMUs that are decided to be used in actual implementation of DEA and discusses the reasons behind the modification of the comprehensive lists (presented in the previous section) to such final lists. First part of this section deals with the input and output variables and the second part deals with the DMUs.

4.1.2.1 Final List of Variables to be included in the DEA Model

As was underlined in **Section 3.6**, once the initial comprehensive list of input and output variables is developed, such list should be reinvestigated and refined to include only the most

relevant and important variables to be able to increase the discriminating power of DEA models. As presented in **Table 4.1**, the comprehensive list for the "Bridges" element has a total of 27 variables. Considering the number of DMUs presented in **Table 4.2**, using so many variables in the DEA model would definitely preclude the model to discriminate between efficient and inefficient DMUs. The refinement process for such list is discussed below.

On the outputs side, the output variables air pollution (labeled as 25 in **Table 4.1**), water pollution (26), and noise pollution (27) can directly be removed from the list. They are different from the common concept of the output of a process as they are undesirable outputs (i.e. the less of them, the better). From an efficiency point of view, the inclusion of them in the DEA model (including undesirable outputs in DEA models is a rather new concept in the DEA literature as discussed in **Section 3.3**) is not critical but nonetheless given the availability of data, they should be included in the model. For our case, they will be disregarded since (i) no data is available for those undesirable outputs and (ii) those variables are not deemed critical as far as their effect on overall efficiency of a DMU is concerned. The only data that has traditionally been collected for the bridges is for the Deck (20), Superstructure (21), Substructure (22), and Slope/Channel Protection (23) conditions. Such data is collected as a part of the Federally-mandated *National Bridge Inventory* (NBI[8]) program and thus is well-documented (FHWA 1995). However, cost data with respect to the maintenance of Slope/Channel Protection (23) is not made available to Virginia Tech. Thus, such variable also needs to be removed from the analysis. The data with respect to other parts of the bridge such as joints, paint, and etc. (24) is never collected as such information is mostly covered by the information collected for the abovementioned four components. Thus, such output variable can also be removed from the list. The remaining three output variables (20, 21, and 22) can be combined into one variable, "Change in Overall Bridge Condition", by using a weighting scheme that is developed and implemented by Virginia Tech as agreed by VDOT. Such weighting scheme is presented in **Section 4.1.3**. As a result of all of the refinements discussed within this paragraph, only one single output, "Change in Overall Bridge Condition", remains to be included in the DEA model for the maintenance of the "Bridges" element as shown in **Table 4.4**.

---

[8] Based on the NBI inspections, each element of the bridge is assessed by the inspectors following the guidelines provided by the NBI Program and given a rating ranging from 0 to 9, latter corresponding to the best condition (Piñero 2003).

On the inputs side, only the cost variable (1) is a controllable variable (i.e. directly controllable by the decision maker, i.e. VDOT's Asset Management Division). All of the remaining inputs (2-19) are uncontrollable variables representing the following four types of effects on the highway maintenance process:

(i) Environmental effects on the deterioration of the bridges (Variables 2, 9, 15, and 17)

(ii) Environmental effects on the maintenance efforts (Variables 3, 16, and 18)

(iii) Operational effects on the deterioration of the bridges (Variables 4, 6, 7, 8, 10, 11, 13, and 14)

(iv) Operational effects on the maintenance efforts (Variables 5, 12, and 19)

Dadson, by utilizing the regional divisions used by Virginia State Climatology Office and reviewing the climatic data, divided the state of Virginia into six environmental regions as depicted in **Figure 4.1**. This was achieved by grouping together the districts that have similar terrain and climatic conditions such as rainfall, snowfall, humidity, temperature, and freeze-thaw cycles (Dadson 2001).

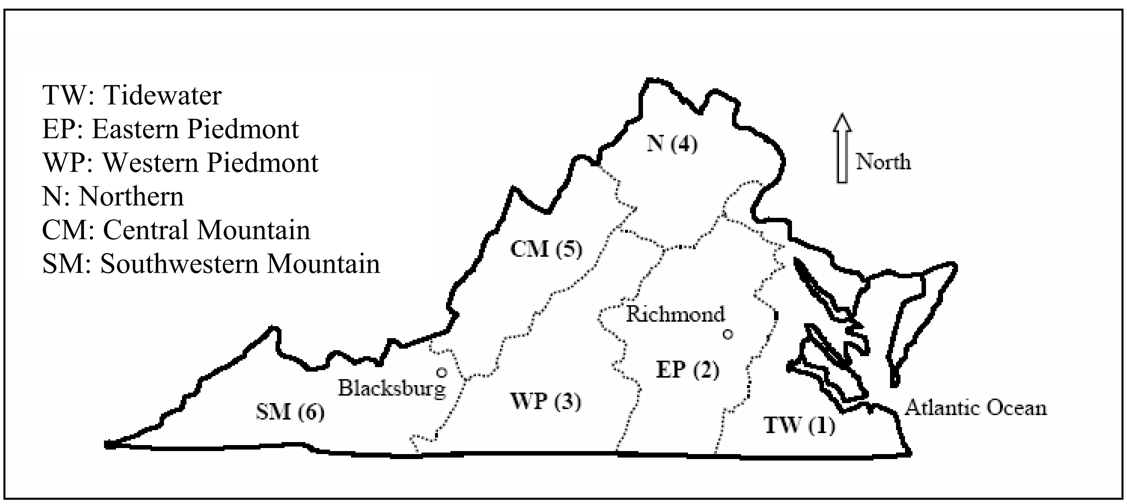


Figure 4.1: Environmental Regions of Virginia (Dadson 2001, p.30)

After the environmental regions were assigned, a methodology was developed to determine the effects of such environmental regions on the mean service life estimates of the concrete deck and steel girder paint. The main purpose of the study was to develop an environmental classification that depicts the relative rate of deterioration of bridge parts (i.e. deck and steel girder paint) in different regions of the state of Virginia. This was achieved by performing statistical analyses on the bridge inspection field data collected for the bridge parts and protective systems by bridge inspectors (Dadson 2001). The main assumption of the study was that any deterioration on the bridge parts could be attributed to the environmental effects (i.e. terrain and climatic conditions) that are defined in the study. By this assumption, the effect of actual maintenance expenditures (i.e. Variable 1 in **Table 4.1**) was disregarded as the variation in that was deemed to be negligible for each bridge across the state of Virginia (Dadson et al. 2002). The study defines two deterioration levels based on the Average Daily Traffic (ADT) values (i.e. Level 1 deterioration is for ADT<5000 and Level 2 deterioration is for ADT>5000) and then by performing the statistical analyses on the bridge condition data, assigns each environmental region a severity grade (Low, Medium, or Severe) based on each's effect on the deterioration of the bridge parts in the given deterioration level (i.e. Level 1 and Level 2). As an example, the findings of the study for the concrete decks are presented in **Table 4.3** (Dadson 2001).

Table 4.3: Effect of Environmental Region on the Deterioration of the Concrete Decks

	Effect of Environmental Region on the Deterioration of the Concrete Deck	
Environmental Region	**Level 1 (ADT<5000)**	**Level 2 (ADT>5000)**
Southwestern	Medium*	Low
Tidewater	Medium*	Medium
Central Mountain	Medium*	Medium
Western Piedmont	Medium*	Medium
Eastern Piedmont	Medium*	Medium
Northern	Medium*	Severe

*: The study by Dadson indicates that the statistical analyses for Level 1 did not yield to significant pairwise comparisons and thus for the sake of completeness, this document assigns each environmental Region a "Medium" effect.

This study aims to use the results of Dadson's research to combine 16 input variables (Variable 2- Variable 4 and Variable 6-Variable 18) into a single input variable that represents all of those to a great extent. It can be asserted that the effect (Low, Medium, or Severe) of different environmental regions of Virginia on the deterioration on the bridge parts can not be attributed to only the differences in their terrain and climatic conditions which were used to define such environmental regions in the first place. Such effect, in fact, should be resulting from a combination of effects represented by all of the input variables mentioned above as none of those variables is accounted for in the statistical analyses performed to reach the results of the research. Thus, in essence, the effect assigned to an environmental region (Low, Medium, or Severe) within Dadson's study represents the combination of effects of Variable 2- Variable 4 and Variable 6-Variable 18 as defined in this study. This fact can be used to combine all of those variables into one variable, "Regional Effect Variable" namely, which in fact represents the environmental effect classification developed by Dadson. Given this combination, the only remaining input variables to consider are Variable 1, Variable 5, and Variable 19. Variable 1 should be kept as is since it represents the total maintenance expenditures made within a DMU (i.e. Virginia's county). Similarly, Variable 19 should be kept as is since it represents the total area of bridges maintained within a DMU. The only factor that was accounted for in Dadson's statistical analyses was ADT (which is the metric for Variable 5 within this study), which was used to define the Level 1 and Level 2 deteriorations as discussed above. Thus, Variable 5 will be used to decide on which "Regional Effect Variable" (i.e. either the value in Level 1 column or Level 2 column in **Table 4.3**) to assign to the DMU according to its location within Virginia. Thus, even though Variable 5 is not directly included in the DEA study as an input variable, it is still needed to be used indirectly to account for the differences in ADT of the DMUs.

Due to all of the variable refinements presented in the preceding paragraphs, the final list of variables to be used in the DEA model for bridges contains 3 inputs and 1 output as presented in **Table 4.4**. It is important to note that, as was discussed earlier, the study by Dadson determined the effects of environmental regions on the mean service life estimates of the **deck** and **steel girder paint** parts of a bridge structure. The study's reasoning for investigating only those two parts is that they are exposed to the effects of environment much more than the other parts of the bridge (Dadson et al. 2002). With a similar logic, this research aims to use the findings of Dadson's study with respect to the **deck** to assign the value of the "Regional Effect Variable" to respective DMUs as the deck is the main part of the bridge that is exposed to majority of the environmental and operational effects represented by the variables that are listed in **Table 4.1**.

Table 4.4: Final List of Variables to be used in the DEA Model for Bridges

Variable Type	Variable Name	Variable Explanation and/or Metric
Input	Cost for Maintaining the Bridges	$
	Regional Effect Variable	A grade (Low, Medium, or Severe) based on the effect (using the results of Dadson's study)
	Total Area Served	Sum of the area (Deck Length* Deck Width) of all of the bridges within the DMU
Output	Change in Overall Bridge Condition	Bridge Rating$_{t1}$-Bridge Rating$_{t0}$

: The reason for computing the difference of ratings at time "t1" and "t0" will be explained in Section 4.1.3 of this chapter.

4.1.2.2 Final List of DMUs to be included in the DEA Model

Even though **Table 4.2** presents all of the counties that encompass the VDOT Control Sections, not all of the counties listed there can be included in the DEA model developed in this research. Following are the counties that will be excluded from this research:

(i) **Caroline County**: As can be seen in **Table 4.2**, the portion of VDOT Control Section 5 which falls within the limits of this county (from Milemarker 108.87 to Milemarker 116.87) does not entirely cover this county. Thus, the bridge condition information gathered for the MRP through NBI only covers the bridges that fall within the Milemarkers 108.87-116.87. However, the cost data that is provided by VDOT[9] is for the entire Caroline County (i.e. from Milemarker 101.33 to Milemarker 116.87), and thus covers the portion of Caroline County (from Milemarker 101.33 to Milemarker 108.87) for which no bridge condition data is available. As there is no way to apportion this cost data to the desired portion of the county for which bridge condition data is available, it is decided to exclude the Caroline County from the analysis as inclusion of it is prone to introduce a substantial amount of error in the efficiency evaluations.

(ii) **Nelson County**: No cost data for this county is provided by VDOT as only a very small portion of this county encompasses the VDOT Control Section 9. Even if there was cost data for this county, it would be meaningless to try to calculate the Interstate bridge maintenance efficiency of a county which only has 1.36 miles of

[9] VDOT keeps track of and thus provides its cost data for each Interstate at the county level.

Interstate within its jurisdiction. So, Nelson County is excluded from the DEA model.

(iii) **Roanoke County for VDOT Control Section 11**: For this county, there is no bridge condition data available for consecutive fiscal years. As will be presented in **Section 4.1.3** in detail, condition data of consecutive fiscal years is needed to be able to use condition data in the DEA model. Given this, the portion of the Roanoke County which encompasses VDOT Control Section 11 is excluded from the analysis. It is important to note that the Roanoke County is still a part of the analysis as it also encompasses VDOT Control Section 10 for which both bridge condition and cost data are available.

Table 4.5 presents the final list of DMUs that are decided to be included in the DEA model for bridges based on the discussion presented above.

Table 4.5: Final List of DMUs to be included in the DEA Model for Bridges

DMU Name
Albemarle
Alleghany
Augusta
Fauquier
Henrico
Roanoke
Rockbridge
Spotsylvania

4.1.3 Data Preparation Process

This section presents the steps taken for the data preparation process that is performed to obtain data and then to make such data ready to be used in the DEA model for bridges. These steps are data gathering, data mining, data cleaning, and data conversion/rearrangement.

4.1.3.1 Step 1- Data Gathering

Data gathering efforts were mainly focused at obtaining the following: (i) Bridge Condition Data, (ii) Bridge Area Data, (iii) Bridge ADT data, and (iv) Bridge Cost Data.

Virginia Tech already possesses Bridge Condition Data as such was gathered for MRP for the fiscal years 2002, 2003, 2004, and 2005. Such data has consistently been provided to

Virginia Tech by the personnel in VDOT's Asset Management Division (AMD). It has been acknowledged by VDOT's AMD that such data is gathered by VDOT as a part of the Federally-mandated NBI process and thus is well-documented. It can be asserted that the Bridge Condition Data is very reliable as it is provided to Federal Highway Administration and kept in its database to be used to establish investment requirements; to develop data summaries at the national level for reports to Congress, and to respond to inquiries from entities such as Congress, the National Transportation Safety Board, and others (ESRI 2004). The database that contains the "Bridge Condition Data" also has the data for (i) the area of the bridges (i.e. "Bridge Area Data"- information related to the Total Area Served input variable to be used in the DEA model) and (ii) ADT on the bridges (i.e. "Bridge ADT Data"- information to be used to decide on which Regional Effect Variable (i.e. either the value in Level 1 column or Level 2 column of **Table 4.3**) to assign to the DMU).

Cost Data has also been provided by VDOT's AMD. According to the statement made by Dennis Domayer from VDOT's AMD, "*The information was derived from FMS II using the VGLN50 reports Program 6040100 for the districts involved. Drills were run by route and then by county and then by activity. The original request was to extract the 7XXXX series of activity codes and omit all other activity codes*" (Domayer 2006). In further communication with the personnel from VDOT's AMD, the following information have been gathered about the Cost Data (Domayer 2006):

- The Cost Data includes only routine/ordinary maintenance (i.e. preventive maintenance and restorative maintenance) expenditures. No rehabilitative maintenance (i.e. reconstruction, and major repair/replacement) expenditure is included.
- No district or central office overhead is included in the Cost Data.
- Incident response expenditures are included in the Cost Data if such are coded to the activity codes that are extracted. Snow removal expenditures are captured in the 6XXXX series of activity codes and thus are not included in the Cost Data.
- All labor expenditures (including the labor burden) are included in the Cost Data if they are coded to the activity codes that are extracted.
- Costs of the private contracts (used by VDOT to perform maintenance) are included in the Cost Data if they are charged to county, route and asset but they are not included in

the Cost Data if they are charged to a cost center, such as the Public- Private Transportation Act (PPTA) cost center which includes the VMS contract. Cost of maintenance performed by in-house forces (i.e. self-performed work) is included in the Cost Data.

4.1.3.2 Step 2- Data Mining

The raw data obtained for the bridge condition had to be mined in terms of date and the structures inspected to be able to obtain the portion of it which is to be included in the analysis. Such raw data contained inspections made that are not within the fiscal years of 2002, 2003, 2004, and 2005 (i.e. the years that are under investigation). Thus, data mining had to be performed to extract the data belonging to the fiscal years that are under investigation from such raw data. The raw data also contained condition data for the bridges that are maintained by cities, towns, or counties that are not within the list of counties presented in **Table 4.5**. Further data mining was performed to extract from the raw data only the bridges that are maintained by the counties that are listed in **Table 4.5**. Finally the raw data contained the condition data for culverts. As there is no cost data available for culverts, and as this study focuses only on the bridges, data mining was performed to remove the culverts from the raw data. To illustrate an example of the results of this data mining process, **Table 4.6** presents the Fauquier County's Bridge Condition Data as extracted from the raw data for the fiscal year 2002. The codes that are used within the table are explained right below the table. It is important to note that the bridge condition ratings used for the NBI range between 0 (worst condition) and 9 (best condition) (FHWA 1995). It is also important to note that regardless of the actual location of the bridge (i.e. whether it is an overpass above the interstate or a bridge on the interstate), any bridge identified as being maintained by the county is included in the Bridge Condition Data to be used in this study. This is mainly due to the fact that once a bridge associated to the interstate (i.e. whether it is an overpass above the interstate or a bridge on the interstate) is maintained by a county, the cost to maintain such bridge is included in the Cost Data provided by VDOT's AMD as such cost is charged to that county.

The data obtained for the cost was already in the desired date range and covered only the Interstates and counties that are under investigation. As a matter of fact, as Virginia Tech was very specific in terms of what it wants for the Cost Data when such request was made to

VDOT's AMD, all data mining was performed by VDOT's AMD. Given this, no further data mining was needed to be performed for the Cost Data. **Table 4.7** presents Fauquier County's Cost Data for fiscal years 2002, 2003, 2004, and 2005 with respect to bridges, as received from VDOT's AMD.

Table 4.6: Fauquier County's Bridge Condition Data for Fiscal Year 2002

brkey	county _id	struc _num	routenum	milepost	featint	facility	area	adttotal	suprating	subrating	dkrating	chanrating	culvrating	inspdate
7216	030	2022	00066	35.22	RTE 55	EBL ROUTE 0066	10495.03	16709	8	7	8	N	N	9/19/2001
7218	030	2023	00066	35.43	RTE 55	WBL ROUTE 0066	10495.03	15275	7	7	8	N	N	9/19/2001
7193	030	2003	00066	31.67	ROUTE 245	EBL ROUTE 0066	9139.91	16709	7	7	7	N	N	10/24/2001
7191	030	2002	00066	31.88	ROUTE 245	ROUTE 0066_WBL	9139.91	13500	7	7	7	N	N	10/24/2001
7151	030	1041	00066	28.66	RTE 66	WINCHESTER RD.	38404.91	33001	7	7	7	N	N	2/19/2002
7228	030	2044	00066	33.15	BROAD RUN & RTE 698	EBL ROUTE 0066	25574.44	16709	7	5	8	8	N	6/10/2002
7230	030	2045	00066	33.40	BROAD RUN & RTE 698	WBL ROUTE 0066	26972.81	15275	7	5	8	7	N	6/11/2002
7227	030	2043	00066	32.51	RELOCATED BROAD RUN	EBL ROUTE 0066	9485.90	16709	6	5	7	7	N	6/12/2002
7226	030	2042	00066	32.70	RELOCATED BROAD RUN	WBL ROUTE 0066	9485.90	15275	6	6	7	7	N	6/12/2002
7222	030	2031	00066	22.16	RELOCATED RTE 55	EBL ROUTE 0066	8113.02	16859	7	5	7	N	N	6/27/2002
7220	030	2030	00066	22.31	RELOCATED RTE 55	WBL ROUTE 0066	8413.50	13000	7	5	7	N	N	6/27/2002

brkey: This is a unique identification number used by FHWA that represents the structure identifier.
county _id: Virginia's county identification number as used by VDOT.
struc _num: VDOT structure number. This number is unique only in a particular county.
featint: Description of the features intersected by the structure.
facility: Facility being carried by the structure.
area: Structure Length*Structure Width of deck out to out (square feet)
adttotal: Recent Average Daily Traffic
suprating: Superstructure General Condition Rating
subrating: Substructure General Condition Rating
dkrating: Deck General Condition Rating
chanrating: Slope/Channel General Condition Rating
culvrating: Culvert General Condition Rating
inspdate: Most recent inspection date
N: Not applicable

Table 4.7: Fauquier County's Cost Data with respect to Bridges

Route	County	Asset	FY 2002	FY 2003	FY 2004	FY 2005
I0066	Fauquier	500 - Deck	$1,242.61	$660.24	$158,027.02	$106,343.57
		520 - Superstructure	$39,803.41	$27,997.40	$50,716.87	$33,559.12
		540 - Substructure	$0.00	$1,420.91	$76,722.01	$109,869.14
		Total	41,046.02	30,078.55	285,465.90	249,771.83

4.1.3.3 Step 3- Data Cleaning

After the data mining process, the resulting data was investigated for errors and inconsistencies. Such investigation identified some problems in the Bridge Condition Data. These problems and the remedies applied to resolve such problems are listed below:

- **Milemarker Inconsistency**: Some records had inconsistent milemarker information. For example, as listed in **Table 4.2**, Fauquier County is located between the milemarkers 14.66 and 36.59 on Interstate 66. However, there were a number of records, which were identified with the county _id "030" (Fauquier County) but which also had milemarker information indicating that they are located completely out of the abovementioned milemarkers. Such records were removed from the Bridge Condition Data to avoid any inconsistency. The frequency of occurrence of this type of inconsistency was very low and thus did not result in a significant loss of information.
- **Duplicate Records**: Within the Henrico County and for the fiscal years 2004 and 2005, some records were duplicated within the same fiscal year with different ADT information. As a matter of fact, the differences in ADT information were very substantial for all records under question (e.g. 29000 vs. 54000, 96000 vs. 154000, and etc.). To decide on which record to keep and which one to delete, the ADT information of the same bridges for previous fiscal years were investigated. After such investigation, the records that have ADT of similar value to the previous years were kept and others were discarded.
- **Same Bridge with Different Area**s: In all cases except one, the area of a bridge is same within all fiscal years. However in one case within Henrico County, the same bridge had different areas for fiscal year 2003 and fiscal year 2005. For this bridge, the area in fiscal year 2003 is recorded as 10,019 square feet and the area in fiscal year 2005 is recorded as 10,105. To be able to calculate the Total Area Served (as listed in **Table 4.4**) variable for the Henrico County, a single area value for this particular bridge was required. It was decided to use the data from the most current record (10105 square feet) for the purposes of this analysis.
- **ADT Issue**: Within the Alleghany County, for the fiscal year 2005, there were two bridge records whose ADT values are recorded as "0". Since this is an obvious error, those two records were removed from the Bridge Condition Data. It can be asserted that the removal of these 2 records did not result in a significant loss of information.

4.1.3.4 Step 4- Data Conversion/Rearrangement

Once all the impurities in the data had been removed, it was needed to be converted into the format suitable to represent the variables listed in **Table 4.4**. Moreover some rearrangements (e.g. combining data) had to be made in the data to make it meet the structuring requirements of the DEA model. These conversions and rearrangements made in the data are discussed below.

4.1.3.4.1 Converting the "Bridge Cost Data" to Represent the Variable "Cost for Maintaining the Bridges"

4.1.3.4.1.1 Problems with Obtaining the Complete Cost Data

The Cost Data (as described in **Section 4.1.3.1**), in essence, includes the total costs of sub-contracts to VDOT and the direct costs of routine maintenance activities for the self-performed work (i.e. cost of labor, cost of material, and cost of equipment as depicted in **Figure 3.7**). Even though such direct costs constitute a substantially large portion of the total costs for the self-performed work, they do not include items such as district and central office overhead and some other items. **Figure 4.2** illustrates the typical total cost breakdown for the routine maintenance (i.e. preventive maintenance and restorative maintenance) activities for VDOT for the maintenance of the "Bridges" element.

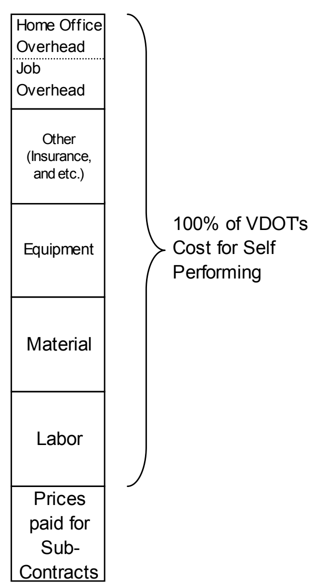


Figure 4.2: Typical Breakdown of Cost to VDOT for Routine Maintenance Activities for the Maintenance of the "Bridges" Element

Table 4.7 presented the cost for VDOT for the routine maintenance of the deck, superstructure, and substructure of the "Bridges" element in a given fiscal year at the county level. These are the cost figures reached when highway maintenance is performed by traditional means. The data in this table may seem as if the one that would directly be used in the DEA models. Nonetheless such data is not complete as the cost figures shown in **Table 4.7**, for the self-performed work, only include the field costs (labor, material, and equipment) and labor burden for performing the maintenance of the "Bridges" element. In other words, those cost figures, for the self-performed work, do not reflect the **total costs** of such maintenance process. This is mainly due to the fact that the cost figures presented in **Table 4.7** do not include the items such as overhead (both home office and job), insurance, cost of capital, cost of idle time, and etc. Moreover, the cost figures presented in **Table 4.7** do not include any administrative costs incurred by VDOT in performing the maintenance the traditional way. It is important to note that the cost of capital is a very important item that should be acknowledged as a resource utilized. At the same time, it is the most difficult to define and measure for an entity (Craig and Harris 1973).

The problems associated with obtaining complete cost information through VDOT's cost management system were recognized in a number of earlier attempts in obtaining such information. For evaluating the cost effectiveness of the Contractor's proposal submitted in 1996, VDOT decided that its own cost for the maintenance of interstate needed to be determined. During this time, VDOT recognized that even though there was a large amount of data in its fiscal systems, actual cost data for specific activities for such an evaluation was not available at the necessary level of detail (JLARC 2001). Later on, in 2000, VDOT tried to determine the cost effectiveness of the same Contract by trying to use the cost data obtained from its Financial Management System (FMS II) which reports expenditures at the county level in several ways that include (i) Charges directly related to asset activities, and (ii) Universal Project Charges (UPC) generally associated with contract activities. Such an effort led to the conclusion that the costs associated with maintenance process can be very difficult to identify, yet VDOT's FMS II has the potential to capture a large portion of expenditures charged for interstate at the county level (VDOT 2000). Nonetheless, when using FMS II, VDOT needs to make some assumptions related to indirect and administrative costs. In fact, it was concluded that the one issue that would create a large amount of difficulty for VDOT in determining its total costs is identifying indirect and administrative costs (JLARC 2001).

If the cost data belonging to VDOT is incomplete, using such incomplete data in the DEA models would result in some unfair comparisons to be made. This is mainly due to the fact that the input variable, the cost, may be underestimated for the counties which have higher costs (that are unaccounted for in the cost figures) than other counties, resulting in a situation in which such counties are portrayed as spending less amount of money than they actually spend. This would not only prevent a fair comparison of the efficiency from being made, but would also undermine the whole purpose of this research of providing VDOT (or any other transportation agency) with a solid decision-making tool. Nonetheless, there is an approach (which possesses some basic assumptions) that can be employed to remedy the situation. Cost data, as enhanced/modified through the use of such approach as discussed in the next section can then be used to provide a fair comparison.

4.1.3.4.1.2 Remedies and Assumptions to Resolve the Cost Data Issue

It can be stated that the main component that is missing from VDOT's cost data is the indirect cost component which includes items such as home office overhead, job overhead, insurance, administrative and similar costs. Within these costs, overhead (home office and job) constitute a very large portion. Therefore, although the total cost figures will never be obtained (as such detailed data is not available from VDOT's AMD), the "almost complete" total cost figures can be calculated for each county if the job (district) and home office (central office) overhead costs are obtained for each county.

A literature review about this issue revealed that VDOT is using a constant percentage rate applied to the direct cost to calculate its total overhead cost. In the cost study performed by de la Garza and Vorster in 2000, such rate for the maintenance expenditures was 4.6% and was provided to researchers by VDOT's Controller Office (de la Garza and Vorster 2000). In a similar study performed in 2002, the very same rate was used. Same study stated that such rate was determined and provided by VDOT's Fiscal Division (VDOT 2002a). Given all of these, it can be asserted that this rate can be used to enhance the cost data and convert it to the "almost complete" total cost as discussed above. The application of 4.6% overhead rate on the Cost Data results in the conversion of it to the cost figures that can be used for the variable "Cost for Maintaining the Bridges".

It is expected that through this cost data enhancement effort, somewhere between 90% and 95% complete cost data is achieved. It is acknowledged that 100% complete cost data can never be achieved. Nonetheless, an "almost complete" cost information is better than no information at all and such information can be used for the purposes of this research and can still provide a fair comparison.

4.1.3.4.2 Rearranging the "Bridge Condition Data" to Represent the Variable "Change in Overall Bridge Condition"

Four different steps of rearrangement had to be performed on the Bridge Condition Data (as described in **Section 4.1.3.1**) to be able to obtain the values that can be used for the variable "Change in Overall Bridge Condition". These steps are as follows:

1) The first rearrangement has something to do with combining data. As a part of the NBI, a specific bridge within a county is inspected every other fiscal year. Thus, within one fiscal year, not every bridge within a county is inspected. Therefore, to be able to get the complete bridge condition information for a county, the condition data for two consecutive fiscal years needs to be combined. This combination makes the time wise unit of analysis two fiscal years but assures that <u>almost all bridges</u>[10] within a county are accounted for. To serve this purpose, the data for fiscal years of 2002 and 2003 (2004 and 2005 likewise) are combined to get a complete picture of condition of bridges within each county. **Table 4.8** illustrates an example of this combination (fiscal years 2002 and 2003) for the Fauquier County.

2) Once the data for two consecutive fiscal years are combined for each county, the condition rating for all individual bridges (with respect to superstructure, substructure, and deck) and the ADT on such individual bridges within that county should be combined and rolled up to the county level as the DMU for this research is the county. To do this, a weighting scheme, which considers the total area of the bridges as weight factors, is used. The main reasons to use the total area of the bridges as weight factors are: (i) the measurements to assign condition ratings to the bridges are performed along

[10] There may be instances in which the condition data for a bridge is missing within two consecutive fiscal years. Nonetheless, combining two consecutive fiscal years of data provides the condition information for almost all bridges within a county.

the total area of the bridges and (ii) ADT is present on the total area of the bridges. **Table 4.9** presents the result of application of such a weighting scheme for the Fauquier County for combined fiscal years of 2002 and 2003; and 2004 and 2005.

Table 4.8: Fauquier County's Bridge Condition Data for Combined Fiscal Years 2002 and 2003

brkey	county _id	struc _num	routenum	milepost	featint	facility	area	adttotal	suprating	subrating	dkrating	chanrating	culvrating	inspdate
7216	030	2022	00066	35.22	RTE 55	EBL ROUTE 0066	10495.03	16709	8	7	8	N	N	9/19/2001
7218	030	2023	00066	35.43	RTE 55	WBL ROUTE 0066	10495.03	15275	7	7	8	N	N	9/19/2001
7193	030	2003	00066	31.67	ROUTE 245	EBL ROUTE 0066	9139.91	16709	7	7	7	N	N	10/24/2001
7191	030	2002	00066	31.88	ROUTE 245	ROUTE 0066_WBL	9139.91	13500	7	7	7	N	N	10/24/2001
7151	030	1041	00066	28.66	RTE 66	WINCHESTER RD.	38404.91	33001	7	7	7	N	N	2/19/2002
7228	030	2044	00066	33.15	BROAD RUN & RTE 698	EBL ROUTE 0066	25574.44	16709	7	5	8	8	N	6/10/2002
7230	030	2045	00066	33.40	BROAD RUN & RTE 698	WBL ROUTE 0066	26972.81	15275	7	5	8	7	N	6/11/2002
7227	030	2043	00066	32.51	RELOCATED BROAD RUN	EBL ROUTE 0066	9485.90	16709	6	5	7	7	N	6/12/2002
7226	030	2042	00066	32.70	RELOCATED BROAD RUN	WBL ROUTE 0066	9485.90	15275	6	6	7	7	N	6/12/2002
7222	030	2031	00066	22.16	RELOCATED RTE 55	EBL ROUTE 0066	8113.02	16859	7	5	7	N	N	6/27/2002
7220	030	2030	00066	22.31	RELOCATED RTE 55	WBL ROUTE 0066	8413.50	13000	7	5	7	N	N	6/27/2002
7224	030	2040	00066	31.89	RELOCATED BROAD RUN	EBL ROUTE 0066	16152.45	16709	7	6	7	7	N	7/17/2002
7225	030	2041	00066	32.10	RELOCATED BROAD RUN	WBL ROUTE 0066	16152.45	14000	7	6	7	7	N	7/17/2002
7189	030	2001	00066	22.86	RT 731	EBL ROUTE 0066	5319.60	16859	6	7	5	N	N	7/18/2002
7187	030	2000	00066	23.01	RTE 731	RTE. I-66 W.B.L.	5319.60	12859	6	6	5	N	N	7/18/2002
7239	030	2054	00066	35.77	RTE 628	RTE.66 EB&WB	9549.16	33418	7	6	7	N	N	8/19/2002
7238	030	2053	00066	36.58	BROAD RUN	RTE.66 EB&WB	20755.11	33418	6	6	6	8	N	10/17/2002
7204	030	2015	00066	18.84	RTE 688	EBL ROUTE 0066	6501.73	16859	6	6	8	N	N	11/1/2002
7206	030	2016	00066	19.00	RTE 688	WBL ROUTE 0066	6501.73	15794	6	6	6	N	N	11/1/2002
7212	030	2020	00066	15.84	RTE 725	EBL ROUTE 0066	5449.34	15745	6	5	8	N	N	11/25/2002
7214	030	2021	00066	15.99	RTE 725	WBL ROUTE 0066	5752.09	14753	6	5	7	N	N	11/25/2002
7408	030	6017	00066	27.35	RTE I 66	FREE STATE RD.	19637.09	40419	7	7	7	N	N	12/2/2002
7208	030	2018	00066	20.13	RTE 724 (RELOCATED)	EBL ROUTE 0066	5787.27	16859	6	6	8	N	N	12/16/2002
7210	030	2019	00066	20.27	RTE 724 (RELOCATED)	WBL ROUTE 0066	6056.44	13000	6	6	8	N	N	12/16/2002
7412	030	6289	00066	24.57	RTES 17, 55 & I 66	ASHVILLE RD.	5973.92	39509	6	6	7	N	N	12/16/2002
7198	030	2011	00066	26.00	ROUTE 732 (RAMEY ROAD)	WBL ROUTE 0066	6069.24	19754	7	4	8	N	N	3/12/2003
7200	030	2012	00066	26.20	ROUTE 732 (RAMEY ROAD)	EBL ROUTE 0066	5622.34	19084	7	4	8	N	N	3/12/2003
7203	030	2014	00066	20.45	SOU. RWY. & GOOSE CREEK	RTE. 66 W.B.L.	12527.73	13000	6	5	5	6	N	6/25/2003
7202	030	2013	00066	20.30	SOU.RWY.& GOOSE CREEK	RTE. 66 E.B.L.	12037.57	16859	6	5	6	6	N	6/26/2003

Table 4.9: The Condition Ratings and ADT for the Bridges within the Fauquier County at the County Level

County	Fiscal Years	Superstructure	Substructure	Deck	ADT
Fauquier	2002 and 2003	6.68	5.90	7.07	21126
	2004 and 2005	6.57	5.69	6.91	20922

3) As the third step, Superstructure, Substructure, and Deck values (as presented in **Table 4.9**) are combined into one value that represents the overall bridge condition of the county (due to the reasons discussed in **Section 2.5.3.2** and **Section 3.6**). This is done by using the weighting scheme that is developed and implemented by Virginia Tech as agreed by VDOT. Such weighting scheme is presented in **Table 4.10** (VT 2006). The results of the application of such a weighting scheme for the Fauquier County for combined fiscal years of 2002 and 2003; and 2004 and 2005 are presented in **Table 4.11**.

Table 4.10: Bridge Weighting Scheme developed by Virginia Tech

Bridge Part	Weight
Superstructure	9.90
Substructure	9.90
Deck	9.83

Table 4.11: Overall Bridge Condition for the Fauquier County

County	Fiscal Years	Overall Bridge Condition
Fauquier	2002 and 2003	6.55
	2004 and 2005	6.39

4) The output of the bridge maintenance process is not the absolute "Overall Bridge Condition" attained at the end of a period (i.e. two consecutive fiscal years). The output is rather the change in the overall bridge condition within a period. This is mainly because the controllable input, i.e. the money spent to perform maintenance on bridges within a period, as well as the uncontrollable inputs, i.e. regional effect and total area served representing the same time period, results in a change of the overall bridge condition within a period as opposed to resulting in the absolute overall bridge condition at the end of a period. For this reason, to be able to calculate the efficiency of the counties for the time period of combined fiscal years of 2004 and 2005, one needs to identify for each county: (i) the expenditures made within that time period, (ii) the total area served within that time period (i.e. the total area of all bridges within the county), (iii) ADT that is present within that time period to identify- (iv) the regional effect within that time period, and (v) the change in the overall bridge condition within that time period. The last item is, in fact, equal to the difference between overall bridge condition at the end of the time period and at the beginning of the time period. For the purposes of this research, for the time period of combined fiscal years of 2004 and 2005, the overall bridge condition at the end of the time period is defined as the Overall Bridge Condition for the combined fiscal years of 2004 and 2005; and the overall bridge condition at the beginning of the time period (which, in essence, is the overall bridge condition at the end of the time period of combined fiscal years of 2002 and 2003) is defined as the Overall Bridge Condition for the combined fiscal years of 2002 and 2003. **Table 4.12** presents the Change in Overall Bridge Condition variable for the Fauquier County which is calculated using this principle.

Table 4.12: Change in Overall Bridge Condition for the Fauquier County

County	Change in Overall Bridge Condition
Fauquier	-0.16

Table 4.13 presents the input and output variables' data in addition to the ADT and the Virginia Environmental Region information for the combined fiscal years of 2004 and 2005 with respect to each county decided to be included in this study. Such data is obtained by performing all the steps discussed within this section (i.e. **Section 4.1.3**). It is important to note that the Regional Effect Variable was assigned to each county by using each county's environmental region in Virginia (as assigned to it based on its location- see **Figure 4.1**), ADT for the combined fiscal years of 2004 and 2005 and Dadson's findings of the effect of environmental regions on the deterioration of concrete deck. As a matter of fact, since the ADT of all counties are greater than 5000, the effect of environmental regions on the deterioration of concrete deck for Level 2 deterioration (the third column in **Table 4.3**) was used. It is also important to note that the value

for the Total Area Served variable represents the total area of all bridges within a county, not the total area of the bridges for which data is available for the combined fiscal years of 2004 and 2005. As discussed in **Footnote 10**, there may be instances in which the combined data for two consecutive fiscal years may be missing one or two bridges that is/are present in a county. Therefore, to be able to get the actual total area of all bridges present in a county, the area data for bridges for all fiscal years (i.e. 2002, 2003, 2004, and 2005) was combined and duplications were removed. Finally, it is important to note that the inflation/deflation cost adjustment as discussed in **Section 3.11.1** is applied to the data since the analysis includes the cost information belonging to different periods (i.e. 2004 and 2005). Thus, the cost figures represented in **Table 4.13** incorporate the adjustments made through the utilization of the values listed for the *Composite Bid Price Index for Highway Construction* as shown in **Table 3.9**.

Table 4.13: Input and Output Variables' Data for the Combined Fiscal Years of 2004 and 2005

County	Fiscal Years	Cost for Maintaining the Bridges	VA Environmental Region	ADT	Regional Effect Variable	Total Area Served	Change in Overall Bridge Condition
Albemarle	2004 and 2005	$755,020	Western Piedmont	19601	Medium	567652	0.00
Alleghany	2004 and 2005	$916,891	Central Mountain	5435	Medium	438939	0.20
Augusta	2004 and 2005	$255,220	Central Mountain	31729	Medium	403882	-0.02
Fauquier	2004 and 2005	$616,329	Northern	20922	Severe	345707	-0.16
Henrico	2004 and 2005	$1,267,821	Eastern Piedmont	68366	Medium	731659	-0.11
Roanoke	2004 and 2005	$12,517	Central Mountain	29283	Medium	217398	-0.22
Rockbridge	2004 and 2005	$154,862	Central Mountain	6251	Medium	289260	0.03
Spotsylvania	2004 and 2005	$1,132,980	Eastern Piedmont	60386	Medium	157985	0.40

4.1.4 DEA Model Selection, Final Refinements in Data and Results of DEA

Based on the fact that the Constant Returns to Scale (CRS), which is a special case of the Variable Returns to Scale (VRS), is not that frequently encountered in processes, it can be asserted that the VRS approach is appropriate for the shape of the production possibility set of the inputs and output for the bridge maintenance process as presented in **Table 4.4**. Thus, it is decided to use the BCC formulation (the formulation with the convexity constraint which is used for the processes which experience VRS) for the DEA model of this study. It is also necessary to decide on the orientation (i.e. input oriented or output oriented) of the model once the type of the model is selected. As discussed in **Section 3.8,** ideally this decision is made based on the dynamics of the process that is analyzed and the choice of the decision makers to seek either input reductions or output increases in the process. However for this study, the decision for the orientation of the model is not based on the decision makers' choice, bur rather it is based on the necessity to address the issue of zero and negative values for the output variable. As can be seen in **Table 4.13**, there is 1 DMU whose output value is zero and there are 4 DMUs whose output values are negative[11]. However the original formulations of DEA (CCR and BCC) require all input and output values to be positive (Pastor 1996). To overcome the issue of non-positive data, one can transform the variable which has non-positive values into another variable for all DMUs in the data set. This can be done by adding a value larger than the most negative value to the original values of all DMUs. However if one is to use BCC model; and the negative values are on the output side (the case within this study), such transformation can be made only if the input oriented model is used. In other words, the BCC input oriented model is output translation invariant (i.e. an affine transformation of data can be performed with no impact in the DEA efficiency results). Similarly the BCC output oriented model is input translation invariant (Pastor 1996). Given all of these, the issue of non-positive values in the "Change in Overall Bridge Condition" variable can be addressed by adding 0.23 (a value which is larger than absolute value of the smallest negative value, -0.22, in the data set) to the output values of all DMUs to make sure that all values to be used in the DEA model are positive. However this requires the input oriented model to be used. Therefore, the model to be used in this study is input oriented BCC model. This transformation is made for the values of the variable "Change in Overall Bridge Condition" for all the counties; and newly formed variable is named as the "Modified Change in Overall Bridge Condition".

Another refinement that needs to be made in the data is for the "Total Area Served" variable. As can be seen in **Table 4.4**, this is an input variable. However, keeping the values of every other input variable the same, an increase in the value of this variable is likely to result in a decrease in the output variable's (Modified Change in Overall Bridge Condition) value as it will be harder to maintain a larger area of bridge at the same quality with the same amount of expenditures. However, in a DEA model, input variables should be defined such that an increase in the defined input variables should be accompanied by an increase in the output variables. This is referred to as the isotonicity principle (Thanassoulis 2001). To avoid the cases in which non-isotonic inputs are present, the literature suggests subtracting the non-isotonic input from a large

[11] This means that although resources have been allocated to such DMUs within the combined fiscal years of 2004 and 2005, no improvement in the overall condition of bridges within them is obtained. Moreover, their deteriorations have been in such a rate that they have ended up being in a worse condition at the end of the combined fiscal years of 2004 and 2005 than what they were at the beginning of the combined fiscal years of 2004 and 2005.

positive number or dividing it into a number so that the larger the non-isotonic input, the lower the transformed input level used within the model (Thanassoulis 2001). A study by Scheel (2001) comparing different approaches that are used to deal with non-isotonic variables identified that the approach which suggests using the multiplicative inverse of the non-isotonic variables in DEA models is the most restrictive one in the sense that it results in a less number of efficient DMUs (Scheel 2001). Given the results of this study, in an effort to be on the conservative end, this research uses the multiplicative inverse approach to address the non-isotonicity issue. It is important to note this approach is also employed by Golany and Roll (1989); Athanassopoulos and Thanassoulis (1995); and Athanassopoulos (1998) in their respective research (Athanassopoulos 1998; Athanassopoulos and Thanassoulis 1995; Golany and Roll 1989). Therefore, to resolve the non-isotonicity issue inherent in the "Total Area Served" variable, the values of that variable for each county is divided to one (i.e. value's multiplicative inverse is calculated). By this transformation, a direct proportion between this input variable and the output variable is established (i.e. larger the input, larger the output). The newly formed variable is named as the "DMU_{TAS}".

As the final refinement, the qualitative values in the "Regional Effect Variable" as presented in **Table 4.13** need to be quantified. This is mainly because qualitative variables need to be assigned numerical values to be used in the mathematical evaluation of efficiency as used in DEA. The common practice to perform this is to find some measurable surrogate variable which possesses a known relation to the varying levels of the qualitative variable (Golany and Roll 1989). This method cannot be applied to the "Regional Effect Variable" as such surrogate variables cannot be found. Nonetheless, by introducing a simple, yet valid assumption, the qualitative "Regional Effect Variable" can be transformed to a quantitative variable. This assumption states that the difference between the severity grades (Low, Medium, or Severe) established by Dadson to define the effect of environment on the deterioration of bridge parts is the same, i.e. 1 unit. With this assumption, the grades "Low", "Medium" and "Severe" can be assigned a numerical value that keeps the severity relationship between them the same as what is reflected in the qualitative definition. Since the "Regional Effect Variable" is an input variable, the isotonicity issue discussed in the preceding paragraph needs to be taken into consideration as well while assigning such numerical values (i.e. the larger numerical value of this variable should result in a larger value for the variable "Modified Change in Overall Bridge Condition").

Given this, and for the purposes of this study, "Low" grade is assigned the numerical value "3", "Medium" grade is assigned the numerical value "2", and "Severe" grade is assigned the numerical value "1". The newly formed quantitative variable is named as the "DMU $_{\text{REGIONAL EFFECT}}$".

Table 4.14 presents the final refined values for the input and output variables for each county, as transformed to the formats suitable to be used in the input oriented BCC model for "Bridges".

Table 4.14: Data to be used in the Input Oriented BCC Model for "Bridges"

	Input Data			Output Data
County	Cost for Maintaining the Bridges	DMU $_{\text{REGIONAL EFFECT}}$	DMU $_{\text{TAS}}$	Modified Change in Overall Bridge Condition
Albemarle	$755,020	2	0.00000176	0.23
Alleghany	$916,891	2	0.00000228	0.43
Augusta	$255,220	2	0.00000248	0.21
Fauquier	$616,329	1	0.00000289	0.07
Henrico	$1,267,821	2	0.00000137	0.12
Roanoke	$12,517	2	0.00000460	0.01
Rockbridge	$154,862	2	0.00000346	0.26
Spotsylvania	$1,132,980	2	0.00000633	0.63

As discussed earlier, *Frontier Analyst* is the software package that is chosen to be used to solve the DEA models developed in this research as it possesses the most professional user interface with the added benefit of numerous visual displays. Once the software is loaded with the input and output data (as presented in **Table 4.14**) for each county, the user needs to specify which inputs are the controllable inputs and which ones are the uncontrollable ones. Next step is to specify the kind of DEA model that is requested to be run in the software. For this study, DMU $_{\text{TAS}}$ and DMU $_{\text{REGIONAL EFFECT}}$ are specified as uncontrollable inputs and the type of model is specified as input oriented BCC model. It is important to note that specifying such inputs as uncontrollable results in the application of the modified formulation developed by Banker and Morey (1986) (Banker and Morey 1986a) (which is the approach chosen to deal with the uncontrollable factors as discussed at the beginning of this chapter) by the software's algorithm. **Figure 4.3** illustrates the screenshot of the software in the step where data is loaded. **Figure 4.4** illustrates another screenshot depicting the results of the model obtained once the software was run with the modified formulation (as discussed above) of the input oriented BCC model. **Table 4.15** presents the detailed results of the model as extracted to a spreadsheet.

