ABSTRACT

SITZABEE, WILLIAM EMIL. A Spatial Asset Management Study Through an Analysis of Pavement Marking Performance. (Under the direction of Joseph E. Hummer and William J. Rasdorf.)

This research evaluates pavement marking performance characteristics of NC's highways and proposes asset management guidelines that will enable NC to effectively implement new Federal standards. Predictive models were developed and used to forecast the performance of pavement markings retroreflectivity over time. Consideration was given to the analysis of the relationships between pavement marking retroreflectivity values and variables such as marking color, marking age, pavement surface, and lateral location. Understanding retroreflectivity performance over time facilitated the development and implementation of guidelines and tools that will be used for holistic asset management. The guidelines and tools enable pavement-marking managers to focus limited resources where they are most needed and avoid replacing materials with effective life still remaining. Additionally, this research provides a means for NCDOT to establish the condition state of pavement markings throughout the State of North Carolina. This can be used to determined if they will be in compliance with pending minimum retroreflectivity standards that the Federal Highway Administration is proposing to publish.

The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

A Spatial Asset Management Study Through an Analysis of Pavement Marking Performance

by
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DEDICATION

This work is dedicated to my beloved wife Whitney Sitzabee and my dear children Kaylen and Brennan. Their significant support and understanding were crucial in my successful completion of this research study.

BIOGRAPHY

William E. Sitzabee, JR. grew up in Seaford NY and graduated from Seaford High School in 1989. In 1993 William earned a Bachelor of Science in Civil Engineering from Norwich University. William was licensed as a professional engineer in 1998 and maintains his license in NC. In 2004 William earned his Masters of Science in Engineering and Environmental Management from the Air Force Institute of Technology. In 2005 William started his pursuit as a Doctor of Philosophy under an Air Force Sponsored fellowship at North Carolina State University. William is commissioned as an officer in the United States Air Force and holds the rank of Major. William's research interests include infrastructure management, geographical information systems, and construction management.

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TABLE OF CONTENTS

LIST OF FIGURES ..... **vii**
LIST OF TABLES ..... **viii**
1.0 Introduction **1**
1.1 Problem **2**
1.2 Research Approach **3**
1.3 Research Objectives **4**
2.0 Background and Literature Review **7**
2.1 Asset Management **12**
2.1.1 Federal Approach to Asset Management 12
2.1.2 Location Referencing 17
2.1.3 Geographical Information Sciences 17
2.2 Proposed FHWA Minimum Retroreflectivity Standards **19**
2.3 Evaluation of Current Retroreflectometer Technology **22**
2.4 Pavement Marking Performance and Management **23**
2.4.1 South Carolina Study 24
2.4.2 Washington State Study 29
2.4.3 Michigan Study 31
2.4.4 Migletz Study 33
2.4.5 Iowa Study 36
2.4.6 Alabama (2002) 38
2.5 Literature Review Summary **40**
3.0 Methodology For Pavement Marking Perfromance **41**
3.1 Data Collection **41**
3.1.1 Mobile Collection Device 42
3.2 Data Organization **49**
3.2.1 South Carolina Data Organization 49
3.2.2 North Carolina Data Organization 50
3.3 Data Analysis **62**
3.3.1 Validation of Variables 62
3.3.2 Modeling 67
4.0 Methodology for Asset Management **70**
4.1 Goals and Policy Development **70**
4.2 Assess, Develop, and Maintain an Asset Management Inventory **73**
4.3 Pavement Marking Database Management and Modeling **74**
4.4 Implementation Strategy **76**
5.0 Results for Pavement Marking Performance **77**
5.1 Markov Analysis **77**
5.2 Variables **80**
5.2.1 Explanation of Independent Variables 82
5.3 Models **95**
5.3.1 Thermoplastics 95
5.3.2 Paints 109
5.4 Model Validation **114**
5.4.1 Logical Review of the Model 114

5.4.2 Comparison to Existing Models 116
5.4.3 Actual Verses Predicted plot of model data 118
5.4.4 Comparison of Predicted Values to Independent Sample 120
5.5 Summary of Results 123
6.0 Pavement Marking Asset management System 127
6.1 Goals and Policy Development 128
6.1.1 Asset Parameters 128
6.1.2 Governing Regulations for Pavement Marking 130
6.1.3 Overview of Finance and Budget Process 130
6.1.4 Pavement Marking Retroreflectivity Level of Service 133
6.2 Assess, Develop, and Maintain an Asset Management Inventory 140
6.2.1 Attributes for Performance Modeling 141
6.2.2 Attributes for Asset Management 145
6.2.3 Data Collection Plan 149
6.2.4 Pavement Marking Inspection and Data Collection Process 159
6.3 Pavement Marking Database Management and Modeling 163
6.3.1 Conceptual Model 164
6.3.2 Logical Model 165
6.3.3 Physical Model 167
6.3.4 Normalization 169
6.3.5 Data Model Diagrams 170
6.3.6 Algorithm 179
6.3.7 Demonstration 182
6.3.8 Asset Management Strategies 186
6.3.9 Sensitivity Analysis 187
6.4 Implementation of a Transportation Asset Management System 189
6.4.1 Measured Data 190
6.4.2 Condition Decision to Perform Queries and Develop Strategies 191
6.4.3 Limitations 193
6.4.4 Implementation 199
7.0 Conclusions 202
7.1 Performance Modeling 203
7.2 Asset Management 205
8.0 Recommendations 208
8.1 Limitations of the Current Research 209
8.2 Recommendations for Future Research 209
9.0 References 214
10.0 Annotated Bibliography 219
APPENDICES 231
11.0 Appendix A 232
12.0 Appendix B 249
13.0 Appendix C 252
14.0 Appendix D 257

LIST OF FIGURES

Figure 2.1. Illustration of 4 Lane Primary Road Pavement Marking Lateral Location 8
Figure 2.2. Basic Principles of Pavement Marking Retroreflectivity 10
Figure 2.3. 30-Meter Retroreflectivity Geometry 12
Figure 2.4. Retroreflected Raised Pavement Marking 20
Figure 2.5. Predictive Curve for Newly Placed Pavement Marking 27
Figure 2.6. Predictive Curve for Existing Pavement Markings 27
Figure 2.7. Predictive Curves for Remarking and Snowplowing 27
Figure 2.8. Pavement Marking Accepted Service Life Matrix 35
Figure 2.9. Iowa Longitudinal Pavement Markings Application Matrix 38
Figure 3.1. Vehicle Mounted Laserlux 43
Figure 3.2. Data Collecting Laser 44
Figure 5.1. Transition Matrices 79
Figure 5.2. Average RL Values Over Time of Yellow Thermoplastics (Un-weighted) 86
Figure 5.3. Average RL Values Over Time of White Thermoplastics (Un-weighted) 87
Figure 5.4. Average Value Over Time of Yellow Thermoplastics (Weighted) 89
Figure 5.5. Average Value Over Time of White Thermoplastics (Weighted) 90
Figure 5.6. Consolidated Model Residual Plot of Predicted Values 99
Figure 5.7. Consolidated Model Residual Plot of Predicted Values 100
Figure 5.8. Consolidated Model Q-Q Plot 101
Figure 5.9. White Edge Residual Plot of Predicted Values 102
Figure 5.10. White Edge Q-Q Plot 103
Figure 5.11. White Middle Residual Plot of Predicted Values 104
Figure 5.12. White Middle Q-Q Plot 105
Figure 5.13. Yellow Edge Residual Plot of Predicted Values 106
Figure 5.14. Yellow Edge Q-Q Plot 107
Figure 5.15. Yellow Middle Residual Plot of Predicted Values 108
Figure 5.16. Yellow Middle Q-Q Plot 109
Figure 5.17. Residual Plot of the Predicted Values for Paints 111
Figure 5.18. Q-Q Plot for Residuals of Paints 113
Figure 5.19. Q-Q Plot for Log Transformed Residuals of Paints 113
Figure 5.20. Plot of Average RL Values Over Time 115
Figure 5.21. Actual Verses Predicted Values for the Consolidated Thermoplastic Model 119
Figure 5.22. Actual verses Predicted with White and Yellow Thermoplastics 120
Figure 6.1. Presumed Pavement Marking Degradation Curve with LOS Increments 140
Figure 6.2. Pavement Marking Management System Conceptual Model 165
Figure 6.3.Pavement Marking Management System Logical Model 166
Figure 6.4. Physical Database Management Model 171
Figure 6.5. Pavement Marking Database Schema 173
Figure 6.6. Pavement Marking Retroreflectivity Algorithm 180
Figure 6.7. I-95 Actual R_L Values for Yellow Edge Pavement Markings 183
Figure 6.8. I-95 Actual and Predicted R_L Values for Yellow Edge Pavement Markings 185
Figure 6.9. Transportation Asset Management System 190

LIST OF TABLES

Table 2.1. Pavement Marking Materials in Use....9
Table 2.2. Recommendations for Minimum Retroreflectivity Values [Turner, 1998] 20
Table 2.3. Proposed State, County, and Local Minimum Retroreflectivity Standards 21
Table 2.4. Summary Table of Key Pavement Marking Performance Studies 24
Table 2.5. South Carolina Study Summary 29
Table 2.6. Washington Study Summary....31
Table 2.7. Michigan Study Summary....33
Table 2.8. Migletz Study Summary 35
Table 2.9. Iowa Study Summary....38
Table 2.10. Summary of Modeling Studies 40
Table 3.1. Segment Run Retroreflectivity Data Collection Flat File 46
Table 3.2. Run Instance Data Collection Flat File 47
Table 3.3. South Carolina Analysis Categories 50
Table 3.4. NC Analysis Categories; Step 1 for Asphalt 55
Table 3.5. NC Analysis Categories; Step 1 For Concrete 56
Table 3.6. NC Analysis Categories; Step 2 for Asphalt and Concrete....57
Table 3.7. NC Analysis Categories; Step 3 for Asphalt and Concrete....58
Table 3.8. NC Analysis Categories; Step 4 for Asphalt and Concrete....59
Table 3.9. NC Durable Categories Included in Research....59
Table 3.10. NC Categories, Non-durable for Future Research....60
Table 3.11. Summary of Available Data 60
Table 3.12. Summary of Available Data Non-Durables 60
Table 5.1. Effects Test for White Edge Using the F-Statistic....81
Table 5.2. Average R_L Values Over Time of Yellow Thermoplastics (Un-weighted) 87
Table 5.3. Average R_L Values Over Time of White Thermoplastics (Un-weighted) 87
Table 5.4. Average R_L Values Over Time of Yellow Thermoplastics (Weighted) 89
Table 5.5. Average R_L Values Over Time of White Thermoplastics (Weighted) 90
Table 5.6. ANOVA F-test Results for White and Yellow Thermoplastics (Un-weighted)....92
Table 5.7. ANOVA F-test Results for White and Yellow Thermoplastics (Weighted)....93
Table 5.8. Summary of Thermoplastic Retroreflectivity Degradation Models 97
Table 5.9. Consolidated Model Parameter Estimates....98
Table 5.10. White Edge Parameter Estimates....102
Table 5.11. White Middle Parameter Estimates 104
Table 5.12. Yellow Edge Parameter Estimates....106
Table 5.13. Yellow Middle Parameter Estimates 108
Table 5.14. Paint Parameter Estimates....111
Table 5.15. Simple Statistics of the Pavement Marking Retroreflectivity Data....116
Table 5.16. Comparison of Degradation Rates and Service Life of Models....118
Table 5.17. Predictive Estimate Compared to Summary of Validation Data....122
Table 5.18. Summary of Thermoplastic Pavement Marking Service Life by Category 125
Table 6.1. LOS Increments and NC Minimum Retroreflectivity Standards 136
Table 6.2. Pavement Marking Installation Attributes for Asset Management 147
Table 6.3. Pavement Marking Time-based Retroreflectivity Attributes....148
Table 6.4. Pavement Attributes for Pavement Marking Asset Management 149

Table 6.5. NC Durable Categories Included in Research 157
Table 6.6. NC Non-durable Categories, for Future Research 158
Table 6.7. Process Input and Output for Pavement marking Algorithm 181
Table 6.8. Predicted RL and Cost Data for I-95 Halifax Example 187
Table 6.9. Simulator Parameter and Coefficient Estimate Values 188
Table 6.10. Summary of NC Initial R_L Values 196
Table 10.1. Performance of Pavement Marking Retroreflectivity 219

1.0 INTRODUCTION

An overall asset management strategy is necessary to successfully manage pavement marking retroreflectivity. The North Carolina Department of Transportation (NCDOT) is charged with managing all aspects of a 78,000-mile roadway system, which includes over 312,000 lane miles of pavement markings [Howard, 2006]. Pavement markings cost NC approximately $14.5 million a year in contractor-performed work which represents two percent of the $700 million NCDOT budget [Howard, 2006]. Strategic approaches to pavement marking management will not only ensure efficient use of a limited budget but will enable NCDOT to follow Federal guidance in asset management.

According to the Federal Highway Administration (FHWA), asset management is a strategic approach to managing physical infrastructure using cost-effective solutions based on sound engineering and business principles [Cambridge Systems, Inc., 2002]. Asset management should consider both short-term and long-term system needs using a holistic, life-cycle approach. NCDOT is taking steps to improve pavement marking infrastructure management in order to meet projected Federal minimum pavement marking retroreflectivity requirements. These steps include shaping their asset management strategy based on the guidelines and principles set forth in FHWA's Asset Management Guide [Cambridge Systems, Inc., 2002].

Section 406 of the United States Department of Transportation and Related Agency Appropriation Act of 1993 directed the Secretary of Transportation to revise the Manual on Uniform Traffic Control Devices (MUTCD) to include a minimum standard of

retroreflectivity for pavement markings [United States Congress, 1993]. This Congressional directive applies to all roads that are open to the public. The Federal Highway Administration (FHWA) published 69 FR 45623 on 30 July 2004 and included directives for sign retroreflectivity but did not include the minimum required retroreflectivity for road pavement markings. Candidate minimum values for road pavement markings have been established [Turner, 1998], and the FHWA is expected to publish pavement marking retroreflectivity standards in the near future.

1.1 Problem

There are two aspects to this pavement marking research problem. First, the current management approach is not performance based which means that there is a potential for cost savings and increased service life for pavement markings. Second, there is a legislative requirement to implement pending Federal standards for minimum retroreflectivity values on all public roads.

A private contractor, Precision Scan LLC, has collected several years of pavement markings retroreflectivity data for the Work Zone Traffic Control Unit (WZTCU) of the NCDOT. The original intent of the data collection was to clearly identify the current condition of North Carolina's pavement marking inventory and to use the information as a quality control tool for managing the large amount of contractor-accomplished pavement-marking operations. The data collection exceeded the WZTCU expectations for quality control and has resulted in an opportunity to develop a pavement marking management strategy based on a detailed scientific analysis of NCDOT's pavement markings.

The WZTCU requested that North Carolina State University (NCSU) develop a pavement markings research plan in order to analyze relationships between pavement marking retroreflectivity values and variables such as marking color, marking age, and pavement surface. NCSU did this and submitted its report in summer 2006 [Rasdorf et al., 2006]. The preliminary analysis outlined by NCSU aided the WZTCU to better understand pavement marking performance and enable the NCDOT to make cost-effective decisions with respect to this asset.

Understanding retroreflectivity performance over time is important to establishing a pavement marking strategy that maximizes the material's lifecycle and minimizes replacement of pavement markings that still have sufficient retroreflectivity. On 1 July 2007 the NCDOT formalized the relationship and funded NCSU to research pavement marking degradation through NCDOT research project 2008-05 which is a $174, 800 two-year research grant (NCDOT, 2007). This research begins to implement the NCSU plan to manage pavement-markings from a holistic asset management approach.

1.2 Research Approach

This research follows a two-phase approach:

- The first phase is to determine the performance characteristics of pavement markings in NC and create viable predicative models.
- Focused on asset management, the second phase is to incorporate the predictive models into a GIS application that can be used to perform queries and predict future pavement

marking performance based on a specified set of given parameters. The developed GIS application will be used to formalize pavement marking management strategies and guidelines.

According to Migletz and Graham, several states are starting pavement marking management programs but none are fully developed [2002]. South Carolina and Iowa are working on developing pavement marking management systems and each have included some form of GIS into the foundation but none are fully developed [Sarasua, Clarke, and Davis, 2003; Hawkins, Samdi, and Hans, 2005]. Research that combines pavement marking predicted behavior with GIS applications is not only timely but will certainly enhance the fields of pavement markings and asset management. Ultimately, the goal of this research is to provide insight, establish a process, and develop techniques that can be expanded beyond pavement markings and used for the management of any continuous infrastructure system such as, Pavement condition, guardrails, drainage, and pipelines.

1.3 Research Objectives

The objectives of this research plan address both pavement marking material performance and pavement marking asset management. An appropriate set of work tasks, to meet each objective, is specified below.

Material Performance

- Evaluate the retroreflectivity (R_L) performance of pavement markings based on their installation and material characteristics.

- Determine rates, relationships, and correlations between analysis variables.
- Predict the life of pavement markings, based on their deterioration rate and on FHWA/NCDOT minimum levels.

Asset Management

- Develop goals and policies
- Assess, develop, and maintain an asset inventory
- Database management and modeling
- Implementation strategy development

In order for NCDOT to better understand the performance of different types of pavement markings, the deterioration of R_L over time will need to be evaluated for a given set of variables such a surface type, material type, location, and color. Once determined, the deterioration rates can be compared to existing rates already established in the Michigan State and Clemson studies. Correlations found between R_L and other factors, such as traffic levels and installation date, can be used by NCDOT to better predict when markings will need to be replaced.

With information about how pavement markings deteriorate and a general idea of the characteristics and age of a set of pavement markings, NCDOT can determine how many markings are below standard through use of a Geographical Information System (GIS) based pavement marking lifetime performance model. The results of the model can be used to

develop pavement marking selection and replacement guidelines that can be incorporated into an interactive pavement management tool for NCDOT to use across the state.

2.0 BACKGROUND AND LITERATURE REVIEW

This literature review establishes a critical knowledge base explaining the impact of pavement marking retroreflectivity on a driver's visibility. Specifically, this review compiles information on pavement marking retroreflectivity and how pavement markings perform over time. Understanding retroreflectivity performance over time is important to establishing a pavement marking strategy that maximizes the material's lifecycle by minimizing replacement of pavement markings that still have sufficient retroreflectivity.

According to the American Association of State Highway and Transportation Officials (AASHTO), markings and markers, like signs, have the function of controlling traffic to encourage safe and expeditious operations [AASHTO, 2004]. For highways and streets AASHTO classifies markings into three general types, which are pavement markings, object markings, and delineators [AASHTO, 2004]. This research focuses on pavement markings, which AASHTO further defines as center stripes, lane lines, no-passing barriers, and edge striping [AASHTO, 2004]. In all cases pavement markings refer to long-lines and should not be confused with object markings or delineators. Pavement markings are sometimes defined by type. For this research project the type of pavement marking will be defined by its lateral location on the roadway. Figure 2.1 is one example of lateral location and shows an illustration of the location of pavement markings on a roadway.

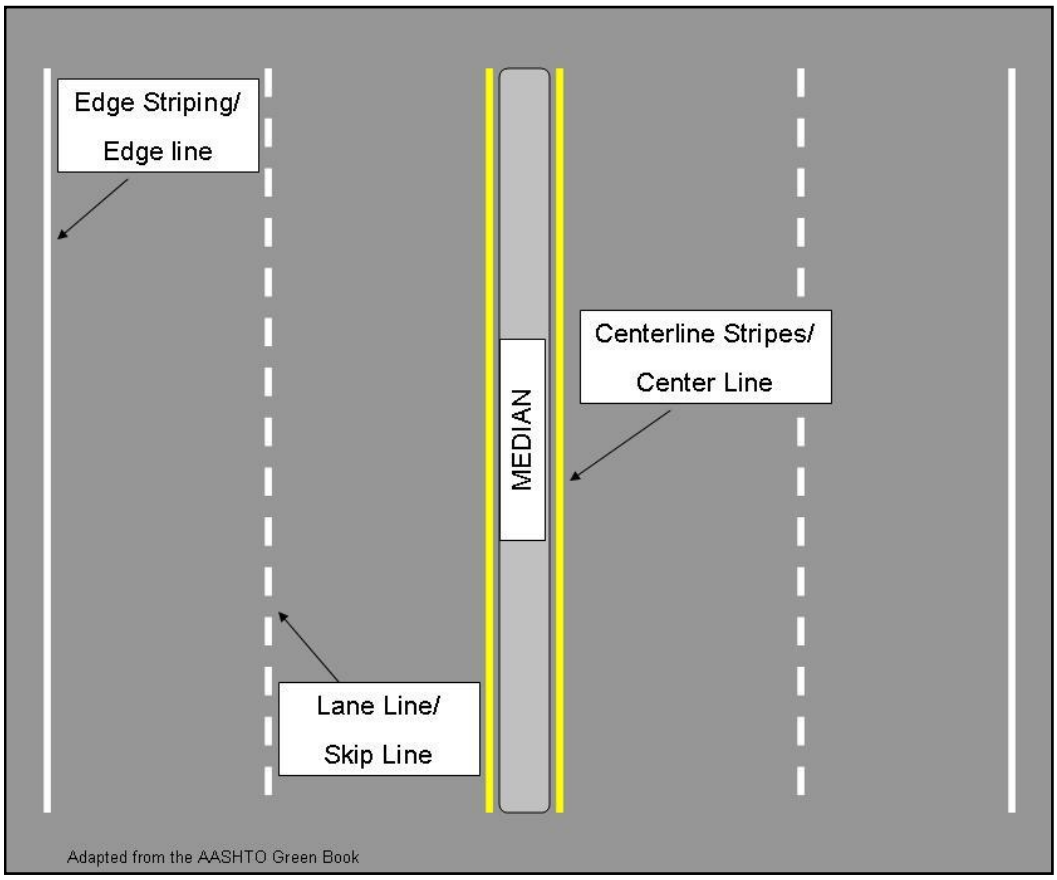


Figure 2.1. Illustration of 4 Lane Primary Road Pavement Marking Lateral Location

The objective of this literature search is to understand what has been done in the pavement markings field and to identify where critical research gaps exist. This review will cover governmental reports, legislation, periodic reviews, journal publications, conference proceedings, and expert interviews. This literature review covers the following topics:

- Asset Management
- Proposed FHWA minimum retroreflectivity standards
- Evaluation of the current retroreflectometer technology
- Pavement marking performance and management

Pavement marking retroreflectivity is a term used to describe the amount of light returned back to a driver from a vehicle's headlights as it is reflected from the pavement marking. The light provides drivers with critical information about the road and enables the driver to navigate safely at night. Ultimately, retroreflectivity directly relates to driver safety.

There are 16 types of line marking materials available on the market [Migletz and Graham, 2002]. Table 2.1 was adapted from Migletz and Graham [2002] and shows the 16 pavement marking materials in use. The majority of the materials are defined as durable pavement markings which mean pavement markings that are expected to last longer than one year. Waterborne and solvent based paints are considered nondurable pavement markings with a short service life of one year or less. According to the WZTCU, the NCDOT primarily uses four which are paint, thermoplastics, epoxy, and polyurea and are highlighted in Table 2.1.

Table 2.1. Pavement Marking Materials in Use

	Pavement Marking Material Type	**Percentage of Use**
1	Waterborne paint	59.9
2	Thermoplastics	22.7
3	Conventional solvent paint	6.5
4	Polyester	3.8
5	Epoxy	2.7
6	Preformed tape – flat	< 1.0
7	Preformed Tape - profiled	< 1.0
8	Methyl methacrylate	< 1.0
9	Thermoplastics profiled	< 1.0
10	Polyurea	< 1.0
11	Cold applied plastics	< 1.0
12	Experimental	< 1.0
13	Green lite powder	< 1.0
14	Polyester profiled	< 1.0
15	Tape removable	< 1.0
16	HD-21	< 1.0
Adapted from Migletz and Graham, 2002		

Pavement marking materials provide a base line of retroreflectivity. However, the bulk of the retroreflectance is achieved through the addition of glass beads embedded into the pavement marking material. The glass beads significantly improve the retroreflectivity of the pavement marking material. Figure 2.2 shows the basic concept of retroreflectivity and how the light from a vehicle's headlights is retroreflected off of a glass bead in the pavement marking back to the driver's eye and is adapted from ASTM standards [ASTMa, 2005].

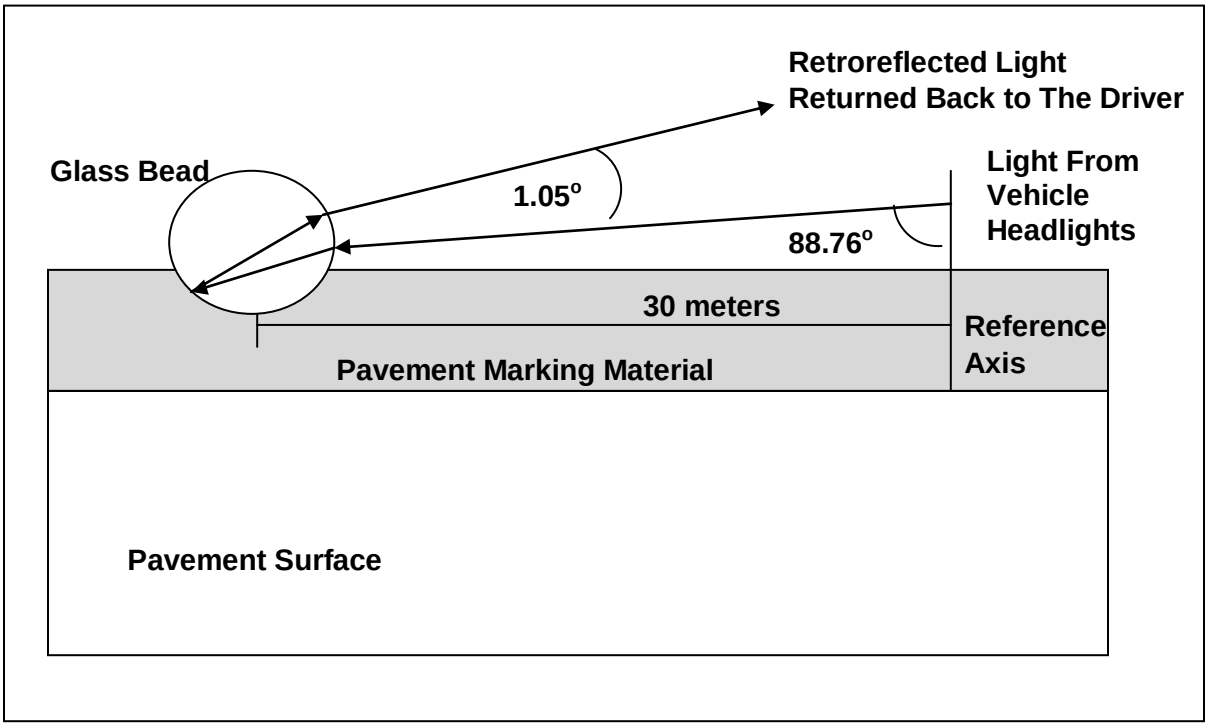


Figure 2.2. Basic Principles of Pavement Marking Retroreflectivity

ASTM standard number E1710-05 specifies that pavement marking retroreflectivity should be determined by measuring the amount of light returned from a pavement marking when a handheld device (using 30-meter geometry) directs light at the pavement marking at an entrance angle of 88.76 degrees measured from the reference axis which is a perpendicular line from the pavement surface. The returned amount of light is measured at an observation

angle of 1.05 degrees which is the angle measured from the difference of the vehicle's headlight back to the drivers view from a point 30 meters in front of the vehicle [ASTMa, 2005].

The standard used to measure retroreflectivity of pavement markings is the coefficient of retroreflected luminance (R_L) in units of millicandles/m^2/Lux (mcd/m^2/lx) [ASTMa, 2005]. ASTM E 1710-05 describes the testing standards using portable retroreflective measurement devices [ASTMa, 2005]. Current ASTM standards require a specific geometry commonly called 30-meter geometry. The basis behind 30-meter geometry is to measure the retroreflectivity at a point 30 meters ahead of a vehicle. The angle of 1.05^o is the difference required for light to reflect back from the headlight to the driver's field of vision based on a spot 30 meters in front of the driver's vehicle. This is believed to be the point at which most drivers observe the roadway at night.

ASTM E 808, specifies two angles to evaluate pavement marking retroreflectivity using 30-meter geometry. The entrance angle must be 88.76^o , and the observation angle must be 1.05^o [ASTM 2005b]. Figure 2.3 was adapted from ASTM E 808 and shows the basic geometry required to evaluate retroreflectivity at 30-meter geometry [ASTMb, 2005]. ASTM E 808 specifies that all new pavement marking materials have a minimum retroreflectivity value of 250 mcd/m^2/lux for white markings and 175 mcd/m^2/lux for yellow markings [ASTMb, 2005].

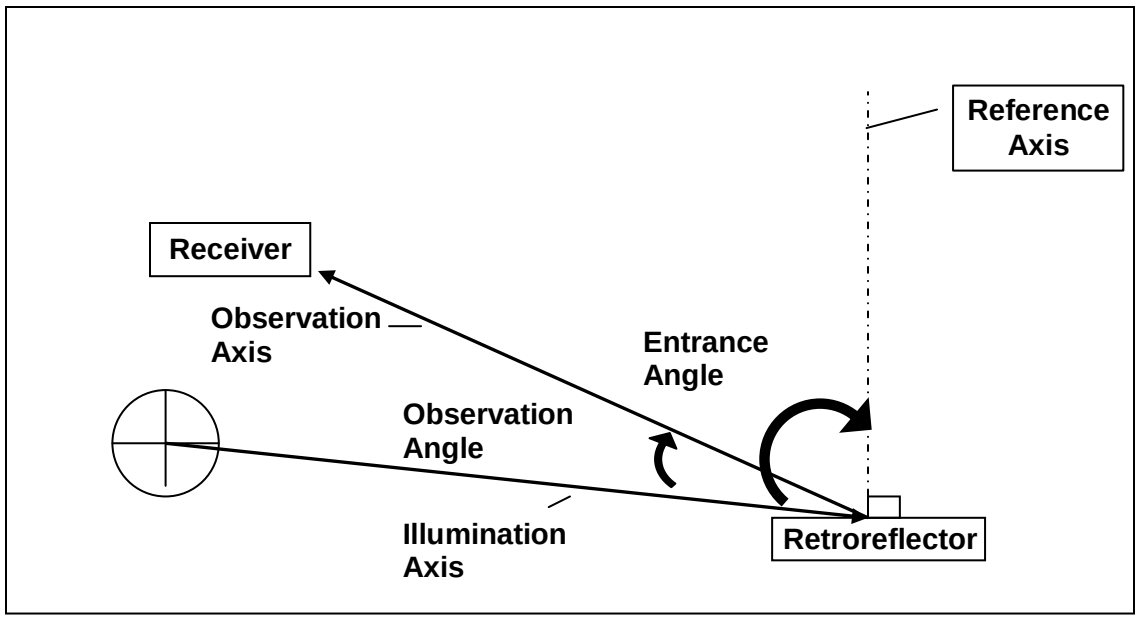


Figure 2.3. 30-Meter Retroreflectivity Geometry

2.1 Asset Management

This section discusses a seven-step approach to asset management endorsed by the FHWA. Presented next is a discussion on the current literature dealing with spatial concepts specifically, the use of linear referencing in transportation networks. Finally, this section introduces geographical information systems as a means of modeling transportation systems.

2.1.1 Federal Approach to Asset Management

According to the FHWA, asset management is a cost effective approach to systematically maintain, upgrade and operate a physical asset. The process combines engineering principles with sound business practices and economic theory for the purpose of improving decisions [FHWA, 1999]. A pavement management system is considered the backbone of transportation asset management and has long been considered a tool for collecting and monitoring information [FHWA, 1999]. Three principal components to a pavement management system are (1) data collection and management, (2) analysis, and (3) feedback

to the system. Each component is part of the process to manage the current pavement as well as forecast future conditions to evaluate and prioritize alternatives for maintenance, rehabilitation, and new construction [FHWA, 1999].

The FHWA Asset Management Guide states that the key aspect to asset management is to organize project priority based on measurable objectives established from well-defined goals. This approach is the defining aspect of the recommended FHWA asset management [Cambridge Systems Inc., 2002] approach and includes:

1) Develop goals and policies
2) Perform and maintain an asset inventory
3) Perform a condition assessment and conduct performance modeling
4) Alternative evaluation and program optimization
5) Develop short and long range plans (project selection)
6) Performance monitoring
7) Program implementation

According to the FWHA the first step in developing an asset management strategy is to define the organization's mission, goals, and policies. The goals need to be defined by measurable objectives. The second step is to perform and maintain an inventory of the system that enables the users to clearly understand the current condition of the asset. The third step is to use the knowledge of the system condition to perform an assessment of system

performance and create models of the system that will enable mangers to predict future conditions. The fourth step is to create alternatives to system projects and optimize those alternatives to produce the best projects for the system based on performance and sound business practices. The development of alternatives can lead to the development of short and long range plans and enable managers to effectively choose the right alternative. The next step, step six, is to monitor the performance of the chosen alternative. Finally, step seven is to implement the program and monitor feedback so that goals and policies can be adjusted accordingly.

NCHRP Report 551, Performance Measures and Targets for Transportation Asset Management, provides an update to the transportation asset management principles and further guidance on the development and implementation of performance measures and targets used for asset management [Cambridge Systematics, Inc., 2006]. The backbone to this asset management approach is a performance-based framework for decision makers that transcend all levels of the organization both horizontally and vertically [Cambridge Systems Inc., 2006].

The five key principles for the performance-based asset management approach [Cambridge Systems Inc., 2006], are:

1. Policy driven – Decisions on infrastructure management reflect policy goals and objectives that define asset condition, level of performance, and quality of services to meet customer needs and broader economic, community, and environmental goals.

2. Performance based – Goals and objectives must be tied to clear measures of performance. Targets established for these performance measures will guide decision makers through the analysis of options, setting of priorities, and program budgeting and implementation.

3. Analysis of options and tradeoffs – Consideration of options and evaluating the tradeoffs among alternatives is caused by competition for scarce resources and interrelationships among decision makers.

4. Decisions based on quality information – Choices among options during program development, project selection, and program and service delivery are based on their relative costs and consequences in meeting performance targets. Objective, high-quality information is applied at each step, using analytical methods and decision criteria that are consistent with policy goals and objectives and an agency's business processes.

5. Monitoring to provide clear accountability and feedback - Performance measures are monitored and reported, providing feedback on effectiveness of transportation investments and services, work accomplished, and program and service delivery.

Consistent with the FHWA Asset Management Guide [Cambridge Systems Inc., 2002], the first principle to the performance measures and target approach requires the establishment of clear goals and objectives that drive the organization's policies. Principle two shows how true performance-based decision-making relies on clear and measurable objectives that focus on a measurable target. Next, principle three is the need to establish options that enable the decision maker to weigh the tradeoffs of the options and the impact of shifting resources. This is an important principle because it highlights to the decision maker what needs to be

decided. Furthermore, is summarizes the impact and consequences across the organization and on the overall function of the asset. The next two principles call for quality information and feedback. Realistically, these principles need to be carried throughout the entire process.

NCHRP Report 551 highlights the need for quality information, including the use of scientific methods to collect and analyze data. Collecting inventory data can be time consuming and costly. The use of statistical methods to estimate the condition of the asset is one way the document recommends of providing quality information yet minimizing data collection costs.

To date no studies have been identified that match asset management concepts with pavement marking performance. Specifically, there have not been any performance models of pavement markings, a step identified in the FHWA asset management process, that have been incorporated into an overall pavement management system. Iowa developed an application matrix that provides guidance for pavement marking applications [Hawkins et al., 2005]. Iowa has only completed phase one of three and is still working on developing operational tasks and implementation strategies to implement the matrix into a comprehensive pavement management system [Hawkins et al., 2005].

Several other studies have developed pavement marking performance predictions but no model has been developed and accepted as a complete representation of all the suspected variables that impact pavement marking performance [Masliah et al., 2005]. Masliah et al.

[2005] argue that models of pavement marking and marker visibility are a critical research gap in pavement marking performance.

2.1.2 Location Referencing

Location referencing systems (LRSs) consist of techniques and procedures for accurately collecting, storing, maintaining, and retrieving location information [Flintsch et al., 2004]. Pavement management systems typically use a location referencing system known as linear referencing. This is particularly useful in transportation networks because of the ability to accurately locate most transportation features, including pavement markings, in a one-dimensional way throughout a link-node network system [Flintsch et al., 2004]. Additionally, LRSs are easily integrated into most GIS applications.

The increased use of GIS technologies and automated data collection equipment has increased the use of GPS as a location referencing method [Flintsch et al., 2004]. In a nation wide survey of DOT's, 35 percent of agencies surveyed indicated they used a GPS based latitude and longitude location referencing system. An additional 13 percent indicated they used a GPS based state plane coordinate system. Most agencies indicated that the inclusion of GPS technology was not the sole LRS used and that linear referencing methods were still used in conjunction with the GPS based LRS [Flintsch et al., 2004].

2.1.3 Geographical Information Sciences

Spatial technologies are particularly appropriate for integrating highway data because of the ability to link the geographic data with geometric and tabular data [Flintsch et al., 2004]. Transportation systems are complex networks that require large databases that are often

maintained in different areas within a DOT and are most often compatible. The power of a GIS is the ability of a user to integrate information from various sources and spatially connect that information to identify aspects of the transportation system that would otherwise be unapparent [Flintsch et al., 2004].

Ontology is a description of concepts and relationships that can exist for a domain [Gruber, 1993]. The basic premise is to define the domain in terms of elements such as objects, classes, attributes, and relationships, with semantics that can be interpreted by both humans and machines [Weng and Chang, 2007]. Ontology provides the basic building blocks for developing a data model and provides humans with a framework for interacting with application systems by providing a representation about a domain in a form of components [Weng and Chang, 2007].

Longley et al. state that a data model is a set of constructs for representing objects and processes in the digital environment [Longley et al., 2005]. The model enables a user to simplify the real world to perform meaningful analysis on complex systems. Decisions about the type of data model to use are strongly influenced by types of analysis expected and the level of information available or needed to fully understand the complexity of the system modeled [Longley et al., 2005]. Defining the data model with ontologies takes humanistic definitions about the system and applies semantics that enable the model to interact with a given application [Weng and Chang, 2008].

Longley states that there are four major phases to developing a working model of the real world [2005]. In the first phase designers try to understand the reality of the system and the

major components that influence the system. Second is the development of a conceptual model, which is a human-oriented, often partially structured, model of selected objects and processes that are thought relevant to a particular problem domain. Third is the development of a logical model, which is an implementation-oriented representation of reality that is often expressed in the form of diagrams and list. Finally, the physical model portrays the actual implementation in a GIS and often comprises tables stored as files or databases.

2.2 Proposed FHWA Minimum Retroreflectivity Standards

The FHWA has developed a proposed set of minimum pavement marking retroreflectivity standards [Turner, 1998]. The candidate standards are summarized in Table 2.2. The proposed standards remain unpublished since the FHWA is awaiting recommendations from an American Association of State Highway and Transportation Officials (ASSHTO) retroreflectivity task force before proceeding with the publication [Hawkins, 2000].

The proposed standards are set up as a matrix that accounts for three major variables. First, the matrix is divided into three option fields based on the type and speed of the roadway. The three options will need to be reduced to a single definition of the roadway classification and speed before publication. Second, the matrix separates roadways with and without retroreflected raised pavement markings (RRPMs). Figure 2.4 shows a picture of an RRPM. Finally, the matrix separates the standards based on color, either white or yellow.

For example, white pavement markings on a road with a speed limit of 70 mph and without RRPM would require a value of 150 mcd/m^2/lx, as shaded in Table 2.2.

Table 2.2. Recommendations for Minimum Retroreflectivity Values [Turner, 1998]

Option 1		Non-Freeway ≤ 45 mph	Non-Freeway ≥ 45 mph	Freeway ≥ 55 mph
Option 2		≤ 40 mph	≥ 45 mph	≥ 60 mph and ≥ 10,000AADT
Option 3		≤ 40 mph	45 – 55 mph	≥ 60 mph
With RRPM	White	30	35	70
	Yellow	30	35	70
Without RRPM	White	85	100	150
	Yellow	55	65	100

Note: Retroreflectivity values are mcd/m2/lux and measured with 30-m geometry
RRPMs – Retroreflective Raised Pavement Markers.



Figure 2.4. Retroreflected Raised Pavement Marking

Other candidate standards have been discussed and a joint state, county, and local task force has proposed one viable alternative. This alternative proposal is simplified and the minimum retroreflectivity values are significantly reduced. The state proposal eliminates the need for three options and simply classifies the roadways into three speed categories. Table 2.3 summarizes the state, local, and county recommendations [Hawkins, 2000]. Two significant

differences from the Federal proposal are seen in this proposal. First is the introduction of the concept of presence markings, which are pavement markings with no requirement for retroreflectivity. Second, there is no need for retroreflectivity values on roads with raised retroreflectivity markers.

Table 2.3. Proposed State, County, and Local Minimum Retroreflectivity Standards

Material Color	Local & Minor Collector (30 mph)	Major Collector & Arterial (35-50 mph)	Highways, Freeways, and All Roads (>55 mph)
White	Presence	80	100
Yellow	Presence	65	80

Note: Retroreflectivity values are mcd/m^2/lux and measured with 30-m geometry

The Federal standards have not been published yet because the uncertainty of the relationship between driver safety and visibility. Identified as a gap in research is the relationship between safety and visibility [Masliah, M., Bahar, G., Erwin, T., and Tan, E., 2005]. In some studies the research has revealed that increased visibility, due to greater retroreflectivity, has decreased driver safety [Masliah et al., 2005]. NCHRP project 17-28 concluded there is no correlation between safety and the level of pavement markings retroreflectivity [Bahar, G., Masliah, M., Erwin, T., and Tan, E., 2006]. However, a significant limitation of the NCHRP 17-28 study is that it did not address the effect of pavement markings or markers but only the correlation of safety and level of retroreflectivity. Ultimately, retroreflectivity is what makes pavement markings visible at night and this directly relates to driver safety [Al-Masaeid and Sinha 1994]. It seems intuitive that increased visibility would result in safer driving conditions but the relationship of driver safety and visibility remains a gap in the research and is a substantial reason for the delay in publishing the Federal standards.

2.3 Evaluation of Current Retroreflectometer Technology

There are both objective and subjective evaluation systems in use today to measure retroreflectivity of pavement markings. Objective measurements use retroreflectometers (mobile or handheld) while subjective evaluations are done through visual inspections by a trained observer. Both approaches are viable because there is no nationally calibrated standard for measuring retroreflectivity in the United States [Migletz and Graham, 2002]. In order to calibrate instruments and evaluate the accuracy of the measurements a national standard must be determined and this is a key to successfully developing minimum pavement marking retroreflectivity values [Migletz and Graham, 2002].

Six retroreflectometers were evaluated by the Highway Innovative Technology Center (HITEC) and represent the six leading units used by transportation agencies [Texas Transportation Institute, 2001]. Four of the six units were handheld devices and two were mobile units. All the units that were evaluated used 30-meter geometry to measure retroreflectivity. The Mirolux 12 was also evaluated but was left out of this summary because it uses 15-meter geometry, which is no longer acceptable under ASTM standards. The four handheld units evaluated were LTL 2000, MX30, MP-30, and FRT01. The two mobile units evaluated were the ECODYN and the Laserlux.

According to the HITEC summary, field tests verified that all six devices produce reliable results for measuring pavement marking retroreflectivity [Texas Transportation Institute, 2001]. The HITEC evaluation indicated that each unit comes with different capabilities and transportation agencies should evaluate the cost verses capability before deciding on which

unit would be best to purchase for that agency. Ultimately, any of the six retroreflectometers mentioned would produce viable results [Texas Transportation Institute, 2001].

Handheld verses mobile collection methods each have advantages and disadvantages as well. The handheld units are inexpensive but require a large crew for safety reasons in order to collect a small number of samples. Mobile devices are significantly more expensive but provide for a safer collection method and can collect continuous data throughout the system at highway speeds.

2.4 Pavement Marking Performance and Management

There are six major studies that summarize current research into pavement marking retroreflectivity performance. These six studies are the South Carolina, Washington, Michigan, Migletz, Iowa studies and Alabama. All six studies researched pavement marking retroreflectivity performance over time. The goal of each study was to understand the performance characteristics of various materials so that predictive models or degradation curves could be established. Table 2.4 identifies the primary purpose of each study and its key findings.

Table 2.4. Summary Table of Key Pavement Marking Performance Studies

Year	Name	Organization	Purpose of Study	Key Findings
2003	South Carolina	Clemson University & The Citadel	Performance curves	3 predictive models GIS application
2004	Washington	Washington State Transportation Center	Performance of water-borne paints	Inconclusive results based on large variations in data
1999	Michigan	Michigan State University	Performance of pavement marking materials	Waterborne paints are most cost effective Snowplowing has significant impact on performance
2001	Migletz	Transportation Research Board	Evaluate life-cycle of durable pavement markings	Great variation within pavement marking performance
2005	Iowa	Center for Transportation Research and Education	Evaluate Iowa's pavement marking practices	Calibration is key data Application matrix Combine handheld/mobile GIS integration issues
2002	Alabama	Auburn University	Service life of pavement markings and relationship to crash data	Concluded that AADT is a factor Developed a logarithmic model

2.4.1 South Carolina Study

The South Carolina Department of Transportation (SCDOT) supported a combined research project at Clemson University and The Citadel to evaluate the effective life cycle of pavement marking retroreflectivity over time [Sarasua et al., 2003]. This was done primarily because SCDOT felt their pavement marking management strategy was inefficient since it was not based on material performance. Additionally, SCDOT felt that they needed to better understand pavement marking management in order to comply with the expected implementation of new FWHA pavement marking minimum retroreflectivity standards. The primary research objective was to develop predictive models that could estimate the rate of pavement marking degradation. The models could then be applied to an overall pavement markings management plan.

The project was focused on SC interstate highways and evaluated pavement marking retroreflectivity performance during a 28-month period. Data were collected 6 times at over 150 sites throughout SC's interstate system. An average value was established for each site from a series of 11 measurements taken with an LTL-2000 at each data collection site for each collection interval. Other devices were used during the research but only the data from the LTL-2000 was used in the analysis. Furthermore, the data were collected using 30-meter geometry, which is the required geometry identified in ASTM E 1710-97.

During the data analysis portion of the research, retroreflectivity performance was based on four major independent variables: surface type, marking material, marking color, and maintenance activities. Each variable was analyzed using regression analysis and was compared to the dependent variables. The dependent variables were the differences in retroreflectivity values and the percent differences in retroreflectivity values. Several other variables were considered but only these four were determined statistically to be viable independent variables that affect the performance of pavement markings over time. Traffic volume was one variable that was initially thought to impact performance but was later eliminated. Traffic volume was inversely correlated to the dependent variables and was adequately accounted for within the aspects of the variable time.

The analysis resulted in the development of three predictive models that demonstrate how the marking materials perform over time. All three models are shown in Figures 2.5 to 2.7 below [Sarasua et al., 2003].

The first model, shown in Figure 2.5, demonstrates that the retroreflectivity of new pavement markings increased non-linearly during some initial time period after installation [Sarasua et al., 2003]. This was due to a greater number of reflective beads being exposed as the marking began to initially wear. After this initial time period, retroreflectivity was found to decrease linearly over time with a slight asymptotic curve at the end.

The second model, shown in Figure 2.6, was for existing pavement markings [Sarasua et. al., 2003]. The initial value of the retroreflectivity was typically lower than for new markings and there was a noticeable absence of the upward increase in retroreflectivity values.

Finally, the last model, shown in Figure 2.7 followed the same trends as the first two models but with a noticeable shift in retroreflectivity values that was due to maintenance activity [Sarasua et al., 2003]. The shift was observed in two different ways based on the type of maintenance activity performed. First, if the activity was snowplowing, there was a noticeable shift downward in the curve but the curve maintained the same linear downward trend after the activity was finished. Second, a re-striping maintenance activity would reset the retroreflectivity value back to the retroreflectivity value of a new marking and then the curve would follow the same trend as the first model.

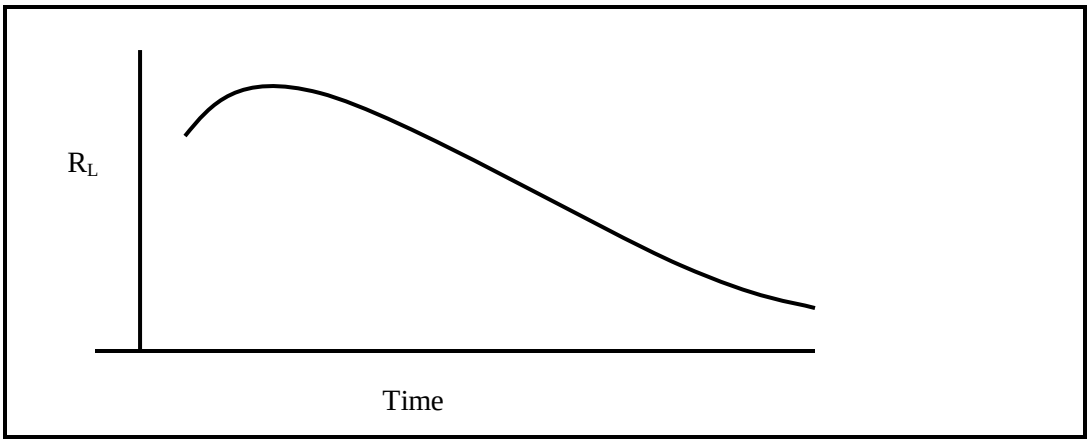


Figure 2.5. Predictive Curve for Newly Placed Pavement Marking

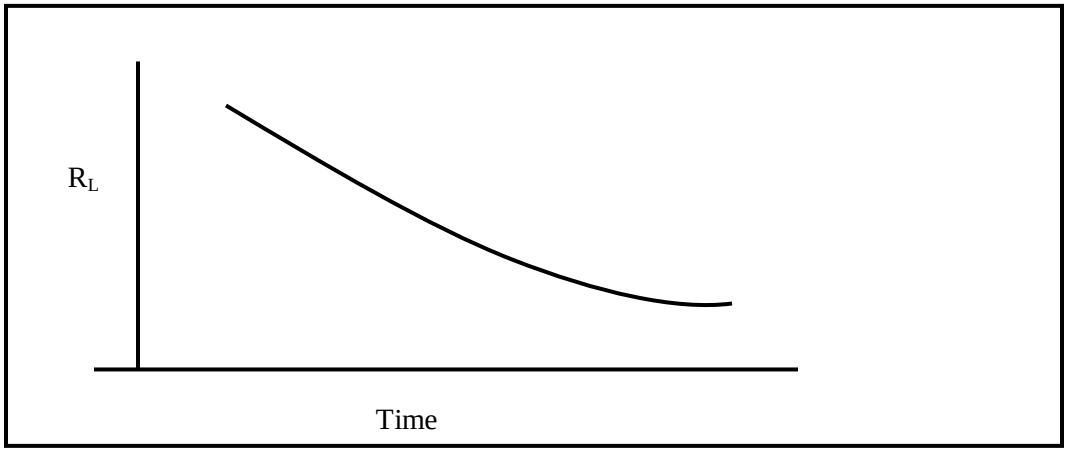


Figure 2.6. Predictive Curve for Existing Pavement Markings

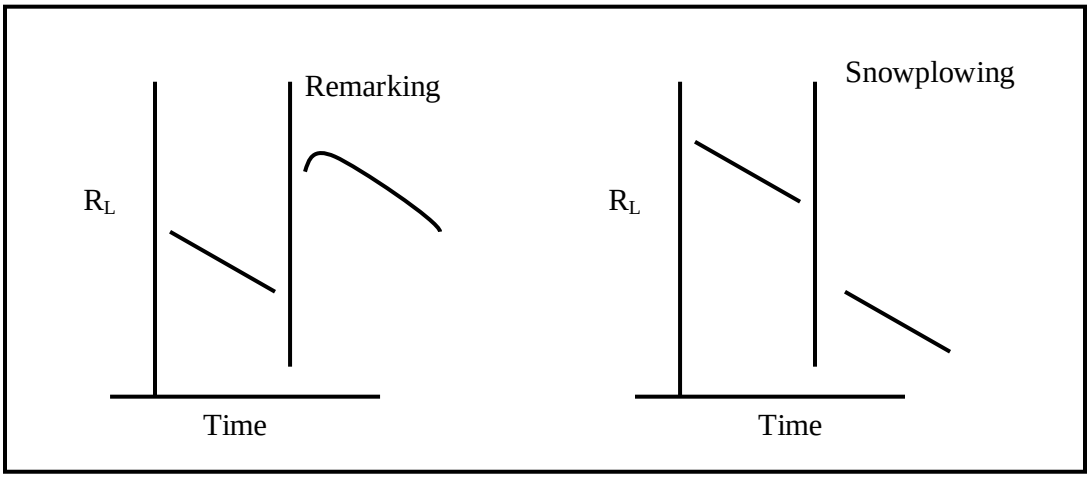


Figure 2.7. Predictive Curves for Remarking and Snowplowing

Additionally, SC developed two types of models for each combination of pavement marking material, surface material and color. One model was non-linear and represented the initial "break-in" period. The initial, non-linear model, calculates the number of days it takes for the material to rise and fall back to the original retroreflectivity value. The second model was linear and represented the degradation characteristics of the pavement marking retroreflectivity and starts when the initial value has risen and fallen back to the initial retroreflectivity value.

