AN ASSET MANAGEMENT FRAMEWORK BASED ON FIELD PERFORMANCE OF PAVEMENT MARKINGS

A Thesis

by

SAM PRASHIEL RAJ MADIRI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Civil Engineering

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Approved by:

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ABSTRACT

An Asset Management Framework Based on Field Performance of Pavement Markings.
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Performance-based asset management provides a strategic framework for managing transportation infrastructure to improve existing procedures for resource allocation. The importance of comprehensive management of pavement marking assets not only results in monetary benefits to the agencies but also complements other management systems in providing safer driving conditions. A majority of research concerned with pavement markings addresses installation, performance, maintenance, and economic evaluation. Although agencies have developed guides and manuals on these subjects, they had difficulties in practical implementation.

The purpose of this study was to address the issues that were identified in the practical implementation of analytical and information tools of asset management practice in the field of pavement markings. Problems of limited variable data, censored data and uncertainty in field evaluation and retroreflectivity based prediction were addressed by adopting statistical techniques. Sectional assessment and management methods were proposed as a part of a practical restriping methodology. An information tool was developed in a geographic information system (GIS) environment as an application.

Retroreflectivity was the only performance measure on which the analysis and application was carried out. Two case studies were conducted, one for statistical techniques with retroreflectivity data collected by the National Transportation Product Evaluation Program (NTPEP) on U.S. Highway 78 westbound, Lee County, Mississippi.

The other for application with retroreflectivity data collected using mobile retroreflectivity unit (MRU) on FM 57, Fisher County, Texas.

This research effort provides a framework for an agency in developing a pavement marking management program to maintain good visibility of markings. It also provides a basis for further research in building an integrated asset management system based on other transportation assets.

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CHAPTER I
INTRODUCTION

PAVEMENT MARKINGS – FUNCTIONS

Pavement markings are unique traffic control devices that convey continuous information to the motorists about the roadway path. They play an essential role in the safe and efficient movement of traffic by maintaining a safe driving environment for road users. This includes information related to passing, direction, lateral lane position and boundaries of a roadway segment. According to the Manual on Uniform Traffic Control Devices (MUTCD) "pavement markings on highways have important functions in providing guidance and information for the road user" such as:

- To guide users with directional information supplementing road signs and signals.
- To warn users about their position with center, lane and edge markings.
- To inform users about the course of road like no-passing, overtaking zones etc.

It also points that markings that must be visible at night should be retroreflective unless ambient illumination ensures adequate visibility (1). Transportation agencies spend huge amounts on pavement markings each year. It has been estimated that the annual expenditure exceeds 1.5 billion dollars for over 17 million miles of pavement markings in the United States (2). With increasing highway travel demand and dwindling funding sources maintenance of transportation assets has become important in many ways. Therefore it is very important to maximize the effectiveness of the existing highways by adopting asset management practices.

This thesis follows the style of the *Transportation Research Record.*

BACKGROUND

The benefits of asset management and performance measurement are multifold for transportation agencies, which help in tracking the investments and provide accountability to the public. Several agencies have adopted asset management practices in pavement and bridge management in a larger scale, but little importance was given when it comes to the management of non-pavement and non-bridge assets viz. pavement markings materials (PMMs) (3). Implementation of a management system in the field of PMMs not only complements the framework of overall management of assets for a transportation agency but also helps improve safety for end users and meets the required standards.

Pavement markings play an essential role in the safe and efficient movement of traffic. There are no standards for minimum retroreflectivity values for pavement markings on public roads as of now, forcing agencies to set their own standards. As a result, agencies tend to specify levels of minimum retroreflectivity standards in two ways: by recognizing that increased retroreflectivity equals increased visibility for drivers under nighttime conditions, and that increased visibility equals increased safety for road users (4). This in turn may lead to uneconomical maintenance procedures if proper management is not adopted. For example, in an attempt to maintain higher values of retroreflectivity, transportation agencies often tend to restripe compromising with the service lives of these assets and leading to inefficient use of resources. With these challenges added to the economic constraints, it is beneficial for a transportation agency to implement asset management for pavement markings based on field performance.

In this study, two issues were identified in the practical implementation of analytical and information tools of asset management practice in the field of pavement markings.

First, it was found that results of statistical models used to estimate pavement marking degradation varied considerably compared to actual field performance. This was partly attributed to limited variable data, censored data (short-term data) and uncertainty in field evaluation (5). This study explains the problems of limited variable data, censored data and addresses those using statistical techniques. These techniques can be used to reduce the uncertainty in prediction models and also aids in developing a more economical work plan for field evaluations. Consequently statistical (deterioration) models of retroreflectivity used in the past research efforts are compared based on their prediction accuracies and practical applicability.

Second, there is need for definite guidelines and standards related to pavement marking failure, sampling protocols, and maintenance methods (5, 6, 7). This study proposes an assessment and management method to implement restriping activity at the section-level. The assessment method provides a systematic procedure to perform repeatable and reproducible evaluation of marking retroreflectivity. The management method could be used to implement pavement marking restriping along a section. Finally an information tool is devised to manage and integrate information with other asset categories.