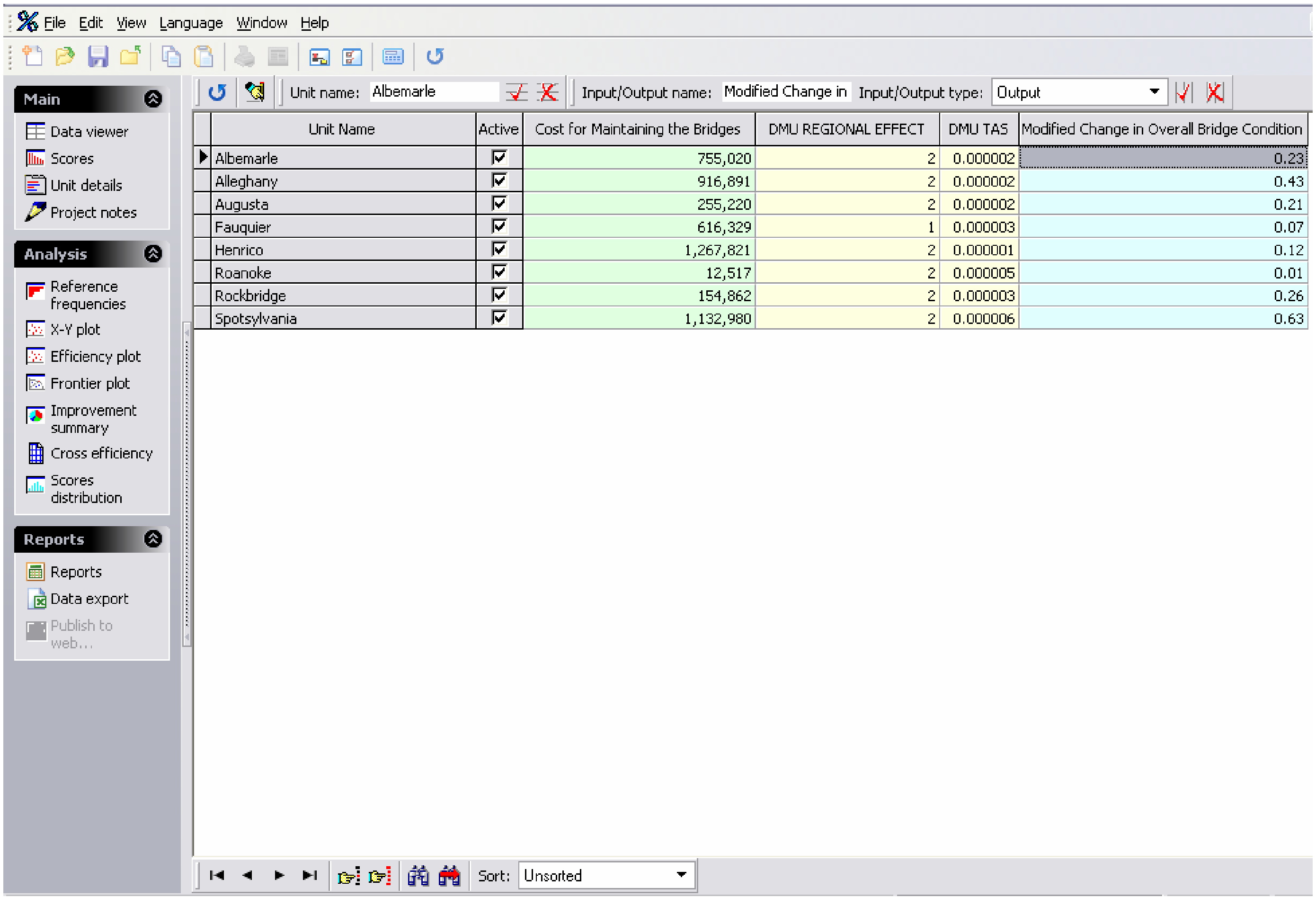


Figure 4.3: Frontier Analyst Data Loading Step Screenshot

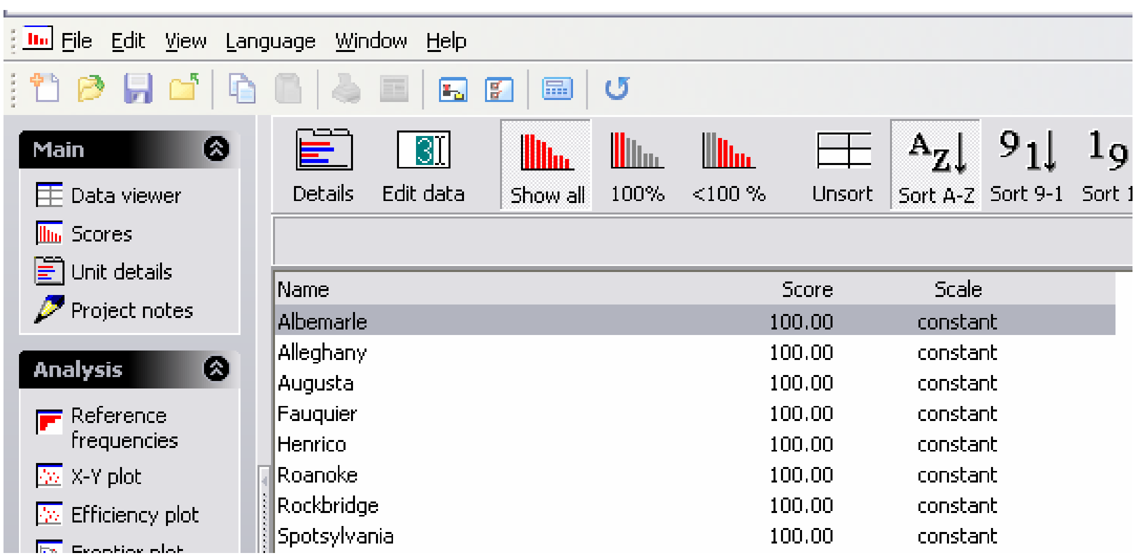


Figure 4.4: Frontier Analyst Results of the Model Screenshot

Table 4.15: Detailed Results of the Input Oriented BCC Model (as Extracted from the Frontier Analyst)

Unit name	Score	Actual Cost for Maintaining the Bridges	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in Overall Bridge Condition	Target Cost for Maintaining the Bridges	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in Overall Bridge Condition
Albemarle	100%	$755,020	2	0.00000176	0.23	$755,020	2	0.00000176	0.23
Alleghany	100%	$916,891	2	0.00000228	0.43	$916,891	2	0.00000228	0.43
Augusta	100%	$255,220	2	0.00000248	0.21	$255,220	2	0.00000248	0.21
Fauquier	100%	$616,329	1	0.00000289	0.07	$616,329	1	0.00000289	0.07
Henrico	100%	$1,267,821	2	0.00000137	0.12	$1,267,821	2	0.00000137	0.12
Roanoke	100%	$12,517	2	0.00000460	0.01	$12,517	2	0.00000460	0.01
Rockbridge	100%	$154,862	2	0.00000346	0.26	$154,862	2	0.00000346	0.26
Spotsylvania	100%	$1,132,980	2	0.00000633	0.63	$1,132,980	2	0.00000633	0.63

4.1.5 Conclusions

As can be seen in **Table 4.15**, the application of the DEA model to the "Bridges" element for VDOT Control Sections resulted in all of the counties (DMUs) in the data set to receive an efficiency score of 100%. This can lead to two alternative and conflicting conclusions as presented below:

Conclusion 1: All counties under investigation possess the same efficiency score of 100% and thus they are efficient relative to each other. Therefore, this study cannot suggest any improvements (i.e. input reductions) to be made in the bridge maintenance process of the counties. Furthermore, this study cannot suggest any comparisons to be made between the counties as far as their bridge maintenance policy is concerned as there is no basis for such a comparison. In other words, a policy analysis investigating the bridge maintenance policy of each county is irrelevant as the results of the DEA model suggest that all counties are efficient, so whatever each's bridge maintenance policy is, it works fine.

Conclusion 2: The model, as structured and run above, is not able to discriminate between the DMUs and thus overlooks the relative efficiency differences (inherent within the DMUs) that exist in reality. This can be attributed to two reasons, one of which is an issue specific to DEA and one of which is an issue that can be encountered in any modeling approach (be it statistical or non-statistical). The reason specific to DEA is the issue with the discriminating power of DEA. As mentioned in **Section 2.5.3.2** and **Section 3.6**, when number of DMUs is not sufficiently larger than the total number of variables utilized in the model, DEA cannot discriminate among the DMUs as it is supposed to do. Even though the model developed and presented in this write-up barely meets the requirement stated within the rule of thumb that was mentioned earlier, it is always desirable to have much more observations (DMUs) in the model than the number of variables utilized. The other reason of the developed model's inability to discriminate between the DMUs is the total number of observations used in the model. In any given model (be it statistical or non-statistical), one needs to have a sufficient number of observations to be able to find differences between such observations. This is mainly because the probability of finding differences between observations increases when the number of such observations increases. This certainly applies to the DEA case where the probability of finding efficiency differences between DMUs increases when the number of DMUs included in the model increases.

4.1.6 Findings Gathered from the Further Analyses

The reasoning suggested in **Conclusion 2** is much more compelling than that suggested in **Conclusion 1**. Therefore, it is decided to investigate possible ways to enhance the already-developed original model to be able to increase its discriminating power and thus to perform further analyses to identify the efficiency differences (between the counties) that exist in reality. If there is not any efficiency difference between the DMUs in reality (the case suggested in **Conclusion 1**), then these further analyses would yield to the same result anyway, proving **Conclusion 1** and rendering **Conclusion 2** invalid. Given this, it is in the best interest of the researchers to perform further analyses to either prove **Conclusion 1** or disprove it and identify the actual efficiency differences between the counties. Such further analyses are presented below.

4.1.6.1 Reducing the Number of Variables

As detailed in **Section 3.6.1.3**, to increase the discriminating power of the DEA model, and thus to underline the efficiency differences that may exist between the counties, the number of variables can be reduced by using the DEA based sensitivity analysis procedure. The sensitivity analysis procedure was performed for this study by removing one uncontrollable variable from- and keeping the other in- the analysis. This resulted in two additional DEA model runs apart from the original model which included all variables.

In the first additional model, the DMU $_{TAS}$ variable was removed from the analysis. The detailed results of the application of input oriented BCC formulation for this model are presented in **Table 4.16**. As can be seen in such table, the removal of the DMU $_{TAS}$ variable from the model changes the efficiency scores significantly and thus should be avoided. Therefore, this additional run of the model does not give any additional information (compared to the original model) about the efficiencies of the counties as the results of this model are not acceptable.

Table 4.16: Detailed Results of the Input Oriented BCC Model without the DMU $_{TAS}$ Variable

Unit name	Score	Actual Cost for Maintaining the Bridges	Actual DMU REGIONAL EFFECT	Actual Modified Change in Overall Bridge Condition	Target Cost for Maintaining the Bridges	Target DMU REGIONAL EFFECT	Target Modified Change in Overall Bridge Condition
Albemarle	18.25%	$755,020	2	0.23	$137,781	2	0.23
Alleghany	65.90%	$916,891	2	0.43	$604,268	2	0.43
Augusta	49.52%	$255,220	2	0.21	$126,393	2	0.21
Fauquier	100.00%	$616,329	1	0.07	$616,329	1	0.07
Henrico	5.93%	$1,267,821	2	0.12	$75,149	2	0.12
Roanoke	100.00%	$12,517	2	0.01	$12,517	2	0.01
Rockbridge	100.00%	$154,862	2	0.26	$154,862	2	0.26
Spotsylvania	100.00%	$1,132,980	2	0.63	$1,132,980	2	0.63

In the second additional model, the DMU $_{REGIONAL\ EFFECT}$ variable was removed from the analysis. The detailed results of the application of input oriented BCC formulation for this model are presented in **Table 4.17**. As can be seen in such table, the removal of the DMU $_{REGIONAL\ EFFECT}$ variable from the model has no impact on the efficiency scores of all but one DMU. By just considering this, one can then state that the DMU $_{REGIONAL\ EFFECT}$ variable can be removed from the analysis and when such is done the results of the model suggest that: (i) Fauquier County is inefficient compared to the other counties and (ii) the efficiencies of all remaining counties are equal. However, as was discussed in **Section 4.1.2.1**, the Regional Effect Variable represents a great number of environmental and operational effects and thus its removal from the analysis should require a great amount of caution and approval of the decision maker.

Table 4.17: Detailed Results of the Input Oriented BCC Model without the DMU $_{REGIONAL\ EFFECT}$ Variable

Unit name	Score	Actual Cost for Maintaining the Bridges	Actual DMU TAS	Actual Modified Change in Overall Bridge Condition	Target Cost for Maintaining the Bridges	Target DMU TAS	Target Modified Change in Overall Bridge Condition
Albemarle	100.00%	$755,020	0.00000176	0.23	$755,020	0.00000176	0.23
Alleghany	100.00%	$916,891	0.00000228	0.43	$916,891	0.00000228	0.43
Augusta	100.00%	$255,220	0.00000248	0.21	$255,220	0.00000248	0.21
Fauquier	33.79%	$616,329	0.00000289	0.07	$208,282	0.00000289	0.17
Henrico	100.00%	$1,267,821	0.00000137	0.12	$1,267,821	0.00000137	0.12
Roanoke	100.00%	$12,517	0.00000460	0.01	$12,517	0.00000460	0.01
Rockbridge	100.00%	$154,862	0.00000346	0.26	$154,862	0.00000346	0.26
Spotsylvania	100.00%	$1,132,980	0.00000633	0.63	$1,132,980	0.00000633	0.63

In conclusion, the results of the both additional runs (and hence the sensitivity analysis) cannot convincingly suggest the removal of either uncontrollable input variable from the DEA model. Thus, there is really no means to decrease the number of variables any further than what is used in the original DEA model run. Therefore, in this particular case, the discriminating power of DEA cannot be increased through the removal of the variables. The next analysis is to find ways to increase the number of DMUs (and hence observations) included in the DEA study as suggested in **Section 3.6**. As indicated earlier, by having a larger data set, the probability of obtaining relative efficiency differences between the counties gets higher and thus with a larger data set, the DEA model can highlight such relative efficiency differences.

4.1.6.2 Increasing the Number of DMUs

Earlier, it was stated that the complete condition and cost data are present only for the eight counties used in the original DEA model run. Therefore the number of DMUs cannot be increased by adding more counties to the analysis. One approach to increase the number of DMUs is to disaggregate the DMUs into smaller but meaningful units. However, this cannot be done for this study as well due to data availability issues. As mentioned earlier, even though the condition data can be obtained at a level smaller than the county (i.e. 10-mile-long highway section), cost data cannot be obtained at such level as VDOT's county is the minimum size of a DMU at which the cost data is available. Another approach that can be used to increase the number of DMUs in this case is to make use of the data representing the condition and cost information of different periods and for each county, to include such data from different periods as different observations (belonging to the same county) in the analysis. In other words, if there are n DMUs, and input/output data associated to those DMUs exist for each of the k periods, then each DMU can be treated as a different one for each period of time. By this approach, we can have $n*k$ (n: number of DMUs in the original model, k: number of periods for which the condition and cost data are available) observations in the model as opposed to the n observations that were used in the original model, because the same DMU in k successive periods is treated as k DMUs, increasing the number of DMUs in the amount of ($k*n-n$). Not only this approach would significantly increase the number of DMUs included in the DEA model (and thus address the issue of discriminating power) but it also may help the analyzer to capture and scrutinize the variations in efficiency over time for a particular DMU (county in this case). For example, a substantial change in the efficiency score of a particular DMU over a time period may indicate the occurrence of something unusual that needs further investigation. It can be asserted that, the average of the efficiency scores obtained for each period of time for a particular DMU results in an acceptable estimate of the overall efficiency of such DMU (Boussofiane et al. 1991; Charnes and Cooper 1990).

As mentioned before, the condition and cost data for bridges are available for only fiscal years of 2002, 2003, 2004, and 2005. The original DEA model run called for the combination of two successive fiscal years (e.g. fiscal year 2002 and fiscal year 2003) as the time unit due to the fact that the condition data for a particular bridge is collected in every other fiscal year (as detailed in **Section 4.1.3**). However, using the time unit as the combination of two successive fiscal years precludes the abovementioned analysis as it uses up all of the condition information belonging to four fiscal years and results in one value for the output (Modified Change in Overall Bridge Condition) for each county. Therefore, to be able to perform the abovementioned analysis, the time unit of measurement as used in the original DEA model run (combination of two successive fiscal years) needs to be redefined to represent just an individual fiscal year. Only through this way, the information in hand for four fiscal years (2002, 2003, 2004, and 2005) can be used to obtain different observations of eight (*n*) counties for three (*k*) successive periods (three: less than four due to the fact that for the output variable, the difference of overall bridge condition between two fiscal years is used). When the time unit of measurement is redefined to be an individual fiscal year, the bridge condition data obtained for any county does not reflect the condition of all bridges located within such county (due to the abovementioned reason that the condition data for a particular bridge is collected in every other fiscal year). Nonetheless, this does not pose any problem as far as the reliability and completeness of the data is concerned. This is mainly due to the fact that the bridge condition data, as collected by visiting a certain number of bridges of a county within a fiscal year, can be used to represent the condition of all of the bridges within such county for that fiscal year. As a matter of fact, this is very similar to the reasoning used by Virginia Tech for the utilization of one fiscal year's bridge condition data (as gathered through NBI) for the generation of the yearly MRP reports (to be submitted to and accepted by VDOT) to communicate the Interstate bridge maintenance performance of the private contractor and VDOT for that fiscal year. Virginia Tech even performs a trend analysis to identify the changes in the bridge maintenance performance of the private contractor and VDOT in successive fiscal years by using the bridge condition data of successive fiscal years even though such data contains the information for completely different bridges within each fiscal year. In conclusion, it is acceptable to use the bridge condition data collected within one fiscal year to represent how a county maintains all of its bridges within such fiscal year. Condition data may be of different bridges for each fiscal year but nonetheless represents the maintenance performance of a county within a fiscal year.

Once all of the steps and modifications presented in **Section 4.1.3** (other than the step in which the condition data for two consecutive fiscal years are combined) and **Section 4.1.4** are applied to the data for individual fiscal years, the variable data for 24 DMUs are obtained as shown in **Table 4.18.A**. It is important to note that within such table, for any county, the subscripts 1, 2, and 3 represent the fiscal years 2003, 2004, and 2005 respectively.

Table 4.18.A: Data to be used in the DEA Model with DMUs as Counties of Individual Fiscal Years

	Input Data			Output Data
DMU	Cost for Maintaining the Bridges	$DMU_{REGIONAL\ EFFECT}$	DMU_{TAS}	Modified Change in Overall Bridge Condition
$Albemarle_1$	$1,136,387	2	0.00000176	0.99
$Albemarle_2$	$504,674	2	0.00000176	1.18
$Albemarle_3$	$250,346	2	0.00000176	1.18
$Alleghany_1$	$452,135	2	0.00000228	1.45
$Alleghany_2$	$791,309	2	0.00000228	1.11
$Alleghany_3$	$125,583	2	0.00000228	1.25
$Augusta_1$	$127,062	2	0.00000248	1.10
$Augusta_2$	$79,292	2	0.00000248	1.04
$Augusta_3$	$175,928	2	0.00000248	1.27
$Fauquier_1$	$38,561	1	0.00000289	0.63
$Fauquier_2$	$355,068	1	0.00000289	1.33
$Fauquier_3$	$261,261	1	0.00000289	0.82
$Henrico_1$	$129,761	2	0.00000137	0.51
$Henrico_2$	$819,377	2	0.00000137	2.02
$Henrico_3$	$448,444	2	0.00000137	0.01
$Roanoke_1$	$2,594	2	0.00000460	1.67
$Roanoke_2$	$789	2	0.00000460	0.45
$Roanoke_3$	$11,728	2	0.00000460	1.54
$Rockbridge_1$	$107,715	2	0.00000346	0.19
$Rockbridge_2$	$143,160	2	0.00000346	2.03
$Rockbridge_3$	$11,703	2	0.00000346	0.20
$Spotsylvania_1$	$322,309	2	0.00000633	1.19
$Spotsylvania_2$	$579,099	2	0.00000633	1.43
$Spotsylvania_3$	$553,881	2	0.00000633	1.20

Using this data in the *Frontier Analyst* software and running the input oriented BCC model (as discussed in **Section 4.1.4**) results in a wide range of efficiency scores as can be seen in **Table 4.19**. Such result disproves **Conclusion 1** and thus proves **Conclusion 2**. **Table 4.19** presents the detailed results of this model as extracted to a spreadsheet. **Table 4.20** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county. It is important to note that same data is utilized and the same model is run in two other commercially available software packages as well, *OnFront* and *DEAFrontier*, and exact same results, as presented in **Table 4.19**, are obtained.

Table 4.19: Detailed Results of the DEA Model with DMUs as Counties of Individual Fiscal Years (as Extracted from the Frontier Analyst)

Unit name	Score	Actual Cost for Maintaining the Bridges	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in Overall Bridge Condition	Target Cost for Maintaining the Bridges	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in Overall Bridge Condition	Lambda 1	Peer 1	Lambda 2	Peer 2	Lambda 3	Peer 3
Albemarle1	16.2%	$1,136,387	2	0.00000176	0.99	$184,451	2	0.00000176	0.99	0.46	Albemarle3	0.23	Alleghany3	0.31	Henrico1
Albemarle2	49.6%	$504,674	2	0.00000176	1.18	$250,346	2	0.00000176	1.18	1.00	Albemarle3				
Albemarle3	100.0%	$250,346	2	0.00000176	1.18	$250,346	2	0.00000176	1.18	1.00	Albemarle3				
Alleghany1	49.3%	$452,135	2	0.00000228	1.45	$222,820	2	0.00000228	1.45	0.68	Albemarle3	0.01	Henrico2	0.31	Rockbridge2
Alleghany2	13.7%	$791,309	2	0.00000228	1.11	$108,536	2	0.00000228	1.11	0.54	Alleghany3	0.38	Augusta2	0.08	Henrico1
Alleghany3	100.0%	$125,583	2	0.00000228	1.25	$125,583	2	0.00000228	1.25	1.00	Alleghany3				
Augusta1	69.2%	$127,063	2	0.00000248	1.1	$87,931	2	0.00000248	1.1	0.15	Alleghany3	0.82	Augusta2	0.03	Rockbridge2
Augusta2	100.0%	$79,292	2	0.00000248	1.04	$79,292	2	0.00000248	1.04	1.00	Augusta2				
Augusta3	63.9%	$175,928	2	0.00000248	1.27	$112,407	2	0.00000248	1.27	0.56	Alleghany3	0.33	Augusta2	0.11	Rockbridge2
Fauquier1	100.0%	$38,561	1	0.00000289	0.63	$38,561	1	0.00000289	0.63	1.00	Fauquier1				
Fauquier2	100.0%	$355,068	1	0.00000289	1.33	$355,068	1	0.00000289	1.33	1.00	Fauquier2				
Fauquier3	47.6%	$261,261	1	0.00000289	0.82	$124,470	1	0.00000289	0.82	0.73	Fauquier1	0.27	Fauquier2		
Henrico1	100.0%	$129,761	2	0.00000137	0.51	$129,761	2	0.00000137	0.51	1.00	Henrico1				
Henrico2	100.0%	$819,377	2	0.00000137	2.02	$819,377	2	0.00000137	2.02	1.00	Henrico2				
Henrico3	28.9%	$448,444	2	0.00000137	0.01	$129,761	2	0.00000137	0.51	1.00	Henrico1				
Roanoke1	100.0%	$2,594	2	0.00000460	1.67	$2,594	2	0.00000460	1.67	1.00	Roanoke1				
Roanoke2	100.0%	$789	2	0.00000460	0.45	$789	2	0.00000460	0.45	1.00	Roanoke2				
Roanoke3	20.5%	$11,728	2	0.00000460	1.54	$2,402	2	0.00000460	1.54	0.89	Roanoke1	0.11	Roanoke2		
Rockbridge1	10.9%	$107,715	2	0.00000346	0.19	$11,703	2	0.00000346	0.2	1.00	Rockbridge3				
Rockbridge2	100.0%	$143,160	2	0.00000346	2.03	$143,160	2	0.00000346	2.03	1.00	Rockbridge2				
Rockbridge3	100.0%	$11,703	2	0.00000346	0.2	$11,703	2	0.00000346	0.2	1.00	Rockbridge3				
Spotsylvania1	0.6%	$322,309	2	0.00000633	1.19	$1,884	2	0.00000460	1.19	0.61	Roanoke1	0.39	Roanoke2		
Spotsylvania2	0.4%	$579,099	2	0.00000633	1.43	$2,239	2	0.00000460	1.43	0.80	Roanoke1	0.20	Roanoke2		
Spotsylvania3	0.3%	$553,881	2	0.00000633	1.2	$1,899	2	0.00000460	1.2	0.61	Roanoke1	0.39	Roanoke2		

Table 4.20: Overall Efficiency Scores of the Counties

County	Overall Efficiency Score of the County
Albemarle	55.3%
Alleghany	54.3%
Augusta	77.7%
Fauquier	82.5%
Henrico	76.3%
Roanoke	73.5%
Rockbridge	70.3%
Spotsylvania	0.4%

The overall observations that are obtained based on the results of this DEA run are summarized as follows:

1) Out of 24 DMUs, only 11 are 100% efficient.
2) Based on the overall efficiency scores presented in **Table 4.20**, the most efficient county is the Fauquier County (82.5%). The overall efficiency scores of all other counties, but Spotsylvania County, are within a 30% range from that of the Fauquier County.
3) Particular county of concern is the Spotsylvania County, whose DMUs average a mere 0.4% efficiency.
4) The only county whose DMUs never (whether it is for the fiscal year 2003, 2004, or 2005) get an efficiency score of 100% is the Spotsylvania County.
5) Roanoke County is the one whose DMUs are most frequently referenced (8 times) as peers by other DMUs (of the same and different counties).
6) The only county whose DMUs are never referenced by other DMUs is the Spotsylvania County.
7) Albemarle is the only county which consistently and drastically improved its efficiency score over the time period of fiscal years 2003, 2004, and 2005.
8) Spotsylvania is the only county which consistently worsened its efficiency score over the time period of fiscal years 2003, 2004, and 2005.
9) Fauquier, Henrico, and Roanoke counties kept their efficiency scores at 100% in the fiscal years 2003 and 2004 but then worsened their efficiency scores drastically to lower values in the fiscal year 2005.
10) Rockbridge County increased its efficiency score drastically from fiscal year 2003 to fiscal year 2004 and kept it at the same level (100%) in fiscal year 2005.

Figure 4.5 presents the peer relationships of the DMUs belonging to each county. Arrows in this figure represent where the inefficient DMUs should search for their peer(s). If an arrow starts at a county and points back, it means that the inefficient DMU(s) in this county should search for efficient DMU(s) within the same county. On the other hand, if an arrow starts at a county (County 1) and points to another county (County 2), it means that the inefficient DMU(s) in this county (County 1) should search for efficient DMU(s) in that other county (County 2).

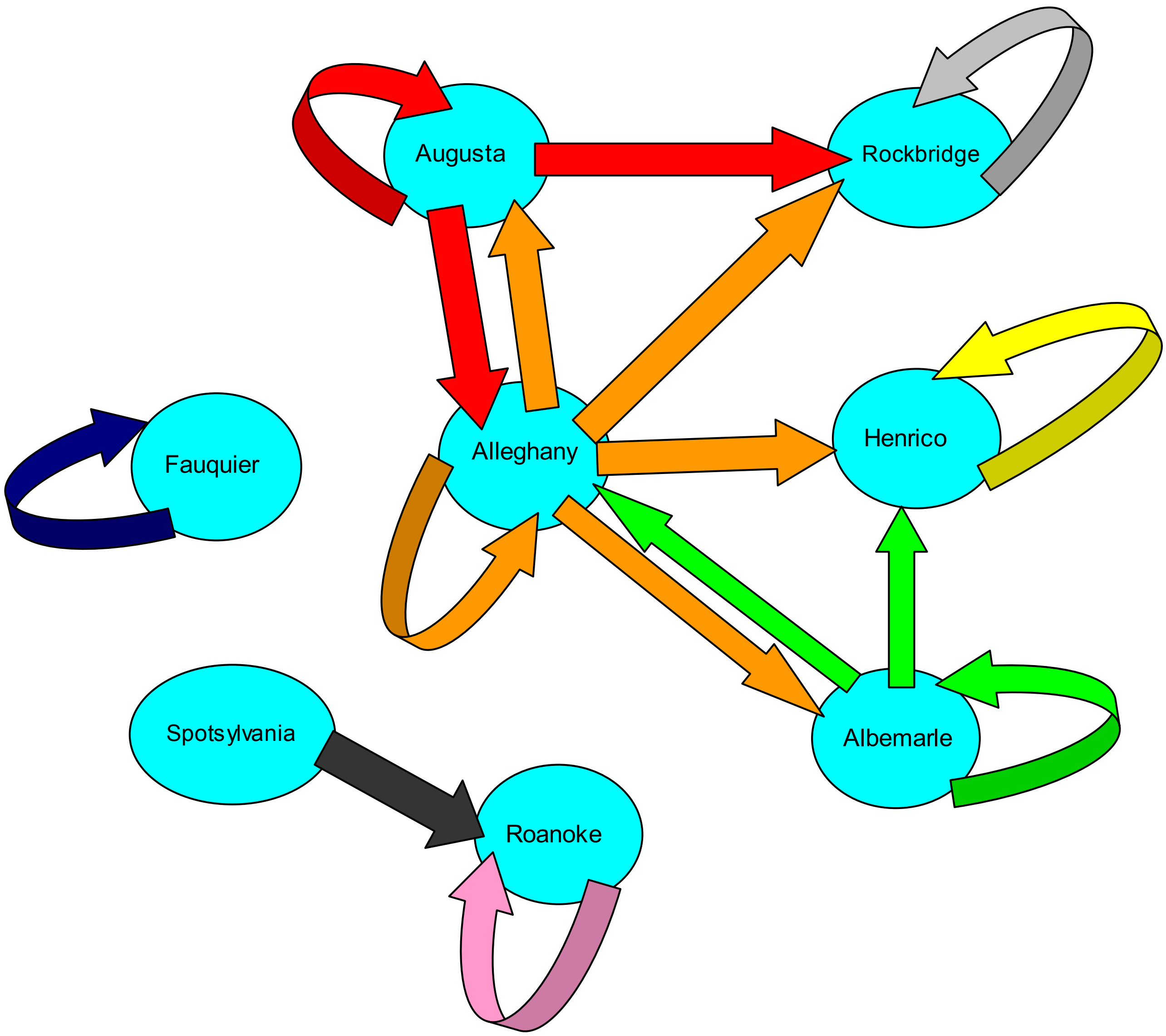


Figure 4.5: Peer Relationships of the DMUs for "Bridges"

As can be seen in **Figure 4.5**, the DMUs that belong to the Fauquier, Henrico, Roanoke, and Rockbridge counties are only looking within their own counties to identify peer DMUs that belong to the same county. This indicates that such counties already have the means in place to be efficient (as each of them has been efficient in two fiscal years out of three) and thus do not need to identify the practices of other counties as best practices. Of these counties, Rockbridge

County has drastically increased its efficiency in fiscal year 2004 from 10.9% to 100% and then kept the same efficiency level for the fiscal year 2005 as well. Thus, whatever operational and strategic policy Rockbridge County implemented starting in fiscal year 2004 should be kept as is to keep its efficiency at 100% in the future as well. Fauquier, Henrico, Roanoke counties, on the other hand, have been 100% efficient until the fiscal year 2005 and then drastically dropped their efficiencies. To address this sudden efficiency drop, the decision makers within these counties (e.g. County Maintenance Administrator) should try to identify the changes that were introduced (in fiscal year 2005) to the operational and/or strategic policies that have been implemented in the previous fiscal years. Such changes are most likely the causes for the efficiency drop. Moreover, the decision makers should observe their own practices and operational and strategic policies belonging to the earlier fiscal years to be able to identify what changes are needed to be implemented to go back to the efficiency levels reached within the earlier fiscal years.

It is important to note that the DMUs that belong to the Fauquier County are never referenced by any other county's DMUs even though it is the most efficient county based on the overall efficiency scores presented in **Table 4.20**. This can be attributed to the way that BCC formulation works. As the regional effect (which is the combination of environmental and operational effects) on the DMUs belonging to the Fauquier County is significantly different from such effect on the DMUs belonging to the other counties, BCC formulation restricts the peer comparison set of this county only to the DMUs belonging to the same county. For the very same reason, none of the DMUs belonging to the Fauquier County is referenced by the DMUs belonging to other counties.

Albemarle County's efficiency has shown a consistent and drastic upward trend until it finally reached 100%. Thus, whatever operational and strategic policy Albemarle County has been implementing over the fiscal years should be kept as is to keep its efficiency at 100% in the future as well. Alleghany County, after facing a substantial amount of efficiency drop within fiscal year 2004 over fiscal year 2003, reaches the 100% efficiency in fiscal year 2005. Thus, whatever operational and strategic policy Alleghany County implemented starting in fiscal year 2005 should be kept as is to keep its efficiency at 100% in the future as well. For Augusta County, just reverting back to the operational and strategic policy that was implemented in fiscal year 2004 (the fiscal year in which Augusta County's efficiency is 100%) is not sufficient to make its efficiency 100% in fiscal year 2005 and beyond. This can be attributed to the fact that the peers for the DMU representing the fiscal year 2005 performance of the Augusta County ($Augusta_3$) are the DMUs that belong to the Alleghany and Rockbridge counties in addition to the DMU representing the fiscal year 2004 performance of the Augusta County ($Augusta_2$). Given this, a more profound change should be made by the decision makers of the Augusta County as far as its operational and strategic policy is concerned. This change requires a deeper analysis and observation of the operational and strategic policies and general maintenance practices of Alleghany and Rockbridge counties for fiscal years 2005 and 2004 respectively in addition to observing its own practices and operational and strategic policies belonging to the fiscal year 2004 in an effort to adopt such practices.

The most apparent result that can be obtained from this run of the DEA model is with respect to the Spotsylvania County. In this relative efficiency study in which 24 DMUs that belong to 8 different counties are included, all of the DMUs that belong to the Spotsylvania County receive efficiency scores which are much lower than that of other DMUs. As a matter of fact, all of the DMUs that belong to the Spotsylvania County receive an efficiency score that is less than 1%. Moreover, Spotsylvania County has consistently worsened its efficiency score over the time period of fiscal years 2003, 2004, and 2005. This result should definitely raise a red flag for the decision makers within this county. A number of radical measures should be taken to stop this trend and to increase the efficiency of the Spotsylvania County. The very first step to be taken is to identify the peer DMUs for this county's DMUs. As can be seen in **Table 4.19**, the peer DMUs are the same for each of the DMU that belongs to the Spotsylvania County: (i) the DMU representing the fiscal year 2003 performance of the Roanoke County ($Roanoke_1$) and (ii) the DMU representing the fiscal year 2004 performance of the Roanoke County ($Roanoke_2$). Given this consistency of the peers, the decision makers of the Spotsylvania County should work closely with the decision makers of the Roanoke County to identify the operational and strategic policies and general maintenance practices implemented by the Roanoke County for the fiscal years 2003 and 2004 in an effort to adopt such practices. It is important to note that the DMUs that belong to the Roanoke County are affected by environmental and operational factors very similar to those that affect the DMUs belonging to the Spotsylvania County. Therefore, having peer relationships with the Roanoke County is of much benefit for the Spotsylvania County decision makers as they can disregard the effects of environmental and operational factors on the maintenance efficiency while trying to identify the best practices of the Roanoke County.

Another apparent and important result of the model is with respect to the Alleghany County, Henrico County, and Rockbridge County. They are the counties whose DMUs are most frequently referenced as peers by the DMUs of other counties. Although Fauquier and Augusta counties are the first and the second most efficient counties respectively as far as their overall efficiency is concerned (see **Table 4.20**), their DMUs are not referenced as frequently as those of the Alleghany County, Henrico County, and Rockbridge County by other counties. Thus, it is recommended that the maintenance management practices within these three counties be investigated more in depth by the upper management of VDOT.

In conclusion, by looking at the results of the model (examining **Table 4.19**, **Table 4.20**, and **Figure 4.5**), some county-specific operational and strategic decisions can be made as presented above. It is recommended for VDOT to carefully investigate the practices within the Alleghany County, Henrico County, and Rockbridge County (due to the reason stated in the preceding paragraph) as some very valuable insight can be gained which later may lead to some changes to be implemented all across the state of Virginia.

As evidenced by the efficiency scores and the differences in such scores obtained through the implementation of the DEA model, there are differences between the counties of Virginia as far as their "bridges" maintenance efficiencies are concerned. Therefore, the results of the DEA model presented herein confirm the validity of the first hypothesis of this research (as presented in **Chapter 1**) which is: "Within the state of Virginia, some counties are more efficient than others in performing highway maintenance operations."

4.1.6.3 Excluding the DMUs that Belong to the Roanoke County from the Analysis

It is important to note that, the main reason for DEA to identify $Roanoke_1$ and $Roanoke_2$ as the peers of the DMUs belonging to Spotsylvania County is the fact that Roanoke County is the county that is the closest one to the Spotsylvania County as far as the values of the uncontrollable variables DMU_{TAS} and $DMU_{REGIONAL\ EFFECT}$ are concerned. As discussed in **Chapter 2**, this is the direct result of the BCC model which ensures that the peer reference set of a DMU is composed of DMUs that are operating in a similar scale (which in this case is defined by the uncontrollable variables of DMU_{TAS} and $DMU_{REGIONAL\ EFFECT}$) as such DMU. When such observation is made, the main reason for the Spotsylvania County to end up having DMUs with such low efficiency scores can be understood. Due to the way that the BCC formulation works, DEA dictates that the DMUs that belong to the Spotsylvania County be compared against the DMUs that belong to the Roanoke County for efficiency calculations (due to the concept of "similarity of scale" as indicated above). With the exception of fiscal year 2004, Roanoke County has outperformed the Spotsylvania County as far as the "Modified Change in Overall Bridge Condition" is concerned. Nonetheless, even though being outperformed by the Spotsylvania County in the fiscal year 2004, Roanoke County has spent only about 0.1% of what Spotsylvania County has spent on bridge maintenance within the same fiscal year. Moreover, the Roanoke County has consistently spent far less money than the Spotsylvania County (when all three fiscal years are concerned, the total bridge maintenance spending made by the Roanoke County is just 1% of what is made by the Spotsylvania County). Given such figures, a relative efficiency comparison to be performed between the Roanoke County and the Spotsylvania County can easily yield to large efficiency differences between those counties and thus very low efficiency scores for the Spotsylvania County as can be seen in **Table 4.19**.

When the cost data for the Roanoke County is observed, it can be noticed that the bridge maintenance spending of such county is extremely low. The reasons for this can only be identified by further investigation. One possible reason may be the errors made by VDOT in the cost data recording. An alternative reason can be the extraordinary operational and strategic decisions made by the Roanoke County as far as the bridge maintenance spending is concerned. Whatever the reason may be, until it is identified, an analysis involving the Roanoke County should be performed very cautiously. Given this, and to make sure that the efficiency of Spotsylvania County is not underestimated due to some errors that may be present in the cost data of the Roanoke County, a second analysis that excludes the DMUs belonging to the Roanoke County should also be performed. The main purpose of this analysis is to identify whether the Spotsylvania County is still inefficient when it does not have to be compared to the Roanoke County, cost data of which needs some further verification.

The results of a DEA run which excludes the DMUs that belong to the Roanoke County (with every other aspect remaining the same as the previously performed DEA run) are presented in **Table 4.21.A**. As can be seen in **Table 4.21.A**, all of the efficiency scores for the DMUs that belong to the counties other than the Spotsylvania County have remained unchanged compared to the previously performed DEA run. The efficiency scores of the DMUs that belong to the Spotsylvania County have slightly increased. Nonetheless, as can be seen in **Table 4.22.A**, the overall efficiency score of the Spotsylvania County is still far less than that of the other counties. Moreover, just as in the previous DEA run, the results of this DEA run suggest that the Spotsylvania County has consistently worsened its efficiency score over the time period of fiscal years 2003, 2004, and 2005. Given the fact that the Roanoke County is excluded from this analysis, the peer DMUs for the DMUs belonging to the Spotsylvania County are now $Fauquier_1$ and $Rockbridge_2$ for all three fiscal years. These results confirm the findings of the previous DEA model run and clearly indicate that the Spotsylvania County is facing some efficiency problems and should seek ways and communicate with peers to resolve such problems.

Table 4.21.A: Detailed Results of the DEA Model with DMUs as Counties of Individual Fiscal Years (as Extracted from the Frontier Analyst) Excluding Roanoke County from the Analysis

Unit name	Score	Actual Cost for Maintaining the Bridges	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in Overall Bridge Condition	Target Cost for Maintaining the Bridges	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in Overall Bridge Condition	Lambda 1	Peer 1	Lambda 2	Peer 2	Lambda 3	Peer 3
Albemarle1	16.2%	$1,136,387	2	0.00000176	0.99	$184,451	2	0.00000176	0.99	0.46	Albemarle3	0.23	Alleghany3	0.31	Henrico1
Albemarle2	49.6%	$504,674	2	0.00000176	1.18	$250,346	2	0.00000176	1.18	1.00	Albemarle3				
Albemarle3	100.0%	$250,346	2	0.00000176	1.18	$250,346	2	0.00000176	1.18	1.00	Albemarle3				
Alleghany1	49.3%	$452,135	2	0.00000228	1.45	$222,820	2	0.00000228	1.45	0.68	Albemarle3	0.01	Henrico2	0.31	Rockbridge2
Alleghany2	13.7%	$791,309	2	0.00000228	1.11	$108,536	2	0.00000228	1.11	0.54	Alleghany3	0.38	Augusta2	0.08	Henrico1
Alleghany3	100.0%	$125,583	2	0.00000228	1.25	$125,583	2	0.00000228	1.25	1.00	Alleghany3				
Augusta1	69.2%	$127,063	2	0.00000248	1.1	$87,931	2	0.00000248	1.1	0.15	Alleghany3	0.82	Augusta2	0.03	Rockbridge2
Augusta2	100.0%	$79,292	2	0.00000248	1.04	$79,292	2	0.00000248	1.04	1.00	Augusta2				
Augusta3	63.9%	$175,928	2	0.00000248	1.27	$112,407	2	0.00000248	1.27	0.56	Alleghany3	0.33	Augusta2	0.11	Rockbridge2
Fauquier1	100.0%	$38,561	1	0.00000289	0.63	$38,561	1	0.00000289	0.63	1.00	Fauquier1				
Fauquier2	100.0%	$355,068	1	0.00000289	1.33	$355,068	1	0.00000289	1.33	1.00	Fauquier2				
Fauquier3	47.6%	$261,261	1	0.00000289	0.82	$124,470	1	0.00000289	0.82	0.73	Fauquier1	0.27	Fauquier2		
Henrico1	100.0%	$129,761	2	0.00000137	0.51	$129,761	2	0.00000137	0.51	1.00	Henrico1				
Henrico2	100.0%	$819,377	2	0.00000137	2.02	$819,377	2	0.00000137	2.02	1.00	Henrico2				
Henrico3	28.9%	$448,444	2	0.00000137	0.01	$129,761	2	0.00000137	0.51	1.00	Henrico1				
Rockbridge1	10.9%	$107,715	2	0.00000346	0.19	$11,703	2	0.00000346	0.2	1.00	Rockbridge3				
Rockbridge2	100.0%	$143,160	2	0.00000346	2.03	$143,160	2	0.00000346	2.03	1.00	Rockbridge2				
Rockbridge3	100.0%	$11,703	2	0.00000346	0.2	$11,703	2	0.00000346	0.2	1.00	Rockbridge3				
Spotsylvania1	25.0%	$322,309	2	0.00000633	1.19	$80,401	1.4	0.00000312	1.19	0.60	Fauquier1	0.40	Rockbridge2		
Spotsylvania2	17.0%	$579,099	2	0.00000633	1.43	$98,332	1.57	0.00000322	1.43	0.43	Fauquier1	0.57	Rockbridge2		
Spotsylvania3	14.7%	$553,881	2	0.00000633	1.2	$81,148	1.41	0.00000312	1.2	0.59	Fauquier1	0.41	Rockbridge2		

Table 4.22.A: Overall Efficiency Scores of the Counties Excluding Roanoke County from the Analysis

County	Overall Efficiency Score of the County
Albemarle	55.3%
Alleghany	54.3%
Augusta	77.7%
Fauquier	82.5%
Henrico	76.3%
Rockbridge	70.3%
Spotsylvania	18.9%

4.1.7 Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency

As was presented in **Chapter 1**, the framework developed by this research is aimed to measure the relative efficiency of different units (performing highway maintenance) while considering the effects of environmental and operational factors (both of which are beyond the control of the decision-maker, i.e., the maintenance manager) on such efficiency. Consequently, all of the DEA implementation examples (for bridges) that are presented so far have taken the effects of the environmental and operational uncontrollable factors on the efficiency into consideration; and thus intrinsically accounted for (and thus removed) the amount of inefficiency resulting from such uncontrollable factors, as the framework developed in **Chapter 3** incorporates them into the DEA model as uncontrollable variables.

This section presents a modified version of the DEA model run presented in **Section 4.1.6.3** (whose results are presented in **Table 4.21.A**). In such version, the uncontrollable variables for all DMUs are assigned the same value with the purpose of testing the second hypothesis of this research which is: "Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties." Assigning the same value to the uncontrollable variables for all DMUs means that all DMUs are experiencing the same uncontrollable factors. Therefore, a DEA model that is run with such values represents the case where the differences between the environmental and operational factors experienced by each DMU are neglected. This, in effect, is the same as not acknowledging the effects of the environmental and operational factors on the efficiency of the DMUs and thus not accounting for the amount of inefficiency created by such factors. The reason that the uncontrollable variables are not completely removed from the model but instead assigned the same value is to keep the number of variables unchanged. This way, the results of the two models (the one acknowledging the effects of uncontrollable factors on the efficiency of units and the one ignoring such) can be comparable as both models contain the same number of variables. In other words, one can attribute all of the efficiency differences (in the same DMUs) between the two models to the effects of the uncontrollable factors as artificial efficiency changes that could be resulting from the change in the number of variables (due to the way that the DEA works as detailed in **Section 3.6**) between the two models are prevented with such approach.

Table 4.18.B presents the variable data for 21 DMUs to be used in the DEA model for the bridges which ignores the effects of uncontrollable factors (and thus which does not account for the amount of inefficiency created by such) by assigning the same value to the uncontrollable variables for all DMUs. The data for such table is different from the one presented in **Table 4.18.A** with respect to 2 items: (i) **Table 4.18.B** does not include the DMUs for the Roanoke County (due to the reasons discussed in **Section 4.1.6.3**) and (ii) the values for $DMU_{REGIONAL\ EFFECT}$ and DMU_{TAS} variables (the uncontrollable variables in the model) are assigned the same value of "1". It is important to note that any other value could have been chosen to be assigned to these variables as the results of the DEA model are not affected with that particular value as long as such value is assigned to all DMUs.