SC developed the models based on two different types of dependent variables. This first was the difference in retroreflectivity values over time which is the absolute difference in retroreflectivity values. The second was a percent difference in retroreflectivity values over time, which is the percentage of change in values over time. The models were developed for thermoplastics and epoxy. The thermoplastics on asphalt models are:

For White Thermoplastics: Diff = -0.06*(Days) –6.80 R^2 = .47 (2.1)

% Diff = -0.03*(Days) – 3.29 R^2 = .39 (2.2)

For Yellow Thermoplastics: Diff = -0.03*(Days) –3.63 R^2 = .21 (2.3)

% Diff = -0.02*(Days) – 2.35 R^2 = .24 (2.4)

Where

Diff = Difference in retroreflectivity over time

% Diff = Percentage of difference in retroreflectivity over time

Days = Time in days

The end of service life for this model was defined by reaching a retroreflectivity value of 100 $mcd/m^2/lx$

Table 2.5. South Carolina Study Summary

Objective	Evaluate the effective life cycle of pavement marking retroreflectivity over time and create predictive models
Important Parameters	• Study was complete in 2003. • Evaluate interstates highways only. • Data were collected for 150 sites over a 28 month period. • Study used an LTL-2000 handheld device with 30-m geometry. • Introduced dynamic segmentation to manage attribute information in a GIS.
Key Findings	• Three basic shapes represent performance of pavement marking retroreflectivity. • Developed two mathematical models based on difference of retroreflectivity and percent difference of retroreflectivity. • Snow plowing and remarking have significant impact on performance characteristics. • Mobile collection devices are efficient because they use continuous readings to collect large amounts of data and are safer to use. Handheld units are more accurate and cost less but are less efficient since they cannot collect large amounts of data.

Sources: [Thamizharasan et. al., 2002; Sarasua et. al., 2003]

2.4.2 Washington State Study

This study was conducted by the Washington State Transportation Center from July 2003 to July 2004 using the Laserlux mobile retroreflectometer with 30-m geometry [Kopf, 2004]. The study evaluated the performance of pavement markings throughout Washington. Focusing on waterborne and solvent-based paints, the goal of this study was to develop predictive degradation curves for pavement marking performance. The research project was conducted using 80 test sites throughout the state. The data collection was repeated 11 times throughout the year at monthly increments. Kopf used 100 $mcd/m^2/lx$ as the minimum

threshold value to indicate satisfactory performance [2004]. This value was arbitrarily specified based on the literature review performed by Kopf [2004].

Similar to the methodology used by NCDOT, Washington used the Laserlux mobile collection device because of the ability to safely and efficiently collect a large amount of data in a small period of time. The device was mounted on a 1995 Chevrolet Beauville van. The collection speed was 60 mph or the posted speed limit and collected a scan width of 1.1 meters. The device collects over 1500 measurements per mile and uses an onboard computer to calculate the average retroreflectivity every 250 feet. This distance was set by the user and was used to calculate the overall average retroreflectivity value for the entire test section. Linear referencing was used to designate the location of each test site and a GPS tag was captured, providing latitude and longitude coordinates for the test sample.

Regression analysis was used to fit curves to the data and determine the overall degradation of the pavement markings. The results were statistically inconclusive. The standard deviation in values was quite large and the variations in the data were too large for any curves to reasonably be fitted to the data.

The researchers in the Washington study indicated that variations in the data were probably attributed to numerous causes. One of their key findings was that the results were inconclusive since there were large variances in data. Variances were attributed to calibration issues and precision of location referencing information. The final result of the project was the recommendation that Washington continue with their current practice of

remarking with paint based on an annual schedule and remarking heavy use areas twice a year.

Table 2.6. Washington Study Summary

Objective	Develop retroreflectivity degradation curves for roadway pavement markings
Important Parameters	• Study was completed in 2004. • Data were collected from 80 test sites throughout a 1-year period. • Used a mobile collection device (vehicle mounted Laserlux). • Study was primarily focused on waterborne paints. • Minimum acceptable retroreflectivity threshold was set at 100 mcd/m2/lux.
Key Findings	• Variation in the data resulted in inconclusive results. • Variations were attributed to data collection issues, including calibration of collection devices and repeatability due to precision of the location referencing. • Washington should continue to remark with paint at least once a year and twice a year in heavy use areas.

Source: [Kopf, 2004]

2.4.3 Michigan Study

Michigan State University evaluated the performance of several pavement-marking materials in the mid 90's [Lee et al., 1999]. The purpose of the study was to provide insight and guidance to implement cost effective procedures for pavement marking management. Focused on four major marking materials (paints, thermoplastics, thermosets, and tapes) the study used 50 sample sites throughout Michigan. The research objective was to determine the degradation rates for the various materials. A minimum threshold value of 100 mcd/m^2/lux was used to indicate satisfactory marking performance.

The measuring device used was the Mirolux 12, which is a 15-meter geometry device. The author indicated that there was a great deal of variability in the retroreflectivity values from this device and that any future studies should consider better data collection equipment and methods.

This study attempted to establish a service life for marking materials. However, large variances in the extent of the material service life were shown and a clear explanation of what caused the large variance was not given. Time limitations minimized the amount of temporal data that were collected for each site, which could be a contributing factor. The degradation rates were deemed linear, but the R^2 values ranged from 0.14 to 0.18 which are extremely low, showing little confidence that linear degradation was the best fit. Shown below is the model developed for thermoplastics which is:

$$R_L = -0.3622*X + 254.82 \qquad R^2 = 0.14 \qquad (2.5)$$

Where

R_L = Retroreflectivity of pavement marking and

X = Age of the pavement marking in days

The end of service life for this model was defined by reaching a retroreflectivity value of 100 $mcd/m^2/lx$.

Of significant note, snowfall (snow plowing) was highly correlated to retroreflectivity degradation. Alternatively, AADT, speed limit, and percent commercial traffic did not correlate with retroreflectivity degradation. The basic conclusions of the study indicated that water-borne pavement markings are the most cost effective. This was based on reasonable performance compared to the low cost. Other materials perform better but the cost involved

did not justify the improved service life. Michigan is a high snowfall (snow plowing) state. Therefore, cost comparisons to a low snow plowing state like N.C. may not be wise.

Table 2.7. Michigan Study Summary

Objective	Develop retroreflectivity degradation rates for roadway pavement markings
Important Parameters	• Study was completed in mid-90's. • Data were collected from 50 test sites. • Used a handheld collection device (Mirolux with 12-meter geometry). • Study focused on paints, thermoplastics, thermosets, and tapes. • Minimum acceptable retroreflectivity threshold was set at 100 mcd/m2/lux.
Key Findings	• Data included large, unexplained, variations in the retroreflectivity values. • Handheld device (12-meter geometry) showed many drawbacks. • Basic conclusion is that waterborne paint is most cost effective for high snowplow states.

Source: [Lee, 1999]

2.4.4 Migletz Study

Conducted by the Transportation Research Board using the Laserlux mobile retroreflectometer with 30-meter geometry, this study took place from 1994 to 1998 [Migletz et al., 2001]. Its purpose was to evaluate the life of durable pavement markings. Included in the study as a benchmark, was some limited evaluation of waterborne paints. The research collected data on 362 longitudinal (edge, center, & lane) pavement-marking lines from 85 sites across 19 states.

The Migletz study used regression analysis to evaluate various materials and establish a predictive degradation curve of the material performance over time. Marking material type, road surface type, and marking material color where the independent variables evaluated.

Results from the regression analysis indicate there was a great deal of variation in identical materials at different sites. The variation was attributed to differences in roadway type,

region of the country, marking specifications, quality control, and winter maintenance. No discussion was provided regarding the current age of the pavement markings when the study was performed. Furthermore, analysis indicated that yellow lines performed better than white but this was attributed to the use of a lower threshold of material expectations rather than on superior performance.

In a follow up study, Migletz et. al. (unpublished 2000) established an accepted service life matrix that provides degradation rates sorted by cumulative traffic passages (CTP) and elapsed months. The matrix in Figure 2.8, is an adaptation of Migletz's matrix and shows the average service life for each material type in months.

The matrix is sorted by line color and type of marking material and provides an average service life and standard deviation in months. Additionally, the matrix gives a service life range in months. The two most common pavement marking materials are:

- Ave Life of Waterborne paint is 10.4 months (white)
- Ave Life of Thermoplastics is 26.2 months (white) and 27.5 months (yellow)

Included in the matrix is cost data that reflects the combined cost of both contractor and in-house pavement marking costs for a given pavement marking material. The cost data is presented in dollars per linear-foot and is an approximation based on a survey of 37 states, 5 counties, and 4 cities. The complete cost data presented by Migletz also included a range of values but is not included in Figure 2.8 [Migletz et al., 2001].

Material	No of Pavement Marking Lines	Service Life In Elapsed Months			Combined Cost
		Average	Standard Dev	Range	$/Linear-ft
White Lines					
Waterborne Paint	3	10.4	7.3	4.1 –18.4	0.06
Epoxy	18	23	17.1	1 - 56	0.26
Methyl methacrylate	7	14.4	7.6	6.8 – 29.3	1.22
Methyl methacrylate Profiled	9	21	13.4	7.8 – 43.2	1.44
Polyester	5	24.7	7.9	14.7 – 34.1	0.13
Polyester - Profiled	1	45.9	-	45.9 – 45.9	2.33
Thermoplastics	19	26.2	14.1	7.4 – 49.7	0.32
Thermoplastics - Profiled	14	23.8	12.8	4.7 – 55.7	0.87
Preformed Tape	11	27.4	13.6	11.7 – 60.0	1.41
Yellow Lines					
Epoxy	15	34.3	14.6	12.6 – 57.8	0.26
Methyl methacrylate	4	16.8	4.2	12.6 – 20.5	1.22
Methyl methacrylate Profiled	5	25.0	6.0	18.1 – 32.8	1.44
Polyester	2	43.8	5.8	39.7 – 47.9	0.13
Polyester - Profiled	1	39.6	-	39.6 – 39.6	2.33
Thermoplastics	10	27.5	12.1	11.0 – 41.6	0.32
Thermoplastics - Profiled	8	26.7	10.3	17.8 – 50.7	0.87
Preformed Tape	7	30.6	11.9	19.6 – 53.4	1.41
Adapted from Migletz et. al. (unpublished 2000), Sites Without Roadway Lighting and RRPM					

Figure 2.8. Pavement Marking Accepted Service Life Matrix

Table 2.8. Migletz Study Summary

Objective	Develop retroreflectivity degradation rates for roadway pavement markings
Important Parameters	• Study was from 1994-1998. • Data were collected from 85 sites across 19 states. • Used a mobile collection device (Laserlux with 30-m geometry). • Study focused on various durable pavement markings.
Key Findings	• Large variations in the shape of the degradation curves. • Regional changes influenced the shape of the curve for identical materials, and line type. • Matrix of service life degradation rates established based on unpublished data. • Average Life of waterborne paint is 10.4 months. • Average Life of thermoplastics is 26.2 months. • Average Life of polyurea is 24.7 months. • Average life of epoxy is 23.0 months.

Sources: [Migletz unpublished, 2000; Migletz et. al., 2001]

2.4.5 Iowa Study

This project was the first phase of a multi-phase research program to evaluate the Iowa DOT pavement marking practices [Hawkins et al., 2005]. The project used retroreflectivity measurements to establish an application matrix based on material performance. The matrix included type of roadway, remaining service life, speed limits, traffic volume, and marking material. Phase two of this project is ongoing.

The Iowa DOT has one Lazerlux van, which is used to take continuous measurements of retroreflectivity throughout Iowa. The van is equipped with a 30-m geometry Laserlux retroreflectometer and collects data at a highway speed of 55 mph. The data collection uses a linear referencing system to collect location information and averages the retroreflectivity value for every tenth of a mile throughout the road segment. Each segment is then averaged over a specific route using the mileposts to mark the beginning and end of the route. GPS data are collected for each run and are recorded as attribute data. Standard linear referencing, based on milepost markings and offsets, was used to identify the location of each road segment.

Each of Iowa's six districts has a Delta LTL-X handheld retroreflectometer, which is used during ongoing pavement-marking operations as a means of ensuring quality control. The LTL-X is also capable of 30-m geometry and collects GPS data for each site measured.

Calibration was considered a key aspect to ensuring accurate data collection and was accomplished for both handheld and mobile collections. Calibration was performed at least

once a day or when erratic values were observed. The calibration process enabled the researchers to accommodate different temperature and humidity changes from day to day.

GPS data were collected for each test section. Significant issues were encountered when combining GPS data and the linear referencing system into a common GIS. The GPS data did not line up exactly with county referencing information already in the GIS. Additionally, changing route numbers at county borders created frustrations in organizing the data. Data from the mobile device were translated directly into a spreadsheet whereas the data from the handheld device were formatted through an additional program called CITRIX [Hawkins et al., 2005].

The first phase of this research project was considered successful in the development of the application matrix, shown in Figure 2.9 [Hawkins et al., 2005]. The matrix provides technicians with a practical approach to pavement marking management based on a given set of variables. The matrix provides a marking material for the given combination of road classification and number of service life years remaining.

Snow plowing and edge maintenance were both identified as maintenance issues that significantly impact pavement-marking performance. Even though snow plowing has been identified in several studies this was the first time that other significant maintenance activities, like edge maintenance, were specifically identified as influencing pavement marking performance.

Pavement Surface Life	Primary 2 & 3 - Lane	Primary 4+ - Lane		Interstate	
	Rural + Urban ≤ 55 mph	Rural	Urban High Traffic	< 50,000 AADT	> 50,000 AADT
< 2 yrs	Waterborne	Waterborne	Durable WB Waterborne	Waterborne	Durable WB
3 – 5 yrs	Durable WB	Durable WB Waterborne	Durable WB Waterborne Epoxy Polyurea	Durable WB	Durable WB Polyurea Epoxy
5+ yrs	Durable WB Waterborne Epoxy Polyurea	Durable WB Waterborne Epoxy Polyurea	Durable WB Epoxy Polyurea Tape	Durable WB Epoxy Polyurea	Tape Durable WB Epoxy Polyurea

Durable WB: durable waterborne paints
Adapted from Hawkins, et. al., 2005

Figure 2.9. Iowa Longitudinal Pavement Markings Application Matrix

Table 2.9. Iowa Study Summary

Objective	Evaluate Pavement Marking Practices
Important Parameters	• Study was for a 12-month period. • Used both mobile and handheld collection devices (Laserlux with 30-m geometry and the LTL-X). • Combined GPS data with tradition linear referencing to locate test sites in a GIS.
Key Findings	• Developed application matrix based on material performance. • Calibration of collection equipment was key to good data. • Combined use of mobile and handheld equipment to collect data. • Combining mobile and handheld units created integration issues when populating a GIS with location referencing information.

Sources: [Hawkins, et. al., 2005]

2.4.6 Alabama (2002)

This study explored application cost, service-life, and user cost associated with crashes as related to pavement marking retroreflectivity in Alabama. Abboud and Bowman developed a logarithmic regression model to depict the connection between pavement marking retroreflectivity and vehicle exposure (VE). Where VE was defined as a relationship between annual average daily traffic (AADT) and pavement marking age [2002].

Unique to this model is the use of VE as an independent variable, where VE is a function of the combination of time and AADT together. Also unique to this model is the absence of marking color and surface material, which have been established as independent variables for pavement marking degradation in other key pavement marking degradation studies. The degradation model presented in this research was for white thermoplastics edge lines and is presented below. A model for paints is also presented below. In each case pavement marking life and AADT were substituted with VE.

For Paint:

$$R_L = -19.457*\ln(VE) + 26.27 \qquad R^2 = 0.31 \qquad (2.6)$$

For White Thermoplastic Edge Lines:

$$R_L = -70.806*\ln(VE) + 639.66 \qquad R^2 = 0.58 \qquad (2.7)$$

Where

RL = pavement marking retroreflectivity (mcd/m^2/lx)

ln = natural logarithm, and

VE = Vehicle exposure which is: VE = AADT * PM_age *0.0304

AADT = Average Daily Traffic per lane

PM_age = age in months

The end of service life for this model was defined by reaching a retroreflectivity value of 150 mcd/m^2/lx

2.5 Literature Review Summary

This literature review established the knowledge base and explained what has currently been done in the field of pavement marking. The review summarized the FHWA asset management approach, the status of the proposed Federal standards, a review of retroreflectivity data collection technology and a summary of six studies that focused on pavement marking performance. Five of the six studies created models. Table 2.10 shows a summary of the five studies and gives the type of each model. These studies show a significant difference in the degradation models. Three of the five studies concluded that pavement markings degrade linearly while two concluded they follow a logarithmic decay.

Table 2.10. Summary of Modeling Studies

Research Sponsor	Year	Author	Model Type	R^2	Marking Material
NCHRP	1997	Andrady	Logarithmic	Unavailable	Unavailable
MSU	1999	Lee et al	Linear	0.14	Thermo
TRB	1999	Migletz	Linear	Unavailable	Paint & Thermo
Alabama DOT	2002	Abboud & Bowman	Logarithmic	.31 - .58	Paint & thermo
SCDOT	2003	Sarasua et.al.	Linear	.21 - .47	Thermo
TRB: Transportation Research Board, Thermo: thermoplastics					

Throughout the literature review, three key concepts were identified as gaps in pavement marking research. First, no studies have been identified that match asset management concepts with pavement marking performance. Second, there is no proven relationship between the proposed Federal standards and safety of the driver. Third, a gap exists in the research that clearly defines the impact of lateral line location on the overall performance of pavement markings.

3.0 METHODOLOGY FOR PAVEMENT MARKING PERFROMANCE

This section presents the methodology used for analyzing pavement marking performance. First, the data collection process in presented. Next, the data organization is discussed. Finally, the analysis process used is presented.

3.1 Data Collection

Using a contractor, NCDOT personnel collected retroreflectivity data via a mobile device because of the ability to collect a large amount of data in a safe and efficient manner. This study took place from June 1999 through June 2006 and collected nearly 30,000 lane miles of data throughout N.C. The use of a contractor enables NCDOT to use state of the art equipment and experienced personnel without having to purchase equipment or permanently hire qualified personnel. NCDOT believed that eliminating the ability for a technician to choose a specific spot, such as commonly done with a handheld device, ensured the collection remained objective [McDiarmid, 2001].

In June of 1999 NCDOT hosted a field evaluation of various retroreflectivity collection devices. During the evaluation NCDOT personnel determined that the Delta LTL 2000 was the best handheld unit and that the LaserLux was the best mobile collection device for collecting retroreflectivity data on NC's roads [McDiarmid, 2001].

Mobile and handheld retroreflectivity measuring devices collect retroreflectivity data in different ways and therefore require different standards. Currently, there are published

ASTM standards for using a handheld device; there are no published ASTM standards for measuring retroreflectivity using a mobile collection device.

3.1.1 Mobile Collection Device

The data collection for this research used the Laserlux vehicle mounted mobile collection device calibrated with an LTL 2000 handheld device. This section explains the use of the mobile collection device. First, the vehicle and instrument are presented. Next, the data files are discussed. Third, the location referencing system is introduced. Finally, the calibration process is presented.

3.1.1.1 Vehicle and Data Collection Instrument

The data collection device used in this study was a modified Laserlux mobile retroreflectometer mounted on a Chevy Suburban, shown in Figure 3.1. Currently, ASTM standards are not published for measuring retroreflectivity using a mobile collection device but proposed methods are currently under review. In order to provide accurate readings that consider the current published ASTM standards, the contractor used an LTL-2000 handheld retroreflectometer and current ASTM procedures for handheld units in order to calibrate the Laserlux mobile reflectometer prior to each collection run. Each collection run consisted of a single road segment with segments being of varying lengths. Each segment was homogenous with respect to pavement marking material, material color, and road surface.



Figure 3.1. Vehicle Mounted Laserlux

The retroreflectometer collected data using the standard 30-meter geometry by applying a 1/3 scale that measures approximately 10-m ahead of the vehicle. Figure 3.1 shows how a scanning laser measured a 42" wide swath that collected retroreflectivity values at a rate of 100 readings per second at a speed of 60 miles per hour. This equates to approximately 600 data points for a tenth mile road segment, which in turn translates to approximately 1 data reading for every 11 inches. The computer was set to collect values only within a given R_L range. This enabled the computer to recognize very large or very small values and remove them from the recorded data used to calculate the average retroreflectivity value for the road segment. An example of a low value would be from a section of unmarked pavement. The computer would recognize that this value is outside the preset range and discard it. Reflective raised pavement markers would be an example of something that would return an especially high R_L value and again the computer would discard this value as well.

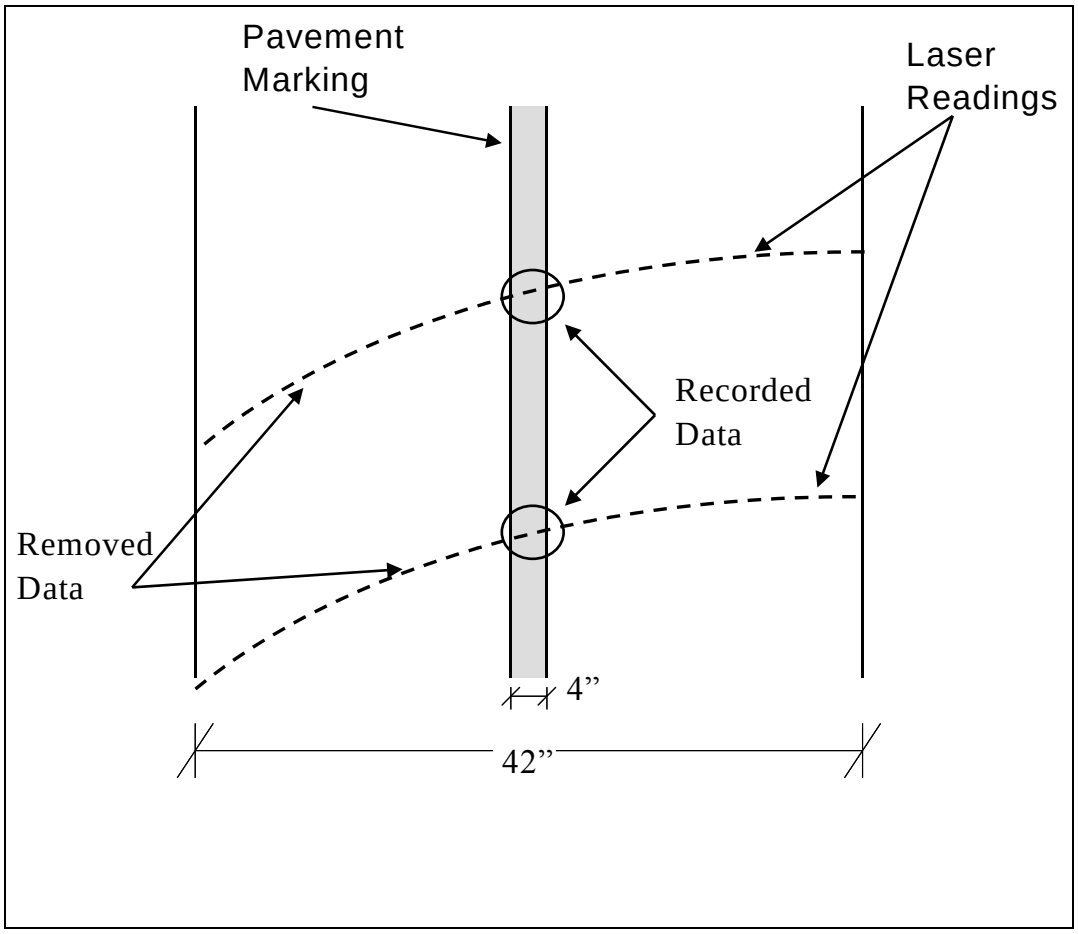


Figure 3.2. Data Collecting Laser

The dashed lines in Figure 3.2 illustrate the collection path of the laser as the vehicle travels down the road segment (upward in the figure) and the laser sweeps across the pavement (shown as left to right in the figure) collecting retroreflectivity values. The dashed lines are arced because the laser swings from one side to the other while the vehicle is traveling at highway speeds. The laser then resets and starts the next collection sweep from the same side proceeding in the same direction for each sweep.

The R_L readings are averaged for every tenth of a mile and recorded into the onboard computer. Additionally, a continuous average was recorded throughout the entire roadway

segment using all the valid data points that were determined to lie on the pavement marking. The R_L value is an average of all the valid scans recorded for a tenth-mile road segment. For a tenth-mile road segment there were approximately 600 data points evaluated but nearly 83 percent of the data are rejected because these values fell outside the preset range. This ensured only R_L values for pavement markings were recorded and not the background R_L for the road surface or for raised reflective pavement markers.

The vehicle was set up so that a single person can operate the vehicle and collect the data simultaneously. The operator was able to record any significant events using an event recorder that adds pre-designated codes to the data fields of the roadway segment. Significant events are those that might affect the meaning or interpretation of the data. Examples of event codes are roadway construction, intersections, or new paint. In addition to inputs from the Laserlux instrument and operator, a vehicle-mounted video camera recorded the entire data collection run for each segment. There is also a GPS device mounted in the vehicle and integrated into the onboard computer, which records the position data in the database at appropriate intervals.

In the case of data collection for double centerlines the laser will record data points from both lines. Since the centerline provides retroreflective feedback to drivers in both directions there is an issue of directionality. In all other cases the installation and measurement of a pavement markings is done with the direction of travel. Preliminary analysis by the researcher has shown that directionality can affect the retroreflective value as much as 50

mcd/m^2/lx. Establishing the most appropriate value to record (high value, low value, or average value) becomes a data collection issue.

3.1.1.2 *Data Collection*

Data files are collected to the onboard computer as flat files. The two basic flat files recorded are shown in Table 3.1 and Table 3.2. The flat files are link to a third that contains all the attribute data about the road segment. This third file contains over 125 different fields of information. The three files are linked via the "Run Id" and "Run Instance Id" fields.

Table 3.1. Segment Run Retroreflectivity Data Collection Flat File

Run Instance ID	Latitude	Longitude	Chainage	Valid Scans	RL Average
062106_09-00 [1 NOR 158 EAST WE (12)]	36.4031	77.4004	0.0	107	237
062106_09-00 [1 NOR 158 EAST WE (12)]	36.4043	77.3994	0.1	101	339
062106_09-00 [1 NOR 158 EAST WE (12)]	36.4058	77.3886	0.2	114	196

There are six fields of information collected in the Segment Run data collection flat file. Each field is defined as:

1. Run Instance Id: is a unique name given to every data collection run.
2. Latitude: is the GPS based latitude coordinate for the start of the road segment.
3. Longitude: is the GPS based longitude coordinate for the start of the road segment.
4. Chainage: is the tenth mile chainage for the road segment. This value always starts at zero for a segment run and increases in tenth mile increments until the segment run ends.
5. Valid Scans: this is the number of valid scans that the computer recorded for the length of the road segment.

6. R_L Average: this is the average retroreflectivity value for the road segment. This value is an average of all the valid scans recorded for a tenth mile. As previously mentioned approximately 600 data points are collected but nearly 83 percent of the data is rejected because it is outside the preset range. This is how the device only keeps R_L values for pavement markings and not the background R_L for the road surface.

Table 3.2. Run Instance Data Collection Flat File

Run Instance ID	Run ID	Collection Date
062106_09-00 [1 NOR 158 EAST WE (12)]	1 NOR 158 EAST WE (12)	6/21/2006
062106_09-15 [1 NOR 158 WEST WE (12)]	1 NOR 158 WEST WE (12)	6/21/2006
062106_10-06 [1 NOR 158 WEST YC]	1 NOR 158 WEST YC	6/21/2006

There are three fields collected in the Run Instance data collection flat file. This file is primarily used to link the segment retroreflectivity data to the road segment attribute data. Each field is defined below:

1. Run Instance ID: is a unique name given to every data collection run.
2. Run ID: is a link key that matches the road segment attribute data maintained in an excel file.
3. Collection Date: this is the date the collection run was performed.

3.1.1.3 *Location Referencing*

The location of each roadway segment is recorded using a linear reference system. The road segment is designated at the start and finish of each run using route numbers and milepost markings. The linear referencing information is recorded in the Microsoft Excel attribute

table. The designated start point corresponds to the Zero chainage value in the Segment Run table (Table 3.1). Descriptive names were given in cases where milepost markers where not available. The onboard computer uses a signal transmitted directly from the vehicle's transmission to avoid error that may come from a factory installed odometer. In 2006, GPS coordinate data were collected for each roadway segment as a segment attribute. Future collection may include using the GPS for location referencing.

3.1.1.4 *Calibration*

Calibration was identified in the literature review as a significant issue that affects the data collection and ultimately the analysis of pavement markings. Vehicle-mounted devices are subject to errors from variations in the suspension of the vehicle itself and in the roadway. The calibration process used throughout the collection process minimizes these precision errors. There were two basic forms of calibration for the Laserlux data collection instrument. First, calibration of the Laserlux was initially performed at the fleet's maintenance facility. Second, calibration was also periodically performed in the field throughout the data collection process.

As part of a six-vehicle fleet, each LaserLux unit is calibrated on a known test bed of pavement markings near the fleet's maintenance facility. The test bed is comprised of pavement markings with a known retroreflectivity value that is calculated using the LTL 2000. Having a known test bed enables the maintenance crews to calibrate each unit to a known standard as well as each other. The calibration process accounts for errors due to changes in vehicle load, tire pressure and ambient light.

An LTL-2000 is used for establishing the retroreflectivity of the test bed. The LTL-2000 is also used in the field during collection operations. During field collection, the technicians measure the retroreflectivity of a test section using an LTL-2000 and then calibrate the mobile unit using that same test section with known retroreflectivity. Daily calibration accounts for local climate changes and minimizes errors that may come from temperature and humidity.

3.2 Data Organization

The data collection process collected information in 125 different fields of information for several thousand records. Each record included various levels of data that ranged from nominal data to ratio data. Having such a large dataset required the researchers to organize and stratify the data and follow a logical reduction in order to fully understand all the information provided. The basic structure for organizing the data for this research project used the South Carolina study as a template [Sarasua et al., 2003].

3.2.1 South Carolina Data Organization

Sarasua et al., [2003] stated that the amount of data collected required a great deal of stratification in order to build a robust model that could accurately reflect the performance characteristics of pavement markings. Possible combinations of variables, based on three major subject areas, were usable. These areas are:

1) Pavement surface – asphalt or concrete;
2) Marking material – thermoplastics, epoxy, or tape, and

3) Marking color – yellow or white.

South Carolina established 12 possible combinations of variables, but only 9 had sufficient data to analyze. After establishing the nine categories, they eliminated five categories based on existing SCDOT policy, which is to limit the use of thermoplastics on concrete and epoxy on asphalt. Tapes were eliminated as well, due to their overall limited use. The end results of the data stratification were four analysis categories, shown in table 3.3.

Table 3.3. South Carolina Analysis Categories

White Thermoplastic on Asphalt	White Epoxy on Concrete
Yellow Thermoplastic on Asphalt	Yellow Epoxy on Concrete

3.2.2 North Carolina Data Organization

Similar to the South Carolina studies, the data for this research project were organized into major categories based on the logical combination of variables that were needed to fully understand the performance characteristics of pavement markings. Unlike South Carolina, this research included lateral location as a new subject area. In addition to the same materials used by South Carolina this research included data on polyurea, hot spray thermoplastics, and three types of paint.

The major variables were divided into four areas as defined below:

1) Pavement Surface – asphalt or concrete.

2) Marking Color – white or yellow.

3) Lateral Location – edge lines or middle lines.

4) Marking Material – Thermoplastics, hot spray thermoplastics plastics, epoxy, polyurea, waffle tape, paint (Dow), paint (Roman-Haas), and paint (standard).

The robust amount of data collected yielded a total of 96 possible categories.

An interview with the NCDOT was conducted on 11 October 06 for the purpose of understanding the basic pavement marking policies used throughout the state [Howard, 2006]. Typical pavement marking applications were highlighted and categories were eliminated based on limited use situations discovered during the interview. The overall organization, stratification, and reduction of the possible categories followed a six-step process. The premise behind the reduction was to logically reduce categories that did not exist, were not widespread or were not used due to policy decisions.

The first step was to establish all of the possible combinations of categories based on the variables. This resulted in 96 total categories. Because there are only four existing combinations of color and location and because the two specialty paints were never used on concrete, there were 56 total possible categories available for study. Table 3.4 shows all the possible categories for asphalt surfaces and Table 3.5 shows all the possible categories for concrete.

Roman-Haas and Dow long life specialty paints, make up less than two percent of the total data collected on retroreflectivity in NC. Because of the limited use it was decided to eliminate these paints from the analysis. However, prior to eliminating the specialty paints

the research team asked the NCDOT about the impact of this decision [Howard, 2006]. NCDOT considered both Roman-Haas and Dow paints as experimental and felt that it was reasonable to eliminate these materials. NCDOT has concluded that these long life specialty paints do not perform well in cold weather applications. As a policy NCDOT is not committed to their use and does not consider these materials in their specifications [Howard, 2006]. Additionally, waffle contrast tape, which makes up less than two percent of the data was also eliminated from the list because of its limited use throughout the state. This decision was also confirmed by NCDOT during the interview. The elimination of the two specialty paints and the waffle tape resulted in a reduction from 56 categories to the 40 categories shown in Table 3.6. The rows that were removed are lightly shaded in Tables 3.4 and 3.5

In step three it was decided to eliminate epoxy from the research project because of the limited amount of data recorded in the collection process. Even though epoxy represents twenty percent of the total data collected, this data is incomplete and was not recorded for the full five years of data collection. In 2004 NCDOT decided to replace epoxy with polyurea as a pavement marking material [Howard, 2006]. While epoxy is still in use in some limited applications few future uses of it are foreseen in NC. For example, epoxy is used on asphalt in heavily snowplowed regions because of its low profile. Epoxy is a viable material but has limited use throughout the state; it is currently being used in only one of NCDOT's divisions and will not be put back into service anywhere else [Howard, 2006]. The limited use justified its elimination from the research project, reducing the total number of categories

from 40 to 32 as shown in Table 3.7. The rows that were removed are lightly shaded in Table 3.6

Step four assessed the remaining categories and compared them to NCDOT policy regarding the combination of possible of variables. As a general rule in NC, thermoplastics are not used on concrete surfaces because the material does not hold up well [Howard, 2006]. Additionally, polyurea has limited use on asphalt [Howard, 2006]. The policy limited the use of pavement marking materials to a specific surface type. This made sense and matched the same polices found throughout the literature review. For example, South Carolina had the same policy and did not use thermoplastics on concrete and epoxy on asphalt [Sarasua et al., 2003]. Step five logically eliminated a total of 12 possible combinations and reduced the overall number of categories from 32 to 20 as table 3.8 shows. The rows that were removed are lightly shaded in Table 3.7

In step five it was decided to separate the possible categories into durable pavement markings and non-durable pavement markings. Basically, this step separated paints from thermoplastics and polyurea. Based on the literature review and interview with NCDOT personnel, it was determined that paints make up the majority of markings on NC roads. Migletz et al., determined that paints make up approximately 60 percent of the markings on roadways in 19 different states [2001]. Paints are mainly used on secondary and local roads. Separating paints was logical since the paints made up a large portion of pavement markings and the management of paints in NC is handled differently than durable markings. There are

many differences but the three major reasons for separating the durables from the non-durables are summarized below.

First is an issue of who designates when a marking is remarked. For non-durable markings each Division determines when to remark a surface based on a visual inspection performed by its Traffic Services Unit. But it is contractors (managed by the division engineers) who typically install durable markings. Second, the funding source for durable markings is different from the funding source of non-durable markings. Non-durable markings are typically funded out of the traffic services maintenance budget. Durable markings are typically installed by contractors and are funded from a specific budget line item designated to the division based on a statewide equity formula. Finally, paints were separated from this portion of the research project because of the known short lifespan. Migletz argued that paints typically last less than a year with an average life span of approximately 10.4 months [2001]. NCDOT confirmed this and indicated that paints rarely last more than a year in NC [Howard, 2006]. It was determined that the funding process for non-durable markings is based on an annual cycle and that there is little chance of changing the policy to fund remarking of paints on a less than yearly cycle.

The management approach at NCDOT to remarking non-durable paints was consistent with information found in the literature review and warranted a different asset management approach to paint. Future research is certainly warranted in evaluating the asset management of non-durable pavement markings in NC. This research would include evaluation of the different paint materials, such as the experimental paints that were eliminated early, as well

as evaluating the funding process and paint cycle for non-durable markings. The stratification and reduction resulted in 12 categories of durable pavement markings (shown in Table 3.9) and 8 categories of non-durable pavement markings (paints) (shown in Table 3.10.)

Table 3.4. NC Analysis Categories; Step 1 for Asphalt

Pavement Type	Material Type	Color	Location
Asphalt	Thermoplastic	White	Edge
Asphalt	Thermoplastic	White	Middle
Asphalt	Thermoplastic	Yellow	Middle
Asphalt	Thermoplastic	Yellow	Edge
Asphalt	Hot Spray Thermo	White	Edge
Asphalt	Hot Spray Thermo	White	Middle
Asphalt	Hot Spray Thermo	Yellow	Middle
Asphalt	Hot Spray Thermo	Yellow	Edge
Asphalt	Epoxy	White	Edge
Asphalt	Epoxy	White	Middle
Asphalt	Epoxy	Yellow	Middle
Asphalt	Epoxy	Yellow	Edge
Asphalt	Polyurea	White	Edge
Asphalt	Polyurea	White	Middle
Asphalt	Polyurea	Yellow	Middle
Asphalt	Polyurea	Yellow	Edge
Asphalt	Waffle Contrast	White	Edge
Asphalt	Waffle Contrast	White	Middle
Asphalt	Waffle Contrast	Yellow	Middle
Asphalt	Waffle Contrast	Yellow	Edge
Asphalt	Paint	White	Edge
Asphalt	Paint	White	Middle
Asphalt	Paint	Yellow	Middle
Asphalt	Paint	Yellow	Edge
Asphalt	Paint- Dow	White	Edge
Asphalt	Paint- Dow	White	Middle
Asphalt	Paint- Dow	Yellow	Middle
Asphalt	Paint- Dow	Yellow	Edge
Asphalt	Paint - Roman Haas	White	Edge
Asphalt	Paint - Roman Haas	White	Middle
Asphalt	Paint - Roman Haas	Yellow	Middle
Asphalt	Paint - Roman Haas	Yellow	Edge

Table 3.5. NC Analysis Categories; Step 1 For Concrete

Pavement Type	Material Type	Color	Location
Concrete	Thermoplastic	White	Edge
Concrete	Thermoplastic	White	Middle
Concrete	Thermoplastic	Yellow	Middle
Concrete	Thermoplastic	Yellow	Edge
Concrete	Hot Spray Thermo	White	Edge
Concrete	Hot Spray Thermo	White	Middle
Concrete	Hot Spray Thermo	Yellow	Middle
Concrete	Hot Spray Thermo	Yellow	Edge
Concrete	Epoxy	White	Edge
Concrete	Epoxy	White	Middle
Concrete	Epoxy	Yellow	Middle
Concrete	Epoxy	Yellow	Edge
Concrete	Polyurea	White	Edge
Concrete	Polyurea	White	Middle
Concrete	Polyurea	Yellow	Middle
Concrete	Polyurea	Yellow	Edge
Concrete	Waffle Contrast	White	Edge
Concrete	Waffle Contrast	White	Middle
Concrete	Waffle Contrast	Yellow	Middle
Concrete	Waffle Contrast	Yellow	Edge
Concrete	Paint	White	Edge
Concrete	Paint	White	Middle
Concrete	Paint	Yellow	Middle
Concrete	Paint	Yellow	Edge

Table 3.6. NC Analysis Categories; Step 2 for Asphalt and Concrete

Pavement Type	Material Type	Color	Location
Asphalt	Thermoplastic	White	Edge
Asphalt	Thermoplastic	White	Middle
Asphalt	Thermoplastic	Yellow	Middle
Asphalt	Thermoplastic	Yellow	Edge
Asphalt	Hot Spray Thermo	White	Edge
Asphalt	Hot Spray Thermo	White	Middle
Asphalt	Hot Spray Thermo	Yellow	Middle
Asphalt	Hot Spray Thermo	Yellow	Edge
Asphalt	Epoxy	White	Edge
Asphalt	Epoxy	White	Middle
Asphalt	Epoxy	Yellow	Middle
Asphalt	Epoxy	Yellow	Edge
Asphalt	Polyurea	White	Edge
Asphalt	Polyurea	White	Middle
Asphalt	Polyurea	Yellow	Middle
Asphalt	Polyurea	Yellow	Edge
Asphalt	Paint	White	Edge
Asphalt	Paint	White	Middle
Asphalt	Paint	Yellow	Middle
Asphalt	Paint	Yellow	Edge
Concrete	Thermoplastic	White	Edge
Concrete	Thermoplastic	White	Middle
Concrete	Thermoplastic	Yellow	Middle
Concrete	Thermoplastic	Yellow	Edge
Concrete	Hot Spray Thermo	White	Edge
Concrete	Hot Spray Thermo	White	Middle
Concrete	Hot Spray Thermo	Yellow	Middle
Concrete	Hot Spray Thermo	Yellow	Edge
Concrete	Epoxy	White	Edge
Concrete	Epoxy	White	Middle
Concrete	Epoxy	Yellow	Middle
Concrete	Epoxy	Yellow	Edge
Concrete	Polyurea	White	Edge
Concrete	Polyurea	White	Middle
Concrete	Polyurea	Yellow	Middle
Concrete	Polyurea	Yellow	Edge
Concrete	Paint	White	Edge
Concrete	Paint	White	Middle
Concrete	Paint	Yellow	Middle
Concrete	Paint	Yellow	Edge

Table 3.7. NC Analysis Categories; Step 3 for Asphalt and Concrete

Pavement Type	Material Type	Color	Location
Asphalt	Thermoplastic	White	Edge
Asphalt	Thermoplastic	White	Middle
Asphalt	Thermoplastic	Yellow	Middle
Asphalt	Thermoplastic	Yellow	Edge
Asphalt	Hot Spray Thermo	White	Edge
Asphalt	Hot Spray Thermo	White	Middle
Asphalt	Hot Spray Thermo	Yellow	Middle
Asphalt	Hot Spray Thermo	Yellow	Edge
Asphalt	Polyurea	White	Edge
Asphalt	Polyurea	White	Middle
Asphalt	Polyurea	Yellow	Middle
Asphalt	Polyurea	Yellow	Edge
Asphalt	Paint	White	Edge
Asphalt	Paint	White	Middle
Asphalt	Paint	Yellow	Middle
Asphalt	Paint	Yellow	Edge
Concrete	Thermoplastic	White	Edge
Concrete	Thermoplastic	White	Middle
Concrete	Thermoplastic	Yellow	Middle
Concrete	Thermoplastic	Yellow	Edge
Concrete	Hot Spray Thermo	White	Edge
Concrete	Hot Spray Thermo	White	Middle
Concrete	Hot Spray Thermo	Yellow	Middle
Concrete	Hot Spray Thermo	Yellow	Edge
Concrete	Polyurea	White	Edge
Concrete	Polyurea	White	Middle
Concrete	Polyurea	Yellow	Middle
Concrete	Polyurea	Yellow	Edge
Concrete	Paint	White	Edge
Concrete	Paint	White	Middle
Concrete	Paint	Yellow	Middle
Concrete	Paint	Yellow	Edge

Table 3.8. NC Analysis Categories; Step 4 for Asphalt and Concrete

Pavement Type	Material Type	Color	Location
Asphalt	Thermoplastic	White	Edge
Asphalt	Thermoplastic	White	Middle
Asphalt	Thermoplastic	Yellow	Middle
Asphalt	Thermoplastic	Yellow	Edge
Asphalt	Hot Spray Thermo	White	Edge
Asphalt	Hot Spray Thermo	White	Middle
Asphalt	Hot Spray Thermo	Yellow	Middle
Asphalt	Hot Spray Thermo	Yellow	Edge
Asphalt	Paint	White	Edge
Asphalt	Paint	White	Middle
Asphalt	Paint	Yellow	Middle
Asphalt	Paint	Yellow	Edge
Concrete	Polyurea	White	Edge
Concrete	Polyurea	White	Middle
Concrete	Polyurea	Yellow	Middle
Concrete	Polyurea	Yellow	Edge
-	Paint	White	Edge
Concrete	Paint	White	Middle
Concrete	Paint	Yellow	Middle
Concrete	Paint	Yellow	Edge

Table 3.9. NC Durable Categories Included in Research

Pavement Type	Material Type	Color	Location
Asphalt	Thermoplastic	White	Edge
Asphalt	Thermoplastic	White	Middle
Asphalt	Thermoplastic	Yellow	Middle
Asphalt	Thermoplastic	Yellow	Edge
Asphalt	Hot Spray Thermo	White	Edge
Asphalt	Hot Spray Thermo	White	Middle
Asphalt	Hot Spray Thermo	Yellow	Middle
Asphalt	Hot Spray Thermo	Yellow	Edge
Concrete	Polyurea	White	Edge
Concrete	Polyurea	White	Middle
Concrete	Polyurea	Yellow	Middle
Concrete	Polyurea	Yellow	Edge

Table 3.10. NC Categories, Non-durable for Future Research

Pavement Type	Material Type	Color	Location
Asphalt	Paint	White	Edge
Asphalt	Paint	White	Middle
Asphalt	Paint	Yellow	Middle
Asphalt	Paint	Yellow	Edge
Concrete	Paint	White	Edge
Concrete	Paint	White	Middle
Concrete	Paint	Yellow	Middle
Concrete	Paint	Yellow	Edge

Table 3.11. Summary of Available Data

Pavement Type	Material Type	Color	Location	Data Counts (Number of Road Segments)						
				0 months	6 months	12 months	24 months	36 months	48 months	60 months
Asphalt	Thermo	White	Edge	111	111	105	75	46	34	28
Asphalt	Thermo	White	Middle	90	90	82	63	34	24	8
Asphalt	Thermo	Yellow	Middle	36	36	36	13	11	6	6
Asphalt	Thermo	Yellow	Edge	63	63	57	51	31	24	14
Asphalt	Hot Spray Thermo	White	Edge	22	22	22	20	8	2	-
Asphalt	Hot Spray Thermo	White	Middle	34	34	34	32	8	2	-
Asphalt	Hot Spray Thermo	Yellow	Middle	3	3	3	1	-	-	-
Asphalt	Hot Spray Thermo	Yellow	Edge	16	16	16	14	6	2	-
Concrete	Polyurea	White	Edge	28	22	20	12	4	2	-
Concrete	Polyurea	White	Middle	30	30	26	20	6	2	-
Concrete	Polyurea	Yellow	Middle	-	-	-	-	-	-	-
Concrete	Polyurea	Yellow	Edge	28	22	20	12	4	2	-

Table 3.12. Summary of Available Data Non-Durables

Pavement Type	Material Type	Color	Location	Data Counts (Number of Road Segments)						
				0 months	6 months	12 months	24 months	36 months	48 months	60 months
Asphalt	Paint	White	Edge	16	16	16	-	-	-	-
Asphalt	Paint	Yellow	Middle	7	7	7	-	-	-	-
Concrete	Paint	White	Edge	4	4	4	-	-	-	-
Concrete	Paint	White	Middle	6	6	6	-	-	-	-
Concrete	Paint	Yellow	Edge	4	4	4	-	-	-	-

Table 3.11 shows a summary of the available data for each of the 12 durable pavement-marking categories that were to be analyzed. Table 3.12 shows the entire available non-durable pavement marking categories.

Significant limitations in the amount of time based existed for all polyurea and hot spray thermoplastics. For the polyurea on concrete categories only 6 road segments were collected for a full 4 years and only 14 for a full 3 years. There were no cases of polyurea on concrete where the data were collected for more than four years. With a life expectancy of eight to ten years this severely limits the analysis that can be performed on the polyurea on concrete categories. The hot spray thermoplastics on asphalt were also limited in the amount of time based data available. Table 3.11 shows that there are only 6 road segments with a full 4 years of data and 22 road segments for a full 3 years.

Based on the amount of available data the researchers focused the analysis of durable pavement markings on thermoplastics on asphalt. For all thermoplastics on asphalt categories there were over 300 road segments with retroreflectivity data for the initial year. However, these road segments were paired down to only 56 road segments by year five. Although limited, 56 data points are sufficient for meaningful statistical inferences about the performance characteristics of pavement marking retroreflectivity.