This study only focuses on limited issues and does not provide all the elements of a comprehensive management program. However, it forms a solid framework to develop an integrated and comprehensive pavement marking management program. Also, it may reduce the risk of potential liability and additional financial burden in complying with forthcoming guidelines of required minimum retroreflectivity levels.

RESEARCH OBJECTIVES

Four main objectives were identified as part of this research in the process of developing an asset management framework for pavement markings. The objectives of this thesis were:

1. To address the field evaluation problems of limited variable data, censored data and uncertainty through statistical techniques.
2. To compare and validate statistical prediction models based on field data to check their accuracy and practical applicability.
3. To establish a methodology for roadway section sampling, assessment and management procedures in order to implement restriping of pavement markings effectively and efficiently.

4. To devise an integrated application tool in geographic information system (GIS) that helps to manage and integrate information with other asset categories.

RESEARCH METHODOLOGY

Relevant literature was reviewed with a brief overview of asset management and different phases involved in it. Also included were the statistical and information tools used under different management programs employed in the field of pavement markings. The issues and gaps identified in the practical implementation of these tools were discussed and addressed in two separate chapters.

First, the practical problems of censored data and limited variable sample (in the field evaluation) leading to uncertainty in performance prediction models were explained. Two statistical techniques, imputation method and Bayesian regression were used to address these problems with three-year retroreflectivity data from the Mississippi National Transportation Product Evaluation Program (NTPEP) test deck. The practical significance of these techniques in devising economical work plans was also discussed. Statistical prediction models: classical linear regression, autoregressive integrated moving average (ARMA) and Bayesian regression were compared for their statistical accuracies and practical applicability based on actual field measurements. Models were developed to study the marking performance for two years and then compared based on the prediction for the third year retroreflectivity measurements. Additionally end-of-service of four marking products was determined by assuming a threshold limit of retroreflectivity as a case study. Retroreflectivity was the single performance measure and time was the only variable considered for analysis purpose due to data constraints.

To address the second issue an assessment and management method were proposed to implement restriping activities practically and cost-effectively at the section-level. Section assessment method (SAM) was developed for sampling and evaluating retroreflectivity of an individual section of road segment. Section management method (SMM) was developed to find the centrality of location to perform restriping activity cost-effectively based on moment of inertia method. Both SAM and SMM were demonstrated in a step-by-step procedure using an example and a case study based on retroreflectivity data from Fisher County, Texas. Consequently an information tool was devised on GIS platform with a detailed process for planning and development.

Finally, results, concluding remarks, limitations and prospects for future research of the study were provided.

RESEARCH BENEFITS

This research may be used to resolve several issues in effectively implementing performance-based asset management in the field of PMMs. It helps a transportation agency to be prepared with a pavement marking management program to adhere to the forthcoming guidelines for minimum retroreflectivity and to reduce potential risk of liability. Statistical techniques developed are used to deal with the practical problems in field evaluations leading to uncertainties in performance prediction. The assessment method proposed provides a systematic procedure for measuring pavement marking retroreflectivity of in-service markings using either hand-held or mobile units. The management method provides a cost-effective method to restripe a road section and to implement maintenance activities. In conclusion it helps in improving agency's existing procedures for resource allocation, utilizing the assets efficiently, lowering long-term installation and maintenance costs and improving the safety standards of the transportation facilities. The management method and integrated application can serve as a complement to an existing pavement and bridge management in implementing asset management.

THESIS OVERVIEW

This thesis is divided into five chapters. Chapter I presents an introduction and overview to the research. Chapter II is a literature review that briefly describes asset management practice with an overview of analytical and information tools used in the field of pavement markings. Chapter III deals with development of statistical techniques and comparison of prediction models based on retroreflectivity. In Chapter IV, a practical restriping methodology is proposed and an information tool based on GIS is developed and demonstrated. Chapter V provides concluding remarks, and further discussion of the limitations of the study and prospects for future research.

CHAPTER II
LITERATURE REVIEW

INTRODUCTION

In recent years transportation agencies are relying upon the field performance of the PMMs for maintenance activities. Color, durability (presence), and retroreflectivity are some of the measures that are identified for performance-based evaluations according to Federal Highway Administration's delineation practices handbook (8). These evaluations are either subjective or objective in nature. Coefficient of retroreflected luminance (R_L) is the primary objective performance measure for visibility measured in units of millicandelas per square meter per lux (mcd/m^2/lux). Several factors contribute to pavement marking retroreflectivity degradation such as passage of time, traffic, external elements, snowplow operations, marking material specifications, pavement surface preparation, and quality control at the time of installation (9).