Table 4.18.B: Data to be used in the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency

	Input Data			Output Data
DMU	Cost for Maintaining the Bridges	$DMU_{REGIONAL\ EFFECT}$	DMU_{TAS}	Modified Change in Overall Bridge Condition
$Albemarle_1$	$1,136,387	1	1	0.99
$Albemarle_2$	$504,674	1	1	1.18
$Albemarle_3$	$250,346	1	1	1.18
$Alleghany_1$	$452,135	1	1	1.45
$Alleghany_2$	$791,309	1	1	1.11
$Alleghany_3$	$125,583	1	1	1.25
$Augusta_1$	$127,062	1	1	1.10
$Augusta_2$	$79,292	1	1	1.04
$Augusta_3$	$175,928	1	1	1.27
$Fauquier_1$	$38,561	1	1	0.63
$Fauquier_2$	$355,068	1	1	1.33
$Fauquier_3$	$261,261	1	1	0.82
$Henrico_1$	$129,761	1	1	0.51
$Henrico_2$	$819,377	1	1	2.02
$Henrico_3$	$448,444	1	1	0.01
$Rockbridge_1$	$107,715	1	1	0.19
$Rockbridge_2$	$143,160	1	1	2.03
$Rockbridge_3$	$11,703	1	1	0.20
$Spotsylvania_1$	$322,309	1	1	1.19
$Spotsylvania_2$	$579,099	1	1	1.43
$Spotsylvania_3$	$553,881	1	1	1.20

Table 4.21.B presents the detailed results of this model as extracted to a spreadsheet. **Table 4.22.B** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county. **Table 4.21.C** presents the efficiency scores of the DMUs obtained from both DEA models (i.e., the one that acknowledges the effects of the uncontrollable factors and the one that ignores those) side by side for comparison purposes. Similarly, **Table 4.22.C** presents the overall efficiency scores of the counties obtained from both DEA models (i.e., the one that acknowledges the effects of the uncontrollable factors and the one that ignores those) side by side for comparison purposes.

Table 4.21.B: Detailed Results of the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency

Unit name	Score	Actual Cost for Maintaining the Bridges	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in Overall Bridge Condition	Target Cost for Maintaining the Bridges	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in Overall Bridge Condition	Lambda 1	L-Peer 1	Lambda 2	L-Peer 2
Albemarle1	5.8%	$1,136,387	1	1	0.99	$65,458	1	1	0.99	0.74	Fauquier1	0.26	Rockbridge2
Albemarle2	15.8%	$504,674	1	1	1.18	$79,653	1	1	1.18	0.61	Fauquier1	0.39	Rockbridge2
Albemarle3	31.8%	$250,346	1	1	1.18	$79,653	1	1	1.18	0.61	Fauquier1	0.39	Rockbridge2
Alleghany1	22.1%	$452,135	1	1	1.45	$99,826	1	1	1.45	0.41	Fauquier1	0.59	Rockbridge2
Alleghany2	9.4%	$791,309	1	1	1.11	$74,424	1	1	1.11	0.66	Fauquier1	0.34	Rockbridge2
Alleghany3	67.6%	$125,583	1	1	1.25	$84,883	1	1	1.25	0.56	Fauquier1	0.44	Rockbridge2
Augusta1	58.0%	$127,063	1	1	1.1	$73,676	1	1	1.1	0.66	Fauquier1	0.34	Rockbridge2
Augusta2	87.3%	$79,292	1	1	1.04	$69,194	1	1	1.04	0.71	Fauquier1	0.29	Rockbridge2
Augusta3	49.1%	$175,928	1	1	1.27	$86,378	1	1	1.27	0.54	Fauquier1	0.46	Rockbridge2
Fauquier1	100.0%	$38,561	1	1	0.63	$38,561	1	1	0.63	1.00	Fauquier1		
Fauquier2	25.6%	$355,068	1	1	1.33	$90,860	1	1	1.33	0.50	Fauquier1	0.50	Rockbridge2
Fauquier3	20.2%	$261,261	1	1	0.82	$52,757	1	1	0.82	0.86	Fauquier1	0.14	Rockbridge2
Henrico1	23.9%	$129,761	1	1	0.51	$31,066	1	1	0.51	0.72	Fauquier1	0.28	Rockbridge3
Henrico2	17.4%	$819,377	1	1	2.02	$142,413	1	1	2.02	0.01	Fauquier1	0.99	Rockbridge2
Henrico3	2.6%	$448,444	1	1	0.01	$11,703	1	1	0.2	1.00	Rockbridge3		
Rockbridge1	10.9%	$107,715	1	1	0.19	$11,703	1	1	0.2	1.00	Rockbridge3		
Rockbridge2	100.0%	$143,160	1	1	2.03	$143,160	1	1	2.03	1.00	Rockbridge2		
Rockbridge3	100.0%	$11,703	1	1	0.2	$11,703	1	1	0.2	1.00	Rockbridge3		
Spotsylvania1	25.0%	$322,309	1	1	1.19	$80,401	1	1	1.19	0.60	Fauquier1	0.40	Rockbridge2
Spotsylvania2	17.0%	$579,099	1	1	1.43	$98,332	1	1	1.43	0.43	Fauquier1	0.57	Rockbridge2
Spotsylvania3	14.7%	$553,881	1	1	1.2	$81,148	1	1	1.2	0.59	Fauquier1	0.41	Rockbridge2

Table 4.22.B: Overall Efficiency Scores of the Counties for the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Bridge Maintenance Efficiency

County	Overall Efficiency Score of the County
Albemarle	17.8%
Alleghany	33.0%
Augusta	64.8%
Fauquier	48.6%
Henrico	14.6%
Rockbridge	70.3%
Spotsylvania	18.9%

Table 4.21.C: Efficiency Scores of the DMUs obtained from both DEA Models for Bridges

Unit name	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model (*DEA 1*)	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model (*DEA 2*)
Albemarle1	16.2%	5.8%
Albemarle2	49.6%	15.8%
Albemarle3	100.0%	31.8%
Alleghany1	49.3%	22.1%
Alleghany2	13.7%	9.4%
Alleghany3	100.0%	67.6%
Augusta1	69.2%	58.0%
Augusta2	100.0%	87.3%
Augusta3	63.9%	49.1%
Fauquier1	100.0%	100.0%
Fauquier2	100.0%	25.6%
Fauquier3	47.6%	20.2%
Henrico1	100.0%	23.9%
Henrico2	100.0%	17.4%
Henrico3	28.9%	2.6%
Rockbridge1	10.9%	10.9%
Rockbridge2	100.0%	100.0%
Rockbridge3	100.0%	100.0%
Spotsylvania1	25.0%	25.0%
Spotsylvania2	17.0%	17.0%
Spotsylvania3	14.7%	14.7%

Table 4.22.C: Overall Efficiency Scores of the Counties obtained from both DEA Models for Bridges

County	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model (*DEA 1*)	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model (*DEA 2*)
Albemarle	55.3%	17.8%
Alleghany	54.3%	33.0%
Augusta	77.7%	64.8%
Fauquier	82.5%	48.6%
Henrico	76.3%	14.6%
Rockbridge	70.3%	70.3%
Spotsylvania	18.9%	18.9%

When the results from both models (*DEA 1* and *DEA 2*) within each of the tables are compared, it can be seen that a portion of the inefficiencies (which is lowering the efficiency scores) inherent in the DMUs as seen in the *DEA 2* model (i.e. when the effects of uncontrollable factors are not acknowledged in the DEA model) can be attributed to the effects of the uncontrollable factors faced by such DMUs. This is simply because for all counties but two (Rockbridge and Spotsylvania), the efficiency scores are higher when the DEA model is run by acknowledging the effects of the uncontrollable factors on the efficiency of DMUs. Such DEA model (*DEA 1* model), by considering the effects of the uncontrollable factors, calculates the efficiency of the DMUs given the uncontrollable factors they face. Therefore, the amount of inefficiency that is the result of the uncontrollable factors (e.g. bad climate, heavy traffic, etc.) is accounted for by the DEA model. In other words, *DEA 1* model, by considering the effects of the uncontrollable factors: (i) creates a leveled playing field, (ii) eliminates the artificial inefficiencies created by the effects of such uncontrollable factors, and (iii) reflects the pure relative efficiencies of the DMUs for their bridge maintenance operations. This result confirms the validity of the second hypothesis of this research (as presented in **Chapter 1**) which is: "Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties."

It is important to note that by taking the difference of the efficiency scores obtained from *DEA 1* Model and *DEA 2* Model within each of the tables, one can easily identify the effects of the uncontrollable factors on the efficiencies of the DMUs (which is one of the objectives of this research as presented in **Chapter 1**). For example, the uncontrollable factors reduce the relative bridge maintenance efficiency of the Augusta County in the amount of 12.9% (77.7%-64.8%) according to the DEA models run for the implementation example presented herein. According to the results of the same relative efficiency models though, Rockbridge and the Spotsylvania counties' efficiencies do not seem to be affected by the uncontrollable factors (as such counties' efficiencies as calculated by *DEA 1* Model and *DEA 2* Model are the same as can be seen in **Table 4.22.C**). This can be attributed to the fact that, relative to the other counties used in the model, these counties are enjoying milder uncontrollable factors as reflected by the "DMU_{TAS}" uncontrollable variable of such counties (they are the counties that have the smallest area of bridges among all of the counties used in this implementation example) and thus relative to the other counties, these two counties' efficiencies are not adversely affected by the uncontrollable factors.

4.2 APPLICATION OF THE FRAMEWORK TO THE "PAVED LANES" ELEMENT OF THE LEVEL-OF-SERVICE COMPONENT FOR THE MAINTENANCE PERFORMED BY TRADITIONAL METHODS

This section presents the application of the framework developed in **Chapter 3** to the 215 miles of Virginia's Interstate where maintenance is performed on a traditional basis by VDOT (i.e. VDOT Control Sections for the Maintenance Rating Program (MRP) project). Such application of DEA is focused on the "Paved Lanes" element of the level-of-service component, only for the years in which paved lanes condition and cost data are available. Just as in the case for bridges, the approaches and concepts that are parts of the framework developed in **Chapter 3** are utilized for the purposes of this section. This section, first, presents the comprehensive lists of variables and DMUs that have initially been decided to be included in the DEA study for the paved lanes. Then, it presents the final lists of variables and DMUs that are decided to be used in actual implementation of DEA and discusses the reasons behind the modification of the comprehensive lists to such final lists. After that, it illustrates the data preparation (gathering, mining, cleaning, and conversion/rearrangement) process performed to make such data ready to be used in the DEA model. Then, it discusses the reasons for the selection of the particular DEA model that is used in this study along with final data refinements and presents the results of the application of such model to the prepared data for the "Paved Lanes" element (of the level-of-service component) for VDOT Control Sections. Finally, it presents the conclusions, findings gathered from the further analysis, and effects of uncontrollable factors on the paved lanes maintenance efficiency of units under investigation.

It is important to note that this section possesses a full implementation example (for the "Paved Lanes" element of the level-of-service component) of the comprehensive highway maintenance efficiency framework developed in **Chapter 3**.

4.2.1 Comprehensive Lists of Variables and DMUs

This section is divided into two parts. First part presents the most comprehensive list of variables that can be used in the DEA model for the maintenance of the "Paved Lanes" element of the level-of-service component. The second part presents the issues with the selection of DMUs to be included in such DEA model and presents the information for the identification/location of those DMUs.

4.2.1.1 Comprehensive List of Variables

Based on the discussion presented in **Section 3.7.2**, it is decided to utilize the Banker and Morey (1986) (Banker and Morey 1986a) approach to deal with uncontrollable factors for the "Paved Lanes" element of the level-of-service component as presented in **Table 3.2**. Therefore, such uncontrollable factors are decided to be treated as uncontrollable variables in the DEA models. Thus, the uncontrollable factors presented for the "Paved Lanes" element in **Table 3.2** become uncontrollable input variables due to their effects on the maintenance of such element. **Table 4.23** presents the most comprehensive list of input and output variables that can be used in the DEA model for the maintenance of the "Paved Lanes" element of the level-of-service component. It is important to note that such table is a subset of **Table 3.2** (with the sole difference that the uncontrollable factors in **Table 3.2** are now the uncontrollable input variables in **Table 4.23**) which was developed in **Chapter 3** by using the process definition and the approaches to develop the list of controllable variables and uncontrollable factors as presented in the same chapter.

Table 4.23: The Comprehensive List of Input and Output Variables for the DEA Model of the Maintenance of the "Paved Lanes" Element of the Level-of Service Component

Component	Element		Variable Name	Variable Explanation and/or Metric
Level of Service	Paved Lanes (Traveled portion of the Pavement)	INPUTS	(1) Cost for maintaining the paved lanes	$
			(2) Climate- Effect on deterioration of the paved lanes	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles
			(3) Climate- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity- availability of crews)	Yearly precipitation amounts (inches)
			(4) Traffic- Effect on deterioration of the paved lanes	Equivalent Single Axle Load (ESAL)
			(5) Traffic- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity- availability of crews)	Average Daily Traffic (ADT)
			(6) Snow treatment- Effect on deterioration of the paved lanes	count (of chloride applications)
			(7) Speed limit- Effect on deterioration of the paved lanes	miles/hr
			(8) Accidents damaging paved lanes- Effect on deterioration of the paved lanes	count (of accidents damaging paved lanes)/year
			(9) Subsurface conditions- Effect on deterioration of the paved lanes	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)
			(10) Subgrade-- Effect on deterioration of the paved lanes	Compaction etc…
			(11) Base- Effect on deterioration of the paved lanes	Aggregate mix etc…
			(12) Thickness of the different layers of the paved lanes- Effect on deterioration of the paved lanes	Inches
			(13) Type of paved lanes-Effect on deterioration of the paved lanes)	Concrete, Asphalt (give a grade based on the effect)
			(14) Type of paved lanes- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity of crews)	Concrete, Asphalt (give a grade based on the effect)
			(15) Age of paved lanes- Effect on deterioration of the paved lanes	Years
			(16) Terrain- Effect on deterioration of the paved lanes	Slope, Elevation, and Orientation
			(17) Terrain- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity of crews)	Slope, Elevation, and Orientation
			(18) Total Area Served- Effect on maintenance efforts performed for meeting Level of Service requirements for the paved lanes (productivity of crews)	Sum of the area (lane miles*lane width) of all of the paved lanes within the DMU
		OUTPUTS	(19) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to load-related damages)	LDR_{t1}-LDR_{t0}
			(20) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to non load-related damages)	NDR_{t1}-NDR_{t0}
			(21) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to ride quality)	IRI_{t1}-IRI_{t0}
			(22) Change in the condition of the Paved Lanes (which are maintained to meet the Level of Service requirements with respect to rutting, skid index etc…)	%$LOSp_{t1}$-%$LOSp_{t0}$
			(23) Air Pollution	Emission amounts
			(24) Water Pollution	Emission amounts
			(25) Noise Pollution	Emission amounts

: The reason for computing the difference of ratings at time "t1" and "t0" will be explained in Section 4.2.3 of this chapter.

4.2.1.2 Comprehensive List of DMUs

Given the discussion presented in **Section 2.5.3.2** and **Section 3.6** with respect to the discriminating power of DEA, and given the fact that the DEA model will be applied for an approximately 430 directional miles of Interstate portion which is maintained on a traditional basis (the VDOT Control Sections for which condition data is available to Virginia Tech), initially it was decided to define the DMU as a 10-mile-long highway section of this 430 mile portion in an effort to maximize the number of DMUs while assigning a meaningful size to such DMUs as far as DEA is concerned. Such a definition would yield to 43 DMUs, which is likely to be a sufficient number (as far as the discriminating power of DEA is concerned) once the comprehensive list of variables is refined as discussed in **Section 3.6**. However, as mentioned in the implementation example for the "Bridges" element, defining a DMU as a 10-mile-long highway section presented a major obstacle in the data gathering process. It was indicated by VDOT that the data for arguably the most important variable, the cost variable, cannot be gathered at a 10-mile-long highway section level as VDOT's FMS keeps track of the costs at the county level for each Interstate. Given this restriction, just as in the case for bridges, the definition of DMUs was changed to be the counties of Virginia (that encompass the portions of the interstate system that are under investigation), which is the minimum size of a DMU at which the cost data is available. **Table 4.24** presents the identification/location information of the counties that encompass the VDOT Control Sections.

As a final note, since the cost data that is provided by VDOT is in VDOT's fiscal years, all analysis will be performed on a fiscal year time frame basis. This means that all input-output data should be yearly data covering the time span of VDOT's fiscal years, i.e. July 1st of the previous year to June 30th of the current year.

Table 4.24: The Comprehensive List of DMUs for the DEA Model of the Maintenance of the "Paved Lanes" Element of the Level-of-Service Component

MRP* Section	Route	County (DMU)	Route Relative		Closest County Relative	
			Begin Milemarker	End Milemarker	Begin Milemarker	End Milemarker
5-VDOT Control	I-95	Caroline	108.87	116.87	7.54	15.54
5-VDOT Control	I-95	Spotsylvania	116.87	132.40	0.00	15.53
6-VDOT Control	I-66	Fauquier	14.66	36.59	0.00	21.93
7-VDOT Control	I-64	Henrico	175.70	187.46	0.00	11.76
7-VDOT Control	I-64	Henrico	190.66	204.6[&]	14.96	28.90
8-VDOT Control	I-64	Alleghany	0.00	40.99	0.00	40.99
8-VDOT Control	I-64	Rockbridge	40.99	57.23	0.00	16.24
9-VDOT Control	I-64	Nelson	99.96	101.32	0.00	1.36
9-VDOT Control	I-64	Albemarle	101.32	131.16	0.00	29.84
10-VDOT Control	I-81	Roanoke	130.59	147.45	0.00	16.86
11-VDOT Control	I-581	Roanoke	0.00	6.64	0.00	6.64
12-VDOT Control	I-81	Augusta	206.04	237.51	0.00	31.47

*: MRP- Maintenance Rating Program- The program that is used by Virginia Tech to evaluate the Interstate maintenance performance in terms of effectiveness.
&: In January 2006, this Milemarker was changed to 200.9 as a private contractor started to undertake the maintenance of a portion of the Interstate beginning at milemarker 200.9.

4.2.2 Final Lists of Variables and DMUs to be included in the DEA Model

This section presents the final lists of variables and DMUs that are decided to be used in actual implementation of DEA and discusses the reasons behind the modification of the comprehensive lists (presented in the previous section) to such final lists. First part of this section deals with the input and output variables and the second part deals with the DMUs.

4.2.2.1 Final List of Variables to be included in the DEA Model

As was underlined in **Section 3.6**, once the initial comprehensive list of input and output variables is developed, such list should be reinvestigated and refined to include only the most

relevant and important variables to be able to increase the discriminating power of DEA models. As presented in **Table 4.23**, the comprehensive list for the "Paved Lanes" element has a total of 25 variables. Considering the number of DMUs presented in **Table 4.24**, using so many variables in the DEA model would definitely preclude the model to discriminate between efficient and inefficient DMUs. The refinement process for such list is discussed below.

On the outputs side, the output variables air pollution (labeled as 23 in **Table 4.23**), water pollution (24), and noise pollution (25) can directly be removed from the list. They are different from the common concept of the output of a process as they are undesirable outputs (i.e. the less of them, the better). From an efficiency point of view, the inclusion of them in the DEA model (including undesirable outputs in DEA models is a rather new concept in the DEA literature as discussed in **Section 3.3**) is not critical but nonetheless given the availability of data, they should be included in the model. For our case, they will be disregarded since (i) no data is available for those undesirable outputs and (ii) those variables are not deemed critical as far as their effect on overall efficiency of a DMU is concerned. The only data that has traditionally been collected for the paved lanes is the Load-Related Distress Rating (LDR[12]) (labeled as 19 in **Table 4.23**), Non Load-Related Distress Rating (NDR[13]) (20), and International Roughness Index (IRI[14]) (21). Such data is collected as a part of VDOT's Pavement Management System to be used for budgetary decisions. However, VDOT has also defined another index, Critical Condition Index (CCI), which is the lower of either LDR or NDR. VDOT uses such index (as opposed to the LDR or NDR) to identify the deficient sections of the paved lanes as such index simply shows the critical condition of the paved lanes (JLARC 2002). Given this, and in an effort to refine the comprehensive list of variables, this research will also use CCI to account for both the LDR and NDR. The data with respect to rutting, skid index, and etc. (22) is never collected as such information is mostly covered by the information collected for the abovementioned three

---

[12] **LDR** is an index that depicts the state of the paved lanes from the perspective of the damage due to the traffic load. This index, as assigned to the paved lanes by inspectors based on visual inspection ranges from 0 to 100, the latter corresponding to the best condition (JLARC 2002).

[13] **NDR** is an index that depicts the state of the paved lanes from the perspective of the damage due to the climate related issues such as temperature and moisture change over time. This index, as assigned to the paved lanes by inspectors based on visual inspection ranges from 0 to 100, the latter corresponding to the best condition (JLARC 2002).

[14] **IRI** is an indicator of overall pavement smoothness. Such data is collected using an instrumented vehicle that measures the road surface roughness in inches of vertical deviation per mile of the traveled road. Smaller IRI values indicate a better road surface. This index may range from 0 to an upper value with no theoretical limit, the former corresponding to the best condition (JLARC 2002).

components. Thus, such output variable can also be removed from the list. As a result of all of the refinements discussed within this paragraph, only two outputs, “Change in CCI” and “Change in IRI” remain to be included in the DEA model for the maintenance of the “Paved Lanes” element as shown in **Table 4.25**.

On the inputs side, only the cost variable (1) is a controllable variable (i.e. directly controllable by the decision maker, i.e. VDOT’s Asset Management Division). All of the remaining inputs (2-18) are uncontrollable variables representing the following four types of effects on the highway maintenance process:

(i) Environmental effects on the deterioration of the paved lanes (Variables 2, 9, and 16)
(ii) Environmental effects on the maintenance efforts (Variables 3 and 17)
(iii) Operational effects on the deterioration of the paved lanes (Variables 4, 6, 7, 8, 10, 11, 12, 13, and 15)
(iv) Operational effects on the maintenance efforts (Variables 5, 14, and 18)

By utilizing the same approach performed for bridges, this study aims to use the results of Dadson’s research to combine 15 input variables (Variable 2- Variable 4 and Variable 6-Variable 17) belonging to the paved lanes into a single input variable that represents all of those to a great extent. As was presented earlier, for the case of bridges, this research aggregated a number of input variables into an overall regional effect variable by using the effects of environmental regions on the mean service life estimates of the **deck** of a bridge structure as studied by Dadson (Dadson et al. 2002). Given the fact that the uncontrollable effects (e.g., climate, traffic, and etc.) that the deck of a bridge is exposed to is quite similar to those that the paved lanes are exposed to, the results of such study can also be used in a similar manner to refine the comprehensive list of input variables for the paved lanes as was done for bridges. In other words, Dadson’s study’s findings (as achieved through statistical analyses) for the deck of the bridges can be assumed to be applicable for the paved lanes as the deck of a bridge consists of the traveled roadway which essentially is the same as the paved lanes.

Due to all of the variable refinements presented in the preceding paragraphs, the final list of variables to be used in the DEA model for paved lanes contains 3 inputs and 2 outputs as presented in **Table 4.25**.

Table 4.25: Final List of Variables to be used in the DEA Model for Paved Lanes

Variable Type	Variable Name	Variable Explanation and/or Metric
Input	Cost for Maintaining the Paved Lanes	$
	Regional Effect Variable	A grade (Low, Medium, or Severe) based on the effect (using the results of Dadson's study)
	Total Area Served	Sum of the area (lane miles*lane width) of all of the paved lanes within the DMU
Output	Change in CCI	$CCI_{t1}-CCI_{t0}$
	Change in IRI	$IRI_{t1}-IRI_{t0}$

: The reason for computing the difference of ratings at time "t1" and "t0" will be explained in Section 4.2.3 of this chapter.

4.2.2.2 Final List of DMUs to be included in the DEA Model

Even though **Table 4.24** presents all of the counties that encompass the VDOT Control Sections, not all of the counties listed there can be included in the DEA model developed in this research. Following are the counties that will be excluded from this research:

(i) **Caroline County**: As can be seen in **Table 4.24**, the portion of VDOT Control Section 5 which falls within the limits of this county (from Milemarker 108.87 to Milemarker 116.87) does not entirely cover this county. Thus, the paved lanes condition information gathered for the MRP through VDOT's pavement management system only covers the paved lanes that fall within the Milemarkers 108.87-116.87. However, the cost data that is provided by VDOT is for the entire Caroline County (i.e. from Milemarker 101.33 to Milemarker 116.87), and thus covers the portion of Caroline County (from Milemarker 101.33 to Milemarker 108.87) for which no paved lanes condition data is available. As there is no way to apportion this cost data to the desired portion of the county for which paved lanes condition data is available, it is decided to exclude the Caroline County from the analysis as inclusion of it is prone to introduce a substantial amount of error in the efficiency evaluations.

(ii) **Nelson County**: No cost data for this county is provided by VDOT as only a very small portion of this county encompasses the VDOT Control Section 9. Even if there was cost data for this county, it would be meaningless to try to calculate the Interstate paved lanes maintenance efficiency of a county which only has 1.36 miles of Interstate within its jurisdiction. So, Nelson County is excluded from the DEA model.

Table 4.26 presents the final list of DMUs that are decided to be included in the DEA model for paved lanes based on the discussion presented above.

Table 4.26: Final List of DMUs to be included in the DEA Model for Paved Lanes

DMU Name
Albemarle
Alleghany
Augusta
Fauquier
Henrico
Roanoke
Rockbridge
Spotsylvania

4.2.3 Data Preparation Process

This section presents the steps taken for the data preparation process that is performed to obtain data and then to make such data ready to be used in the DEA model for paved lanes. These steps are data gathering, data mining, data cleaning, and data conversion/rearrangement.

4.2.3.1 Step 1- Data Gathering

Data gathering efforts were mainly focused at obtaining the following: (i) Paved Lanes Condition Data, (ii) Paved Lanes Area Data, (iii) Interstate ADT Data, and (iv) Paved Lanes Cost Data.

Virginia Tech already possesses Paved Lanes Condition Data as such was gathered for MRP for the fiscal years 2002, 2003, 2004, and 2005. Such data has consistently been provided to Virginia Tech by the personnel in VDOT's Asset Management Division (AMD). It has been acknowledged by VDOT's AMD that such data is gathered by VDOT as a part of their Pavement Management System and thus is well-documented. It can be asserted that the Paved Lanes

Condition Data is very reliable as it has to pass a strict QA/QC program performed by VDOT as it is used by VDOT for budget generation purposes. The database that contains the "Paved Lanes Condition Data" also has the data for the area of such paved lanes (i.e. "Paved Lanes Area Data"- information related to the Total Area Served input variable to be used in the DEA model).

VDOT makes the average daily traffic volumes on the interstate, primary, and arterial routes for the state of Virginia publicly available each year through a publication (VDOT 2002b; VDOT 2003; VDOT 2004; VDOT 2005a). Such publication was used to gather the ADT data for interstate routes within the counties considered for this study. As discussed earlier, such information is to be used to decide on which Regional Effect Variable (i.e. either the value in Level 1 column or Level 2 column of **Table 4.3**) to assign to the DMU.

Cost Data has been provided by VDOT's AMD. According to the statement made by Dennis Domayer from VDOT's AMD, "*The information was derived from FMS II using the VGLN50 reports Program 6040100 for the districts involved. Drills were run by route and then by county and then by activity. The original request was to extract the 7XXXX series of activity codes and omit all other activity codes*" (Domayer 2006). In further communication with the personnel from VDOT's AMD, the following information have been gathered about the Cost Data (Domayer 2006):

- The Cost Data includes only routine/ordinary maintenance (i.e. preventive maintenance and restorative maintenance) expenditures. No rehabilitative maintenance (i.e. reconstruction, and major repair/replacement) expenditure is included.
- No district or central office overhead is included in the Cost Data.
- Incident response expenditures are included in the Cost Data if such are coded to the activity codes that are extracted. Snow removal expenditures are captured in the 6XXXX series of activity codes and thus are not included in the Cost Data.
- All labor expenditures (including the labor burden) are included in the Cost Data if they are coded to the activity codes that are extracted.

- Costs of the private contracts (used by VDOT to perform maintenance) are included in the Cost Data if they are charged to county, route and asset but they are not included in the Cost Data if they are charged to a cost center, such as the Public- Private Transportation Act (PPTA) cost center which includes the VMS contract. Cost of maintenance performed by in-house forces (i.e. self-performed work) is included in the Cost Data.

4.2.3.2 Step 2- Data Mining

The raw data obtained for the paved lanes' condition had to be mined in terms of the interstate sections inspected to be able to obtain the portion of it which is to be included in the analysis. The raw data contained condition data for the paved lanes that are maintained by counties that are not within the list of counties presented in **Table 4.26**. Therefore, data mining was performed to extract from the raw data only the paved lanes that are maintained by the counties that are listed in **Table 4.26**. To illustrate an example of the results of this data mining process, **Table 4.27** presents the Fauquier County's Paved Lanes Condition Data (for CCI) as extracted from the raw data for the fiscal year 2002. **Table 4.28** presents just a portion of the Fauquier County's Paved Lanes Condition Data (for IRI) resulting from a similar data mining process for fiscal year 2002. The codes that are used within the tables are explained right below.

Similarly, the publication listing the ADT on the interstate, arterial, and primary routes statewide within Virginia had to be mined to be able to obtain the ADT information that pertain to the counties and interstates that are included in the analysis. This needed to be done for each of the publications listing the ADT information for calendar years 2002, 2003, 2004, and 2005. **Table 4.29** presents the ADT information for Interstate 66 (I-66) that is within the Fauquier County for the calendar years 2002, 2003, 2004, and 2005.

The data obtained for the cost was already in the desired date range and covered only the interstates and counties that are under investigation. As a matter of fact, as Virginia Tech was very specific in terms of what it wants for the Cost Data when such request was made to VDOT's AMD, all data mining was performed by VDOT's AMD. Given this, no further data mining was needed to be performed for the Cost Data. **Table 4.30** presents Fauquier County's Cost Data for fiscal years 2002, 2003, 2004, and 2005 with respect to paved lanes, as received from VDOT's AMD.

Table 4.27: Fauquier County's Paved Lanes Condition Data (for CCI) for Fiscal Year 2002

county	route_type	route_num	route_dir	lanestotal	begin_mp	end_mp	length	Lanemiles	CCI
30	IS	66	E	2	0	4.21	4.21	8.42	90
30	IS	66	E	2	4.21	5.69	1.48	2.96	90
30	IS	66	E	2	5.69	6.3	0.61	1.22	90
30	IS	66	E	2	6.3	7.6	1.3	2.6	100
30	IS	66	E	2	7.6	10.61	3.01	6.02	58
30	IS	66	E	2	10.61	12.8	2.19	4.38	97
30	IS	66	E	2	12.8	13.91	1.11	2.22	62
30	IS	66	E	2	13.91	18.6	4.69	9.38	90
30	IS	66	E	2	18.6	21.21	2.61	5.22	90
30	IS	66	E	2	21.21	21.93	0.72	1.44	90
30	IS	66	W	2	0	5.45	5.45	10.9	52
30	IS	66	W	2	5.45	6.28	0.83	1.66	87
30	IS	66	W	2	6.28	9.86	3.58	7.16	52
30	IS	66	W	2	9.86	11.46	1.6	3.2	68
30	IS	66	W	2	11.46	13.84	2.38	4.76	85
30	IS	66	W	2	13.84	17.91	4.07	8.14	90
30	IS	66	W	2	17.91	19.34	1.43	2.86	90
30	IS	66	W	2	19.34	19.89	0.55	1.1	87
30	IS	66	W	2	19.89	20.64	0.75	1.5	90
30	IS	66	W	2	20.64	21.97	1.33	2.66	87

county: Virginia's county identification number as used by VDOT.
route_type: type of the route whose paved lanes are inspected, i.e. Interstate (IS), Primary (PR), or Secondary (SC).
route_num: the number of the route whose paved lanes are inspected.
route_dir: the direction of the traffic.
lanestotal: the total number of lanes that the route carries and inspected.
begin_mp: the county relative beginning milemarker of the inspected paved lanes.
end_mp: the county relative ending milemarker of the inspected paved lanes.
length: the length of the inspected paved lanes (in miles).
lanemiles: number of lanes*the length of the inspected paved lanes.
CCI: the Critical Condition Index of the inspected paved lanes.

Table 4.28: Fauquier County's Paved Lanes Condition Data (for IRI) for Fiscal Year 2002

County	LaneNumber	Beg MP	End MP	Length	AvgIRI
30	2	0.000	0.100	0.100	75
30	2	0.100	0.200	0.100	77
30	2	0.200	0.300	0.100	63
30	2	0.300	0.400	0.100	78
30	2	0.400	0.500	0.100	76
30	2	0.500	0.600	0.100	77
30	2	0.600	0.709	0.109	62
30	2	0.709	0.800	0.091	66
30	2	0.800	0.910	0.110	73
30	2	0.910	1.000	0.090	70
30	2	1.000	1.100	0.100	64
30	2	1.100	1.170	0.070	64
30	2	1.210	1.300	0.090	79
30	2	1.300	1.400	0.100	55
30	2	1.400	1.500	0.100	69
30	2	1.500	1.600	0.100	63
30	2	1.600	1.700	0.100	86
30	2	1.700	1.800	0.100	85
30	2	1.800	1.900	0.100	64
30	2	1.900	2.000	0.100	74

County: Virginia's county identification number as used by VDOT.
LaneNumber: the total number of lanes that the route carries and inspected.
Beg MP: the county relative beginning milemarker of the inspected paved lanes.
End MP: the county relative ending milemarker of the inspected paved lanes.
Length: the length of the inspected paved lanes (in miles).
AvgIRI: the International Roughness Index of the inspected paved lanes.

Table 4.29: Fauquier County's ADT information for Interstate 66 (I-66)

Calendar Year / County	2002		2003		2004		2005	
	Total Mile	ADT	Total Mile	ADT	Total Mile	ADT	Total Mile	ADT
Fauquier	3.96	16000	3.96	17000	3.96	19000	3.96	19000
	5.21	17000	5.21	18000	5.21	20000	5.21	20000
	3.36	19000	3.36	20000	3.36	23000	3.36	23000
	1.34	20000	1.34	20000	1.34	22000	1.34	22000
	3.02	17000	3.02	17000	3.02	18000	3.02	18000
	5.04	16000	5.04	16000	5.04	19000	5.04	19000

Table 4.30: Fauquier County's Cost Data with respect to Paved Lanes

Route	County	Asset	FY 2002	FY 2003	FY 2004	FY 2005
I0066	Fauquier	400 - Flexible Pavements	$918,673.76	$1,197,059.50	$1,496,471.69	$731,915.97
		430 - Rigid Pavement	$0.00	$0.00	$0.00	$0.00
		Total	$918,673.76	$1,197,059.50	$1,496,471.69	$731,915.97

4.2.3.3 Step 3- Data Cleaning

After the data mining process, the resulting data was investigated for errors and inconsistencies. Such investigation identified only one problem which is related to the area of the paved lanes. As seen in **Table 4.27** and **Table 4.28**, the Paved Lanes Condition Data also presents the total number and length of the lanes for which condition inspections are made. Therefore, the total area of the paved lanes (that are investigated in this implementation example) maintained in a county can be calculated by representing the total lane miles within a county in feet and then multiplying this number with 12 ft as it is the common lane width for interstates. However, when such calculation was made for each county and for each of the yearly data, for some counties it was identified that the total area of the paved lanes within a given county for a year is not the same as the total area within such county for another year. In trying to identify the reason behind this, it was concluded that some years' paved lanes condition data was missing a few records. In other words, there are some cases in which not all of the paved lanes within a county are inspected. This does not have any implication on the overall condition results for a given county as there are just a few sections of the interstate that were not inspected. However, in order to get a correct value for the total area of the paved lanes in a given county, multiple years of data was listed side by side to fill the gaps in a given year (by using for such gap the information obtained from another year's data). This way the final value for the Total Area Served variable for each county was computed.

4.2.3.4 Step 4- Data Conversion/Rearrangement

Once the data was mined and cleaned, it was needed to be converted into the format suitable to represent the variables listed in **Table 4.25**. Moreover, some rearrangements had to be made in the data (e.g. combining data using weights) to make it meet the structuring requirements of the DEA model. These conversions and rearrangements made in the data are discussed below.

4.2.3.4.1 Converting the "Paved Lanes Cost Data" to Represent the Variable "Cost for Maintaining the Paved Lanes"

The cost data provided by VDOT had to go through two conversions to be able to be utilized in the DEA model for the "Paved Lanes":

i. **Conversion to account for Inflation**: The inflation/deflation cost adjustment as discussed in **Section 3.11.1** is applied to the cost data since the analysis includes the cost information belonging to different periods (i.e. different fiscal years). Thus, the cost figures used in the DEA model for "Paved Lanes" incorporate the adjustments made through the utilization of the values listed for the *Composite Bid Price Index for Highway Construction* as shown in **Table 3.9**.

ii. **Conversion to account for Overhead Cost**: Just as in the case for "Bridges", the raw cost data provided by VDOT does not include the overhead cost. Following the same reasoning presented in **Section 4.1.3.4.1**, after the inflation/deflation adjustment was made, the 4.6% overhead rate was applied to the cost data to enhance it and convert it to the "almost complete" total cost. The application of 4.6% overhead rate on the cost data results in the conversion of it to the cost figures that can be used for the variable "Cost for Maintaining the Paved Lanes".

4.2.3.4.2 Rearranging the Interstate ADT Data

Even though ADT is not a variable that is listed in **Table 4.25**, it will be used to decide on which "Regional Effect Variable" (i.e. either the value in Level 1 column or Level 2 column in **Table 4.3**) to assign to the DMU according to its location within Virginia. Thus, even though ADT is not directly included in the DEA study as an input variable, it is still needed to be used indirectly to account for the differences in ADT of the DMUs. Therefore, for each county, a value representing such county's overall ADT needs to be calculated. In **Table 4.29**, the ADT raw data as mined for the Fauquier County for the calendar years 2002, 2003, 2004, and 2005 was presented. As can be seen in such table, there are several ADT values representing the traffic amounts within different portions of the I-66 within the Fauquier County. To be able to roll these values up to the county level, a weighting scheme which uses the mileage as the weight factor was used. **Table 4.31** presents the overall ADT values obtained for the Fauquier County (for I-66) for the calendar years 2002, 2003, 2004, and 2005 after such computation is performed.

Table 4.31: Fauquier County's Overall ADT for Interstate 66 (I-66) for Calendar Years

Calendar Year / County	2002			2003			2004			2005		
	Total Mile	ADT	Overall ADT	Total Mile	ADT	Overall ADT	Total Mile	ADT	Overall ADT	Total Mile	ADT	Overall ADT
Fauquier	3.96	16000	17079	3.96	17000	17651	3.96	19000	19896	3.96	19000	19896
	5.21	17000		5.21	18000		5.21	20000		5.21	20000	
	3.36	19000		3.36	20000		3.36	23000		3.36	23000	
	1.34	20000		1.34	20000		1.34	22000		1.34	22000	
	3.02	17000		3.02	17000		3.02	18000		3.02	18000	
	5.04	16000		5.04	16000		5.04	19000		5.04	19000	

After this was done, another rearrangement was needed. The ADT data is for calendar years. However, as discussed earlier, the DEA model for "Paved Lanes" will use fiscal years for the time unit of analysis. Thus, in an effort to identify the ADT of the DMUs (counties) in a given fiscal year (e.g. Fiscal Year 2005), the previous calendar year's (e.g. Calendar Year 2004) ADT value and current calendar year's (e.g. Calendar Year 2005) ADT value were combined by assigning a 50% weight to each value. This is simply because a given fiscal year (e.g. Fiscal Year 2005) is composed of half of the previous calendar year (e.g. July 1st-December 31st of Calendar Year 2004) and half of the current calendar year (e.g. January 1st-June 30th of Calendar Year 2005). **Table 4.32** presents the ADT values (as computed through this method) that belong to fiscal years 2003, 2004, and 2005 for the Fauquier County (for I-66).

Table 4.32: Fauquier County's Overall ADT for Interstate 66 (I-66) for Fiscal Years

Fiscal Year / County	2003	2004	2005
Fauquier	17365	18773	19896

4.2.3.4.3 Rearranging the "Paved Lanes Condition Data" to Represent the Variables "Change in CCI" and "Change in IRI"

Three different steps of rearrangement had to be performed on the Paved Lanes Condition Data (as described in **Section 4.2.3.1**) to be able to obtain the values that can be used for the variables "Change in CCI" and "Change in IRI" as listed in **Table 4.25**. These steps are as follows:

1) The condition rating for all of the inspected segments of the paved lanes (with respect to both CCI and IRI) within a given county should be combined and rolled up to the county level as the DMU for this implementation example is the county. To do this, a weighting scheme, which considers the area of the individual inspected segments as weight factors, is used. The main reason to use the area as weight factors is the fact that the measurements to identify the CCI and IRI values for the paved lanes are performed along the total area of the paved lanes. **Table 4.33** presents the results of application of such a weighting scheme for the Fauquier County for fiscal years of 2002, 2003, 2004 and 2005 for both CCI and IRI.

Table 4.33: The condition ratings (CCI and IRI) for the Paved Lanes within the Fauquier County at the County Level

County	Fiscal Year	CCI	IRI
Fauquier	2002	79	74
	2003	79	78
	2004	80	69
	2005	80	70

2) The output of the paved lanes maintenance process is not the absolute "Paved Lanes Condition" (represented by CCI and IRI values) attained at the end of a period (i.e. a fiscal year). The output is rather the change in the paved lanes condition within a period. This is mainly because the controllable input, i.e. the money spent to perform maintenance on paved lanes within a period, as well as the uncontrollable inputs, i.e. regional effect and total area served representing the same time period, results in a change of the paved lanes condition within a period as opposed to resulting in the absolute paved lanes condition at the end of a period. For this reason, to be able to calculate the paved lanes maintenance efficiency of the counties for the time period of a fiscal year, one needs to identify for each county: (i) the expenditures made within that time period, (ii) the total area served within that time period (i.e. the total area of the paved lanes within the county), (iii) ADT that is present within that time period to identify- (iv) the regional effect within that time period, and (v) the change in the paved lanes condition within that time period. The last item is, in fact, equal to the difference between the paved lanes condition (represented by CCI and IRI values) at the end of the time period and at the beginning of the time period. For the purposes of this research, as the time unit of analysis is a fiscal year, the paved lanes condition at the beginning of a given fiscal year is assumed to be the paved lanes condition calculated for the previous fiscal year; and the paved lanes condition at the end of a given fiscal year is assumed to be the paved lanes condition calculated for such given fiscal year. **Table 4.34** presents the Change in Paved Lanes Condition represented by CCI and IRI for the Fauquier County for fiscal years 2003, 2004, and 2005.

Table 4.34: Change in Paved Lanes Condition for the Fauquier County

County	Fiscal Year	Change in CCI	Change in IRI
Fauquier	2003	0	4
	2004	1	-9
	2005	0	1

3) As mentioned earlier the value of CCI ranges from 0 to 100, latter corresponding to the best condition. On the other hand, the condition of the paved lanes moves from the best to the worst as the IRI value increases from 0 to larger numbers. Therefore, for an inspected segment of paved lanes to be in good condition, such segment should have a high CCI and a low IRI value. Correspondingly, if the condition of an inspected segment of paved lanes increases over a time period, such segment should have a positive change in its CCI and a negative change in its IRI. Given all of these, it can be stated that a DMU is better off to have a large positive value in its “Change in CCI” variable and a small negative value (i.e. a large absolute value) in its “Change in IRI” variable. Given the opposite behavior of these variables as far as their real life interpretation is concerned, an adjustment needs to be made to make them in line with each other as a DEA model just works with numbers without necessarily considering the interpretations of variables. Therefore, it is decided to multiply the values for the "Change in IRI" variable with -1 to make it behave the same way as the "Change in CCI" variable does as far as a DEA model is concerned. **Table 4.35** shows the results of such adjustment for the Fauquier County.

Table 4.35: Original and Adjusted "Change in IRI" Variable for the Fauquier County

County	Change in IRI	Adjusted Change in IRI
Fauquier	4	-4
	-9	9
	1	-1

Table 4.36 presents the input and output variables' data in addition to the ADT and the Virginia Environmental Region information for the fiscal years of 2003, 2004 and 2005 (the only fiscal years that all relevant data is available for) with respect to each county decided to be included in this study. Such data is obtained by performing all the steps discussed within this section (i.e. **Section 4.2.3**). It is important to note that the Regional Effect Variable was assigned to each county by using each county's environmental region in Virginia (as assigned to it based on its location- see **Figure 4.1**), its ADT and Dadson's findings of the effect of environmental regions on the deterioration of concrete deck. As a matter of fact, since the ADT of all counties are greater than 5000 (the ADT of the Rockbridge County is a little less than 5000 but for practical purposes and for the sake of this implementation example it can also be assumed to be equal to 5000), the effect of environmental regions on the deterioration of concrete deck for Level 2 deterioration (the third column in **Table 4.3**) was used. For the cases where two consecutive fiscal years' CCI data was not available, the "Change in CCI" variable could not be computed and is shown as "N/A" in **Table 4.36**.

Table 4.36: Input and Output Variables' Data for the Fiscal Years of 2003, 2004 and 2005 for Paved Lanes

County	Fiscal Year	Cost for Maintaining the Paved Lanes	VA Environmental Region	ADT	Regional Effect Variable	Total Area Served	Change in CCI	Adjusted Change in IRI
Albemarle	2003	$24,095	Western Piedmont	16243	Medium	7562650	-7	0
	2004	$42,805		16862			6	-3
	2005	$1,103,894		17391			-1	-3
Alleghany	2003	$2,353,764	Central Mountain	6204	Medium	10388506	-1	-2
	2004	$1,261,419		6310			2	8
	2005	$2,420,704		6053			3	1
Augusta	2003	$4,283,514	Central Mountain	22439	Medium	8314099	N/A	5
	2004	$4,170,892		23373			-3	8
	2005	$810,399		23982			6	-1
Fauquier	2003	$1,534,646	Northern	17365	Severe	5557939	0	-4
	2004	$1,861,339		18773			1	9
	2005	$765,584		19896			0	-1
Henrico	2003	$2,739,509	Eastern Piedmont	33710	Medium	7210368	N/A	-5
	2004	$3,152,315		34516			N/A	9
	2005	$3,303,413		36244			17	50
Roanoke	2003	$944,874	Central Mountain	29406	Medium	6797261	-4	-4
	2004	$1,480,185		29709			-6	5
	2005	$1,219,686		29666			3	1
Rockbridge	2003	$1,121,149	Central Mountain	4654	Medium	4115866	N/A	17
	2004	$24,114		4782			N/A	-2
	2005	$20,500		4701			2	-4
Spotsylvania	2003	$971,925	Eastern Piedmont	48872	Medium	5903885	4	11
	2004	$541,702		50823			6	5
	2005	$861,288		52618			10	-4

4.2.4 DEA Model Selection, Final Refinements in Data and Results of DEA

Based on the fact that the Constant Returns to Scale (CRS), which is a special case of the Variable Returns to Scale (VRS), is not that frequently encountered in processes, it can be asserted that the VRS approach is appropriate for the shape of the production possibility set of the inputs and outputs for the paved lanes maintenance process as presented in **Table 4.25**. Thus, it is decided to use the BCC formulation (the formulation with the convexity constraint which is used for the processes which experience VRS) for the DEA model within this implementation example. It is also necessary to decide on the orientation (i.e. input oriented or output oriented) of the model once the type of the model is selected. As discussed in **Section 3.8,** ideally this decision is made based on the dynamics of the process that is analyzed and the choice of the decision makers to seek either input reductions or output increases in the process. However for this study, the decision for the orientation of the model is not based on the decision makers' choice, bur rather it is based on the necessity to address the issue of zero and negative values for the output variable. As can be seen in **Table 4.36**, there is a number of DMUs whose output variables ("Change in CCI" and/or "Adjusted Change in IRI") are either zero or negative[15]. However the original formulations of DEA (CCR and BCC) require all input and output values to be positive (Pastor 1996). To overcome the issue of non-positive data, one can transform the variable which has non-positive values into another variable for all DMUs in the data set. This can be done by adding a value larger than the most negative value to the original values of all DMUs. However if one is to use BCC model; and the negative values are on the output side (the case within this example), such transformation can be made only if the input oriented model is used. In other words, the BCC input oriented model is output translation invariant (i.e. an affine transformation of data can be performed with no impact in the DEA efficiency results). Similarly the BCC output oriented model is input translation invariant (Pastor 1996). Given all of these, the issue of non-positive values in the "Change in CCI" and "Adjusted Change in IRI" variables can be addressed by doing both of the following items:

i) Adding 8 (a value which is larger than the absolute value of the smallest negative value of the "Change in CCI" variable, -7, in the data set) to the "Change in CCI" variable's values for all DMUs to make sure that all values to be used in the DEA model are positive.
ii) Adding 6 (a value which is larger than the absolute value of the smallest negative value of the "Adjusted Change in IRI" variable, -5, in the data set) to the "Adjusted Change in IRI" variable's values for all DMUs to make sure that all values to be used in the DEA model are positive.