3.3 Data Analysis

Based on the existing availability of data, the study focused on thermoplastics on asphalt. With continued data collection, future analysis of the polyurea on concrete and hot spray thermoplastics categories is possible.

Data analysis was conducted in three stages. The first stage validated the variables that impact pavement marking performance. The second stage identified pavement marking retroreflectivity levels of service ranges. The final stage analyzed the data using regression analysis. An attempt was made to analyze the data using a Markov process so that the researcher could use empirical data to forecast the probabilities of condition states of the pavement marking retroreflectivity. For reasons explained below, this process was abandoned and replaced by regression analysis.

3.3.1 Validation of Variables

Time, surface type, material, AADT, and color were identified in the literature review as independent variables significantly impacting the performance of pavement marking retroreflectivity [Migletz and Graham, 2002]. The literature also identified lateral location as a possible impacting variable, but it has not been included as an independent variable in prediction equations. For example, in South Carolina degradation of pavement markings at different lateral locations was assumed to be a function of tire wear and the researchers determined that the variable time already included the impact of tire wear [Sarasua et al., 2003].

Lateral location was identified in the literature review as a gap in the research. To date no studies have been identified that accurately and safely captured lateral location information during retroreflectivity data collection. The data used in this study did include this information.

An average value analysis established the initial findings using both weighted and un-weighted averages. Second, an analysis of variance (ANOVA) was used to confirm these findings with a more sophisticated statistical test. The ANOVA test method allowed use of the data from roads that had not yet been observed for the full five-year period, thus giving us a larger sample to analyze.

3.3.1.1 Average Value Analysis

To conduct an initial analysis, the data set on thermoplastics was reduced to only those points that had a full five years of data available. This dramatically reduced the size of the data set, but still left enough road segments to conduct the analysis. The number of segments for which data were usable was as follows:

- Yellow center lines versus yellow edge lines (28 data points on 8 road segments)
- White skip lines versus white edge lines (14 data points on 6 road segments)

Even with the reduced data set, this still represented 419 miles of roadway with white markings and 210 miles of roadway with yellow marking. For each measurement time period (time = 0 to 5 years), the average R_L value was computed as:

$$RL_{ave} = \sum (RL_i) \ / \ N_t \qquad (3.1)$$

where

RL_{ave} = average retroreflectivity for each time period in mcd/m^2/lx

RL_i = measured retroreflectivity of road segment *i* in mcd/m^2/lx

N_t = number of road segments measured for each category & time period.

A weighted average analysis used weighted data based on the length of the road segment measured. Because the road segments did not have a uniform length, it is possible that the variation in segment length could skew the average value analysis. Road segments varied in length from 4 to 32 miles, with an average value of approximately 11 miles. The weighted analysis determined if segment length significantly affected the outcome of the analysis. For each measurement time period (time = 0 to 5 years) the average weighted R_L value was computed using an weighted average value method such that:

$$RL_{ave} = \sum (RL_i * L_i) \ / \ \sum L_i \qquad (3.2)$$

where

RL_{ave} = average retroreflectivity for each time period in mcd/m^2/lx

RL_i = measured retroreflectivity of road segment *i* in mcd/m^2/lx

L_i = length of road segment *i* in miles

$\sum L_i$ = sum of all road segment lengths in miles

3.3.1.2 Analysis of Variance

The average value analysis described above determined only that there may be a difference in the rates of retroreflectivity degradation based on lateral line location. An ANOVA can accurately establish whether that difference is statistically significant. ANOVA is a statistical procedure for determining whether the difference between two sample means is statistically significant.

ANOVA analysis was valuable because it allowed the use of all available data sets, not just those that had been under observation for five years. Due to the ongoing nature of the data collection activity, many of the road segments had been under observation for less than a full five years. Average value analysis as described above was only valid for comparing sets that had all been under observation for the entire time. ANOVA compares the data at a certain time interval to all the other data at the same time interval, allowing the use of road segments that had been under observation for less than a full five years to be studied. This meant that the sample size was different at each time interval and decreased as time went on.

The null hypothesis (H_0) stated that the difference between the centerline mean and the edge line mean was statistically insignificant. The alternative hypothesis (H_a) stated that the difference in the means between centerline and edge line was statistically significant. A probability of F-value less than $\alpha = 0.05$ indicates that the null hypothesis should be rejected in favor of the alternative hypothesis and that the difference between the two means is statistically significant at that confidence level.

Using all the available data on thermoplastic markings, an ANOVA was conducted at each time period for all data available at that time period. All the initial measurements (that is, time = 0) of yellow centerlines were compared to all the initial measurements of all yellow edge lines. Then the comparison was run at each successive time period using all available data in each time period. Because of the nature of the available data, the number of points analyzed was smaller in each successive time period. For both yellow and white markings, only about 25 percent of the total road segments had a full five years of data available. However, there were still enough road segments measured for a full five years that the results are considered to be sufficiently representative.

The ANOVA used data from approximately 2,414 miles of NC roads out of a total of approximately 78,000 miles of primary and secondary roads. Thermoplastics markings are used on 22.7 percent of these roads, meaning that there are approximately 19,500 miles of road in NC marked with thermoplastics. Thus the sample size of 2,414 miles of road comprised approximately 12 percent of roads marked with thermoplastics.

As previously mentioned, the road segments used for the study were not uniform in length, varying from 4 to 32 miles with an average value of 11 miles. To account for this variation, the ANOVA was conducted a second time with values weighted according to the length of the measured road segment. This analysis was initiated to determine if there was any bias in the first ANOVA due to excessively long or short road segments.

3.3.2 Modeling

Initially an attempt was made to analyze pavement marking performance characteristics using a Markov chain approach to determine the degradation rate for pavement markings based on a current condition state. Originally the Markov chain approach was chosen as the primary data analysis method for two reasons. First, analyzing the data based on discrete intervals allows for the definition of Level of Service (LOS) classifications based on qualitative asset management concepts using empirical data. Second, Markov chains enable the analysis of a dynamic system based on the assumption that the current state or state immediately before the current state are the greatest influence on the probability of transitioning to the next state [Ang and Tang, 1984].

After the initial analysis began the researcher found that the data did not support using a Markov analysis because the data were not collected for a full life cycle of the material. In essence this methodology would only allow the researchers to predict the probable time it would take to reach half of the materials life-cycle and not full degradation of the material

The researcher needed to adjust the methodology to predict pavement marking retroreflectivity performance without having data on the complete lifecycle of durable pavement markings. General linear modeling using the method of least squares was conducted in order to develop a model that would describe the performance characteristics of pavement marking materials without having a complete set of empirical data for the full life cycle of thermoplastics on asphalt.

Using Jump software, the statistical method of least squares was used to fit a general linear model to the data. Jump is a SAS based statistical software package with a graphical user interface. Both continuous and categorical data were considered in fitting the model to the data. An estimate equation was developed and each suspect variable was checked to determine and evaluate its impact on the model.

The analysis for thermoplastics on asphalt included 56 road segments all of which had a full five years of pavement marking data that were collected at the following monthly increments: 0, 6, 12, 24, 36, 48, and 60 months. The dataset included pavement marking retroreflectivity values, time, initial retroreflectivity, AADT, region, line width, line thickness and snowplow activity.

The method of least squares is a statistical approach that is used to find the best-fit curve to a set of empirical data by minimizing the sum of the square residuals. A measure of how well the curve was fitted to the data is known as the coefficient of determination (R^2), which estimates the variation in the response around the mean that can be attributed to variables in the model and not random error. R^2 is also the square of the correlation between the empirical data and the predicted responses of the model.

$$R^2 = \text{Sum of Squares (Model)/Sum of Square (Total)} \qquad (3.3)$$

Also considered is the use of an adjusted R^2 that is an adjustment based on the number of variables used in the model. The adjusted R^2 uses degrees of freedom in the computation and is the ratio of the mean squares verses the sum of squares used in the traditional R^2

calculation. Evaluation of the adjusted R^2 was done to compare different candidate models with a varied number of parameters.

$$\text{Adjusted } R^2 = 1-(\text{Mean Square Error/Mean Square Total}) \qquad (3.4)$$

A stepwise selection process was used in developing the model. Each candidate variable was inserted into the model one by one and checked. Only those variables that reached a level of significance greater than 95 percent were left in the model. In this case the significance level is set so that $\alpha = 0.05$. Once the variables were defined the candidate model was developed and evaluated based on R^2 and adjusted R^2.

A linear regression model makes two major assumptions. First, that the responses are independent and normally distributed [Rao, 1998]. The Q-Q plot is a method used to check that this assumption is true. The Q-Q plot is a graph of the residual plotted against a set of percentiles of the standard normal distribution. Under the assumption of normality, the Q-Q plot should approximate a straight line. The second assumption is that the population variances are equal. A plot of the residuals against the predicted values is used to check this assumption [Rao, 1998]. The residual plot of the predicted values is a graphical representation of the offset of each value. The desired outcome is an even distribution of residuals around the mean value. A consistent pattern that shows equal offsets is expected if the variances are equal. An equal variance assumption is usually violated because the variances typically increase or decrease with the expected response showing a cone shape [Rao, 1998].

4.0 METHODOLOGY FOR ASSET MANAGEMENT

This section presents the methodical approach developed to create an asset management system for pavement markings. This approach can be used to develop an asset management system for any transportation asset and in some cases for any generic long line infrastructure system. The approach is broken into four sections, which are:

1. Develop goals and policies
2. Assess, develop, and maintain an asset inventory
3. Database management and modeling
4. Implementation strategy development

4.1 Goals and Policy Development

The mission statement for the WZTCU is, "To serve the public by providing the safest, most efficient and economical traffic control, pavement marking, and roadway delineation plan for all utility, maintenance, and Transportation Improvement Projects."

Defining the goals and policies for pavement markings was determined in terms of its key parameters. NCDOT uses a standard format that includes six parameters in defining an asset [Love, 2007]. These are given below and each was determined for pavement markings.

1. Asset: This is a definition of the asset.
2. Activity: This is a definition of the major management actions and decisions that are needed to effectively manage this asset.

3. Condition indicator: This is a measurable system to identify the condition of the asset.
4. Performance measure: is a specific characteristic of the asset that can be quantifiably measured and related to the performance of the asset.
5. Performance target: is a percent compliance with the standard and is directly related to management's goals for this asset.
6. NC minimum standard: This is the standards for which the asset is measured against to determine compliance with state and federal regulations.

Consistent with the mission statement the goal for NCDOT's pavement marking asset has two key aspects: (1) NCDOT wants to achieve the highest level of compliance with the federal standards, and (2) NCDOT wants to maximize the cost effectiveness of pavement markings. NCDOT wants to maximize the service life of pavement markings while maintaining the highest level of compliance. This requires balanced economical tradeoffs that relates the service life to the level of compliance achieved.

Following a performance based asset management approach a set of pavement marking retroreflectivity standards were developed. An acceptable minimum threshold for pavement marking retroreflectivity was established for NCDOT and is linked to LOS classifications. The standards are based on proposed Federal standards; NCDOT is currently in compliance since the standards have not been published. NCDOT is prepared to meet the Federal standards once they are published and become statutory by adopting and implementing state standards conforming to the proposed Federal standards.

An evaluation of the budget process is necessary to blend sound business practices with engineering principles. Many aspects of the budget process are governed by statute and are difficult to change. However, this research sought out opportunities to adjust the current budget process and implement performance-based budgeting for pavement marking projects. The evaluation of the budget process was accomplished primarily through interviews with key NCDOT personnel.

A brief summary of cost data was presented in figure 2.8 of the literature review and showed the average cost of a given material per linear foot. The cost for pavement marking identified are simple direct cost and do not reflect the various indirect cost associated with pavement markings. For example, the direct cost of pavement markings includes materials and labor whereas the indirect cost includes roadway closures, inspections, and accidents.

In this research the evaluation of the budget process included an assessment of current direct cost for thermoplastics and paints. Assessment of cost data can be combined with service life evaluation to enable managers to make holistic decisions about pavement marking replacement strategies. Understanding that indirect cost can be significant this research did not explore the impact of indirect cost on pavement marking performance.

This principle was achieved by:

- Determining the regulations governing pavement-marking retroreflectivity.

- Defining the six parameter of this asset which includes the performance target.
- Establishing a minimum threshold for pavement marking retroreflectivity that meets FHWA and NCDOT requirements.
- Evaluating the current pavement marking budgeting process through interviews with key NCDOT personnel.

4.2 Assess, Develop, and Maintain an Asset Management Inventory

Collecting and maintaining inventory data for a pavement management systems, is both time consuming and costly. A key to data collection is to avoid collecting redundant data, which is important to minimize cost and to avoid error in the maintenance of the model. It is also critical to collect the correct data, i.e. the data needed by the NCDOT.

This principle was achieved by accomplishing the following tasks:

- Identifying all pavement-marking attributes and define each attribute's characteristics
- Identifying pavement marking attributes to maintain.
    - Determine the critical attributes for pavement markings.
    - Determine what pavement-marking attributes need to be maintained.
    - Determine where and by whom the attribute should be maintained.
- Developing a pavement marking data collection plan for NCDOT.
    - Summarize retroreflectivity data collection standards
    - Evaluate the current retroreflectory technology

- Evaluate the current data collection method
- Determines what data has already been collected
- Evaluate the quality of the data already collected
- Determine what data should be collected in the future

- Evaluating the existing NCDOT pavement marking inspection process used for installation and develop inspection guidelines for pavement markings restriping.

4.3 Pavement Marking Database Management and Modeling

Following Longley's process [Longley et al., 2005], this research project developed a conceptual data management model for the pavement marking system. The conceptual model is followed by a logical data management model and then finally a physical model. The models included the architecture of the required databases, geographic data, and road inventory data needed to successfully manage pavement markings.

Included in the development of this database management system is an ARCGIS based example that highlights the potential for the system should a DOT decide to implement it. The significant contribution to the ARCGIS product is the incorporation of an algorithm that used the performance models developed in phase one of the research. The goal of the algorithm is to populate the inventory and predict the future condition state of pavement markings.

The NCDOT pavement marking retroreflectivity data were collected using a localized LRS that does not conform to either the state or county milepost system. Furthermore, the NCDOT does not prescribe that pavement marking retroreflectivity data be collected using a particular location referencing method.

This study evaluated the current LRSs used by NCDOT and recommends a common LRS for pavement markings. Furthermore, the research explored the integration of global positioning system (GPS) technology as another means of locating pavement marking retroreflectivity data in a GIS based architecture. As appropriate this research made recommendations for improved future data collection.

This principle was achieved by accomplishing the following tasks:

- Creating the architecture for a conceptual model which is a human-oriented, often partially structured, model of selected objects and processes that are thought relevant to a particular problem domain [Longley et al., 2005].
    - Determining the basic structure of the pavement marking data management system.
    - Identifying the major components and their interaction.
    - Determining the information needs.
- Creating the architecture for a logical model which is an implementation-oriented representation of reality that is often expressed in the form of diagrams and list [Longley et al., 2005].

- Enhancing the conceptual model so that specific components are defined and represent the reality of NCDOT's data management
- Structure the information flow between components
- Determining the database software and the relationships within the databases

- Creating the architecture for a physical model, this portrays the actual implementation in a GIS and often comprises tables stored as files or databases [Longley et al., 2005].
  - Evaluating the current LRS and recommending the appropriate LRS
  - Developing an algorithm that will function in a GIS and incorporate the predictive models developed in phase one
  - Identifying the specific inputs, processes, and outputs that will enable to assessment of the performance target identified in the goals development step.
  - Create a prototype of the physical model in ARCGIS that uses sample databases and the developed algorithm.

4.4 Implementation Strategy

The final step of this asset management research developed an overall implementation strategy for pavement marking management. This phase summarized all the lessons learned in the first three phases and developed specific guidelines and action steps to implement NCDOT's pavement marking management.

5.0 RESULTS FOR PAVEMENT MARKING PERFORMANCE

This chapter presents the analysis and results used to establish pavement marking degradation models. First, the chapter presents the initial finding of the Markov Chain approach and summarizes why this was abandoned. Second, the chapter presents the results of determining the variables that affect pavement marking degradation. Third the models developed for both thermoplastics and paint pavement markings are presented. Finally, a short discussion of model validation is presented.

5.1 Markov Analysis

It was presumed that the use of a Markov chain analysis would have resulted in the ability to predict the future condition of NC pavement marking retroreflectivity and show the probable condition states for various replacement schemes based on the current condition.

The first task in attempting to analyze the data was the development of transition probability matrices for each category of variables. The matrices were developed based on empirical data and used four LOS classifications. Each row in the transition matrix shows the probability of moving from the state of the given row to the other possible states. Therefore the sum of the probabilities of a row must equal one.

To develop the transition matrices the data were organized into discrete ranges and then the frequency of each range was recorded for every combination of variables (category). The data were then evaluated to record the number of times that range transitions from one state to the next state. This was used to determine the transition matrix for a given set of variables.

Two key assumptions are made in developing the transition matrix. The first assumption is that the LOS determination remained constant for the initial period. Even though the retroreflectivity value may increases during the break-in period, the LOS will already be at the highest level possible and will not transition to a higher state. The second assumption was that the pavement markings remained in the current state or they transitioned to a lower state but never increased to a higher state. This puts directionality into the transition matrix.

Transition matrices, shown in Figure 5.1, were built for 11 of the 12 categories. *Polyurea on concrete yellow centerline* did not have any data. Significant limitations presented themselves because of the incomplete empirical data available. In all of the *polyurea on concrete* and *hot spray on asphalt* cases the transition matrices yielded an absorbing state at LOS yellow that would indicate, for these materials, the service life was infinite since the materials will never degrade beyond LOS Yellow.

Recall that LOS Yellow indicates the material is nearing the end of service life but still has one to two years of life left. An absorbing state at LOS Yellow was clearly not logical and is the results of the limited availability of empirical data. In this case an absorbing state is defined as a state that cannot reach any other states in the system except itself and has a transitional probability equal to 1.0.

The transition states for the matrices are defined by LOS increment and in Figure 5.1 these are summarized using the letters A through D. The specific definitions are:

1. A is defined as LOS Blue
2. B is defined as LOS Green
3. C is defined as LOS Yellow
4. D is defined as LOS Red

Concrete Poly White Skip Line

	A	B	C	D	
A	0.742	0.226	0.032	0.000	1
B		0.700	0.300	0.000	1
C			1.000	0.000	1
D				0.000	0

Asphalt Thermo White Skip

	A	B	C	D	
A	0.385	0.523	0.092	0.000	1
B		0.650	0.350	0.000	1
C			0.945	0.055	1
D				1.000	1

Asphalt Hot Spray Thermo White Edge

	A	B	C	D	
A	0.176	0.765	0.059	0.000	1
B		0.684	0.316	0.000	1
C			1.000	0.000	1
D				0.000	0

Concrete Poly White Edge Line

	A	B	C	D	
A	0.878	0.122	0.000	0.000	1
B		0.800	0.200	0.000	1
C			1.000	0.000	1
D				0.000	0

Asphalt Thermo White Edge

	A	B	C	D	
A	0.584	0.350	0.066	0.000	1
B		0.754	0.246	0.000	1
C			1.000	0.000	1
D				1.000	1

Asphalt Hot Spray Thermo White Skip

	A	B	C	D	
A	0.000	1.000	0.000	0.000	1
B		0.711	0.289	0.000	1
C			1.000	0.000	1
D				0.000	0

Concrete Poly Yellow Edge Line

	A	B	C	D	
A	0.964	0.036	0.000	0.000	1
B		1.000	0.000	0.000	1
C			0.000	0.000	0
D				0.000	0

Asphalt Thermo Yellow Edge

	A	B	C	D	
A	0.569	0.412	0.020	0.000	1
B		0.829	0.171	0.000	1
C			1.000	0.000	1
D				1.000	1

Asphalt Hot Spray Thermo Yellow Ed

	A	B	C	D	
A	0.000	1.000	0.000	0.000	1
B		0.860	0.140	0.000	1
C			1.000	0.000	1
D				0.000	0

Asphalt Thermo Yellow Center

	A	B	C	D	
A	0.553	0.395	0.053	0.000	1
B		0.885	0.115	0.000	1
C			0.889	0.111	1
D				1.000	1

Asphalt Hot Spray Yellow Cntr

	A	B	C	D	
A	0.000	1.000	0.000	0.000	1
B		0.625	0.375	0.000	1
C			0.000	0.000	0
D				0.000	0

Poly: Polyurea
Thermo: Thermoplastic

Figure 5.1. Transition Matrices

In the case of the thermoplastics, the matrices were more fully developed but still yielded illogical results. Two of the four categories yielded absorbing states at LOS Yellow. The other two categories had transition probabilities near 90 percent for LOS Yellow, which makes them, suspect as well.

To empirically establish accurate transition matrices for use in a Markov chain analysis a full lifecycle of data needed to be collected. According to Migletz et al, [2001] durable pavement markings are expected to have a functional service life of three to five years. The NC pavement marking retroreflectivity dataset was for a full five years of data so it was assumed the database would support the Markov approach. However, as the researcher started the analysis it became evident that durable pavement markings in NC have a much greater service life than Migletz et al. forecasted. This is good news for NC but limited the ability to use the Markov process for data analysis. A systemic limitation in the Markov approach was the lack of empirical pavement marking retroreflectivity data that has reached the end of service life as defined by LOS Red.

Based on the limited amount of empirical data that was collected at the end of the pavement marking service life and with the approval of the researcher's doctoral committee, the Markov approach was abandoned because. It was clear that the data did not sufficiently support using this methodology. However, the use of a Markov process to analyze pavement-marking retroreflectivity is still assumed to be valid but will require additional data collection. Data needs to be collected for a full life cycle of the material to accurately establish a transition matrix that fully accounts for LOS Red.

5.2 Variables

Using a stepwise selection method a statistical effects test was done for each model using the F-statistic to check the effect of the variable on the model. A forward stepwise selection was done where the model starts with one independent variable and the effect was checked using

the F-statistic. During each step forward a new independent variable was added and checked. If the variable passed the effects test it was retained in the model. If it failed the variable was removed from the model. This process was repeated until all the variables had been checked.

The F Ratio is the *F*-statistic used to test that the effect is zero. The definition of the F ratio is the ratio of the mean square for the effect divided by the mean square for error. The mean square for the effect is the sum of squares for the effect divided by its degrees of freedom. The Probability >F is defined as the probability of the level of significance for the *F*-ratio. A level of significance of $\alpha = 0.05$ was used and is the probability that if the null hypothesis were true, a larger *F*-statistic would only occur due to random error five percent of the time.

Retroreflectivity (R_L) was chosen as the dependent variable. The results of the effects test for the white edge model are summarized in Table 5.1 which shows that time, initial R_L value, AADT each presented as an independent variable that affected the model. Lateral location and color are each categorical data and were used to establish the different categories of models. Snowplow, region, line width, and line thickness were each checked and determined to have no statistically significant effect on the model.

Table 5.1. Effects Test for White Edge Using the F-Statistic

Variables	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F
Time	1	535700	189	< 0.0001
Initial RL	1	129090	46	<0.0001
AADT	1	73461	26	<0.0001

For the effects test the null hypothesis (H_0) stated that the impact of the variable on the degradation of pavement marking retroreflectivity was insignificant. The alternative

hypothesis (H_a) stated that the impact of the variable on the performance of pavement marking retroreflectivity was statistically significant. A probability of F-value less than alpha = 0.05 indicates that H_0 should be rejected in favor of H_a and the variable should be kept in the model because there is statistical evidence that the variable impacts the performance of pavement marking retroreflectivity.

All the models were checked the same way and each were found to have similar results except for the yellow middle model. In that case the result of the effects test suggest removing AADT as an independent variable and is the reason the yellow middle model is different as presented below.

5.2.1 Explanation of Independent Variables

1. Time – is a continuous parameter and is the most significant variable affecting degradation of pavement marking retroreflectivity. All pavement-marking studies reviewed included time as the most significant variable affecting retroreflectivity degradation. Time is measured in months.
2. Initial R_L value – is a continuous variable measured in mcd/m^2/lx. This variable is the initial value of retroreflectance and is measured within the first 30 days of application of the marking.
3. AADT – Annual Average Daily Traffic is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day. The AADT values used in this study are from the year 2006. Sarasua et al, argued that AADT was not significant and was accounted for as a function of time. However, in our model this variable was

included as a suspect variable because of the previous report by Abboud and Bowman [2002], which indicated that AADT had a significant impact on pavement marking degradation apart from time.

4. Lateral location – is a categorical parameter that is defined by the transverse position of the pavement marking on the roadway. This variable was included because of the intuitive perception of different vehicle wear attributed to the location of the line on the roadway. This parameter has two positions: edge lines or middle lines. For the purpose of this study centerlines and skip lines are both defined as middle lines.

5. Color – is a categorical parameter that defines the color of the pavement marking material. In this study color is either white or yellow.

6. Snow Plow – is a categorical parameter and is defined by the presence or absence of snowplowing on the road segment.

7. Region – is a categorical parameter that represents one of the three major regions in NC. Theses regions are defined as coastal, piedmont, and mountain. The diversity of the climate and size of the population of NC warrant the exploration of this parameter in pavement marking degradation studies.

8. Width – is an ordinal parameter and defines the width of the pavement marking. Two widths were considered in this study: four-inch and six-inch as these are the most commonly encountered.

9. Thickness – is an ordinal parameter and defines the thickness of the pavement marking material. Two common thicknesses were considered in the study: 90 mils and 120 mils.

The AADT and initial R_L variables warrant a short discussion. First, AADT is typically forecasted in transportation studies. The AADT values used in this model were 2006 values and did not vary for each individual year that the R_L value was collected. Future studies would enhance the model by tracking the actual AADT per year along with the R_L value recorded. Even though this is a limitation in the current model and contributes to some unknown error it was assumed that this change would have only a small effect on the overall model since the coefficient was small. Additionally, the AADT values are not updated every year for every road type and thus are not available. Still, when using the model to predict future R_L values a forecasted AADT value could be used to further refine the quality of the predicted life cycle of the pavement marking. Also note that since AADT is a one-time value there is no danger of intercorrelation.

The initial R_L variable can be handled two ways in the model. NCDOT required that the initial R_L values meet a minimum specification value. Forecasters can use the model along with and the initial specification values for R_L, in predicting the pavement marking lifecycle. This would be useful in a large majority of the cases where the initial values are not known. However, use of the actual initial R_L values would give forecasters a better prediction of the lifecycle and is highly recommended in future studies.

5.2.1.1 Lateral Location Variable

The impacts of lateral location on pavement marking degradation have not been identified in previous studies and warranted an exploration of this variable. This section presents the results of the data analysis on lateral location of thermoplastics on asphalt. The average

value results are shown first followed by the ANOVA results. Finally, these results are compared to those reported in previous literature.

Throughout this section the lateral location, defined as middle and edge above were further subdivided. Middle lines were divided into centerlines and skip lines. Edge line remains as a single variable.

5.2.1.1.1 Average Value Analysis (Un-weighted)

The un-weighted average value analysis showed that there was a difference in the degradation rates of center and edge lines for both white and yellow markings. Figure 5.2 and Table 5.2 show the results from the analysis of yellow thermoplastics. As expected both center line and edge line show an initial drop in retroreflectivity in the first two years and then show a much shallower, or even a flat curve beyond that. The two curves do not start at the exact same initial value due to the fact that they represent two averages of all centerlines and edges lines, and they are not matched pairs on the exact same group of road segments. The two curves are roughly parallel but the somewhat faster degradation in the centerline curve is visible. The third data series and trend line at the bottom of the chart shows the delta (difference) between the two average measurements at each time period. This trend line has a positive slope, indicating that the delta is increasing over time and therefore the two groups are degrading at different rates.

The results from the comparison of white edge lines to white skip lines are shown in Figure 5.3 and Table 5.3. Similar to the yellow thermoplastics, the two curves show a difference in

the rate of degradation, but this difference is more pronounced. In this case, the average value for white skip lines starts out higher than for edge lines at the initial observation, yet after five years the skip lines have a lower value, indicating a larger difference in degradation rate. The delta data series and trend line at the bottom of the chart shows the difference between the measurements at each time period. Similar to yellows thermoplastics, this trend line has a positive slope, indicating that the degradation rates between the edge and skip lines are different.

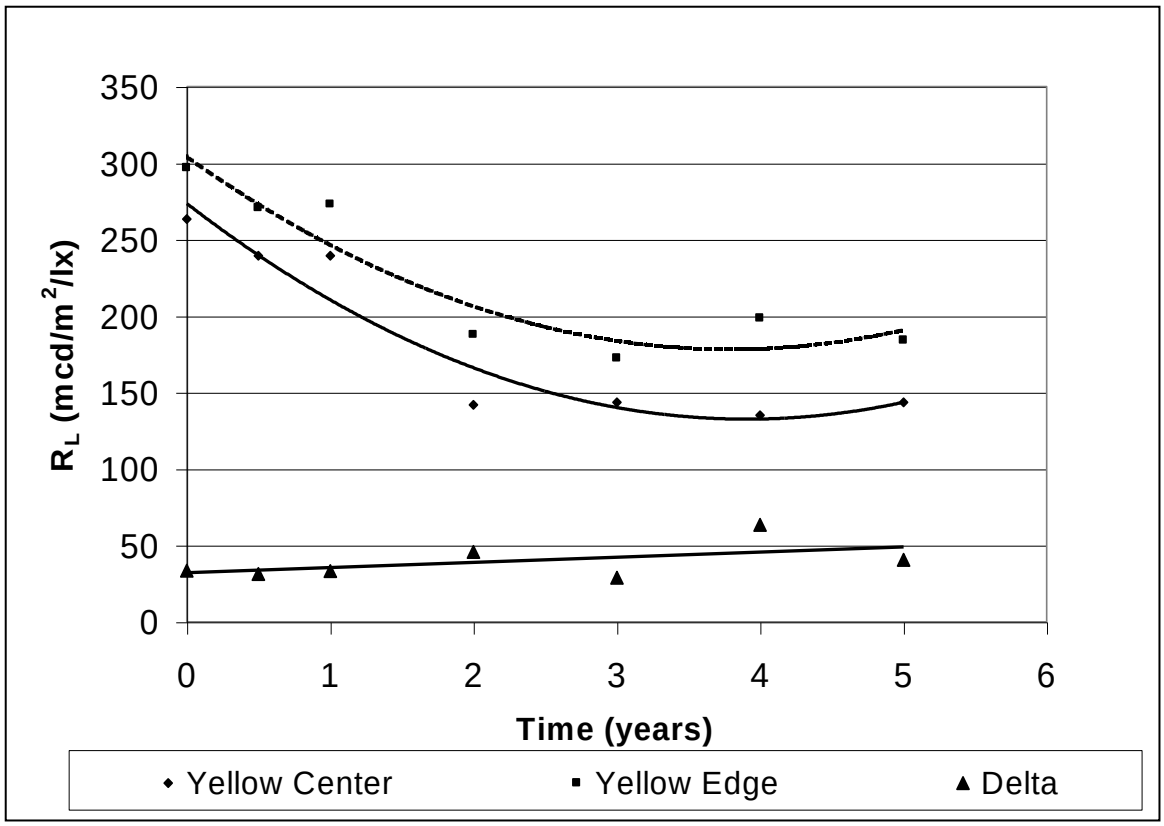


Figure 5.2. Average RL Values Over Time of Yellow Thermoplastics (Un-weighted)

Table 5.2. Average R_L Values Over Time of Yellow Thermoplastics (Un-weighted)

TIME (years)	0	0.5	1	2	3	4	5
Yellow Edge	297	271	273	188	173	199	184
Yellow Center	263	240	240	142	144	135	144
Delta	34	31	33	46	29	63	41

***** Values given in mcd/m^2/lux***

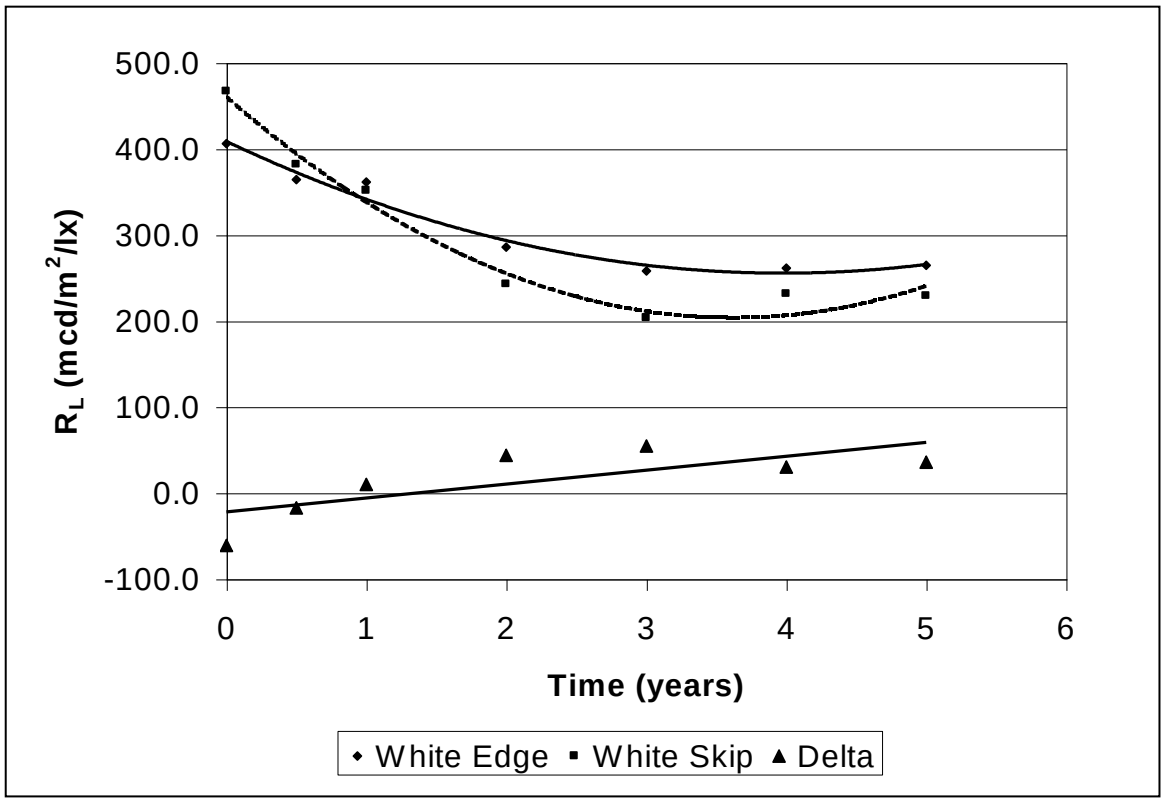


Figure 5.3. Average RL Values Over Time of White Thermoplastics (Un-weighted)

Table 5.3. Average R_L Values Over Time of White Thermoplastics (Un-weighted)

TIME (years)	0	0.5	1	2	3	4	5
Yellow Edge	406	364	362	286	258	261	265
Yellow Center	467	382	352	242	204	231	229
Delta	-61	-18	10	44	54	30	36

***** Values given in mcd/m^2/lux***

5.2.1.1.2 Average Value Analysis (Weighted)

The weighted average analysis produced results very similar to the un-weighted analysis. Figure 5.4 and Table 5.4 show the retroreflectivity degradation of yellow thermoplastics weighted to account for variation in length of road segments. This curve is nearly identical to the un-weighted analysis for yellow thermoplastics shown in Figure 5.2. Both center and edge lines show an initial drop in retroreflectivity in the first two years of service and then exhibit a flat curve beyond that point. The delta data series shows the difference between two averages at each time interval. Its trend line shows a positive increase over time, indicating that the centerlines are degrading at a higher rate than the edge lines. Additionally, the weighted trend line shows a much steeper slope than the trend line in the un-weighted trend line in Figure 5.2. This means that the difference between the lateral locations is more pronounced in this analysis.

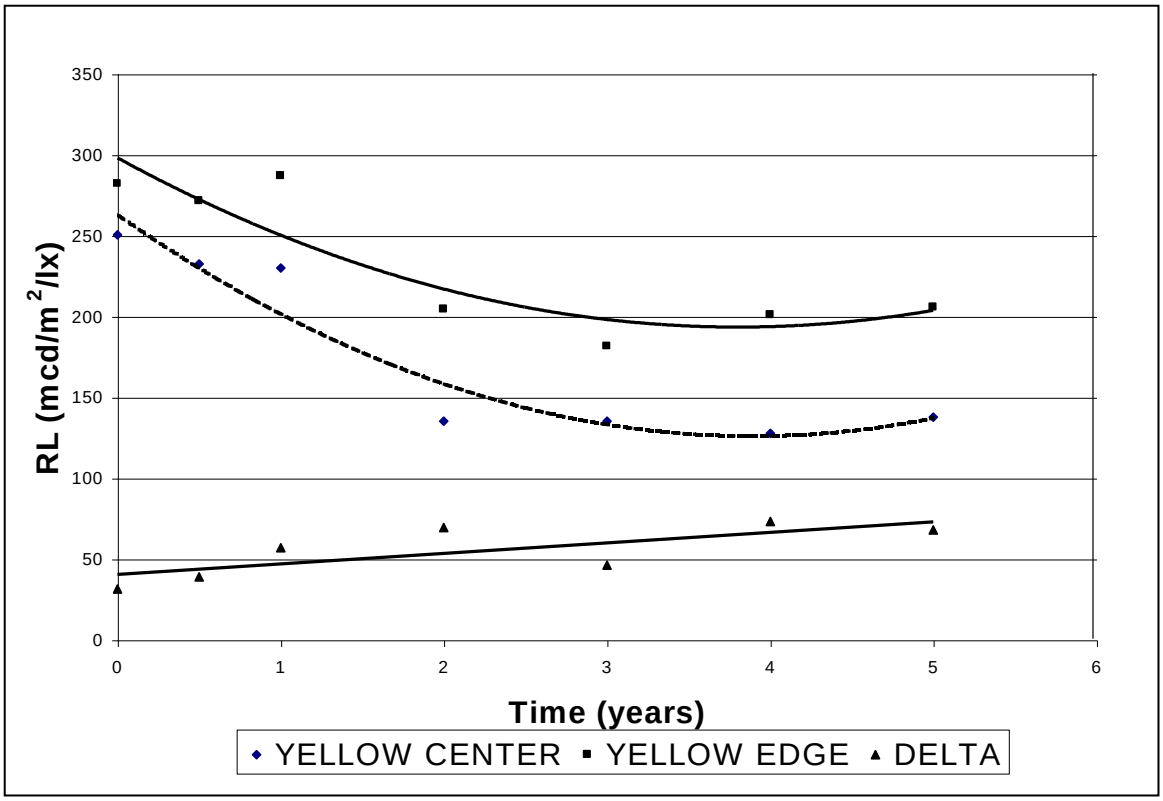


Figure 5.4. Average Value Over Time of Yellow Thermoplastics (Weighted)

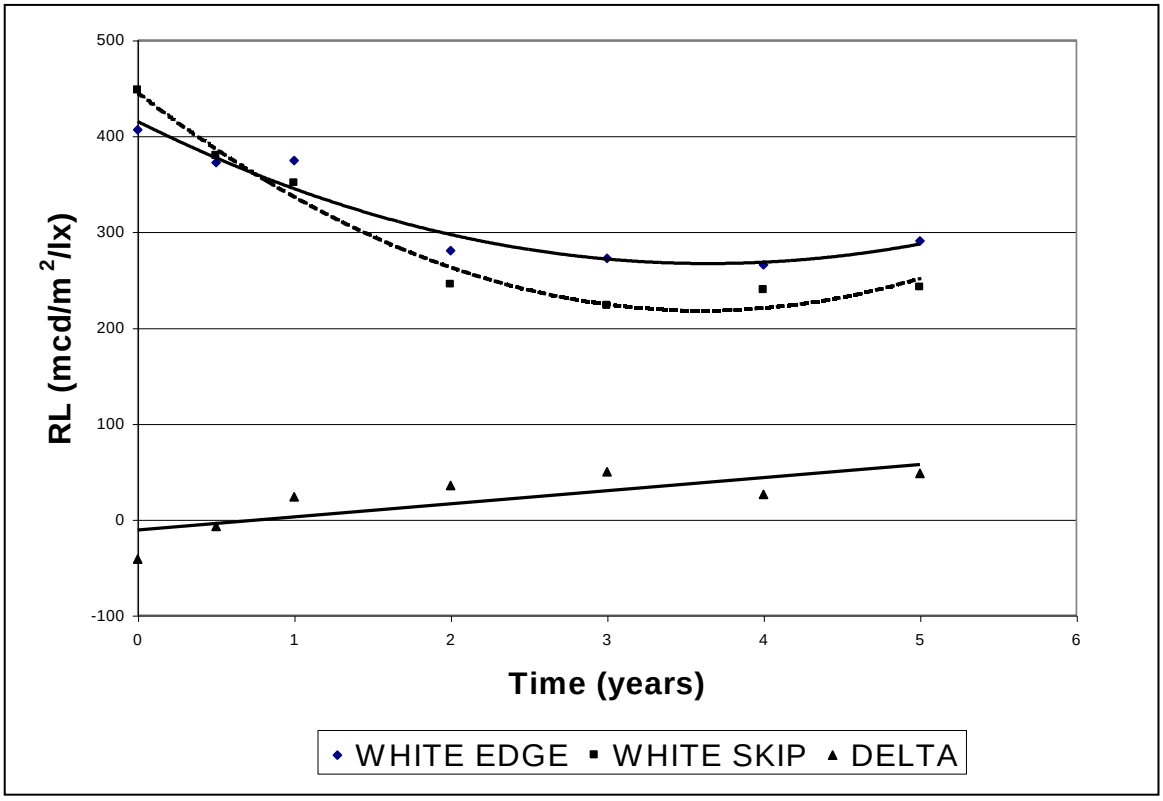
Table 5.4. Average R_L Values Over Time of Yellow Thermoplastics (Weighted)

TIME (years)	0	0.5	1	2	3	4	5
Yellow Edge	282	272	287	205	181	201	206
Yellow Center	251	233	230	135	135	128	138
Delta	31	39	57	69	46	73	68

***** Values given in mcd/m^2/lux***

Figure 5.5 and Table 5.5 show the retroreflectivity degradation of white thermoplastics weighted to account for variation in length of road segments. Again, this curve is very similar to the curves shown in the un-weighted analysis of white thermoplastics shown in Figure 5.3. Both skip and edge lines showed the initial drop in retro reflectivity in the first two years and then show a much shallower degradation rate. Additionally, as in Figure 5.3 the white skip lines starts with a higher initial average than white edge lines, but the two curves cross, indicating the skip line is degrading at faster rate than the edge line. Finally the

trend line of the delta exhibits a positive slope, confirming that the skip line has degraded



faster.

Figure 5.5. Average Value Over Time of White Thermoplastics (Weighted)

Table 5.5. Average R_L Values Over Time of White Thermoplastics (Weighted)

TIME (years)	0	0.5	1	2	3	4	5
White Edge	406	372	374	280	272	266	290
White Skip	448	379	351	245	223	240	242
Delta	-41	-7	24	35	49	26	48

***** Values given in mcd/m^2/lux***

Both the un-weighted and weighted methodologies produced very similar results in this analysis. The two methods confirm the results of each other, and also indicate that weighting

the data based on varying road segment has little effect on the outcome. For both colors, edge lines appear to degrade at a slower rate than center or skip lines.

5.2.1.1.3 Analysis of Variance (Un-weighted)

The ANOVA analysis was performed using the following null and alternative hypotheses:

- H_0 Null Hypothesis: The difference between the centerline mean and the edge line mean was statistically insignificant such that [R_L degradation of edge lines] = [R_L degradation of center lines] for all time periods.

- H_a Alternative Hypothesis: The difference between the centerline mean and edge line mean was statistically significant such that [R_L degradation of edge lines] $\neq$ [R_L degradation of center lines] for all time periods.

If the F-value from the analysis is less than or equal to the level of significance of $\alpha = 0.05$, this indicates there is sufficient statistical proof to reject the null hypothesis in favor of the alternative hypothesis. The results of the analysis are shown in Table 5.6. Values below .05 are highlighted in dark grey and those values between .05 and .1 are highlighted in light grey.

Table 5.6. ANOVA F-test Results for White and Yellow Thermoplastics (Un-weighted)

	INITIAL	6 MONTHS	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
White Edge vs. White Skip Lines	0.5426	0.0001	0.0001	0.0003	0.0687	0.0778	0.0625
White Sample Sizes (Edge /Skip)	115 / 78	111 / 88	105 / 80	73 / 61	46 / 32	32 / 20	30 / 18
Yellow Edge vs. Yellow Center Lines	0.3718	0.1053	0.0875	0.0866	0.0595	0.0041	0.0529
Yellow Sample Sizes (Edge /Center)	59 / 37	59 / 38	55 / 36	47 / 16	29 / 10	20 / 6	18 / 6

Both comparisons show a statistically insignificant difference in the initial time period (0.5426 and 0.3718), as expected. Ideally edge lines and centerlines marked at approximately the same time would have similar R_L values. Since this is not a matched paired analysis (where we are comparing center lines and edge lines from the same road segment) it is expected that there will be some variation between the two population means. For white markings, there is an extremely significant difference between edge and skip lines between six months and two years (0.0001 to 0.0003). Because most of the degradation is expected to occur during this time period, it makes sense that these time periods would show the most significant difference in degradation. For three to five years, some of the values are out side of the 95 percent level of significance criteria (0.0625 to 0.0778) but remain close enough to indicate a high level of confidence that there is a statistically significant difference.

For yellow markings, the six-month comparison is just below the 90 percent confidence mark with an F-value of 0.1053. From year one through year three and again in year five, the F-values indicate that there is greater than 90 percent chance that edge and center lines have

degraded at different rates. Year four exhibits a 99 percent certainty that the difference in the two group means is statistically significant.

5.2.1.1.4 Analysis of Variance (Weighted)

The ANOVA procedure shown above was repeated with the average values weighted according to the length of the individual road segments. The results of the analysis are shown in Table 5.7. Values below 0.05 are considered to be statistically significant and are highlighted in dark grey. Those values between 0.05 and 0.1 indicate a close proximity to the 95 percent level of confidence and are highlighted in light grey.

Table 5.7. ANOVA F-test Results for White and Yellow Thermoplastics (Weighted)

	INITIAL	6 MONTHS	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
White Edge vs. White Skip Lines	0.0363	0.0035	0.0009	0.1383	0.1363	0.0738	0.0754
White Sample Sizes (Edge /Skip)	740 / 433	736 / 550	709 / 512	575 / 433	457 / 331	326 / 209	302 / 185
Yellow Edge vs. Yellow Center Lines	0.2828	0.1474	0.1126	0.0302	0.0143	0.0007	0.0032
Yellow Sample Sizes (Edge /Center)	415 / 184	434 / 180	412 / 174	371 / 116	308 / 86	209 / 58	185 / 59

The data for white thermoplastics indicate that there are statistically significant differences between the edge and skip line populations. The initial, 6-month, and 1-year periods have F-values less than 0.05, indicating the two populations are clearly different. It also shows very low F-values throughout the rest of the series, indicating an 85 percent or greater confidence level that the two populations exhibit a different rate of degradation. The low F-

value at the initial reading is contrary to what we would expect, since ideally both the edge and center lines should have very nearly identical retroreflectivity values when the are first placed. However this analysis is conducted using two large populations, and this aberration is most likely due to normal variations in the two respective populations. As will be discussed in the recommendations, a matched pair analysis, comparing center and edge lines on the same road segment, would account for this variation.

Yellow thermoplastics also exhibit a statistically significant difference in degradation rates. As expected, the initial F-value is high, indicating that any difference between the two populations is due to normal variance within the populations. The F-value decreases steadily with time, and reaches the 95 percent confidence level at the 2-year through 5-year mark. This indicates that by year two, the edge and centerline populations are exhibiting clearly different rates of degradation.

5.2.1.1.5 Conclusions about Lateral Location as a Variable

There is clear statistical evidence that shows a difference in the rate of retroreflectivity degradation between edge lines and centerlines for both yellow and white thermoplastic markings. The data was analyzed using four different methodologies, which all consistently showed a difference in the degradation rates between edge lines and center or skip lines. Both weighted and un-weighted average value analysis showed nearly identical results and indicated that edge lines degrade at a slower rate than center or skip lines for both white and yellow thermoplastics.

Additionally, both the un-weighted and weighted ANOVA analysis indicate that there is a consistent 85 percent or greater probability that edge lines and center lines degrade at different rates from six months through five years for both yellow and white thermoplastic markings. In most cases the level of significance is above 90 percent and reaches as much as 99 percent. For both white and yellow thermoplastics, the available data set supports the conclusion that centerline degrade more rapidly than edge lines from six months to five years.

It is important to note that the curves shown in Figures 6.1 to 6.4 are not proposed models. These curves are smoothed trend lines shown specifically to aid the reader in separating the two data populations. The next section shows the result of the mathematical models developed for thermoplastics and paints.

5.3 Models

This section shows the results for the models developed for thermoplastics and paints. First, a summary is presented of the candidate models. Next, each model is presented followed by the residual plot of the predicted values and the normal q-q plot.

5.3.1 Thermoplastics

First a general linear model was developed for all thermoplastics on asphalt. This model, called the consolidated model, includes all the data and uses both color and lateral location as variables in the model. The model produced an R^2 of 0.60. Based on the literature this R^2 value was weak but still better than any of the previous studies.

Next, a general linear model was developed for each of the four categories of thermoplastics on asphalt based for the variables that were validated by the effects test which are time, initial R_L value, AADT. However, the data was presorted so that a model was developed specifically for each category of color and lateral location. This was done because the analysis of lateral location suggested that lines of different color and location degraded at different rates. The researchers were willing to sacrifice confidence in the model, as determined by the R^2 values, in order to establish a more specific degradation rate for each category.

Sorting the data by color and lateral location divided the total number of road segments into four subcategories. Unfortunately the four categories were not equally distributed and some of the power of the analysis gained as a consolidated model is lost in creating the individual models. This is one possible cause for a decrease in the R^2 values of White-Edge and Yellow-Edge models.

As noted in the presentation of variables, AADT falls out of the yellow middle category. Table 5.8 shows each of the models by category and presents the R^2 and the adjusted R^2 values. The key column is the adjusted R^2 value, which should be used when comparing models with different parameters.