PMMs display varied performance because of the combination of these factors and it has been observed that results from lab testing do not correlate with that of field evaluations. Therefore, it is important to evaluate pavement marking products in the field under the influence of these external factors. However monitoring the performance of pavement markings involves huge amount of time, money and resources. The data collected from field evaluations are often used to study performance behavior either to compare different products or to estimate the performance of markings. It is essential to have good quality data that are helpful in the implementation of any further analysis for which field evaluations techniques and databases play a vital role (5, 8, 10). Field performance data is important as it gives an idea of the present condition and also the past performance of an asset. This data provides input to database and forecasting tools which converts this data into useful information. An asset management system can be effective in managing and integrating the activities of data collection, forecasting and maintenance of markings so that the markings are at serviceable level.

The literature review is organized into three sections. The first section provides a brief outline of asset management and its different phases. The second includes a summary of the analytical tools (statistical analysis methods) that have been used to estimate the service life of pavement markings. The third section provides the role of information tools in asset management and tools developed in the past.

ASSET MANAGEMENT

Though infrastructure asset management is an old concept it is a still-emerging concept in transportation industry (11). Generally, with age infrastructure assets need to be serviced or replaced and this mission is taken up by asset managers, engineers, and administrators by implementing the principles of asset management.

Asset management is gaining importance in transportation field to manage infrastructure assets. Association of State Highway and Transportation Officials (AASHTO) and Federal Highway Administration (FHWA) made several efforts for the implementation of asset management as a strategic initiative in the U.S. transportation industry. Asset management can be defined in many ways, FHWA presented a working definition as — "Asset management is as a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning." (12). Figure 1 presents an overview of transportation asset management from asset management primer developed by FHWA (13). Principles of engineering, economics and business are integrated to effectively invest, operate and maintain assets. It complements in decision-making process in resource allocation and utilization in managing complicated system of transportation infrastructure.

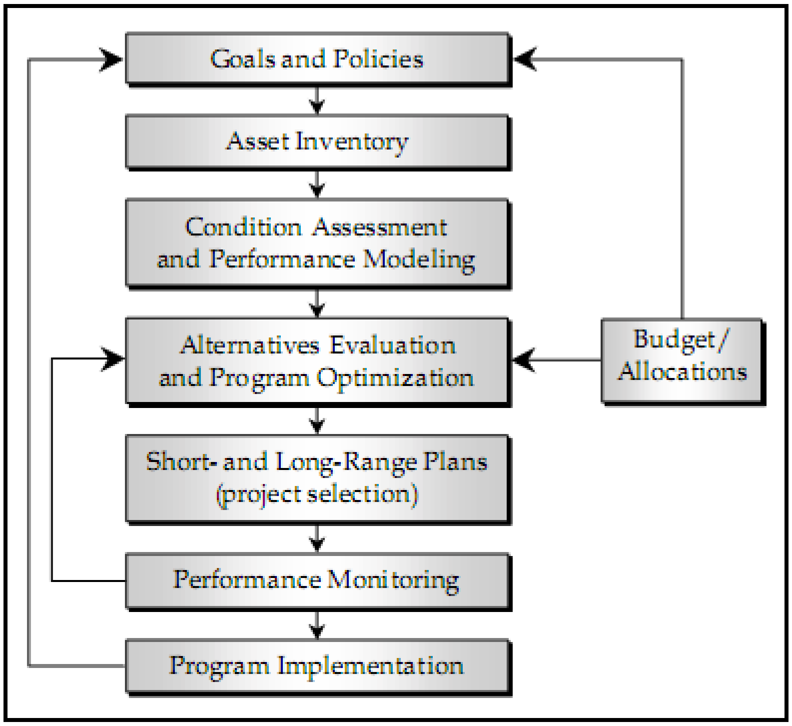


Figure 1 Overview of Transportation Asset Management (13).

In transpiration scenario, infrastructure assets are deteriorating due to continuous usage, aging and environmental impacts. So, there is a necessity to construct new facilities or maintain the existing ones, this brings the subject of budget – both the availability of, and demand for funds. Budgets are limited by shrinking funding sources and of the fact that funds are diverted to areas outside transportation projects. Over the years, tax payers have invested through governments in the construction, maintenance, and operation of the nation's highway system. Accordingly there will be expectations from both public and commercial side in quality of service in terms of convenience, comfort, safety and reliability. The concerned agencies are accountable for their decisions analyzing the tradeoffs between investments and maintenance. Therefore, these agencies must adopt management practices to attain performance goals, manage financial resources, maintain standards and operational level of service, and finally to make decisions. Asset management practices can be broadly divided into three phases (11, 13).

Phase I

This phase is mainly goal, policy and budget driven, performance-based approach. A set of organizational goals, policies are laid taking budget and performance measures into consideration. This phase is used as a guide across other two phases for analytical and decision-making framework.

Phase II

Data, information and analytical tools play a key role in this phase. Condition and performance of an asset is monitored to provide qualitative and quantitative inputs to the management system. Data is processed using database tools offering valuable information on the current status and past trends of asset performance. In recent years with the technological advancements, these tools are also used to integrate the information across different asset types. In addition to these, future system performance is predicted using statistical and analytical tools.