However doing so requires the input oriented model to be used. Therefore, the model to be used in this study is input oriented BCC model. This transformation is made for the values of the variables "Change in CCI" and "Adjusted Change in IRI" for all the counties; and newly formed variables are named as the "Modified Change in CCI" and "Modified Change in IRI" respectively.

[15] This means that although resources have been allocated to such DMUs within a given fiscal year, no improvement in the condition (as represented by the "Change in CCI" and/or "Adjusted Change in IRI" variable) of the paved lanes within them is obtained. Moreover, their deteriorations have been in such a rate that they have ended up being in a worse condition at the end of the fiscal year than what they were at the beginning of such fiscal year.

Another refinement that needs to be made in the data is for the “Total Area Served” variable. As can be seen in **Table 4.25**, this is an input variable. However, keeping the values of every other input variable the same, an increase in the value of this variable is likely to result in a decrease in the output variables’ (“Modified Change in CCI” and “Modified Change in IRI”) values as it will be harder to maintain a larger area of paved lanes at the same quality with the same amount of expenditures. Given the detailed discussion presented in **Section 4.1.4** about the isotonicity concept and in an effort to resolve the non-isotonicity issue inherent in the “Total Area Served” variable, the values of that variable for each county is divided to one (i.e. value’s multiplicative inverse is calculated). By this transformation, a direct proportion between this input variable and the output variables is established (i.e. larger the input, larger the output). The newly formed variable is named as the “DMU_{TAS}”.

As the final refinement, the qualitative values in the “Regional Effect Variable” as presented in **Table 4.36** was quantified using the exact same reasoning and approach detailed in **Section 4.1.4** for the implementation example presented for “Bridges”. The newly formed quantitative variable is named as the “$DMU_{REGIONAL\ EFFECT}$”.

Table 4.37.A presents the final refined values for the input and output variables for each county, as transformed to the formats suitable to be used in the input oriented BCC model for “Paved Lanes”. As can be seen in such table, for each county, 3 separate DMUs are derived based on the different input-output data belonging to different fiscal years. Such DMUs are denoted by appropriate subscripts to indicate the fact that even though they belong to the same county, they are different DMUs for the purposes of this implementation example.

Table 4.37.A: Data to be used in the Input Oriented BCC Model for "Paved Lanes"

	Input Data			Output Data	
DMU	Cost for Maintaining the Paved Lanes	DMU REGIONAL EFFECT	DMU TAS	Modified Change in CCI	Modified Change in IRI
Albemarle1	$24,095	2	0.00000013	1	6
Albemarle2	$42,805	2	0.00000013	14	3
Albemarle3	$1,103,894	2	0.00000013	7	3
Alleghany1	$2,353,764	2	0.00000010	7	4
Alleghany2	$1,261,419	2	0.00000010	10	14
Alleghany3	$2,420,704	2	0.00000010	11	7
Augusta1	$4,283,514	2	0.00000012	N/A	11
Augusta2	$4,170,892	2	0.00000012	5	14
Augusta3	$810,399	2	0.00000012	14	5
Fauquier1	$1,534,646	1	0.00000018	8	2
Fauquier2	$1,861,339	1	0.00000018	9	15
Fauquier3	$765,584	1	0.00000018	8	5
Henrico1	$2,739,509	2	0.00000014	N/A	1
Henrico2	$3,152,315	2	0.00000014	N/A	15
Henrico3	$3,303,413	2	0.00000014	25	56
Roanoke1	$944,874	2	0.00000015	4	2
Roanoke2	$1,480,185	2	0.00000015	2	11
Roanoke3	$1,219,686	2	0.00000015	11	7
Rockbridge1	$1,121,149	2	0.00000024	N/A	23
Rockbridge2	$24,114	2	0.00000024	N/A	4
Rockbridge3	$20,500	2	0.00000024	10	2
Spotsylvania1	$971,925	2	0.00000017	12	17
Spotsylvania2	$541,702	2	0.00000017	14	11
Spotsylvania3	$861,288	2	0.00000017	18	2

As can be seen in **Table 4.37.A**, there is a number of DMUs for which the "Modified Change in CCI" variable's value is not calculated (and represented as "N/A"). This is due to the fact that for such DMUs, two consecutive fiscal years' CCI data was not available as discussed earlier. Since DEA needs a valid value for each of the variables used in the model, such DMUs cannot be included in the model. As discussed earlier, *Frontier Analyst* is the software package that is chosen to be used to solve the DEA models developed in this research as it possesses the most professional user interface with the added benefit of numerous visual displays. Once the data is loaded to such software, it enables the user to select the DMUs to be included in the model, lets the user specify which inputs are the controllable inputs and which ones are the uncontrollable ones and the kind of DEA model that is requested to be run in the software.

Figure 4.6 illustrates the screenshot of the software in the step where data is loaded and all of the abovementioned selections are made.

It is important to note that specifying some of the inputs as uncontrollable results in the application of the modified formulation developed by Banker and Morey (1986) (Banker and Morey 1986a) (which is the approach chosen to deal with the uncontrollable factors as discussed at the beginning of this implementation example) by the software's algorithm. **Table 4.38** presents the detailed results of the model as extracted to a spreadsheet. **Table 4.39** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county.

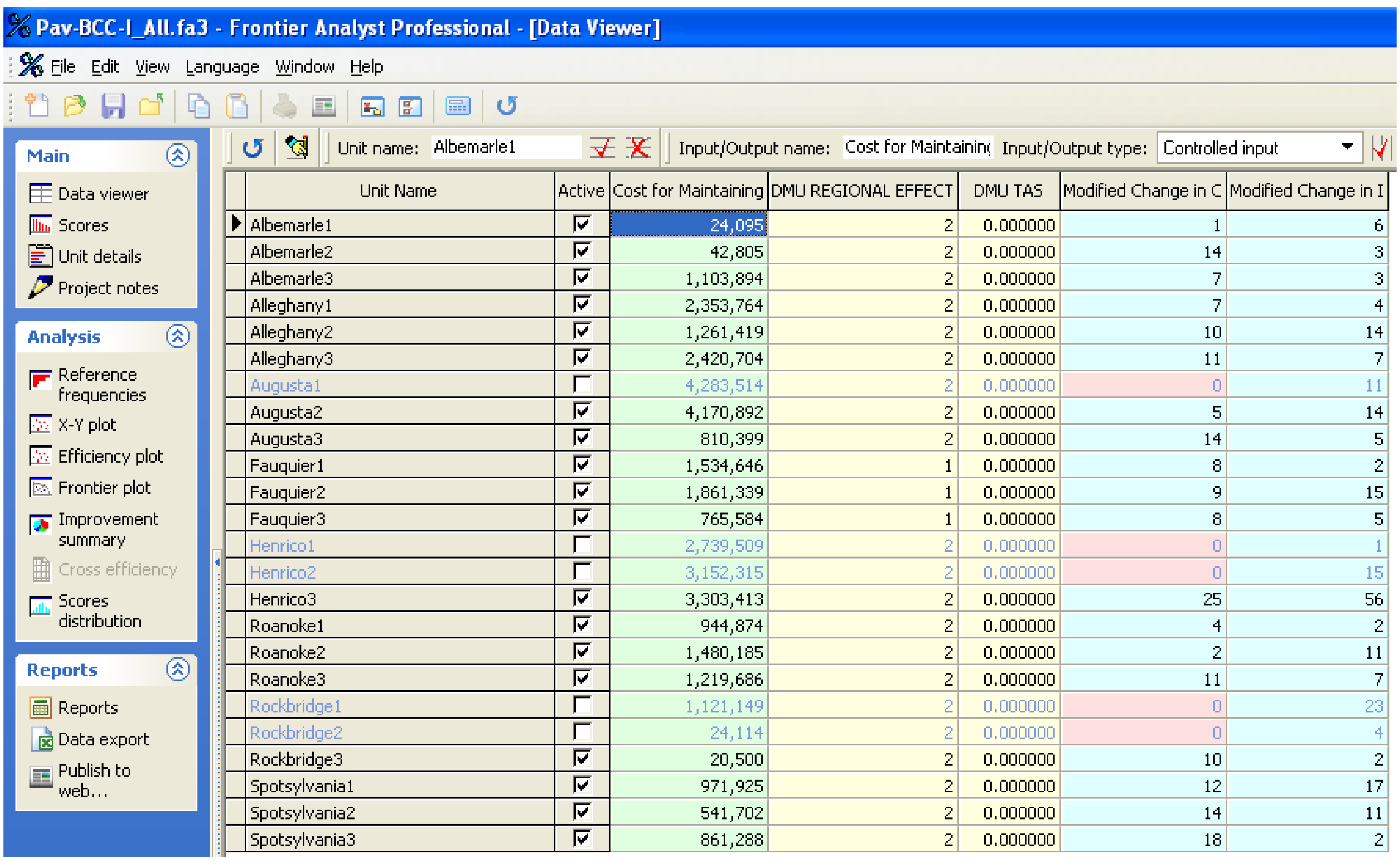


Figure 4.6: Frontier Analyst Data Loading Step Screenshot-Paved Lanes

Table 4.38: Detailed Results of the Input Oriented BCC Model for "Paved Lanes" (as Extracted from the Frontier Analyst)

Unit name	Score	Actual Cost for Maintaining the Pavement	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in CCI	Actual Modified Change in IRI	Target Cost for Maintaining the Pavement	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in CCI	Target Modified Change in IRI	Lambda 1	L-Peer 1	Lambda 2	L-Peer 2	Lambda 3	L-Peer 3
Albemarle1	100.0%	$24,095	2	0.00000013	1	6	$24,095	2	0.00000013	1	6	1.00	Albemarle1				
Albemarle2	100.0%	$42,805	2	0.00000013	14	3	$42,805	2	0.00000013	14	3	1.00	Albemarle2				
Albemarle3	3.0%	$1,103,894	2	0.00000013	7	3	$32,730	2	0.00000013	7	4.62	0.54	Albemarle1	0.46	Albemarle2		
Alleghany1	53.6%	$2,353,764	2	0.00000010	7	4	$1,261,419	2	0.00000010	10	14	1.00	Alleghany2				
Alleghany2	100.0%	$1,261,419	2	0.00000010	10	14	$1,261,419	2	0.00000010	10	14	1.00	Alleghany2				
Alleghany3	100.0%	$2,420,704	2	0.00000010	11	7	$2,420,704	2	0.00000010	11	7	1.00	Alleghany3				
Augusta2	19.4%	$4,170,892	2	0.00000012	5	14	$810,385	2	0.00000012	6.73	14	0.53	Albemarle1	0.37	Alleghany2	0.10	Henrico3
Augusta3	100.0%	$810,399	2	0.00000012	14	5	$810,399	2	0.00000012	14	5	1.00	Augusta3				
Fauquier1	49.9%	$1,534,646	1	0.00000018	8	2	$765,584	1	0.00000018	8	5	1.00	Fauquier3				
Fauquier2	100.0%	$1,861,339	1	0.00000018	9	15	$1,861,339	1	0.00000018	9	15	1.00	Fauquier2				
Fauquier3	100.0%	$765,584	1	0.00000018	8	5	$765,584	1	0.00000018	8	5	1.00	Fauquier3				
Henrico3	100.0%	$3,303,413	2	0.00000014	25	56	$3,303,413	2	0.00000014	25	56	1.00	Henrico3				
Roanoke1	2.7%	$944,874	2	0.00000015	4	2	$25,404	2	0.00000015	4	4.96	0.71	Albemarle1	0.11	Albemarle2	0.18	Rockbridge3
Roanoke2	23.8%	$1,480,185	2	0.00000015	2	11	$352,027	2	0.00000013	3.4	11	0.90	Albemarle1	0.10	Henrico3		
Roanoke3	19.0%	$1,219,686	2	0.00000015	11	7	$231,736	2	0.00000013	11	7	0.28	Albemarle1	0.66	Albemarle2	0.06	Henrico3
Rockbridge3	100.0%	$20,500	2	0.00000024	10	2	$20,500	2	0.00000024	10	2	1.00	Rockbridge3				
Spotsylvania1	85.5%	$971,925	2	0.00000017	12	17	$830,897	2	0.00000013	12	17	0.36	Albemarle1	0.40	Albemarle2	0.24	Henrico3
Spotsylvania2	94.2%	$541,702	2	0.00000017	14	11	$510,197	2	0.00000013	14	11	0.12	Albemarle1	0.74	Albemarle2	0.14	Henrico3
Spotsylvania3	100.0%	$861,288	2	0.00000017	18	2	$861,288	2	0.00000017	18	2	1.00	Spotsylvania3				

Table 4.39: Overall Efficiency Scores of the Counties for "Paved Lanes"

County	Overall Efficiency Score of the County
Albemarle	67.7%
Alleghany	84.5%
Augusta	59.7%
Fauquier	83.3%
Henrico	100.0%
Roanoke	15.2%
Rockbridge	100.0%
Spotsylvania	93.2%

4.2.5 Conclusions

The overall observations that are obtained based on the results of this implementation example are summarized as follows:

1) Out of 19 DMUs, only 10 are 100% efficient.
2) Based on the overall efficiency scores presented in **Table 4.39**, the most efficient counties are the Henrico County and Rockbridge County both of which attain a 100% efficiency score. However, it is important to note that only one DMU for each of these counties was included in the DEA model as discussed in the previous section. The overall efficiency scores of all other counties, but Roanoke County, are within a 40% range from that of the Henrico and Rockbridge counties.
3) Particular county of concern is the Roanoke County, whose DMUs average a 15.2% efficiency.
4) The only county whose DMUs never (whether it is for the fiscal year 2003, 2004, or 2005) get an efficiency score of 100% is the Roanoke County.
5) Albemarle County is the one whose DMUs are most frequently referenced (12 times) as peers by other DMUs (of the same and different counties).
6) The only counties whose DMUs are never referenced by other DMUs is the Augusta County, Roanoke County, and Spotsylvania County.
7) Spotsylvania County consistently improved its efficiency score over the time period of fiscal years 2003, 2004, and 2005.
8) Albemarle County kept its efficiency scores at 100% in the fiscal years 2003 and 2004 but then worsened its efficiency scores drastically to a very low value (3%) in the fiscal year 2005.
9) Alleghany County and Fauquier County increased their efficiency scores drastically from fiscal year 2003 to fiscal year 2004 and kept it at the same level (100%) in fiscal year 2005.

Figure 4.7 presents the peer relationships of the DMUs belonging to each county. Arrows in this figure represent where the inefficient DMUs should search for their peer(s). If an arrow starts at a county and points back, it means that the inefficient DMU(s) in this county should search for efficient DMU(s) within the same county. On the other hand, if an arrow starts at a county (County 1) and points to another county (County 2), it means that the inefficient DMU(s) in this county (County 1) should search for efficient DMU(s) in that other county (County 2).

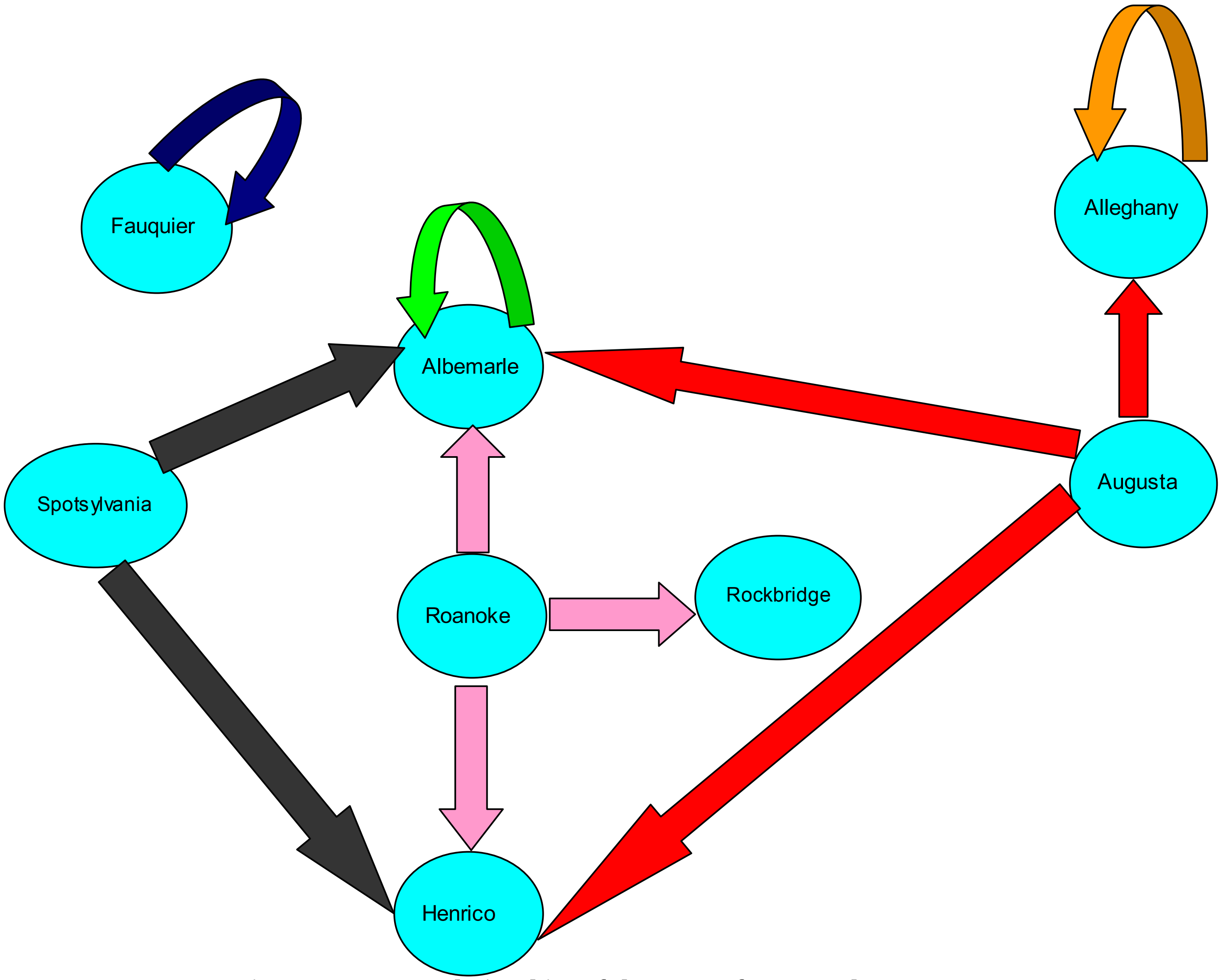


Figure 4.7: Peer Relationships of the DMUs for "Paved Lanes"

As can be seen in **Figure 4.7**, the DMUs belonging to Henrico and Rockbridge counties do not search for a peer within or outside of their counties. This is mainly due to the fact that the DMUs within these counties are 100% efficient as presented in **Table 4.38**. It is important to note that each of these counties is represented by only one DMU in this model due to data availability issues discussed earlier.

As can be seen in **Figure 4.7**, the DMUs that belong to the Albemarle, Alleghany, and Fauquier counties are only looking within their own counties to identify peer DMUs that belong to the same county. This indicates that such counties already have the means in place to be efficient (as each of them has been efficient in two fiscal years out of three) and thus do not need to identify the practices of other counties as best practices. Of these counties, Alleghany and Fauquier counties have drastically increased their efficiency in fiscal year 2004 from low values to 100% and then kept the same efficiency level for the fiscal year 2005 as well. Thus, whatever operational and strategic policy such counties implemented starting in fiscal year 2004 should be kept as is to keep their efficiency at 100% in the future as well.

Albemarle County, on the other hand, has been 100% efficient until the fiscal year 2005 and then drastically dropped its efficiency. To address this sudden efficiency drop, the decision makers within this county (e.g. County Maintenance Administrator) should try to identify the changes that were introduced (in fiscal year 2005) to the operational and/or strategic policies that have been implemented in the previous fiscal years. Such changes are most likely the causes for the efficiency drop. Moreover, the decision makers should observe their own practices and operational and strategic policies belonging to the earlier fiscal years to be able to identify what changes are needed to be implemented to go back to the efficiency levels reached within the earlier fiscal years. Alternatively, this substantial decrease in the efficiency score of the Albemarle County can be attributed to the deferred maintenance approach that the decision makers in such county could have implemented. As discussed in **Section 3.1.2**, deferred maintenance results in faster deterioration; and generally results in increased cost of future maintenance. This could have been the case for Albemarle County. As evidenced by the data and model, even though there was a significant increase in the money spent in fiscal year 2005 over the previous fiscal years, there was not any improvement in the condition of the paved lanes. In other words, such county may look efficient in fiscal years 2003 and 2004 (as represented by the DMUs $Albemarle_1$ and $Albemarle_2$) due to the fact that a very little amount of money was spent for maintenance in that time period due to the deferred maintenance approach that could have been inherent in such county.

It is important to note that the DMUs that belong to the Fauquier County are never referenced by any other county's DMUs even though it has a high overall efficiency score (83.3%) as presented in **Table 4.39**. This can be attributed to the way that BCC formulation works. As the regional effect (which is the combination of environmental and operational effects) on the DMUs belonging to the Fauquier County is significantly different from such effect on the DMUs belonging to the other counties, BCC formulation restricts the peer comparison set of this county only to the DMUs belonging to the same county. For the very same reason, none of the DMUs belonging to the Fauquier County is referenced by the DMUs belonging to other counties.

Spotsylvania County's efficiency has shown a consistent upward trend until it finally reached 100%. Thus, whatever operational and strategic policy Spotsylvania County has been implementing over the fiscal years should be kept as is to keep its efficiency at 100% in the future as well. Same is also the case for the Augusta County.

The most apparent result that can be obtained from this implementation example is with respect to the Roanoke County. In this relative efficiency study in which 19 DMUs that belong to 8 different counties are included, all of the DMUs that belong to the Roanoke County receive very low efficiency scores. This result should definitely raise a red flag for the decision makers within this county. A number of radical measures should be taken to increase the efficiency of the Roanoke County. The very first step to be taken is to identify the peer DMUs for this county's DMUs. As can be seen in **Table 4.38**, the peer DMUs belong to Albemarle, Henrico, and Rockbridge counties. However, identifying $Albemarle_1$ and $Albemarle_2$ as peers (as the DEA results suggest) should be approached with caution. As discussed earlier, such DMUs could be looking efficient just because the decision makers in the Albemarle County implemented a deferred maintenance approach. If that is the case, the decision makers in the Roanoke County may decide not to select $Albemarle_1$ and $Albemarle_2$ as peers since deferred maintenance is not necessarily a good approach. On the other hand, the decision makers of the Roanoke County should work closely with the decision makers of the Henrico and Rockbridge counties to identify the operational and strategic policies and general maintenance practices implemented by them for the fiscal year 2005 in an effort to adopt such practices. It is important to note that the peer DMU that belong to the Henrico County is affected by environmental and operational factors very similar to those that affect the DMUs belonging to the Roanoke County. Therefore, having peer relationships with the Henrico County is of much benefit for the Roanoke County decision makers as they can disregard the effects of environmental and operational factors on the maintenance efficiency while trying to identify the best practices of the Henrico County.

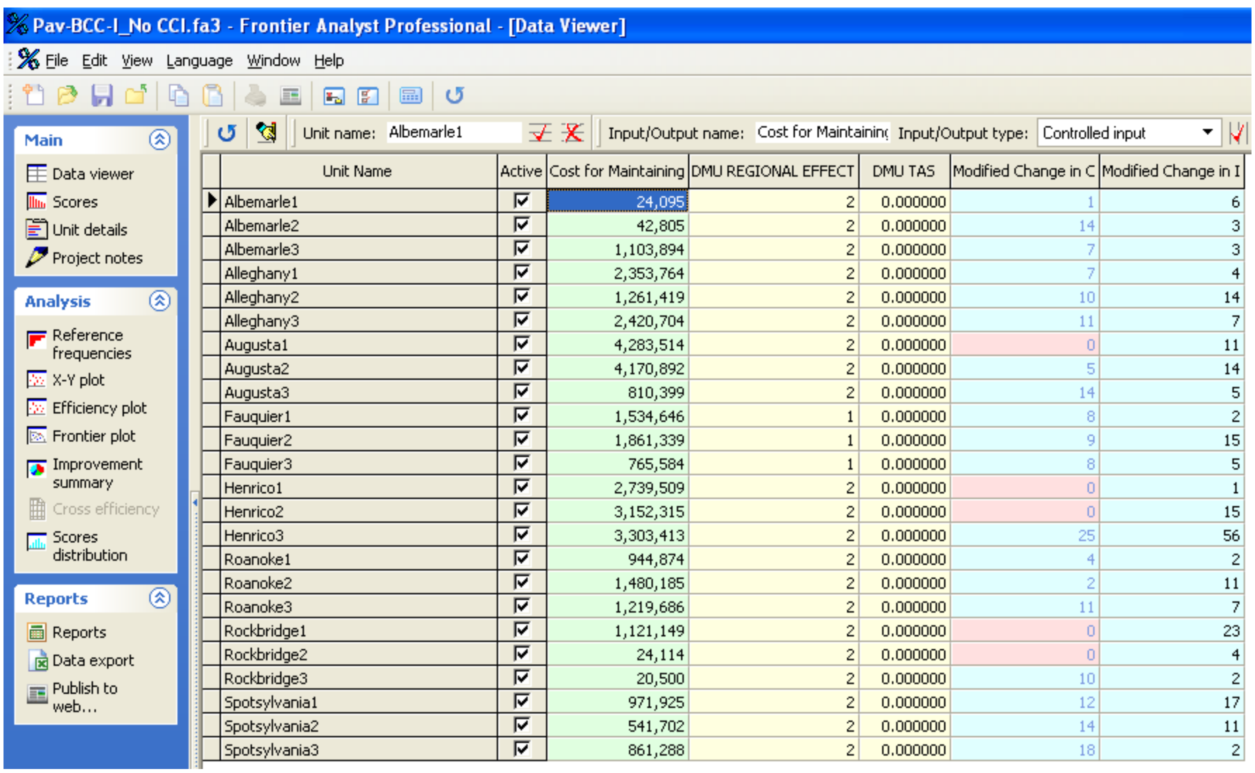
Another apparent and important result of the model is with respect to the Albemarle County and Henrico County. They are the counties whose DMUs are most frequently referenced as peers by the DMUs of other counties. Although the Rockbridge County is as efficient as the Henrico County and much more efficient than the Albemarle County as far as its overall efficiency is concerned (see **Table 4.39**), its DMU is not referenced as frequently as those of the Albemarle County and Henrico County by other counties. Thus, it is recommended that the maintenance management practices within the Albemarle and Henrico counties be investigated more in depth by the upper management of VDOT.

In conclusion, by looking at the results of the model (examining **Table 4.38**, **Table 4.39** and **Figure 4.7**), some county-specific operational and strategic decisions can be made as presented above. It is recommended for VDOT to carefully investigate the practices within the Albemarle County and Henrico County (due to the reason stated in the preceding paragraph) as some very valuable insight can be gained which later may lead to some changes to be implemented all across the state of Virginia.

4.2.6 Analysis Excluding the "Modified Change in CCI" Output Variable

The DEA model for paved lanes as discussed above did not include all of the DMUs that could possibly be included in the model. Due to the fact that some of the counties were missing the necessary data to compute the "Modified Change in CCI" output variable for all fiscal years included in the analysis (i.e. 2003, 2004, and 2005), a number of DMUs belonging to such counties could not be included in the model. This resulted in Henrico and Rockbridge counties to be represented by one DMU and Augusta County to be represented by two DMUs in the model as opposed to the other counties represented by three DMUs. Thus for these counties, the results of the DEA model may not be as conclusive as that for other counties. This is especially the case for the Rockbridge County. When the data for its only DMU, Rockbridge_3 is investigated it can be seen that such DMU spent a very little amount of money for the maintenance of its paved lanes in fiscal year 2005, which in turn resulted in an efficiency score of 100%. Nonetheless, this could be because such county could also be implementing a deferred maintenance approach as discussed for the Albemarle County. However, given the fact that only one fiscal year's DMU is included in the DEA model for this county, it is difficult to make a determination to that extent. In conclusion each county should be given the same opportunity to represent itself through the same number of DMUs to be able to make further analysis and to draw further conclusions. To be able to do this though, the variable for which data is not available for the abovementioned counties for all fiscal years should be removed from the analysis.

This section presents a second DEA model for the paved lanes in which "Modified Change in CCI" variable is removed from the analysis. As can be seen in **Figure 4.8**, *Frontier Analyst* allows for the removal of any variable from the analysis as it allows for the exclusion of any DMU as was shown in **Figure 4.6**. Running the input oriented BCC model (this time excluding the "Modified Change in CCI" variable from the model) led to the results shown in **Table 4.40.A**. **Table 4.41.A** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county.



Unit Name	Active	Cost for Maintaining	DMU REGIONAL EFFECT	DMU TAS	Modified Change in C	Modified Change in I
Albemarle1	☑	24,095	2	0.000000	1	6
Albemarle2	☑	42,805	2	0.000000	14	3
Albemarle3	☑	1,103,894	2	0.000000	7	3
Alleghany1	☑	2,353,764	2	0.000000	7	4
Alleghany2	☑	1,261,419	2	0.000000	10	14
Alleghany3	☑	2,420,704	2	0.000000	11	7
Augusta1	☑	4,283,514	2	0.000000	0	11
Augusta2	☑	4,170,892	2	0.000000	5	14
Augusta3	☑	810,399	2	0.000000	14	5
Fauquier1	☑	1,534,646	1	0.000000	8	2
Fauquier2	☑	1,861,339	1	0.000000	9	15
Fauquier3	☑	765,584	1	0.000000	8	5
Henrico1	☑	2,739,509	2	0.000000	0	1
Henrico2	☑	3,152,315	2	0.000000	0	15
Henrico3	☑	3,303,413	2	0.000000	25	56
Roanoke1	☑	944,874	2	0.000000	4	2
Roanoke2	☑	1,480,185	2	0.000000	2	11
Roanoke3	☑	1,219,686	2	0.000000	11	7
Rockbridge1	☑	1,121,149	2	0.000000	0	23
Rockbridge2	☑	24,114	2	0.000000	0	4
Rockbridge3	☑	20,500	2	0.000000	10	2
Spotsylvania1	☑	971,925	2	0.000000	12	17
Spotsylvania2	☑	541,702	2	0.000000	14	11
Spotsylvania3	☑	861,288	2	0.000000	18	2

Figure 4.8: Frontier Analyst Data Loading Step Screenshot-Paved Lanes without "Modified Change in CCI" Variable

Table 4.40.A: Detailed Results of the Input Oriented BCC Model for "Paved Lanes" without "Modified Change in CCI" Variable (as Extracted from the Frontier Analyst)

Unit name	Score	Actual Cost for Maintaining the Pavement	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in IRI	Target Cost for Maintaining the Pavement	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in IRI	Lambda 1	L-Peer 1	Lambda 2	L-Peer 2	Lambda 3	L-Peer 3
Albemarle1	100.0%	$24,095	2	0.00000013	6	$24,095	2	0.00000013	6	1.00	Albemarle1				
Albemarle2	56.3%	$42,805	2	0.00000013	3	$24,095	2	0.00000013	6	1.00	Albemarle1				
Albemarle3	2.2%	$1,103,894	2	0.00000013	3	$24,095	2	0.00000013	6	1.00	Albemarle1				
Alleghany1	53.6%	$2,353,764	2	0.00000010	4	$1,261,419	2	0.00000010	14	1.00	Alleghany2				
Alleghany2	100.0%	$1,261,419	2	0.00000010	14	$1,261,419	2	0.00000010	14	1.00	Alleghany2				
Alleghany3	52.1%	$2,420,704	2	0.00000010	7	$1,261,419	2	0.00000010	14	1.00	Alleghany2				
Augusta1	14.0%	$4,283,514	2	0.00000012	11	$600,095	2	0.00000012	11	0.61	Albemarle1	0.35	Alleghany2	0.04	Henrico3
Augusta2	19.4%	$4,170,892	2	0.00000012	14	$810,385	2	0.00000012	14	0.53	Albemarle1	0.37	Alleghany2	0.10	Henrico3
Augusta3	53.9%	$810,399	2	0.00000012	5	$436,536	2	0.00000012	8.67	0.67	Albemarle1	0.33	Alleghany2		
Fauquier1	49.9%	$1,534,646	1	0.00000018	2	$765,584	1	0.00000018	5	1.00	Fauquier3				
Fauquier2	100.0%	$1,861,339	1	0.00000018	15	$1,861,339	1	0.00000018	15	1.00	Fauquier2				
Fauquier3	100.0%	$765,584	1	0.00000018	5	$765,584	1	0.00000018	5	1.00	Fauquier3				
Henrico1	0.9%	$2,739,509	2	0.00000014	1	$23,768	2	0.00000014	5.64	0.91	Albemarle1	0.09	Rockbridge3		
Henrico2	19.5%	$3,152,315	2	0.00000014	15	$612,994	2	0.00000014	15	0.77	Albemarle1	0.15	Henrico3	0.08	Rockbridge1
Henrico3	100.0%	$3,303,413	2	0.00000014	56	$3,303,413	2	0.00000014	56	1.00	Henrico3				
Roanoke1	2.5%	$944,874	2	0.00000015	2	$23,442	2	0.00000015	5.27	0.82	Albemarle1	0.18	Rockbridge3		
Roanoke2	23.6%	$1,480,185	2	0.00000015	11	$348,834	2	0.00000015	11	0.78	Albemarle1	0.04	Henrico3	0.18	Rockbridge1
Roanoke3	7.3%	$1,219,686	2	0.00000015	7	$88,628	2	0.00000013	7	0.94	Albemarle1	0.06	Rockbridge1		
Rockbridge1	100.0%	$1,121,149	2	0.00000024	23	$1,121,149	2	0.00000024	23	1.00	Rockbridge1				
Rockbridge2	92.5%	$24,114	2	0.00000024	4	$22,298	2	0.00000019	4	0.50	Albemarle1	0.50	Rockbridge3		
Rockbridge3	100.0%	$20,500	2	0.00000024	2	$20,500	2	0.00000024	2	1.00	Rockbridge3				
Spotsylvania1	76.1%	$971,925	2	0.00000017	17	$739,193	2	0.00000017	17	0.55	Albemarle1	0.10	Henrico3	0.35	Rockbridge1
Spotsylvania2	64.0%	$541,702	2	0.00000017	11	$346,758	2	0.00000016	11	0.71	Albemarle1	0.29	Rockbridge1		
Spotsylvania3	2.7%	$861,288	2	0.00000017	2	$22,788	2	0.00000017	4.55	0.64	Albemarle1	0.36	Rockbridge3		

Table 4.41.A: Overall Efficiency Scores of the Counties for "Paved Lanes" without "Modified Change in CCI" Variable

County	Overall Efficiency Score of the County
Albemarle	52.8%
Alleghany	68.6%
Augusta	29.1%
Fauquier	83.3%
Henrico	40.1%
Roanoke	11.1%
Rockbridge	97.5%
Spotsylvania	47.6%

The overall observations that are obtained based on the results of this implementation example are summarized as follows:

1) Out of 19 DMUs, only 7 are 100% efficient.
2) Based on the overall efficiency scores presented in **Table 4.41.A**, the most efficient County is the Rockbridge County which attains a 97.5% efficiency score.
3) Particular county of concern is the Roanoke County, whose DMUs average an 11.1% efficiency.
4) The only counties whose DMUs never (whether it is for the fiscal year 2003, 2004, or 2005) get an efficiency score of 100% is Augusta County, Roanoke County, and Spotsylvania County.
5) Albemarle County is the one whose DMUs are most frequently referenced (14 times) as peers by other DMUs (of the same and different counties).
6) The only counties whose DMUs are never referenced by other DMUs is the Augusta County, Roanoke County, and Spotsylvania County.
7) Augusta County and Henrico County consistently improved their efficiency scores over the time period of fiscal years 2003, 2004, and 2005.
8) Albemarle County and Spotsylvania County consistently worsened their efficiency scores over the time period of fiscal years 2003, 2004, and 2005.
9) Fauquier County increased its efficiency scores drastically from fiscal year 2003 to fiscal year 2004 and kept it at the same level (100%) in fiscal year 2005.

Figure 4.9 presents the peer relationships of the DMUs belonging to each county. Arrows in this figure represent where the inefficient DMUs should search for their peer(s). If an arrow starts at a county and points back, it means that the inefficient DMU(s) in this county should search for efficient DMU(s) within the same county. On the other hand, if an arrow starts at a county (County 1) and points to another county (County 2), it means that the inefficient DMU(s) in this county (County 1) should search for efficient DMU(s) in that other county (County 2).

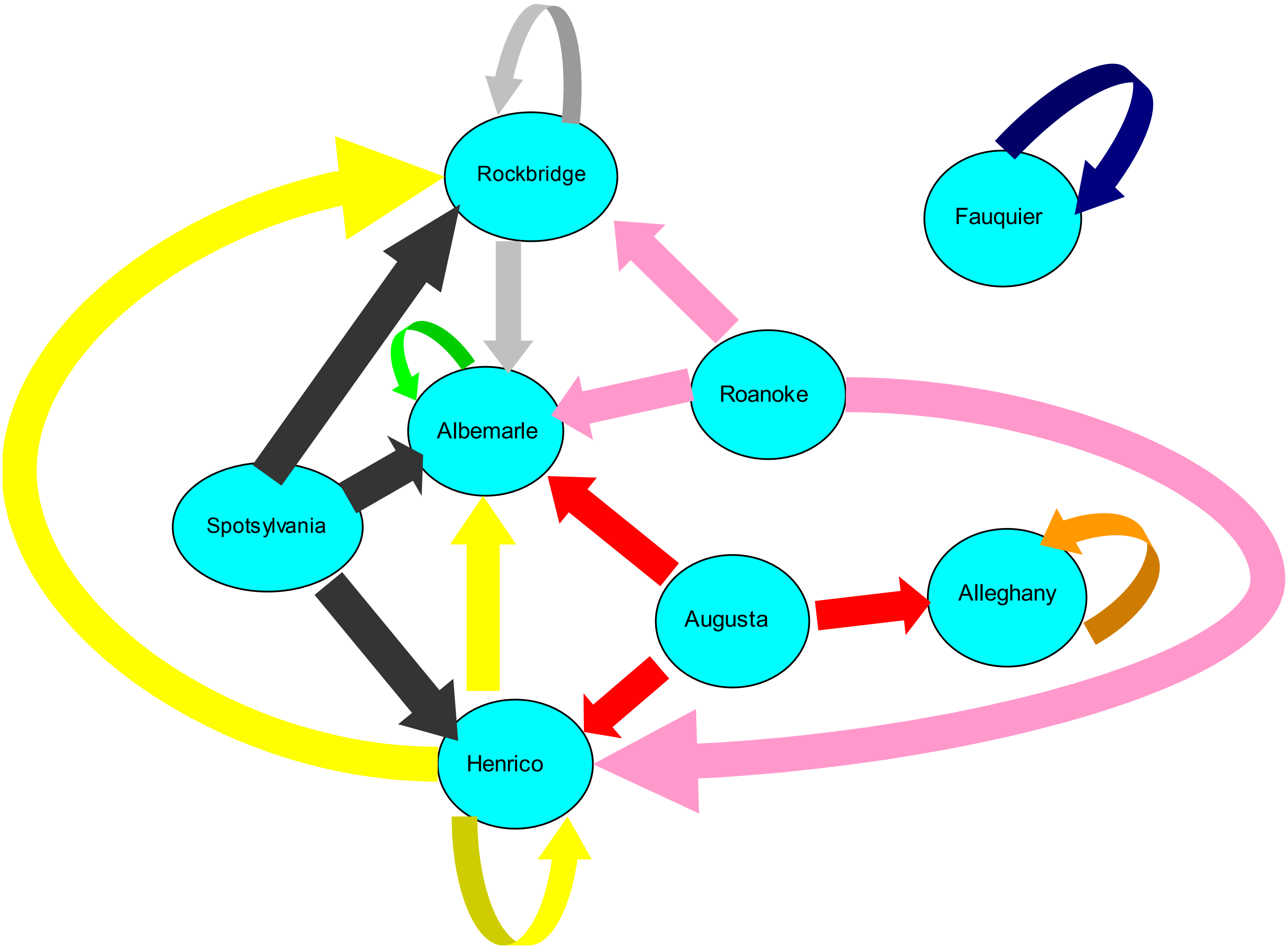


Figure 4.9: Peer Relationships of the DMUs for "Paved Lanes" without "Modified Change in CCI" Variable

As can be seen in **Figure 4.9**, the DMUs that belong to the Albemarle, Alleghany, and Fauquier counties are only looking within their own counties to identify peer DMUs that belong to the same county. This indicates that such counties already have the means in place to be efficient (as each of them has been efficient in one or two fiscal years) and thus do not need to identify the practices of other counties as best practices. Of these counties, Fauquier County has drastically increased its efficiency in fiscal year 2004 from 49.9% to 100% and then kept the same efficiency level for the fiscal year 2005 as well. Thus, whatever operational and strategic policy such county implemented starting in fiscal year 2004 should be kept as is to keep its efficiency at 100% in the future as well. Similarly, Alleghany County increased its efficiency in fiscal year 2004 from 53.6% to 100%. However its efficiency did not stay at the same level in fiscal year 2005, dropping back to 52.1%. To address this issue, the decision makers within the Alleghany County should observe their own practices and operational and strategic policies belonging to the fiscal year 2004 (when such county was 100% efficient) to be able to identify what changes are needed to be implemented to go back to the efficiency level reached within fiscal year 2004.

Albemarle County, on the other hand, has been 100% efficient in fiscal year 2003 and thereafter started to drop its efficiency, finally down to 2.2% in fiscal year 2005. To address this continuous efficiency drop, the decision makers within this county (e.g. County Maintenance Administrator) should try to identify the changes that were introduced (starting with fiscal year 2004) to the operational and/or strategic policies that have been implemented in fiscal year 2003. Such changes are most likely the causes for the efficiency drop. Moreover, the decision makers should observe their own practices and operational and strategic policies belonging to the fiscal year 2003 to be able to identify what changes are needed to be implemented to go back to the efficiency levels reached within such fiscal year. Alternatively, the substantial decrease in the efficiency score of the Albemarle County, especially in fiscal year 2005, can be attributed to the deferred maintenance approach that the decision makers in such county could have implemented. As discussed in **Section 3.1.2**, deferred maintenance results in faster deterioration; and generally results in increased cost of future maintenance. This could have been the case for Albemarle County. As evidenced by the data and model, even though there was a significant increase in the money spent in fiscal year 2005 over the previous fiscal years, there was not any improvement in the condition of the paved lanes. In other words, such county may look more efficient in fiscal years 2003 and 2004 (as represented by the DMUs Albemarle_1 and Albemarle_2) due to the fact that a very little amount of money was spent for maintenance in that time period due to the deferred maintenance approach that could have been inherent in such county. Similarly the continuous efficiency drop within this county can be attributed to the deferred maintenance approach that may be inherent in this county.

It is important to note that the DMUs that belong to the Fauquier County are never referenced by any other county's DMUs even though it is the second most efficient county based on the overall efficiency scores presented in **Table 4.41.A**. This can be attributed to the way that

BCC formulation works. As the regional effect (which is the combination of environmental and operational effects) on the DMUs belonging to the Fauquier County is significantly different from such effect on the DMUs belonging to the other counties, BCC formulation restricts the peer comparison set of this county only to the DMUs belonging to the same county. For the very same reason, none of the DMUs belonging to the Fauquier County is referenced by the DMUs belonging to other counties.

Henrico County's efficiency has shown a consistent upward trend until it finally reached 100%. Thus, whatever operational and strategic policy Henrico County has been implementing over the fiscal years should be kept as is to keep its efficiency at 100% in the future as well.

Augusta County has also experienced an upward trend over the fiscal years. Nonetheless, it still needs a lot of improvement as evidenced by its efficiency score for the fiscal year 2005 which is 53.9%. To identify the areas for improvement, Augusta County should work with its peers (for the DMU representing the fiscal year 2005 performance of the Augusta County ($Augusta_3$)) $Albemarle_1$ and $Alleghany_2$. This way, necessary changes can be made by the decision makers of the Augusta County as far as its operational and strategic policy is concerned. This change requires a deeper analysis and observation of the operational and strategic policies and general maintenance practices of Albemarle and Alleghany counties for fiscal years 2003 and 2004 respectively. However, identifying $Albemarle_1$ as one of its peers (as the DEA results suggest) should be approached with caution. As discussed earlier, such DMU could be looking efficient just because the decision makers in the Albemarle County implemented a deferred maintenance approach. If that is the case, the decision makers in the Augusta County may decide not to select $Albemarle_1$ as a peer since deferred maintenance is not necessarily a good approach.

Contrary to Henrico and Augusta counties, Spotsylvania County has experienced a downward trend in its efficiency, ending with an efficiency of 2.7% in fiscal year 2005. To address this, it should work with its peers (for the DMU representing the fiscal year 2005 performance of the Spotsylvania County ($Spotsylvania_3$)) $Albemarle_1$ and $Rockbridge_3$. This way, necessary changes can be made by the decision makers of the Spotsylvania County as far as its operational and strategic policy is concerned. This change requires a deeper analysis and observation of the operational and strategic policies and general maintenance practices of Albemarle and Rockbridge counties for fiscal years 2003 and 2005 respectively. However, identifying $Albemarle_1$ as one of its peers (as the DEA results suggest) should be approached with caution. As discussed earlier, such DMU could be looking efficient just because the decision makers in the Albemarle County implemented a deferred maintenance approach. If that is the case, the decision makers in the Spotsylvania County may decide not to select $Albemarle_1$ as a peer since deferred maintenance is not necessarily a good approach.

Rockbridge County is the most efficient county based on the overall efficiency scores presented in **Table 4.41.A**. Such county also consistently has very high efficiency scores, without any substantial increase or decrease in its efficiency scores over different fiscal years. Also in the DEA model (which includes the "Modified Change in CCI" variable) presented in the previous section, this county was identified to be the most efficient one. However, at that time, the validity of such conclusion was questioned as such county was represented with only one DMU. Nonetheless, the results of this model run confirm that this county is the most efficient one in maintaining the paved lanes. As a matter of fact, the only peer for this county (other than itself) is $Albemarle_1$, which does not necessarily need to be identified as a peer if it is implementing deferred maintenance approach as discussed earlier. The issue of whether Rockbridge County is implementing deferred maintenance approach or not cannot be addressed by this model too as there is not sufficient number of data points (i.e. fiscal years) to investigate that.