Table 5.8. Summary of Thermoplastic Retroreflectivity Degradation Models

Category	Model	R^2	Adj R
Consolidated Model	$R_L = 190 + 0.39*R_{L\ Initial} - 2.09*time - 0.0011*AADT + 20.7*X_1 - 20.7*X_2 + 19*X_3 - 19*X_4$	.60	.59
White Edge	$R_L = 223 + 0.39*R_{L\ Initial} - 2.09*time - 0.0010*AADT$	0.38	0.36
White Middle	$R_L = 173 + 0.59*R_{L\ Initial} - 2.89*time - 0.0026*AADT$	0.53	0.50
Yellow Edge	$R_L = 193 + 0.40*R_{L\ Initial} - 1.69*time - 0.0016*AADT$	0.45	0.43
Yellow Middle	$R_L = 128 + 0.41*R_{L\ Initial} - 1.99*time$	0.64	0.62

Where:

R_L = Retroreflectivity in mcd/m^2/lx

$R_{L\ Initial}$ = Initial Retroreflectivity in mcd/m^2/lx

time = time in months

AADT = Annual Average Daily Traffic in vehicles per day

X_1 = Edge Line (1,0)

X_2 = Middle Line (1,0)

X_3 = White (1,0)

X_4 = Yellow (1,0)

Even though the R^2 value dropped in most cases, compared to the consolidated model, the R^2 and adjusted R^2 values for all four thermoplastic models in this study were still better than previous studies. Recall from Section 2.4 that the South Carolina study [Sarasua et al., 2003] produced four linear models with an R^2 that ranged from 0.24 to 0.47 for thermoplastics and Michigan study [Lee et al., 1999] produced a linear model with an R^2 equal to 0.14.

5.3.1.1 Consolidated Model

There were a total of 336 observation recorded for all thermoplastics on asphalt. The data were collected at the initial time, six-month point and then every year for a full five years. The consolidated model produced an R^2 equal to 0.60 and an adjust R^2 equal to 0.59 which were both considered to be very good compared to previous studies reviewed in the literature.

Table 5.9 shows a summary of the parameter estimates for the consolidated model and gives the standard error, t-ratio, and Probability > |t| values. Here the estimator represents the mathematical coefficient used for each independent variable in the model. The standard error column shows the standard error of the estimator and gives a sense of the uncertainty in the estimator. The t ratio is provided but the column of interest is the Probability > |t| value. Similar to the F statistic used to establish the inclusion of the variable in the model, the probability > |t| value gives a sense of the weight of the parameter in the model.

Table 5.9. Consolidated Model Parameter Estimates

Estimator	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	190.7	17.7	10.18	<0.0001
RL Initial	0.385	0.057	6.75	<0.0001
Time	-2.090	0.152	-13.75	<0.0001
ADT	-0.00113	0.0002	-5.09	<0.0001
Line Type	20.7	3.44	6.02	<0.0001
Color	19.0	4.85	3.91	0.0001

Figure 5.6 shows a residual plot for the models predicted values. The desired effect is to have an even distribution of the residuals around the mean value which is represented by the

horizontal line about zero. The plot shows a fairly distributed set of residuals about the mean indicating that the variances are consistent across the population of predicted R_L values.

However, at first glance there appears to be a slight fan like distribution in the values below the mean presenting a heteroskedastic pattern. This is represented by the dashed line in Figure 5.6. At first several transformations were explored but were found to be inappropriate.

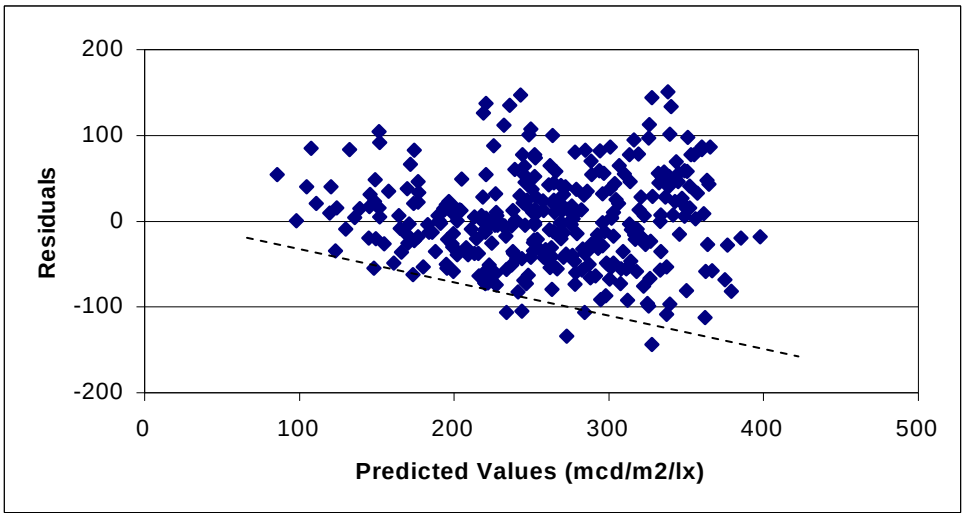


Figure 5.6. Consolidated Model Residual Plot of Predicted Values

Another way to look at the residuals is to view them as two independent groups which are shown by the squares in Figure 5.7. These squares provide a visual queue to see the two groups. It is possible that either color or lateral location, which has an impact on pavement marking performance, could be impacting the distribution of the residual.

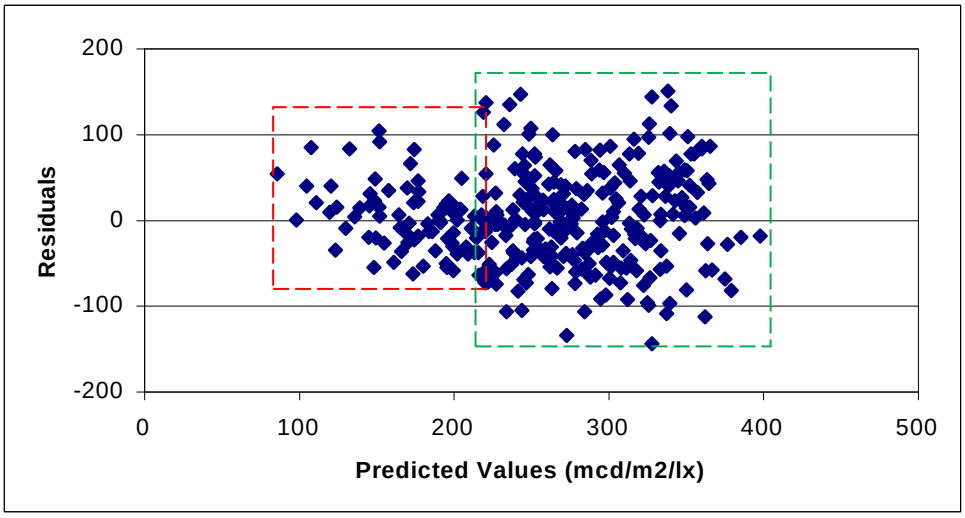


Figure 5.7. Consolidated Model Residual Plot of Predicted Values

Figure 5.8 shows the q-q plot of the consolidated model residuals. The plot clearly shows a straight-line pattern. A straight-line pattern is a visual cue that the distribution is normal. A Shapiro-Wilk goodness of fit test is a statistical check that can be done to mathematically determine if the distribution can be assumed normal. In a Shapiro-Wilk test the null hypothesis states that the population is normal and that any value below 0.05 would support rejecting the null hypothesis. In this case the probability of P < W equaled 0.2142 providing statistical evidence to keep the null hypothesis and conclude the distribution is normal. This is an important step in validating a regression model since the model relies heavily on the assumption of normality.

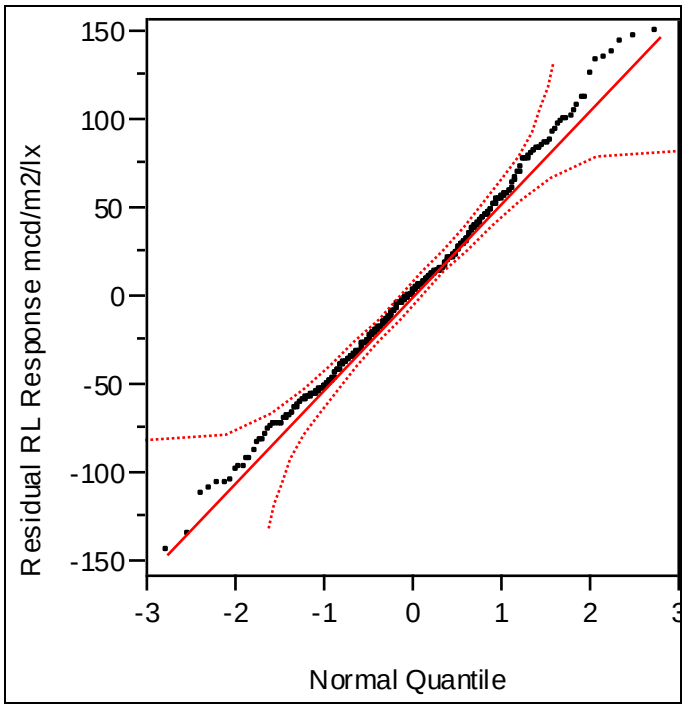


Figure 5.8. Consolidated Model Q-Q Plot

Statistical tests can give a great deal of insight. After reviewing the results from the residual plot of the predicted values it was clear that further refinement of the model was necessary. Since transformations of the model did not work further evaluation of the models by category was accomplished. As a result, the following four individual models were created based on the combination of color and lateral location. These are presented below.

5.3.1.2 White Edge Thermoplastics on Asphalt

There were a total of 168 observations recorded for the white edge thermoplastics on asphalt. The data were collected at the initial time, six-month point and then every year for a full five years. This model produced the lowest R^2 (0.38) and adjusted R^2 (0.36) values of the four thermoplastic models but both were considered to be reasonable compared to previous studies.

Table 5.10 shows a summary of the parameter estimates for white edge thermoplastics and gives the standard error, t-ratio, and Probability > |t| values. As you can see in this case all the parameters are significant but AADT has a lesser effect on the model than time or the intercept value.

Table 5.10. White Edge Parameter Estimates

Estimator	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	223	38.4	5.81	<.0001
RL Initial	0.387	0.100	3.84	0.0002
Time	-2.086	0.227	-9.15	<.0001
ADT	-0.0010	0.0003	-2.61	0.0099

Figure 5.9 shows a residual plot for the models predicted values. The desired effect is to have an even distribution of the residuals around the mean value which is represented by the horizontal line about zero. The plot shows a fairly distributed set of residuals about the mean indicating that the variances are consistent across the population of predicted R_L values.

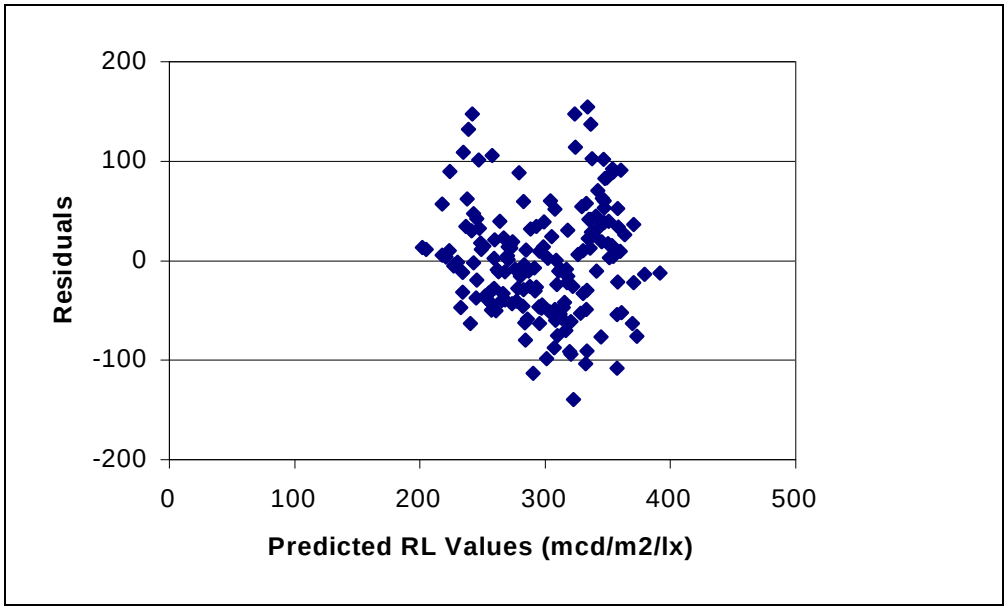


Figure 5.9. White Edge Residual Plot of Predicted Values

Figure 5.10 shows the q-q plot of the white edge thermoplastic residuals. The plot shows a straight-line pattern. A straight-line pattern is a visual cue that the distribution is normal. In this case the probability of P < W equaled 0.1017 providing statistical evidence to keep the null hypothesis and conclude the distribution is normal. This is an important step in validating a regression model since the model relies heavily on the assumption of normality.

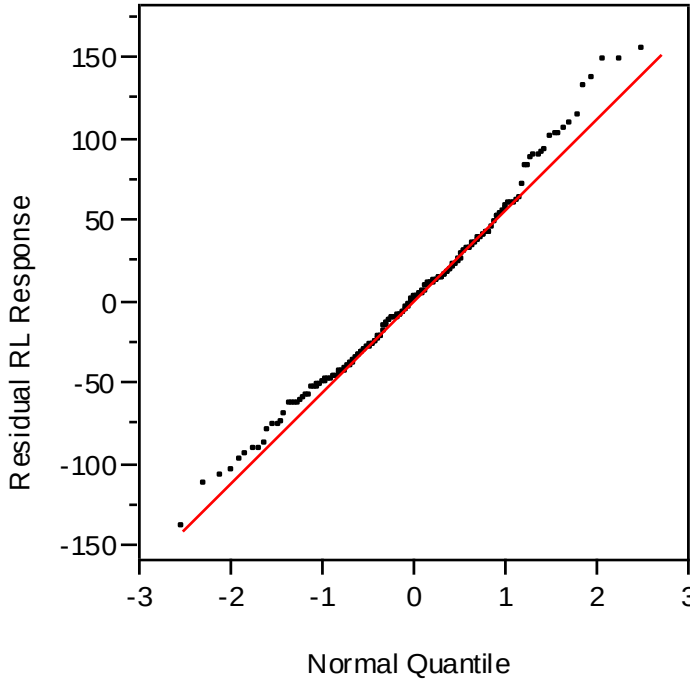


Figure 5.10. White Edge Q-Q Plot

5.3.1.3 White Middle Thermoplastics on Asphalt

There were a total of 48 observations recorded for the white middle thermoplastics on asphalt. The data were collected at the initial time, six-month point and then every year for a full five years. The Table 5.11 shows the summary of the parameter estimates and gives the standard error, t-ratio and Prob > |t| values. The R^2 (0.53) and adjusted R^2 (0.50) values for

white middle were considered to be very good compared to previous models discovered in the literature.

Table 5.11. White Middle Parameter Estimates

Estimator	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	173	90.0	1.92	0.0619
RL Initial	0.587	0.233	-2.52	0.0155
Time	-2.086	0.458	-6.30	<0.0001
ADT	-0.00258	0.0003	-3.11	0.0033

Figure 5.11 shows a residual plot for the models predicted values. The plot shows a fairly distributed set of residuals about the mean indicating that the variances are consistent across the population of predicted R_L values.

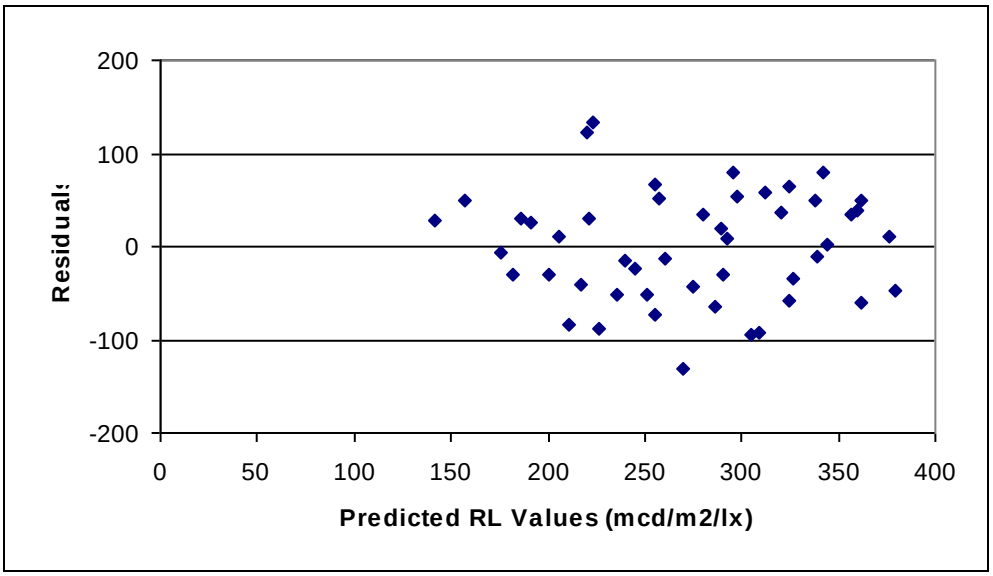


Figure 5.11. White Middle Residual Plot of Predicted Values

Figure 5.12 shows the q-q plot of the thermoplastic residuals. The plot clearly shows a straight-line pattern, which supports the conclusion that the residuals are normally distributed. This is an important step in validating a regression model since the model relies heavily on the assumption of normality. In this case the Shapiro-Wilk probability of P < W

equaled 0.2661 providing statistical evidence to keep the null hypothesis and conclude the distribution is normal.

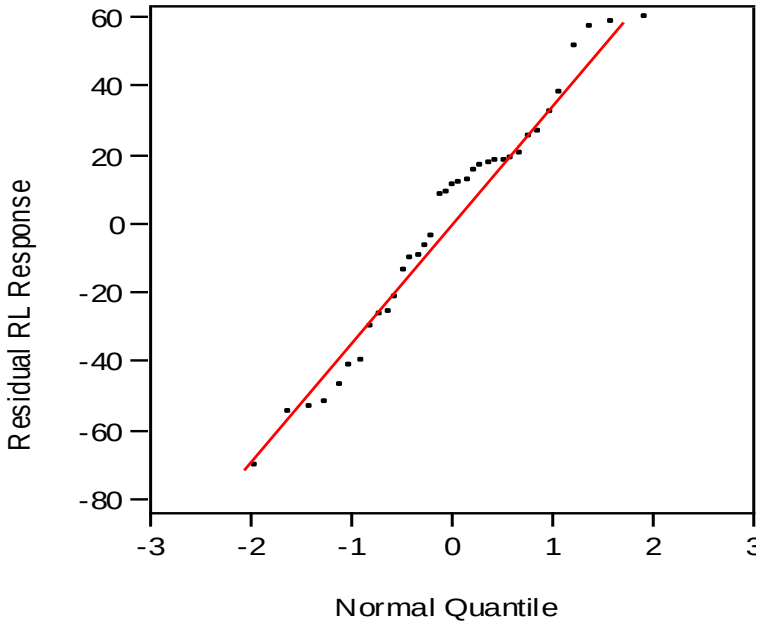


Figure 5.12. White Middle Q-Q Plot

5.3.1.4 Yellow Edge Thermoplastics on Asphalt

There were a total of 84 observations recorded for the yellow edge thermoplastics on asphalt. The data were collected at the initial time, six-month point, and then every year for a full five years. The Table 5.12 shows the summary of the parameter estimates and gives the standard error, t-ratio and Prob > |t| values. The R^2 (0.45) and adjusted R^2 (0.43) values for yellow edge were considered to be good compared to previous models discovered in the literature.

Table 5.12. Yellow Edge Parameter Estimates

Estimator	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	193	21.1	9.15	<0.0001
RL Initial	0.396	0.084	4.74	<0.0001
Time	-1.685	0.260	-6.49	<0.0001
ADT	-0.0016	0.0004	-3.65	0.0005

Figure 5.13 shows a residual plot for the models predicted values. The plot shows a fairly distributed set of residuals about the mean which is represented by the horizontal line about zero and indicating that the variances are equally distributed across the population of predicted R_L values.

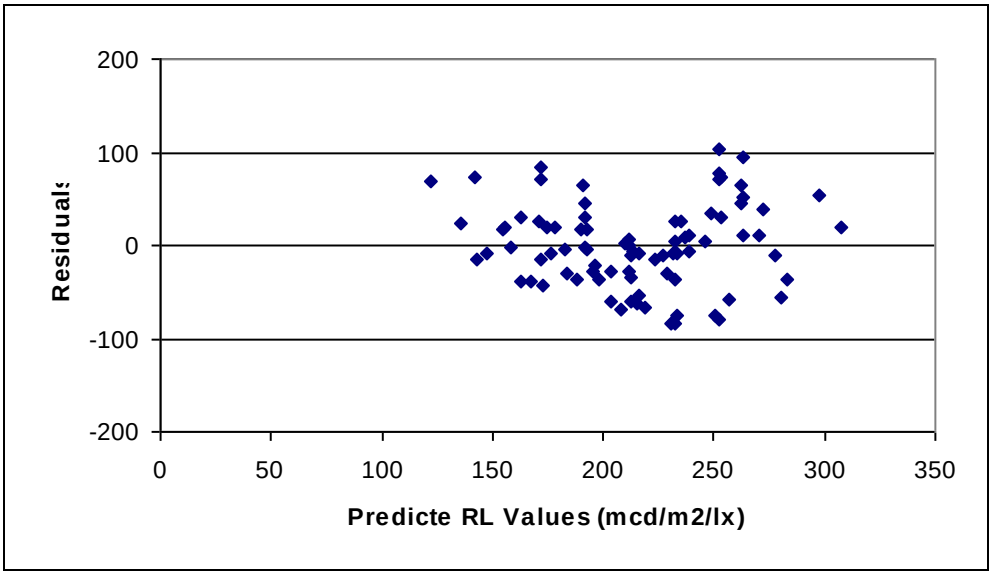


Figure 5.13. Yellow Edge Residual Plot of Predicted Values

Figure 5.14 shows the q-q plot of the thermoplastic residuals. The plot clearly shows a straight-line pattern, which supports the conclusion that the residuals are normally distributed. This is an important step in validating a regression model since the model relies heavily on the assumption of normality. In this case the Shapiro-Wilk probability of P < W

equaled 0.2958 providing statistical evidence to keep the null hypothesis and conclude the distribution is normal.

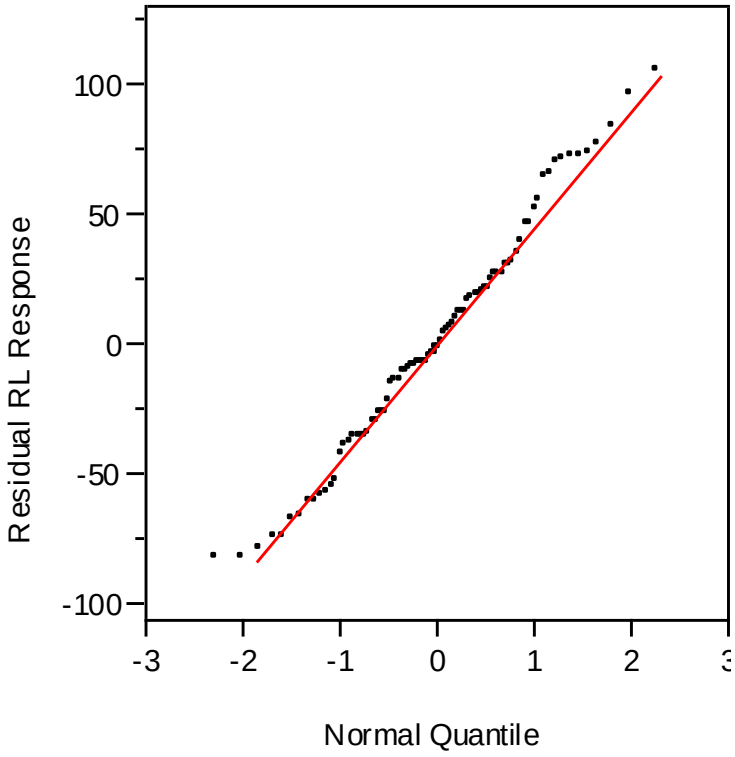


Figure 5.14. Yellow Edge Q-Q Plot

5.3.1.5 Yellow Middle Thermoplastics on Asphalt

There were a total of 36 observations recorded for the yellow middle thermoplastics on asphalt. The data were collected at the initial time, six-month point, and then every year for a full five years. As stated above, the AADT variable did not past the effects test and was removed from the model. The Table 5.13 shows the summary of the parameter estimates and gives the standard error, t-ratio and Prob > |t| values. The R^2 (0.64) and adjusted R^2 (0.62) values for yellow edge are better than previous models discovered in the literature.

Table 5.13. Yellow Middle Parameter Estimates

Estimator	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	128	27.5	4.65	<0.0001
RL Initial	0.408	0.095	4.29	<0.0001
Time	-1.99	0.316	-6.29	<0.0001

Figure 5.15 shows a residual plot for the models predicted values. The plot shows a fairly distributed set of residuals about the mean which is the horizontal line about zero and indicating that the variances are consistent across the population of predicted R_L values for yellow middle thermoplastics.

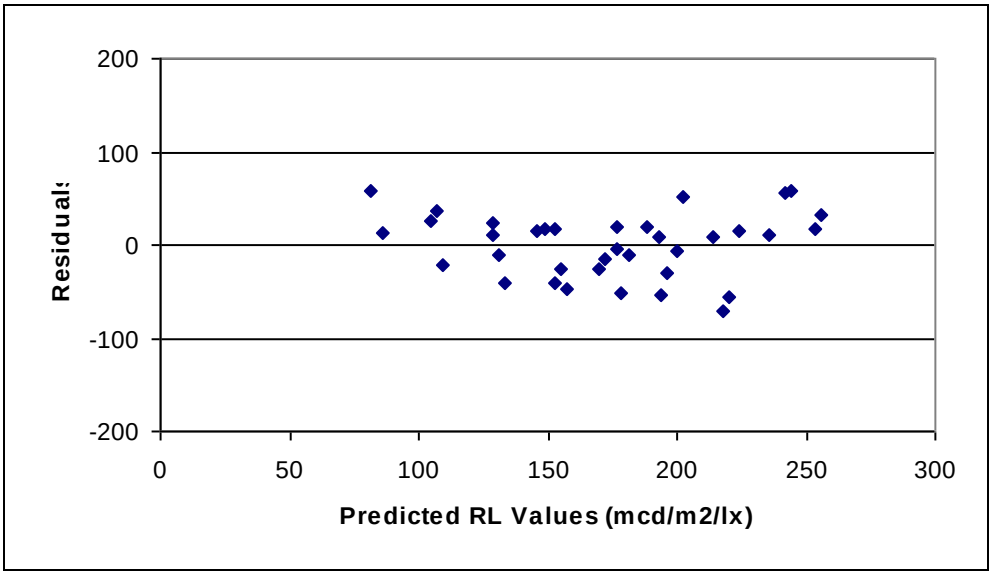


Figure 5.15. Yellow Middle Residual Plot of Predicted Values

Figure 5.16 shows the q-q plot of the thermoplastic residuals. The plot shows a straight-line pattern that falls within the confidence intervals but the line is not as straight as the others. This is probably due to the small number of observations compared to the three other models. However, we can still conclude that the residuals are normally distributed. In this case the

Shapiro-Wilk probability of P < W equaled 0.8278 providing statistical evidence to keep the null hypothesis and conclude the distribution is normal.

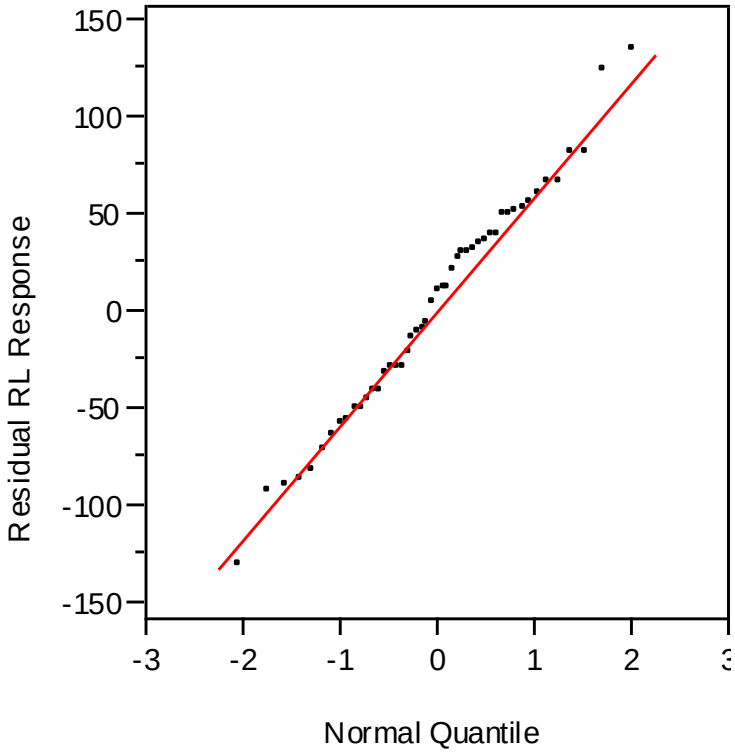


Figure 5.16. Yellow Middle Q-Q Plot

5.3.2 Paints

Originally paints were believed to have a limited service life of approximately one year and therefore were not the primary focus of this research. This was assumed based on the literature where Migletz et al. determined the life of paint to be approximately 10 months [Migletz et al., 1999]. The original intent in collecting paint data was entirely for quality assurance and the data were not intended for analysis. Therefore only a limited number of data points were collected for paints. However, because paints make up nearly 60 percent of

the pavement markings on the roadway an evaluation of the available paint data was performed with surprisingly good results.

There were 37 road segments that had a full year of available data. The data were collected for paint at the initial, six-month and one-year points. The data collected included R_L values, initial $R_{L,}$ time, road surface, material, color, and lateral location. The data collected for paints were for roads that were marked by contractors and therefore had to meet the minimum specification required by NC. It is important to note that the majority of paint operations are performed in house and are not checked to confirm the initial R_L value achieved.

Due to the small sample size only one candidate model was deemed to be appropriate and was developed. It is a general linear model for all paints on both asphalt and concrete. An effects test, using the F-statistic, was performed. The test revealed that the only valid variables are initial R_L and time. Lateral location, color, surface material AADT, snowplow, thickness, and width were all ruled out by the effects test using the F-statistic. The pavement marking retroreflectivity degradation model for paint is:

$$R_L = 55.2 + 0.77*R_{L\ Initial} - 4.17*time \qquad R^2 = 0.75 \qquad (5.1)$$

Where:

R_L = Retroreflectivity in mcd/m^2/lx

$R_{L\ Initial}$ = Initial retroreflectivity in mcd/m^2/lx

time = time in months

Table 5.14 shows the summary of the parameter estimates and gives the standard error, t-ratio and Prob > |t| values. The R^2 (0.75) and adjusted R^2 (0.75) values for all paints were considered to be very good.

Table 5.14. Paint Parameter Estimates

Estimator	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	55	12.0	4.58	<0.0001
RL Initial	0.769	0.045	19.97	<0.0001
Time	-4.17	.606	-6.89	<0.0001

Figure 5.17 shows a residual plot for the model's predicted values. The desired effect is to have an even distribution of the residuals around the mean value, which is the horizontal line at zero. The plot does not show an even distribution of residuals about the mean and introduces the idea of heteroskedasticity indicating that the variances are un equally distributed across the population of R_L values. This was the first indication that a transformation of the model would need to be explored.

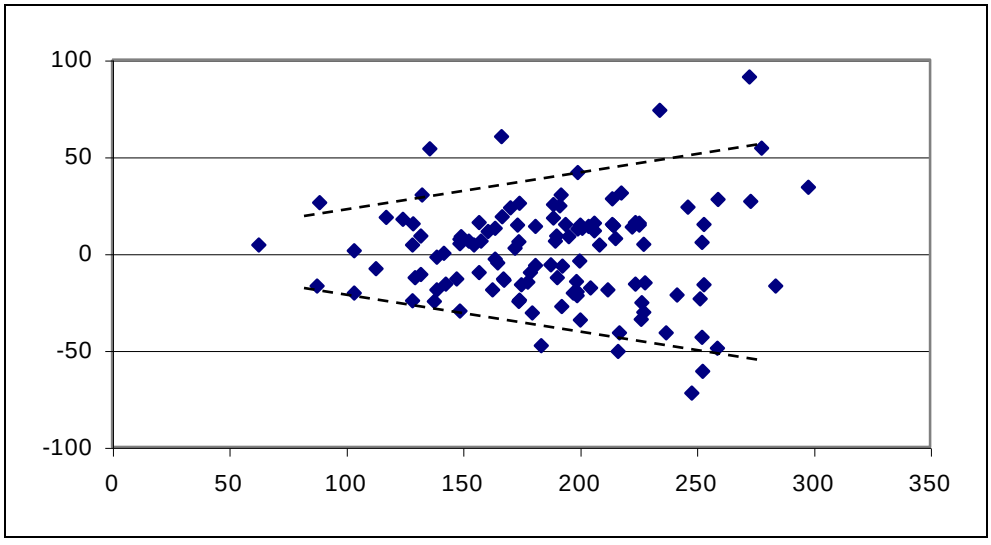


Figure 5.17. Residual Plot of the Predicted Values for Paints

Figure 5.18 shows the QQ-plot of the paint residuals. The plot shows a straight-line pattern, which supports the conclusion that the residuals are normally distributed. However, based on the fan like distribution of the residuals a log transformation was tried and a Shapiro-Wilk test was performed. The test revealed that the P < W value was equal to 0.0414. This value is below the desired value of 0.05 and would suggest rejecting the null hypothesis.

Recall that the null hypothesis was defined as the distribution of residuals is normally distributed. Because of the results of the residual plot and the Shapiro-Wilk goodness of fit test a log transformation was performed on the model. The results of the transformation revealed a similar QQ-plot, shown as Figure 5.19. Even though the plot of the transformed model looks similar in form to that of Figure 5.18, the Shapiro-Wilk test resulted in a P < W value equal to 0.0133. This gave evidence that a log transformation was not the right solution. The possible cause of the lack of normality is that this model combines the paint data into a single model. Both exponential and polynomial transformations were also tried with ineffective results.

As a result of the failing transformations our best estimate remains a linear model. After two years the majority of paint data were still above the standard supporting our finding that paints have a service life of two years or more.

Combining color and lateral location into a single model could be one cause for the lack of normality. Based on this conclusion there is clear evidence to support the development of

individual models for paints similar to the ones this study developed for thermoplastics. Future research should collect the appropriate data and explore this.

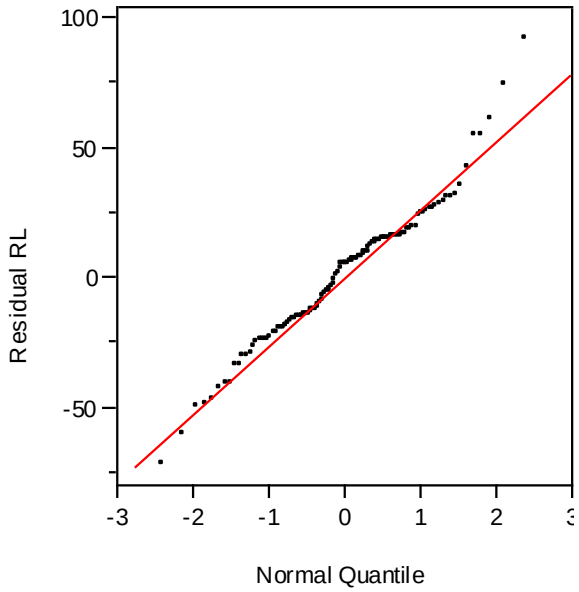


Figure 5.18. Q-Q Plot for Residuals of Paints

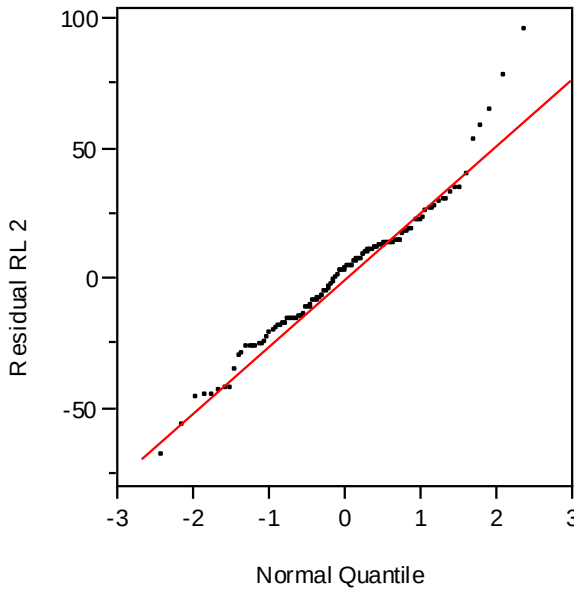


Figure 5.19. Q-Q Plot for Log Transformed Residuals of Paints

5.4 Model Validation

Model validation was looked at in four ways. First was a logical assessment of the models. Second was a comparison of the models developed in this research with other previously established linear models. Third was an assessment of the actual verses predicted values used in developed the models. Fourth was the validation of the models by comparison to an independently collected data set.

5.4.1 Logical Review of the Model

The objective of the logical review was to make sure the models made sense. Before any other validation was performed it was important that the models passed the common sense test from two perspectives. First the model needed to be evaluated to ensure it was in fact linear. Second was to evaluate, in general terms, what the simple statistics of the model showed about the five years of data.

Recall from Table 2.10 that the literature established both linear and logarithmic approaches as effective means of modeling pavement marking degradation. After the NC data were sorted and organized the average R_L values of the 56 road segments were plotted over time and a curve was fitted to the values. Figure 5.20 shows the plot where each point represents the average of the 56 values for that time increment. A linear trend line was added with an R^2 value of 0.78. A logarithmic trend line was attempted and achieved an R^2 of 0.59. Based on this initial assessment it was determined that a linear model was a good approach.

After determining that NC pavement markings were degrading in a linear way it was important to assess what the actual data looked like compared to the predicted values. Recall that there were 56 road segments for thermoplastics.

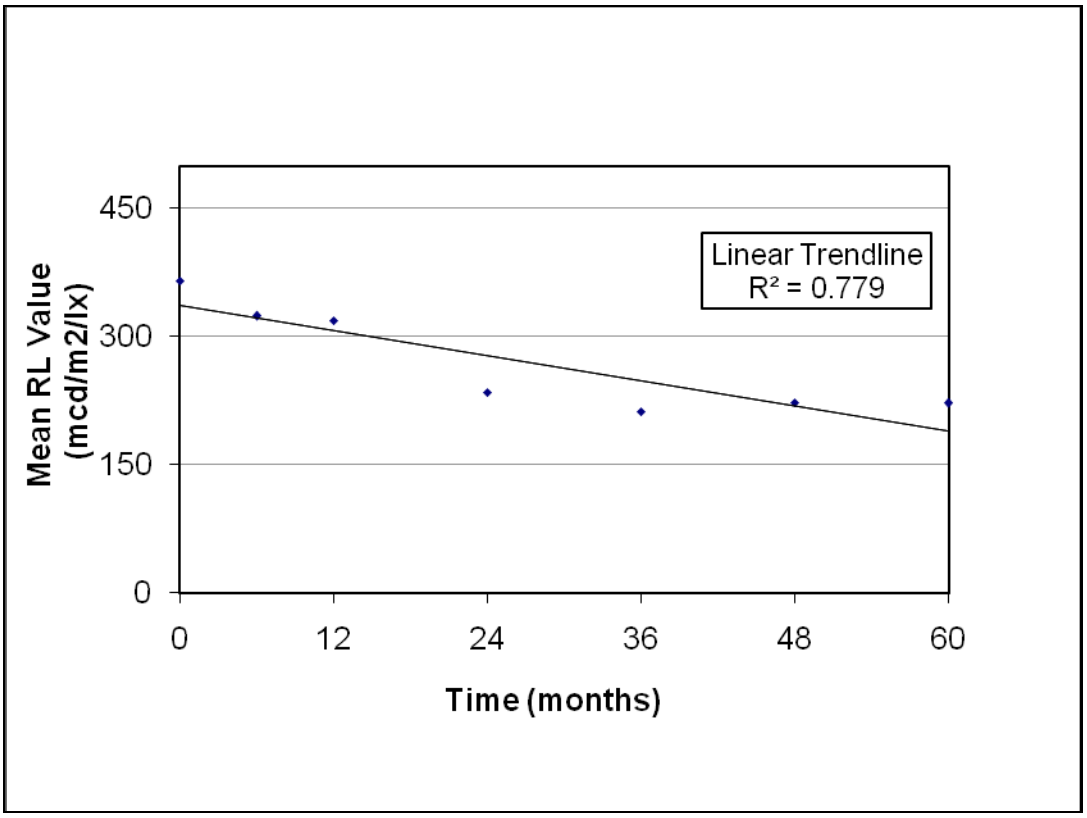


Figure 5.20. Plot of Average RL Values Over Time

Table 5.15 reports the simple statistics of the actual pavement marking thermoplastic data by time increment. The average R_L value of the 56 road segments is reported in the second column labeled RL Mean. The standard deviation is reported in the third column. Columns four through seven report the calculated range of values based on the standard deviations with columns four and five showing the 0.5 standard deviation increment and columns six and seven showing one full standard deviation.

Table 5.15. Simple Statistics of the Pavement Marking Retroreflectivity Data

Time	RL Mean (mcd/m^2/lx)	Std Dev (mcd/m^2/lx)	+ 0.5 Std Dev (mcd/m^2/lx)	- 0.5 Std Dev (mcd/m^2/lx)	+ 1 Std Dev (mcd/m^2/lx)	- 1 Std Dev (mcd/m^2/lx)
0	365	103	417	314	468	262
6	324	82	365	283	406	242
12	319	85	362	277	404	234
24	235	75	273	198	310	160
36	212	67	246	179	279	145
48	223	62	254	192	285	161
60	222	75	260	185	297	147

It is important to note that the reported values in table 5.15 included all the data which has both white and yellow makings. As you can see in the seventh column of the table both the 36 and 60 month values fall just below the minimum standard for white thermoplastics. Since yellow markings have a minimum standard of 100 mcd/m^2/lx, it is reasonable to assume that those markings values are still mostly within the minimum standards.

As an example, a specific look at the 60 month average R_L value shows that thermoplastics average 222 mcd/m^2/lx with a standard deviation of 75 mcd/m^2/lx. This meant that 84.1 percent of the data were still clearly above the more stringent standard for white markings after 60 months. Reviewing the raw data for the 60 month time increment revealed that only 6 of the 56 road segments had a value below the minimum standard for white of 150 mcd/m^2/lx. All of the six values below were in fact yellow markings which may have a lower minimum standard of 100 mcd/m^2/lx.

5.4.2 Comparison to Existing Models

The next step in validating the model was to compare the results with other models established through previous studies. In this case, the established degradation rates for

thermoplastics and paints were compared to linear models established by South Carolina and Michigan. Furthermore, the established service life of thermoplastics and paints were compared to South Carolina, Michigan, and the Migletz studies.

Table 5.16 summarizes the degradation rates and service lives of four linear approaches to modeling pavement marking performance. The first half of the table shows the degradation rates established by each model. The second half shows the predicted service life based on the model.

Michigan determined a general degradation rate for thermoplastics. As SC included color into their model the degradation rates fell significantly and the coefficient of determination increased. In this research the NC models go one step further by establishing a degradation rate with the inclusion of lateral location. This refined the degradation rates and increased the coefficient of determination even more.

In each case it was necessary to use the same end state so that an equal comparison of the predicted service life could be performed. These are listed under the end state column. For example, all white thermoplastics were evaluated with the end state defined as 150 $mcd/m^2/lx$. However, it is important to note that in the literature each modeling effort defined the end state differently. For example, SC defined the end of service life for white thermoplastics as 100 $mcd/m^2/lx$.

Table 5.16. Comparison of Degradation Rates and Service Life of Models

	NC Model R^2 = 0.38-0.75	SC Model R^2 = 0.21-0.47	Michigan Model R^2 = 0.14	Migletz
	Degradation Rates – values in mcd/m^2/lx per month			
White Thermoplastic	2.09 (edge) 2.89 (middle)	1.8	10.87	N/A
Yellow Thermoplastic	1.69 (edge) 1.99 (middle)	0.9		
Paint	4.17	N/A	N/A	N/A
	Service Life – values in months			
End State				
White Thermoplastic 150 mcd/m^2/lx	76 (middle) 100 (edge)	121	9.6	7.4 – 49.7
Yellow Thermoplastic 100 mcd/m^2/lx	65 (middle) 105 (edge)	162	14	11.0 – 41.6
White Paint 100 mcd/m^2/lx	31	N/A	N/A	4.1 – 18.4
Yellow Paint 65 mcd/m^2/lx	26	N/A	N/A	N/A

The service life estimates by the Michigan and Migletz models show a shorter life span than those of NC and SC. This made sense since these studies were heavily influenced by northern climate effects. Specifically, both Michigan and the Migletz studied areas that are heavily affected by snow removal operations. In this case SC provides a better comparison since it is a southern tier state with a similar climate to North Carolina.

5.4.3 Actual Verses Predicted plot of model data

Figure 5.21 shows the actual verse predicted values for the consolidated thermoplastic model which were plotted to gain insight as to the performance of the model. On the y-axis are the predicted values and on the x-axis are the actual values.

There is a slight downward trend in the larger actual values. Several possibilities could explain the skew in plot. Possibly the markings are degrading in a nonlinear way. However, the researcher ruled this out based on the literature and based on the results of section 5.4.1. Another possible source of the skew in the data is the influence from exceptionally high initial R_L values. These larger initial values could influence the markings degradation. However, the model accounts for the influence of the initial R_L and should dampen the affect we see in the plot.

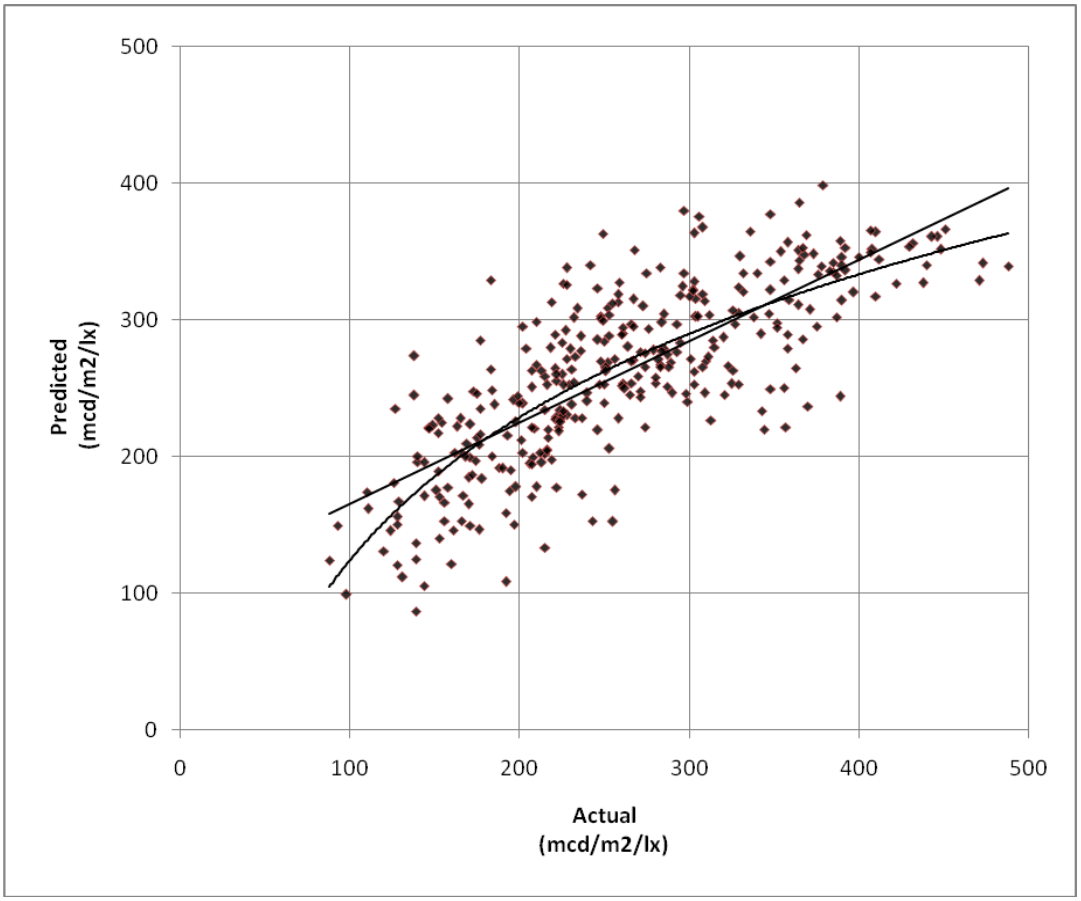


Figure 5.21. Actual Verses Predicted Values for the Consolidated Thermoplastic Model

The researcher deemed the most likely cause of the skew in the plot is due to the influence of the color on the consolidated model. Figure 5.22 shows the same plot as Figure 5.21 but the two populations of white and yellow are highlighted by different symbols and a separate trend line is added for each. In this figure it is easy to see that two populations exist and supports the decision to separate the consolidated model into four individual models.

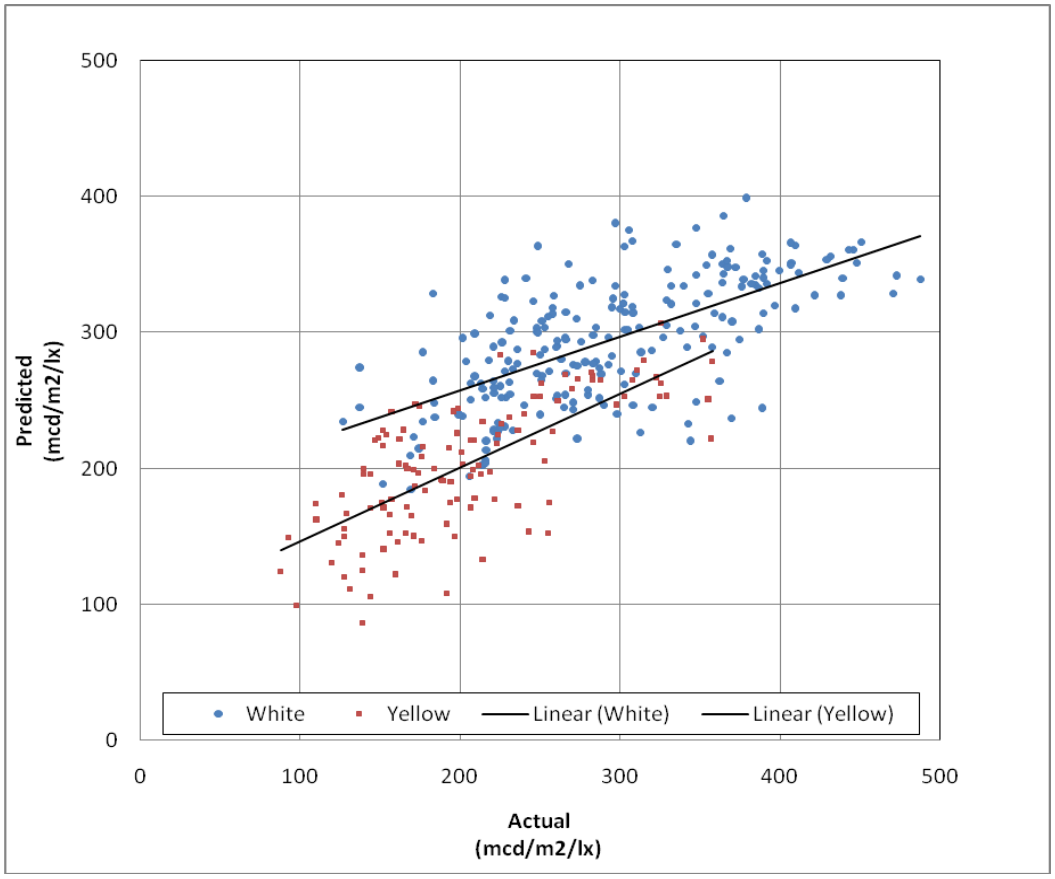


Figure 5.22. Actual verses Predicted with White and Yellow Thermoplastics

5.4.4 Comparison of Predicted Values to Independent Sample

A good way to validate the model is to reserve data from the original collection and then compare them to the developed model. This was considered early on in the research but the limited amount of data in some areas would not allow for a random removal of the reserved

data without negatively impacting the ability to divide the data into four categories. It was evident that additional data would need to be collected in order to validate the model.