Phase III

Information on budget, goals, policies, condition and performance are taken as an input to formulate a decision-making framework. Trade-off analyses are performed across different alternatives taking the above inputs into consideration. Managers at different levels are equipped with this information to make decisions on resource allocation. Finally the entire system is evaluated to incorporate changes or adjustments with a good feedback mechanism.

It certainly has a very broad extent which is out of the scope of this study. The present study deals with development and functions of analytical and information technology tools that is the second phase in the field of pavement markings.

ANALYTICAL AND INFORMATION TOOLS

Analytical and information tools complement decision-making processes and organizational roles and responsibilities. They support good asset management practice in:

- Data collection – by gathering and managing data,
- Data conversion – by processing data into useful information, and
- Communication – by integrating information across different asset categories.

Pavement Marking Degradation Models

In the field of pavement markings statistical models are one of the commonly used analytical tools used to estimate degradation of their performance. In the past several research efforts have been published to estimate the service life of pavement markings. The focus of this study is not to predict the service lives of PMMs and hence only different model types used in the past are discussed in this section without concentrating on the estimates (results). Migletz et al. used regression models to quantify the service life of all-weather pavement markings — epoxy, methyl-methacrylate (MMA), flat and profiled polyester, flat and profiled thermoplastics, profiled preformed tape, conventional paints and water-based paints. First-order linear regression, second-order linear regression, and exponential decay models were considered to model pavement marking retroreflectivity. Cumulative traffic passages (CTPs) was the only factor considered as independent variable. The service life estimates varied considerably even if the data was from a single type of material, a single application, and a single road class collected from different highways (14). Similar studies were conducted by Perrin et al. and Lindly and Wijesundera to forecast the retroreflectivity life-cycle by analyzing degradation of retroreflectivity over time (15, 16).

Thamizharasan et al. developed regression models to forecast the lifecycle based on the decay of retroreflectivity over time. This was a part of comprehensive system for South Carolina Department of Transportation (SCDOT) to evaluate the retroreflectivity of pavement markings in a goal to develop a pavement marking evaluation system

(PMES). The data was collected for a 28-month period on interstate system which included retroreflectivity based on pavement type, marking type, log of maintenance activities. The change in the trend of retroreflectivity values with time is presented in three different patterns based on initial rise in retroreflectivity degradation and frequency of maintenance activities. It was found that pavement surface type, pavement marking material type, and the frequency of maintenance activities are the most significant factors that influence the performance of the markings (17).

Zhang and Wu estimated service lives of durable tapes, preformed thermoplastic, thermoplastic and three-year waterborne paints based on NTPEP data from Mississippi test deck. The smoothing spline method and ARMA time series modeling approach were used. Among the two, ARMA time series modeling had relatively good prediction accuracy. Pavement marking age in months was the only factor considered for analysis (18). Sathyanarayanan et al. performed Weibull analysis to estimate Weibull scale and shape parameters based on retroreflectivity data of two-year waterborne paints from the Pennsylvania NTPEP test deck. Data were considered interval-level duration data and different models were used taking pavement surface type, marking color and location into consideration (19).

Information Tools

This entire study focuses on the second phase of the three phases of asset management practice which helps in processing data to convert into useful information and to display information. It is important to translate data into useful information before any further analysis (13, 20). Figure 2 illustrates how information technology (IT) integrates essential components of strategic asset management. IT has become an integral part of asset management framework which complements decision-making process in two ways explained below (11).

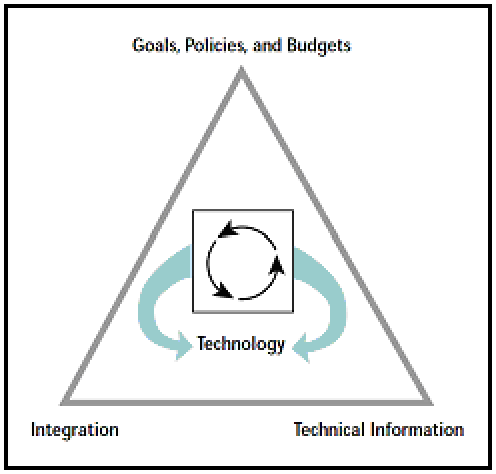


Figure 2 Integration of Various Components of Strategic Asset Management through Information Technology (11).

Collection, storage and analysis of information

Data on inventory, condition and performance of an asset is collected quickly and with more accuracy with the advancement of technology. For example, mobile retroreflectivity units (MRUs) are used to collect retroreflectivity information quickly and also with spatial information. Statistical sampling techniques and procedures are also used for better data representation and to minimize costs. Different database and software tools are used to organize data collected and to integrate information across different asset types. Lastly analytical tools which include mathematical and statistical techniques are used to analyze the condition and performance to forecast future changes.