The most apparent result that can be obtained from this implementation example is with respect to the Roanoke County. In this relative efficiency study in which 24 DMUs that belong to 8 different counties are included, all of the DMUs that belong to the Roanoke County receive very low efficiency scores. This result should definitely raise a red flag for the decision makers within this county. A number of radical measures should be taken to increase the efficiency of the Roanoke County. The very first step to be taken is to identify the peer DMUs for this county's DMUs. As can be seen in **Table 4.38**, the peer DMUs belong to Albemarle, Henrico, and Rockbridge counties. However, identifying $Albemarle_1$ as one of its peers (as the DEA results suggest) should be approached with caution. As discussed earlier, such DMU could be looking efficient just because the decision makers in the Albemarle County implemented a deferred maintenance approach. If that is the case, the decision makers in the Roanoke County may decide not to select $Albemarle_1$ as a peer since deferred maintenance is not necessarily a good approach. On the other hand, the decision makers of the Roanoke County should work closely with the decision makers of the Rockbridge County to identify the operational and strategic policies and general maintenance practices implemented by them for the fiscal year 2003 and 2005 in an effort to adopt such practices. Similarly, the decision makers of the Roanoke County should work closely with the decision makers of the Henrico County to identify the operational and strategic policies and general maintenance practices implemented by them for the fiscal year 2005 in an effort to adopt such practices. It is important to note that the peer DMU that belong to the Henrico County is affected by environmental and operational factors very similar to those that affect the DMUs belonging to the Roanoke County. Therefore, having peer relationships with the Henrico County is of much benefit for the Roanoke County decision makers as they can disregard the effects of environmental and operational factors on the maintenance efficiency while trying to identify the best practices of the Henrico County.

Another apparent and important result of the model is with respect to the Albemarle County. It is the county whose DMUs are most frequently referenced as peers by the DMUs of other counties. Although Alleghany, Fauquier, and Rockbridge counties' overall efficiency scores are higher than that of Albemarle County, such counties' DMUs are not referenced as frequently as those of the Albemarle County by other counties. Thus, it is recommended that the maintenance management practices within the Albemarle County be investigated more in depth by the upper management of VDOT.

In conclusion, by looking at the results of the model (examining **Table 4.40.A**, **Table 4.41.A** and **Figure 4.9**), some county-specific operational and strategic decisions can be made as presented above. It is recommended for VDOT to carefully investigate the practices within the Albemarle County (due to the reason stated in the preceding paragraph) as some very valuable insight can be gained which later may lead to some changes to be implemented all across the state of Virginia.

4.2.7 Comparison of the Results of the 2 DEA Models for the Paved Lanes and Overall Conclusions

As presented in the preceding sections, two separate DEA models are produced for the "Paved Lanes" element. The first model, referred to as Model 1 henceforth within this section, utilized all of the input-output variables but did not incorporate a number of DMUs. The second model, referred to as Model 2 henceforth within this section, incorporated all the DMUs but excluded the "Modified Change in CCI" variable from the analysis. An ideal model would be the one which incorporates all of the input-output variables and DMUs decided to be utilized for this implementation example. Unfortunately that was not possible as there was not sufficient data to do so. Nonetheless, an effort should be made to generate some valid conclusions using the results of the both models. As a matter of fact, between the two models, some important conclusions can be drawn, at least for a number of counties as listed below:

1) The first and foremost conclusion can be drawn for the Roanoke County. Both models identify such county as the least efficient county. Moreover, both models identify the same peers for this county.
2) While discussing the results of the Model 1, it was brought up that it is likely that the Albemarle County is implementing a deferred maintenance approach. The results of Model 2 also suggest the same. It is important to note that even though both models confirm each other for this result, this assertion still needs verification from the decision makers within such county.
3) Even though the only DMU representing the Rockbridge County was identified as the most efficient county (along with the Henrico County) by Model 1, the applicability of this result to the Rockbridge County in general was questioned mainly due to the fact that the only DMU representing such county spent a very little amount of money for the maintenance of its paved lanes in fiscal year 2005, which could be an indicator of deferred maintenance practices. Nonetheless, such county is identified as the most efficient county in Model 2 as well. However, the issue of whether such county is implementing deferred maintenance approach or not cannot be addressed by both of the models as there is not sufficient number of data points (i.e. fiscal years) to investigate that.
4) Just like the Rockbridge County, Henrico County was also represented by just one DMU in Model 1. Thus, even though such DMU received an efficiency score of 100%, its applicability to the Henrico County in general was questioned. Model 2 resulted in an overall efficiency score of 40.1% for this county, supporting the assertion that the results of the Model 1 for this county may not be representative of the actual efficiency of this county. Therefore, it can be concluded that this county is not the most efficient one as far as maintaining the paved lanes is concerned.

5) Even though the DMUs belonging to the Fauquier County are not referenced by the DMUs belonging to any other county (due to the reason explained numerous times earlier), the results of Model 1 and Model 2 confirm that such county is in the top tier as far as its overall paved lanes maintenance efficiency is concerned.
6) As evidenced by the efficiency scores and the differences in such scores obtained through the implementation of the DEA models, there are differences between the counties of Virginia as far as their "paved lanes" maintenance efficiencies are concerned. Therefore, the results of the DEA models presented herein confirm the validity of the first hypothesis of this research (as presented in **Chapter 1**) which is: "Within the state of Virginia, some counties are more efficient than others in performing highway maintenance operations."

4.2.8 Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency

As was presented in **Chapter 1**, the framework developed by this research is aimed to measure the relative efficiency of different units (performing highway maintenance) while considering the effects of environmental and operational factors (both of which are beyond the control of the decision-maker, i.e., the maintenance manager) on such efficiency. Consequently, all of the DEA implementation examples (for paved lanes) that are presented so far have taken the effects of the environmental and operational uncontrollable factors on the efficiency into consideration; and thus intrinsically accounted for (and thus removed) the amount of inefficiency resulting from such uncontrollable factors, as the framework developed in **Chapter 3** incorporates them into the DEA model as uncontrollable variables.

This section presents a modified version of the DEA model run presented in **Section 4.2.6** (whose results are presented in **Table 4.40.A**). In such version, the uncontrollable variables for all DMUs are assigned the same value with the purpose of testing the second hypothesis of this research which is: "Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties." Assigning the same value to the uncontrollable variables for all DMUs means that all DMUs are experiencing the same uncontrollable factors. Therefore, a DEA model that is run with such values represents the case where the differences between the environmental and operational factors experienced by each DMU are neglected. This, in effect, is the same as not acknowledging the effects of the environmental and operational factors on the efficiency of the DMUs and thus not accounting for the amount of inefficiency created by such factors. The reason that the uncontrollable variables are not completely removed from the model but instead assigned the same value is to keep the number of variables unchanged. This way, the results of the two models (the one acknowledging the effects of uncontrollable factors on the efficiency of units and the one ignoring such) can be comparable as both models contain the same number of variables. In other words, one can attribute all of the efficiency differences (in the same DMUs) between the two models to the effects of the uncontrollable factors as artificial efficiency changes that could be resulting from the change in the number of variables (due to the way that the DEA works as detailed in **Section 3.6**) between the two models are prevented with such approach.

Table 4.37.B presents the variable data for 24 DMUs to be used in the DEA model for the paved lanes which ignores the effects of uncontrollable factors (and thus which does not account for the amount of inefficiency created by such) by assigning the same value to the uncontrollable variables for all DMUs. The data for such table is different from the one presented in **Table 4.37.A** with respect to 2 items: (i) **Table 4.37.B** does not include the "Modified Change in CCI" variable as this model is in line with the model presented in **Section 4.2.6** and (ii) the values for $DMU_{REGIONAL\ EFFECT}$ and DMU_{TAS} variables (the uncontrollable variables in the model) are assigned the same value of "1". It is important to note that any other value could have been chosen to be assigned to these variables as the results of the DEA model are not affected with that particular value as long as such value is assigned to all DMUs.

Table 4.37.B: Data to be used in the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency

	Input Data			Output Data
DMU	Cost for Maintaining the Paved Lanes	DMU REGIONAL EFFECT	DMU TAS	Modified Change in IRI
Albemarle1	$24,095	1	1	6
Albemarle2	$42,805	1	1	3
Albemarle3	$1,103,894	1	1	3
Alleghany1	$2,353,764	1	1	4
Alleghany2	$1,261,419	1	1	14
Alleghany3	$2,420,704	1	1	7
Augusta1	$4,283,514	1	1	11
Augusta2	$4,170,892	1	1	14
Augusta3	$810,399	1	1	5
Fauquier1	$1,534,646	1	1	2
Fauquier2	$1,861,339	1	1	15
Fauquier3	$765,584	1	1	5
Henrico1	$2,739,509	1	1	1
Henrico2	$3,152,315	1	1	15
Henrico3	$3,303,413	1	1	56
Roanoke1	$944,874	1	1	2
Roanoke2	$1,480,185	1	1	11
Roanoke3	$1,219,686	1	1	7
Rockbridge1	$1,121,149	1	1	23
Rockbridge2	$24,114	1	1	4
Rockbridge3	$20,500	1	1	2
Spotsylvania1	$971,925	1	1	17
Spotsylvania2	$541,702	1	1	11
Spotsylvania3	$861,288	1	1	2

Table 4.40.B presents the detailed results of this model as extracted to a spreadsheet. **Table 4.41.B** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county. **Table 4.40.C** presents the efficiency scores of the DMUs obtained from both DEA models (i.e., the one that acknowledges the effects of the uncontrollable factors and the one that ignores those) side by side for comparison purposes. Similarly, **Table 4.41.C** presents the overall efficiency scores of the counties obtained from both DEA models (i.e., the one that acknowledges the effects of the uncontrollable factors and the one that ignores those) side by side for comparison purposes.

Table 4.40.B: Detailed Results of the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency

Unit name	Score	Actual Cost for Maintaining the Pavement	Actual DMU REGIONAL EFFECT	Actual DMU TAS	Actual Modified Change in IRI	Target Cost for Maintaining the Pavement	Target DMU REGIONAL EFFECT	Target DMU TAS	Target Modified Change in IRI	Lambda 1	L-Peer 1	Lambda 2	L-Peer 2
Albemarle1	100.0%	$24,095	1	1	6	$24,095	1	1	6	1.00	Albemarle1		
Albemarle2	50.0%	$42,805	1	1	3	$21,399	1	1	3	0.25	Albemarle1	0.75	Rockbridge3
Albemarle3	1.9%	$1,103,894	1	1	3	$21,399	1	1	3	0.25	Albemarle1	0.75	Rockbridge3
Alleghany1	1.0%	$2,353,764	1	1	4	$22,298	1	1	4	0.50	Albemarle1	0.50	Rockbridge3
Alleghany2	42.8%	$1,261,419	1	1	14	$540,356	1	1	14	0.53	Albemarle1	0.47	Rockbridge1
Alleghany3	3.7%	$2,420,704	1	1	7	$88,628	1	1	7	0.94	Albemarle1	0.06	Rockbridge1
Augusta1	8.1%	$4,283,514	1	1	11	$346,758	1	1	11	0.71	Albemarle1	0.29	Rockbridge1
Augusta2	13.0%	$4,170,892	1	1	14	$540,356	1	1	14	0.53	Albemarle1	0.47	Rockbridge1
Augusta3	2.9%	$810,399	1	1	5	$23,197	1	1	5	0.75	Albemarle1	0.25	Rockbridge3
Fauquier1	1.3%	$1,534,646	1	1	2	$20,500	1	1	2	1.00	Rockbridge3		
Fauquier2	32.5%	$1,861,339	1	1	15	$604,889	1	1	15	0.47	Albemarle1	0.53	Rockbridge1
Fauquier3	3.0%	$765,584	1	1	5	$23,197	1	1	5	0.75	Albemarle1	0.25	Rockbridge3
Henrico1	0.8%	$2,739,509	1	1	1	$20,500	1	1	2	1.00	Rockbridge3		
Henrico2	19.2%	$3,152,315	1	1	15	$604,889	1	1	15	0.47	Albemarle1	0.53	Rockbridge1
Henrico3	100.0%	$3,303,413	1	1	56	$3,303,413	1	1	56	1.00	Henrico3		
Roanoke1	2.2%	$944,874	1	1	2	$20,500	1	1	2	1.00	Rockbridge3		
Roanoke2	23.4%	$1,480,185	1	1	11	$346,758	1	1	11	0.71	Albemarle1	0.29	Rockbridge1
Roanoke3	7.3%	$1,219,686	1	1	7	$88,628	1	1	7	0.94	Albemarle1	0.06	Rockbridge1
Rockbridge1	100.0%	$1,121,149	1	1	23	$1,121,149	1	1	23	1.00	Rockbridge1		
Rockbridge2	92.5%	$24,114	1	1	4	$22,298	1	1	4	0.50	Albemarle1	0.50	Rockbridge3
Rockbridge3	100.0%	$20,500	1	1	2	$20,500	1	1	2	1.00	Rockbridge3		
Spotsylvania1	75.5%	$971,925	1	1	17	$733,954	1	1	17	0.35	Albemarle1	0.65	Rockbridge1
Spotsylvania2	64.0%	$541,702	1	1	11	$346,758	1	1	11	0.71	Albemarle1	0.29	Rockbridge1
Spotsylvania3	2.4%	$861,288	1	1	2	$20,500	1	1	2	1.00	Rockbridge3		

Table 4.41.B: Overall Efficiency Scores of the Counties for the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Paved Lanes Maintenance Efficiency

County	Overall Efficiency Score of the County
Albemarle	50.6%
Alleghany	15.8%
Augusta	8.0%
Fauquier	12.3%
Henrico	40.0%
Roanoke	11.0%
Rockbridge	97.5%
Spotsylvania	47.3%

Table 4.40.C: Efficiency Scores of the DMUs obtained from both DEA Models for Paved Lanes

Unit name	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model (*DEA 1*)	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model (*DEA 2*)
Albemarle1	100.0%	100.0%
Albemarle2	56.3%	50.0%
Albemarle3	2.2%	1.9%
Alleghany1	53.6%	1.0%
Alleghany2	100.0%	42.8%
Alleghany3	52.1%	3.7%
Augusta1	14.0%	8.1%
Augusta2	19.4%	13.0%
Augusta3	53.9%	2.9%
Fauquier1	49.9%	1.3%
Fauquier2	100.0%	32.5%
Fauquier3	100.0%	3.0%
Henrico1	0.9%	0.8%
Henrico2	19.5%	19.2%
Henrico3	100.0%	100.0%
Roanoke1	2.5%	2.2%
Roanoke2	23.6%	23.4%
Roanoke3	7.3%	7.3%
Rockbridge1	100.0%	100.0%
Rockbridge2	92.5%	92.5%
Rockbridge3	100.0%	100.0%
Spotsylvania1	76.1%	75.5%
Spotsylvania2	64.0%	64.0%
Spotsylvania3	2.7%	2.4%

Table 4.41.C: Overall Efficiency Scores of the Counties obtained from both DEA Models for Paved Lanes

County	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model (*DEA 1*)	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model (*DEA 2*)
Albemarle	52.8%	50.6%
Alleghany	68.6%	15.8%
Augusta	29.1%	8.0%
Fauquier	83.3%	12.3%
Henrico	40.1%	40.0%
Roanoke	11.1%	11.0%
Rockbridge	97.5%	97.5%
Spotsylvania	47.6%	47.3%

When the results from both models (*DEA 1* and *DEA 2*) within each of the tables are compared, it can be seen that a portion of the inefficiencies (which is lowering the efficiency scores) inherent in the DMUs as seen in the *DEA 2* model (i.e. when the effects of uncontrollable factors are not acknowledged in the DEA model) can be attributed to the effects of the uncontrollable factors faced by such DMUs. This is simply because for all counties but one (Rockbridge), the efficiency scores are higher when the DEA model is run by acknowledging the effects of the uncontrollable factors on the efficiency of DMUs. Such DEA model (*DEA 1* model), by considering the effects of the uncontrollable factors, calculates the efficiency of the DMUs given the uncontrollable factors they face. Therefore, the amount of inefficiency that is the result of the uncontrollable factors (e.g. bad climate, heavy traffic, etc.) is accounted for by the DEA model. In other words, *DEA 1* model, by considering the effects of the uncontrollable factors: (i) creates a leveled playing field, (ii) eliminates the artificial inefficiencies created by the effects of such uncontrollable factors, and (iii) reflects the pure relative efficiencies of the DMUs for their paved lanes maintenance operations. This result confirms the validity of the second hypothesis of this research (as presented in **Chapter 1**) which is: "Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties."

It is important to note that by taking the difference of the efficiency scores obtained from *DEA 1* Model and *DEA 2* Model within each of the tables, one can easily identify the effects of the uncontrollable factors on the efficiencies of the DMUs (which is one of the objectives of this research as presented in **Chapter 1**). For example, the uncontrollable factors reduce the relative paved lanes maintenance efficiency of the Augusta County in the amount of 21.1% (29.1%-8.0%) according to the DEA models run for the implementation example presented herein. According to the results of the same relative efficiency models though, Rockbridge County's efficiency does not seem to be affected by the uncontrollable factors (as such county's efficiency as calculated by *DEA 1* Model and *DEA 2* Model is the same as can be seen in **Table 4.41.C**). This can be attributed to the fact that, relative to the other counties used in the model, this county is enjoying milder uncontrollable factors as reflected by the "DMU_{TAS}" uncontrollable variable of such county (it is the county that has the smallest area of paved lanes among all of the counties used in this implementation example) and thus relative to the other counties, this county's efficiency is not adversely affected by the uncontrollable factors.

4.3 APPLICATION OF THE FRAMEWORK TO THE "FENCE TO FENCE ASSET GROUPS" ELEMENT OF THE LEVEL-OF-SERVICE COMPONENT FOR THE MAINTENANCE PERFORMED BY TRADITIONAL METHODS

This section presents the application of the framework developed in **Chapter 3** to the 215 miles of Virginia's Interstate where maintenance is performed on a traditional basis by VDOT (i.e. VDOT Control Sections for the Maintenance Rating Program (MRP) project). Such application of DEA is focused on the "Fence to Fence Asset Groups" (called as "Asset Groups" henceforth) element of the level-of-service component, only for the years in which asset groups' condition and cost data are available. Just as in the case for bridges and paved lanes, the approaches and concepts that are parts of the framework developed in **Chapter 3** are utilized for the purposes of this section. This section, first, presents the comprehensive lists of variables and DMUs that have initially been decided to be included in the DEA study for the asset groups. Then, it presents the final lists of variables and DMUs that are decided to be used in actual implementation of DEA and discusses the reasons behind the modification of the comprehensive lists to such final lists. After that, it illustrates the data preparation (gathering, mining, cleaning, and conversion/rearrangement) process performed to make such data ready to be used in the DEA model. Then, it discusses the reasons for the selection of the particular DEA model that is used in this study along with final data refinements and presents the results of the application of such model to the prepared data for the "Asset Groups" element (of the level-of-service component) for VDOT Control Sections. Finally, it presents the conclusions and effects of uncontrollable factors on the asset groups maintenance efficiency of units under investigation.

It is important to note that this section possesses a full implementation example (for the "Asset Groups" element of the level-of-service component) of the comprehensive highway maintenance efficiency framework developed in **Chapter 3**.

4.3.1 Comprehensive Lists of Variables and DMUs

This section is divided into two parts. First part presents the most comprehensive list of variables that can be used in the DEA model for the maintenance of the "Asset Groups" element of the level-of-service component. The second part presents the issues with the selection of DMUs to be included in such DEA model and presents the information for the identification/location of those DMUs.

4.3.1.1 Comprehensive List of Variables

Based on the discussion presented in **Section 3.7.2**, it is decided to utilize the Banker and Morey (1986) (Banker and Morey 1986a) approach to deal with uncontrollable factors for the "Asset Groups" element of the level-of-service component as presented in **Table 3.2**. Therefore, such uncontrollable factors are decided to be treated as uncontrollable variables in the DEA models. Thus, the uncontrollable factors presented for the "Asset Groups" element in **Table 3.2** become uncontrollable input variables due to their effects on the maintenance of such element. **Table 4.42** presents the most comprehensive list of input and output variables that can be used in the DEA model for the maintenance of the "Asset Groups" element of the level-of-service component. It is important to note that such table is a subset of **Table 3.2** (with the sole difference that the uncontrollable factors in **Table 3.2** are now the uncontrollable input variables in **Table 4.42**) which was developed in **Chapter 3** by using the process definition and the approaches to develop the list of controllable variables and uncontrollable factors as presented in the same chapter.

Table 4.42: The Comprehensive List of Input and Output Variables for the DEA Model of the Maintenance of the "Asset Groups" Element of the Level-of Service Component

Component	Element	Variable Name		Variable Explanation and/or Metric
Level of Service	Fence to Fence Asset Groups	INPUTS	(1) Cost for maintaining the asset items	$
			(2) Climate- Effect on deterioration of the asset items	Yearly temperature cycles (Δ Temperature), number of yearly freeze-thaw cycles
			(3) Climate- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity- availability of crews)	Yearly precipitation amounts (inches)
			(4) Traffic- Effect on deterioration of the asset items	Equivalent Single Axle Load (ESAL)
			(5) Traffic- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity- availability of crews)	Average Daily Traffic (ADT)
			(6) Speed limit- Effect on deterioration of the asset items	miles/hr
			(7) Accidents damaging asset items- Effect on deterioration of the asset items	count (of accidents damaging asset items)/year
			(8) Subsurface conditions- Effect on deterioration of the asset items	Good, Poor, Rock Soil, Water table etc... (give a grade based on effect)
			(9) Age of asset items- Effect on deterioration of the asset items	Years
			(10) Terrain- Effect on deterioration of the asset items	Slope, Elevation, and Orientation
			(11) Terrain- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity of crews)	Slope, Elevation, and Orientation
			(12) Total Area Served- Effect on maintenance efforts performed for meeting Level of Service requirements for the asset items (productivity of crews)	Asset density (number of assets to maintain)
		OUTPUTS	(13) Change in the condition of Asset Items (which are maintained to meet the Level of Service requirements)	$\%LOS_{t1}-\%LOS_{t0}$
			(14) Air Pollution	Emission amounts
			(15) Water Pollution	Emission amounts
			(16) Noise Pollution	Emission amounts

: The reason for computing the difference of ratings at time "t1" and "t0" will be explained in Section 4.3.3 of this chapter.

4.3.1.2 Comprehensive List of DMUs

Given the discussion presented in **Section 2.5.3.2** and **Section 3.6** with respect to the discriminating power of DEA, and given the fact that the DEA model will be applied for an approximately 430 directional miles of Interstate portion which is maintained on a traditional basis (the VDOT Control Sections for which condition data is available to Virginia Tech), initially it was decided to define the DMU as a 10-mile-long highway section of this 430 mile portion in an effort to maximize the number of DMUs while assigning a meaningful size to such DMUs as far as DEA is concerned. Such a definition would yield to 43 DMUs, which is likely to be a sufficient number (as far as the discriminating power of DEA is concerned) once the comprehensive list of variables is refined as discussed in **Section 3.6**. However, as mentioned in the implementation example for the "Bridges" and "Paved Lanes" elements, defining a DMU as a 10-mile-long highway section presented a major obstacle in the data gathering process. It was indicated by VDOT that the data for arguably the most important variable, the cost variable, cannot be gathered at a 10-mile-long highway section level as VDOT's FMS keeps track of the costs at the county level for each Interstate. Given this restriction, just as in the case for bridges and paved lanes, the definition of DMUs was changed to be the counties of Virginia (that encompass the portions of the interstate system that are under investigation), which is the minimum size of a DMU at which the cost data is available. **Table 4.43** presents the identification/location information of the counties that encompass the VDOT Control Sections.

As a final note, since the cost data that is provided by VDOT is in VDOT's fiscal years, all analysis will be performed on a fiscal year time frame basis. This means that all input-output data should be yearly data covering the time span of VDOT's fiscal years, i.e. July 1st of the previous year to June 30th of the current year.

Table 4.43: The Comprehensive List of DMUs for the DEA Model of the Maintenance of the "Asset Groups" Element of the Level-of-Service Component

MRP* Section	Route	County (DMU)	Route Relative		Closest County Relative	
			Begin Milemarker	End Milemarker	Begin Milemarker	End Milemarker
5-VDOT Control	I-95	Caroline	108.87	116.87	7.54	15.54
5-VDOT Control	I-95	Spotsylvania	116.87	132.40	0.00	15.53
6-VDOT Control	I-66	Fauquier	14.66	36.59	0.00	21.93
7-VDOT Control	I-64	Henrico	175.70	187.46	0.00	11.76
7-VDOT Control	I-64	Henrico	190.66	204.6[&]	14.96	28.90
8-VDOT Control	I-64	Alleghany	0.00	40.99	0.00	40.99
8-VDOT Control	I-64	Rockbridge	40.99	57.23	0.00	16.24
9-VDOT Control	I-64	Nelson	99.96	101.32	0.00	1.36
9-VDOT Control	I-64	Albemarle	101.32	131.16	0.00	29.84
10-VDOT Control	I-81	Roanoke	130.59	147.45	0.00	16.86
11-VDOT Control	I-581	Roanoke	0.00	6.64	0.00	6.64
12-VDOT Control	I-81	Augusta	206.04	237.51	0.00	31.47

*: MRP- Maintenance Rating Program- The program that is used by Virginia Tech to evaluate the Interstate maintenance performance in terms of effectiveness.
&: In January 2006, this Milemarker was changed to 200.9 as a private contractor started to undertake the maintenance of a portion of the Interstate beginning at milemarker 200.9.

4.3.2 Final Lists of Variables and DMUs to be included in the DEA Model

This section presents the final lists of variables and DMUs that are decided to be used in actual implementation of DEA and discusses the reasons behind the modification of the comprehensive lists (presented in the previous section) to such final lists. First part of this section deals with the input and output variables and the second part deals with the DMUs.

4.3.2.1 Final List of Variables to be included in the DEA Model

As was underlined in **Section 3.6**, once the initial comprehensive list of input and output variables is developed, such list should be reinvestigated and refined to include only the most

relevant and important variables to be able to increase the discriminating power of DEA models. As presented in **Table 4.42**, the comprehensive list for the "Asset Groups" element has a total of 16 variables. Considering the number of DMUs presented in **Table 4.43**, using so many variables in the DEA model would definitely preclude the model to discriminate between efficient and inefficient DMUs. The refinement process for such list is discussed below.

On the outputs side, the output variables air pollution (labeled as 14 in **Table 4.42**), water pollution (15), and noise pollution (16) can directly be removed from the list. They are different from the common concept of the output of a process as they are undesirable outputs (i.e. the less of them, the better). From an efficiency point of view, the inclusion of them in the DEA model (including undesirable outputs in DEA models is a rather new concept in the DEA literature as discussed in **Section 3.3**) is not critical but nonetheless given the availability of data, they should be included in the model. For our case, they will be disregarded since (i) no data is available for those undesirable outputs and (ii) those variables are not deemed critical as far as their effect on overall efficiency of a DMU is concerned. The only data that has traditionally been collected for the asset groups is the level-of-service (LOS- labeled as 13 in **Table 4.42**). Such data is collected as a part of the Maintenance Rating Program (MRP) inspections performed to measure the level-of-service effectiveness of VMS and VDOT as detailed in **Section 4.0.1**. Given this, only one output, "Change in LOS", remains to be included in the DEA model for the maintenance of the "Asset Groups" element as shown in **Table 4.44**.

On the inputs side, only the cost variable (1) is a controllable variable (i.e. directly controllable by the decision maker, i.e. VDOT's Asset Management Division). All of the remaining inputs (2-12) are uncontrollable variables representing the following four types of effects on the highway maintenance process:

(i) Environmental effects on the deterioration of the asset groups (Variables 2, 8, and 10)

(ii) Environmental effects on the maintenance efforts (Variables 3 and 11)

(iii) Operational effects on the deterioration of the asset groups (Variables 4, 6, 7, and 9)

(iv) Operational effects on the maintenance efforts (Variables 5 and 12)

The "Asset Groups" element is composed of a large number of asset items which can be divided into 4 major groups as was shown in **Table 4.0**: (i) Shoulders, (ii) Roadside, (iii) Drainage, and (iv) Traffic. Each asset group has a number of asset items with diverse characteristics. The reason for all of these asset items to be included in a single DEA model is the fact that the cost data for them is not available at a more disaggregate level. In other words, even though the cost data for the paved lanes and bridges is provided separately as both elements are major cost drivers for the interstate maintenance, cost data for the remaining asset items are not provided at the asset item level; but rather provided at an aggregate level covering all such asset items. Each of these asset items' deterioration is affected by different environmental and operational uncontrollable variables as listed in items (i) and (iii) above. In other words, an uncontrollable variable that affects the deterioration of a particular asset item may not necessarily affect the deterioration of another asset item. For example, the environmental variable "freeze and thaw cycles" affects the deterioration of the "paved ditches" and "concrete barriers" asset items but does not affect the deterioration of "pavement messages" and "pavement markers" asset items. Conversely, the operational variable "Equivalent Single Axle Load" affects the deterioration of the "pavement messages" and "pavement markers" asset items but does not affect the deterioration of "paved ditches" and "concrete barriers" asset items. The variables which are not applicable to all of the asset items cannot be included in the DEA model which investigates the efficiency with respect to all such asset items. When the list of uncontrollable variables effecting the deterioration (variables 2, 4, 6, 7, 8, 9 and 10) is investigated, it can be noticed that there are only 2 uncontrollable variables (Variable 7-count of accidents damaging asset items and Variable 9- age of asset items) that are applicable to all of the asset items to be included in the DEA model. Therefore, of all the uncontrollable variables affecting the deterioration of asset items, only such 2 variables can be included in the DEA model. However, if included in the DEA model, the numerical value for these variables would be different for each asset item, again making these variables unusable. Even if these variables were tried to be included by introducing certain assumptions (e.g., calculating an overall value that represents all of the asset items by summing or averaging), they still could not be included in the model as no data is available as far as these variables are concerned. Given all of these, it can be stated that none of the uncontrollable variables affecting the deterioration of asset items as listed in items (i) and (iii) above can be included in the DEA model. This issue, again, underlines the importance of data availability and data compatibility issues that accompany the DEA concept. Had more disaggregate cost data (i.e. at the asset item level) been made available, separate DEA models could be run for each asset item, this time including the relevant uncontrollable factors affecting the deterioration of such asset item in each model. The framework developed by this research calls for the obtainment and utilization of as disaggregate data as possible.

As far as the other sets of uncontrollable variables, uncontrollable variables that affect the maintenance efforts as listed in items (ii) and (iv) above, are concerned, it can be stated that the abovementioned phenomenon is not applicable. In other words, each of those variables (3, 5, 11, and 12) is applicable to all of the asset items as they pertain to the availability and productivity of maintenance crews. When a crew's productivity is affected due to uncontrollable variables, such in turn affects the preventive and restorative maintenance actions employed by such crew to address the issue of deterioration. Since this phenomenon is independent of the asset item that such crew is dealing with, all of the abovementioned uncontrollable variables should be included in the DEA model representing all of the asset items. For the purposes of refining such list though, "Terrain" variable (Variable 11) is decided to be removed from the list as its effect on the productivity of crews can be regarded as negligible.

Due to all of the variable refinements presented in the preceding paragraphs, the final list of variables to be used in the DEA model for asset groups contains 4 inputs and 1 output as presented in **Table 4.44**.

Table 4.44: Final List of Variables to be used in the DEA Model for Asset Groups

Variable Type	Variable Name	Variable Explanation and/or Metric
Input	Cost for Maintaining the Asset Groups	$
	Climate- Precipitation Amount	inches
	Traffic- Count	Average Daily Traffic (ADT)
	Total Area Served	Asset density (number of assets to maintain)
Output	Change in LOS Rating Percentage	LOS_{t1}-LOS_{t0}

: The reason for computing the difference of ratings at time "t1" and "t0" will be explained in Section 4.3.3 of this chapter.

4.3.2.2 Final List of DMUs to be included in the DEA Model

Even though **Table 4.43** presents all of the counties that encompass the VDOT Control Sections, not all of the counties listed there can be included in the DEA model developed in this research. Following are the counties that will be excluded from this research:

(i) **Caroline County**: As can be seen in **Table 4.43**, the portion of VDOT Control Section 5 which falls within the limits of this county (from Milemarker 108.87 to Milemarker 116.87) does not entirely cover this county. Thus, the asset groups' condition information gathered through MRP only covers the asset groups that fall within the Milemarkers 108.87-116.87. However, the cost data that is provided by VDOT is for the entire Caroline County (i.e. from Milemarker 101.33 to Milemarker 116.87), and thus covers the portion of Caroline County (from Milemarker 101.33 to Milemarker 108.87) for which no asset groups condition data is available. As there is no way to apportion this cost data to the desired portion of the county for which asset groups condition data is available, it is decided to exclude the Caroline County from the analysis as inclusion of it is prone to introduce a substantial amount of error in the efficiency evaluations.

(ii) **Nelson County**: No cost data for this county is provided by VDOT as only a very small portion of this county encompasses the VDOT Control Section 9. Even if there was cost data for this county, it would be meaningless to try to calculate the Interstate asset groups maintenance efficiency of a county which only has 1.36 miles of Interstate within its jurisdiction. So, Nelson County is excluded from the DEA model.

Table 4.45 presents the final list of DMUs that are decided to be included in the DEA model for asset groups based on the discussion presented above.

Table 4.45: Final List of DMUs to be included in the DEA Model for Asset Groups

DMU Name
Albemarle
Alleghany
Augusta
Fauquier
Henrico
Roanoke
Rockbridge
Spotsylvania

4.3.3 Data Preparation Process

This section presents the steps taken for the data preparation process that is performed to obtain data and then to make such data ready to be used in the DEA model for asset groups. These steps are data gathering, data mining, data cleaning, and data conversion/rearrangement.

4.3.3.1 Step 1- Data Gathering

Data gathering efforts were mainly focused at obtaining the following: (i) Asset Groups Condition Data, (ii) Asset Groups Density Data, (iii) County Precipitation Data, (iv) Interstate ADT Data, and (v) Asset Groups Cost Data.

Virginia Tech already possesses Asset Groups Condition Data as such was gathered through MRP inspections performed once in every year by the field crews hired by Virginia Tech. Such field crews are composed of experienced inspectors, majority of whom has been performing these inspections for a long time. Such field crews go through a well-structured training each year before being sent to the field. Furthermore, during the inspections these field crews are made subject to very strict quality assurance and quality control programs. It is important to note that MRP inspections typically last 3 months. In 2002, such inspections were performed from October through December; in 2003 from September through November; in 2004 from August through October; and in 2005 from July through September. The one month earlier start implemented in each year was designed intentionally to capture the seasonal effects on the condition of the asset items. The inspections through which condition of the asset groups are determined do not cover a complete fiscal year as in the cases for bridges and paved lanes. Since the inspections just took 3 months of a year in 2002, it is decided to use the results of the inspections performed in 2002 (from October through December) to represent the conditions of the asset groups for fiscal year 2002 even though the months when inspections took place do not belong to fiscal year 2002. This is mainly because such inspections, even though taking place after the end of fiscal year 2002, have captured the conditions of the asset groups as affected by the improvements made to the asset groups and/or the deterioration impacting the asset groups in fiscal year 2002. In other words, such inspections capture the condition of the asset groups as attained at the end of fiscal year 2002. Same is the case for inspections performed in 2003, 2004, and 2005. Inspections performed in 2003 (from September through November) is assumed to represent the condition for fiscal year 2003, inspections performed in 2004 (from August through

October) is assumed to represent the condition for fiscal year 2004, and inspections performed in 2005 (from July through September) is assumed to represent the condition for fiscal year 2005. As mentioned above, this is an assumption necessitated by the fact that the inspections do not cover a complete fiscal year as was the case for bridges and paved lanes for which no such assumption was needed to be made.

In 2002, Virginia Tech performed an asset density study with the purpose of identifying which asset items are present in a given 0.1 mile long segment for all of the interstate portions that are included in MRP inspections. Such study was performed using construction plans and windshield inspections. Through this study, an asset density database was developed indicating, for each segment, the presence or absence of the asset items within the shoulders, roadside, drainage, and traffic asset groups. Furthermore, such asset density database has been enhanced over the course of subsequent MRP inspections to reflect a more up to date depiction of field conditions. It is important to note that the updates on the asset density mainly targeted the issue of false presence. In other words, asset items which are deemed to be present in the segments according to the initial asset density study but which are not present are removed during such updates. Whereas, if new asset items are added since the time the asset density study was performed, they are disregarded and thus this case is not reflected in the subsequent updates. Nonetheless, with the last MRP inspections performed in Spring 2007, it is believed that a very robust asset density database, depicting the presence of asset items in the 0.1 mile long segments to the best extent possible, is developed. Since that is the best asset density database that have been gathered to date, it is assumed to be applicable to all of the fiscal years (2003, 2004, and 2005) that will be investigated in the DEA model for the asset groups. The number derived from the asset density database for each county (i.e., the resulting total number of assets in a given county) will be representing the "Total Area Served" uncontrollable variable as listed in **Table 4.44**. It is important to underline the fact that such number represents the presence of asset items (asset density), not the actual number (asset inventory) of them. For example, even though there can be 3 pipes to maintain in a given 0.1 mile long segment, the asset density database states just the presence of pipes in this segment. Given the fact that, not all of the asset items are inspected in all of the sites during the MRP inspections (i.e. random selection of asset items to inspect as was discussed earlier), there is not a complete database which shows the number of instances an asset item is recorded in a given segment. Following the example above, even though we may know that there are 3 pipes in Segment #1 as such segment is selected to be inspected for pipes by random selection, Segment #2 may have never been selected to be inspected for pipes (even though we know the presence of at least 1 pipe within such segment); and thus the only information that we have is the presence of pipe(s) in Segment #2. Therefore, since there is not a complete asset inventory database, it has been decided to use the asset density database to represent the Total Area Served variable. This assures that all segments and counties are represented using the same scale and approach (i.e. presence of asset items).

Various historical climate information such as total monthly precipitation, monthly mean temperature, monthly mean maximum temperature, and monthly mean minimum temperature is recorded by weather stations and made available to National Climatic Data Center (NCDC) to be published on its website (NCDC 2007). Such web site was used to gather the precipitation data recorded by the weather stations within the counties considered for this study. Such information is to be used for the "Climate-Precipitation Amount" uncontrollable variable as listed in **Table 4.44**. In order to obtain the climate data, a query was created and submitted to NCDC to request the information needed as far as specific counties and specific time periods are concerned. This query resulted in the information for a number of weather stations (belonging to each county) to be retrieved from NCDC's databases. However, such query resulted in no results for the Spotsylvania County due to the following two reasons: (i) 3 weather stations within such county do not have data for the specific time period requested and (ii) the data belonging to the remaining 1 weather station within such county cannot be retrieved. Consequently, NCDC was contacted to identify any other means to retrieve the data for such weather station; however no response was received. Furthermore, research was performed in an effort to identify whether such weather station's (Shannon Airport) database could be accessed without going through NCDC; this resulted in no further information either. Finally, another weather station, Fredericksburg Sewage, which is not within the physical limits of the Spotsylvania County but which is just 1.15 miles from the Shannon Airport was decided to be used to obtain the climatic information for the Spotsylvania County. Even though it is acknowledged that Fredericksburg Sewage weather station is in Fredericksburg County and not in Spotsylvania County, it is safe to use such weather station's records in lieu of Shannon Airport weather station's records as such stations are just 1.15 miles apart and thus are very likely to face very similar climatic conditions and thus have very similar climatic records.

VDOT makes the average daily traffic volumes on the interstate, primary, and arterial routes for the state of Virginia publicly available each year through a publication (VDOT 2002b; VDOT 2003; VDOT 2004; VDOT 2005a). Such publication was used to gather the ADT data for interstate routes within the counties considered for this study. Such information is to be used for the “Traffic-Count” uncontrollable variable as listed in **Table 4.44**.

Cost Data has been provided by VDOT’s AMD. According to the statement made by Dennis Domayer from VDOT’s AMD, “*The information was derived from FMS II using the VGLN50 reports Program 6040100 for the districts involved. Drills were run by route and then by county and then by activity. The original request was to extract the 7XXXX series of activity codes and omit all other activity codes*” (Domayer 2006). In further communication with the personnel from VDOT’s AMD, the following information have been gathered about the Cost Data (Domayer 2006):

- The Cost Data includes only routine/ordinary maintenance (i.e. preventive maintenance and restorative maintenance) expenditures. No rehabilitative maintenance (i.e. reconstruction, and major repair/replacement) expenditure is included.
- No district or central office overhead is included in the Cost Data.
- Incident response expenditures are included in the Cost Data if such are coded to the activity codes that are extracted. Snow removal expenditures are captured in the 6XXXX series of activity codes and thus are not included in the Cost Data.
- All labor expenditures (including the labor burden) are included in the Cost Data if they are coded to the activity codes that are extracted.
- Costs of the private contracts (used by VDOT to perform maintenance) are included in the Cost Data if they are charged to county, route and asset but they are not included in the Cost Data if they are charged to a cost center, such as the Public- Private Transportation Act (PPTA) cost center which includes the VMS contract. Cost of maintenance performed by in-house forces (i.e. self-performed work) is included in the Cost Data.

4.3.3.2 Step 2- Data Mining

The raw data obtained for the asset groups' condition had to be mined in terms of the interstate sections inspected to be able to obtain the portion of it which is to be included in the analysis. The raw data contained condition data for the asset groups that are maintained by counties that are not within the list of counties presented in **Table 4.45**. Therefore, data mining was performed to extract from the raw data only the data belonging to the counties that are listed in **Table 4.45**. To illustrate an example of the results of this data mining process, **Table 4.46** presents the Rockbridge County's Asset Groups Condition Data (for a few asset items and segments due to space limitations) as extracted from the raw data for the fiscal year 2005.

The asset density database updated as of 2007 also had to be mined to be able to obtain the portion of it which is to be included in the analysis. The asset density database contains the asset presence/absence information for 9567 segments covering about 930 directional miles of interstate mainline and ramp sections as investigated by the research performed by Virginia Tech. Such database has information for the counties that are not within the list of counties presented in **Table 4.45**. Therefore, data mining was performed to extract from this database only the information for the segments belonging to the counties that are listed in **Table 4.45**. To illustrate an example of the results of this data mining process, **Table 4.47** presents the Rockbridge County's Asset Groups Density Data (for the same asset items as presented in **Table 4.46** and a few segments due to space limitations) as extracted from the comprehensive asset density database as updated in 2007.

Similarly, the publication listing the ADT on the interstate, arterial, and primary routes statewide within Virginia had to be mined to be able to obtain the ADT information that pertain to the counties and interstates that are included in the analysis. This needed to be done for each of the publications listing the ADT information for calendar years 2002, 2003, 2004, and 2005. **Table 4.48** presents the ADT information for Interstate 64 (I-64) that is within the Rockbridge County for the calendar years 2002, 2003, 2004, and 2005.

The data obtained for the cost was already in the desired date range and covered only the interstates and counties that are under investigation. As a matter of fact, as Virginia Tech was very specific in terms of what it wants for the Cost Data when such request was made to VDOT's AMD, all data mining was performed by VDOT's AMD. Given this, no further data mining was needed to be performed for the Cost Data. It is important to note that the cost data provided to Virginia Tech was broken down in three separate tables: (i) a table including the all cost elements, (ii) a table including the paved lanes cost elements, and (iii) a table including the bridges cost elements. Therefore, the cost associated to asset groups was calculated by subtracting the costs associated to items (ii) and (iii) from the cost associated to item (i). This way of calculation to identify the cost for asset groups was suggested and approved by VDOT. **Table 4.49** presents Rockbridge County's Cost Data for fiscal years 2002, 2003, 2004, and 2005 with respect to asset groups, as received from VDOT's AMD.

Table 4.46: Rockbridge County's Asset Groups Condition Data for Fiscal Year 2005

Segment No	Route	Direction	Start Milepost	End Milepost	DateRecorded	Fence Total	Fence Pass	Paved Ditches Total	Paved Ditches Pass	Unpaved Ditches Total	Unpaved Ditches Pass	Pipes Total	Pipes Pass
7460	64	E	41	41.1	08/05/2005	0	0	1	1	1	1	0	0
7461	64	E	41.1	41.2	08/05/2005	0	0	0	0	0	0	0	0
7463	64	E	41.3	41.4	08/05/2005	0	0	2	2	0	0	0	0
7464	64	E	41.4	41.5	09/01/2005	0	0	0	0	0	0	0	0
7465	64	E	41.5	41.6	08/05/2005	0	0	1	1	3	2	1	1
7466	64	E	41.6	41.7	09/01/2005	0	0	1	0	0	0	0	0
7474	64	E	42.4	42.5	08/05/2005	0	0	1	0	5	5	2	2
7476	64	E	42.6	42.7	09/01/2005	0	0	0	0	0	0	2	2
7477	64	E	42.7	42.8	09/01/2005	0	0	0	0	0	0	2	2
7478	64	E	42.8	42.9	08/05/2005	0	0	0	0	0	0	0	0
7481	64	E	43.1	43.2	08/05/2005	0	0	0	0	0	0	0	0
7482	64	E	43.2	43.3	08/05/2005	0	0	0	0	0	0	0	0
7484	64	E	43.4	43.5	08/03/2005	0	0	3	3	3	3	0	0
7486	64	E	43.6	43.7	08/03/2005	0	0	2	2	2	2	0	0
7487	64	E	43.7	43.8	08/03/2005	0	0	0	0	2	2	0	0
7488	64	E	43.8	43.9	08/03/2005	0	0	0	0	0	0	0	0
7489	64	E	43.9	44	08/03/2005	0	0	0	0	0	0	0	0
7493	64	E	44.3	44.4	08/03/2005	1	0	7	4	3	3	2	2
7494	64	E	44.4	44.5	08/03/2005	0	0	0	0	0	0	1	1
7497	64	E	44.7	44.8	08/03/2005	0	0	0	0	0	0	0	0
7498	64	E	44.8	44.9	08/03/2005	0	0	1	1	2	2	0	0
7500	64	E	45	45.1	08/03/2005	0	0	0	0	0	0	0	0

Table 4.47: Rockbridge County's Asset Density Database as updated in 2007

Segment No	Route	Direction	Start Milepost	End Milepost	Fence	Paved Ditch	Unpaved Ditches	Pipes
7460	64	E	41	41.1	1	1	1	0
7461	64	E	41.1	41.2	1	1	1	0
7462	64	E	41.2	41.3	1	1	1	1
7463	64	E	41.3	41.4	0	1	0	0
7464	64	E	41.4	41.5	0	1	1	0
7465	64	E	41.5	41.6	1	1	1	1
7466	64	E	41.6	41.7	1	1	1	0
7467	64	E	41.7	41.8	1	1	1	0
7468	64	E	41.8	41.9	0	1	1	0
7469	64	E	41.9	42	1	1	1	0
7470	64	E	42	42.1	1	1	1	1
7471	64	E	42.1	42.2	1	1	1	1
7472	64	E	42.2	42.3	1	1	1	1
7473	64	E	42.3	42.4	0	0	0	1
7474	64	E	42.4	42.5	1	1	1	1
7475	64	E	42.5	42.6	1	1	1	1
7476	64	E	42.6	42.7	1	1	1	1
7477	64	E	42.7	42.8	0	1	1	1
7478	64	E	42.8	42.9	1	0	1	1
7479	64	E	42.9	43	1	0	1	0
7480	64	E	43	43.1	1	0	1	0
7481	64	E	43.1	43.2	1	0	1	0
7482	64	E	43.2	43.3	1	0	1	1
7483	64	E	43.3	43.4	1	0	1	0
7484	64	E	43.4	43.5	0	1	1	0
7485	64	E	43.5	43.6	0	1	1	1
7486	64	E	43.6	43.7	0	1	1	0
7487	64	E	43.7	43.8	0	0	1	0
7488	64	E	43.8	43.9	0	0	1	0
7489	64	E	43.9	44	1	0	1	0
7490	64	E	44	44.1	1	1	1	0
7491	64	E	44.1	44.2	0	1	1	0
7492	64	E	44.2	44.3	0	1	1	0
7493	64	E	44.3	44.4	1	1	1	1
7494	64	E	44.4	44.5	1	0	1	1
7495	64	E	44.5	44.6	1	1	1	1
7496	64	E	44.6	44.7	1	0	1	0
7497	64	E	44.7	44.8	1	1	1	1
7498	64	E	44.8	44.9	1	1	1	0
7499	64	E	44.9	45	1	0	1	1
7500	64	E	45	45.1	1	0	1	0

1= Asset Item is Present
0= Asset Item is not Present

Table 4.48: Rockbridge County's ADT information for Interstate 64 (I-64)

Calendar Year / County	2002		2003		2004		2005	
	Total Mile	AADT	Total Mile	AADT	Total Mile	AADT	Total Mile	AADT
Rockbridge	1.92	4600	1.92	4900	1.92	4300	1.92	4100
	7.38	4300	7.38	4400	7.38	4500	7.38	4300
	5.39	4500	5.39	4800	5.39	5100	5.39	4900
	1.55	5800	1.55	6200	0.98	6400	0.98	6200
					0.57	4200	0.57	4100

Table 4.49: Rockbridge County's Cost Data with respect to Asset Groups

Route	County	Asset	FY 2003	FY 2004	FY 2005
I0064	Rockbridge	Fence to Fence Asset Items	$349,823.68	$245,775.29	$139,291.00

4.3.3.3 Step 3- Data Cleaning

After the data mining process, the resulting data was investigated for errors and inconsistencies. Such investigation identified only one problem which is related to the precipitation data belonging to the weather stations. For certain weather stations, the precipitation information belonging to all of the time periods (fiscal years 2002, 2003, 2004, and 2005) investigated in the DEA model was not available. For example “Brownsburg 2W Station” in Rockbridge County does not have any precipitation data for years 2002 and 2003; but it has precipitation data for years 2004 and 2005. In these cases, such stations were removed from the data set as including them in the calculations for certain fiscal years and not being able to include them in others (due to lack of data) would preclude the uniformity of data among different fiscal years. In short, data cleaning is performed to make sure that same stations are used for the precipitation amount calculations belonging to different fiscal years. Another issue that resulted in the removal of a number of stations from the data set was the fact that such stations, in a given fiscal year, were missing a substantial amount of monthly data. The data obtained from NCDC’s website through a number of queries lists the monthly values for the precipitation amount as recorded by weather stations. For certain stations, the data had not been collected or recorded for a number of months in a given fiscal year. To ensure that a good yearly (fiscal) precipitation amount representation of each station is obtained, stations with months which have no data in a given fiscal year were also removed from the data set. In doing so, it was decided to still give some leeway and identify the threshold amount as 3 months in a given fiscal year (for which no data is available) in deciding on whether to keep or remove a station. The threshold was decided to be 3 months for the sake of still being able to keep a sufficient number of weather stations in the data set which is essential to make precipitation amount calculations for the counties in the data set. **Table 4.50** presents the list of the weather stations belonging to the counties and indicates the ones that are discarded due to either of the two reasons discussed above. The Fredericksburg Sewage weather station, even though not belonging to the Spotsylvania County, is listed as the only station to represent the precipitation amount for such county due to the reason discussed in **Section 4.3.3.1**.