On September 18th and 20th of 2007 additional data were collected for the purpose of validating the thermoplastic and paint models previously established. The data were collected as a combined effort from the WZTCU and NCSU while Divisions 5 and 6 supported with the necessary traffic control.

A one mile road segment was identified for both thermoplastics and paint. The thermoplastic segment was NC 98 in Division 5. It had an eight year old white edge line and five year old yellow center and white skip lines. The paint segment was SR 2023 and was located in Division 6. It had a two year old segment of white edge line and yellow centerline. From these segments a sampling of 35 retroreflectivity readings were collected for both thermoplastics and paints. The 35 readings were taken along the one mile road at random points selected by a random number generator. The distribution of the sample was evaluated and deemed normal which enable the research to make the inference that the sample of validation data represented the larger population of thermoplastics in NC.

Table 5.17 shows the predicted estimate in the first column and the summary of the simple statistics for the validation data in columns two through four. In all cases the actual time and AADT values established for the validation segment were used to establish the predictive estimate. Since the initial R_L values were not known for the road segments the average value for initial R_L was taken from the database and used to establish the estimate.

Table 5.17. Predictive Estimate Compared to Summary of Validation Data

	Estimate Value from Model (mcd/m2/lx)	Validation Segment Mean (mcd/m2/lx)	Validation Segment Standard Deviation (mcd/m2/lx)	Validation Segment Lower CI (mcd/m2/lx)	Validation Segment Upper CI (mcd/m2/lx)	Time (Months)	AADT (vpd)	Initial RL (mcd/m2/lx)
Thermoplastic								
White Edge Cons Model	169	156	37	144	169	96	22000	423
White Edge Indv Model	165							
Yellow Mid Cons Model	112	167	26	158	176	60	22000	286
Yellow Mid Indv Model	125							
White Mid Cons Model	204	199	30	188	209	60	22000	423
White Mid Indv Model	191							
Paint	128	127	67	111	143	24	1300	225

The predicted estimate was very close for both cases of white thermoplastic pavement markings and for paint pavement markings. The model comes within one unit of predicting the actual value for paint. In each case, except yellow middle markings, the lower and upper 95 percent confidence interval clearly hooks the predicted value. Additionally, the predicted value was within one standard deviation.

Unfortunately, the predicted estimate for yellow middle markings was outside the 95 percent confidence interval and close to 2 standard deviations away from the actual value. However,

it is important to note that during the collection of the yellow middle validation data the researcher observed a section of the markings that had clearly been overlaid with new material. It is possible that the time estimate used for the yellow middle value is not accurate or at least not accurate for a portion of the one mile road segment. The inaccurate time value could significantly affect the predictive value. Unfortunately, the time and labor required to close a road prohibits the researcher from collecting more validation data by hand.

In summary it is critical to any research effort to establish confidence in the outcome. The established models were validated in four different ways each contributing to a better understanding of the models and their limitations. Based on the results of the validation process the researcher is confident that pavement markings in NC degrade linearly. Although logarithmic decay is a possible modeling alternative it is not appropriate for NC pavement markings.

5.5 Summary of Results

This chapter presents the derivation and validation of pavement marking degradation models for thermoplastics and waterborne paints. The consolidated model for thermoplastics yielded a degradation rate of 2.09 mcd/m2/lx per month. The individual models yielded more specific degradation rates for thermoplastics in the range of 1.69 mcd/m^2/lx per month to 2.89 mcd/m^2/lx per month. Even though the coefficient of determination dropped in some categories the researcher felt it was important to show the individual degradation rates for each category of thermoplastics. For paints the model yielded a degradation rate of 4.17 mcd/m^2/lx per month. With these rates service life can be estimated.

A key component to pavement marking management is the designation of initial and minimum standards of retroreflectivity. When combined, both the standards and the models yield an effective service life for a given category of pavement marking as shown in Table 5.18.

Column one of the Table 5.18 shows the individual category, color, and material of the pavement marking. Columns two and three show the minimum required retroreflectivity value required by NCDOT for the marking to be useful and the initial specification value, respectively. Columns three and four show the resulting service life for pavement markings in months and years. An AADT of 10,000 was used to calculate the generic service life of a pavement marking in each category. For more accurate service life of pavement markings on a given road segment the actual initial R_L value recorded and the forecasted AADT could be used.

An example calculation is provided for white edge thermoplastics. In this example the following values are used:

R_L = 150 mcd/m^2/lx, which is the minimum value required by NCDOT.

$R_{L\ Initial}$ = 375 mcd/m^2/lx, which is the initial specification value required by NCDOT.

AADT = 10,000.

Time is in months.

The known values are substituted into the equation for white edge thermoplastics and then solved for time.

$$R_L = 223 + 0.39*R_{L\ Initial} - 2.09*time - 0.0010*AADT$$

$$(150) = 223 + 0.39*(375) - 2.09*time - 0.0010*(10{,}000) \rightarrow -209.25 = -2.09*time$$

$$time = -209.25/-2.09 = 100 \text{ months}$$

Table 5.18. Summary of Thermoplastic Pavement Marking Service Life by Category

Category	Minimum Standard (mcd/m2/lx)	Initial Spec Value (mcd/m2/lx)	Estimated Service life (Months)	Estimated Service Life (Years)
White Edge Thermoplastic	150	375	100	8.3
White Middle Thermoplastics	150	375	76	6.3
Yellow Edge Thermoplastics	100	250	105	8.75
Yellow Middle Thermoplastics	100	250	65	5.4
White Paints	100	225	31	2.6
Yellow Paints	65	200	26	2.2

Previous research has established degradation rates and service lives that are similar to the models developed in this research. However, this research makes a significant contribution by evaluating the affects of lateral location on pavement marking degradation. The lateral location modeling is a significant contribution and the Journal of Public Works Management

and Policy has published an article based on the analysis and finding of this portion of the research. A copy of the article is located in the appendix.

As part of an ongoing research project NCDOT supplied the researcher with an updated database in 2007. The developed models will be further refined and expanded to other materials. Additionally, further validation of the thermoplastic and paint models will be will be accomplished by other members of the research team as part of a future phase of this research stream using the updated database.

6.0 PAVEMENT MARKING ASSET MANAGEMENT SYSTEM

There are many components to asset management which include things like asset inventories, condition assessments, and data integration strategies. In many highway agencies separate data managements systems are often incompatible and data integration among these systems becomes impractical or expensive [Gharaibeh, Darter, and Uzarski, 1999]. Assessing the condition of an asset is labor, equipment, and data intensive and requires the implementation of computing tools. Specifically, the FHWA Office of Asset Management Research and Development Activities highlighted the need for agencies to conduct research on data integration and the various uses of integrated data for asset management [FHWA, 2007]. The goal is to evaluate tools and technologies for data integration including software, hardware, and communication technologies and then documents the data integration initiative through specific case studies [FHWA, 2007].

Currently, many large highway agencies do not have a complete inventory or condition assessment of pavement markings. Furthermore, with pavement markings constantly degrading condition assessments quickly become out-of-date. Other typical condition assessment programs are based on random sampling and limited criteria such as "present, visible, reflective at night" [FHWA , 2007]. Pending FHWA requirements call for assessing the condition of pavement marking retroreflectivity, which means that incorporating computer based automated measurement tools, can greatly improve the assessment process. More specifically, most agencies cannot afford to measure all markings once or twice a year. This paper provides a solution to the data integration problem of incorporating various

attributes of the pavement markings, both measured and predicted, into an existing transportation asset management (TAM) system.

This chapter presents the results of an effort to develop a pavement marking transportation asset management (TAM) system. Although NC is used as the particular case for developing this system many of the concepts can be used by other departments of transportation. This chapter has four sections which start first with goals and policy development. Second is an assessment of the pavement marking inventory. Presented third is the development of data management models which enable performance modeling and provide managers with a method for conducting a condition assessment. Finally, section four summarizes the implementation strategy for the pavement marking database model.

6.1 Goals and Policy Development

This section presents the goals and policy structure for a pavement marking asset management system. Presented first are the key parameters defining pavement markings as a transportation asset. Presented next is a brief summary of the governing regulations for pavement markings. Presented next is a brief summary of NCDOTs budget process. Finally, level of service (LOS) increments and the proposed minimum standard for pavement markings are presented.

6.1.1 Asset Parameters

As described in Section 2.1.1 the goals for a transportation asset should be performance-based and measurable. Additionally the goals should transcend all levels of the organization both horizontally and vertically. The six parameters below define the pavement marking

asset in a measurable way that provides a common understanding throughout the organization. The key parameters of pavement markings are defined below using a standard format for NC's transportation assets [Love, 2007].

1. Asset: Pavement marking.
2. Activity: Marking/re-marking. Management is concerned about all the issues associated with marking and remarking pavements. This would include safety, service life, budgeting, and compliance with Federal standards. Specifically, management is concerned with two components to this asset [Love, 2007]. First, NCDOT needs to implement a plan for compliance with pending Federal standards. Second, NCDOT wants to develop a replacement strategy that maximizes service life of the asset.
3. Condition indicator: The condition indicator defines the basic LOS increment term; here, color-coding is used to define the condition of pavement markings. The color-coding represents both quantitative and qualitative definitions of the performance measures. The color code ratings are equated to letter ratings already in use by NCDOT.
4. Performance measure: The performance measure for pavement markings is the coefficient of retroreflectivity luminance (R_L), which is measured in mcd/m^2/lx.
5. Performance target: The performance target is a percent compliance with an established NC standard for pavement markings. The performance target is the specific and measurable goal that NC would like to achieve with this asset. In this case, NC would like to measure the percent compliance with the established NC standard, which is linked to the proposed Federal standards. The goal for percent compliance is further divided into three tiers (state, regional, sub-regional) where the statewide goal is 95 percent,

regional is 90 percent, and sub-regional is 80 percent. Additionally, NC would like to minimize the cost per foot per year for pavement markings.

6. NC minimum standard: The minimum standard for pavement marking retroreflectance, represented by a LOS "red" is defined in detail in Section 6.1.3 and shown in Table 6.1 below. The standard complies with proposed Federal standards and is clearly measurable.

6.1.2 Governing Regulations for Pavement Marking

Section 2.2 of the literature review established the current and anticipated regulations regarding pavement marking retroreflectivity. Although no standards are published yet, proposed standards will likely be published in the near future.

6.1.3 Overview of Finance and Budget Process

The NCDOT is moving towards a performance based budget process. This section provides a general description of the NCDOT pavement marking budget process. It identifies service life as the key pavement marking performance measure that impacts budget decisions.

The budget evaluation was accomplished by conducting two interviews with NCDOT personnel in August 2007. This first interview was with the NCDOT headquarters asset management office. The second was with the Division 6 traffic and assistant traffic engineers. The WZTCU identified Division 6 as one of the leading divisions with regards to pavement marking management and is one of the primary reasons that Division 6 was chosen for the interview. Both interviews were conducted as a combined effort of the researcher

and Ms. Elizabeth Harris, who is currently researching NCDOT's sign management program. This was done to minimize the impact on the offices that were interviewed.

It was deemed unnecessary to speak directly with the NCDOT financial office since both groups interviewed work regularly with the budget but these groups work specifically with the pavement marking budget process. It was important, however, to interview both the headquarters and the division levels. The headquarters level interview gave a great deal of insight from a broad, state-wide perspective while the division level interview gave insight into the specifics of the budget process. Both groups interviewed understood the budget process well and both provided consistent answers about the process.

NCDOT follows an annual budgeting cycle where division funds are divided into budgeting categories (buckets) based on the following: primary roads, secondary roads, general maintenance reserve, and system preservation. Special item funding can be designated by the Board of Transportation to go towards inmate work crews, condition assessment, and emergency funds. Once designated, funds can not be moved from one bucket to another. However, funds can be balanced within a functional bucket meaning that money can be transferred from one area to another as long as it remains in the functional "bucket".

In all cases the headquarters distributes operations and maintenance funds for pavement markings based on two categories; primary roads or secondary roads. Interstates are a subset of the primary category. NCDOT headquarters drafts a spending and work plan by function code that is then forwarded to the division. The amount given to each division for operations

and maintenance is typically based on historical operations and maintenance costs and the number of lane miles and bridges in the division.

The divisions typically request primary and secondary funds by county. This money is then sent to the division traffic services unit. Balancing the operations and maintenance needs drives the division's traffic services unit to decide how much money goes towards pavement markings by county. Usually, most of the primary roads funding goes towards signs because pavement markings on primary roads are typically durable markings that last seven to ten years. The goal is to match the marking cycle with the resurfacing cycle. Thus, most primary road pavement markings are included in resurfacing projects. With very few exceptions, the divisions use only two kinds of pavement marking material which are paint and heat-in-place thermoplastics.

In the future, the Asset Management Unit would like to incorporate performance measures as the primary decision tool for balancing funds, at all levels, in the budgeting process. The goal is to move away from historically-based funding and move towards performance-based funding so that NCDOT can maximize the impact of each dollar spent. Performance based funding relies on accurate condition assessment data.

Condition assessments are based on the use of the maintenance management system (MMS) to analyze performance measures, function codes, tasks/work orders and to provide an "ideal" work plan. The MMS can determine how much funding it would take to reach a

certain performance target or what performance level can be reached given an amount of funding. The MMS can help identify deficiencies and target spending to high priority needs.

A condition assessment conducted by the NCDOT maintenance unit is paid for out of the maintenance fund. Condition assessments are conducted on a sample of roads every two years, except for interstate pavements which are inspected annually. Additionally, accurate condition assessments are needed since the NCDOT senior leadership uses the assessments in seeking funds for the transportation budget.

The WZTCU is charged with managing pavement markings and implementing the standards and specifications. Additionally, the WZTCU is responsible for implementing the Federal standards once they are finalized. However, it is important to note that the WZTCU is outside the budget loop. They do not review the requirements or budgets submitted from the divisions nor do they review or approve the budgets distributed by the headquarters. The WZCTU's independence from the budget process limits their ability to manage pavement markings throughout the state. Even though they set the technical specifications and perform statewide training they have no financially based official role in the implementation of pavement markings.

6.1.4 Pavement Marking Retroreflectivity Level of Service

The concept of Level of Service (LOS) is widely understood throughout transportation management and is a methodology that applies classifications to subjectively rated areas of transportation management and design [AASHTO, 2004]. Traffic flow LOS classifications

are defined by AASHTO using an "A" through "F" rating scale. Each class is given a definition that is both qualitative and quantitative. Furthermore, the definitions are specific to the highway type.

Using the proposed Federal standards for pavement marking retroreflectivity as a guide, LOS thresholds are based on discrete intervals of retroreflectivity. The LOS increments and NC minimum standards are derived from existing pavement marking specifications for retroreflectivity. The standards were vetted through the NCDOT WZTCU, the unit that is ultimately responsible for pavement marking management for the NCDOT [Mcdiarmid, 2007].

Defining LOS classification ratings for retroreflectivity enables the research to combine quantitative analysis approaches with qualitative asset management concepts. Large variations in initial retroreflectivity levels have frustrated pavement marking researchers and prevented good modeling of the entire lifecycle of pavement markings. Using LOS classes will minimize the impact of retroreflectivity variations because the LOS approach assumes the starting values are above the required specification value for initial retroreflectivity value. It assigns all starting values the highest LOS classification.

The LOS determinations vary for material type and material color. Even though drivers are not concerned with what type of material is used the LOS increments are different between thermoplastics and paint. Recall that thermoplastics are durable markings and paints are non-durable. Their performance characteristics differ greatly. However, it is important to note

that lower standards for paint applications are considered acceptable because of the restricted application of paint based markings. Recall that paints are only used by NCDOT on low traffic volume roads with an AADT of 4000 or less.

All other constants do not influence the LOS determinations. LOS increments are consistent with the proposed Federal standards [Turner, 1998] and depend on the material type (either durable or non-durable) and also the material color (white or yellow). To be consistent with the proposed Federal standards the NCDOT LOS levels do not include lateral location and surface type.

Table 6.1 shows the five LOS increments that were established for and used in this research. The chart is broken down into two parts. The left columns contain the increment values for thermoplastic markings and the right columns show the increment values for waterborne paint markings. All values are in $mcd/m^2/lx$ and are rounded to the nearest whole number. The proposed Federal standards are separated into two sections based on the presence or absence of retroreflective raised pavement markings. NC has published guidance on the use of RRPM but does not mandate their application [McDiarmid, 2007]. Therefore the WZTCU determined that the minimum standards for NC should not include allowances for RRPM. The red LOS, highlighted in Table 6.1, indicates the minimum level for retroreflectivity that will be used by NC until the Federal standard is published.

Table 6.1. LOS Increments and NC Minimum Retroreflectivity Standards

LOS	Thermoplastics		Waterborne Paint	
	White	Yellow	White	Yellow
Blue (A)	≥ 275	≥ 210		
Green (B)	200-274	145-209	≥ 250	≥ 215
Yellow (C)	175-199	125-144	150-250	115-215
Amber (D)	150 - 174	100 - 124	100-149	65-114
Red (F)	≤ 149	≤ 99	≤ 99	≤ 65
All values are in mcd/m2/lx				

The five-tier color-coding concept for LOS was adapted from the NC condition assessment format. We chose it because of the simplified and easy to understand nomenclature consistent with current NCDOT asset management procedures. This follows the basic asset management principle, to organize and define asset conditions in a way that is easy to understand throughout all levels of the organization as well as political and public audiences [Cambridge Systems Inc., 2006].

A graduated scale was used where blue indicates the pavement marking is at the highest LOS and red indicates the pavement marking no longer meets the minimum requirements for NC pavement marking retroreflectivity. A letter system of A, B, C, D, and F is overlaid on the color coding to equate the LOS system to the current NCDOT condition assessment rating. The color coded ratings are necessary to allow for visual displays on maps where as a letter system would not work as efficiently. The scale in Table 6.1 gives specific quantitative values for each LOS increment. The following statements qualitatively define the LOS increments for NC pavement markings:

1. LOS Blue (A): This section of pavement marking is operating at the highest level of service with greater than five years of service life remaining. No action is necessary.
2. LOS Green (B): This section of pavement marking is operating sufficiently and is expected to have two to five years of service life remaining. No action is necessary.
3. LOS Yellow (C): This section of pavement marking is nearing the end of its effective service life and likely has one to two years of service life remaining.
4. LOS Amber (D): This section of pavement is within one year of failure and will likely need to be replaced in the next year's restriping schedule.
5. LOS Red (F): This section of pavement marking is below the minimum standard for pavement marking. There is no remaining service life left and this section should be replaced as soon as possible.

The proposed minimum Federal standards for retroreflectivity [Turner, 1998] were used to set the values for LOS Red (F). Specifically, the values for red in the thermoplastic column correlate to the same values proposed for freeways in the minimum Federal standards, while the red values for waterborne paint markings correlate to the same values for non-freeways with a speed over 45 mph. This was done based on the primary application of durable and non-durable materials in NC [NCDOT, 2006]. Upon publication of the Federal standards NC can easily update the LOS scale to reflect the appropriate minimum values.

NCDOT uses a three tiered system to prioritize assets. The highest tier is the statewide tier. Next are the regional tier and the sub-regional tier. The tier system is used to prioritize resources to maximize efficiency. As such, assets that are statewide receive a greater priority

in the system. Additionally, there is an expectation for these assets to be maintained at a higher level of compliance. For example, statewide tier pavement markings might have an expected compliance rating of 95 percent, where the regional tier is set at 90 percent and the sub-regional tier is set to 80 percent.

On 21 December 2007 the Manual on Uniform Traffic Control Devices was updated to establish regulations for sign retroreflectivity [FHWA, 2007]. The update states that DOTs are required to implement an assessment method or management method to meet minimum sign retroreflectivity standards as defined in the manual [FHWA, 2007]. Pavement marking retroreflectivity standards are expected to follow similar guidance. A key point is that DOTs have been given the flexibility to establish their own standards as long as they correspond to an engineering study and consider the standards established in the MUTCD. Of course NCDOT would like to achieve 100 percent compliance for pavement markings. However, funds are limited and a performance-based priority system needs to be implemented to maximize the effect of tax payer dollars. The goal is to use the tiered system to balance the approach across all the transportation assets.

Once the minimum standards were established the degradation rates from the modeling (described in Chapter 5) were used to establish the increments of the LOS categories based time increments defined above. Specifically, Table 6.1 uses the degradation rate of 2.09 mcd/m^2/lx per month for white thermoplastics and 1.80 mcd/m^2/lx per month for yellow thermoplastics. Additionally, a rate of 4.17 mcd/m^2/lx per month was used for paints. All values are rounded to the nearest 5 mcd/m2/lx. For example, white thermoplastics have a

minimum standard of 150 mcd/m^2/lx. To establish the amber category range the value of 2.09 mcd/m^2/lx per month is multiplied by 12 months. The resulting value is 25 mcd/m^2/lx. This is then added to the minimum standard of 150 mcd/m^2/lx resulting in a value of 175 mcd/m^2/lx. The increment value for amber is then set so that all values are less than 175 mcd/m^2/lx and greater than or equal to 150 mcd/m^2/lx

Figure 6.1 shows an example of how LOS classifications would overlay a generic pavement marking degradation curve. The longitudinal lines, labeled Blue to Red, represent the cutoff R_L values enumerated above. The curve represents the R_L degradation over time for a specific pavement marking material.

The proposed Federal standards are used to set the baseline for LOS increments. Keeping the LOS Red (F) static, any department of transportation could easily adopt the LOS concept as is or could adjust the LOS increments using their own degradation model. This flexibility is particular useful when translating pavement marking degradation asset management principles from a southern tier state like NC to a northern tier state with a dramatically different climate. The only necessary adjustments are in setting the actual ranges for a given LOS. With its own degradation model any state can easily translate the LOS scale by starting with the same LOS Red (F) increment and adjusting for a different degradation rate accordingly.

For example, the literature indicates that during the initial break-in period, pavement-marking retroreflectivity values may increase nonlinearly [Sarasua et al., 2003] as suggested

in Figure 6.1. However, to date no studies have been able to clearly define what the nonlinear curve looks like. Assigning the highest LOS possible to the initial value of retroreflectivity allows for fluctuations in pavement marking retroreflectivity that are assumed to increase during the initial break-in period. This can be done based on two assumptions. First, the initial retroreflectivity value could be well above the minimum threshold value. Second, the initial value could be close to the highest value that will ever be achieved throughout the pavement marking service life.

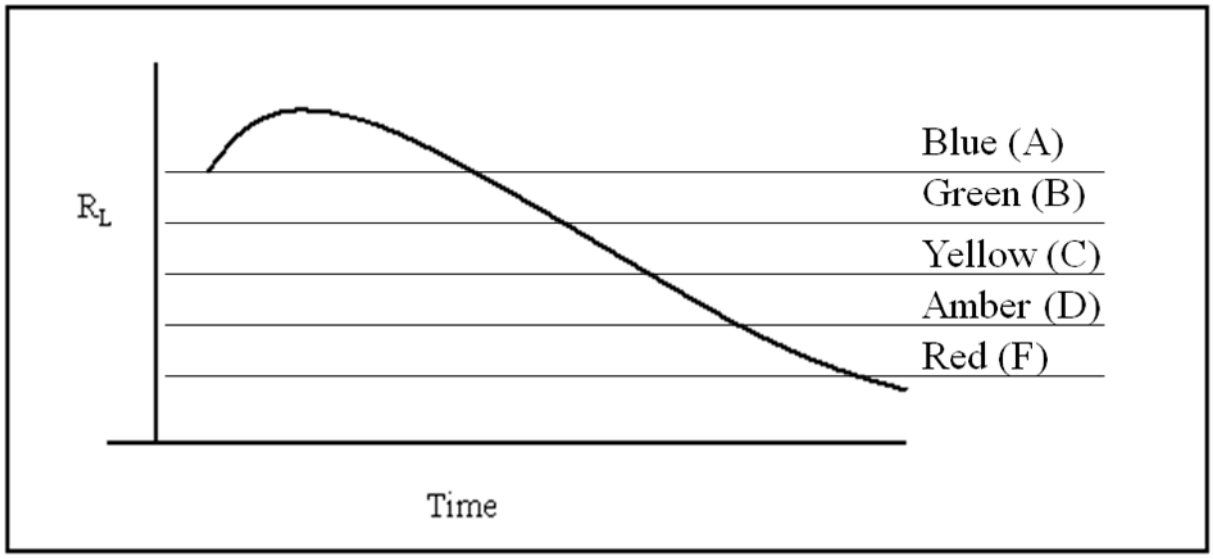


Figure 6.1. Presumed Pavement Marking Degradation Curve with LOS Increments

6.2 Assess, Develop, and Maintain an Asset Management Inventory

This section presents the key attributes and data collection necessary to effectively manage a pavement marking inventory both for performance modeling and holistic asset management. Following the presentation of the attributes is a data collection plan presented for pavement marking asset management. Finally, this section presents a summary of the current pavement marking inspection process.

The first step in managing an asset's inventory is to clearly define the attributes of the asset under consideration. Attributes are the characteristics of the asset that affect its performance. Attributes are those elements which provide a place, time, or some descriptive property of the system under consideration [Longley et al, 2005]. Transportation systems include hundreds of attributes that all have some influence on the overall system. However, several attributes can be viewed as critical components to a pavement marking system. Attributes influence the specific characteristics of pavement markings and are considered variables.

It is important to distinguish between the efforts achieved in modeling thermoplastics and paints in Chapter 5 and the need for a holistic assessment of pavement markings attributes and the inventory system used to maintain them. This section is focused on establishing the attributes and the data collection requirements necessary for system wide asset management of pavement markings. Performance modeling is a subset to holistic asset management and is designed to provide a performance-based managerial approach. Admittedly there is a great deal of overlap between Chapter 5 and Chapter 6 with regards to attributes.

6.2.1 Attributes for Performance Modeling

There are 12 key attributes that are important for conducting pavement marking performance modeling. The inclusion of these attributes in the analysis of pavement markings is based on three aspects. First, pavement-marking literature is a primary source of the attributes that contribute to performance. Second, the use of statistical methods, such as stepwise selection, is needed to evaluate the necessity of the attributes based on the available data. Finally, there

is a need to apply logical reasoning based on consistency and repeatability of the attributes across analysis procedures. Other pavement marking attributes exist and are included in Section 6.2.2; however, these 12 warrant a detailed description.

Most of the assets identified below are similar to the variables used to define pavement marking performance modeling. Recall from section 5.2 that only time, initial R_L, AADT, lateral location, and color were used in the chosen models for thermoplastics and paint. However, ongoing research is still exploring the performance characteristics of other materials and consideration of the rest of the attributes is essential for future performance modeling of pavement markings, a key step to performance based asset management. It is important to note that several of the attributes were not considered in the performance modeling because of the manner in which data were collected about the attribute. This will be further discussed in the data collection portion of this chapter.

The 12 key pavement marking retroreflectivity attributes (variables) include:

1. Retroreflectivity (R_L) – is a term used to describe the amount of light returned back to a driver from a vehicle's headlights as it is reflected from the pavement marking. This is the key attribute used to measure the effectiveness of pavement markings and is the dependent variable used in the mathematical modeling of pavement marking degradation. R_L is measured in terms of $mcd/m^2/lx$. For this research the R_L value is based on averaging the total number of readings for every tenth mile increment.
2. Material Type: This is an enumerated value and is the base material used to provide the retroreflective line. The most common are thermoplastics, paint, polyurea, and epoxy.

Each marking material can be defined in terms of more specific attributes such as material manufacture, product name, and cost per foot.

3. Time – is a continuous variable and is the most significant variable affecting degradation of pavement marking retroreflectivity. All pavement-marking studies reviewed included time as the most significant variable affecting retroreflectivity degradation. This is because time is really a surrogate for other physical processes related to exposure of the pavement marking. Weather, sunlight and AADT are all elements that make up exposure and the trick is separate these elements that make up time to better understand its influence. In this research AADT is separated from time but in other research AADT is incorporated under time. In this case time is measured in months. There is a time measurement (date) for each instance of a retroreflectivity data collection run, for example, initial, 6 month, 1 year, etc.

4. Initial Retroreflectivity (R_{Li}) – is a continuous variable measured in mcd/m^2/lx. This variable is the initial value of retroreflectance and is measured within the first 30 days of application of the marking. R_{Li} is measured in terms of mcd/m^2/lx.

5. Lateral location – is a categorical parameter that is defined by the transverse position of the pavement marking on the roadway. This variable was included because of the intuitive perception of different vehicle wear attributed to the location of the line on the roadway. This parameter has two positions: edge lines or middle lines. For the purpose of this study centerlines and skip lines are both defined as middle lines. Note that in a more complete data set these could perform differently too.

6. Color – is a categorical parameter that defines the color of the pavement marking material. In this study color is either white or yellow.

7. Width – is an ordinal parameter and defines the width of the pavement marking. Two widths were considered in this study. Both four-inch and six-inch marking widths since these are the most commonly encountered. Note that actual widths may vary.

8. Thickness – is an ordinal parameter and defines the thickness of the pavement marking material measures in mils. In this study the thermoplastics were set at 90 mils or 120 mils. Note that actual thickness may vary.

9. Bead type – glass beads enable a pavement marking to be retroreflective. There are three major bead types used (standard, large, and highly reflective).

10. AADT – Annual average daily traffic is a continuous parameter that measures the volume of traffic on the roadway in vehicles per day. The AADT values used in this study are from the year 2006. Sarasua et al. argued that AADT was not statistically significant and was accounted for as a function of time. However, in our model this variable was statistically significant and included which is consistent with previous report by Abboud and Bowman [2002], which indicated that AADT had a significant impact on pavement marking degradation apart from time.

11. Snow Plow – is a categorical parameter and is defined by the presence or absence of snowplowing on the road segment. This attribute is suspected of having a greater influence of pavement marking performance and future collection of snow plow data should include the number of time per year a road segment is plowed.

12. Region – is a categorical parameter that represents one of the three major regions in NC. Theses regions are defined as coastal, piedmont, and mountain. The diversity of the climate and size of the population of NC warrant the exploration of this parameter in pavement marking degradation studies. Region is suspected of having a greater influence on pavement marking performance throughout the US because of the diverse climate nationally.

6.2.2 Attributes for Asset Management

Performance-based pavement marking management requires the inclusion of a large set of attributes that go beyond those needed to analyze the performance characteristics of pavement markings. This is because of the large number of factors that fall under the control of decision makers. Table 6.2 through Table 6.4 summarizes a list of attributes used for pavement marking asset management. Although the list is not necessarily comprehensive it provides the basis from which to organize a pavement-marking database. Additionally, the list begins to identify other attributes that are maintained throughout the NCDOT such as cost per foot or application contractor.

Table 6.2 presents pavement marking specific attributes that are not needed anywhere else in the DOT. Table 6.2 contains general attributes common to all pavement markings. These attributes are static for a given road segment and once in place these attributes will not change for the duration of the pavement markings service life. For example, the material type or color will remain constant independent of the temporal aspect of the database.

Table 6.3 contains the specific pavement marking retroreflectivity data separated by a unique time increment. Each section can be maintained as a separate attribute table since the retroreflectivity value will change over time. There is a distinct advantage to dividing the values into subsections which is the reduction in time it takes to retrieve and manipulate data. This is a distinct advantage when databases maintain information on tens of thousands of miles of roads. Alternatively, all the pavement marking attributes could be maintained in a single database table to reduce the overall complexity of the database. However, a single database table is more cumbersome and could slow down retrieval of data. This becomes less of an issue with the ever increasing speed of computers.

Table 6.4 contains the pavement attributes and identifies key attributes that affect pavement markings that are common to the entire road network. These attributes are collected and maintained by other departments within the DOT. The particular database is identified in the last column. For example, the traffic survey unit is responsible for estimating the annual average daily traffic values. These data are maintained in the universe file and it is inefficient for the pavement marking unit to collect and maintain these data when the AADT can be retrieved from the universe file.

Table 6.2. Pavement Marking Installation Attributes for Asset Management

Pavement Marking Attribute	Type of Data	Modeling	Data Maintained by
Place ID	Categorical	X	NCDOT GIS Unit
Color	Categorical	X	WZTCU
Type Marking Material	Categorical	X	WZTCU
Lateral Location (Type)	Categorical	X	WZTCU
Thickness (mils)	Categorical	X	WZTCU
Width (Inches)	Categorical	X	WZTCU
Bead Type	Categorical		WZTCU
Cost of marking material per foot	Continuous		WZTCU
Manufacture/Product name	Categorical		WZTCU
Application Contractor	Categorical		WZTCU
Air temperature during application	Continuous		WZTCU
Total length of pavement marking	Continuous		WZTCU
Application date	Continuous	X	WZTCU
Device used to collect RL	Categorical	X	WZTCU
GPS Coordinates	Continuous		All

Table 6.3. Pavement Marking Time-based Retroreflectivity Attributes

Pavement Marking Attribute	Type of Data	Modeling	Data Maintained by
Initial Pavement Marking Retroreflectivity Data			
Place ID	Categorical	X	NCDOT GIS Unit
RL Initial	Continuous	X	WZTCU
Date Initial RL	Continuous	X	WZTCU
Number of Valid Scan Initial	Continuous	X	WZTCU
Chainage Initial	Continuous	X	WZTCU
6 Month Pavement Marking Retroreflectivity Data			
Place ID	Categorical	X	NCDOT GIS Unit
RL 6 Month	Continuous	X	WZTCU
Date 6 Month RL	Continuous	X	WZTCU
Number of Valid Scan 6 Month	Continuous	X	WZTCU
Chainage 6 Month	Continuous	X	WZTCU
Recurring Pavement Marking Retroreflectivity Data			
Place ID	Categorical	X	NCDOT GIS Unit
RL	Continuous	X	WZTCU
Date RL	Continuous	X	WZTCU
Number of Valid Scan Annual	Continuous	X	WZTCU
Chainage Annual	Continuous	X	WZTCU

Chainage – is the tenth mile increment for the road segment under consideration. The value always starts at zero from the beginning road segment node and increases in tenth mile increments until the segment run ends.

Table 6.4. Pavement Attributes for Pavement Marking Asset Management

Pavement Marking Attribute	Type of Data	Modeling	Asset Mgmt	Data Maintained by	Table Name
Place ID	Categorical	X	X	NCDOT GIS Unit	PlaceID
Surface Material	Categorical	X	X	NCDOT GIS Unit	Surface Type
AADT	Continuous	X	X	NCDOT GIS Unit	AADTxx
Snowplow activity	Continuous		X	State Maintenance	
Presence of RRPM	Categorical		X	State Maintenance	
Division	Categorical		X	NCDOT GIS Unit	Counties
County	Categorical		X	NCDOT GIS Unit	Counties
Number of Lanes	Enumerated		X	NCDOT GIS Unit	Through Lanes
Speed of road segment	Interval		X	NCDOT GIS Unit	Speed Limit
Pavement maintenance activities	Categorical		X	State Maintenance	
Projected maintenance activities	Categorical		X	State Maintenance	

6.2.3 Data Collection Plan

The objective of the data collection plan is to define the data collection requirements for NCDOT to effectively manage pavement markings beyond what they are already doing. A full copy of the data collection plan was submitted to NCDOT on 30 Sep 2007 as part of the research quarterly report. The basic structure of the data collection plan is as follows:

- Summarization of retroreflectivity data collection standards
- Evaluation of the current retroreflectivity technology
- Evaluation of the current data collection method
- Determination of what data have already been collected
- Evaluation of the quality of the data already collected
- Determination of what data should be collected in the future

6.2.3.1 Summary of Retroreflectivity Data Collection Standards

Section 2.0 of the literature review presents an overview of pavement marking retroreflectivity and the standards used to collect retroreflectivity data.

6.2.3.2 Evaluation of Current Retroreflectometer Technology

Section 2.3 of the literature review presents an evaluation of six retroreflectometers that were considered as part of the Highway Innovative Technology Center (HITEC) review of retroreflectometer technology. Four of the six units were handheld devices and two were mobile units. The four handheld units evaluated were LTL 2000, MX30, MP-30, and FRT01. The two mobile units evaluated were the ECODYN and the Laserlux.

In June of 1999 NCDOT hosted a field evaluation of various retroreflectivity collection devices. During the evaluation NCDOT personnel determined that the Delta LTL 2000 was the best handheld unit and that the Laserlux was the best mobile collection device for collecting retroreflectivity data on NC's roads [McDiarmid, 2001].

The NCDOT has fully funded the fielding of the LTL-2000 resulting in each division having their own handheld device. Additionally, the NCDOT has a statewide contract with Precision Scan LLC to collect retroreflectivity data throughout the state as necessary by using a modified Laserlux. Currently, the contractor collects pavement marking data on approximately 10 percent of the roads in NC.

6.2.3.3 Evaluation of the Current Data Collection use in NC

Section 3.1 presented a detailed account of the NCDOT's current pavement marking retroreflectivity data collection. Section 3.1 presented a detailed review of the mobile collection device, organization of the data files, location referencing, and calibration of the mobile device.

6.2.3.4 Evaluate the quality of the data already collected

The overall quality of the data collected by Precision Scan is considered to be pretty good. Previous studies have had difficulties in dealing with large variations in the data due to the use of mobile collection devices. Using a large dataset and an extensive calibration process eliminated many of these concerns. However, an overall assessment of the data collection process yielded a few concerns in managing the collected data. These are summarized below.

1. The ability to clearly identify a road segment is a crucial aspect for good asset management. Inconsistent nomenclature in the *runinstance* field of the retroreflectivity tables made it difficult to ensure consistency from one year to the next. Use of a consistent LRS and naming convention that is compatible across NCDOT would significantly improve the analysis of data. Furthermore it would enable the integration of this database with other NCDOT databases, specifically the NCDOT universe file. A primary key, which uniquely identifies each entry, needs to be established for pavement markings. The primary key needs to be compatible with the NCDOT universe file and

enable the linkage between a localized pavement-marking database and other key NCDOT attributes found in the universe file.

2. In many cases the non-available data were recorded with a value of zero. This makes the assumption that the value is actually zero and not missing. In all areas where data are unavailable leave the cell blank so that the statistical software can deal with the missing data appropriately. Statistical software counts a zero as a value, which skews the analysis. Unavailable data recorded as a zero requires an extensive effort to clean the database and replace all zeros with blank cells.

3. All data should be recorded with a single value per cell. This is specifically a problem for snowplowing where multiple entries are recorded into a single cell. For example, a cell for a road segment for one year will be recorded as [(2)(3)(3)(5)]. This inhibits the use of the data entirely. The data should be recorded as either a total value (for example, 13) or in multiple columns.

4. The database should be accompanied with a companion file (metadata) that identifies each field in the database and provides a complete and clear definition of the field. The definition should include an explanation of the units.

5. Units should be labeled in the column header and provide a clear description of the values recorded in that attribute column. If units are recorded in the cell this reduces the data to the lowest level and it is recorded as nominal data. For example, record thickness as 90 and not 90 mil. In this example the units from the data cells must be "cleaned" if the data are to be used as continuous and not nominal data.

6. All data should be classified into one of four categories and should be recorded in its most influential form which is defined by the hierarchy list below:

    a) Continuous: provides the most realistic representation of the real world by recording numeric values with an infinite number of variables.

    b) Interval: provides a ranking with discrete increments between values

    c) Ordinal: provides ranking between values with no sense of value between variables.

    d) Nominal or categorical: provides only descriptive information about the data

6.2.3.5 Future Data Collection Recommendations

These recommendations were provided specifically to the research steering committee for NC pavement markings. However, the recommendations should be considered by any state or federal highway agency planning to collect pavement marking data.

One objective during future data collection is to maintain continuity on the temporal stream. As such, an effort should be made to continue to collect data on all of the road segments identified in the database. However, a priority should be given to continuing to collect data on road segments with previous pavement marking data in the database. Continued data collection will grow the temporal aspect of the data significantly and greatly improve the capability of future analysis.

Future data should be organized and recorded using an LRS with a primary key field that specifies road segment under consideration. It is recommended that the primary key field be consistent with the NCDOT universe file and enable spatial recognition of the road segment by the NCDOT GIS unit. The "Place ID" primary key found in the NCDOT universe file is a viable solution and will ensure integration with other NCDOT databases [Smith et al., 2001]. According to Smith et al, the Place ID field is a unique name/label given to the segment of road under consideration [Smith et al., 2001].

Alternatively, latitude and longitude coordinates have been collected in 2006 and 2007. Using the GPS coordinates is another viable option for identifying the road segment under consideration and assigning retroreflectivity values to a road segment. This is a supported LRS by the NCDOT [NCDOT, 2006]. However, it is important to note that use of the coordinate system requires post-processing of the data. Routes must be created and the GPS coordinates must be "snapped" to the route. This can be done in ARCGIS but could require a great deal of work for a large database.

Determining the right sample size for future paint data collection is necessary so that the result is meaningful. Alternatively, collecting too much data is time consuming and costly. A minimum sample size of 30 would be appropriate based on the central limit theorem [Rao, 1998]. This allows us to apply a normal distribution to the data and fairly represent the true population [Rao, 1998]. However, at 30 samples we need to still understand the margin of error, which is the difference in the mean of the observed values of retroreflectivity compared to the true mean of retroreflectivity.

Using the 2006 paint data, a standard deviation of 54 mcd/m^2/lx was calculated. From this a sample size was estimated using equation 6.1. Two key things are presented here. First, the estimated sample size of 50 data points was calculated given a 95 percent level of significance and a margin of error of 15 mcd/m^2/lx. Second, using equation 6.2 the margin of error was calculated at 19 mcd/m2/lx with a sample size of 30.

$$\text{Sample Size} = (Z^*\sigma/E)^2 \qquad (6.1)$$

$$\text{Sample Size} = (1.96^*54/15)^2 = 49$$

$$\text{Margin of Error} = Z^* \sigma/ \sqrt{n} \qquad (6.2)$$

$$\text{Margin of Error} = 1.96^*54/\sqrt{30} = 19 \text{ mcd/m}^2\text{/lx}$$

This would mean that 30 data collection sites are needed for each category to obtain a margin of error equal to 19 mcd/m^2/lx. To minimize the margin of error to 15 mcd/m^2/lx would require increasing the sample size to 50 data collection sites. On average one year of degradation for paints is approximately 50 mcd/m^2/lx which corresponds to one LOS increment in our scale. So accepting a margin of error at 19 mcd/m^2/lx should be adequate for data collection.

Furthermore, a larger sample size of 35 to 40 is recommended since it is likely that several of the sites could be compromised and be removed from the database over a period of three to

five years. Keep in mind that removal of samples will introduce a bias into the process. If samples are removed because they have failed and were replaced this has implications on the performance of pavement markings. The extra samples are intended for samples that are removed from external factors such as a pavement overlay.

Tables 6.5 and 6.6 represent all the categories of interest for NCDOT pavement markings. Table 6.5 represents the durable markings while Table 6.6 represents the non-durable markings. In each category the goal is to collect retroreflectivity data on 35 to 40 road segments for the full life-cycle of the material. In many of these categories significant amounts of historical retroreflectivity data have already been collected. With the exception of future calibration, once a DOT has a good equation for a given material and set of variables, that the need for continued data collection goes away.

It is noteworthy to say that limitations in the data are not a lack of continued data collection but a delayed start in collecting the data. For example, the 56 road segments of thermoplastics were started by NCDOT in 2001 and then more and more road segments were added each consecutive year. Therefore, a significant effort should be made to continue to collect retroreflectivity data on all of the thermoplastic, polyurea and hot spray road segments already in the database. This will continue the temporal stream of data and enable future research to better model those materials.

Paints make up the overwhelming majority of pavement markings and warrant further data collection. The paint data in the 2006 database were limited since the study used existing

data collected only at the initial, six-month, and one-year increments. In the future we highly recommend an increased frequency in the data collection rate for paints. This is based on the assumption that mobile retroreflectometers can collect enough data to minimize variations in the data but increase frequency would offer better insight of the degradation rate of a material that only has a two year life expectance.

For example, lateral location is believed to impact paint degradation but the degradation rates are high and the varying rates are not captured in yearly increments. Section 5.3.2 presented results that suggested the paint data come from different populations separated by color and lateral location. Increased frequency in future data collection should provide insight as to the impact of color and lateral location on the degradation. Furthermore, the data should be collected for the full life-cycle of the material which could be up to three years.

Table 6.5. NC Durable Categories Included in Research

Pavement Type	Material Type	Color	Location
Asphalt	Thermoplastic	White	Edge
Asphalt	Thermoplastic	White	Middle
Asphalt	Thermoplastic	Yellow	Middle
Asphalt	Thermoplastic	Yellow	Edge
Asphalt	Hot Spray Thermo	White	Edge
Asphalt	Hot Spray Thermo	White	Middle
Asphalt	Hot Spray Thermo	Yellow	Middle
Asphalt	Hot Spray Thermo	Yellow	Edge
Concrete	Polyurea	White	Edge
Concrete	Polyurea	White	Middle
Concrete	Polyurea	Yellow	Middle
Concrete	Polyurea	Yellow	Edge

As a southern tier state the climate in NC limits the amount of snowplowing. Furthermore, most of the snowplowing is in the western part of the state. In the 2006 database the data

collected for the snowplow variable were categorical, meaning that only a "yes" or a "no" was recorded if a road segment was plowed. Alternatively, future research should collect continuous data on snow plowing; recording the number of times a year that a road segment is plowed and then exploring the impact that plowing has on pavement marking degradation. Having the maintenance units collect snow plow data could be a cumbersome task but is one way to capture this data. An alternative is to establish some test sections in an area with a high plow rate. This could minimize the burden of collecting data to a limited but focused effort. As mentioned in the example above, continuous data were collected on snow plowing but the manner in which it was recorded reduced the values for this attribute to a nominal level only.

Table 6.6. NC Non-durable Categories, for Future Research

Pavement Type	Color	Location
Asphalt	White	Edge
Asphalt	White	Middle
Asphalt	Yellow	Middle
Asphalt	Yellow	Edge
Concrete	White	Edge
Concrete	White	Middle
Concrete	Yellow	Middle
Concrete	Yellow	Edge

Collecting data past the service life is an important step in fully understanding the performance characteristics. Mostly since some markings will be out there past their service life. The literature indicated in some cases that marking materials degrade as a logarithmic decay pattern. However, collecting data on active pavements does not allow for the full development of the degradation pattern because active pavement markings require replacement of the material at a point before drivers are affected. This process does not

allow for full degradation of the material and a true understanding of the performance characteristics. The designation of a test section would allow for detailed evaluation to explore the full degradation of material. The section would need to be short enough to minimize the risk to drivers exposed to failed pavement markings. Data collected from this test facility would enable researchers to fully model pavement marking degradation.

6.2.4 Pavement Marking Inspection and Data Collection Process

There are three major players that perform pavement marking inspections and data collection in NCDOT. They are the WZTCU, the State Maintenance Unit, and the individual divisions. Each player performs a different kind of inspection on pavement markings and collects a different set of pavement marking data. A brief description of each is included below.

6.2.4.1 WZTCU

The WZTCU unit is charged with setting standards and specification for pavement markings. Additionally, they are the lead unit responsible for implementing the legislative standards that will require minimum retroreflectivity levels for pavement markings. As such, the WZTCU collects pavement marking retroreflectivity data using both the handheld LTL 2000 and also a contracted Laserlux mobile collection device. The data collected are used for managing NCDOT's pavement marking specifications and was used in this research for developing the performance characteristics of pavement markings in NC. Section 3.1 gives a detailed description of the data collection used by the WZTCU.

6.2.4.2 State Maintenance Unit

The State Maintenance Unit collects pavement marking data through the Maintenance Condition Assessment Program (MCAP). These data are used to provide a statewide condition of roadside appurtenances. The MCAP is conducted biennially. The last MCAP was conducted in 2006 with the next assessment scheduled for 2008. The purpose of the MCAP is to provide a statewide condition assessment of all roadside appurtenances. Pavement, bridges and other assets are evaluated under different programs.

The MCAP looks specifically at five elements:

1. Unpaved shoulders and ditches
2. Drainage
3. Roadside
4. Traffic control device
5. Environmental

Pavement markings fall under the traffic control device element which assesses four subcategories:

1. Traffic signs
2. Pavement striping
3. Words and symbols
4. Pavement markers

The MCAP assessment is a manual inspection where the inspectors walk two tenths of a mile of road segment evaluating all the elements identified above. The total inventory and the condition of each element are recorded on a one-page worksheet.

The road segments are picked randomly following the procedures outlined by Foyle et al. [2006]. The road segments are identified using the primary LRS system, which is a route-based beginning mile-post and end mile-post system. All the location information, including directions, is recorded on the top of the form. The form includes the inspector's names, dates, city, county, and division information.

The basic structure is to determine the total amount of a given asset in that section of road and then determine percent of the asset that is deficient. This is a manual assessment performed by inspectors who walk each road segment that is evaluated. The amount of inventory is first defined by determining the total length of pavement striping in the segment. For example, if a typical two-lane roadway is being inspected (with edge lines and double yellow centerlines), the total pavement striping length will be 4,224 feet (0.2 mi x 5,280 ft/mi x 4 solid lines). If assessing a five-lane road (two through lanes each direction with a two-way left-turn lane) the total length will be 5,280 feet (0.2 mi x 2,280 ft/mi x 4 solid lines + 4 broken lines at 0.2 mi x 5,280 ft/mi x 10 ft/40 ft). Next, the total number of feet that are worn, missing, or obliterated is recorded.

The form is then loaded into an Oracle database. This is later translated into a Microsoft Access database where the State Maintenance Unit then cleanses the data using a series of

SQL functions. For example, a value outside of a logical range would be reviewed and corrected or thrown out.

Finally, the number of deficient feet of the asset is divided by the total number of feet of asset to determine the percent deficient. This is then translated into a statewide condition based on the sampling process.