Communication and presentation

Information technology facilitates horizontal and vertical communication across an agency to implement decisions at different management levels. It also helps in presenting reports on accomplishments and program delivery to executives, managers (internal) and to policy makers and stakeholders (external).

Transportation asset management guide presented information and analysis diagnostic to assess the asset management practices of an agency (13). The guide provided benchmarks and common gaps in practical implementation of information technology in asset management principles. Table 1 presents excerpt from the self assessment diagnostic in field of data collection and information access.

Table 1 Benchmark and Common Gaps in Implementation (13)

Benchmark	Common Gaps
EFFECTIVE AND EFFICIENT DATA COLLECTION	
Complete and current asset inventory and condition data	Data do not reflect full range of assets under agency responsibility
Efficient data collection and processing methods provide credible data at acceptable cost	Existing data lack credibility; data collection perceived as not worth its cost
Information on customer perceptions collected and used	Information on customer perception of condition/performance unavailable
INFORMATION INTEGRATION AND ACCESS	
Managers at all levels can easily access information they need	Lack of data sharing across units; duplication and inconsistency
Maps of asset condition, need, and projects are readily available	Staff lack good tools to access data or lack training on their use
Geographic referencing and data standards in place	Lack of consistent geographic referencing

The common gaps in information access presented in the above table can be addressed by developing a set of different software tools if these gaps are only restricted to one single asset category. If theses same gaps are extended across various asset categories the problem of managing data and communications becomes more complicated. For example, it is appropriate to check the sewer pipeline condition before repaving a road segment. It becomes difficult to take a strategic decision if information about these assets is in different formats and handled by different departments.

Database plays an integral role in providing credible information to all participating groups. Developing separate stand-alone systems for managing marking assets can be easy and simple to implement. But in practice, pavement marking projects comprises a small part of construction and maintenance budget allotted for an entire road project construction. Also management practices (maintenance, rehabilitation and repair) are well established in the field of pavement assets. Therefore it makes logical sense to *integrate* management system for pavement markings with existing more established pavement management systems (21).

The report ‘Current Asset Management Practices Applied to Pavement Markings’ showed that more than 30 % of the participating agencies use management systems or simple programs to maintain pavement markings. 20% to 25% of the agencies responded that they use a dedicated management system for markings. Though many agencies have reported to be using information technology tools, response to the usage of GIS interface and maps was about 8% to 15% (21). Two important observations can be made from this survey, one is that agencies were using separate management tools for managing marking assets and secondly the use of GIS based tools is also very small.

Asset management is a data-intensive process and advances in information technology enabled to integrate various tasks such as gathering, processing, analyzing, storing, retrieving, and communicating enormous quantities of data. One such versatile tool is GIS, Huxhold and Levinsohn defined GIS as “a collection of information technology, data and procedures for collecting, storing, manipulating, analyzing, and presenting maps and descriptive information about features that can be represented on maps." (22) To integrate tasks of data collection, storage, analysis, communication and presentation this study used GIS. Moreover, it obviates the usage of separate systems for different functions.

Geographic Information System

GIS can be defined as "a computerized database management system for capture, storage, retrieval, analysis, and display of spatial (locationally defined) data." (23) It is a tool that can integrate tabular database information with graphical location component that facilitates spatial data analysis. It is more than a mapping tool as the features of computer and information systems such as computer cartography, remote sensing, database management, and computer aided design are built-in (24). As mentioned earlier, instead of developing different systems for various tasks GIS serves as a perfect tool to accomplish all the above mentioned tasks. Another working definition given by Environmental Systems Research Institute (ESRI) rightly describes the multi-tasking nature of GIS as "an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information." (25) Apart from using the relational database feature GIS also integrates attributes using location reference across different categories (Figure 3). The above mentioned elements reiterate the importance of GIS as a suitable tool in asset management.

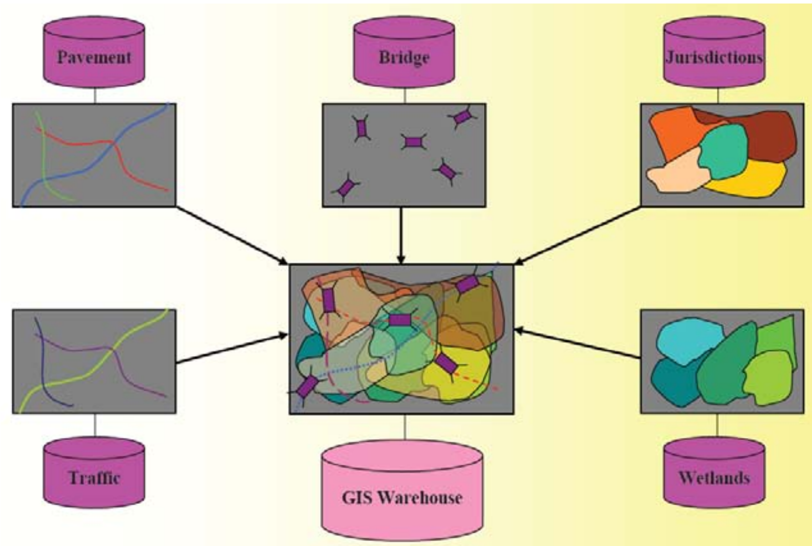


Figure 3 Integration of Information Across Categories.