Table 4.50: List of the Weather Stations Used and Discarded

COUNTY	STATION NAME	REASON FOR DISCARDING THE STATION
ALBEMARLE	CHARLOTTESVILLE 2W	N/A
	FREE UNION	2
	MONTICELLO	N/A
ALLEGHANY	COVINGTON FILTER PLANT	N/A
	EARLEHURST	N/A
	GATHRIGHT DAM	N/A
AUGUSTA	CRAIGSVILLE 2 S	N/A
	STAUNTON SEWAGE PLANT	N/A
FAUQUIER	THE PLAINS 2 NNE	N/A
	WARRENTON 3 SE	1 and 2
HENRICO	RICHMOND INTERNATIONAL AP	N/A
	SANDSTON	N/A
ROANOKE	ROANOKE 8 N	N/A
	ROANOKE REGIONAL AP	N/A
ROCKBRIDGE	BROWNSBURG 2 W	1
	BUENA VISTA	N/A
	GLASGOW 1 SE	N/A
	GOSHEN	N/A
	KERRS CREEK 6 WNW	N/A
	LEXINGTON	N/A
SPOTSYLVANIA	FREDERICKSBURG SEWAGE	N/A

N/A: Station not discarded.
1: Climatic information for all years is not available.
2: Missing 3 or more months of data in one or more fiscal years.

4.3.3.4 Step 4- Data Conversion/Rearrangement

Once the data was mined and cleaned, it was needed to be converted into the format suitable to represent the variables listed in **Table 4.44**. Moreover, some rearrangements had to be made in the data (e.g. combining data using weights) to make it meet the structuring requirements of the DEA model. These conversions and rearrangements made in the data are discussed below.

4.3.3.4.1 Converting the "Asset Groups Cost Data" to Represent the Variable "Cost for Maintaining the Asset Groups"

The cost data provided by VDOT had to go through two conversions to be able to be utilized in the DEA model for the "Asset Groups":

i. **Conversion to account for Inflation**: The inflation/deflation cost adjustment as discussed in **Section 3.11.1** is applied to the cost data since the analysis includes the cost information belonging to different periods (i.e. different fiscal years). Thus, the cost figures used in the DEA model for “Asset Groups” incorporate the adjustments made through the utilization of the values listed for the *Composite Bid Price Index for Highway Construction* as shown in **Table 3.9**.

ii. **Conversion to account for Overhead Cost**: Just as in the case for “Bridges” and “Paved Lanes”, the raw cost data provided by VDOT does not include the overhead cost. Following the same reasoning presented in **Section 4.1.3.4.1**, after the inflation/deflation adjustment was made, the 4.6% overhead rate was applied to the cost data to enhance it and convert it to the “almost complete” total cost. The application of 4.6% overhead rate on the cost data results in the conversion of it to the cost figures that can be used for the variable “Cost for Maintaining the Asset Groups”.

4.3.3.4.2 Rearranging the “County Precipitation Data” to Represent the Variable “Climate-Precipitation Amount”

As can be seen in **Table 4.44**, “Climate-Precipitation Amount” is an uncontrollable variable which is to be included in the DEA model for the asset groups. Therefore, for each county, a value representing such county’s overall precipitation amount needs to be calculated. As was discussed earlier and listed in **Table 4.50**, with the exception of the Spotsylvania County and Fauquier County, all counties’ precipitation information is represented by more than one weather station. The average of the precipitation amounts recorded by multiple stations in a county should be calculated to be able to identify an overall precipitation value that would represent such county for a given fiscal year as the DMU for the “Asset Groups” DEA model is the county for a given fiscal year. To do that, first the precipitation amounts recorded in the months belonging to the fiscal year for which the overall value is being identified need to be averaged for each station. It is decided to average the monthly precipitation amounts as opposed to summing them to minimize the data noise resulting from the months for which no precipitation data is available (as was discussed in **Section 4.3.3.3**). Through averaging method, such months are disregarded as opposed to being counted as “0” which would be the case had the summing method been used. **Table 4.51** presents the precipitation data (in inches) for the stations belonging to the Rockbridge County per month for years 2002, 2003, 2004, and 2005. **Table 4.52** presents the overall amounts (in inches) for the stations within the Rockbridge

County for fiscal years 2003, 2004, and 2005 (the fiscal years to be included in the DEA model) as calculated using the method discussed above. Once, the overall values for fiscal years per stations are calculated, such values can be averaged to obtain the overall value for the county as discussed above. **Table 4.53** presents the overall precipitation amounts (in inches) for Rockbridge County per fiscal years.

It is important to note that for the Fauquier County, the overall precipitation amount could be calculated only for fiscal year 2005 as 3 and more monthly data (the threshold discussed in **Section 4.3.3.3)** is missing for such county's only weather station (The Plains 2 NNE) for fiscal years 2003 and 2004.

Table 4.51: Precipitation Data for Stations that belong to Rockbridge County

COUNTY	STATION NAME	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Rockbridge	BUENA VISTA	2002	1.05	NA	NA	NA	NA	NA	NA	0.81	4.04	5.49	4.76	3.67
		2003	1.48	6.55	4.03	3.72	8.68	4.74	3.69	6.59	8.63	2	6.9	3.95
		2004	1.53	2.37	1.56	4.51	4.25	5.71	7.89	1.28	10.02	2.58	3.97	2.22
		2005	3.43	1.41	4.22	3.49	2.61	1.04	5.15	2.19	0.08	7.88	5.95	3.16
	LEXINGTON	2002	1.43	0.61	3.58	4.45	3.1	1.23	8.63	0.49	2.96	4.88	5.17	4.04
		2003	2.28	5.57	3.45	3.44	8.09	5.87	3.4	7.41	8.81	1.46	6.39	3.58
		2004	NA	2.8	1.48	4.38	4.67	7.3	6.23	1.73	9.15	1.4	4.13	2
		2005	2.77	1.61	3.56	3.55	2.94	1.27	4.15	4.74	0.11	6.6	5.16	2.62
	GLASGOW 1 SE	2002	1.75	0.7	4.89	3.26	2.38	0.83	5.05	1.15	3.89	6.7	5.18	4.52
		2003	2.69	7.37	5.15	4.47	9.28	5.86	3.91	8.17	9.7	2.29	6.41	5.01
		2004	2.19	2.6	2.05	5.37	4.49	3.61	4.55	2.51	13.75	2.29	4.46	3.75
		2005	4.19	1.32	4.96	3.66	3.38	2.28	6.03	2.99	0.21	10.48	8.43	3.64
	GOSHEN	2002	1.32	0.45	3.83	4.1	2.95	1.58	5.69	0.22	3.6	5.79	5.09	2.05
		2003	2.52	5.23	2.57	3.24	7.33	8.48	6.43	5.18	7.25	2.09	5.82	6.65
		2004	1.78	1.55	2.35	4.35	10.88	4.51	3.68	3.36	12.18	1.28	4.6	3.25
		2005	2.58	1.09	3.85	5.44	2.75	1.32	5.62	8.9	0.22	4.36	4.9	0.73
	KERRS CREEK 6 WNW	2002	1.69	0.73	3.39	5.02	2.97	2.62	6.31	0.42	3.76	4.56	8.13	2.68
		2003	1.81	6.38	1.55	3.34	7.86	6.94	3.41	3.13	8.03	1.48	7.32	3.2
		2004	0.93	1.29	1.32	4.07	6.83	5.92	5.12	3.42	13.55	1.88	4.29	3.3
		2005	3.14	0.99	4.81	4.68	2.6	1.82	5.13	9.08	0.23	5.71	6.53	2.6

Table 4.52: Overall Precipitation Amounts for Stations that belong to Rockbridge County for Fiscal Years 2003, 2004, and 2005

COUNTY	STATION NAME	FY 2003	FY 2004	FY 2005
Rockbridge	BUENA VISTA	4.4	4.3	3.7
	LEXINGTON	4.6	4.7	3.4
	GLASGOW 1 SE	5.1	4.7	4.3
	GOSHEN	4.3	4.9	3.8
	KERRS CREEK 6 WNW	4.5	3.9	4.1

Table 4.53: Overall Precipitation Amounts for Rockbridge County for Fiscal Years 2003, 2004, and 2005

Fiscal Year / County	2003	2004	2005
Rockbridge	4.6	4.5	3.8

4.3.3.4.3 Rearranging the "Interstate ADT Data" to Represent the Variable "Traffic-Count"

As can be seen in **Table 4.44**, "Traffic-Count" is an uncontrollable variable which is to be included in the DEA model for the asset groups. Therefore, for each county, a value representing such county's overall ADT needs to be calculated. In **Table 4.48**, the ADT raw data as mined for the Rockbridge County for the calendar years 2002, 2003, 2004, and 2005 was presented. As can be seen in such table, there are several ADT values representing the traffic amounts within different portions of the I-64 within the Rockbridge County. To be able to roll these values up to the county level, a weighting scheme which uses the mileage as the weight factor was used. **Table 4.54** presents the overall ADT values obtained for the Rockbridge County (for I-64) for the calendar years 2002, 2003, 2004, and 2005 after such computation is performed.

Table 4.54: Rockbridge County's Overall ADT for Interstate 64 (I-64) for Calendar Years

Calendar Year	2002			2003			2004			2005		
County	Total Mile	ADT	Overall ADT	Total Mile	ADT	Overall ADT	Total Mile	ADT	Overall ADT	Total Mile	ADT	Overall ADT
	1.92	4600		1.92	4900		1.92	4300		1.92	4100	
	7.38	4300		7.38	4400		7.38	4500		7.38	4300	
Rockbridge	5.39	4500	4545	5.39	4800	4764	5.39	5100	4801	5.39	4900	4601
	1.55	5800		1.55	6200		0.98	6400		0.98	6200	
							0.57	4200		0.57	4100	

After this was done, another rearrangement was needed. The ADT data is for calendar years. However, as discussed earlier, the DEA model for "Asset Groups" will use fiscal years for the time unit of analysis. Thus, in an effort to identify the ADT of the DMUs (counties) in a given fiscal year (e.g. Fiscal Year 2005), the previous calendar year's (e.g. Calendar Year 2004) ADT value and current calendar year's (e.g. Calendar Year 2005) ADT value were combined by assigning a 50% weight to each value. This is simply because a given fiscal year (e.g. Fiscal Year 2005) is composed of half of the previous calendar year (e.g. July 1st-December 31st of Calendar Year 2004) and half of the current calendar year (e.g. January 1st-June 30th of Calendar Year 2005). **Table 4.55** presents the ADT values (as computed through this method) that belong to fiscal years 2003, 2004, and 2005 for the Rockbridge County (for I-64).

Table 4.55: Rockbridge County's Overall ADT for Interstate 64 (I-64) for Fiscal Years

Fiscal Year / County	2003	2004	2005
Rockbridge	4654	4782	4701

4.3.3.4.4 Rearranging the "Asset Groups Condition Data" to Represent the Variable "Change in LOS Rating Percentage"

Two different steps of rearrangement had to be performed on the Asset Groups Condition Data (as described in **Section 4.3.3.1**) to be able to obtain the values that can be used for the variable "Change in LOS Rating Percentage" as listed in **Table 4.44**. These steps are as follows:

1) **Table 4.0** lists all of the fence to fence asset items that are evaluated through MRP inspections. During inspections, evaluators determine whether the asset item(s) they are supposed to inspect in a given 0.1 mile segment meet certain pre-defined performance criteria. In each segment that is visited, evaluators record the total number of a certain asset item (e.g. pipe) inspected and the number of such asset item that meet the performance criteria. This is done for each type of asset item that is supposed to be evaluated in a given segment. These numbers for each asset item should be combined and rolled up to the county level as the DMU for this implementation example is the county. This can easily be done, for each asset item, by summing the values for each segment and obtaining the total number inspected and total number that meet the criteria. **Table 4.56** presents the results of such operation for the Rockbridge County for fiscal year 2005. Once this is done, the resulting numbers for each asset item should be combined in a way to represent the overall fence to fence asset item level-of-service (LOS) rating for the county. This is done by using the weighting scheme that is implemented by Virginia Tech as agreed by VDOT (Piñero 2003). Such weighting scheme is presented in **Table 4.57**. As can be seen within such table, there are weights that are developed at the asset item level as well as the asset group level. The results of the application of such a weighting scheme for the Rockbridge County for fiscal years 2002, 2003, 2004, and 2005 are presented in **Table 4.58**.

Table 4.56: The Condition Ratings at the Asset Item Level for the Rockbridge County for Fiscal Year 2005

Asset Group	Asset Item	No. of Samples	No. of Passing Samples
Shoulders	Shoulders- Hard Surfaced	77	76
	Shoulders- Non-hard Surfaced	0	0
Roadside	Grass	25	16
	Debris and Road Kill	87	86
	Litter	77	77
	Landscaping	2	2
	Brush and Tree Control	69	69
	Concrete Barrier	1	1
	Sound Barrier	1	1
	Slopes	77	75
	Fence	71	50
Drainage	Paved Ditches	108	83
	Unpaved Ditches	216	211
	Pipes	62	60
	Box Culverts	0	0
	Under/Edge Drains	5	4
	Storm Drains/ Drop Inlets	18	18
	Curb and Gutter	1	1
	Sidewalks	0	0
	Stormwater Management Ponds	0	0
Traffic	Signals	0	0
	Pavement Messages	0	0
	Pavement Striping	83	83
	Pavement Markers	163	158
	Delineators/Object Markers	61	27
	Glare Foils	0	0
	Regulatory Signs	48	48
	Other Signs	71	71
	Luminaries	0	0
	Guardrail	178	178
	Impact Attenuators	0	0
	Truck Ramps	0	0
	Cross Overs	8	8
	Rumble Strips	106	106

Table 4.57: Asset Items and Groups Weighting Scheme Implemented by Virginia Tech

Asset Group	Asset Item	Asset Item Weighting	Asset Group Weighting
Shoulders	Shoulders- Hard Surfaced	7.17	0.1560
	Shoulders- Non-hard Surfaced	1.00	
Roadside	Grass	5.67	0.2350
	Debris and Road Kill	8.50	
	Litter	4.67	
	Landscaping	4.83	
	Brush and Tree Control	5.33	
	Concrete Barrier	8.17	
	Sound Barrier	4.83	
	Slopes	5.83	
	Fence	5.00	
Drainage	Paved Ditches	6.67	0.2370
	Unpaved Ditches	6.33	
	Pipes	8.50	
	Box Culverts	8.00	
	Under/Edge Drains	8.33	
	Storm Drains/ Drop Inlets	8.67	
	Curb and Gutter	4.00	
	Sidewalks	3.17	
	Stormwater Management Ponds	5.33	
Traffic	Signals	9.17	0.3720
	Pavement Messages	6.33	
	Pavement Striping	8.67	
	Pavement Markers	8.00	
	Delineators/Object Markers	4.83	
	Glare Foils	5.50	
	Regulatory Signs	8.00	
	Other Signs	8.00	
	Luminaries	6.50	
	Guardrail	8.50	
	Impact Attenuators	9.33	
	Truck Ramps	6.00	
	Cross Overs	5.00	
	Rumble Strips	5.00	

Table 4.58: The Level-of-Service Rating for the Rockbridge County for Fiscal Years 2002, 2003, 2004, and 2005

County	Fiscal Year	Overall Asset Groups LOS Rating
Rockbridge	2002	92.91%
	2003	84.44%
	2004	94.74%
	2005	94.94%

2) The output of the asset groups' maintenance process is not the absolute "LOS Rating" attained at the end of a period (i.e. a fiscal year). The output is rather the change in the LOS Rating within a period. This is mainly because the controllable input, i.e. the money spent to perform maintenance on asset groups within a period, as well as the uncontrollable inputs, i.e. precipitation amount, traffic count, and total area served representing the same time period, results in a change of the asset groups' condition within a period as opposed to resulting in the absolute condition at the end of a period. For this reason, to be able to calculate the asset groups maintenance efficiency of the counties for the time period of a fiscal year, one needs to identify for each county: (i) the expenditures made within that time period, (ii) precipitation amount within that time period, (iii) traffic count within that time period, (iv) the total area served within that time period (i.e. the total number of asset items within the county), and (v) the change in the asset groups' condition within that time period. The last item is, in fact, equal to the difference between the LOS rating at the end of the time period and at the beginning of the time period. For the purposes of this research, as the time unit of analysis is a fiscal year, the LOS rating at the beginning of a given fiscal year is assumed to be the LOS rating calculated for the previous fiscal year; and the LOS rating at the end of a given fiscal year is assumed to be the LOS rating calculated for such given fiscal year. **Table 4.59** presents the "Change in LOS Rating Percentage" for the Rockbridge County for fiscal years 2003, 2004, and 2005. It is important to note that even though LOS rating is represented in percentage, the "Change in LOS Rating Percentage" output variable is represented without percentage, i.e., by the number itself.

Table 4.59: Change in LOS Rating (for the asset groups) for the Rockbridge County

County	Fiscal Year	Change in LOS Rating Percentage
Rockbridge	2003	-8.47
	2004	10.30
	2005	0.20

Table 4.60 presents the input and output variables' data for the fiscal years of 2003, 2004 and 2005 (the only fiscal years that all relevant data is available for) with respect to each county decided to be included in this study. Such data is obtained by performing all the steps discussed within this section (i.e. **Section 4.3.3**).

Table 4.60: Input and Output Variables' Data for the Fiscal Years of 2003, 2004 and 2005 for Asset Groups

County	Fiscal Year	Cost for Maintaining the Asset Groups	Precipitation Amount (inches)	Traffic Count (ADT)	Total Area Served (Total # of Asset Items)	Change in LOS Rating Percentage
Albemarle	2003	$596,309	5.0	16243	7169	-0.48
	2004	$663,422	4.9	16862		-1.44
	2005	$757,384	3.8	17391		-0.72
Alleghany	2003	$813,425	4.3	6204	8674	-10.80
	2004	$1,042,070	3.8	6310		8.51
	2005	$1,112,299	3.4	6053		-3.46
Augusta	2003	$1,581,745	4.4	22439	7186	-4.33
	2004	$1,639,613	3.9	23373		0.61
	2005	$1,019,826	3.7	23982		1.55
Fauquier	2005	$221,295	4.2	19896	4693	-0.64
Henrico	2003	$2,811,255	4.5	33710	5488	-2.92
	2004	$1,719,112	4.8	34516		4.32
	2005	$1,302,359	4.5	36244		1.42
Roanoke	2003	$2,409,243	4.7	29406	5309	-7.29
	2004	$1,755,507	3.9	29709		5.58
	2005	$902,603	3.8	29666		-2.10
Rockbridge	2003	$448,479	4.6	4654	3337	-8.47
	2004	$305,700	4.5	4782		10.30
	2005	$145,698	3.8	4701		0.20
Spotsylvania	2003	$1,399,457	3.9	48872	3774	-3.12
	2004	$723,740	4.1	50823		7.53
	2005	$851,799	3.4	52618		-4.31

4.3.4 DEA Model Selection, Final Refinements in Data and Results of DEA

Based on the fact that the Constant Returns to Scale (CRS), which is a special case of the Variable Returns to Scale (VRS), is not that frequently encountered in processes, it can be asserted that the VRS approach is appropriate for the shape of the production possibility set of the inputs and output for the asset groups' maintenance process as presented in **Table 4.44**. Thus, it is decided to use the BCC formulation (the formulation with the convexity constraint which is used for the processes which experience VRS) for the DEA model within this implementation example. It is also necessary to decide on the orientation (i.e. input oriented or output oriented) of the model once the type of the model is selected. As discussed in **Section 3.8,** ideally this decision is made based on the dynamics of the process that is analyzed and the choice of the decision makers to seek either input reductions or output increases in the process. However for this study, the decision for the orientation of the model is not based on the decision makers' choice, bur rather it is based on the necessity to address the issue of negative values for the output variable. As can be seen in **Table 4.60**, there is a number of DMUs whose output variable ("Change in LOS Rating Percentage") is negative[16]. However the original formulations of DEA (CCR and BCC) require all input and output values to be positive (Pastor 1996). To overcome the issue of non-positive data, one can transform the variable which has non-positive values into another variable for all DMUs in the data set. This can be done by adding a value larger than the most negative value to the original values of all DMUs. However if one is to use BCC model; and the negative values are on the output side (the case within this example), such transformation can be made only if the input oriented model is used. In other words, the BCC input oriented model is output translation invariant (i.e. an affine transformation of data can be performed with no impact in the DEA efficiency results). Similarly the BCC output oriented model is input translation invariant (Pastor 1996). Given all of these, the issue of non-positive values in the "Change in LOS Rating Percentage" variable can be addressed by adding 10.81 (a value which is larger than the absolute value of the smallest negative value of such variable, -10.80, in the data set) to such variable's values for all DMUs to make sure that all values to be used in the DEA model are positive. However doing so requires the input oriented model to be used. Therefore, the model to be used in this study is input oriented BCC model. This transformation is made for the values of the variable "Change in LOS Rating Percentage"; and newly formed variable is named as the "Modified Change in LOS Rating Percentage".

Another refinement that needs to be made in the data is for the "Total Area Served" variable. As can be seen in **Table 4.44**, this is an input variable. However, keeping the values of every other input variable the same, an increase in the value of this variable is likely to result in a decrease in the output variable's ("Change in LOS Rating Percentage") value as it will be harder to maintain a larger number of asset items at the same quality with the same amount of expenditures. Given the detailed discussion presented in **Section 4.1.4** about the isotonicity concept and in an effort to resolve the non-isotonicity issue inherent in the "Total Area Served"

---

[16] This means that although resources have been allocated to such DMUs within a given fiscal year, no improvement in the condition (as represented by the "Change in LOS Rating Percentage" variable) of the asset groups within them is obtained. Moreover, their deteriorations have been in such a rate that they have ended up being in a worse condition at the end of the fiscal year than what they were at the beginning of such fiscal year.

variable, the values of that variable for each county is divided to one (i.e. value's multiplicative inverse is calculated). By this transformation, a direct proportion between this input variable and the output variables is established (i.e. larger the input, larger the output). The newly formed variable is named as the "DMU $_{TAS}$". The exact same discussion applies to the "Precipitation Amount" and "Traffic Count (ADT)" uncontrollable variables as well. Therefore, to address the non-isotonic nature of these variables, such variables' values' multiplicative inverses are calculated. The newly formed variables are named as "DMU $_{PPT}$" and "DMU $_{ADT}$" for "Precipitation Amount" and "Traffic Count (ADT)" variables respectively.

Table 4.61.A presents the final refined values for the input and output variables for each county, as transformed to the formats suitable to be used in the input oriented BCC model for "Asset Groups". As can be seen in such table, for each county, 3 separate DMUs are derived based on the different input-output data belonging to different fiscal years. Such DMUs are denoted by appropriate subscripts to indicate the fact that even though they belong to the same county, they are different DMUs for the purposes of this implementation example.

Table 4.61.A: Data to be used in the Input Oriented BCC Model for "Asset Groups"

	Input Data				Output Data
DMU	Cost for Maintaining the Asset Groups	DMU $_{PPT}$	DMU $_{ADT}$	DMU $_{TAS}$	Modified Change in LOS Rating Percentage
Albemarle$_1$	$596,309	0.20166373	0.00006157	0.00013949	10.33
Albemarle$_2$	$663,422	0.20373514	0.00005931	0.00013949	9.37
Albemarle$_3$	$757,384	0.26021902	0.00005750	0.00013949	10.09
Alleghany$_1$	$813,425	0.23390293	0.00016119	0.00011529	0.01
Alleghany$_2$	$1,042,070	0.26030369	0.00015848	0.00011529	19.32
Alleghany$_3$	$1,112,299	0.29727498	0.00016520	0.00011529	7.35
Augusta$_1$	$1,581,745	0.22675308	0.00004456	0.00013916	6.48
Augusta$_2$	$1,639,613	0.25654730	0.00004278	0.00013916	11.42
Augusta$_3$	$1,019,826	0.27206566	0.00004170	0.00013916	12.36
Fauquier$_3$	$221,295	0.23952096	0.00005026	0.00021308	10.17
Henrico$_1$	$2,811,255	0.22228397	0.00002967	0.00018222	7.89
Henrico$_2$	$1,719,112	0.20887728	0.00002897	0.00018222	15.13
Henrico$_3$	$1,302,359	0.22427810	0.00002759	0.00018222	12.23
Roanoke$_1$	$2,409,243	0.21186441	0.00003401	0.00018836	3.52
Roanoke$_2$	$1,755,507	0.25415652	0.00003366	0.00018836	16.39
Roanoke$_3$	$902,603	0.25979649	0.00003371	0.00018836	8.71
Rockbridge$_1$	$448,479	0.21892944	0.00021485	0.00029967	2.34
Rockbridge$_2$	$305,700	0.22252041	0.00020911	0.00029967	21.11
Rockbridge$_3$	$145,698	0.26021337	0.00021273	0.00029967	11.01
Spotsylvania$_1$	$1,399,457	0.25789813	0.00002046	0.00026497	7.69
Spotsylvania$_2$	$723,740	0.24119633	0.00001968	0.00026497	18.34
Spotsylvania$_3$	$851,799	0.29717682	0.00001900	0.00026497	6.50

It is important to note that specifying some of the inputs as uncontrollable results in the application of the modified formulation developed by Banker and Morey (1986) (Banker and Morey 1986a) (which is the approach chosen to deal with the uncontrollable factors as discussed at the beginning of this implementation example) by the software's algorithm. **Table 4.62.A** presents the detailed results of the model as extracted to a spreadsheet. **Table 4.63.A** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county.

Table 4.62.A: Detailed Results of the Input Oriented BCC Model for "Asset Groups" (as Extracted from the Frontier Analyst)

Unit name	Score	Actual Cost for Maintaining the Asset Groups	Actual DMU PPT	Actual DMU ADT	Actual DMU TAS	Actual Modified Change in LOS Rating Percentage	Target Cost for Maintaining the Asset Groups	Target DMU PPT	Target DMU ADT	Target DMU TAS	Target Modified Change in LOS Rating Percentage	Lambda 1	L-Peer 1	Lambda 2	L-Peer 2	Lambda 3	L-Peer 3	Lambda 4	L-Peer 4
Albemarle1	100.0%	$596,309	0.20166373	0.00006157	0.00013949	10.33	$596,309	0.20166373	0.00006157	0.00013949	10.33	1.00	Albemarle1						
Albemarle2	100.0%	$663,422	0.20373514	0.00005931	0.00013949	9.37	$663,422	0.20373514	0.00005931	0.00013949	9.37	1.00	Albemarle2						
Albemarle3	90.1%	$757,384	0.26021902	0.00005750	0.00013949	10.09	$682,494	0.21608223	0.00005750	0.00013949	10.74	0.80	Albemarle1	0.20	Augusta3				
Alleghany1	100.0%	$813,425	0.23390293	0.00016119	0.00011529	0.01	$813,425	0.23390293	0.00016119	0.00011529	0.01	1.00	Alleghany1						
Alleghany2	100.0%	$1,042,070	0.26030369	0.00015848	0.00011529	19.32	$1,042,070	0.26030369	0.00015848	0.00011529	19.32	1.00	Alleghany2						
Alleghany3	80.9%	$1,112,299	0.29727498	0.00016520	0.00011529	7.35	$900,336	0.24393823	0.00016016	0.00011529	7.35	0.62	Alleghany1	0.38	Alleghany2				
Augusta1	100.0%	$1,581,745	0.22675308	0.00004456	0.00013916	6.48	$1,581,745	0.22675308	0.00004456	0.00013916	6.48	1.00	Augusta1						
Augusta2	100.0%	$1,639,613	0.25654730	0.00004278	0.00013916	11.42	$1,639,613	0.25654730	0.00004278	0.00013916	11.42	1.00	Augusta2						
Augusta3	100.0%	$1,019,826	0.27206566	0.00004170	0.00013916	12.36	$1,019,826	0.27206566	0.00004170	0.00013916	12.36	1.00	Augusta3						
Fauquier3	100.0%	$221,295	0.23952096	0.00005026	0.00021308	10.17	$221,295	0.23952096	0.00005026	0.00021308	10.17	1.00	Fauquier3						
Henrico1	45.0%	$2,811,255	0.22228397	0.00002967	0.00018222	7.89	$1,264,720	0.22228397	0.00002967	0.00018222	12.52	0.07	Albemarle1	0.07	Henrico2	0.83	Henrico3	0.03	Spotsylvania2
Henrico2	100.0%	$1,719,112	0.20887728	0.00002897	0.00018222	15.13	$1,719,112	0.20887728	0.00002897	0.00018222	15.13	1.00	Henrico2						
Henrico3	100.0%	$1,302,359	0.22427810	0.00002759	0.00018222	12.23	$1,302,359	0.22427810	0.00002759	0.00018222	12.23	1.00	Henrico3						
Roanoke1	56.8%	$2,409,243	0.21186441	0.00003401	0.00018836	3.52	$1,367,225	0.21186441	0.00003401	0.00018518	14.64	0.19	Albemarle1	0.67	Henrico2	0.14	Spotsylvania2		
Roanoke2	100.0%	$1,755,507	0.25415652	0.00003366	0.00018836	16.39	$1,755,507	0.25415652	0.00003366	0.00018836	16.39	1.00	Roanoke2						
Roanoke3	98.2%	$902,603	0.25979649	0.00003371	0.00018836	8.71	$885,987	0.25957736	0.00003371	0.00018836	14.53	0.60	Augusta3	0.03	Fauquier3	0.37	Spotsylvania2		
Rockbridge1	79.3%	$448,479	0.21892944	0.00021485	0.00029967	2.34	$355,735	0.21892944	0.00018371	0.00027209	19.25	0.17	Albemarle1	0.83	Rockbridge2				
Rockbridge2	100.0%	$305,700	0.22252041	0.00020911	0.00029967	21.11	$305,700	0.22252041	0.00020911	0.00029967	21.11	1.00	Rockbridge2						
Rockbridge3	100.0%	$145,698	0.26021337	0.00021273	0.00029967	11.01	$145,698	0.26021337	0.00021273	0.00029967	11.01	1.00	Rockbridge3						
Spotsylvania1	50.8%	$1,399,457	0.25789813	0.00002046	0.00026497	7.69	$710,924	0.24115360	0.00002046	0.00026365	18.13	0.03	Fauquier3	0.97	Spotsylvania2				
Spotsylvania2	100.0%	$723,740	0.24119633	0.00001968	0.00026497	18.34	$723,740	0.24119633	0.00001968	0.00026497	18.34	1.00	Spotsylvania2						
Spotsylvania3	100.0%	$851,799	0.29717682	0.00001900	0.00026497	6.5	$851,799	0.29717682	0.00001900	0.00026497	6.5	1.00	Spotsylvania3						

Table 4.63.A: Overall Efficiency Scores of the Counties for "Asset Groups"

County	Overall Efficiency Score of the County
Albemarle	96.7%
Alleghany	93.6%
Augusta	100.0%
Fauquier	100.0%
Henrico	81.7%
Roanoke	85.0%
Rockbridge	93.1%
Spotsylvania	83.6%

4.3.5 Conclusions

The overall observations that are obtained based on the results of this implementation example are summarized as follows:

1) Out of 22 DMUs, 15 are 100% efficient.
2) Based on the overall efficiency scores presented in **Table 4.63.A**, the most efficient counties are the Augusta County and Fauquier County both of which attain a 100% efficiency score. However, it is important to note that only one DMU for Fauquier County was included in the DEA model as discussed earlier. The overall efficiency scores of all other counties, but Henrico County and Spotsylvania County, are within a 15% range from that of the Augusta and Fauquier counties.
3) The county with the lowest efficiency score relative to the others in the data set is Henrico County (81.7%).
4) All of the counties have received 100% efficiency score at least for one fiscal year.
5) Albemarle County is the one whose DMUs are most frequently referenced (3 times) as peers by the DMUs belonging to different counties.
6) The only county whose DMUs are never referenced by other DMUs is the Roanoke County.
7) Augusta County consistently kept its efficiency score at 100% over the time period of fiscal years 2003, 2004, and 2005
8) Albemarle County and Alleghany County kept their efficiency scores at 100% in the fiscal years 2003 and 2004 but then worsened their efficiency scores, in the amount of 10% and 20% respectively, in the fiscal year 2005.
9) Henrico County, Rockbridge County, and Spotsylvania County increased their efficiency scores drastically from fiscal year 2003 to fiscal year 2004 and kept such at the same level (100%) in fiscal year 2005.

Figure 4.10 presents the peer relationships of the DMUs belonging to each county. Arrows in this figure represent where the inefficient DMUs should search for their peer(s). If an arrow starts at a county and points back, it means that the inefficient DMU(s) in this county should search for efficient DMU(s) within the same county. On the other hand, if an arrow starts at a county (County 1) and points to another county (County 2), it means that the inefficient DMU(s) in this county (County 1) should search for efficient DMU(s) in that other county (County 2).

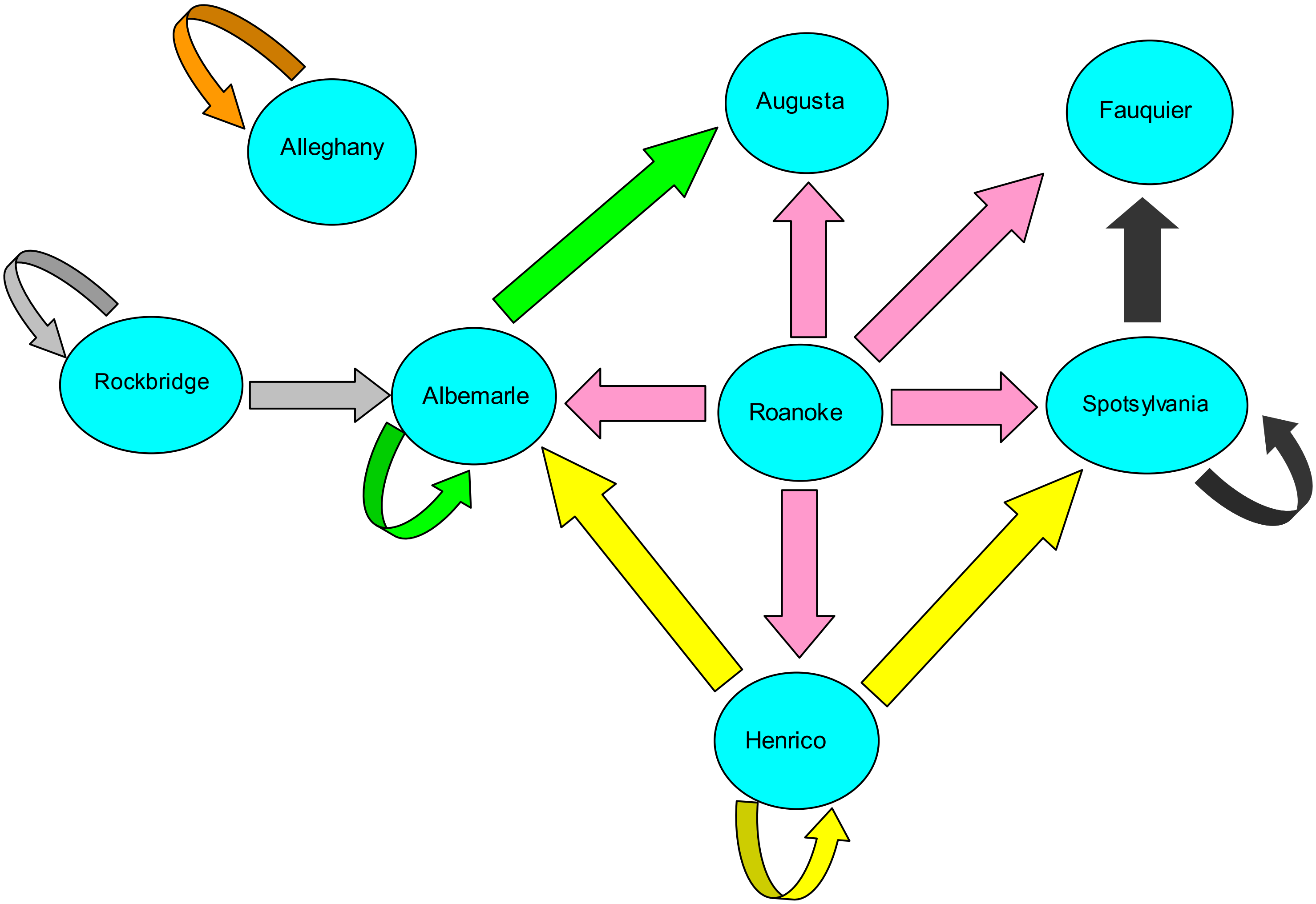


Figure 4.10: Peer Relationships of the DMUs for "Asset Groups"

As can be seen in **Figure 4.10**, the DMUs belonging to Augusta and Fauquier counties do not search for a peer within or outside of their counties. This is mainly due to the fact that the DMUs within these counties are 100% efficient as presented in **Table 4.62.A**. It is important to note that, of these counties, Fauquier County is represented by only one DMU in this model due to data availability issues discussed earlier.

As can be seen in **Figure 4.10**, the DMUs that belong to the Alleghany County are only looking within their own counties to identify peer DMUs that belong to the same county. This indicates that such county already has the means in place to be efficient (as it has been efficient in two fiscal years out of three) and thus do not need to identify the practices of other counties as best practices. Alleghany County has been 100% efficient until the fiscal year 2005 and then dropped its efficiency to 80.9%. To address this sudden efficiency drop, the decision makers within this county (e.g. County Maintenance Administrator) should try to identify the changes that were introduced (in fiscal year 2005) to the operational and/or strategic policies that have been implemented in the previous fiscal years. Such changes are most likely the causes for the efficiency drop. Moreover, the decision makers should observe their own practices and operational and strategic policies belonging to the earlier fiscal years to be able to identify what changes are needed to be implemented to go back to the efficiency levels reached within the earlier fiscal years.

For Albemarle County, just reverting back to the operational and strategic policy that was implemented in earlier fiscal years (i.e., fiscal year 2003 or 2004- the fiscal years in which Albemarle County's efficiency is 100%) is not sufficient to make its efficiency 100% in fiscal year 2005 and beyond. This can be attributed to the fact that the peers for the DMU representing the fiscal year 2005 performance of the Albemarle County ($Albemarle_3$) are the DMU that belongs to the Augusta County in addition to the DMU representing the fiscal year 2003 performance of the Albemarle County ($Albemarle_1$). Given this, a more profound change should be made by the decision makers of the Albemarle County as far as its operational and strategic policy is concerned. This change requires a deeper analysis and observation of the operational and strategic policies and general maintenance practices of the Augusta County for fiscal year 2005 in addition to observing its own practices and operational and strategic policies belonging to the fiscal year 2003 in an effort to adopt such practices.

Even though Roanoke County's fiscal year 2004 performance ($Roanoke_2$) attains an efficiency score of 100%, the DEA model does not identify $Roanoke_2$ as a peer for the fiscal year 2005 performance ($Roanoke_3$) of the same county which attains an efficiency score of 98.2%. DEA model, rather, identifies the DMUs representing the fiscal year 2005 performances of the Augusta and Fauquier counties ($Augusta_3$ and $Fauquier_3$ respectively) and fiscal year 2004 performance of the Spotsylvania County ($Spotsylvania_2$) as the peers of $Roanoke_3$.

Henrico, Rockbridge, and Spotsylvania counties' efficiencies have increased from low values in fiscal year 2003 to 100% in fiscal year 2004. Furthermore, such counties kept their efficiency scores at 100% within fiscal year 2005 as well. Thus, whatever operational and strategic policies these counties have started implementing starting in fiscal year 2004 should be kept as they are to keep their efficiency at 100% in the future as well.

An important result of the model is with respect to the Albemarle County. It is the county whose DMUs are most frequently referenced as peers by the DMUs of other counties. Although Augusta and Fauquier counties' overall efficiency scores are higher than that of Albemarle County, such counties' DMUs are not referenced as frequently as those of the Albemarle County by other counties. Thus, it is recommended that the maintenance management practices within the Albemarle County be investigated more in depth by the upper management of VDOT.

In conclusion, by looking at the results of the model (examining **Table 4.62.A**, **Table 4.63.A** and **Figure 4.10**), some county-specific operational and strategic decisions can be made as presented above. It is recommended for VDOT to carefully investigate the practices within the Albemarle County (due to the reason stated in the preceding paragraph) as some very valuable insight can be gained which later may lead to some changes to be implemented all across the state of Virginia.

As evidenced by the efficiency scores and the differences in such scores obtained through the implementation of the DEA model, there are differences between the counties of Virginia as far as their "asset groups" maintenance efficiencies are concerned. Therefore, the results of the DEA model presented herein confirm the validity of the first hypothesis of this research (as presented in **Chapter 1**) which is: "Within the state of Virginia, some counties are more efficient than others in performing highway maintenance operations."

4.3.6 Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency

As was presented in **Chapter 1**, the framework developed by this research is aimed to measure the relative efficiency of different units (performing highway maintenance) while considering the effects of environmental and operational factors (both of which are beyond the control of the decision-maker, i.e., the maintenance manager) on such efficiency. Consequently, the DEA implementation example (for asset groups) that is presented earlier has taken the effects of the environmental and operational uncontrollable factors on the efficiency into consideration; and thus intrinsically accounted for (and thus removed) the amount of inefficiency resulting from such uncontrollable factors, as the framework developed in **Chapter 3** incorporates them into the DEA model as uncontrollable variables.

This section presents a modified version of the DEA model run presented in **Section 4.3.4** (whose results are presented in **Table 4.62.A**). In such version, the uncontrollable variables for all DMUs are assigned the same value with the purpose of testing the second hypothesis of this research which is: "Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties." Assigning the same value to the uncontrollable variables for all DMUs means that all DMUs are experiencing the same uncontrollable factors. Therefore, a DEA model that is run with such values represents the case where the differences between the environmental and operational factors experienced by each DMU are neglected. This, in effect, is the same as not acknowledging the effects of the environmental and operational factors on the efficiency of the DMUs and thus not accounting for the amount of inefficiency created by such factors. The reason that the uncontrollable variables are not completely removed from the model but instead assigned the same value is to keep the number of variables unchanged. This way, the results of the two models (the one acknowledging the effects of uncontrollable factors on the efficiency of units and the one ignoring such) can be comparable as both models contain the same number of variables. In other words, one can attribute all of the efficiency differences (in the same DMUs) between the two models to the effects of the uncontrollable factors as artificial efficiency changes that could be resulting from the change in the number of variables (due to the way that the DEA works as detailed in **Section 3.6**) between the two models are prevented with such approach.

Table 4.61.B presents the variable data for 22 DMUs to be used in the DEA model for the asset groups which ignores the effects of uncontrollable factors (and thus which does not account for the amount of inefficiency created by such) by assigning the same value to the uncontrollable variables for all DMUs. The data for such table is different from the one presented in **Table 4.61.A** as the values for DMU_{PPT}, DMU_{ADT}, and DMU_{TAS} variables (the uncontrollable variables in the model) are assigned the same value of "1". It is important to note that any other value

could have been chosen to be assigned to these variables as the results of the DEA model are not affected with that particular value as long as such value is assigned to all DMUs.

Table 4.61.B: Data to be used in the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency

	Input Data				Output Data
DMU	Cost for Maintaining the Asset Groups	DMU_{PPT}	DMU_{ADT}	DMU_{TAS}	Modified Change in LOS Rating Percentage
$Albemarle_1$	$596,309	1	1	1	10.33
$Albemarle_2$	$663,422	1	1	1	9.37
$Albemarle_3$	$757,384	1	1	1	10.09
$Alleghany_1$	$813,425	1	1	1	0.01
$Alleghany_2$	$1,042,070	1	1	1	19.32
$Alleghany_3$	$1,112,299	1	1	1	7.35
$Augusta_1$	$1,581,745	1	1	1	6.48
$Augusta_2$	$1,639,613	1	1	1	11.42
$Augusta_3$	$1,019,826	1	1	1	12.36
$Fauquier_3$	$221,295	1	1	1	10.17
$Henrico_1$	$2,811,255	1	1	1	7.89
$Henrico_2$	$1,719,112	1	1	1	15.13
$Henrico_3$	$1,302,359	1	1	1	12.23
$Roanoke_1$	$2,409,243	1	1	1	3.52
$Roanoke_2$	$1,755,507	1	1	1	16.39
$Roanoke_3$	$902,603	1	1	1	8.71
$Rockbridge_1$	$448,479	1	1	1	2.34
$Rockbridge_2$	$305,700	1	1	1	21.11
$Rockbridge_3$	$145,698	1	1	1	11.01
$Spotsylvania_1$	$1,399,457	1	1	1	7.69
$Spotsylvania_2$	$723,740	1	1	1	18.34
$Spotsylvania_3$	$851,799	1	1	1	6.50

Table 4.62.B presents the detailed results of this model as extracted to a spreadsheet. **Table 4.63.B** presents the overall efficiency scores for each county calculated by averaging the efficiency scores of the DMUs belonging to each county. **Table 4.62.C** presents the efficiency scores of the DMUs obtained from both DEA models (i.e., the one that acknowledges the effects of the uncontrollable factors and the one that ignores those) side by side for comparison purposes. Similarly, **Table 4.63.C** presents the overall efficiency scores of the counties obtained from both DEA models (i.e., the one that acknowledges the effects of the uncontrollable factors and the one that ignores those) side by side for comparison purposes.