6.2.4.3 Division Inspections

The current division-level procedures for NCDOT pavement marking inspection of existing markings vary by division but all seem to follow a similar process. That process is typically a windshield inspection that assesses the asset in terms of "present, visible, reflective at night".

The rates of inspection vary by division but the most typical pattern is an annual inspection for primary roads and a biennial inspection for secondary roads. Typically the inspections are conducted by the pavement marking crew supervisors or the division traffic engineer. Records of the inspection process also vary by division but the most common methodology is a hardcopy map of the road system. For instance, Division 6 uses a map and then highlights each road with a color system to reflect when it was inspected and when it was remarked.

Qualifications for the inspectors are typically based on years of experience in marking and remarking operations. Most inspectors have led marking road crews and have a good idea, at least visually, of the condition of the pavement marking. Recall from Section 2.3 that visual

inspections are subjective in nature but the literature has established that a trained individual can be effective in determining the quality of a pavement marking. This approach is less technical than using retroreflectometers but meets the needs of the division in prioritizing what roads will be remarked.

It is important to note that division marking crews deal only with paint-based markings and generally have a good idea of the performance characteristics of paints. A typical division approach is to remark, with paint, based on an annual or biennial cycle. For instance, Division 6 follows a remarking schedule for paints where all primary roads are remarked annually and all secondary roads are remarked biennially. There are exceptions to this rule but it does provide a general sense of the process. With these policies in place, the visual inspection process is more than adequate to meet the needs of the divisions.

6.3 Pavement Marking Database Management and Modeling

Longley argues that there are four major phases to developing a working model of the real world [2005]. The first phase understands the reality of the system and what are the major components that influence the system. Second is the development of a conceptual model. Third is the development of a logical model, and finally, the physical model.

This section presents the conceptual, logical, and physical models developed for asset management of pavement markings. In addition to the database models, an algorithm was developed and is presented along with an ARCGIS-based example established from the algorithm.

6.3.1 Conceptual Model

Figure 6.2 shows a proposed conceptual model that was developed for the pavement marking management system. As discussed in Section 2.1.3, the conceptual model is a partially structured representation of selected objects and processes that are relevant to pavement marking management. The purpose of the conceptual model is to shape the scope of the model. This was done by identifying the information needs and the major components of the system.

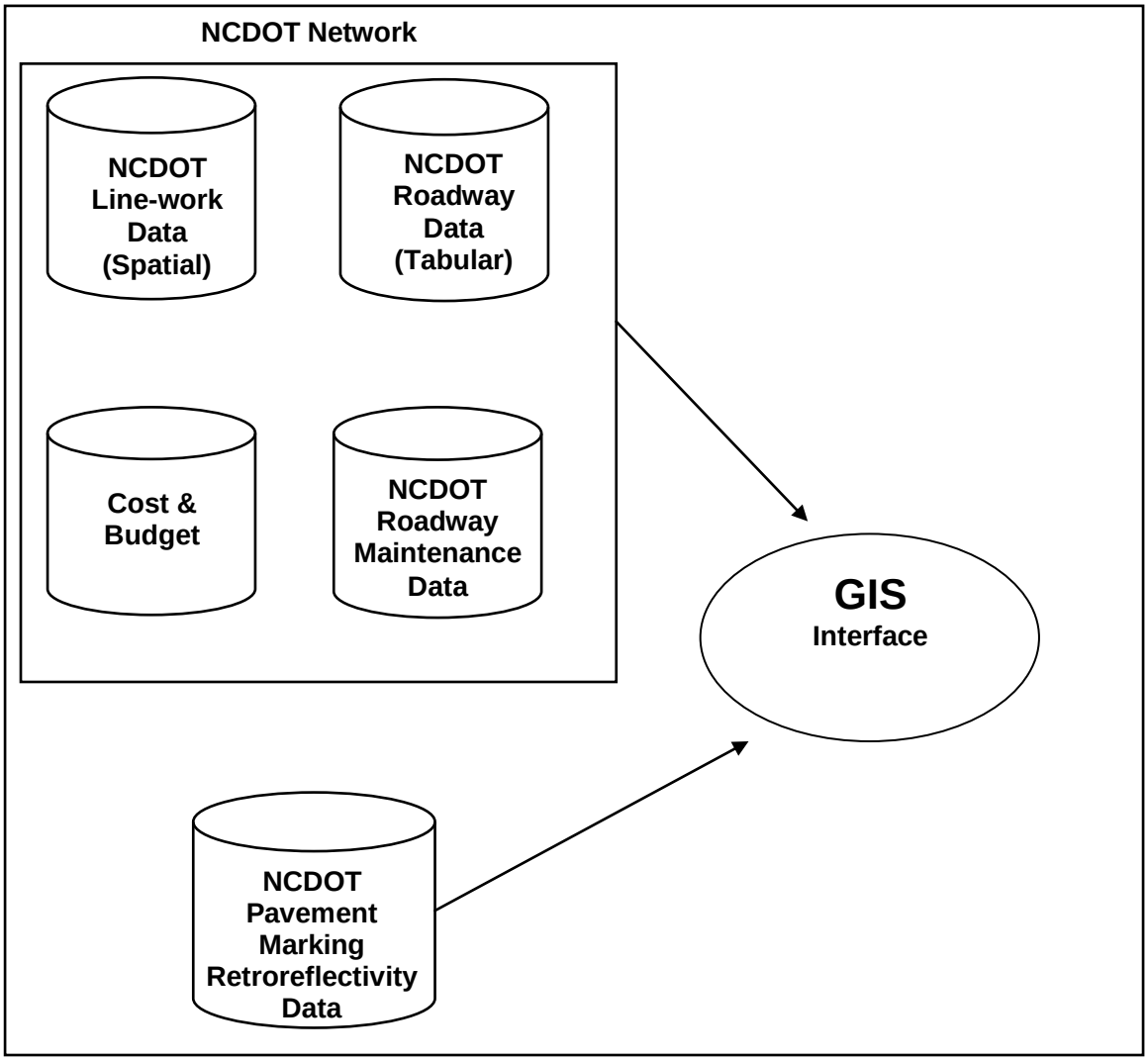


Figure 6.2. Pavement Marking Management System Conceptual Model

As defined by the performance target in Section 6.1.1, NC's primary interest or information need is the value of retroreflectivity for a given section of roadway. The retroreflectivity value represents the information while the comparison to the minimum standards represents the knowledge required to make effective decisions regarding pavement markings.

The various forms of data are all brought together in a GIS interface that combines spatial and non-spatial information about pavement markings. The different data are collected and maintained in different departments all within in the NCDOT network. This includes both spatial and non-spatial roadway data and financial data. The GIS application pulls data from various existing databases and combines them with pavement marking retroreflectivity data necessary for pavement marking management.

There are three basic elements to the pavement marking data management system conceptual model. These are:

1. The NCDOT database network
2. Pavement marking retroreflectivity database
3. A GIS user interface

6.3.2 Logical Model

As discussed in Section 2.1.3, the next step translates the conceptual into a logical model, which is an implementation-oriented representation of reality that is often expressed in the terms of diagrams and lists. Figure 6.3 shows the logical model, which takes the basic

structure of the conceptual model and further develops it by identifying the particular database elements and the relationships between them. The three major components of the logical model are the NCDOT network, the NCDOT pavement marking database, and the GIS software.

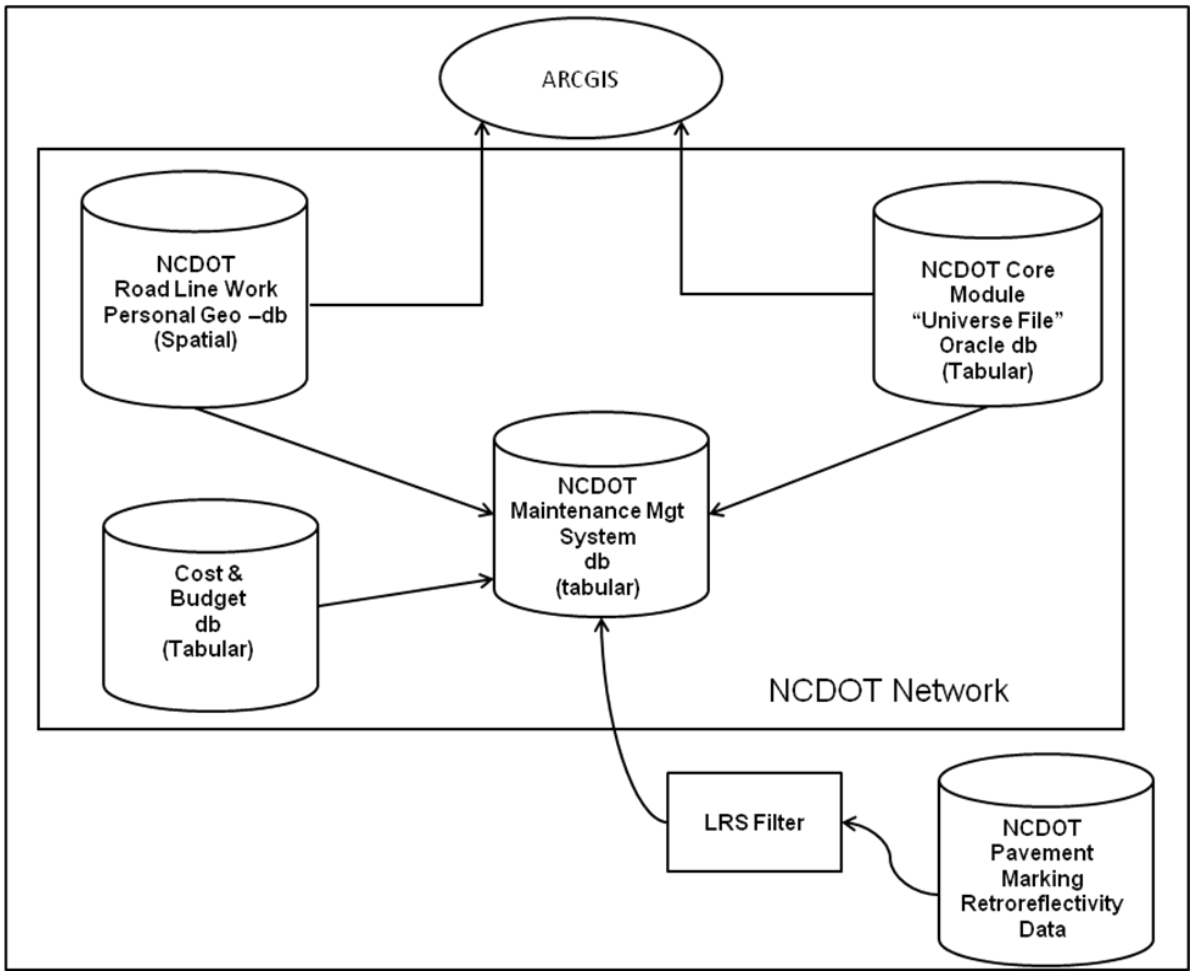


Figure 6.3.Pavement Marking Management System Logical Model

Within the existing network are four elements that affect pavement markings. The road line work and core module (universe file) databases work together to provide the necessary spatial and attribute data while the maintenance management system and cost databases provide the condition-state for a roadway segment. A brief description of each element of the network component is presented below.

1. The road line work database contains enough spatial information about roadways to analyze and manage pavement markings.
2. The core module, also known as the universe file, is the roadway database which contains attribute information about roadways.
3. The cost and budget database contains financial information on operations, maintenance, and repair.
4. The maintenance management system contains data on maintenance and repair work conducted on a road segment.

The second element is the existing pavement marking database which is a Microsoft Access database. Section 3.1.1.2 defines the structure of the existing pavement marking database in detail. The current location referencing system used in the pavement marking database limits an analyst's ability to spatially locate retroreflectivity data in a GIS. In 2006 and 2007 GPS-based latitude and longitude coordinates were included in the pavement marking database. With the GPS coordinates the database can be linked to the existing network via a location referencing system filter that is already in place.

The third element is the GIS interface. ARCGIS is the software package of choice for the GIS component. This is a common GIS software package in use by many highway agencies.

6.3.3 Physical Model

The physical model, introduced in Section 2.1.3, is the database schema that portrays the actual implementation in a GIS. Development of the physical model is the final step in

developing a data management system before actual implementation. In the physical model all the necessary components are identified as well as the specific tables needed in each component. Furthermore, key relationships between databases are also defined in this step.

Using Enterprise Architect software [Sparx Systems, 2008], the ontologies for the physical model were developed. The model is further defined by a data schema which in ontological terms represents the basic object. The object is further defined by individual tables each representing a different class within the object. For each class a set of attributes is defined and finally the relationships between the classes and the object were defined. The purpose of using data modeling software is to create the architecture of a database by building the necessary tables and relationships in a machine language. Enterprise Architect software has the capability to export a data schema into a variety of database formats. For example, this software will easily import into Oracle, Microsoft Access, and SQL databases.

The basic output file generated from the pavement marking data schema is an extensible markup language (XML) file. XML files are expected to become widely accepted and a new interface standard [Halfawy and Froese, 2007]. The advantage to using an XML file is the ease in which the data structure can be shared among various information systems. A distinct advantage with software-generated XML files is the ability to define the specific type of database system that the XML will be imported into. This helps in defining the correct semantics needed to function correctly. A copy of the XML file is located in Appendix B.

The NCDOT MMS uses an Oracle database and becomes the hub for this data model. Importation of the XML file is one way to implement the data schema. However, the MMS also has a front-end software package that will structure the pavement marking database tables. This software package works in a similar way to the Enterprise Architect software but has the advantage of implementing the appropriate menus and windows that would be compatible with the existing system.

To ensure that the data schema could be implemented an XML file was generated for a Microsoft Access database. Once generated, the data schema was exported as an XML file. The XML file was then successfully imported into a Microsoft Access database and the correct table structure was verified. A copy of the MS Access relationship diagram showing the successful importation can be viewed in Appendix B.

6.3.4 Normalization

When structuring tables for a database model it is important to normalize the structure. This means that one needs to consider eliminating redundant data and ensure that data dependencies make sense. The first aspect of normalization is to eliminate redundancy in the data. This can be achieved by establishing the appropriate cardinality in the relationship between tables. In this case the cardinality between tables is a one-to-many relationship. For any given road segment, identified using the LRS with placeID as the primary key, there are multiple tables that each represent a different point in time. For example, for the proposed data schema any road segment might have initial, six-month, and annual retroreflectivity values each represented in a separate table.

Regardless of where the attributes reside the value of the attributes remain independent. Additionally, there can be only one attribute value for each road segment. One way to reduce the one-to-many relationship is to consolidate all the tables into a single table where each temporal value would be represented in a different field. Consolidating the structure into a single table would reduce the cardinality to a one-to-one relationship but this was dismissed for several reasons. First, data retrieval would be faster as separate tables. Second, data are collected by various sources and it was determined to structure the data schema so that each table would represent a single data collection effort. Third, this structure enables individual divisions to maintain their own data.

The second aspect to normalizing the database structure is grouping data into functional areas which make sense. This was achieved by dividing the database tables using a temporal theme. The initial marking table contains all the static characteristics of pavement markings. Each additional table maintains only the attribute values that would change over time and the key used to link to other tables. Although data storage is relatively cheap and calibration issues may warrant keeping the original installation data the table could be replaced with a new installation data when a segment of road is remarked.

6.3.5 Data Model Diagrams

Figure 6.4 shows the physical model that was generated with Enterprise Architect software. Figure 6.5 shows the pavement marking data schema which is represented in the physical model as the pavement marking database. Listed below are the definitions of each database component and the relationships between them.

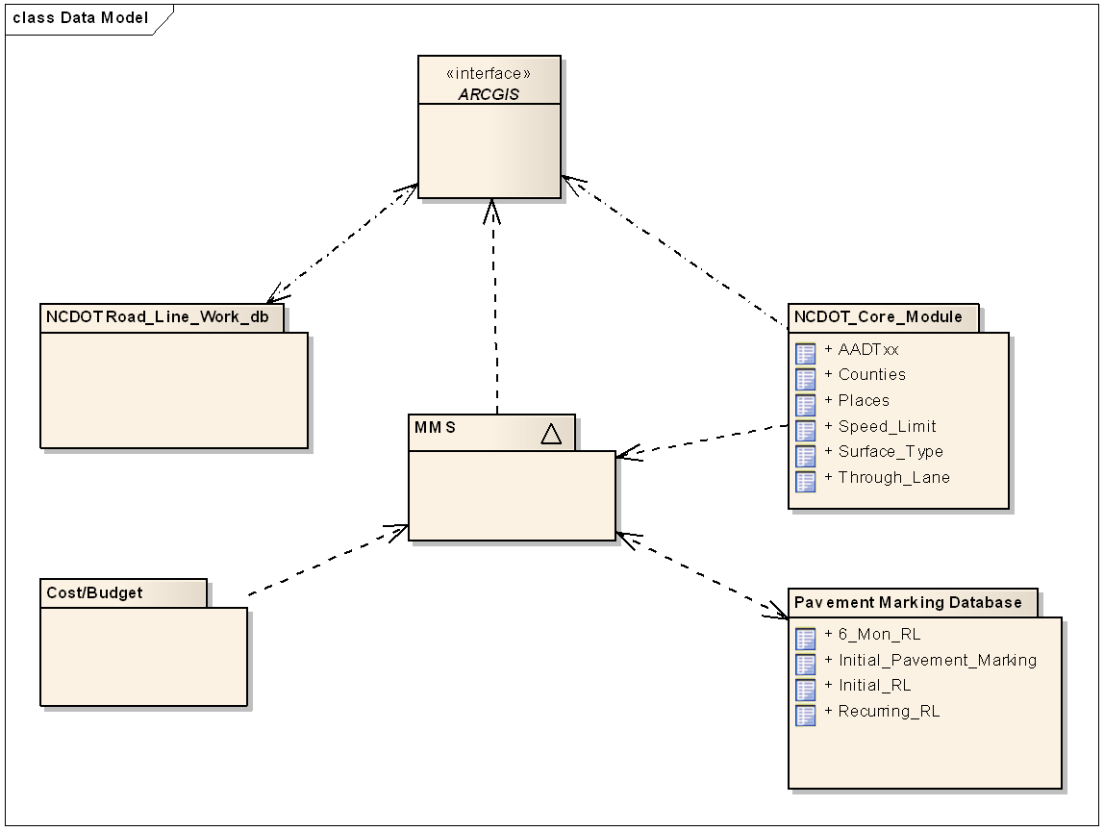


Figure 6.4. Physical Database Management Model

Definition of model elements:

1. The NCDOT core module has the non-spatial information about the road network. This is maintained as tabular data in an Oracle database. There is a great deal of data maintained in this database. Two specific items of interest stand out.
    a. Location information: details are identified in the "Places" table. This is defined in Section 6.3.4. Although this database is non-spatial the location information is used as the primary key to link the data to the spatial data maintained in the road-line-work database.

b. All the other items of interest are included in various tables in the "Universe File" which is defined in Section 6.3.4.

2. The NCDOT road-line-work data are the spatial information about the road system. It is structured as an ARCGIS personal geo-database which is basically a Microsoft Access database that includes all the topological and spatial relationships. The key component of this database is the spatial information. The Places table is defined Section 6.3.4 and shows the spatial information maintained in this database.

3. The cost and budget database is a tabular database that contains the maintenance and repair cost data maintained by the NCDOT. The cost information is maintained in a separate database than that of the roadway data.

4. The NCDOT roadway maintenance database contains information on maintenance and repair work. This is also known as the NCDOT Maintenance Management System (MMS). Structured as an Oracle database, this contains all the non-spatial maintenance and repair information maintained by the NCDOT. This database also contains all the condition assessment information collected during the MCAP. Each data element is recorded in this database using function codes which are all tied to a given road segment. The location of the road segment is then used to link this information to the spatial information available in the road-line-work- database. The MMS becomes the hub for the data model and supports using ARCGIS as the system interface.

5. The proposed pavement marking database schema identifies the necessary attributes needed for pavement marking management and is presented as the pavement marking database schema. Figure 6.5 gives the basic layout of the schema as an Enterprise Architect product. The specific table structure is defined in greater detail in Section 6.3.3.1.

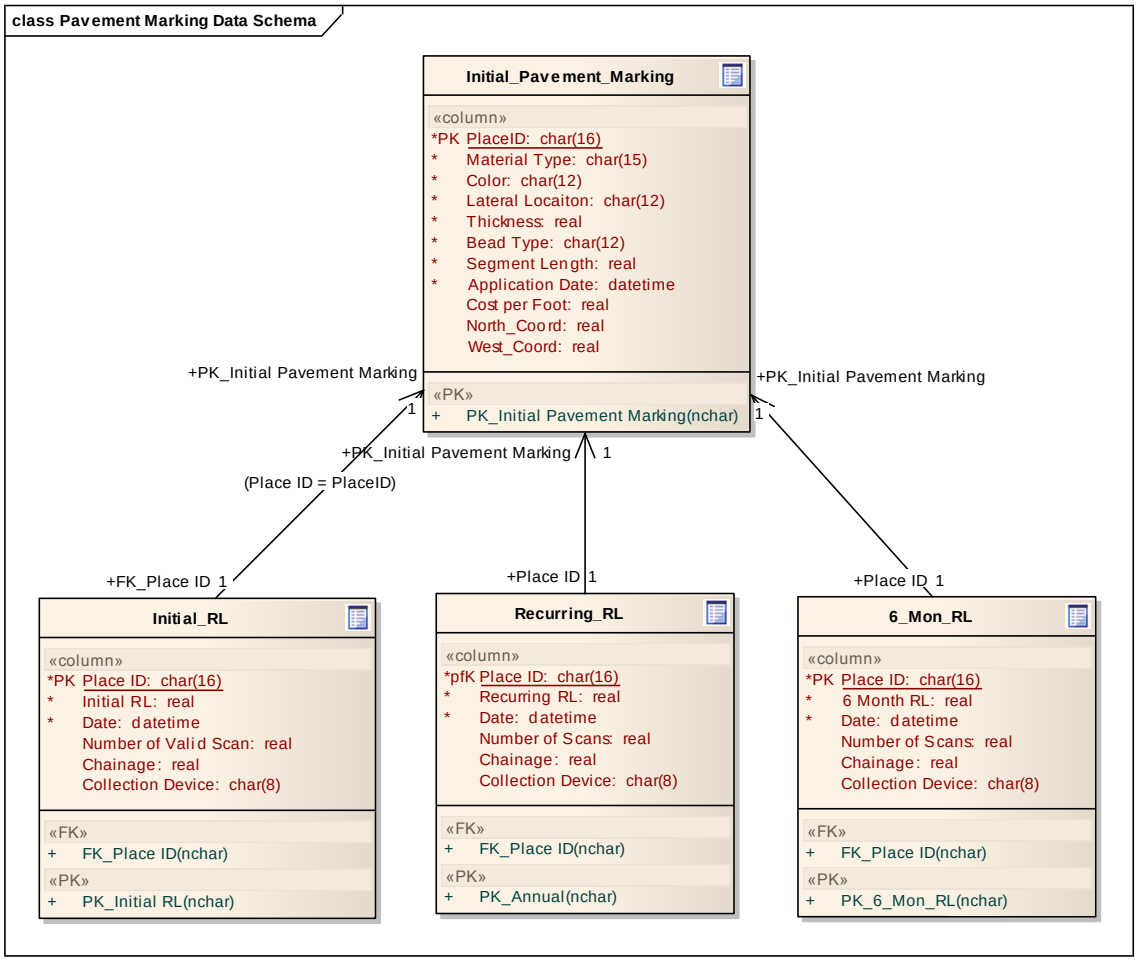


Figure 6.5. Pavement Marking Database Schema

6.3.5.1 Tabular Organization of Pavement Marking Attributes

This section organizes pavement marking attributes into a table format that follows the structure of the NCDOT universe file system [Smith et al., 2001]. This formatting is crucial

since it will enable the linkage of pavement marking data with the myriad of NCDOT data already available. Additionally, this tabular format lays the foundation for structuring the physical data management model.

The tables are presented below using a common format [Smith et al., 2001] where the table name is presented along with its primary key and attributes. The table name is bolded and the primary key is bolded and underlined. Section 6.2.3.1 presented the proposed tables that need to be added while Section 6.2.3.2 presented the existing tables that are already structured in the Universe File. An illustration of the table format is as follows.

Table Name (**Primary Key**, Attribute 1, Attribute 2, Attribute 3, …, Attribute n)

6.3.5.1.1 Proposed Tables for Pavement Markings

This section presents the tabular structure of the pavement marking database. This structure is the foundation for creating the pavement marking data schema. As mentioned above, the MMS has a front-end software package that will create the database structure. Additionally, this package creates all the necessary windows and menus consistent with the rest of the MMS. The tabular structure presented here provides all the necessary information required to implement the data structure using the MMS front-end software.

Initial Pavement Marking (**Place ID**, Color, Material Type, Lateral Location, Thickness, Width, Bead Type, Cost, Manufacturer, Product Name, Installation Temperature, Lineage, Application Date, GPS Coordinates)

The initial pavement marking table contains all the attributes that would be defined at the installation of a pavement marking.

Place ID – Unique name/label given to the pavement marking under consideration
Color – White or yellow
Material Type – Paint, thermoplastic, polyurea, epoxy, or other
Lateral Location – Edge or middle
Thickness – Thickness of marking material in mils
Width – Width of marking in inches
Bead Type – Standard, large, or highly reflective elements
Cost – Cost of marking per linear foot
Manufacturer – Name of the material manufacturer
Product Name – Name of the product used for marking
Installation temperature – Ambient air temperature in degrees Fahrenheit
Length – Length of the pavement marking in miles to the tenth.
Application Date – Date of the marking installation
GPS coordinates – Latitude and longitude of the pavement marking initial start point

Initial R_L (**Place ID**, Initial R_L, Date, Number of Valid Scans, Chainage, Collection Device)

The initial R_L table defines the initial retroreflectivity characteristics associated with the pavement marking. Although the R_L values could be associated with the Initial Pavement Marking table, initial R_L is typically collected 14 – 30 days after the installation of a pavement marking and warrants management in an independent table.

Place ID – Unique name/label given to the road segment under consideration
Initial R_L – Initial retroreflectivity value in $mcd/m^2/lx$
Date – Date of the initial R_L data collection
Number of Valid Scans – Records the number of valid R_L values over a tenth mile increment
Chainage – Tenth mile increment for the road segment under consideration. The value always starts at zero from the beginning road segment node and increases in tenth mile increments until the segment run ends.

Collection Device – Laserlux or LTL 2000

6 Month R_L (**Place ID**, 6 Month R_L, Date, Number of Valid Scans, Chainage, Collection Device)

The 6 Month R_L table defines the retroreflectivity characteristics associated with the pavement marking at 6 months from installation.

Place ID – Unique name/label given to the road segment under consideration
6 Month R_L – Retroreflectivity value in mcd/m^2/lx
Date – Date of the 6 month R_L data collection
Number of Valid Scans – Records the number of valid R_L values over a tenth mile increment
Chainage – is the tenth mile increment for the road segment under consideration. The value always starts at zero from the beginning road segment node and increases in tenth mile increments until the segment run ends.
Collection Device – Laserlux or LTL 2000

Recurring R_L (**Place ID**, R_L, Date, Number of Valid Scans, Chainage, Collection Device)

The Yearly RL table defines the retroreflectivity characteristics associated with the pavement marking at yearly intervals.

Place ID – Unique name/label given to the road segment under consideration
R_L – Retroreflectivity value in mcd/m^2/lx
Date – Date of the R_L data collection
Number of Valid Scans – Records the number of valid R_L values over a tenth mile increment
Chainage – Tenth mile increment for the road segment under consideration. The value always starts at zero from the beginning road segment node and increases in tenth mile increments until the segment run ends.
Collection Device – Laserlux or LTL 2000

6.3.5.1.2 Existing Tables in the Universe File

This section presents the tabular structure that already exists within the NCDOT network. All the tables reside in the core module which is commonly referred to as the universe file.

The MMS has the capability to link each of these data items as well as bring in cost and budget data.

Places(**LRS ID**, NodeID1, NodeID2, Measured From Node ID1, Measured From Node ID2, PlaceID, North Coordinate, West Coordinate).

This table is the unique table that enables spatial location of each road segment in a GIS. There are four supported LRSs in use by the NCDOT and therefore this table has a key field that is a unique LRS ID. With this any supported LRS can be translated into any other supported LRS. In this data management system the Place ID becomes a foreign key that can link the proposed architecture to any supported LRS.

LRS ID – The statewide unique LRS reference code
Node ID1 – Beginning LRS reference node
Measured From Node ID1 – Offset distance from the reference Node ID to the beginning milepost of the place.
Node ID2 – Ending LRS reference node
Measured from Node ID2 – Offset distance from the reference Node ID to the ending milepost of the place
PlaceID – Unique label/name given to the segment of the road under consideration
North Coordinate – Numeric north coordinated value given in degrees- minutes-seconds associated with node ID1
West Coordinated – Numeric west coordinated value given in degrees- minutes-seconds associated with node ID1

Surface Type (**PlaceID**, Surface Code)

This table classifies the type of roadway surface.

Code Manual Reference item 29
Place ID – Unique name/label given to the road segment under consideration
Surface Code as a two digit numeric code

AADTxx (**PlaceID**, Traffic Volume)

This table stores the traffic volume associated with a specific linear segment of roadway for a given year, xx. That is, there would be an AADT01, AADT02, etc., table for each year of data.

Code Manual Reference item 40
Place ID – Unique name/label given to the road segment under consideration
Traffic Volume – Average number of vehicles that pass along this linear segment of road per day

Counties (**County Name**, County Code, Division Code, District Code, Terrain)

This table relates the county name to the standard numeric NC county ID and to its encompassing geographical classifications including division and district. Furthermore it identifies the terrain in which the county is located.

Code Manual Reference – items 2, 13, 16
County Name – Name of county of interest
County Code – Identification number given to a specific county
Division Code – Identification number given to the division in which the county is located
District Code – Identification number given to the district in which the county is located
Terrain – Predominate terrain type through which the section passes (flat, rolling, mountainous)

Through Lanes (**PlaceID,** Number of Through Lanes)

Through Lanes are continuous roadway lanes. This table tells us how many through lanes we have for all roadways.

Code Manual Reference item 27
Place ID – Unique name/label given to the road segment under consideration
Number of Through Lanes – Number of through lanes on this LRS route at this place

Speed Limit (**PlaceID**, Speed Limit)

This table stores the daytime speed limit for automobiles posted or legally mandated on the greater part of the section.

Code Manual Reference item 24
Place ID – Unique name/label given to the road segment under consideration
Speed Limit – Two digit integer speed limit value

6.3.6 Algorithm

Figure 6.6 shows the algorithm developed for processing pavement marking retroreflectivity data. The purpose of the algorithm is to determine retroreflectivity values and spatially display them for a given road segment. The algorithm was developed specifically for NCDOT but the process can be used to spatially display retroreflectivity values for any department of transportation with a similar database structure.

The primary purpose of the developed procedure, identified in the algorithm, is to meet NCDOT's primary asset management goal. Recall that the goal is to determine the percent compliance with established NC standard for pavement markings retroreflectivity which is linked to the proposed Federal standards. The final output will display the performance-based predicted retroreflectivity values in their current or future states.

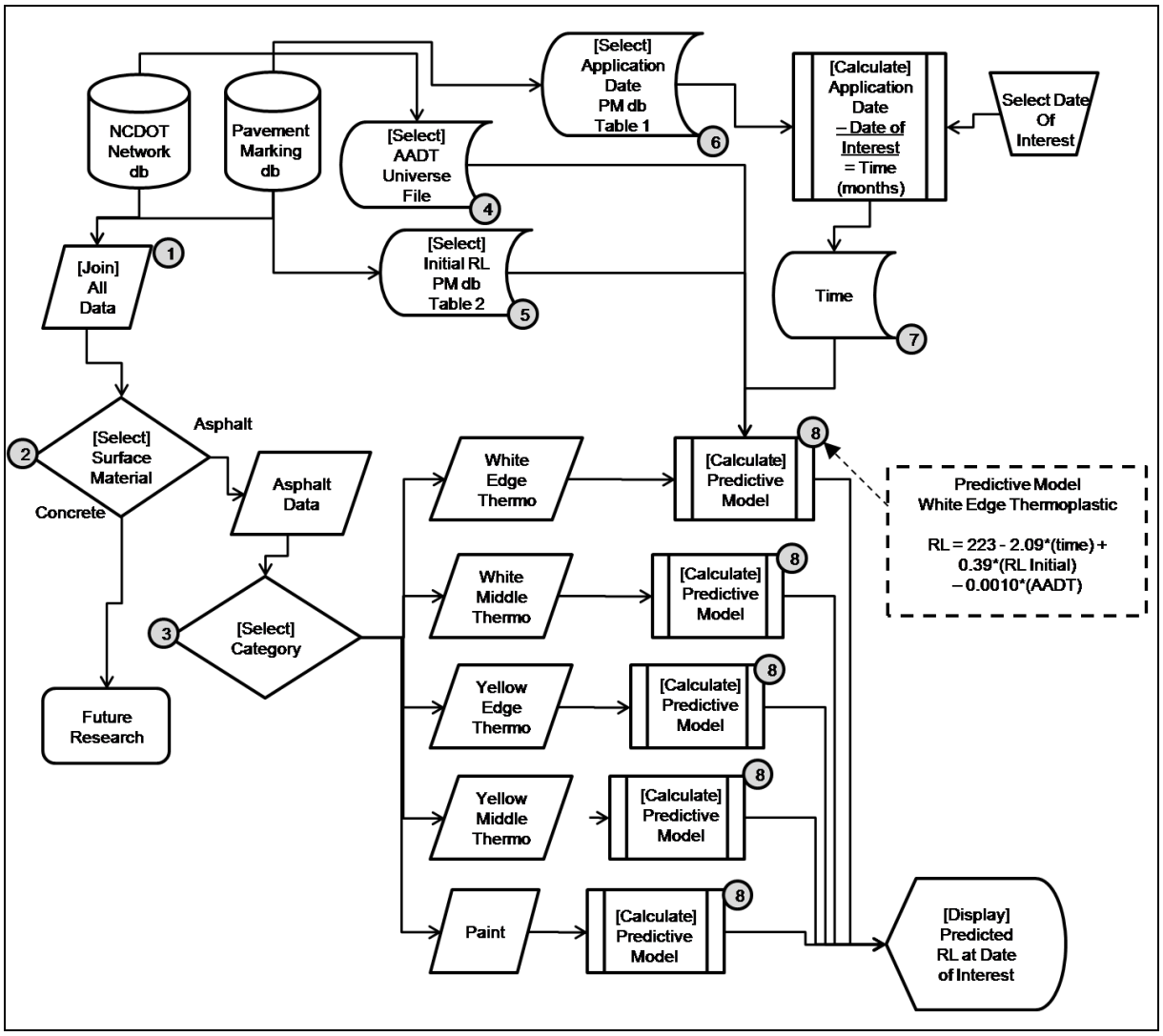


Figure 6.6. Pavement Marking Retroreflectivity Algorithm

Table 6.7 presents each process used in the algorithm. Identified for each process are the required inputs and the expected output. Column two shows the procedural steps which correspond to the step numbers identified in the diagram. The time process requires the user to identify a date of interest. This could be set with a default for the current date and would result in displaying the predicted retroreflectivity values in their current state. However, the date could be easily modified to project the condition state at some point in the future.

The algorithm shows the display as an end state but this could be further refined to display all the retroreflectivity values sorted by LOS increment. This makes it easy to create a cartographic image with all retroreflective values that are below the minimum standard. By adjusting the LOS increments to match their own standards any DOT could implement this algorithm and display predictive retroreflectivity values for their own state.

Table 6.7. Process Input and Output for Pavement marking Algorithm

Process	Step Number	Input	Output
Join all data	1	• Universe file • Road line work • Pavement marking data	All data
Select surface material	2	All data	Asphalt PM data
Select marking material and lateral location (category)	3	Asphalt PM data	PM data by category
Select AADT	4	Universe file	AADT for segment of interest
Select initial RL	5	Pavement marking data	RL for segment of interest
Select application date	6	Pavement marking data	Application date for segment of interest
*Time Process	7	• Application date for segment of interest • *Date of interest	Time in months
**Calculate RL using predictive model	8	• PM data by category • Time • Initial RL • AADT	Display RL at date of interest

* Requires user input

** Use appropriate model for category where Paint only requires time and initial RL

The performance models developed in the first phase of the research were limited to thermoplastics on asphalt and paints. This is a significant limitation in the algorithm. Other limitations include the limited availability of initial R_L values and application dates. In the

case where initial R_L value is not available one could use the average initial value for a given category or the initial required value required by specification. However, the application date is not as easily overcome as a limitation. This is a relatively simple data point to record but in the case of in-house operations markings crews must make the effort to record this.

6.3.7 Demonstration

Recall that our goal is to provide transportation agencies with a mechanism to confidently assess the condition of pavement markings at a point in space and time without having to physically measure all pavement markings. This section presents an example of the end product from implementing the proposed algorithm (using the proposed data structure and pavement marking degradation models). This demonstrates the ability to achieve the goal and provide the condition of pavement markings as desired.

Figure 6.7 is a thematic map developed using the ARCGIS application of our asset management system and displays the actual retroreflectivity data for the northbound yellow edge line along a 12-mile stretch of Interstate 95 in NC. This equates to displaying the measured condition state as shown in Figure 1 which follows the measured data path, bypassing the algorithm. The retroreflectivity data were added using the latitude and longitude coordinates and then the points were "snapped" to a route feature created from the primary roads data file. The values use a graduated scale based on the previously established LOS increments for NC.

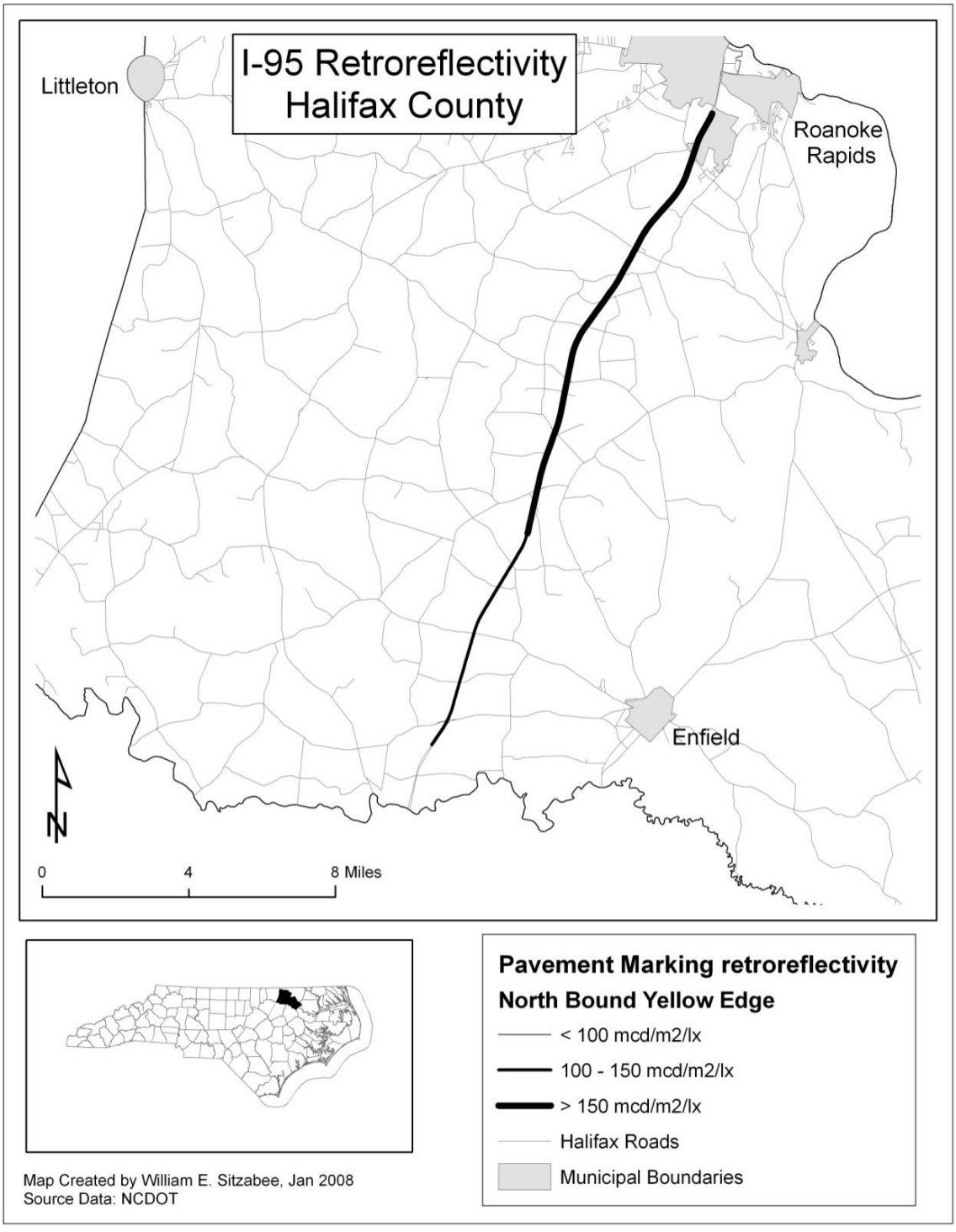


Figure 6.7. I-95 Actual R_L Values for Yellow Edge Pavement Markings

Figure 6.8 shows both the actual and predicted R_L values of the northbound yellow edge line for a portion of the interstate illustrated in Figure 6.7 as of 2006. This demonstrates the ability to show both the predicted and measured R_L values for a given road segment and meets our goal to provide transportation agencies with a condition state for pavement markings. Using the predictive models and algorithm in the TAM system, the predicted line demonstrates the ability for a transportation agency to estimate the condition of the asset without having to physically measure the asset. If desired it is possible to separate and display the measured and predicted data.

Having both he predicted and measured values displayed side-by-side gives the agency a sense of the accuracy of the process. In this case the system achieved a high level of accuracy and was deemed a great success. Specifically, the predicted values were established at 147 mcd/m^2/lx using the degradation model for yellow edge thermoplastics and inputting the initial R_L, time, and AADT. The average of the actual measured R_L values was calculated as 146 mcd/m^2/lx with a standard deviation of 19 mcd/m^2/lx.

Maps like Figures 6.7 and 6.8 at the county, district, or divisional level provides managers with an effective tool to highlight the condition of pavement markings as an asset. This is useful to convey the condition of the asset to the public and to legislators when competing for funding for this asset. However, thematic maps are not the end products in GIS but are a means to store information that is necessary for analysis and decision making [Rasdorf et al., 2003]. Maps, views, reports, displays, etc., can all be extracted from these thematic layers to

meet user needs without changing the underlying thematic maps themselves [Rasdorf et al., 2003].

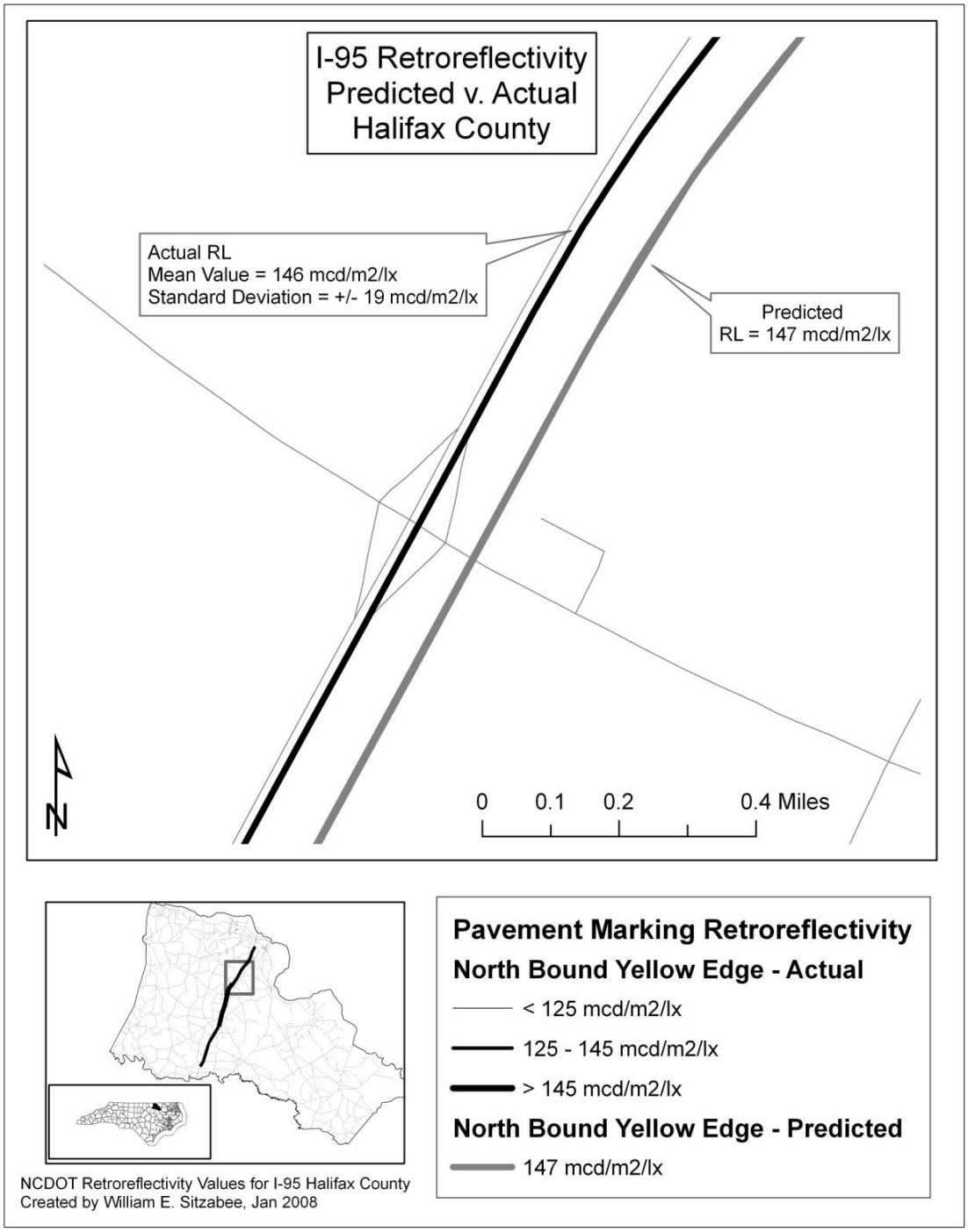


Figure 6.8. I-95 Actual and Predicted R_L Values for Yellow Edge Pavement Markings

6.3.8 Asset Management Strategies

Table 6.8 is an excerpt from the event table generated in the example and is another way for managers to use the available data to make asset management decisions. The location column identifies the specific line segment where N YE represents a northbound yellow edge line. The predicted value represents the condition state at the time of interest, which in this case is October 2007. Also provided in Table 6.8 is the age of the pavement marking when it is expected to reach the minimum standard. This column uses the same predictive model but rearranges the variables to solve for age given R_L equal to the minimum standard value. This enables agencies to determine the year that the marking will need to be replaced, which is the next column.

The TAM system allows for managers to use updated cost figures, which are constantly changing, by integrating data from external sources, like the PMS. The cost per foot column, shaded in Table 6.8, was added to the event table to demonstrate the ability to combine the cost basis with the condition state and estimate the total cost for that section of road, which is also shaded in Table 6.8. Presenting the data in this way allows managers to determine key budget information like when markings need to be replaced and how much money will needed. This is a small example of how queries can be used to influence and help develop pavement marking asset management strategies.

Table 6.8. Predicted RL and Cost Data for I-95 Halifax Example

Location	Predicted R_L ($mcd/m^2/lx$) Oct 2007	Age (months) R_L at min	Minimum Standard ($mcd/m^2/lx$)	Replace in FY	Cost per Foot ($)	Total Cost ($)
I-95 N YE	119	78	100	2008	0.55	35,500
I-95 N WE	244	112	150	2011	0.55	35,500
I-95 N WS	149	67	150	2007	0.65	41,900

6.3.9 Sensitivity Analysis

The goal of the model is to provide insight so that decision makers can make the best possible decision based on the best possible estimate of the assets condition. However, like all models, there is a certain level of uncertainty in the estimate. The uncertainty comes from both the precision and sensitivity of the input parameter values as well as the variance in the variable coefficients.

The estimate provided here is deterministic which provides a finite end state based on a discrete set of variables (initial RL, time, and AADT). The predicted value does not account for variance and can give managers a false sense of the reliability of the model. An alternative to the deterministic approach is a probabilistic approach to identify the sensitivity of the variables.

Because of the deterministic approach used in this modeling effort there remains a level of uncertainty in the predicted value. Recall that the predicted value for the northbound yellow edge was calculated to be 147 $mcd/m^2/lx$. This value was determined using the predicted equation which includes four parameters. The four parameters are the intercept, initial R_L, time, and AADT. The coefficient for each parameter has its own variance. To further understand the variance associated with the predicted value for this case, a series of

simulations was conducted. Summarized in Table 6.9, the simulation used the same input values for the variables as in the single prediction. The difference for the simulation is in the coefficients for each variable as shown in Table 6.9. Here, the coefficients were replaced with a random number generator based on a normal distribution using the mean coefficient value and standard error. The equation used to generate the simulation and the simple statistics are presented in Appendix D.

Table 6.9. Simulator Parameter and Coefficient Estimate Values

Term	Coefficient	Std Error	Variable Input
Intercept	193.3	21.12	-
RL Initial	0.3963	0.0836	243
Time	-1.69	0.260	60
AADT	-0.0016	0.00044	36500

The results after 100 simulations found the average predicted value was 133 mcd/m^2/lx with a standard deviation of 35.9 mcd/m^2/lx. The results of the simulation help us to understand the variance in the predicted value and know that the predicted value can easily differ more than 36 mcd/m^2/lx from the average about 15 percent of the time. This is something that managers would need to account for when making decisions. For example, a predicted value of 147 mcd/ m^2/lx for a yellow edge line would classify the marking as LOS green. For LOS green the range is 145 mcd/ m^2/lx to 209 mcd/ m^2/lx for yellow thermoplastic markings. This means the predicted value is right on the border of LOS green and yellow. In fact the marking could easily be in the LOS yellow range.

Although budget issues and other factors will impact the decision, managers should pay particular attention when markings are within 36 mcd/ m^2/lx of failure in this case. If the

measured values were not available this would be a case where managers should consider moving this up on the priority list for a visual inspection.

Another alternative is to explore the uncertainty with a probabilistic approach which can provide managers with a sense of (1) the probability that the value is above or below the current standard and (2) the probability a value is in a given LOS increment. The probabilistic approach enables researchers to explore the distribution of the models variables and account for this variance in the model prediction. Section 8.2 will offer some possible methods that could be used with this analysis.

6.4 Implementation of a Transportation Asset Management System

The objective of the TAM system is to provide an accurate condition assessment for both the current and future states of pavement markings without having to physically measure every foot of roadway. The condition state becomes a vital component and is used to evaluate and prioritize alternatives for pavement marking operations. For NC this equates to nearly a $1.8 million per year savings in condition assessment.