In the past different tools were developed by agencies ranging from simple inventory management systems to integrated maintenance management systems (5).

Minnesota Department of Transportation (MnDOT) has developed an inventory management system to track installations, inventory, retroreflectivity, specific action steps, costs, suppliers of pavement markings. It was used to tracks the service life of markings with a database program to store information (26). At South Carolina Department of Transportation (SCDOT), GIS was used by researchers to process, manage, and display the enormous amount of data collected by mobile and hand-held retroreflective instruments. They have also developed an application — Multicriteria Dynamic Segmentation (MDS) to manage the data efficiently. The actual distances measured by the mobile instrument were calibrated into GIS route distances. This data were plotted using the thematic mapping capabilities that show levels of retroreflectivity color-coded by direction of travel. The MDS application allows plotting the data by segmenting routes into smaller sections. These segmented lengths were binned to produce thematic maps. Maps were used to identify the areas and the corresponding retroreflectivity levels. GIS application was found to be very powerful tool in the analysis because of the ability to process and manage enormous amount of data efficiently. The system was also used for review and query purposes by pavement marking type, condition, location, and jurisdiction benefits.

Pavement marking management system (PMMS) is a tool developed for Iowa Department of Transportation (IDOT) which uses retroreflectivity data to manage the pavement marking performance throughout the state (27). This marking management system uses the information from a database and assists to manage the retroreflectivity and durability, evaluate new products, and balance the use of materials and budgets statewide. It also integrates the markings information with other database like the crash history which enables to integrate the safety with operations and maintenance activities.

The retroreflectivity data was collected twice once in spring that is before the painting season starts in summer and in fall before the maintenance for the winter painting season starts. In addition to this initial retroreflectivity values were also collected for an initial minimum retroreflectivity check. A threshold value of 150 mcd/m^2/lux for white and 100 mcd/m^2/lux for yellow was used to replace the markings. This information was mapped on to the GIS format to identify the places that are nearing the threshold values in order to maintain a minimum service life of two years. Figure 4 shows the GIS map for spring 2004 yellow centerline retroreflectivity where black color theme was used to indicate locations below minimum level of retroreflectivity.

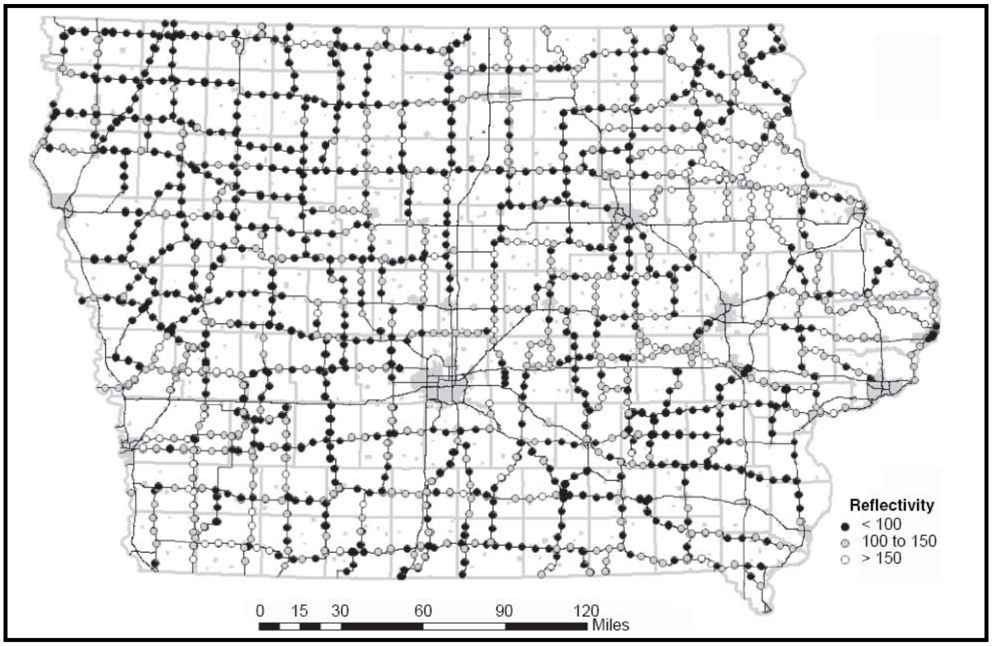


Figure 4 GIS Map for Spring 2004 Yellow Centerline Retroreflectivity (27).