Table 4.62.B: Detailed Results of the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency

Unit name	Score	Actual Cost for Maintaining the Asset Groups	Actual DMU ADT	Actual DMU PPT	Actual DMU AD	Actual Modified Change in Overall Asset Item Score	Target Cost for Maintaining Fence to Fence Asset Items	Target DMU ADT	Target DMU PPT	Target DMU AD	Target Modified Change in Overall Asset Item Score	Lambda 1	L-Peer 1	Lambda 2	L-Peer 2
Albemarle1	24.4%	$596,309	1	1	1	10.33	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Albemarle2	22.0%	$663,422	1	1	1	9.37	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Albemarle3	19.2%	$757,384	1	1	1	10.09	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Alleghany1	17.9%	$813,425	1	1	1	0.01	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Alleghany2	26.6%	$1,042,070	1	1	1	19.32	$277,343	1	1	1	19.32	0.82	Rockbridge2	0.18	Rockbridge3
Alleghany3	13.1%	$1,112,299	1	1	1	7.35	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Augusta1	9.2%	$1,581,745	1	1	1	6.48	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Augusta2	9.3%	$1,639,613	1	1	1	11.42	$152,194	1	1	1	11.42	0.04	Rockbridge2	0.96	Rockbridge3
Augusta3	16.4%	$1,019,826	1	1	1	12.36	$167,085	1	1	1	12.36	0.13	Rockbridge2	0.87	Rockbridge3
Fauquier3	65.8%	$221,295	1	1	1	10.17	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Henrico1	5.2%	$2,811,255	1	1	1	7.89	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Henrico2	12.3%	$1,719,112	1	1	1	15.13	$210,966	1	1	1	15.13	0.41	Rockbridge2	0.59	Rockbridge3
Henrico3	12.7%	$1,302,359	1	1	1	12.23	$165,025	1	1	1	12.23	0.12	Rockbridge2	0.88	Rockbridge3
Roanoke1	6.1%	$2,409,243	1	1	1	3.52	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Roanoke2	13.2%	$1,755,507	1	1	1	16.39	$230,927	1	1	1	16.39	0.53	Rockbridge2	0.47	Rockbridge3
Roanoke3	16.1%	$902,603	1	1	1	8.71	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Rockbridge1	32.5%	$448,479	1	1	1	2.34	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Rockbridge2	100.0%	$305,700	1	1	1	21.11	$305,700	1	1	1	21.11	1.00	Rockbridge2		
Rockbridge3	100.0%	$145,698	1	1	1	11.01	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Spotsylvania1	10.4%	$1,399,457	1	1	1	7.69	$145,698	1	1	1	11.01	1.00	Rockbridge3		
Spotsylvania2	36.2%	$723,740	1	1	1	18.34	$261,818	1	1	1	18.34	0.73	Rockbridge2	0.27	Rockbridge3
Spotsylvania3	17.1%	$851,799	1	1	1	6.5	$145,698	1	1	1	11.01	1.00	Rockbridge3		

Table 4.63.B: Overall Efficiency Scores of the Counties for the DEA Model that Ignores the Effects of the Uncontrollable Factors on the Asset Groups Maintenance Efficiency

County	Overall Efficiency Score of the County
Albemarle	21.9%
Alleghany	19.2%
Augusta	11.6%
Fauquier	65.8%
Henrico	10.0%
Roanoke	11.8%
Rockbridge	77.5%
Spotsylvania	21.2%

Table 4.62.C: Efficiency Scores of the DMUs obtained from both DEA Models for Asset Groups

Unit name	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model (*DEA 1*)	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model (*DEA 2*)
Albemarle1	100.0%	24.4%
Albemarle2	100.0%	22.0%
Albemarle3	90.1%	19.2%
Alleghany1	100.0%	17.9%
Alleghany2	100.0%	26.6%
Alleghany3	80.9%	13.1%
Augusta1	100.0%	9.2%
Augusta2	100.0%	9.3%
Augusta3	100.0%	16.4%
Fauquier3	100.0%	65.8%
Henrico1	45.0%	5.2%
Henrico2	100.0%	12.3%
Henrico3	100.0%	12.7%
Roanoke1	56.8%	6.1%
Roanoke2	100.0%	13.2%
Roanoke3	98.2%	16.1%
Rockbridge1	79.3%	32.5%
Rockbridge2	100.0%	100.0%
Rockbridge3	100.0%	100.0%
Spotsylvania1	50.8%	10.4%
Spotsylvania2	100.0%	36.2%
Spotsylvania3	100.0%	17.1%

Table 4.63.C: Overall Efficiency Scores of the Counties obtained from both DEA Models for Asset Groups

County	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model (*DEA 1*)	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model (*DEA 2*)
Albemarle	96.7%	21.9%
Alleghany	93.6%	19.2%
Augusta	100.0%	11.6%
Fauquier	100.0%	65.8%
Henrico	81.7%	10.0%
Roanoke	85.0%	11.8%
Rockbridge	93.1%	77.5%
Spotsylvania	83.6%	21.2%

When the results from both models (*DEA 1* and *DEA 2*) within each of the tables are compared, it can be seen that a portion of the inefficiencies (which is lowering the efficiency scores) inherent in the DMUs as seen in the *DEA 2* model (i.e. when the effects of uncontrollable factors are not acknowledged in the DEA model) can be attributed to the effects of the uncontrollable factors faced by such DMUs. This is simply because for all counties, the efficiency scores are higher when the DEA model is run by acknowledging the effects of the uncontrollable factors on the efficiency of DMUs. Such DEA model (*DEA 1* model), by considering the effects of the uncontrollable factors, calculates the efficiency of the DMUs given the uncontrollable factors they face. Therefore, the amount of inefficiency that is the result of the uncontrollable factors (e.g. bad climate, heavy traffic, etc.) is accounted for by the DEA model. In other words, *DEA 1* model, by considering the effects of the uncontrollable factors: (i) creates a leveled playing field, (ii) eliminates the artificial inefficiencies created by the effects of such uncontrollable factors, and (iii) reflects the pure relative efficiencies of the DMUs for their asset groups maintenance operations. This result confirms the validity of the second hypothesis of this research (as presented in **Chapter 1**) which is: "Within the state of Virginia, a portion of the inefficiencies of the counties can be attributed to the effects of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) faced by such counties."

It is important to note that by taking the difference of the efficiency scores obtained from *DEA 1* Model and *DEA 2* Model within each of the tables, one can easily identify the effects of the uncontrollable factors on the efficiencies of the DMUs (which is one of the objectives of this research as presented in **Chapter 1**). For example, the uncontrollable factors reduce the relative asset groups maintenance efficiency of the Augusta County in the amount of 88.4% (100.0%-11.6%) according to the DEA models run for the implementation example presented herein.

CHAPTER 5- CONCLUDING REMARKS

This chapter contains an overall assessment of the research presented herein. Within such context, first a summary of the research is presented. Then, specific findings as they relate to the hypotheses and objectives of this research are discussed. After that, data availability issues that prevented the further implementation of the framework to different cases are discussed. Then, the contributions of this research to the body of knowledge are presented along with the overall importance of the study. After that, recommendations are provided for the prospective users of the framework developed by this research. This chapter is finalized by the section discussing some possible future research areas as identified to be related to this study.

5.1 SUMMARY OF THE RESEARCH

For the last two decades, the road maintenance concept has been gaining tremendous attention. The main reason for this is the fact that with the construction of the Interstate system essentially completed, the focus of transportation programs has been moving from capital investment to maintenance and operation. As the infrastructure building is slowing down, the maintenance of the existing infrastructure is becoming much more critical. In 1988, a survey performed on about 10% of all USA infrastructure by the National Council on Public Works Improvement (as appointed by the president of United States) revealed that the nation's roads were in better than fair condition. A number of similar surveys were performed by American Society of Civil Engineers in 1998, 2001, 2003, and 2005. According to the most recent survey performed in 2005, the nation's roads are in poor condition; indicating a severe deterioration over the last two decades (Mirza 2006).

The abovementioned phenomena bring about new institutional changes, predominant of which is the challenge for maintenance managers to achieve maximum performance from the existing system. Such challenge makes it imperative to implement comprehensive systems that measure road maintenance performance. Therefore, maintenance managers should be provided with the mechanisms that allow for the measurement and analysis of maintenance performance, that assure that maximum performance is achieved, and that facilitate the realization of improvements, changes, and decisions (TRB 2006). Furthermore, maintenance managers need to have access to information on the best practices as they relate to the preservation of the infrastructure (Mirza 2006).

Since 2000, Virginia Tech has been involved in performing research to identify innovative methodologies to measure the effectiveness of the highway maintenance services undertaken by Virginia Department of Transportation (VDOT) as well as the contractors working for VDOT. Within the context of such research, a framework has been developed to measure the performance of the highway maintenance services with respect to the effectiveness of the following components: (i) level-of-service, (ii) cost, (iii) timeliness of response, (iv) customer satisfaction, and (v) safety (Piñero 2003). Similarly, the road maintenance performance measurement systems developed and implemented by other state DOTs mainly focus on the effectiveness measures, e.g., the level-of-service. Such measurement systems do not elaborate on the efficiency concept, e.g., the amount of resources utilized to achieve such level-of-service, which is also a very essential performance measurement dimension.

Given the proliferation of the asset management concept that calls for the delivery of "effective" and "efficient" services to the community (JLARC 2002), measuring only "effectiveness" and disregarding "efficiency" is an incomplete approach to performance assessment. Not knowing how "efficient" state DOTs are in being "effective" can lead to excessive and unrealistic maintenance budget expectations. This issue indicates the need for a performance measurement approach that can also take the efficiency concept into account. Another important concept that is not adequately investigated in the current road maintenance performance measurement systems is the effect of the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) on the performance of the road maintenance process. Especially for the cases in which comparative analyses are made, disregarding such external and uncontrollable factors and using pure effectiveness results may lead to unfair comparisons. This issue, again, indicates the need for a performance measurement approach that can also take the external and uncontrollable factors into account.

Given the discussion above, there is a need to develop and implement a comprehensive framework that can measure the overall efficiency of road maintenance operations and that can also consider the effects of environmental and operational factors (both of which are beyond the control of the decision-maker, i.e., the maintenance manager) on such overall efficiency.

This research, by utilizing an approach called Data Envelopment Analysis (DEA) (presented in **Chapter 2**), developed a replicable, generic, and comprehensive framework (presented in **Chapter 3**) which focuses on the efficiency dimension of highway maintenance performance measurement. After the establishment of the framework, full scale examples (based on real data belonging to the interstate sections within Virginia) of this framework were developed (presented in **Chapter 4**) in an effort to (i) present the implementation of the framework and challenges associated with it, (ii) test the hypotheses of the research (presented in **Chapter 1**), and (iii) achieve the specific objectives of this research (presented in **Chapter 1**) and thus to provide VDOT with important information and conclusions about the relative highway maintenance efficiencies of a number of its counties.

5.2 FINDINGS OF THE RESEARCH

As discussed above, this research, after developing a replicable generic framework for highway maintenance efficiency measurement, utilized this framework to provide full scale examples in an effort to (i) present the implementation of the framework and challenges associated with it, (ii) test the hypotheses of the research (presented in **Chapter 1**), and (iii) achieve the specific objectives of this research (presented in **Chapter 1**). The specific findings gathered from these implementation examples as they relate to the hypotheses and objectives of this research are as follows.

The DEA models run for the maintenance of “bridges”, “paved lanes”, and “asset groups” identified the existence of efficiency differences between the eight Virginia counties for which implementation examples are performed. **Table 5.1** presents the overall efficiency scores (obtained by averaging the three consecutive fiscal years’ efficiency scores) for each of these counties and for each model. In such table, the efficiency differences between the eight Virginia counties can be seen. The existence of the efficiency differences between the counties of Virginia as obtained through DEA models confirms the first hypothesis of this research. Furthermore, it underlines the importance of this research which developed a framework that can be used to identify such efficiency differences and help inefficient units by pointing out peers and best practices that can be referred to. It is important to note that, within the data set utilized, the least amount of efficiency differences between the counties is obtained for the maintenance of “asset groups” as can be seen in the results presented in **Table 5.1**.

Table 5.1: Overall Efficiency Scores for Each County and Each Model

County	Overall **Bridges** Maintenance Efficiency Score of the County*	Overall **Paved Lanes** Maintenance Efficiency Score of the County**	Overall **Asset Groups** Maintenance Efficiency Score of the County
Albemarle	55.3%	52.8%	96.7%
Alleghany	54.3%	68.6%	93.6%
Augusta	77.7%	29.1%	100.0%
Fauquier	82.5%	83.3%	100.0%
Henrico	76.3%	40.1%	81.7%
Roanoke	N/A	11.1%	85.0%
Rockbridge	70.3%	97.5%	93.1%
Spotsylvania	18.9%	47.6%	83.6%

*: The results of the model where the DMUs that belong to the Roanoke County are not included.
**: The results of the model where all DMUs are included, i.e. "Modified Change in CCI" variable is disregarded.

This research, by running two separate models (one that acknowledges the effects of the uncontrollable factors on the efficiency and one ignoring such) for the maintenance of “bridges”, “paved lanes”, and “asset groups” identified that uncontrollable factors indeed affect the efficiency of highway maintenance services. **Table 5.2** presents the overall efficiency scores (obtained by averaging the three consecutive fiscal years’ efficiency scores) for each county and for each model for (i) when the effects of uncontrollable factors are acknowledged by the model (ii) when the effects of uncontrollable factors are not acknowledged by the model. In such table, the effects of the uncontrollable factors on the “bridges”, “paved lanes”, and “asset groups” maintenance efficiency of the counties can be seen. The fact that a portion of the inefficiencies of the counties can be attributed to the effects of the uncontrollable factors such as the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) confirms the second hypothesis of this research. It is important to note that, within the data set utilized, the uncontrollable factors seem to be mostly affecting the efficiency of the maintenance of “asset groups” as can be seen in the results presented in **Table 5.2**.

Table 5.2: Overall Efficiency Scores for Each County and Each Model-Effects of Uncontrollable Factors

DEA Model / County	Bridges		Paved Lanes		Asset Groups	
	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model*	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model**	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model	Efficiency Score when the effects of the Uncontrollable Factors are **Acknowledged** in the DEA Model	Efficiency Score when the effects of the Uncontrollable Factors are **not Acknowledged** in the DEA Model
Albemarle	55.3%	17.8%	52.8%	50.6%	96.7%	21.9%
Alleghany	54.3%	33.0%	68.6%	15.8%	93.6%	19.2%
Augusta	77.7%	64.8%	29.1%	8.0%	100.0%	11.6%
Fauquier	82.5%	48.6%	83.3%	12.3%	100.0%	65.8%
Henrico	76.3%	14.6%	40.1%	40.0%	81.7%	10.0%
Roanoke	N/A	N/A	11.1%	11.0%	85.0%	11.8%
Rockbridge	70.3%	70.3%	97.5%	97.5%	93.1%	77.5%
Spotsylvania	18.9%	18.9%	47.6%	47.3%	83.6%	21.2%

*: The results of the model where the DMUs that belong to the Roanoke County are not included.
**: The results of the model where all DMUs are included, i.e. "Modified Change in CCI" variable is disregarded.

To achieve its objectives, this research, in addition to identifying the relative efficiency of these 8 counties in performing highway maintenance operations and the effects of the uncontrollable factors in such efficiencies, identified the benchmarks (peers) and best practices (targets) that pertain to the inefficient counties. Such findings are discussed in detail with the help of figures and tables as presented in **Chapter 4** in an effort to inform the decision makers within such counties of possible efficiency improvements than can be secured in the future. **Table 5.3** presents the summary of the results from the relevant models. The important findings obtained from the DEA results are discussed below:

i. Spotsylvania County has some serious efficiency problems as far as the maintenance of bridges is concerned. Such county should work closely with its peers (as identified though the DEA model) to identify the operational and strategic policies and general maintenance practices implemented by such peers.

ii. Spotsylvania County has consistently worsened its efficiency score over the time period of fiscal year 2003 through fiscal year 2005 for the maintenance of bridges and paved lanes. This, along with the finding listed above, raise a red flag for this county that the upper management in VDOT should be aware of.

iii. Roanoke County has some serious efficiency problems as far as the maintenance of paved lanes is concerned. Such county should work closely with its peers (as identified though the DEA model) to identify the operational and strategic policies and general maintenance practices implemented by such peers.

iv. Albemarle County is very likely to be implementing deferred maintenance practices for the maintenance of its paved lanes. It is important to note that this assertion still needs verification from the decision makers within such county. Deferred maintenance may help such county to be efficient for a certain period of time (as minimal amount of money is spent when deferring the maintenance) but it impacts its overall efficiency in the long run. Therefore, such county should avoid implementing deferred maintenance practices due to the reasons discussed in **Section 3.1.2**.

v. All counties seem to be quite efficient as far as the maintenance of asset groups is concerned.

vi. When the results from the three models representing all the elements of the highway are concerned (i.e., bridges, paved lanes, and asset groups), the most efficient county is the Rockbridge County.

Table 5.3: Summary of the Results from the Relevant Models

Unit name	Bridges Score*	Paved Lanes Score**	Asset Groups Score	Average Score for All Elements
Albemarle1	16.2%	100.0%	100.0%	**68.3%**
Albemarle2	49.6%	56.3%	100.0%	
Albemarle3	100.0%	2.2%	90.1%	
Overall (Average)	55.3%	52.8%	96.7%	
Alleghany1	49.3%	53.6%	100.0%	**72.2%**
Alleghany2	13.7%	100.0%	100.0%	
Alleghany3	100.0%	52.1%	80.9%	
Overall (Average)	54.3%	68.6%	93.6%	
Augusta1	69.2%	14.0%	100.0%	**68.9%**
Augusta2	100.0%	19.4%	100.0%	
Augusta3	63.9%	53.9%	100.0%	
Overall (Average)	77.7%	29.1%	100.0%	
Fauquier1	100.0%	49.9%	NA	**85.4%**
Fauquier2	100.0%	100.0%	NA	
Fauquier3	47.6%	100.0%	100.0%	
Overall (Average)	82.5%	83.3%	100.0%	
Henrico1	100.0%	0.9%	45.0%	**66.0%**
Henrico2	100.0%	19.5%	100.0%	
Henrico3	28.9%	100.0%	100.0%	
Overall (Average)	76.3%	40.1%	81.7%	
Roanoke1	NA	2.5%	56.8%	**48.0%**
Roanoke2	NA	23.6%	100.0%	
Roanoke3	NA	7.3%	98.2%	
Overall (Average)	NA	11.1%	85.0%	
Rockbridge1	10.9%	100.0%	79.3%	**87.0%**
Rockbridge2	100.0%	92.5%	100.0%	
Rockbridge3	100.0%	100.0%	100.0%	
Overall (Average)	70.3%	97.5%	93.1%	
Spotsylvania1	25.0%	76.1%	50.8%	**50.0%**
Spotsylvania2	17.0%	64.0%	100.0%	
Spotsylvania3	14.7%	2.7%	100.0%	
Overall (Average)	18.9%	47.6%	83.6%	

*: The results of the model where the DMUs that belong to the Roanoke County are not included.

**: The results of the model where all DMUs are included, i.e. "Modified Change in CCI" variable is disregarded.

5.3 DATA AVAILABILITY ISSUES THAT PREVENTED THE FURTHER IMPLEMENTATION OF THE FRAMEWORK TO DIFFERENT CASES

All of the implementation examples presented in **Chapter 4** focused on comparing the efficiency of the units (i.e. counties of Virginia) that perform the highway maintenance through traditional means. For all three implementation examples (bridges, paved lanes, and fence to fence asset groups), the relative maintenance efficiency of eight counties of Virginia were identified. Such counties encompass the portions of the interstate for which level-of-service data is collected through the Maintenance Rating Program (MRP) implemented by Virginia Tech as a part of the VDOT-VMS pilot project. Cost data for these counties has been provided to Virginia Tech by VDOT and thus the framework could be fully implemented to the case of traditional maintenance and results that can help the decision making process were obtained.

As a result of the MRP effort, a substantial amount of level-of-service data has been collected also for the contractor that is executing performance-based highway maintenance. Therefore, another implementation of the framework could have been performed, this time for the contractor, by using such data and cost data for the contractor. However, the format of the contractor's cost data that is provided to Virginia Tech by VDOT precluded such an implementation example from being performed. This is mainly due to the fact that such cost data is at a very aggregate level as it is broken only into the following two components: (i) cost for the interstate sections that are maintained by the contractor in the western part of Virginia and (ii) cost for the interstate sections that are maintained by the contractor in the eastern part of Virginia. Since cost data is broken only into two components, only two DMUs can be defined (i.e. $\text{Contractor}_{\text{West}}$ and $\text{Contractor}_{\text{East}}$) to which such cost data can be assigned. This means that for the contractor's DEA model containing the DMUs for fiscal years 2002, 2003, 2004, and 2005 (as was the case for all of the implementation examples presented in **Chapter 4**), there can be a total of only 6 DMUs. Given the number of variables to be included in the DEA models for bridges, paved lanes, and fence to fence asset groups, such number of DMUs would diminish the discriminating power of the DEA and make it identify all 6 DMUs to be efficient just as in the case presented in **Section 4.1.4** where even the DEA model with a larger number of DMUs (8 DMUs) identified all to be efficient. Therefore, an implementation example which investigates the relative efficiency of the contractor's units could not be performed.

The framework could not be implemented to identify the relative efficiencies of different approaches to highway maintenance (i.e. traditional method-based maintenance and performance-based maintenance) either, again, due to the format of the contractor's cost data as provided to Virginia Tech. Such cost data only includes the field costs incurred by the contractor and thus does not include the overhead and profit of the contractor. However, as discussed in detail in **Section 3.10**, to be able to evaluate and compare the efficiency of the performance-based and traditional approaches to highway maintenance, the total cost to the state DOT for each of the two cases (when the state DOT is using the performance-based contract and when the state DOT is using the traditional maintenance means) needs to be identified. This fact necessitates the use of the price of the contractor (and hence the cost of the contractor to VDOT which includes the overhead and profit). Only through this way, the decision-makers within VDOT can be provided with the answer to the question of whether VDOT is more efficient and thus better off in using traditional ways of maintenance or performance-based maintenance. Since the cost data for the contractor does not include overhead and profit, the DEA model which investigates the relative efficiencies of different approaches to highway maintenance (i.e. traditional method-based maintenance and performance-based maintenance) could not be implemented.

5.4 CONTRIBUTIONS TO THE BODY OF KNOWLEDGE AND THE OVERALL IMPORTANCE OF THE STUDY

5.4.1 Contributions to the Body of Knowledge

The contributions of this research to the body of knowledge are believed to be with respect to two different areas of literature: (i) highway maintenance and (ii) performance measurement (specifically DEA). The following sections explain how this research differs from the current research that is being performed within each of these two areas.

5.4.1.1 Contributions to the Body of Knowledge in the Highway Maintenance Domain

Highway maintenance has not been the focus of basic and applied research as topics such as road design, construction, and traffic flow have. Research in the highway arena has traditionally been related to topics like geometric and structural design, selection of materials, specification of sufficient capacity, safety devices, location of intersections and interchanges;

and location and characteristics of signs and signals. Comparatively little research has been performed in the areas of highway maintenance and highway maintenance performance (TRB 2006). TRB (2006) identified that some topics related to maintenance management need more examination. This research addresses, to a certain extent, two of such topics as listed below (TRB 2006):

- Fundamental relationships between highway maintenance levels of service and budget and labor utilizations.
- Best practices in specifying maintenance and operations performance, as used in contracting for these services.

As identified by and underlined throughout this write-up, efficiency is a very important dimension of overall performance and thus should be considered as an indispensable element of the concept of "performance measurement". Nonetheless, none of the performance measurement systems developed for highway maintenance in USA elaborates on the efficiency concept in an effort to measure the efficiency of the highway maintenance process. It is believed that this research, by taking the efficiency concept into account, improves the ways that are currently used to measure and model the performance of highway maintenance.

This research is built on the research already performed at Virginia Tech. As a matter of fact, DEA was identified and recommended as a possible future research area to be explored, by Piñero (Piñero 2003). This research addresses the two short-comings of the already developed five component framework for monitoring performance-based road maintenance by developing a comprehensive highway maintenance efficiency measurement framework, i.e., such framework investigates the efficiency of the highway maintenance process and considers the external and uncontrollable factors that affect the performance of such process in investigating its efficiency. This is believed to substantially improve the framework (for monitoring performance-based road maintenance) that is already developed and in use by Virginia Tech.

This research contributes new knowledge to the asset management field in the highway maintenance domain by providing a framework that is able to differentiate effective and efficient maintenance strategies from effective and inefficient ones; as such, the impact of such framework is believed to be broad, significant, and relevant to all transportation agencies as it can easily be utilized by any transportation agency that is desiring to measure the efficiency of its highway maintenance operations in an effort to improve its performance.

5.4.1.2 Contributions to the Body of Knowledge in the Performance Measurement Domain

As Rouse (1997) pointed out, the performance measurement concept has been the subject of research in many disciplines such as operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management, and public administration (Rouse 1997). Engineering, on the other hand, is not a discipline in which research about performance measurement is performed as much as it is performed in these other disciplines. Specifically in the DEA arena, even though there have been many studies presenting the application of DEA to real-world situations in other disciplines, there has been limited amount of research that uses DEA in the engineering discipline. Such under-utilization of DEA in the engineering discipline can be attributed to many reasons such as the lack of understanding of the role of DEA in evaluating and improving design decisions, the inability to define the transformation process and thus inputs and outputs of a system, and unavailability/inaccessibility of reliable production and engineering data (Triantis 2004). This research is believed to contribute to the literature of performance measurement (specifically DEA) by developing a replicable generic framework that is based on engineering principles. Thus, this research can be labeled as an application of DEA within the engineering discipline.

As far as the application of DEA to highway maintenance is concerned, a thorough literature review revealed that there has been a very few number of studies that utilized this method in performance and efficiency measurement of highway maintenance operations. As presented in **Chapter 2**, the only pieces of literature dealing with this subject are the two studies by Rouse et al. (1997) and Cook et al. (1990, 1994) (Cook et al. 1994; Cook et al. 1990; Rouse et al. 1997b). This research is believed to be more comprehensive than both of these studies. This is mainly because this research takes all elements of level of service (fence to fence asset groups, paved lanes, and bridges as listed in **Table 1.1**) into account, which was not the case in the abovementioned studies. Moreover, this research investigated the timeliness of response component (and developed the comprehensive list of input and output variables and uncontrollable factors for such component), which was not investigated by those studies at all.

Finally, this research developed a more systematic approach in defining and refining the list of the input and output variables (to be used in the DEA models) affecting the performance and efficiency of the highway maintenance process than both of the abovementioned studies.

As a final note, the thorough literature review has not come across any DEA study that is used to compare different highway maintenance approaches (performance-based versus traditional approach) in the transportation arena. This research addresses this issue by trying to evaluate DEA as a potential technique to develop a comprehensive highway maintenance efficiency measurement framework which later can be utilized to evaluate different approaches to highway maintenance given the availability of data.

5.4.2 Overall Importance of the Study

For the last two decades, state DOTs have been in the process of changing the way they do business. A number of initiatives have been tried to address the public expectations for better use of resources. The foremost of these initiatives is asset management (AASHTO 1997). As a matter of fact, in response to the severe deterioration of the country's road systems, the Federal Highway Administration (FHWA) endorsed "asset management" to be the future approach of road maintenance for all state DOTs (JLARC 2002). Asset management is "… *a comprehensive and structured approach to the long-term management of assets as tools for the efficient and effective delivery of community benefits*" (JLARC 2002, p.16). Within the context of transportation in USA, asset management is allocating resources to preserve, operate, and manage the nation's transportation infrastructure. Asset management calls for the utilization of management, engineering, and economic principles to help state DOTs in making decisions as to how resources should be allocated. It is the strategic allocation of resources that improves the system performance, maximizes the return on investment, and increases customer satisfaction (Geiger 2005). Asset management requires state DOTs to implement integrated systems which take environmental conditions, operational conditions, materials, labor, and equipment into account (Venner 2005). Since many state DOTs are now vigorously trying to implement the asset management concept, FHWA is promoting the development of management tools, measurement/analysis methods, and research topics that are needed to accompany such concept (Geiger 2005). Given the proliferation of the asset management concept that calls for the delivery of effective and efficient services to the community (JLARC 2002), multi dimensional performance measurement approaches that can measure the effectiveness and efficiency of services need to be developed.

Another initiative that is aroused by the political climate is the call for a smaller government, resulting in fewer maintenance staff in state DOTs and increased use of private contractors. Almost all states have begun to outsource a portion of their road maintenance program. Method-based contracts have traditionally been the most common form of maintenance contracting. Nonetheless, some states such as Virginia, Florida, Texas, and Massachusetts have taken the traditional maintenance contracting a step further by innovative contracting approaches such as performance-based contracting. It is very likely that use of performance-based contracting is to increase in the future. In a memorandum dated January 1999, the deputy secretary of the U.S. Department of Transportation (USDOT) requested transportation agencies to develop plans to convert their traditional contracts to performance-based contracts as they come up for renewal. In another memorandum, the deputy secretary declared that the conversion to performance-based contracting was to become a ONE-DOT priority (top priority level within USDOT) in state agencies (Tomanelli 2003). Such memorandums clearly show the willingness of the federal transportation authority to increase the use of performance-based contracts within the states' road maintenance works. This imposes a challenge on the maintenance managers because regardless of the fact that road maintenance is being privatized, the ultimate responsibility for the performance of the road system is on the maintenance manager and thus the maintenance managers need to make sure that such new contracting approaches work by measuring the performance of the contractors in a multi dimensional manner as discussed in the preceding paragraph (TRB 2006).

The main product of this research, the framework for highway maintenance efficiency measurement, is a tool that can serve the efficiency measurement needs of the "asset management" and "performance-based road maintenance" concepts as discussed in the preceding two paragraphs. Such framework offers a systematic method of analysis of the multitude of data (e.g. cost, condition, climate, traffic, etc.) collected by transportation agencies to provide valuable results (such as efficiency scores, peers, targets) that can be used to improve performance with respect to efficiency.

A study by National Cooperative Highway Research Program (NCHRP) lists the following item as one of important issues that need to be dealt with (Poister 1997, p. 50): "*To what extent* *can state DOTs develop valid external benchmarks that provide fair and useful comparisons of performance levels?*" Another NCHPR study underlines the importance of using both input measures (resources committed to a specific activity, e.g. highway maintenance) and output measures (product of resource commitment) and not just using one type of measures (NCHRP 2003b).

The framework for highway maintenance efficiency measurement developed by this research addresses the issues raised by the both NCHRP studies discussed in the preceding paragraph. First, such framework has the capability to determine the most relevant benchmarks for units with poor performance such that those benchmarks are chosen from the ones that operate in a similar scale and that face similar environmental and operational factors as the unit for which benchmarks are sought. Second, such framework, by elaborating on the efficiency concept, not only incorporates both input and output measures (as well as uncontrollable considerations), but also uses these measures simultaneously to derive one overall efficiency measure.

A recent report prepared jointly by Urban Land Institute and Ernst&Young estimates a $1.6 trillion deficit in required infrastructure spending through year 2010 for the maintenance (Miller 2007). Since no more funding is likely to be secured to close this gap, the state DOTs should seek all possible ways to improve their "efficiency" with which the "effectiveness" of highway maintenance is being achieved. Only through such efficiency increases can state DOTs meet the maintenance needs with the current funding levels.

The framework developed by this research; by focusing on the efficiency, pointing out the efficiency improvements that can be obtained, and identifying the peers to work with to realize such efficiency improvements; becomes a possible tool that can be utilized by the state DOTs that are in search for ways to achieve better road maintenance efficiency as discussed in the preceding paragraph. Furthermore, once state DOTs get familiar with the road maintenance efficiency measurement framework, they can utilize the concepts inherent in such framework to develop tools to measure and improve the efficiency of their other programs (e.g. construction, transit, etc.).

5.5 RECOMMENDATIONS

5.5.1 Recommendations for Using the Results Obtained through Implementation of the Framework

It is important to note that in any of the implementation examples presented in **Chapter 4**, the results of the model need to be validated and verified by the decision makers at VDOT before actually taking the actions suggested by the models. The main reason for this is the fact that DEA is a technique which does not directly pinpoint the underlying causes of inefficiencies of DMUs (Triantis 2005a). Nonetheless, the results of DEA can be utilized to direct decision makers' attention to develop a better understanding of the reasons why some DMUs are located on the efficient frontier and thus efficient and why others are inefficient. DEA may trigger decision makers to try to identify the differences in formal and strategic structures, operational practices (managerial practices, field practices etc…), or other organizational factors of the DMUs that may account for the observed efficiency differences in such DMUs. The overall objective of DEA is to assign organizational meaning to the observed efficiency differences and to determine the organizational changes that the inefficient DMUs will need to undertake and how to implement such changes. The common methods to be able to reach such objective is benchmarking and describing and documenting the best practice processes of the DMUs that are efficient (i.e. located on the efficient frontier). Given all of these, the findings gathered from the implementation examples presented in **Chapter 4** are not as specific and detailed to point out what the reasons for inefficiencies within the DMUs are and to identify what exactly needs to be done to overcome such inefficiencies. Rather, such findings are intended to be used as guides for managerial actions and policymaking as calculated targets for inputs and outputs indicate potential performance and efficiency increases for inefficient DMUs (Charnes et al. 1994). Therefore, in order to verify and make use of the findings suggested in **Chapter 4**, collaboration from the decision makers in VDOT is essential. Only through such collaboration can policy analysis be performed, possible causes of inefficiencies be pinpointed, and suggestions to the decision makers to help them overcome such inefficiencies be provided.

5.5.2 Recommendations for a Better Cost Data Collection and Recording System that would accommodate the needs of the Framework

As discussed in **Section 5.3**, the format of the contractor's cost data precluded some further analyses from being made. Furthermore in **Chapter 4**, the following cost data issues were identified as issues preventing the efficiency measurement framework from being implemented in an optimum manner:

1. The fact that the smallest level at which the cost data for VDOT is available is Virginia's county resulted in a considerable drop in the number of DMUs to be included in the DEA models. This consequently diminished the discriminating power of the DEA, making it identify a larger number of DMUs as efficient than what would be identified had the DMU been chosen to be a smaller unit than a county, e.g. 10 mile long portion of the interstate as planned originally. Furthermore, having the cost data at the county level resulted in the removal of the Caroline County from the data set. This was mainly because the level-of-service data encompasses only a portion of such county whereas the cost data is for the whole county and cannot be apportioned to be assigned to the portion for which the level-of-service data is available.
2. The fact that the cost for all of the asset items belonging to the fence to fence asset groups was recorded altogether but not separately for each asset item necessitated the development of one single DEA model representing the maintenance efficiency of DMUs for all 34 asset items. This consequently resulted in the utilization of only the uncontrollable variables that apply to all 34 asset items and thus discarding of a number of uncontrollable variables from the DEA model just because such variables do not apply to all of those asset items. Had the cost data been collected and recorded at the asset item level, a separate DEA model would be developed for each asset item and thus all of the uncontrollable variables that may be affecting the efficiency of the maintenance of those asset items could be included in such models.
3. The fact that the cost data for VDOT only includes the field costs and does not include other cost items associated to the maintenance of highways such as the overhead, insurance, etc. resulted in incomplete cost data. This issue was addressed by applying a constant overhead rate of 4.6% to all DMUs of VDOT as recommended in the research

by de la Garza and Vorster (de la Garza and Vorster 2000). Nonetheless, even though the application of such overhead rate improved the cost data for VDOT to a great extent, a complete cost data could not be obtained as discussed in **Section 4.1.3.4.1**.

Given all of the issues reminded above as well as the ones discussed in **Section 5.3,** it is recommended to design a cost data collection system that can record data at more disaggregate levels and that can also record all cost items (e.g.., overhead, profit, etc.) associated to the maintenance of highways. Only with the implementation of such cost data collection system can the needs of the DEA framework developed in this research be fulfilled and more precise and valuable analyses be performed.

5.5.3 Recommendations to Address the Issue of Uncontrollable Factors

As was discussed in **Chapter 1** in detail, one of the objectives of this research was to identify the effects of the uncontrollable factors such as the environmental factors (e.g., climate, location, etc.) and operational factors (e.g., traffic, load, design-construction adequacy, etc.) on the road maintenance efficiency of the units. In an effort to address such objective, this research, through the relevant component of the road maintenance efficiency measurement framework, identified a number of different approaches that can be used to model the uncontrollable factors in DEA.

Within such context, the framework identified that the best approach that can be used to deal with the uncontrollable factors is the approach described in **Section 3.7.1.1.4** (i.e. restricting the peer reference set for the DMU that is under investigation to the DMUs that face similar or harsher environments). This is especially the case when there is a sufficient number of DMUs to address the discriminating power of DEA issue; and one can combine all uncontrollable factors into a single overall harshness index representing all of the uncontrollable factors for a given DMU.

However, since the data used for the implementation examples presented in **Chapter 4** does not satisfy the abovementioned condition (i.e. there is not a sufficient number of DMUs as discussed in **Section 5.5.2**), the second best approach (which is the one described in **Section 3.7.1.1.2** (i.e. using a modified DEA formulation and treating uncontrollable factors as uncontrollable variables to be included in the modified DEA models)) was used to model the uncontrollable factors. Then, the effects of the uncontrollable factors on the efficiency of units were identified through taking the difference between the efficiency scores calculated by running two separate models, one when the uncontrollable variables are assigned the actual value for each DMU, and one when the uncontrollable variables are assigned the same value (i.e. 1) for each DMU. However, this is not a straightforward approach and may not result in as precise results as desired. Furthermore, the results are non-intuitive and thus hard to convey to the decision-makers. In short, the abovementioned approach can mainly be used to get an overall idea about the effects of uncontrollable factors on the efficiency of the units performing road maintenance.

Given the abovementioned discussion, it is recommended to use some accompanying approach such as system dynamics to be able to more precisely pinpoint the effects of uncontrollable factors on the efficiency. Also, since addressing the issue of uncontrollable factors is one of the most important components of the framework, it is once again emphasized that every effort should be made to obtain a sufficient number of DMUs so as to be able to use approach described in **Section 3.7.1.1.4** to deal with such uncontrollable factors.

5.6 POSSIBLE FUTURE RESEARCH AREAS

5.6.1 Developing Modules for the Highway Maintenance Efficiency Measurement Framework

The main purpose of this research was to develop a comprehensive highway maintenance efficiency measurement framework by utilizing an approach called Data Envelopment Analysis (DEA). As a part of the framework, this research developed a number of components and discussed in detail what to perform within a component, how to perform such, and different approaches that can be chosen within a component. Advantages and disadvantages of such approaches (where applicable) and guidelines for selecting one approach over another were also discussed. This framework can further be enhanced by redesigning it to consist of self-contained modules that can be used for the implementation of the framework in different scenarios. Such different scenarios relate to: (i) the different units of comparison, (ii) availability of data in different degrees, and (iii) different models utilized as a part of the DEA approach. Within this context, the applicability of the abovementioned different alternatives to different scenarios can be investigated in an effort to develop separate modules to be implemented for such different scenarios. Once these modules are developed, tools like flowcharts can be used to guide the individuals implementing the framework in choosing the most appropriate module for a given scenario.

5.6.2 Collecting Data and Implementing the Framework to Other Cases

As discussed in **Section 5.3**, the framework could not be implemented to identify the relative efficiencies of different approaches to highway maintenance (i.e. traditional method-based maintenance and performance-based maintenance) due to the format of the contractor's cost data as provided to Virginia Tech. However, the identification of the relative efficiencies of the different approaches to highway maintenance is an important issue. This is mainly because through such an analysis, the decision-makers within the transportation agency can be provided with the answer to the question of whether the transportation agency is more efficient and thus better off in using traditional ways of maintenance or performance-based maintenance. Therefore, every effort should be made to gather the contractor's and VDOT's complete cost data (i.e. that includes all of the cost items associated to the maintenance of highways such as overhead, profit, etc.) as recommended in **Section 5.5.2** and to implement the developed framework to this particular scenario.

The framework developed in this research can also be used by VDOT to perform a large scale analysis of all of the counties or districts within Virginia. Such analysis can be performed with a much more comprehensive set of data that includes not only all of the interstate but also the primary and secondary roads that are under the jurisdiction of such counties or districts.

In 2006, Virginia Governor Tim Kaine signed the legislation that requires all interstate maintenance within Virginia be outsourced by the end of fiscal year 2009 (Caldwell 2006). Given the fact that such outsourcing is to be performed through multiple contracts covering different interstate sections of Virginia, there will be a number of contractors working for VDOT for its interstate maintenance. This will provide VDOT with a substantial amount of cost and condition data that pertain to the work carried out by each contractor. When a sufficient amount of historical data is obtained, VDOT can use the framework developed in this research to perform comparative efficiency analysis of these contractors. This would allow VDOT to obtain valuable information about the past performance of these contractors (as far as their efficiencies are concerned). Such information, along with other parameters, can be utilized by VDOT for the selection of contractors for the subsequent terms of the interstate maintenance contracts. In other words, "past efficiency performance" can be one of the award criteria that VDOT uses for the bid evaluations for the outsourcing of the interstate maintenance.

The framework developed in this research can also be used at a national level. In other words, an analysis including a large number (if not all) of the state transportation agencies in the United States can be performed. Through such analysis, peer state DOTs with high maintenance efficiency scores can be identified; and through inter-agency communication and agreements, the expertise of such efficient state DOTs can be transferred to the inefficient state DOTs. This is a process that would take a long time but if implemented successfully, would greatly benefit the road infrastructure of the nation as a whole. This recommendation is perfectly in line with the recommendation of a study by NCHRP (NCHRP 2003a). Such study recommends, as a part of the action plan to address the challenges and opportunities facing the state DOTs, to initiate a national effort to identify the best practices and to benchmark the performance (with respect to different measures, e.g. effectiveness, efficiency, etc.) of peer states. Such action plan also promotes efficiency of the state DOTs by advising them to work smarter with limited resources to obtain the desired outcomes (NCHRP 2003a).

5.6.3 Collecting Data and Implementing the Framework for the Timeliness of Response Component

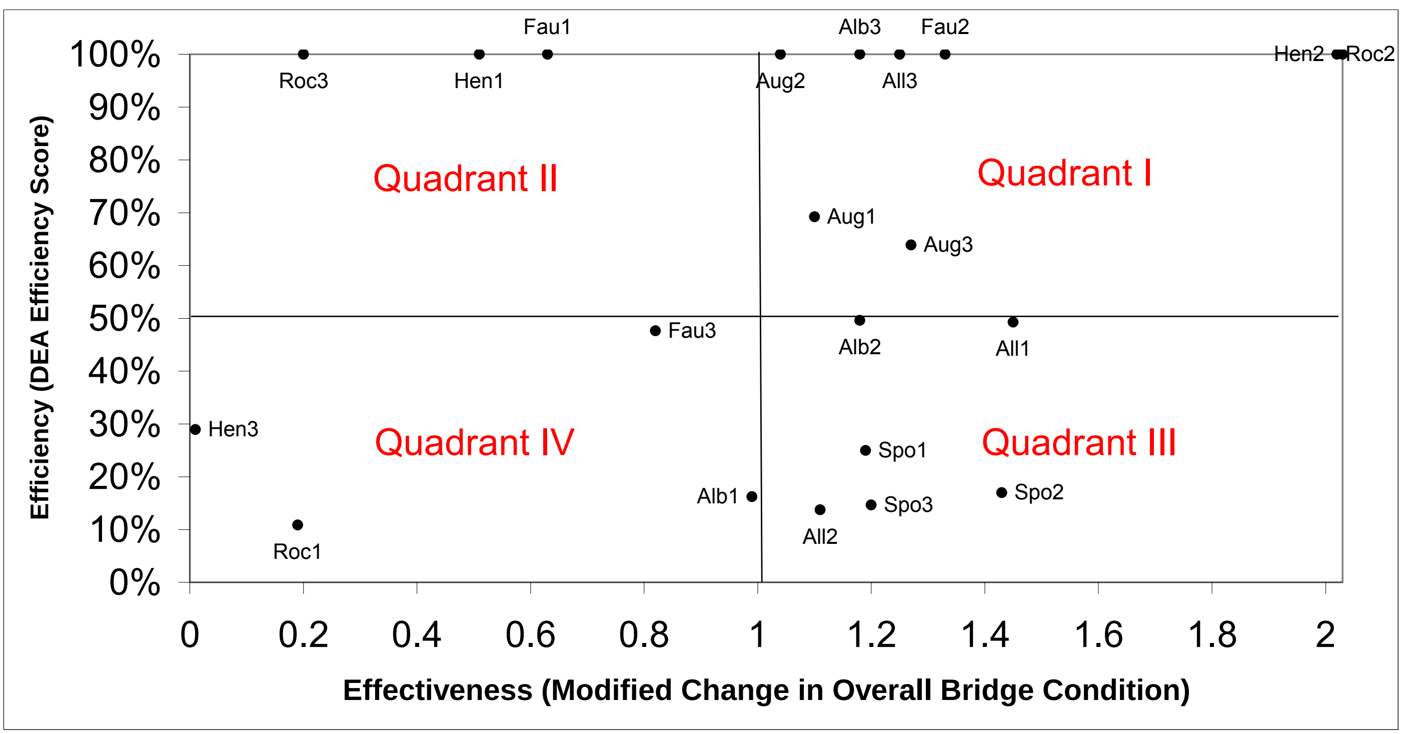
The highway maintenance efficiency measurement framework was developed with level-of-service and timeliness of response components in mind. Therefore, the principles and steps of the framework are applicable to the timeliness of response component as well. Furthermore, the comprehensive list of input and output variables and uncontrollable factors is also developed for the timeliness of response component as can be seen in **Table 3.3**. However, due to data availability issues, the framework could not be implemented for such component (timeliness of response) as discussed in **Section 4.0.1**. A valuable future study would be to collect data for the input-output variables that pertain to the timeliness of response component and implement the framework for such component as well. A high level understanding of the overall performance of the DMUs with respect to efficiency can be attained only if the results for the level-of-service component, timeliness of response component, and quality of service component (as discussed in the preceding section) are evaluated simultaneously.

5.6.4 Using Quality of Service as the Output of the Highway Maintenance Process

The highway maintenance efficiency measurement framework developed in this research, for each element of the highway (i.e., "bridges", "paved lanes", and "asset groups"), defines the output with respect to the level-of-service and uses a metric to measure that output to be able to quantify it. Such metrics relate to the physical level-of-service; for example in the case of bridges it is the "bridge condition rating" obtained through the N*ational Bridge Inventory* inspections. As an alternative to this approach, output can be defined with respect to the quality of service. In this case, the metric to measure such output would be the "customer satisfaction". Adding such a component to the framework and then comparing the results obtained from both components is a research area that can be investigated in the future. Using metrics related to the level-of-service (first component) measures the efficiency of the highway maintenance operations from the perspective of the maintenance provider (i.e. state DOT or contractor); whereas using metrics related to the quality of service (second component) would measure the efficiency of the highway maintenance operations from the perspective of the end user (i.e. drivers as the customers of the highway maintenance service). Incorporating the quality of service component to the highway maintenance efficiency measurement framework would be a valuable addition; as according to a recent research, the level-of-service metrics, which are used to assess the condition of the highway by the state DOTs, do not entirely represent the drivers' assessment of the condition of the highway (Flannery et al. 2005).