The TAM system, shown in Figure 6.9, shows the data integration of pavement marking attributes and predictive models that will provide the best possible prediction of R_L at any given point in time or space. Highlighted by the dashed line are the key components of the system. These components represent the data integration elements of the pavement markings

TAM system. The predictive models were presented in Chapter 5 while the MMS data structure and algorithm are presented in Section 6.3 of this chapter.

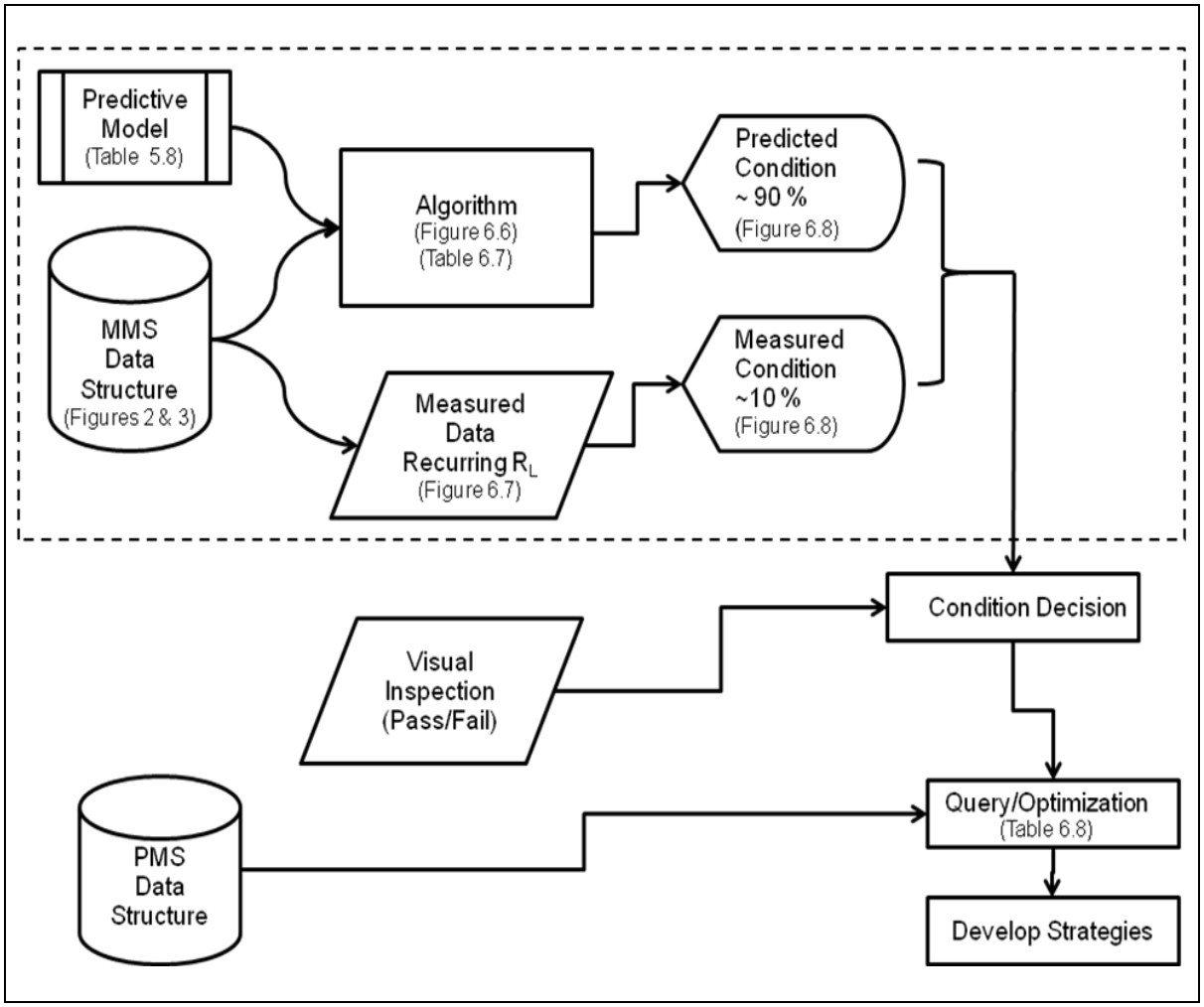


Figure 6.9. Transportation Asset Management System

6.4.1 Measured Data

This section relates to the measured data pathway shown in Figure 6.9. In NC approximately 10 percent of the pavement markings retroreflectivity is still measured on a recurring basis. This is done for several reasons like quality control and pavement marking research. For

roadways with measured data it would be foolish to use predictive models to estimate the retroreflectivity values. In this case the TAM system bypasses the algorithm and goes directly to a display option. Since this data structure uses a relational database the display can be tabular or in an easily understood map.

Of course measured data would be for a single time and will quickly be out of date. In this case, managers have the option to display the condition of the measured data at a specific time side-by-side with the predicted condition at the same time, as shown in Figure 6.8 of the example below. This will give managers the ability to adjust the prediction appropriately for the current condition. Since a small portion of the asset's condition is still measured, these measured sections can be used to calibrate or even update the predictive models used in the process.

6.4.2 Condition Decision to Perform Queries and Develop Strategies

Recall that the goal of this TAM system is to provide managers with the best possible condition of the asset, either predicted or measured. The process presented in Figure 6.9 implements computing tools and enables managers to make decisions based on a state-wide condition assessment that was previously unavailable. With the inclusion of the visual inspection process the decision maker now has a clear and holistic view of the asset. Although not the primary focus of this research this section summarizes the use of visual inspections and the integrated use of a pavement management system as shown outside the dashed line in Figure 6.9.

6.4.2.1 Visual Inspections

There are both objective and subjective evaluation systems in use today to measure retroreflectivity of pavement markings. Objective measurements use retroreflectometers (mobile or handheld) while subjective evaluations are typically done through visual inspections by a trained observer. Both approaches are considered viable methods for measuring retroreflectivity in the United States [Migletz and Graham, 2002]. Trained observers can typically estimate the condition of the asset and determine of the asset needs to be replaced or not [Migletz and Graham, 2002].

Field inspections provide valuable insight into the performance of pavement markings and are a critical component that has been incorporated into the decision loop of the system. In the TAM system we allow for a pass or fail criteria to be assigned to the roadway by inspectors. Incorporating the human factor back into the decision loop provides a feedback loop for the process which helps to evaluate the accuracy and viability of the process. Additionally, the system can be used to prioritize what road segments are identified for visual inspections. For example, managers might want to visual inspect a section of road that is reporting inconsistent predictions or in areas where the measured values are old and no longer reliable.

6.4.2.2 Pavement Management System

Recall that Figure 6.9 shows a link to an existing pavement management system (PMS). This link provides managers with the necessary information to optimize the transportation asset management beyond pavement markings. Using the power of a GIS, a user can

integrate information from various sources and spatially connect that information to identify aspects of the transportation system that would otherwise be unapparent [Flintsch et al., 2004]. Armed with the best possible estimate the asset manager can use a GIS to perform queries on the system and explore spatial relationships of the asset. This is particularly useful in optimizing project funds and leveraging existing systems in developing strategies for pavement markings.

Inclusion of the PMS is an additional piece to the overall strategy development. The PMS database provides a great deal of pavement information. Although external to pavement markings the PMS provides managers with the holistic picture of the roadway and enables managers to make smart decisions regarding pavement markings. For example, on a given road segment a pavement marking manager might decide to use a long-life marking but prior to implementation he queries the projected maintenance activities from the PMS to see that the road segment is scheduled for resurfacing the very next year. Now the appropriate decision might be to use a shorter life material (cheaper) aligning the pavement marking material with that of the road surface.

6.4.3 Limitations

There are two key limitations that need to be overcome in order to implement the proposed TAM process. First, agencies need to implement a protocol to record the necessary variables needed to implement predictive models. Second, agencies need to overcome location referencing issues. This section highlights these limitations and presents recommended solutions.

6.4.3.1 Recording Key Variables

The predictive models require the use of initial R_L, time, and AADT. AADT and time are critical but in most cases are readily available. However, initial R_L values are often not recorded, especially for in-house performed work. In the case of NC this represents approximately 60 percent of the roadway.

For existing markings, initial R_L values are not always readily available. In NC measuring initial R_L is only required when the markings are installed by a contractor as a quality control measure. Recording contractor installed data would only require a small change in the management process which is to consolidate the location where this data is stored. The recommended place to store the data is within the MMS.

The current in-house process does not include measuring or recording initial R_L values. This would require a change in current marking operations where the marking crews would have to add the measurement step to the process. The researchers advocate that recording the initial R_L value and installation date are easy to do. These values can be measured at the time of installation and then recorded in the MMS when the marking crews record other information such as labor hours.

Each division in NC has at least one measurement device so implementing this data collection requirement would only require the minor additional cost of labor. For other agencies that do not have a retroreflectivity data collection device they purchase one for approximately $12,000 depending on the unit of choice. Additional cost would be labor and

these are nominal since the measurements only take a few minutes and marking crews would already have the mobilization and traffic control costs, which are the majority of the expenses, built into the operation.

For example, during the validation of the models the researcher collected 35 measurements at random intervals spread throughout the entire road segment. Once the traffic control was in place this process took approximately 40 minutes to collect. However, based on ASTM 6359 procedures to estimate the initial R_L, the crew would take ten readings at three locations (first 1000 feet, middle, and last 1000 feet) of the road segment. Consolidating the collection locations to three areas reduces the collection time significantly. With traffic control and mobilization already accounted for, the measurement time is estimated to take 20 to 30 minutes.

In the case where initial R_L values are not available and a highway agency didn't want to add the expense of collecting and maintaining initial R_L values they could implement two alternative methods for estimating initial R_L. First, the highway agency can use the average R_L value as measured from empirical data for like materials. For example, Table 6.10 shows the average initial R_L values calculated for NC from the 2006 data set. Included in Table 6.10 are the percentiles where, for example, greater than 90 percent of the white thermoplastic initial values exceed 343 mcd/m^2/lx.

Table 6.10. Summary of NC Initial R_L Values

Material and Color	Initial RL Ave ($mcd/m^2/lx$)	Initial RL Std Dev. ($mcd/m^2/lx$)	75^{th} Percentile	90^{th} Percentile	Initial Spec Value
Thermo White	443	71.8	400	343	375
Thermo Yellow	266	48.3	232	213	250
Paint White	244	46.7	211	178	225
Paint Yellow	182	45.2	155	128	200

The second alternative is the use of the required specification value to estimate the initial R_L value. However, this alternative is not recommended. In theory good quality control measures would ensure that all initial values are at least as high as the specification value. However, a review of the empirical data would indicate that at least ten percent of the initial values don't meet the initial spec value. Reviewing the empirical data lead to two significant asset management findings regarding initial R_L.

First, internal marking crews are not required to measure or record their initial R_L values. With the impact of initial R_L on the service life of pavement markings it would be prudent for NCDOT to implement better quality control measures for the installation of pavement markings. Requiring in-house marking crews to meet a minimum retroreflectivity level for new markings could extend or a least ensure paints last two years. Second, for contractor installed markings the results revealed that more than 10 percent of the initial markings never reached the minimum specification values. Furthermore, with the exception of white thermoplastics, greater than 25 percent of the initial markings never reach the initial

specification values. A review of the contractor installed quality control program would be justified.

6.4.3.2 Location Referencing

Recall from Section 2.1.2 that increased use of GIS technologies and automated data collection equipment has increased the use of GPS-based coordinate referencing as a location referencing method [Flintsch et al., 2004]. Because of the spatial aspect of the transportation system, location referencing is a key component of data integration. This is difficult from a linear referencing system approach in that it identifies a single point in space. Both methods are particularly applicable in transportation applications. Location referencing remains the most popular method for linking transportation asset management databases and implementing a single state-wide referencing system was a key component to successfully integrating their transportation asset management data [FHWAc, 2007]. The key to GIS and transportation data integration is to establish an LRS identifier which is simply a unique individual identifier specific to a given segment of roadway [Rasdorf, Janisch, and Tilley, 2002].

Unfortunately, the LRS used to identify the location of the pavement marking retroreflectivity data in NC did not follow any of the standard linear referencing formats. The data were collected using a localized LRS that does not conform to either the state or county milepost system. Furthermore, the NCDOT's contract with the data collection contractor did not prescribe that pavement marking retroreflectivity data be collected using a particular location referencing method. The system used by the contractor was a blended

system that used route identification with the start and end points of measured sections identified with a mile post, an intersection, or an offset distance.

In some cases the pavement marking retroreflectivity data were recorded with a common name format to identify the start and end point of a data collection run. For example, the location data were recorded with a beginning point at "Jackson East city limit" and end point at "Conway West city limit." The common name had to be matched manually to the route information to locate the segment's position. Although difficult, the links could be established to locate each segment.

Because of the unique LRS used, the localized referencing system precluded or at least significantly complicated the integration of pavement marking retroreflectivity data with the existing database structure. The LRS component had to be resolved before this physical model could be implemented. NC has the capability to match location using an LRS filter. However, the filter requires the use of one of four supported referencing systems [LRS Integration Guide, 2006]. In this case, 2006 and 2007 pavement marking retroreflectivity data contained longitude and latitude data for each 0.1-mile road segment. This information was used by the filter to locate retroreflectivity data in a GIS as a feature. Once the data were implemented as a feature, the data were "snapped" to the existing LRS.

During the data integration case study by the Michigan DOT, they discovered that deciding on a single referencing system enabled Michigan DOT to integrate GPS and GIS capabilities

into their transportation management system. Following the Michigan example, it is our recommendation that agencies implement a single LRS.

6.4.4 Implementation

This chapter presents solutions for data integration issues and presents an integrated TAM system for estimating the current and future condition of pavement markings as a transportation asset. Section 6.3 describes the data structure, in the form of a physical model, specifically integrating a pavement marking data schema with existing IT systems (MMS). Software was found to be useful in developing a data schema. The software produced an XML file that can be easily imported into a variety of existing database structures such as Oracle, SQL, and MS Access.

Additionally, the TAM system included an algorithm that implements the data structure to establish the condition of the asset. Using predictive models based on a small sample of measured sections (10 percent), the algorithm implements the data structure to estimate the condition of the asset (90 percent), at any point on the highway system. With the inclusion of measured data and an allowance for visual inspections managers can query and display the condition of the asset and perform strategy development for maintenance, rehabilitation, or replacement of the asset.

Following FHWA asset management principles, this chapter presented several concepts that bring together a holistic asset management system for pavement markings. In order for NCDOT or any DOT to implement these concepts they will need to:

1. Accept the thermoplastic performance models or develop their own.
2. Accept and implement the LOS increments as defined in Section 6.1.4 or develop their own.
3. Implement future data collection recommendations as presented in the data collection plan (Section 6.2.3.5). Specifically, they will need to collect initial R_L, surface type, color, line type (lateral location), and application date for all new markings.
4. Consolidate pavement marking inspection and data collection into a unified effort. This does not necessarily mean that a single unit should do all the inspection and data collection. The intent is to create a unified effort with common data management that will reduce the overall impact on NCDOT by minimizing redundant efforts. This would require NCDOT to appoint a single unit as the lead on managing all aspects of pavement marking management. There are several ways to do this and NCDOT would need to decide where they want the lead for this function.
5. Implement the TAM system presented in Figure 6.9. This requires adding the data structure, presented in this chapter to the MMS. Implement the data model by adding the tables identified in Figure 6.5. This will set up the database structure within the MMS. Using the pavement marking database schema and importing the pavement marking degradation models would enable the use of built in optimization software that already exist within the MMS. This can be done by using the front-end software already in place and using the tabular structure presented in Section 6.3.3.1. An alternative is to import the XML file into MMS.

6. Offer the physical database structure with accompanying XML files to other DOTs for implementation.

7.0 CONCLUSIONS

The objectives of this research addressed both pavement marking material performance and pavement marking asset management. Understanding retroreflectivity performance over time is important to establishing a pavement marking asset management strategy that meets pending Federal requirements and maximizes the material's lifecycle. This research begins to implement the NCSU plan to manage pavement-markings from a holistic asset management approach.

The research followed a two-phase approach:

- The first phase determined the performance characteristics of pavement markings in NC and created viable predicative models for retroreflectivity degradation.
- Focused on asset management, the second phase incorporated the predictive models into an algorithm that was used to predict the current and future condition state of pavement markings.

This research, which combined pavement marking predicted behavior with computer based tools such as GIS, is not only timely but will certainly enhance the fields of pavement markings and asset management. Ultimately, the goal of this research was to provide insight, establish a process, and develop techniques that can be expanded beyond pavement markings and be used for the management of any continuous infrastructure system.

7.1 Performance Modeling

In the literature review there were five studies identified that have developed various pavement marking degradation models. Three of the five studies concluded that pavement markings degrade linearly while two studies suggest a logarithmic decay. This study confirmed that both thermoplastics on asphalt and paint pavement markings could be successfully modeled as linear decay for 1 – 60 months.

An alternative logarithmic decay degradation model for thermoplastics and paints was also developed and tested but these models were found to be unsuitable. The coefficient of determination dropped for all four thermoplastic models and the residual plots showed no improvement in the distribution of variances. Finally, a polynomial and exponential fit was also checked and found to be ineffective as well.

Specifically this study determined:

1. For an AADT of 10,000 vehicles per day or less the expected service life for thermoplastics on asphalt range from 5.4 years to 8.75 years depending on the color and lateral location.
2. Paints have a service life slightly greater than two years.
3. Both thermoplastic and paint pavement markings were found to have a far greater life expectancy than originally expected.
4. Lateral location is a key independent variable in modeling thermoplastic pavement marking degradation.

5. Although small, this study confirmed that AADT does have an impact on the degradation of pavement markings.

The service life of paint pavement markings turns out to be a significant finding. Paints are typically managed on an annual cycle because the assumption is their service life is approximately one year. The predictive model for paints estimates a two-year service life, which is double the current service life expected by NCDOT. Recall that Migletz reported an average service life for paints to be 10.4 months [Migletz et al., 2001]. This has critical budget implications for pavement marking managers.

This study offers a performance-based model and calls for the adjustment of the NC painting schedule from an annual to a biennial cycle. This step alone will result in a significant cost savings in the budget while maintaining the appropriate service level. It is important to note that the data used to develop the service life was from contractor-performed work. In-house marking operations would need to meet the same initial specifications required for contractors in order fro the markings to deteriorate the same way and achieve the same two-year service life.

This research contributes to pavement marking performance understanding by adding to the body of knowledge regarding pavement markings located in the travel path. Either center or skip lines will degrade faster than pavement markings located at the edge of the pavement.

Finally, there have been conflicting studies about the impact of AADT on pavement marking degradation. Sarasua et al. found that AADT was not a factor [Sarasua et al., 2003] whereas

Abboud and Bowman found that both AADT and time both contribute to the degradation of pavement markings [Abboud and Bowman, 2002]. The modeling effort provided statistical evidence to confirm that AADT and time both impact the degradation of pavement markings.

7.2 Asset Management

This research resulted in several significant contributions to the body of knowledge for pavement marking asset management. Specifically, this study:

1. Used predictive models to determine degradation rates. This led to defining LOS increments and setting a minimum standard for retroreflectivity that is consistent with pending Federal statutory requirements.
2. Developed a "performance-based" set of LOS increments for NC pavement markings based on empirical data and statistical modeling.
3. Identified the attributes needed for both pavement marking performance modeling and pavement marking asset management.
4. Identified a tabular organization and structure for pavement marking attributes.
5. Developed a data collection plan for NCDOT that assessed the current pavement marking data strategy and made recommendations to improve the process.
6. Developed conceptual and logical database management models resulting in a physical database management schema. The physical database schema proves that a pavement marking management database can be developed and executed by NCDOT if they implement a process to collect installation pavement marking data and agree on a consistent LRS that is supportable by the NCDOT GIS unit.

7. Presented a transportation asset management (TAM) system that provides pavement marking managers a way to estimate pavement marking condition, state-wide, without having to physically measure the asset. Ultimately, this process eliminates the need to collect data to establish the condition of an asset. With integrated data and smart computing the TAM system includes the capability to use recorded data that may be required for other needs like quality assurance or research. Our system shows a method to manage pavement markings well without collecting data on every mile of an asset each year. In NC this equates to a $1.8 million savings per year.

8. The TAM system includes AADT, time, and initial R_L as critical variables. AADT, is readily available to most highway agencies. Installation date directly relates to time and is a must have for predictive models. Both installation date and initial R_L need to be collected or at least estimated for use of the predictive models. This research explored the importance of a highway agency to have good protocols for collecting and maintaining initial R_L data for effective asset management of pavement markings.

9. Currently in the NCDOT, there is a distinct misalignment of responsibilities and authorities when it comes to pavement marking management. Holistic asset management of pavement markings requires the consolidation of technical support, data collection, condition reporting, and marking application processes under a unified pavement marking asset management effort. Realignment of responsibilities or formalization of relationships are two possible solutions.

10. Asset management of pavement markings will help the NCDOT, or any highway agency, by preparing them to implement pending Federal regulations. This study has concluded

that an adjustment to the painting cycle alone is not only appropriate but will offer significant savings to NCDOT.

This research provided NCDOT with the specific steps to establish the conditions state for pavement markings throughout NC without having to physically measure them. This is a significant improvement in pavement marking operations. Implementing the recommendations in data collection and data management will position NCDOT to meet pending Federal regulations that will require reporting on the condition state of pavement markings. Furthermore, implementing these recommendations will provide NCDOT with the means to manage pavement markings as a holistic asset.

Although several other studies modeled pavement markings this study established that lateral line location is a key factor in pavement marking degradation. Table 6.8 presented the cost associated with remarking a 12-mile stretch of I-95. In this table, the northbound yellow edge was recommended for replacement in 2008 at a cost of $35,500 while the northbound white edge was recommended for replacement in 2011 at a cost of $35,500. Replacing both lines at the same time, which is the current practice, is not necessary since each marking operation would require separate mobilization and traffic control. Yet extending the life of the white edge line by three years has significant cost savings for the NCDOT and gives the NCDOT the ability to redirect the funds to other areas within pavement marking operations.

8.0 RECOMMENDATIONS

This research project is the first step in a larger research effort on pavement marking management. The research stream explores pavement marking asset management by focusing on pavement marking degradation. The focus of this first part of the research effort was on thermoplastics and paints. Ongoing and future research will explore other marking materials, including polyurea and resin-based paints which should account for nearly 100 percent of the markings in NC.

The inability to locate the attributes of an asset remains the number one issue in implementing effective asset management. Good location referencing is still a significant limitation in managing pavement markings in many DOTs. Because of the spatial aspect of transportation systems it is highly recommended that highway agencies select and implement a single LRS. This will enable agencies to use location as a means of integrating pavement marking data into the overall transportation data management.

It is recommended that highway agencies continue to use visual inspection process in their management of pavement markings. The visual inspection can be used to verify the condition estimates produced by the model. In fact, the model estimates can be used to prioritize the visual inspection plan or even prioritize the limited dollars that are available for retroreflective data collection.

8.1 Limitations of the Current Research

The most significant limitation to implementing the performance models is the lack of initial R_L and application date data for unmeasured roads. Time, as the most significant independent variable, relies on the installation date and is necessary for implementing the model. For most contractor performed pavement marking work the original contract documents are a source of information for the installation date and initial R_L values. However, a sampling of this information proved that only the installation date was recorded as most of the contractor performed markings did not included the initial R_L value. Presented in Section 6.3.6 are some reasonable alternatives to establish an estimate for initial R_L.

The data presented another limitation for this research. Recall that the original intent of the data was for quality control and not necessarily for research. The type of data collected presented significant limitations in analyzing pavement marking performance. For example, the literature revealed that snow plowing and other maintenance activities have a significant impact on pavement marking performance. Because of the limitations in snow plow data the researchers were not able to include this variable in the modeling effort. Several other variables are believed to impact performance but were not included for the same reason. These were the line width, line thickness, and region.

8.2 Recommendations for Future Research

Waterborne paints make up the overwhelming majority of pavement markings and warrant further study. This research was limited in the amount of waterborne paint data collected since the study used existing data collected only at the initial, six-month, and one-year

increments. The limited data contributed to the general form of the paint model. Increased frequency of the data collection of paints is recommended to evaluate the material which degrades at a faster rate then durable markings like thermoplastics. Data collection at six-month increments will only provide five to seven data points for the life of a paint marking. Future research should focus on refining the paint model and exploring the development of individual models based on color and lateral location categories.

The designation of a highly evaluated test section of pavement markings would allow for the full degradation of materials. Data collected from this test facility would enable researchers to fully model pavement marking degradation.

Additionally, further study should be undertaken with respect to the effects of snow plowing on pavement markings. Snowplowing is limited in NC and the data collected for this variable was categorical, meaning that only a yes or a no was recorded if a road segment was plowed. Alternatively, future research should collect continuous data on snow plowing, recording the number of times a year that a road segment is plowed and then explore the impact that plowing has on pavement marking degradation.

Identified in the literature as a significant gap in the current research, this study confirmed that location-referencing systems (LRSs) are problematic. Continued exploration of an appropriate LRS for pavement marking management is needed. In 2006 and 2007 the NCDOT collected latitude and longitude coordinate data as an attribute of pavement markings. Coordinate data are a viable LRS and can be spatially referenced in ARCGIS.

Additionally, future research should evaluate the migration from the four supported LRSs in use at NCDOT to a single LRS.

The physical database schema proves that a pavement marking management database can be developed and executed. However, to make it work NCDOT should implement the data structure shown in Section 6.3.3 with data organized as presented in Section 6.2. Next, NCDOT must decide on using an LRS consistent with one of the four location referencing system supported by NCDOT road line-work database. Finally, NCDOT should implement the collection of initial retroreflectivity values for all new pavement markings and estimate the initial retroreflectivity values based on empirical data for existing pavement markings.

Further evaluation of the NCDOT organizational structure for managing pavement markings is needed. Several units have responsibilities regarding the management of pavement markings but there is no formal relationship between the units. Current practices are sufficient for now but may become problematic once the Federal government requires accurate condition assessment of retroreflectivity values for pavement markings.

Future research should explore the inclusion of pavement marking asset management as a function of the Highway Performance Monitoring System (HPMS) which is the formal structure that the Federal government uses to determine the state of our nation's roads. This system is used to provide data driven performance-based decisions using representative samples to evaluate the condition of assets such as pavement markings. Research in this area would apply to all DOTs and the Federal government.

The pavement marking research effort presented herein illustrates how a transportation asset management system can be developed and implemented. The data collection, analysis, and procedures can be applied to any high-volume low-value asset such as raised reflective pavement markers. Future research should expand these techniques to manage other infrastructure systems.

Section 3.1.1.1 highlighted a data collection issue related to directionality. Future research should explore the impact that direction has on pavement marking retroreflectivity values. This issue relates specifically to centerlines which are shared by drivers in both directions of travel but are installed in a single direction and typically measured in only one direction. Limited experimentation by the researcher has shown that retroreflectivity values can vary by as much 50 $mcd/m^2/lx$ for the same section of pavement marking depending on the direction the measurement is taken.

A great deal of human factors research is exploring the relationship between pavement marking retroreflectivity and safety. Proposed standards are being evaluated based on the impact to drivers. Further research in this area should explore the appropriate distance for which pavement markings should be evaluated and managed. For example, one foot of missing pavement markings will have little effect on the driver's ability to delineate the roadway and presumably no affect on drive safety. But an entire mile of missing pavement markings would have a profound effect. Future research needs to explore the right distance

necessary for drivers to delineate the roadway and relate that distance to the appropriate management steps necessary to operate and maintain pavement markings.

The deterministic approach used to model pavement markings provides a reasonable estimate of the condition state of the asset. However, as shown in Section 6.3.9, there is still a level of uncertainty in the predicted estimate that managers need to be aware of. The initial attempt of the researcher tried to implement a Markov analysis to estimate the probability of the LOS for a given road segment. Since the data did not support the Markov analysis, a regression analysis was used as an alternative. The researcher sees great value in exploring other probabilistic methods to estimate the condition state of pavement markings. Possible alternatives include the use of simulation techniques like a Monte Carlo simulation or survival analysis to estimate probabilities that a given section of pavement marking are at or above a given standard.

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10.0 ANNOTATED BIBLIOGRAPHY

Table 10.1. Performance of Pavement Marking Retroreflectivity

Year	Author (s)	Title
2003	Sarasua, Clarke, & Davis	The Performance of Pavement Marking Retroreflectivity on South Carolina's Interstate System Over Time
2002	Thamizharasan et. al.	A Methodology for Estimating the Lifecycle of Interstate Highway Pavement Marking Retroreflectivity
1999	Lee, Maleck, & Taylor	Pavement Marking Material Evaluation Study in Michigan
2001	Migletz et. al.	Service Life of Durable Pavement Markings
2004	Kopf	Reflectivity of Pavement Markings: Analysis of Retroreflectivity Curves
2005	Hawkins, Smadi, & Hans	Iowa Pavement Marking Management System: Initial Phases
2002	Migletz & Graham	NCHRP Synthesis 306 Long-term Pavement Marking Practices
1997	Andrady, A.L.	Pavement Marking Materials: Assessing Environment-Friendly Performance
2002	Cambridge Systems	Transportation Asset Management Guide
2004	Flintsch et. al.	Pavement Management Applications Using Geographic Information Systems, A synthesis of Highway Practice

Title: The Performance of Pavement Marking Retroreflectivity on South Carolina's Interstate System Over Time

Authors: Sarasua, Wayne A., Clarke, David B., and Davis, William J.

Category: Report

Complete Citation:

Sarasua, Wayne A., Clarke, David B., and Davis, William J. (2003). "Evaluation of Interstate Pavement Marking Retroreflectivity." Report to South Carolina Department of Transportation, Report No. FHWA-SC-03-01

Description:

As a combined research project by Clemson and The Citadel, this report focused on three major aspects of pavement marking retroreflectivity; a survey, comparison of collection devices, and creation of degradation curves.

The survey provided general knowledge to current issues in pavement marking management by DOT's and confirmed the need for research in comparing devices and establishing predictive curves.

Second, a comparative analysis was conducted evaluating three retroreflective measuring devices. The analysis provided insight into some issues resulting from the use of the various devices and how to overcome them. Also, the comparison evaluated the use of handheld units verses mobile units. Handheld devices were found to be more accurate but are incapable of collecting large amounts of data. Mobile units can provide more efficient collection of data in a safer manner because they collect data continuously while in motion at highway speeds.

Finally, this report presented three basic curves representing the degradation of retroreflectivity over time. The researchers introduced a degradation rate of 0.03 to 0.16 $mcd/m^2/lx$ per day.

The researchers used GIS dynamic segmentation as a means of organizing and simplifying the data while still maintaining the integrity of the unique attributes of the individual road segments.

Key Findings:

- Survey confirmed research effort covered new ground and provided background information to pavement marking management systems.
- Mobile collection devices are efficient because they use continuous readings to collect large amounts of data and are safer to use then handheld units.
- Handheld devices are more accurate and cost less than mobile devices but are less efficient since they cannot collect large amounts of data.
- Retroreflectivity prediction curves follow three basic shapes. Newly placed pavement will increase in R_L for up to 1 year. Existing markings deteriorate linearly. Maintenance activities cause noticeable shifts in the curves.

- Pavement marking retroreflectivity degrade at a rate between 0.03 to 0.16 $mcd/m^2/lx$ per day depending on the material used, location, and surface type.

Title: A Methodology for Estimating the Lifecycle of Interstate Highway Pavement Marking Retroreflectivity

Authors: Thamizharasan, A., Sarasua, W. A., Clarke, D B., and Davis, W. J.

Category: Conference Paper

Complete Citation:

Thamizharasan, Akila, Sarasua, Wayne A., Clarke, David B., and Davis, William J. (2002). "A Methodology for Estimating the Lifecycle of Interstate Highway Pavement Marking Retroreflectivity." Transportation Research Board Annual Meeting 2003, TRB Paper Number 03-3867.

Description:

The main focus of this paper was the design and analysis of the research performed by SCDOT. This paper came from the same research used to write the Performance of Pavement Marking Retroreflectivity on South Carolina's Interstate System Over Time.

The researchers used 30-m geometry and collected six rounds of data from 161 sites over a 28-month period. Statistical methods were used to analysis the data and create predictive models. Using regression analysis, the paper establishes the dependent variables as "difference in retroreflectivity" and "percent difference in retroreflectivity." Additionally, the paper signifies which independent variables (time, temperature, and humidity) were found to have significance. Although, temperature and humidity were both accounted for in the calibration process and were found to have no impact on the model. Also, the paper rules out traffic volume as a viable independent variable since it has an inverse correlation with time. Finally, the paper introduces the three basic curves used to model retroreflectivity degradation for pavement markings.

Key Findings:

- Three basic curves are:
    1. Retroreflectivity gradually increases for a short period of time and then decreases linearly with time.
    2. Retroreflectivity gradually decrease with time linearly.
    3. There are noticeable shifts in the pattern when restriping and snowplowing maintenance activities are introduced.

- The most significant factors influencing pavement-marking performance are:
    1. Pavement marking type
    2. Pavement surface type
    3. Marking color
    4. Maintenance activities

Title: Pavement Marking Material Evaluation Study in Michigan
Authors: Lee. J., Maleck, T., and Taylor, W.
Category: Journal Paper
Complete Citation:

Lee, Jung-Taek., Maleck, Thomas L., and Taylor, William C. (1999). "Pavement Marking Material Study in Michigan." *Institute of Transportation Engineering (ITE) Journal*, July 1999, 44-50.

Description:

This paper reports a research study, conducted by Michigan State University in the mid-90's that and evaluated the performance of several pavement-marking materials. The study intended to provide insight and guidance to implement cost effective procedures for pavement marking management. Focused on four major marking materials (paints, thermoplastics, thermosets, and tapes) the study used 50 sample sites throughout Michigan. The research objective was to determine the degradation rates for the various materials and used a minimum threshold value of 100 mcd/m^2/lux to indicate satisfactory marking performance.

The measuring device used was the Mirolux 12, which is a 15-meter geometry device. The author indicated that there was a great deal of variability from this device and that any future studies should consider better data collection equipment and methods.

Large variances in service life were shown but a clear explanation of the variances was not given. Time limitations minimized the amount of data that could be compared over time. Although the degradation rates were deemed linear, the R^2 values seemed low, showing little confidence that linear degradation was the best fit. Of significant note, snowfall (snow plowing) highly correlated to retroreflectivity degradation. Alternatively, AADT, speed limit, and percent commercial traffic did not correlate with degradation of retroreflectivity.

The basic conclusions of the study indicated that water-borne pavement markings are the most cost effective. This was based on reasonable performance compared to the low cost. Other materials perform better but the cost involved did not justify the improved service life. Michigan is a high snowfall (snow plow) state. Therefore, cost comparisons to a low snow plow state like N.C. may not be sensible.

Key Findings:

- Waterborne paints are considerably more cost effective due to low cost.
- Snowplowing has a significant impact on marking material performance.
- Model: $R_L = -0.3622*X + 254.82$, $R^2 = 0.14$
- AADT, Speed limit, and Commercial traffic were considered and eliminated from the model.

Title: Service Life of Durable Pavement Markings
Authors: Migletz, J., Graham, J., Harwood, D.W., and Bauer, K.M.
Category: Conference Preceding
Complete Citation:

Migletz, J., Graham, J., Harwood, D.W., and Bauer, K.M. (2001). "Service Life of Durable Pavement Markings." Transportation Research Record 1749, TRB, National Research Council, Washington D.C., 13-21

Description:

Conducted by the Transportation Research Board, using the Laserlux mobile retroreflectometer with 30-m geometry, this study took place from 1994 to 1998. Its purpose was to evaluate the life of durable pavement markings. Included in the study as a benchmark, was some limited evaluation of waterborne paints. The research collected data on 362 longitudinal (edge, center, & lane) pavement-marking lines from 85 sites across 19 states.

The study used regression analysis to evaluate various materials and establish a predictive degradation curve of the material performance over time. Marking material type, road surface type and marking material color where the independent variables evaluated.

Results from the regression analysis indicate there was a great deal of variation in identical materials at different sites. The variation was attributed to differences in roadway type, region of the country, marking specifications, quality control and winter maintenance. However, no comments were provided regarding the current age of the pavement markings when the study was performed. Furthermore, analysis indicated that yellow lines performed better than white but this was attributed to the use of a lower threshold on material expectations rather than on superior performance.

Key Findings:

- Focused on durable pavement markings (epoxy, tapes, and thermoplastics).
- Regression analysis identified large variations in the shape of the curves.
- For identical materials and types of lines, between different sites in the same state.
- Variations in service life can be attributed to roadway type, region of the country, marking specifications, contractors used, quality control, and winter maintenance policies.

Title: Reflectivity of Pavement Markings: Analysis of Retroreflectivity Curves
Authors: Kopf, Jamie
Category: Report
Complete Citation:

Kopf, Jamie. (2004). "Reflectivity of Pavement Markings: Analysis of Retroreflectivity Curves." Washington State Transportation Center, University of Washington, Report No. WA-RD 592.1.

Description:

This study was conducted by the Washington State Transportation Center from Jul 2003 to July 2004 using the Laserlux mobile retroreflectometer with 30-m geometry. The study evaluated the performance of pavement markings throughout Washington. Focusing on waterborne and solvent-based paints, the goal of this study was to develop predictive degradation curves for pavement marking performance. The research project was conducted using 80 test sites throughout the state. The data collection was repeated 11 times throughout the year. 100 mcd/m2/lux was set as the minimum threshold value to indicate satisfactory performance

The study used the Laserlux mobile collection device because of the ability to safely and efficiently collect a large amount of data in a small period of time. The device was mounted on a 1995 Chevrolet Beauville van. The collection speed was 60 mph or the posted speed limit and collected a scan width of 1.1 meter. The device collects over 1500 measurements per mile and uses an onboard computer to calculate the average retroreflectivity per every 250 feet. This distance was set by the user and was used to calculate the overall average retroreflectivity value for the entire test section. Linear referencing was used to designate the location of each test site and a GPS tag was captured, providing latitude and longitude coordinates for the test sample.

Regression analysis was used to best fit curves into the data and determine the overall degradation of the pavement markings. According to the study the results were statistically inconclusive. The standard deviation in values was significantly large and the variations in the data were too large for any curves to reasonably be fitted into the data. The final result of the project was the recommendation that Washington continue with their current practice of remarking based on an annual schedule.

Variation in the data can come from a litany of things but the variation in the collection device calibration and the ability to consistently capture the data from the same location each time are both issues that would translate into the NCDOT study.

Key Finding: Study was inconclusive and produced unreliable results due to large variances in data.

Title: Iowa Pavement Marking Management System: Initial Phases
Authors: Hawkins, N., Smadi, O., and Hans, Z.
Category: Report
Complete Citation:

Hawkins, Neal R., Smadi, Omar G., and Hans, Zachary. (2005). "Iowa Pavement Marking Management System: Initial Phases" Proceedings of the 2005 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Description:

This project was the first phase to a multi-phase research program to evaluate Iowa's DOT pavement marking practices. Iowa's DOT has one Lazerlux Van, which is used to take continuous measurements of retroreflectivity throughout Iowa. The van is equipped with a 30-m geometry Laserlux retroreflectometer and collects data at a highway speed of 55 mph. The data collection uses a linear referencing system to collect location information and averages the retroreflectivity value for every tenth of a mile throughout the road segment. Each segment is then averaged for a specific route using the mileposts to mark the beginning and end of the route. GPS data is collected for each run but the location information used standard linear referencing based on milepost markings. Calibration is performed at least once a day or when erratic values are observed.

Each of Iowa's six districts has a Delta LTL-X handheld retroreflectometer, which is used during on going pavement-marking operations as a means of ensure quality control. The LTL-X is also capable of 30-m geometry and collects GPS data for each site measured.

GPS data rarely matched locations that were in the GIS based on existing linear referencing methods.

Key Findings:

- Calibration of collection equipment was key to good data.
- Combined use of mobile and handheld equipment to collect data.
- Combining mobile and handheld units created integration issues when populating a GIS with location referencing information.

Title: NCHRP Synthesis 306 Long-term Pavement Marking Practices
Authors: Migletz, J., and Graham, J.
Category: Synthesis of Highway Practice
Complete Citation:

Migletz, J. & Graham, J. (2002). "NCHRP Synthesis 306 Long-term Pavement Marking Practices." Transportation Research Board, Washington D.C.

Description:

The synthesis is a comprehensive review of all the major research efforts regarding pavement marking up through the year 2002. The study highlights that the four major concerns with pavement marking are: funding for pavement markings programs, nighttime visibility in rain and fog, quality control of new markings, and a shortage of quality labor. This report is a comprehensive collection of summaries of a large grouping of literature in the field of pavement marking management.

Key Findings:

- The most commons factors that are used to select material are: line type, pavement surface, type of street and highway, and AADT (pg 34).
- Most agencies are confident that marking material are good quality but are less sure they are receiving adequate application (pg51).
- The four engineering performance goals are high visibility, high durability, convenience, and low cost (pg53).
- Waterborne paint is striped on almost 60% of the total highway mileage at a cost of 17% of the budget. Thermoplastics are used on 23% of the total mileage at a cost of 35% of the total budget (54).
- The factors that contribute to the decrease in pavement-marking retroreflectivity include the passage of time, action of traffic, exposure to ambient weather conditions, snowplow operations, marking material specifications, pavement surface preparation, and quality control at the time markings are placed (Migletz et. al., 2000 unpublished data).
- Cost include application cost for marking material, Cost for inspection and cost for traffic delay pg (61-64).
- Cost for application only (pg 61):
    - Waterborne paint cost ~ $.06 / linear-ft
    - Thermoplastics cost ~$.32/linear-ft
    - Other materials range from $.90 - $4.00 /linear-ft
- Limited use of inventory systems throughout the states (Pg 70-72).

Title: Pavement Marking Materials: Assessing Environment-Friendly Performance
Author: Andrady, A.L.
Category: Study
Complete Citation:

Andrady, A.L. (1997). "." NCHRP Report 392, Transportation Research Board, Washington, D.C.

Description:

In this research Andrady developed one of the first degradation models for pavement marking retroreflectivity. The focus of Andrady's study was to determine the environmental impact of volatile organic compounds and to research alternative pavement marking materials. Part of Andrady's study was to evaluate the performance characteristics of pavement marking retroreflectivity.

Key Findings:

- Andrady created a logarithmic based model represented by the following formula:

$$T_{100} = 10^{(R_0 - 100)/b}$$

Where

T_{100} = Time in months for the retroreflectivity to reach 100 mcd/m2/lx
R_0 = Estimate of the initial retroreflectivity value
b = Gradient of the semi-logarithmic plot of retroreflectivity.

- The end of service life for this model was defined by reaching a retroreflectivity value of 100 mcd/m^2/lx.
- There was no coefficient of determination published for this model.

Title: Transportation Asset Management Guide
Authors: Cambridge Systems, Inc.
Category: Report
Complete Citation:

Cambridge Systems, Inc. (2002b). "Transportation Asset Management Guide." NCHRP Project 20-24(11), Transportation Research Board, Washington, D.C.

Description:

The transportation asset management guide is a comprehensive asset management document. The guide provides a strategic approach to asset management. The guide is designed specifically for DOT's and to provides a step-by-step approach to develop and improve asset management. The guide has nine chapters and provides the tools for a DOT to conduct a self-assessment, develop policies and goals, determine data to collect, and creates action steps for implementation.

Key Findings:

- Identifies a seven-step approach to asset management.
- Provides resources for policy and goals development
- Provides guidelines for transportation specific data collection and organization

Title: Pavement Management Applications Using Geographic Information Systems, A synthesis of Highway Practice

Authors: Flintsch, Gerardo W., Dymond, Randy, Collura, John.

Category: Synthesis

Complete Citation:

Flintsch, G.W., Dymond, R., and Collura, J. (2004). "Pavement Management Applications Using Geographic Information Systems, A Synthesis of Highway Practice." NCHRP Synthesis 335, Transportation Research Board, Washington, D.C.

Description:

This synthesis focused on the application of GIS in pavement management. Information provided was gathered from a comprehensive literature review from 71 sources. Additionally, the synthesis provided the results from an electronic, web-based survey of DOT's from 48 states and 4 Canadian provinces. The paper advocates for a centralized pavement management system that uses GIS to organize and store pavement attributes.

Key Findings:

- Most DOT's either use GIS or plan to in the near future
- The major application for GIS is creating maps and recording attributes
- Little effort is done by DOT's to use GIS for advanced spatial analysis
- Most data in DOT's is maintained in different divisions
- All agencies use some form of a LRS for location information, data collection, and data storage.
- DOT's are implementing coordinate based location systems, like GPS but typically the use of a GPS is redundant to existing LRS. No DOT admitted to using GPS as the sole source of location referencing.
- Three main problems were identified with the development and use of spatial pavement management systems. These are:
    - The use of different location referencing methods,
    - The level of effort required to develop and maintain the spatially enabled databases, and
    - The handling of temporal issues.
- ESRI products make up the overwhelming majority of users (74%)

Title: Pavement Marking Materials and Markers: Testing the Relationship Between Retroreflectivity and Safety

Authors: Bahar, G., Masiliah, M., Erwin, T., and Tan, E.

Category: NCHRP Report

Complete Citation:

Bahar, G., Masiliah, M., Erwin, T., and Tan, E. (2004). "Pavement Marking Materials and Markers: Testing the Relationship Between Retroreflectivity and Safety." NCHRP Report on Project 17-28, Transportation Research Board, Washington, D.C.

Description:

This report summarized a study of the relationship between retroreflectivity and safety. Focused on human factors this study attempted to show the relationship of various factors that affect pavement marking performance. These factors were age, color, material type, traffic volume, pavement surface, climate, and snow removal. The primary objective was to verify the research null hypothesis which was that retroreflectivity and safety are correlated. The researchers hoped to prove that greater retroreflectivity related to greater safety. The study, conducted from 1992 to 1994 and 1997 to 2002, was limited to California and covered approximately 5,000 miles of road segment. The results of the study rejected the null hypothesis and concluded that retroreflectivity is not correlated to safety.

Key Findings:

- Converted pavement marking age to a retroreflectivity for various materials assuming that the impact of retroreflectivity is independent of materials and can be quantified in terms of retroreflectivity level.
- The effects on safety for retroreflectivity age (old or new) were essential zero.
- Presence of markers was important to driver safety but the level of retroreflectivity was not. This is because drivers adapt there driving speed to adjust for lower retroreflectivity levels.
- This study did not address the effect of pavement markings or markers themselves; rather, the focus was on safety of retroreflectivity. This study cannot be used to quantify the safety effect of the presence of or absence of markers.