GPS units are used to get the coordinates for each measurement from the field. They are referenced thorough route and milepost. Initial retroreflectivity values were also taken into the data base at the time of installation to check if the initial minimum requirements are met. These initial values helped in analyzing the deterioration trends to identify the maintenance requirements in winter. The researchers also investigated the relationship between the retroreflectivity and crash history, which has enabled to analyze the crash frequency with that of the markings retroreflectivity. Figure 5 illustrates the comparison of yellow centerline retroreflectivity and crash frequency and type. The PMMS system also enabled the Iowa DOT to link and integrate the data of pavement marking retroreflectivity, crash frequency, and performance of markings, pavement surface information and inventory.

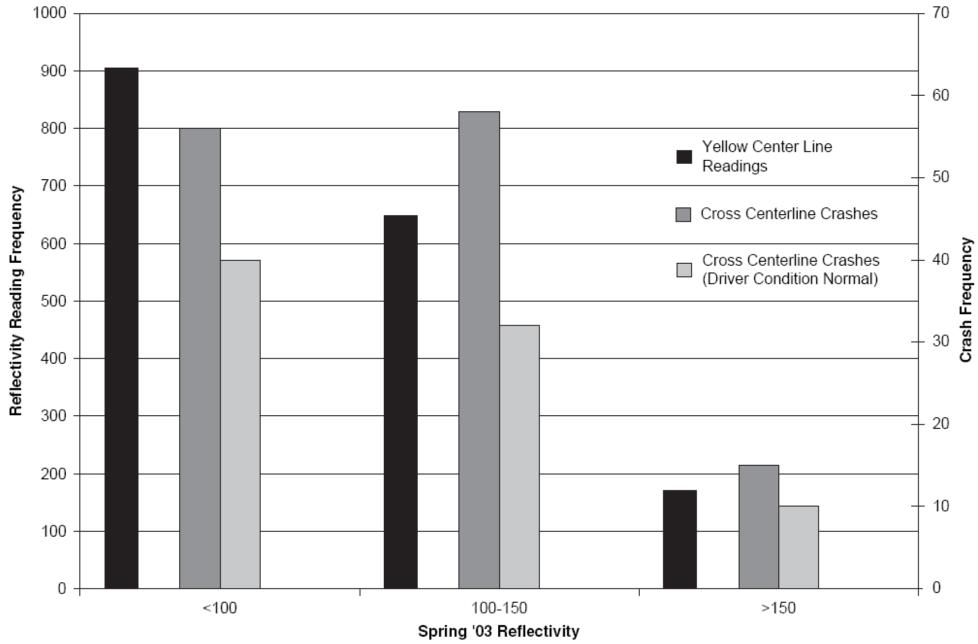


Figure 5 Example Comparison of Yellow Centerline Retroreflectivity and Crash Frequency and Type (27).

CONCLUDING REMARKS

From the published research it was found that regression analysis, time series models, and survival analysis were some of the methods used to predict retroreflectivity degradation. It was found that regression models were the most common statistical modeling method used. Also several factors that may influence retroreflectivity degradation were overlooked in analysis procedures. It was also found that results of statistical models used to estimate pavement marking degradation varied considerably compared to actual field performance (5).

It is evident that these agencies have adopted selective management tools focusing on individual asset classes. Other examples of independent systems commonly in use are pavement and bridge management systems. However, these are not comprehensive in nature and often lead to *stovepipe* operations leading to inadequate communication between different divisions and departments (11). In other words, data were processed and analyzed and the information is shared in different formats that lead to many problems like duplication, integrity and accessibility of different databases (20). Also, investment and maintenance decisions were made separately across different asset categories.

Most of these decisions were based on *worst-first* treatment reflecting tradition, past experience, resource availability and political considerations. But in the present day, these decisions are driven by predetermined goals, policies and performance related to management. Therefore the right tool to address this issue is asset management, which is also a *strategic* process encompassing performance goals and measures, information on resources, condition of assets, performance-prediction tools, information technology tools, analytical tools, useful outputs and feedback procedures. Hence a management system for pavement markings can be designed to integrate with the existing advanced management systems for pavement and bridge assets to manage various activities through out their life cycle.

CHAPTER III
DEVELOPMENT OF STATISTICAL TECHNIQUES AND COMPARISON OF PREDICTION MODELS

INTRODUCTION

The main objective of this research effort is to present a framework for asset management in the field of pavement markings. This study is not a guide for comprehensive management system, but is an effort in that direction to compose a framework to coordinate various processes such as monitoring, prediction and management. Any management system is incomplete without implementing the concept of performance prediction in practice. The information from the behavior of an asset in service facilitates maintenance decisions but if the same information is predicted in advance, it can be used for managing resources and tracking investments. The behavior of a particular marking material and its service life can be known from past installation experience — so then why is the part of prediction important? It is evident from the literature that many factors affect the field performance of pavement markings hence this experience-based approach may lead to erroneous predictions for the same material installed at a different time or location. Also, any new PMMs installed may perform differently from their predecessors (18). Typically statistical models are used to predict the performance of an asset given the performance variables were monitored over time. It is critical that these models are practically accurate in predicting the performance, but it was found that predictions varied considerably compared to actual field performance. This was partly attributed to limited variable data, censored data and uncertainty in field evaluation (5).