5.6.5 Using the Efficiency and Effectiveness Results Simultaneously for Decision-Making

As was discussed in **Chapter 1**, the main problem that this research tried to address was the need to develop and implement a comprehensive framework that can measure the overall efficiency of road maintenance operations and that can also consider the effects of environmental and operational factors (both of which are beyond the control of the decision maker, i.e., the maintenance manager) on such overall efficiency. In trying to address such problem, a highway maintenance efficiency measurement framework is developed and real life implementation examples of such framework are provided. Based on the results of such implementation examples, a number of findings are identified and such findings are discussed in an effort to assist the maintenance managers of the units investigated in the implementation examples in their decision making process. As the focus of this research is efficiency, all of the findings and suggestions derived as a result of the implementation examples are discussed from an efficiency point of view. Nonetheless, more insight can be gained and thus more detailed findings can be derived about the performance of different units if such process is scrutinized through multiple dimensions of the performance such as effectiveness and efficiency. Given this, a possible valuable research area would be to investigate the possibility of combining (i) the research by Piñero (Piñero 2003) which investigates the effectiveness of highway maintenance units in reaching predefined performance criteria and (ii) the research presented herein which investigates the efficiency of highway maintenance units in reaching predefined performance criteria by considering the effects of uncontrollable factors affecting such efficiency. **Figure 5.1** presents a basic approach to perform such combination of effectiveness and efficiency results for the maintenance of the "Bridges" case which was investigated in **Section 4.1**. In such figure, the effectiveness results (Modified Change in Overall Bridge Condition- the output used in the DEA model) and efficiency results as obtained through the DEA model are plotted for each DMU. Then, the obtained cartesian plane is divided into four equal sized pieces (i.e. quadrants).



Alb1=Albemarle1 Alb2=Albemarle2 Alb3=Albemarle3
All1=Alleghany1 All2=Alleghany2 All3=Alleghany3
Aug1=Augusta1 Aug2=Augusta2 Aug3=Augusta3
Fau1=Fauquier1 Fau2=Fauquier2 Fau3=Fauquier3
Hen1=Henrico1 Hen2=Henrico2 Hen3=Henrico3
Roc1=Rockbridge1 Roc2=Rockbridge2 Roc3=Rockbridge3
Spo1=Spotsylvania1 Spo2=Spotsylvania2 Spo3=Spotsylvania3

Figure 5.1: Combining Effectiveness and Efficiency Results

Based on the quadrant division depicted in **Figure 5.1**, some possible basic findings can be listed as:

1. DMUs in *Quadrant I* are both efficient and effective; and thus they can be regarded as true peers for the other DMUs in the data set.
2. DMUs in *Quadrant II* are efficient but not effective. This could mean that even though such DMUs have the necessary management practices to be efficient, they are not spending sufficient amount of resources to maintain the bridges effectively. Therefore, operating at the same efficiency level, they can increase their effectiveness by spending more resources for the maintenance of the bridges.
3. DMUs in *Quadrant III* are effective but not efficient. This could mean that even though such DMUs maintain the bridges effectively, they are spending a large amount of resources to do so. Therefore, they should try to find some ways to be efficient and thus spend fewer resources to still maintain the bridges at the same effectiveness level.
4. DMUs in *Quadrant IV* are neither efficient nor effective; and thus they should introduce radical changes to the way they perform the maintenance of the bridges. They should work with the peers identified in the DEA models as well as the peers located in *Quadrant I* to address both their efficiency and effectiveness problems.

Needless to say, the group that a DMU belongs to (i.e. 1, 2, 3, or 4) depends on the way the cartesian plane is divided. If the sizes of the divisions are defined to be the same (i.e., they are quadrants) as presented in **Figure 5.1**, the findings listed above present valid discussions. However, if different criteria are used to divide the cartesian plane, completely different findings can be derived for each DMU. Obviously, when to deem a unit as "efficient" and when to deem such unit as "effective" (i.e. cut off values to divide the cartesian plane) depend on the policies implemented by the decision makers within the state DOT.

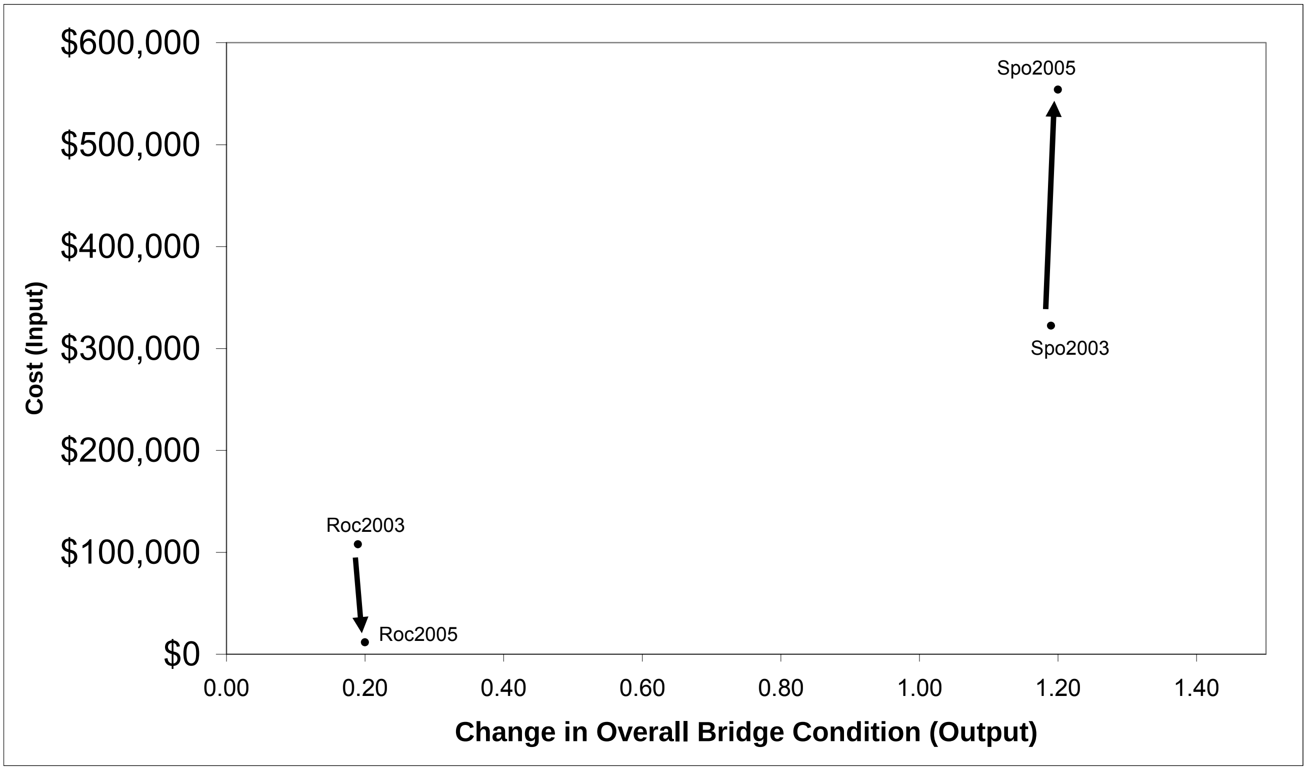
Just plotting the DMUs in the cartesian plane and deriving findings based on the location of the DMUs without necessarily grouping them is another approach that can be used to combine the effectiveness and efficiency results.

Furthermore, some other approaches such as network models (Medina-Borja and Triantis 2006; Medina-Borja 2002) can also be generated to be able perform the multi dimensional analysis described herein. Therefore, identification and generation of approaches to perform the multi dimensional analysis is a fruitful future research area. However one must be aware that developing a multi dimensional performance measurement tool would require a significant amount of commitment from the decision makers (i.e. maintenance managers) of the units that are under investigation.

5.6.6 Using Iso-Output Curves to Identify the Effect of Cost on Efficiency

As discussed in **Section 5.6.5**, performance of road maintenance process can be investigated in two dimensions concurrently, effectiveness and efficiency. Such an analysis would assist the decision makers to a great extent as it can identify a variety of performance issues that need to be addressed. Another valuable analysis that would address the performance issues is to identify the effect of cost on efficiency.

Figure 5.2 depicts the input (cost) and output (change in overall bridge condition) relationship for the Rockbridge and Spotsylvania counties for the fiscal years of 2003 and 2005. As can be seen in such figure, for the Rockbridge County, even though there has been a significant amount of decrease in the expenditures made from 2003 to 2005, approximately same amount of condition improvement is obtained within the both time periods. Conversely, for the Spotsylvania County, even though there has been a significant amount of increase in the expenditures made from 2003 to 2005, approximately same amount of condition improvement is obtained within the both time periods. These phenomena are, indeed, reflected in the efficiency scores of these counties. Rockbridge County has increased its efficiency score from 2003 to 2005; and Spotsylvania County has decreased its efficiency score from 2003 to 2005. Since the DEA models have accounted for the effects of the uncontrollable factors such as climate and traffic while performing the efficiency calculations for each DMU over the abovementioned time period, the effects of such uncontrollable factors cannot be the reason of those efficiency changes within each DMU. Therefore, as was discussed in detail in **Chapter 4**, the change in the efficiency of each county can be attributed to some operational and strategic issues taking place in them.

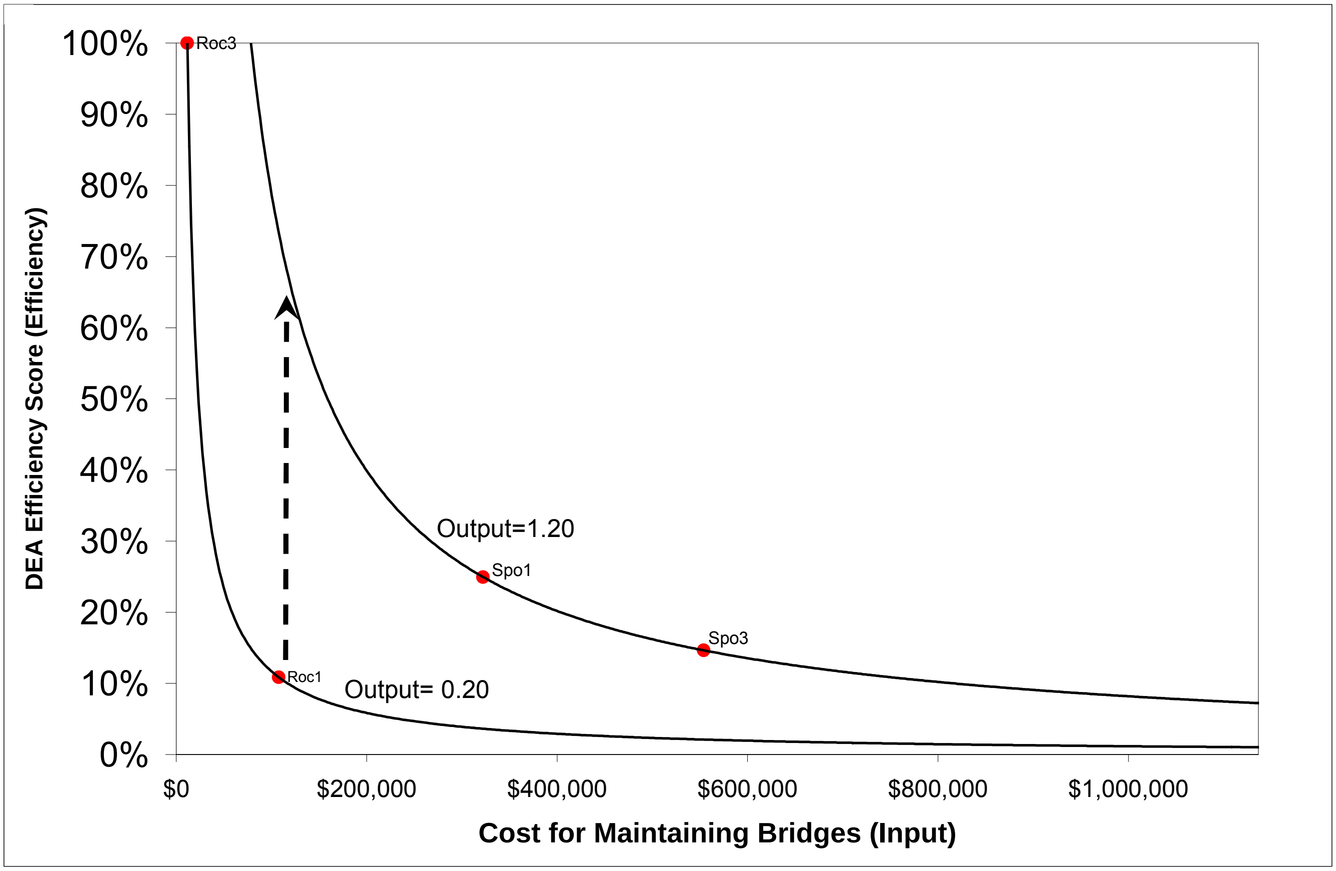


Roc2003: Data representing the 2003 performance of the Rockbridge County
Roc2005: Data representing the 2005 performance of the Rockbridge County
Spo2003: Data representing the 2003 performance of the Spotsylvania County
Spo2005: Data representing the 2005 performance of the Spotsylvania County

Figure 5.2: Input-Output Relationship for the Rockbridge and Spotsylvania Counties

As can be seen in **Figure 5.2**, for each county's case, the outputs obtained for 2003 and 2005 are approximately the same. Given this one can plot iso-output curves for these counties to perform some further analyses, results of which may be of value. **Figure 5.3** presents such curves for both of the counties. As can be seen in such figure, a county should move upwards in a curve to be able to be more efficient. Therefore, counties should seek ways to spend less money (as in the case of the Rockbridge County) to improve their efficiency over time given an output level. If the amount of money spent on maintenance cannot be decreased, then a unit must go from one iso-output curve to another one depicting a higher output level as indicated by the arrow in **Figure 5.3** to be able to improve its efficiency.

Analyses of this type and detail can be performed to further help the decision making process as was detailed in **Chapter 4**. Similarly, iso-cost curves can also be plotted and some conclusions can be drawn. Developing these iso-curves, along with investigating performance in multiple dimensions as discussed in the previous section, is a future research area that can improve the framework developed by this research



Roc2003: Data representing the 2003 performance of the Rockbridge County
Roc2005: Data representing the 2005 performance of the Rockbridge County
Spo2003: Data representing the 2003 performance of the Spotsylvania County
Spo2005: Data representing the 2005 performance of the Spotsylvania County

Figure 5.3: Iso-Output Curves

5.6.7 Including Undesirable Outputs in the DEA Models

As was discussed earlier, the “bridges”, “paved lanes”, “asset groups” maintenance processes result in air pollution, water pollution, and noise pollution (Fitch et al. 2005; TRB 2006; Venner 2005; Williams and Stensland 2006). Such outputs are referred in the DEA literature as another group of outputs: Undesirable Outputs (Amirteimoori et al. 2006; Scheel 2001; Seiford and Zhu 2002). As the name implies, such outputs are not produced as a goal of the highway maintenance process but rather produced as by-products which are not desired to be produced at all. They are different from the common concept of the output of a process as their production is tried to be avoided or minimized at best as opposed to being maximized as desirable outputs. In other words, the less of the undesirable outputs, the better off the process is. The framework and implementation examples presented in this document disregard these undesirable outputs and thus do not incorporate them into the DEA models mainly due to data availability and modeling issues that accompany them. A possible enhancement that can be made to the framework developed in this research is to find ways to incorporate the undesirable outputs into the framework and collect the necessary data (for such undesirable outputs) to be able to include them in the DEA models.

5.6.8 Ranking Efficient Units among Themselves

The DEA formulations that are presented within the framework developed in this research identify the DMUs as efficient when they obtain an efficiency score of 100% and inefficient when they obtain an efficiency score less than 100%. Based on their efficiency scores, DMUs are then ranked. However, no ranking is possible for the efficient units as they all obtain the efficiency score of 100%. There is a number of models that deal with the issue of ranking efficient units (Andersen and Petersen 1993; Khodabakhshi 2007; Li et al. 2007). Ranking the efficient units among themselves is not investigated in this research as this research is more interested in identifying the inefficient units in an effort to derive important findings (such as peers, targets, and maintenance philosophies) that can help them address such inefficiency than in purely ranking DMUs in a comparative manner. Nonetheless, the concept of ranking efficient units is a future research area that can be studied and added to the framework if deemed as valuable.

5.6.9 Combining Statistics with DEA

In literature, DEA is referred to as being a deterministic approach having no statistical underpinnings. DEA typically produces point estimates for the efficiency scores with no measure of uncertainty associated to such scores. However, DEA models can be subject to uncertainty (Simar and Wilson 2000). Therefore such uncertainty should be evaluated and the efficiency scores obtained through DEA models should be assigned confidence intervals calculated by statistical procedures (Simar and Wilson 2000; Simar and Wilson 2001). Assigning confidence intervals to the efficiency scores would also allow hypothesis tests to be performed on such efficiency scores (Lothgren 2000). Simar and Wilson proposes a bootstrap method to be applied on the DEA efficiency scores to be able to assign confidence intervals to such scores (Simar and Wilson 2000; Simar and Wilson 2001). This is an area of literature that can be utilized as a future research to improve the highway maintenance efficiency framework developed in this research.

5.6.10 Imprecise Data Envelopment Analysis (IDEA) and Fuzzy DEA

DEA requires that the values of all input and output variables be known for all DMUs to be included in the model (Zhu 2003). In other words, if a DMU is missing the value for any of the variables, such DMU cannot be included in the model even though the values for all other variables are known. As was presented in **Section 4.2.4**, this was the case for a number of DMUs which did not have the value for the "Modified Change in CCI" variable for the "paved lanes" maintenance efficiency model. Furthermore, this was the case for two DMUs (that belong to the Fauquier County) which were missing data for the DMU_{PPT} variable for the "asset groups" maintenance efficiency model as presented in **Section 4.3.4**. There is a body of literature called Imprecise Data Envelopment Analysis (IDEA) which deals with this case and develops approaches that allow the inclusion of the DMUs with missing data in the DEA models along with the other DMUs with crisp data (Despotis and Smirlis 2002; Smirlis et al. 2006; Zhu 2003). This is an area of literature that can be utilized as a future research to improve the highway maintenance efficiency framework developed in this research by enabling it to include all possible DMUs in the models even though a number of them may be missing some data.

Sometimes, it is not possible to collect the data for the input and output variables precisely. There is also an area of literature (Fuzzy DEA) which addresses such issue of measurement errors. Fuzzy DEA accommodates the measurement inaccuracies by treating the production plans as fuzzy by assigning the inputs and outputs an interval ranging from risk-free bounds to impossible bounds (Girod and Triantis 1999; Triantis 2005d).

5.6.11 Tools to Deal with the Dynamic Nature of the Highway Maintenance Process

The original formulations used in DEA, as presented within the highway maintenance efficiency framework, do not take into consideration the dynamic nature of the processes. This can be an issue as it may take more than one period for the DMUs to adjust the value of their variables if a change is introduced to the process that is being modeled (Sengupta 1994). This research tried to address this issue by performing analysis over multiple periods in an effort to capture the efficiency changes that may be resulting from the changes introduced into the highway maintenance process by the DMUs at a certain period.

One approach to deal model the dynamic nature of the processes using DEA is called Dynamic Data Envelopment Analysis (DDEA) (Fare and Grosskopf 1996). Such approach incorporates the time element into the DEA model. This is done by extending the DEA formulations to an infinite sequence of static equations (Fare and Grosskopf 1996).

Another approach that can address the dynamic nature of the processes is the System Dynamics approach as was discussed in detail along with an example application to the highway maintenance case in **Section 2.8**. As a matter of fact, the System Dynamics approach can be used in conjunction with DEA in the future studies of similar nature. The reasons of the inefficiencies that are obtained through DEA models can be more precisely and easily explained if System Dynamics models are utilized in conjunction with DEA models than if DEA models were used alone to try to explain the reasons of such inefficiencies.

BIBLIOGRAPHY

(1995). "Public- Private Transportation Act." Code of Virginia.

AASHTO. (1997). "Twenty-first Century Asset Management." Center for Infrastructure and Transportation Studies at Rensselaer Polytechnic Institute.

AASHTO. (2000). "New Mexico Paves the Way with a Performance-Based Roadway Warranty." AASHTO Quarterly, 8-9.

Adler, N., and Berechman, J. (2001). "Measuring airport quality from the airlines' viewpoint: an application of data envelopment analysis." *Transport Policy*, 8(3), 171-181.

Adler, N., and Golany, B. (2001). "Evaluation of deregulated airline networks using data envelopment analysis combined with principal component analysis with an application to Western Europe." *European Journal of Operational Research*, 132(2), 260-273.

Adler, N., and Golany, B. (2002). "Including principal component weights to improve discrimination in data envelopment analysis." *Journal of the Operational Research Society*, 53, 985-991.

Afonso, A., and St. Aubyn, M. (2005). "Cross-country Efficiency of Secondary Education Provision: A Semi-parametric Analysis with Non-discretionary Inputs." ECB Working Paper No. 494.

Altman, S. (1979). "Performance Monitoring Systems for Public Managers." *Public Administration Review*, 39(1).

Amirteimoori, A., Kordrostami, S., and Sarparast, M. (2006). "Modeling undesirable factors in data envelopment analysis." *Applied Mathematics and Computation*, 180(2), 444-452.

Andersen, P., and Petersen, N. C. (1993). "A Procedure for Ranking Efficient Units in Data Envelopment Analysis." *Management Science*, 39(10), 1261-1264.

Athanassopoulos, A. D. (1998). "Optimization models for assessing marketing efficiency in multi-branch organizations." *The International Review of Retail, Distribution and Consumer Research*, V8(4), 415-443.

Athanassopoulos, A. D., and Thanassoulis, E. (1995). "Separating Market Efficiency from Profitability and Its Implications for Planning." *The Journal of the Operational Research Society*, 46(1), 20-34.

Banker, R. D., Charnes, A., and Cooper, W. W. (1984). "Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis." *Management Science*, 30(9), 1078-1092.

Banker, R. D., and Morey, R. C. (1986a). "Efficiency Analysis for Exogenously Fixed Inputs and Outputs." *Operations Research*, 34(4), 513-521.

Banker, R. D., and Morey, R. C. (1986b). "The Use of Categorical Variables in Data Envelopment Analysis." *Management Science*, 32(12), 1613-1627.

Barnard, C. I. (1938). *The Functions of the Executive*, Oxford University Press, London.

Barr, R. S. (2004). "DEA Software Tools and Technology." Handbook on Data Envelopment Analysis, W. W. Cooper, L. M. Seiford, and J. Zhu, eds., Kluwer Academic Publishers.

Barth, W., and Staat, M. (2005). "Environmental variables and relative efficiency of bank branches: a DEA-bootstrap approach." *International Journal of Business Performance Management*, 7, 228.

Boussofiane, A., Dyson, R. G., and Thanassoulis, E. (1991). "Applied data envelopment analysis." *European Journal of Operational Research*, 52(1), 1-15.

Brown, M. G. (1996). *Keeping score : using the right metrics to drive world-class performance*, Quality Resources, New York.

Burde, A., Ozbek, M. E., and Sahin, A. (2005). "Development of a Preliminary Performance Measurement System to Evaluate Different Approaches to Highway Maintenance Inherent in VMS and VDOT Maintenance Activities " *ISE 5144 Final Project Report*, Virginia Polytechnic Institute and State University, Blacksburg.

Burley, H. T. (2006). "Accounting for the Influence of the Environment in a Two-Stage Analysis- Public Hospitals." Productivity Analysis in the Service Sector with Data Envelopment Analysis, N. K. Avkiran, ed., Ipswich, 181-192.

Caldwell, J. (2006). "Commonwealth Transportation Board Approves $10.8 Million I-64 Maintenance Contract." VDOT News Release, Richmond.

Caltrans. (1998). "Highway Maintenance Manual."

Charnes, A., and Cooper, W. W. (1990). "Data Envelopment Analysis." Twelfth IFORS International Conference on Operational Research, H. E. Bradley, ed., Pergamon Press, Athens, Greece.

Charnes, A., Cooper, W. W., Lewin, A. Y., and Seiford, L. M. (1994). *Data envelopment analysis : theory, methodology, and applications*, Kluwer Academic Publishers, Boston.

Charnes, A., Cooper, W. W., and Rhodes, E. (1978). "Measuring the efficiency of decision making units." *European Journal of Operational Research*, 2(6), 429-444.

Chasey, A. D. (1995). "A framework for determining the impact of deferred maintenance and/or obsolescence of a highway system," PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Chasey, A. D., de la Garza, J. M., and Drew, D. R. (1997). "Comprehensive Level of Service: Needed Approach for Civil Infrastructure Systems." *Journal of Infrastructure Systems*, 3(4), 143-153.

Chatfield, C., and Collins, A. J. (1980). *Introduction to multivariate analysis*, Chapman and Hall, London ; New York.

Cook, W. D., Kazakov, A., and Roll, Y. (1994). "On the Measurement of Relative Efficiency of Highway Maintenance Patrols." Data Envelopment Analysis: Theory, Methodology, and Applications A. Charnes, W. W. Cooper, A. Y. Lewin, and L. M. Seiford, eds., Kluwer Academic Publishers, Boston, 195-210.

Cook, W. D., Roll, Y., and Kazakov, A. (1990). "A DEA Model for Measuring The Relative Efficiency of Highway Maintenance Patrols." *INFOR*, 28(2), 113-123.

Cooper, W. W., Seiford, L. M., and Tone, K. (1999). *Data Envelopment Analysis: A Comprehensive Text with Models, Applications, References, and DEA-Solver Software*, Kluwer Academic Publishers.

Craig, C. E., and Harris, R. C. (1973). "Total Productivity Measurement at the Firm Level." *Sloan Management Review*(Spring).

Dadson, D. K. (2001). "Impact of Environmental Classification on Steel Girder Bridge Elements using Bridge Inspection Data," PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Dadson, D. K., de la Garza, J. M., and Weyers, R. E. (2002). "Service Life and Impact of Virginia Environmental Exposure Condition on Paint on Steel Girder Bridges." *Journal of Infrastructure Systems*, 8(4), 149-159.

Daraio, C., and Simar, L. o. (2005). "Introducing Environmental Variables in Nonparametric Frontier Models: a Probabilistic Approach." *Journal of Productivity Analysis*, 24(1), 93-121.

de la Garza, J. M., Drew, D. R., and Chasey, A. D. (1998). "Simulating Highway Infrastructure Management Policies." *Journal of Management in Engineering*, 14(5), 64-72.

de la Garza, J. M., Groesbeck, R., Triantis, K., Van Aken, E., Ozbek, M., and Burde, A. (2005). "Evaluation of Alternative Approaches to Highway Maintenance- Proposal Submitted to the Virginia Department of Transportation." Virginia Polytechnic Institute and State University.

de la Garza, J. M., and Vorster, M. C. (2000). "Assessment of VDOT's Equivalent Cost for the Highway Maintenance Activities being performed by VMSI- Proposal submitted to VDOT." Virginia Tech.

Despotis, D. K., and Smirlis, Y. G. (2002). "Data envelopment analysis with imprecise data." *European Journal of Operational Research*, 140(1), 24-36.

Dickinson, T., Saunders, I., and Shaw, D. (2002). "Why Measure?" CSIRO Australia, 1-3.

Djerdjouri, M. (2005). "Assessing and benchmarking maintenance performance in a manufacturing facility: A data envelopment analysis approach." *Quality Control and Applied Statistics*, 50, 701.

Domayer, D. (2006). "Re: RFI about the Cost Data." M. E. Ozbek and J. W. Bryant, eds., Richmond, E-mail Communication.

Dornan, D. L. (2002). "Asset management: remedy for addressing the fiscal challenges facing highway infrastructure." *International Journal of Transport Management*, 1, 41-54.

Doyle, J. R., and Green, R. H. (1994). "Cross Evaluation in DEA: Improving Discrimination Among DMUs." *INFOR*, 33(3), 205-222.

Dunlop, R. J. "Managing Performance of a Highway System in the 21st Century." *World Road Association PIARC Congress*, Kuala Lumpur.

Dunteman, G. H. (1984). *Introduction to multivariate analysis*, Sage Publications, Beverly Hills.

Dyson, R. G., Allen, R., Camanho, A. S., Podinovski, V. V., Sarrico, C. S., and Shale, E. A. (2001). "Pitfalls and protocols in DEA." *European Journal of Operational Research*, 132(2), 245-259.

Efron, B., and Tibshirani, R. (1993). *An introduction to the bootstrap*, Chapman & Hall, New York.

Epstein, M. K., and Henderson, J. C. (1989). "Data Envelopment Analysis for Managerial Control and Diagnosis." *Decision Sciences*, 20, 90-119.

ESRI. (2004). "National Bridge Inventory Data Made GIS Ready." ArcNews.

Falls, L. C., Haas, R., McNeil, S., and Tighe, S. (2001). "Asset Management and Pavement Management: Using Common Elements to Maximize Overall Benefits." *Transportation Research Record*, 1769(01-2415).

Fare, R., and Grosskopf, S. (1996). *Intertemporal Production Frontiers with Dynamic DEA*, Kluwer Academic Publishers, Boston.

Farrell, M. J. (1957). "The Measurement of Productive Efficiency." *Journal of the Royal Statistical Society*, 120(3).

FHWA. (1995). "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges." *FHWA-PD-96-001*, Office of Engineering, Bridge Division, Washington D.C.

FHWA. (2004). "Data Integration: The Virginia Experience." Office of Asset Management.

FHWA. (2006). "Price Trends for Federal-Aid Highway Construction." *FHWA-IF-06-048*.

Fitch, G. M., Bartelt-Hunt, S., and Smith, J. A. (2005). "Characterization and Environmental Management of Storm Water Runoff from Road Salt Storage Facilities." *Transportation Research Record*(1911), 125-132.

Flannery, A., Wochinger, K., and Martin, A. (2005). "Driver Assessment of Service Quality on Urban Streets." *Transportation Research Record*(1920), 25-31.

Flintsch, G. W. (2004). "Assessment of the Performance of Several Roadway Mixes under Rain, Snow, and Winter Maintenance Activities." *VTRC 04-CR18*, VTRC, Charlottesville.

Fried, H. O., and Lovell, C. A. K. (1996). "Searching for the Zeds." Paper presented at the Georgia Productivity Workshop II, University of Georgia, Athens, Georgia.

Geiger, D. (2005). "Asset Management: Working for You." FOCUS, 1-4.

Girod, O. A., and Triantis, K. P. (1999). "The evaluation of productive efficiency using a fuzzy mathematical programming approach: the case of the newspaper preprint insertion process." *Engineering Management, IEEE Transactions on*, 46(4), 429-443.

Golany, B., and Roll, Y. (1989). "An Application Procedure for DEA." *OMEGA International Journal of Management Science*, 17(3), 237-250.

Golany, B., and Roll, Y. (1993). "Some extensions of techniques to handle non-discretionary factors in data envelopment analysis." *Journal of Productivity Analysis*, 4(4), 419-432.

Greitzer, M. S. (1976). "Role of and Need for Maintenance Feedback." *Transportation Research Record*, 613, 59-61.

Hardy, P. (2001). "Austroads Review of Performance Contracts: The Potential Benefits of Performance Contracts " Contracting the Future NZIHT Symposium.

Heggie, I. (2003). "Commercializing management and financing of roads in developing and transition countries." *Transport Reviews*, 23(2), 139-160.

Hussain, A., and Brightman, J. R. (2000). "Frontier Analyst in Depth." Banxia Software Limited, Glasgow.

Jahanshahloo, G. R., Pourkarimi, L., and Zarepisheh, M. (2006). "Modified MAJ model for ranking decision making units in data envelopment analysis." *Applied Mathematics and Computation*, 174(2), 1054-1059.

Jenkins, L., and Anderson, M. (2003). "A multivariate statistical approach to reducing the number of variables in data envelopment analysis." *European Journal of Operational Research*, 147(1), 51-61.

JLARC. (2001). "Review of VDOT's Administration of the Interstate Asset Management Contract." Richmond.

JLARC. (2002). "Adequacy and Management of VDOT's Highway Maintenance Program." Richmond.

Jolliffe, I. T. (2002). *Principal component analysis*, Springer, New York.

Kaplan, R., and Norton, D. (1996). *The Balanced Scorecard*, Harvard Business School Press.

Kardian, R. D., and Woodward, W. W. (1990). "Virginia Department of Transportation's Maintenance Quality Evaluation Program." *Transportation Research Record: Journal of the Transportation Research Board*, 1276, 90-96.

Kennerley, M., and Neely, A. "Performance Measurement Frameworks- A Review." *Proceedings of Performance Measurement 2000: Past Present and Future Conference*, Robinson College, Cambridge, 291-298.

Khodabakhshi, M. (2007). "A super-efficiency model based on improved outputs in data envelopment analysis." *Applied Mathematics and Computation*, 184(2), 695-703.

Li, S., Jahanshahloo, G. R., and Khodabakhshi, M. (2007). "A super-efficiency model for ranking efficient units in data envelopment analysis." *Applied Mathematics and Computation*, 184(2), 638-648.

Lothgren, M. (2000). "On the consistency of the DEA- Based Average Efficiency Bootstrap." *Applied Economics Letters*, 7, 53-57.

MacLean, G. E. (1993). *Documenting Quality for ISO 9000 and Other Industry Standards*, Quality Press, Milwaukee.

Mardia, K. V., Kent, J. T., and Bibby, J. M. (1979). *Multivariate analysis*, Academic Press, London ; New York.

Markow, M. J., Seguin, E. L., Ireland, E. F., and Freund, D. M. (1990). "Feasibility Study of Changes to the Highway Maintenance and Operations Cost Index." *Transportation Research Record*, 1268, 164-169.

Medina-Borja, A., and Triantis, K. (2006). "A conceptual framework to evaluate performance of non-profit social service organisations." *International Journal of Technology Management*, 37, 147-161.

Medina-Borja, N. A. (2002). "A non-parametric approach to evaluate the performance of social service organizations," PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Miller, C. R. (1989). *Indicators of quality in maintenance*, Transportation Research Board National Research Council, Washington, D.C.

Miller, J. D. (2007). "Infrastructure 2007- A Global Perspective." Urban Land Institute and Ernst&Young, Washington, D.C.

Mirack, F. (1981). "1977 Becomes the New Base Year for FHWA's Bid Price Index." *Public Roads*, 45(1).

Mirza, S. (2006). "Durability and sustainability of infrastructure- a state-of-the-art report." *Canadian Journal of Civil Engineering*, 33, 639-649.

Misra, R., and Das, A. (2003). "Identification of Homogeneous Sections from Road Data." *International Journal of Pavement Engineering*, 4, 229-233.

Muniz, M., Paradi, J., Ruggiero, J., and Yang, Z. (2006). "Evaluating alternative DEA models used to control for non-discretionary inputs." *Computers & Operations Research*, 33(5), 1173.

Muniz, M. A. (2002). "Separating managerial inefficiency and external conditions in data envelopment analysis." *European Journal of Operational Research*, 143(3), 625-643.

NCDC. (2007). "National Climatic Data Center Archive of Climate Data." http://www.ncdc.noaa.gov/oa/ncdc.html.

NCHRP. (2003a). "CEO Leadership Forum for State Departments of Transportation: A Summary Report." University of Minnesota Center for Transportation Studies.

NCHRP. (2003b). "Strategic Performance Measures for State Departments of Transportation- A Handbook for CEOs and Executives." *NCHRP Project No. 20-24(20).*

Neely, A., Adams, C., and Kennerley, M. (2002). *Performance Prism: The Scorecard for Measuring and Managing Business Success*, Financial Times Prentice Hall

NIST. (2006). "Criteria for Performance Excellence." Gaithersburg, MD.

NPR. (1997). "Serving the American Public: Best Practices in Performance Measurement Benchmarking Study Report."

Otto, S., and Ariaratnam, S. T. (1999). "Guidelines for Developing Performance Measures in Highway Maintenance Operations." *Journal of Transportation Engineering*, 125(1), 46-54.

Ozbek, M. E. (2004). "Development of Performance Warranties for Performance Based Road Maintenance Contracts," Masters Thesis, Virginia Polytechnic Institute and State University, Blacksburg.

Pastor, J. (1994). "How to Discount Environmental Effects in DEA: An Application to Bank Branches." Paper presented at the IVIE's Workshop "Eficiencia en Banca", Valencia, Spain.

Pastor, J. (1996). "Chapter 3 Translation invariance in data envelopment analysis: A generalization." *Annals of Operations Research*, 66(2), 91-102.

Piñero, J. C. (2003). "A Framework for Monitoring Performance-Based Road Maintenance," PhD Dissertation, Virginia Polytechnic Institute and State University, Blacksburg.

Poister, T. H. (1997). "Performance Measurement in State Departments of Transportation." *TRB-NCHRP-Synthesis of Highway Practice* 238.

Porter, T. (2001). "International Trends in Procurement Models for Highway Maintenance." Contracting the Future NZIHT Symposium.

QuantLink. (2005). "XLMiner Demo Edition 3.0.0."

Ramanathan, R. (2003). *An Introduction to Data Envelopment Analysis : A Tool for Performance Measurement* Sage Publications, Thousand Oaks.

Ray, S. C. (1991). "Resource-Use Efficiency in Public Schools: A Study of Connecticut Data." *Management Science*, 37(12), 1620-1628.

Reeb, J. E., and Leavengood, S. (2000). "Using Duality and Sensitivity Analysis to Interpret Linear Programming Solutions." Oregon State University Extension Service.

Rouse, P. (1997). "A Methodology of Performance Measurement with Applications using Data Envelopment Analysis," PhD Dissertation, The University of Auckland, Auckland.

Rouse, P., and Putterill, M. (2000). "Highway Performance." Handbook of Transportation Modelling, D. A. Hensher and K. J. Button, eds., Elsevier Science.

Rouse, P., and Putterill, M. (2003). "An Integral Framework for Performance Measurement." *Management Decision*, 41(8), 791-805.

Rouse, P., Putterill, M., and Ryan, D. (1997a). "Methodologies for the Treatment of Environmental Factors in DEA." Working Paper, The University of Auckland.

Rouse, P., Putterill, M., and Ryan, D. (1997b). "Towards a General Managerial Framework for Performance Measurement: A Comprehensive Highway Maintenance Application." *Journal of Productivity Analysis*, 8, 127-149.

Ruggiero, J. (1996). "On the measurement of technical efficiency in the public sector." *European Journal of Operational Research*, 90(3), 553-565.

Ruggiero, J. (1998). "Non-discretionary Inputs in Data Envelopment Analysis." *European Journal of Operational Research*, 111, 461-469.

Ruggiero, J. "Input Selection in DEA Models." *2003-School of Business Administration Working Paper Series*, University of Dayton.

Saaty, T. L. (1980). *The analytic hierarchy process : planning, priority setting, resource allocation*, McGraw-Hill International Book Co., New York.

Scheel, H. (2001). "Undesirable outputs in efficiency valuations." *European Journal of Operational Research*, 132(2), 400-410.

Seiford, L. M., and Zhu, J. (2002). "Modeling undesirable factors in efficiency evaluation." *European Journal of Operational Research*, 142(1), 16-20.

Sengupta, J. (1994). "A Model of Dynamic Efficiency Measurement." *Applied Economics Letters*, 1, 119-121.

Sexton, T. R. (1986). "The Methodology of Data Envelopment Analysis." Measuring Efficiency: An Assessment of Data Envelopment Analysis, R. H. Silkman, ed., Jossey-Bass Publishers, San Francisco.

Shang, J., and Sueyoshi, T. (1995). "A unified framework for the selection of a Flexible Manufacturing System." *European Journal of Operational Research*, 85(2), 297-315.

Sharman, P. (1995). "How to Implement Performance Measurement in Your Organization." CMA Magazine, 33-37.

Shucet, P. (2003). "Virginia's Transportation Crisis." The Vecellio Distinguished Lecture, Virginia Polytechnic Insitute and State University.

Silkman, R. H. (1986). "Editor's Notes." Measuring Efficiency: An Assessment of Data Envelopment Analysis, R. H. Silkman, ed., Jossey-Bass Publishers, San Francisco.

Simar, L., and Wilson, P. (2000). "A General Methodology for Bootstrapping in Non-parametric Frontier Models." *Journal of Applied Statistics*, 27(6), 779-802.

Simar, L., and Wilson, P. (2001). "Testing Restrictions in Nonparametric Efficiency Models." *Communications in Statistics: Simulation and Computation*, 30(1), 159-184.

Simar, L., and Wilson, P. W. (2003). "Estimation and Inference in Two-Stage, Semi-Parametric Models of Production Processes." Discussion Paper 0307, Institut de Statistique, Universite Catholique de Louvain.

Simpson, A. L., Ostrom, B. K., and Schmalzer, P. N. (2006). "Guidelines for the Collection of Long-Term Pavement Performance Data." *FHWA-HRT-06-067*, FHWA, McLean.

Simpson, C. (2006). "Turnkey Asset Maintenance Services Initiative." M. Ozbek, ed., Blacksburg, Personal Communication.

Sink, S., and Morris, W. T. (1995). *By What Method*, Institute of Industrial Engineers, Atlanta.

Sinuany-Stern, Z., Mehrez, A., and Hadad, Y. (2000). "An AHP/DEA methodology for ranking decision making units." *International Transactions in Operational Research*, 7(2), 109-124.

Smirlis, Y. G., Maragos, E. K., and Despotis, D. K. (2006). "Data envelopment analysis with missing values: An interval DEA approach." *Applied Mathematics and Computation*, 177(1), 1-10.

Sterman, J. D. (1999). *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin McGraw-Hill, Boston.

Stern, E. L. (1961). "A New Base for the Highway Contsruction Bid Price Index Compiled by the Bureau of Public Roads." *Public Roads*, 31(10).

Stern, E. L. (1970). "The Third Base for the Federal Highway Administration's Contract Price Index." *Public Roads*, 36(4).

Stivers, M. L., Smith, K. L., Hoerner, T. E., and Romine, A. R. (1997). "Maintenance QA Program: Implementation Manual." *NCHRP Final Manual 14-12*.

Thanassoulis, E. (2001). *Introduction to the Theory and Application of Data Envelopment Analysis*, Kluwer Academic Publishers, Norwell.

Thore, S. A. O. (2002). *Technology commercialization : DEA and related analytical methods for evaluating the use and implementation of technical innovation*, Kluwer Academic Publishers ; Distributors for North Central and South America Kluwer Academic Publishers, Boston Norwell, Mass.

Tomanelli, S. N. (2003). *Evaluating and Managing Performance-Based Contracts*, Federal Publications Seminars, LLC, Falls Church.

Tone, K. (2002). "A slacks-based measure of super-efficiency in data envelopment analysis." *European Journal of Operational Research*, 143(1), 32-41.

TRB. (1997). "Project 14-12 Highway Maintenance Quality Assurance." NCHRP.

TRB. (2006). "Maintenance and Operations of Transportation Facilities 2005 Strategic Vision." *E-C092*.

Triantis, K. (2004). "Engineering Applications of Data Envelopment Analysis (DEA)." Handbook on Data Envelopment Analysis W. W. Cooper, L. M. Seiford, and J. Zhu, eds., Kluwer Academic Publishers.

Triantis, K. (2005a). "Data Envelopment Analysis: An Evaluation of the Production Function." ISE 5144 Fall 2005 Class Notes.

Triantis, K. (2005b). "The Dynamics of Efficiency Analysis." ISE 5144 Fall 2005 Class Notes.

Triantis, K. (2005c). "Efficiency Measures and Data Envelopment Analysis " ISE 5144 Fall 2005 Class Notes.

Triantis, K. (2005d). "Fuzzy DEA." ISE 5144 Fall 2005 Class Notes.

Triantis, K. (2005e). "Theory of the Firm." ISE 5144 Fall 2005 Class Notes.

Triantis, K. (2006). "Treatment of Exogenous Variables in DEA." Working Paper.

UIdaho. (2006). "Roadway Design Glossary." Accessed 04/04/2006 @: http://www.webs1.uidaho.edu/niatt_labmanual/Chapters/RoadwayDesign/Glossary/.

VDOT. (1996). "Comprehensive Agreement for Interstate Highway Asset Management Services." Richmond.

VDOT. (2000). "Report on VDOT's Comprehensive Agreement for Interstate Asset Management Services." Maintenance Division, Richmond.

VDOT. (2002a). "An Action Plan for Distributed Authority to Promote Effective Administration and Management of VDOT's Contract with VMS, Inc." Richmond.

VDOT. (2002b). "Average Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial, and Primary Routes."

VDOT. (2003). "Average Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial, and Primary Routes."

VDOT. (2004). "Average Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial, and Primary Routes."

VDOT. (2005a). "Average Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial, and Primary Routes."

VDOT. (2005b). "Request for Proposals for Turnkey Asset Management Services." Richmond.

Venner, M. (2005). "Maintenance Quality Management and Environmental Stewardship- Best Practices in Information Management and Decision Support." *Journal of the Transportation Research Board*, 1911, 3-12.

VT. (2006). "Asset Group and Item Weighting Factors." Civil and Environmental Engineering, Blacksburg.

VTrans2025. (2005). "VTrans 2025 Summary of the Final Report."

Wang, F.-C., Hung, W.-T., and Shang, J.-K. (2006). "Measuring the cost efficiency of international tourist hotels in Taiwan." *Tourism Economics*, 12, 65-85.

Warner, M. R. (2005). "Views from the Chief Executive." 54th Virginia Transportation Conference, Roanoke.

Wells, D. T. (1994). "Environmental Classification Scheme for Pontis." VTRC, Charlottesville.

Williams, A. L., and Stensland, G. J. (2006). "Atmospheric Dispersion Study of Deicing Salt Applied to Roads: Part II Final Report for Period July, 2002 to June, 2004." Illinois State Water Survey Atmospheric Environment Section, Champaign.

Xue, M., and Harker, P. T. (1999). "Overcoming the Inherent Dependency of DEA Efficiency Scores: A Bootstrap Approach." Working Paper 99-17, Financial Institution Center, Wharton School, University of Pennsylvania, Philadelphia, PA.

Yang, Z., and Paradi, J. (2003). "Benchmarking Competitive Banking Units using 'Handicapped' DEA." Omega, submitted for publication.

Zhu, J. (2003). "Imprecise data envelopment analysis (IDEA): A review and improvement with an application." *European Journal of Operational Research*, 144(3), 513-529.

Zietlow, G. (2002). "Cutting Costs and Improving Quality Through Performance-Based Road Management and Maintenance Contracts." University of Birmingham (UK) / Transit New Zealand Senior Road Executive Courses Innovations in Road Management, Birmingham.

VITA

MEHMET EGEMEN OZBEK

Mehmet Egemen Ozbek was born on September 26, 1980 in Ankara, Turkey, as the younger child of Tulay and Ahmet Ozbek. He received his B.S. degree in Civil Engineering after completing his studies in Middle East Technical University (METU), Turkey, in February 2002. In August 2002, he joined the Vecellio Construction Engineering and Management Program (VCEMP) in Virginia Polytechnic Institute and State University to pursue graduate degrees in Civil Engineering. During his studies, he has been a research assistant for a number of projects under the supervision of Dr. Jesus M. de la Garza. He received his M.S. and Ph.D. degrees in Civil Engineering in Spring 2004 and in Fall 2007 respectively. He is planning to continue his studies within VCEMP as a postdoctoral research assistant and then pursue an academic career in a research university.

His e-mail addresses are: meozbek@vt.edu, egemenozbek@yahoo.com