APPENDICES

11.0 APPENDIX A

Jump Software statistical output for thermoplastics

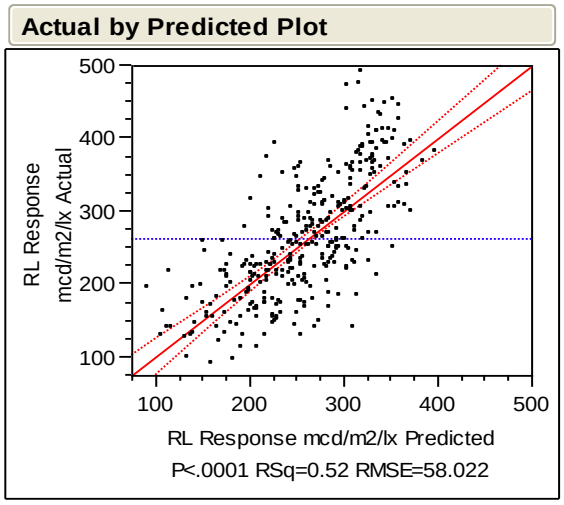
Thermoplastics Consolidated Model

Summary of Fit

RSquare	0.594837
RSquare Adj	0.588698
Root Mean Square Error	53.24883
Mean of Response	260.9226
Observations (or Sum Wgts)	336

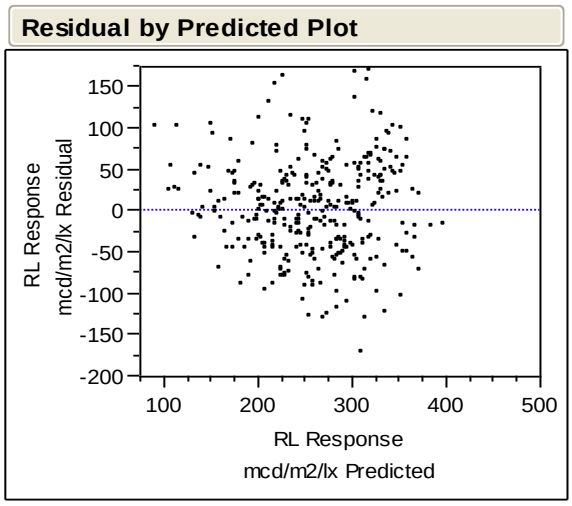
Parameter Estimates

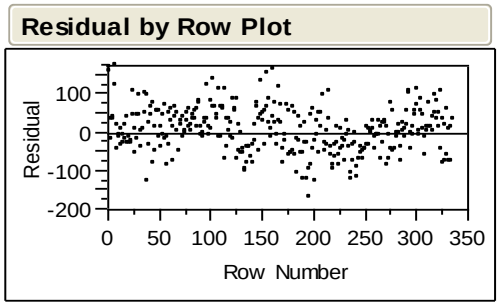
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	190.68	18.73	10.18	<.0001
RL Initial	0.3848	0.057	6.75	<.0001
Time	-2.090	0.1520	-13.75	<.0001
ADT	-0.001134	0.0003	-5.09	<.0001
Line	20.68	3.438	6.02	<.0001
Type				
Color	18.96	4.85	3.91	0.0001

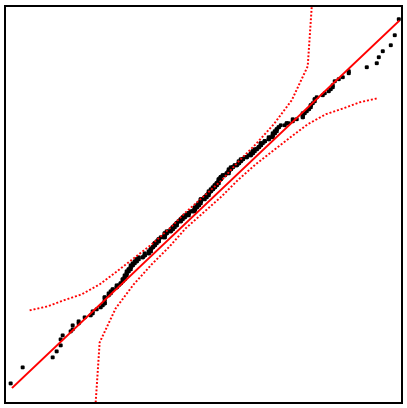


Confidence Intervals and Prediction Intervals

Parameter	Estimate	Lower CI	Upper CI	Lower PI	Upper PI	(1-Alpha)	Future N
Mean	260.9226	254.0507	267.7946	134.7706	387.0746	0.950	1
St Dev	64.03669	59.53327	69.28287				


Residual by Predicted Plot
RL Response
mcd/m2/lx Residual
150
100
50
0
-50
-100
-150
-200
100
200
300
400
500
RL Response
mcd/m2/lx Predicted


Residual by Row Plot
Residual
100
0
-100
-200
0
50
100
150
200
250
300
350
Row Number



White Edge

Summary of Fit

RSquare	0.375707
RSquare Adj	0.364287
Root Mean Square Error	56.44681
Mean of Response	299.3155
Observations (or Sum Wgts)	168

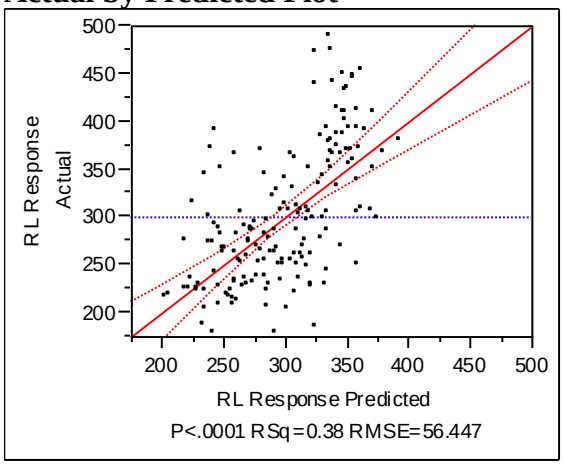
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	223.26676	38.42787	5.81	<.0001
RL Initial	0.3860338	0.100504	3.84	0.0002
Time	-2.086187	0.227949	-9.15	<.0001
ADT	-0.000878	0.000336	-2.61	0.0099

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RL Initial	1	1	47006.68	14.7530	0.0002
Time	1	1	266875.50	83.7587	<.0001
ADT	1	1	21694.57	6.8088	0.0099

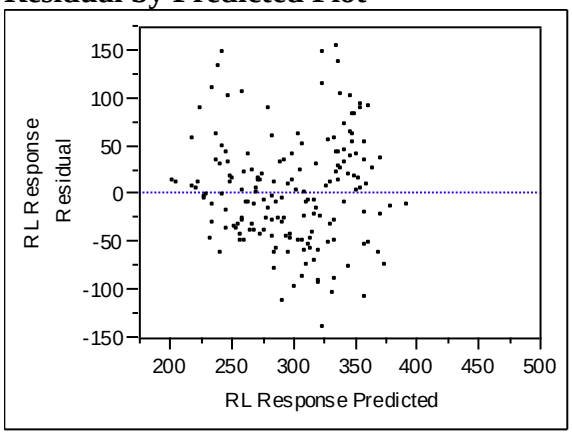
Actual by Predicted Plot



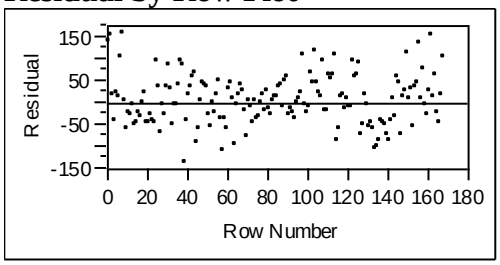
Confidence Intervals and Prediction Intervals

Parameter	Estimate	Lower CI	Upper CI	Lower PI	Upper PI	(1-Alpha)	Future N
Mean	299.3155	292.7057	305.9252	213.3887	385.2423	0.950	1
St Dev	43.39435	39.1975	48.6054				

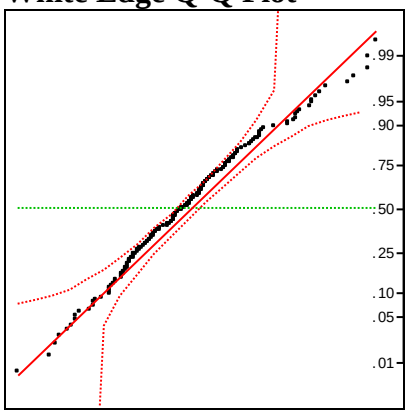
Residual by Predicted Plot



Residual by Row Plot



White Edge Q-Q Plot



White Middle

Summary of Fit

RSquare	0.528711
RSquare Adj	0.496577
Root Mean Square Error	60.64524
Mean of Response	273.25
Observations (or Sum Wgts)	48

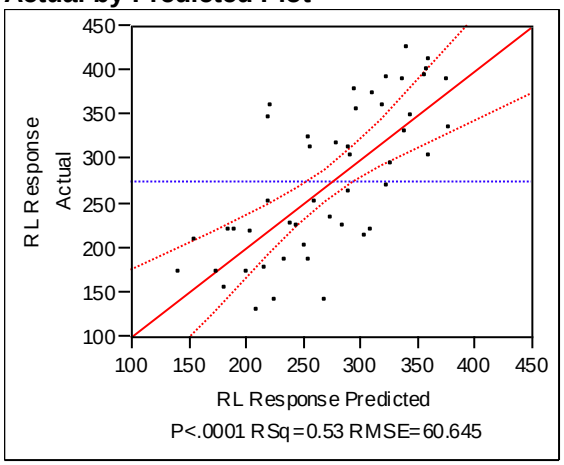
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	172.46717	90.0356	1.92	0.0619
Time	-2.886644	0.458173	-6.30	<.0001
RL Initial	0.5870397	0.233054	2.52	0.0155
ADT	-0.002581	0.00083	-3.11	0.0033

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Time	1	1	145989.13	39.6942	<.0001
RL Initial	1	1	23335.37	6.3448	0.0155
ADT	1	1	35552.05	9.6665	0.0033

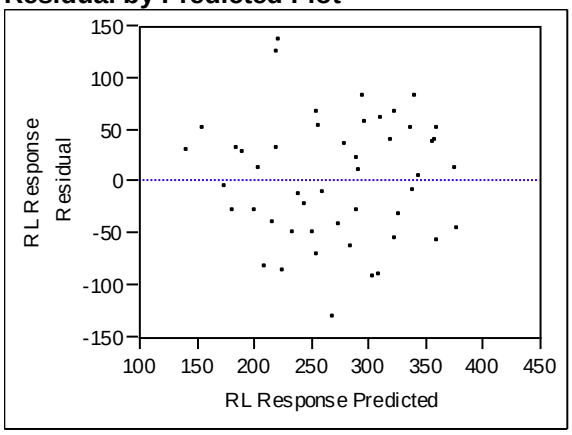
Actual by Predicted Plot



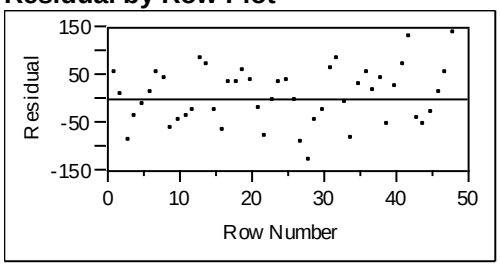
Confidence Intervals and Prediction Intervals

Parameter	Estimate	Lower CI	Upper CI	Lower PI	Upper PI	(1-Alpha)	Future N
Mean	273.25	255.2036	291.2964	146.9251	399.5749	0.950	1
St Dev	62.14975	51.73773	77.84756				

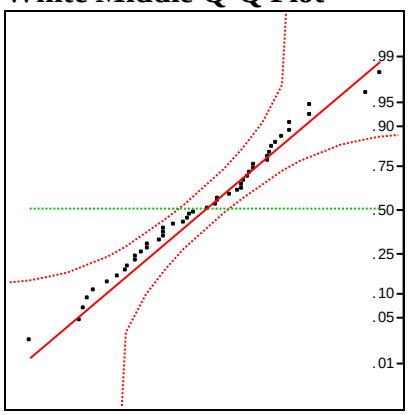
Residual by Predicted Plot



Residual by Row Plot



White Middle Q-Q Plot



Yellow Middle

Summary of Fit

RSquare	0.637351
RSquare Adj	0.615373
Root Mean Square Error	36.23307
Mean of Response	173.8611
Observations (or Sum Wgts)	36

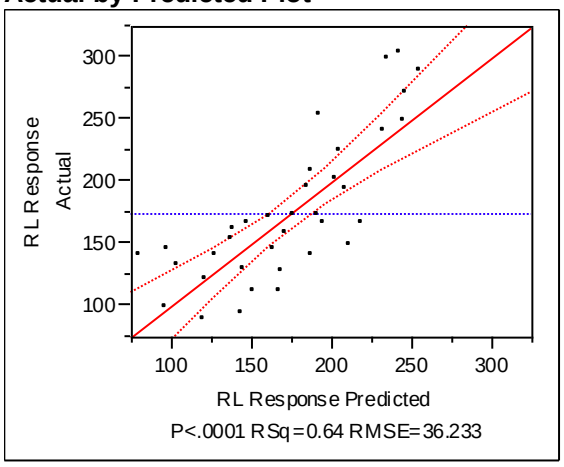
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	76140.74	38070.4	28.9986
Error	33	43323.56	1312.8	Prob > F
C. Total	35	119464.31		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	128.15127	27.53898	4.65	<.0001
RL Initial	0.4076898	0.095006	4.29	0.0001
Time	-1.988661	0.316088	-6.29	<.0001

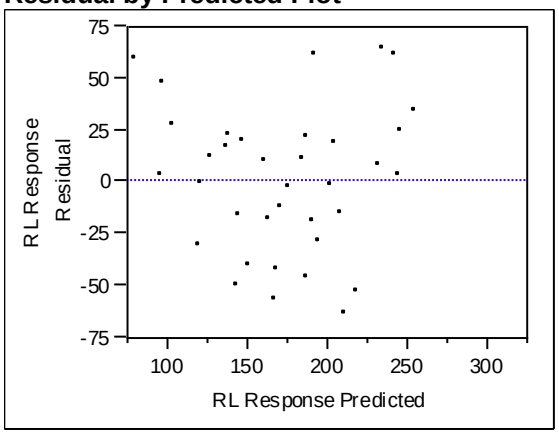
Actual by Predicted Plot



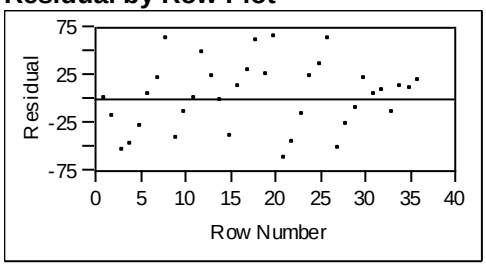
Confidence Intervals and Prediction Intervals

Parameter	Estimate	Lower CI	Upper CI	Lower PI	Upper PI	(1-Alpha)	Future N
Mean	173.8611	157.8868	189.8354	76.69305	271.0292	0.950	1
St Dev	47.21226	38.293	61.58547				

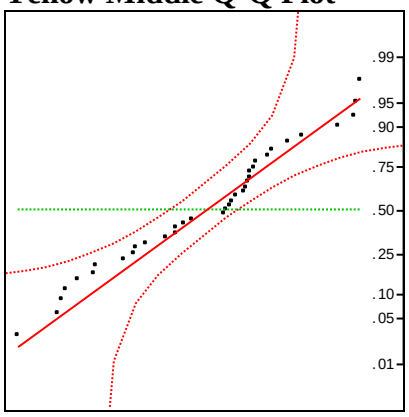
Residual by Predicted Plot



Residual by Row Plot



Yellow Middle Q-Q Plot



Yellow Edge

Summary of Fit

RSquare	0.448061
RSquare Adj	0.427363
Root Mean Square Error	45.49583
Mean of Response	214.4048
Observations (or Sum Wgts)	84

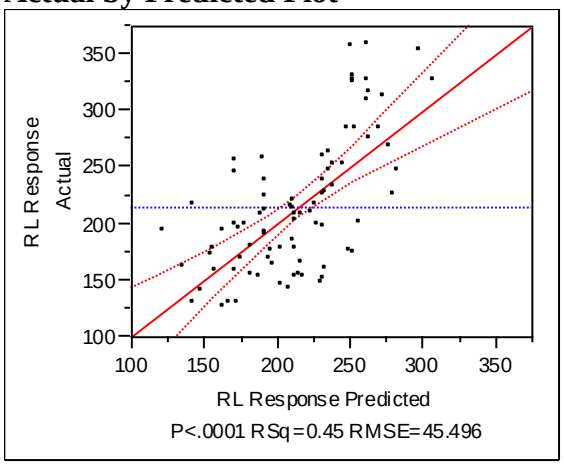
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	193.29778	21.12383	9.15	<.0001
RL Initial	0.3963484	0.083613	4.74	<.0001
Time	-1.685845	0.259828	-6.49	<.0001
ADT	-0.001619	0.000443	-3.65	0.0005

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RL Initial	1	1	46510.464	22.4702	<.0001
Time	1	1	87137.943	42.0983	<.0001
ADT	1	1	27625.445	13.3465	0.0005

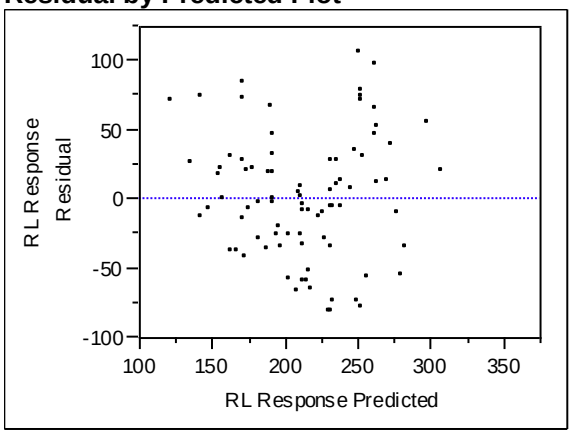
Actual by Predicted Plot



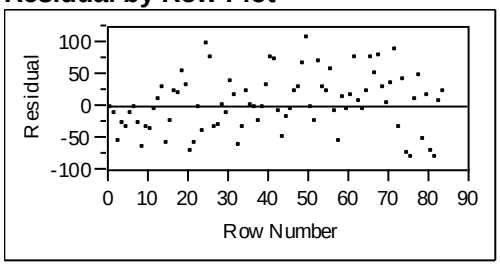
Confidence Intervals and Prediction Intervals

Parameter	Estimate	Lower CI	Upper CI	Lower PI	Upper PI	(1-Alpha)	Future N
Mean	214.4048	205.6713	223.1382	133.8862	294.9234	0.950	1
St Dev	40.24393	34.94339	47.45503				

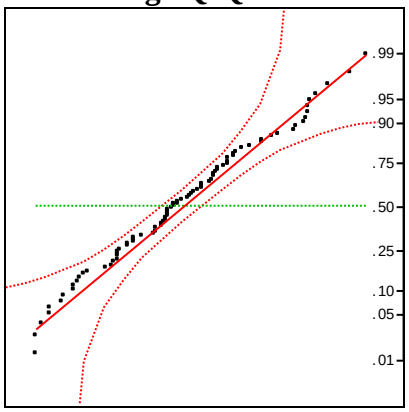
Residual by Predicted Plot



Residual by Row Plot



Yellow Edge Q-Q Plot



Jump Software statistical output for paints

117 Observations (39 Road segments) with a full 1 year of RL values collected at 6 months and 12 months.

$$\mathbf{R_L = 55.2 + 0.77*R_{L\ Initial} - 4.17*time}$$

Where:

R_L: mcd/m^2/lx

$R_{L\ Initial}$: Mcd/m^2/lx at time 0 months

Time: months

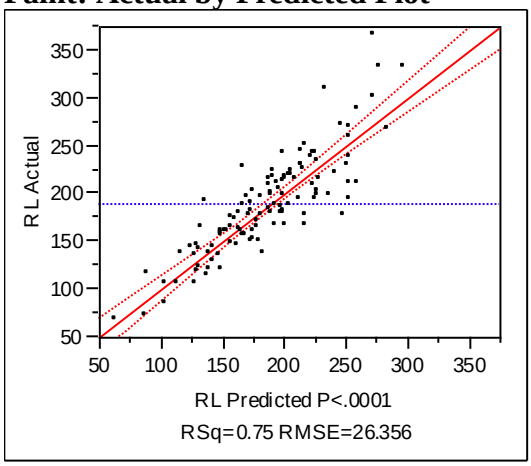
Summary of Fit

RSquare	0.750685
RSquare Adj	0.746311
Root Mean Square Error	26.35602
Mean of Response	187.812
Observations (or Sum Wgts)	117

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	55.161175	12.04437	4.58	<.0001
RL 0	0.7691671	0.045324	16.97	<.0001
Time	-4.171299	0.605794	-6.89	<.0001

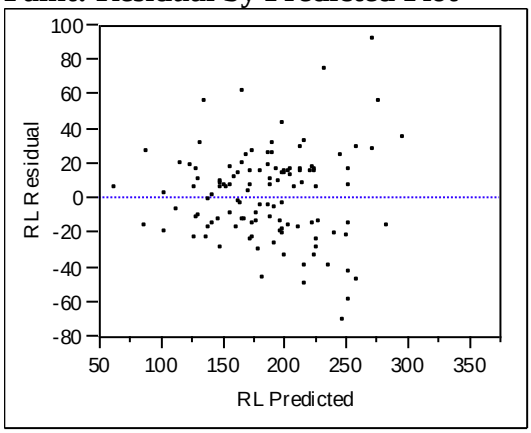
Paint: Actual by Predicted Plot



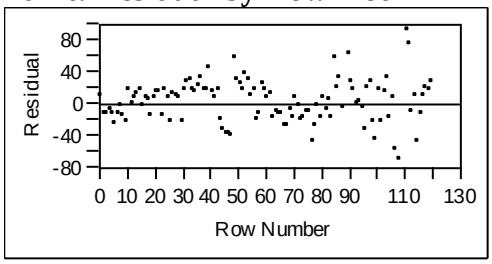
Confidence Intervals and Prediction Intervals

Parameter	Estimate	Lower CI	Upper CI	Lower PI	Upper PI	(1-Alpha)	Future N
Mean	187.812	179.5103	196.1137	97.63237	277.9916	0.950	1
St Dev	45.33752	40.17873	52.02823				

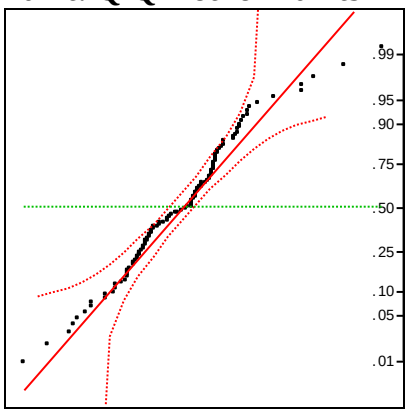
Paint: Residual by Predicted Plot



Paint: Residual by Row Plot

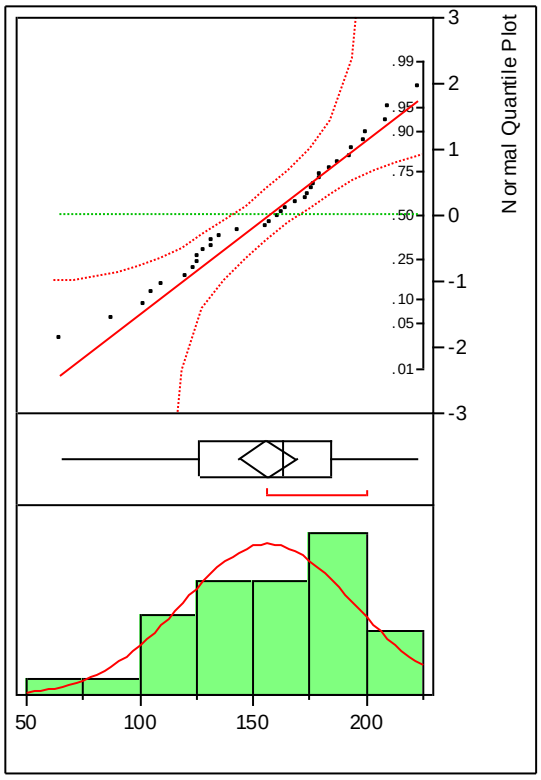


Paint: Q-Q Plot for Paints



Validation Data Analysis

White Edge RL (mcd/m2/lx)



Normal(156.429,37.7805)

Moments

Mean	156.42857
Std Dev	37.780547
Std Err Mean	6.386078
upper 95% Mean	169.40664
lower 95% Mean	143.4505
N	35

Fitted Normal
Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	156.42857	143.4505	169.40664
Dispersion	σ	37.780547	30.559629	49.500153

Goodness-of-Fit Test

Shapiro-Wilk W Test

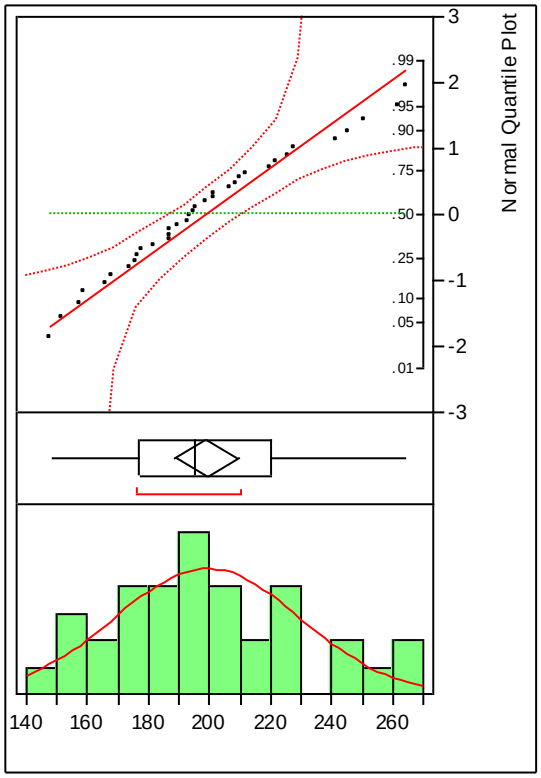
W	Prob<W
0.972775	0.5239

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Confidence Intervals

Parameter	Estimate	Lower CI	Upper CI	1-Alpha
Mean	156.4286	143.4505	169.4066	0.950
Std Dev	37.78055	30.55963	49.50015	

White Skip RL (mcd/m2/lx)



Normal(199.143,30.2957)

Moments

Mean	199.14286
Std Dev	30.295741
Std Err Mean	5.1209149
upper 95% Mean	209.54981
lower 95% Mean	188.73591
N	35

Confidence Intervals

Parameter	Estimate	Lower CI	Upper CI	1-Alpha
Mean	199.1429	188.7359	209.5498	0.950
Std Dev	30.29574	24.50538	39.69354	

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	199.14286	188.73591	209.54981
Dispersion	σ	30.295741	24.505379	39.693544

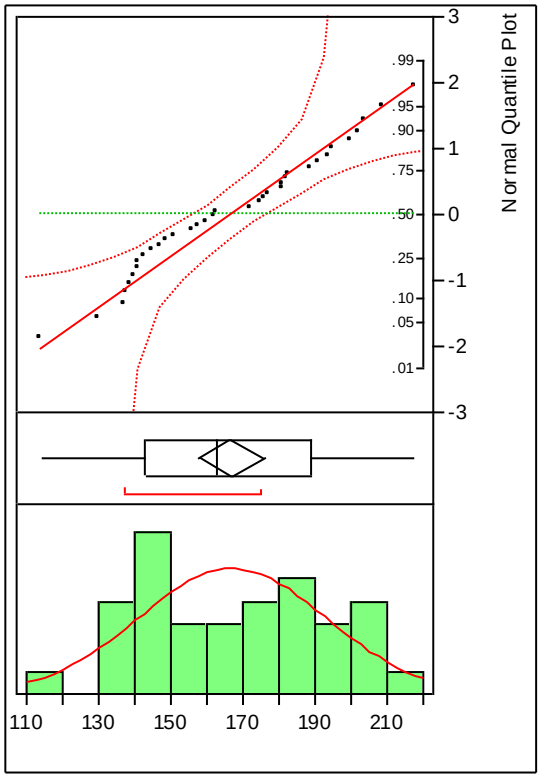
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.968203	0.3958

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Yellow Center RL (mcd/m2/lx)



Normal(166.943,25.941)

Moments

Mean	166.94286
Std Dev	25.941045
Std Err Mean	4.3848369
upper 95% Mean	175.85392
lower 95% Mean	158.0318
N	35

Confidence Intervals

Parameter	Estimate	Lower CI	Upper CI	1-Alpha
Mean	166.9429	158.0318	175.8539	0.950
Std Dev	25.94104	20.98299	33.98801	

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	166.94286	158.0318	175.85392
Dispersion	σ	25.941045	20.982986	33.988012

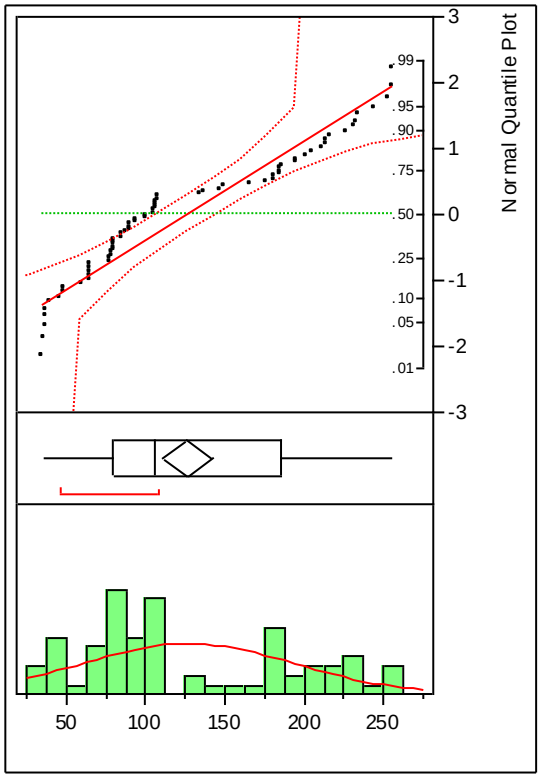
Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.968773	0.4104

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Paint 2 Year White Edge and Yellow Center



Normal(126.614,66.9764)

Moments

Mean	126.61429
Std Dev	66.976373
Std Err Mean	8.0052077
upper 95% Mean	142.58424
lower 95% Mean	110.64433
N	70

Confidence Intervals

Parameter	Estimate	Lower CI	Upper CI	1-Alpha
Mean	126.6143	110.6443	142.5842	0.950
Std Dev	66.97637	57.42673	80.36536	

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	126.61429	110.64433	142.58424
Dispersion	σ	66.976373	57.426727	80.365362

Goodness-of-Fit Test

Shapiro-Wilk W Test

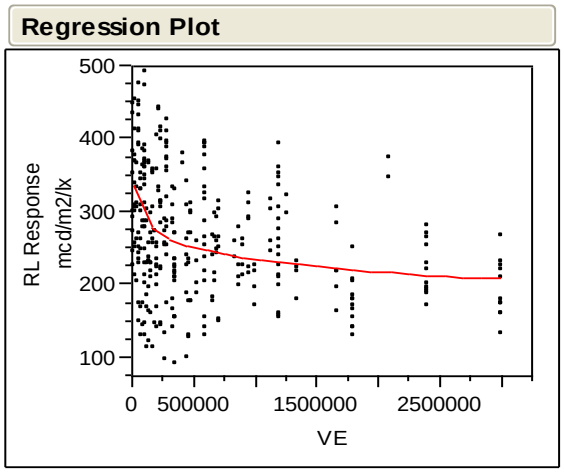
W	Prob<W
0.909050	<.0001

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Logarithmic Decay Plots using Vehicle Exposure

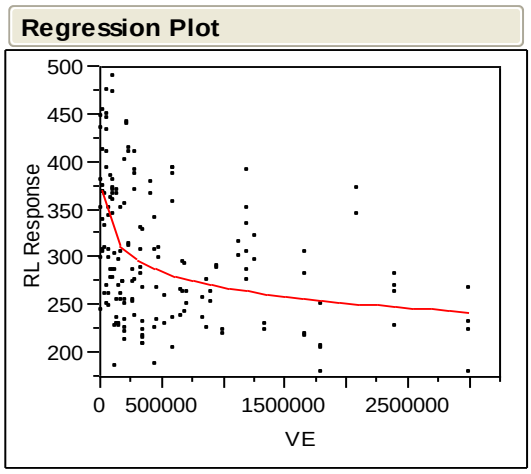
Thermo Logarithmic Decay by VE Consolidated Model R^2 = .13

VE = Time*AADT



White Edge Thermo Log decay R^2 = .18

VE = Time*AADT



12.0 APPENDIX B

Physical Model XML Output

Oracle_XML File

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	<xs:complexType name="Initial_RL">
		<xs:sequence>
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			<xs:element name="Date" type="xs:date" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Number of Valid Scan" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Chainage" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Collection Device" type="xs:string" minOccurs="1" maxOccurs="1"/>
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minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
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			<xs:element name="Segment Length" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Application Date" type="xs:date" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Cost per Foot" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="North_Coord" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="West_Coord" type="xs:string" minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:element name="6_Mon_RL" type="6_Mon_RL"/>
	<xs:complexType name="6_Mon_RL">
		<xs:sequence>
			<xs:element name="Place ID" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="6 Month RL" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Date" type="xs:date" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Number of Scans" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Chainage" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Collection Device" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="PK_Initial Pavement Marking" type="Initial_Pavement_Marking"
minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:element name="Annual_RL" type="Annual_RL"/>
	<xs:complexType name="Annual_RL">
		<xs:sequence>
			<xs:element name="Place ID" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Annual RL" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Date" type="xs:date" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Number of Scans" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Chainage" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Collection Device" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="PK_Initial Pavement Marking" type="Initial_Pavement_Marking"
minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
</xs:schema>
```

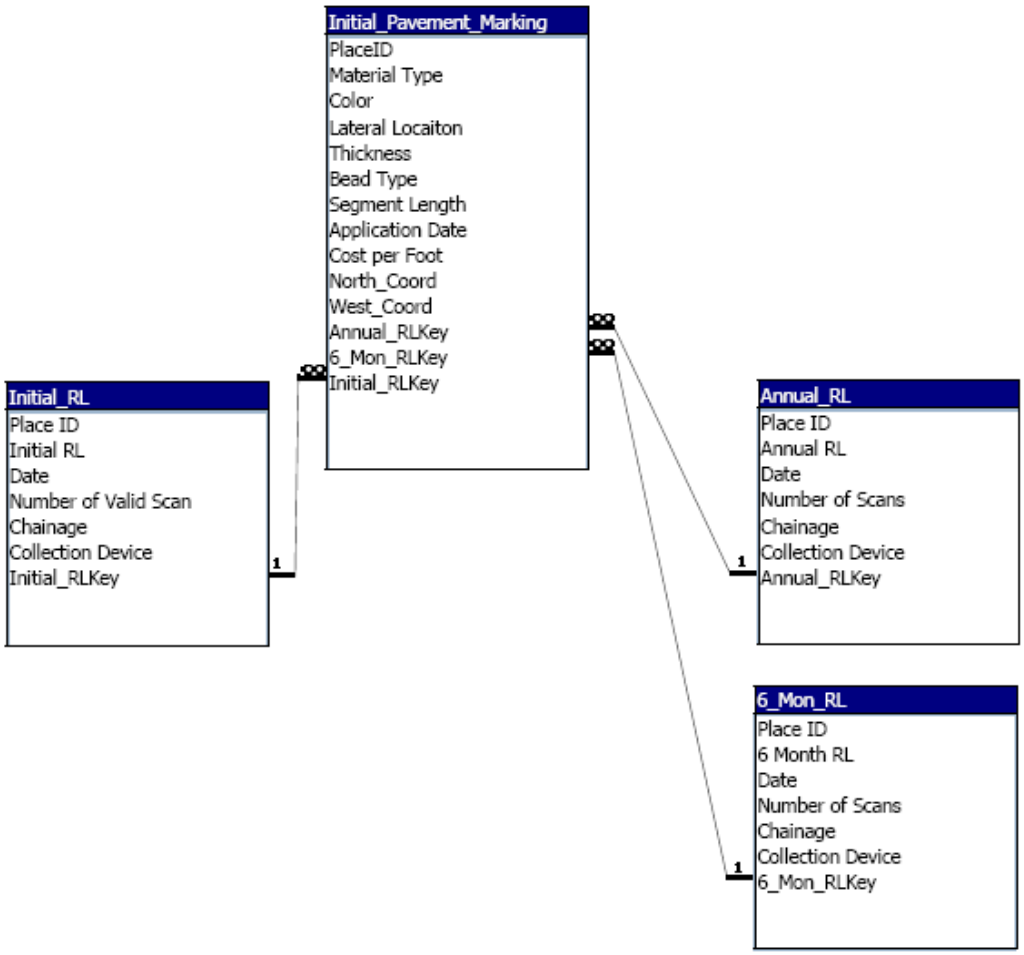
MS Access XML File

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">
	<xs:element name="Initial_RL" type="Initial_RL"/>
	<xs:complexType name="Initial_RL">
		<xs:sequence>
			<xs:element name="Place ID" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Initial RL" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Date" type="xs:dateTime" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Number of Valid Scan" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Chainage" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Collection Device" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="PK_Initial Pavement Marking" type="Initial_Pavement_Marking"
minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:element name="Initial_Pavement_Marking" type="Initial_Pavement_Marking"/>
	<xs:complexType name="Initial_Pavement_Marking">
		<xs:sequence>
			<xs:element name="PlaceID" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Material Type" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Color" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Lateral Locaiton" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Thickness" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Bead Type" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Segment Length" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Application Date" type="xs:dateTime" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Cost per Foot" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="North_Coord" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="West_Coord" type="xs:double" minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:element name="6_Mon_RL" type="6_Mon_RL"/>
	<xs:complexType name="6_Mon_RL">
		<xs:sequence>
			<xs:element name="Place ID" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="6 Month RL" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Date" type="xs:dateTime" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Number of Scans" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Chainage" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Collection Device" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="PK_Initial Pavement Marking" type="Initial_Pavement_Marking"
minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:element name="Annual_RL" type="Annual_RL"/>
	<xs:complexType name="Annual_RL">
		<xs:sequence>
			<xs:element name="Place ID" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Annual RL" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Date" type="xs:dateTime" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Number of Scans" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Chainage" type="xs:double" minOccurs="1" maxOccurs="1"/>
			<xs:element name="Collection Device" type="xs:string" minOccurs="1" maxOccurs="1"/>
			<xs:element name="PK_Initial Pavement Marking" type="Initial_Pavement_Marking"
minOccurs="1" maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
</xs:schema>
```

XML Imported into an MS Access db

Relationships for Database4

Monday, November 05, 2007



13.0 APPENDIX C

Procedure Log for GIS Proof of Concept

Retro-reflectivity Values of Pavement Marking - Interstate I-95 Halifax County NC

Data

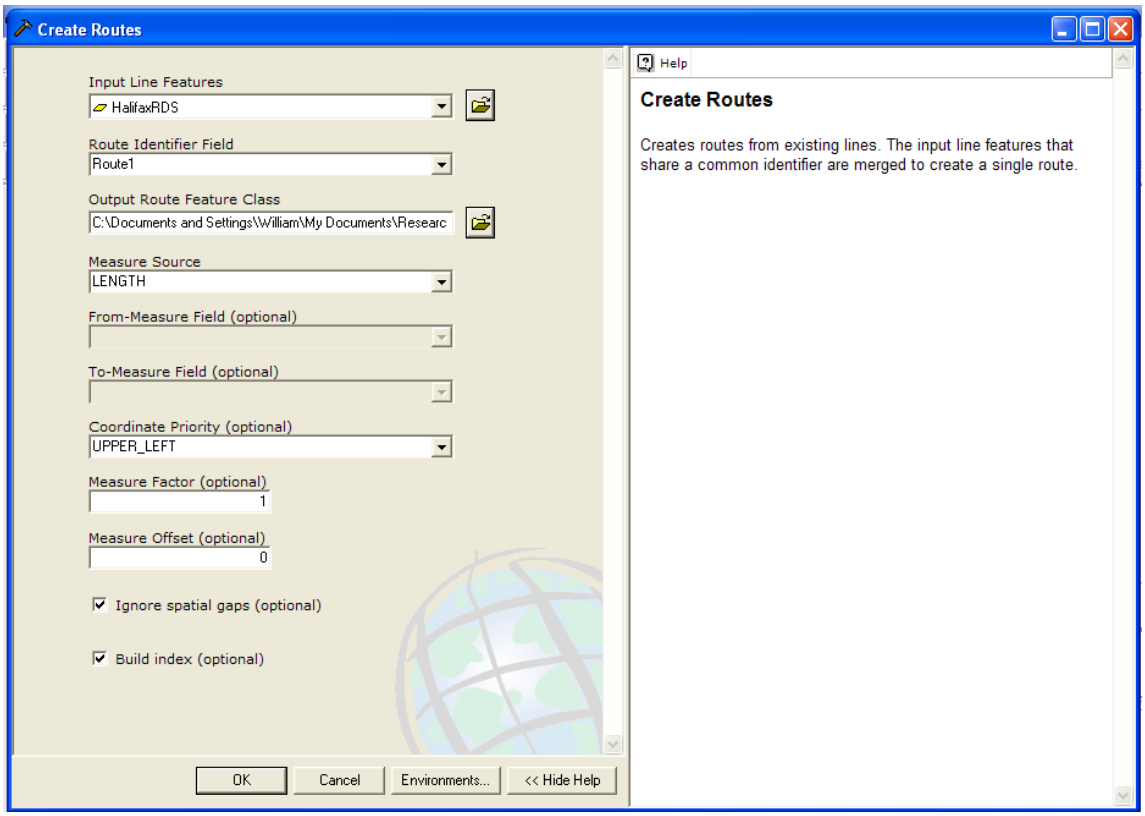
1. Road shapefile, for Halifax County:
   http://www.ncdot.org/it/gis/DataDistribution/DOTData/shapeEnglish.html

   NAD_1983_StatePlane_North_Carolina_FIPS_3200_Feet
   Projection: Lambert_Conformal_Conic
   False_Easting: 2000000.002617
   False_Northing: 0.000000
   Central_Meridian: -79.000000
   Standard_Parallel_1: 34.333333
   Standard_Parallel_2: 36.166667
   Latitude_Of_Origin: 33.750000

2. Linear1.dbf is the "event table" used for this linear referencing example. The Linear1.dbf was generated by the researcher using the NCDOT pavement marking data, NCDOT network data and the algorithm. This table includes retro-reflectivity values at 10^{th} mile increments. Source: The measured pavement marking data came from NCDOT and was collected by a contractor, Precision Scan LLC. The location information for this data was collected using a GPS and a WGS_1984 coordinate system. The predicted values were generated using the mathematical models established in chapter 5.

Procedure Log:

1) Open ArcMap
2) Add the NCDOT Road Characteristics Data
3) Using SQL reduce the data to Halifax County (name: HalifaxRDS)
4) Using the LRS tool <Linear referencing Tools> <Create Routes> (name: HalifaxRDS_Routes)



5) Add the HalifaxRDS_Routes.shp (should be automatic)

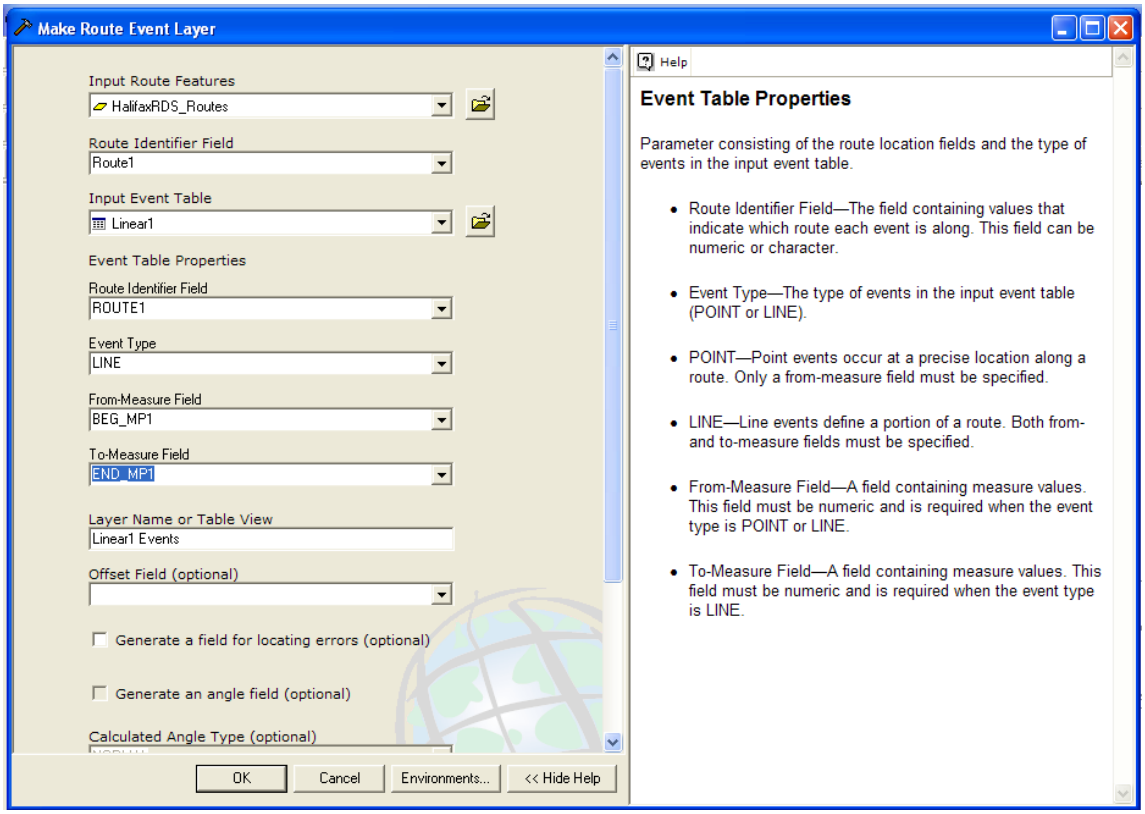
6) Add the Linear1.dbf. This is the event table generated from Microsoft Access and then saved as a .dbf file. This is the output file generated from the algorithm. This file contains all the "Event" data related to retroreflectivity for this 12 mile stretch of I-95. For example, this includes the values measured in the field as well as the predicted values generated from the mathematical models.

7) Use the tool <Linear referencing Tools> <Make Route Event Layer>. A route event layer is a temporary layer that displays event data (based on selection) that is associated with a given route feature. It is necessary for the event data to have a corresponding value for each record that relates to the route. In this case the route feature was label "Route 1". Both the route feature and the event table used the Route 1 filed to identify this segment as I-95. Furthermore, the event data can be displayed as a point or line. Displaying the event as a line requires a "to" and "From" field. "Chainage" also know as stationing data was collected at tenth mile increments. The chainage value was then translated into a "To" and "From" field. This was all that was required to build the route.

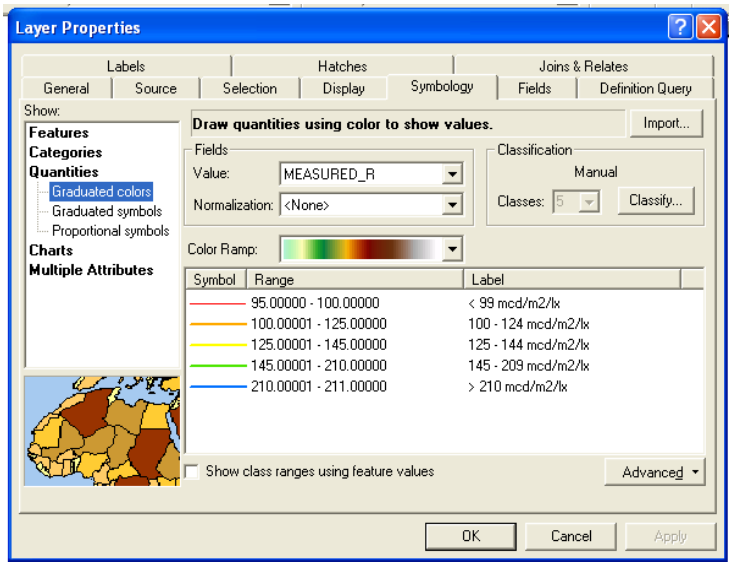
   However, using chainage can cause cumulative errors in location referencing. For example, if each value was off by only 10 feet the error could add up to a 100 foot error each mile and in this case that would result in a possible error of 1200 feet. In order to overcome the cumulative error GPS based coordinated data was used to

associate each record with the corresponding mile post data. Although accuracy issues still exist the cumulative error is thus reduced.

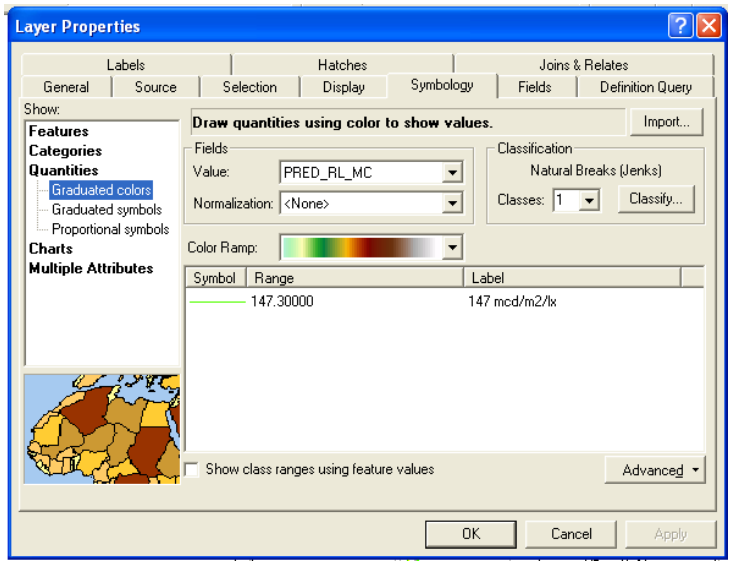
Input Route features - HalifaxRDS_Routes
Route Identifier Field - Route1 (may set be itself)
Input Event Table - Linear1.dbf
Route Identifier Field - Route1
Event Type - Line
From-Measure field - Beg_Mp1
To-Measure Field - End_Mp1



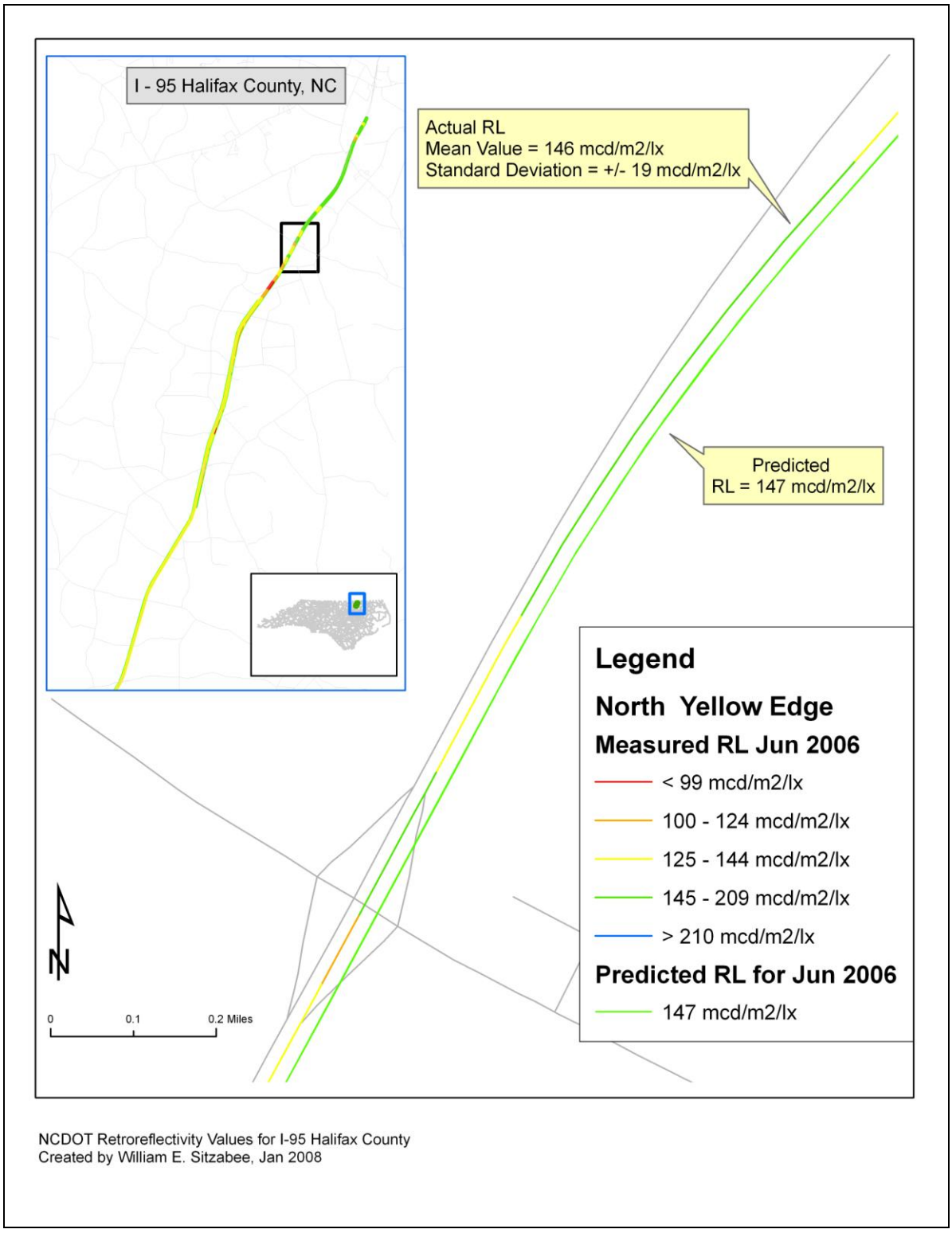
8) Step seven created the route event layer. This would display all the events in the linear1.dbf. So a series of SQL functions was used to select only the North Bound Yellow Edge lines from this event layer and then a new layer was created named "North Yellow Edge Measured RL Jun 2006". In the property box, symbology tab, go to layer properties and select quantities – define 5 classes using the appropriate LOS increments for Yellow thermoplastics. Select the field value "Measured_RL"



9) Step 8 was repeated but this time the field value was set for "Pred_RL_MC" which is the predicted value for Jun 2006.



10) The final step is to set the appropriate cartographic features such as a neatline, legend, scale, etc.
11) Export map to a jpeg.



NCDOT Retroreflectivity Values for I-95 Halifax County
Created by William E. Sitzabee, Jan 2008

14.0 APPENDIX D

MATHCAD Generated Simulation

$n := 100$

$predicted := rnorm(n, 193.3, 21.1) + 243 \cdot rnorm(n, .400, .084) - 60 \cdot rnorm(n, 1.69, .26) - 36500 \cdot rnorm(n, .0016, .00044)$

predicted =

	1
85	73.378
86	92.448
87	155.827
88	148.746
89	159.329
90	113.532
91	108.947
92	158.628
93	88.164
94	70.243
95	150.649
96	136.273
97	157.155
98	167.033
99	181.783
100	147.48

$sum := \sum predicted$

$sum = 13303.9$

$ave := \frac{sum}{n}$

ave = 133

stdev(predicted) = 35.9

Evaluation of Simulated data Using Jump