The purpose of this chapter is to explain and address these issues in the context of retroreflectivity degradation of pavement markings. Also statistical models used in the previous research are compared for their practical reliability and applicability. This chapter is organized as follows: first an overview of data is provided; field evaluations and problems associated with them are presented. Then statistical techniques are developed to deal with issues of censored data, limited variable data and uncertainty. Finally a comparison between the prediction models is presented. All the techniques and models are discussed and demonstrated with sample data as case study.

Typical Field Evaluation and Data Classification Based on Failure

Field evaluations and testing involve a great deal of resources and are used to evaluate the performance of markings. Typically field evaluations in the context of pavement markings are generally carried out as a part of testing techniques (e.g. NTPEP) or as scheduled work plan to monitor their condition. A particular marking is said to have failed or reached its end-of-service-life once the retroreflectivity level falls below a certain threshold value. With various assumptions associated with accommodating driver needs, previous literature suggests a threshold level somewhere between 80 and 125 mcd/m^2/lux (28-36). For explanatory and analysis purposes in this study, a level of 100 mcd/m^2/lux is considered as a retroreflectivity threshold limit.

The quality of data obtained from field evaluations depends on the *duration* and *inspection intervals*. Ideally longer duration of evaluation with shorter inspection intervals yield more data about the general behavior and failure, but are practically not feasible (6). Therefore it is important to use the available data to obtain maximum valuable information by implementing new analytical techniques considering realistic challenges.

In this section an effort has been made to adopt the concepts of reliability to further explain field evaluation and data collection in the field of pavement markings. The test results from field evaluations can be typically characterized as either time-to-failure or time-to-termination depending on the *duration* of tests. For instance, in 2004 NTPEP Mississippi test deck, the evaluation period lasted for a period of three years. Here for two-year water based paints, the test results can be treated as time-to-failure as most of the markings from this product type reached their end-of-service-life (assuming a threshold limit for useful life). In contrast, for the durable products tested the results can be considered as time-to-termination as the evaluation period ends even before these markings have reached their failure. This type of data is called censored data. It falls short to give entire information about the failure but still can be used to derive some important results.

Another important aspect of testing is *inspection interval*, the time gap between the retroreflectivity measurements. Naturally shorter time gaps can be effective to monitor the performance but, due to the resource constraints they are predefined at fixed intervals. Also these time gaps may not be equally spaced because of weather constraints, unexpected situation or due to the actual work plan, such as in the case of NTPEP whose inspection intervals vary during the project duration (5). These constraints and conditions might also result in missing data which could hamper further analysis therefore, efforts should be made to effectively use and understand both censored and missing data (37, 38, 39).

Data collection for monitoring performance of pavement markings is characterized by measurements taken at predefined intervals. Typically the data obtained from evaluation techniques of pavement markings can be considered to be both right censored and interval censored (37, 38, 39). Right censored, because the evaluations are stopped at predetermined time even before the marking fails or in other words retroreflectivity may not fall below the assumed threshold until the end of the study. This is also called Type I right censored data (Figure 6). Furthermore the marking might reach the threshold limit between the inspection intervals which is called readout or interval-censored data (Figure 6).

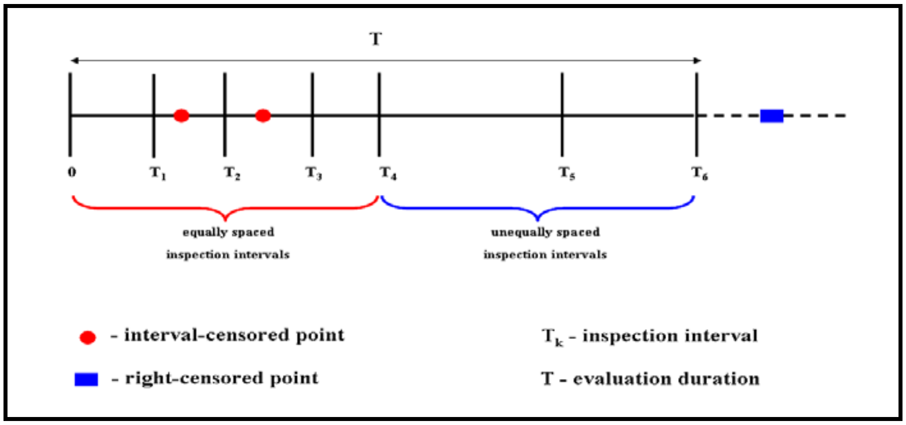


Figure 6 Typical Evaluation Plan with Different Data Classification and Inspection Interval.

PROBLEM OF CENSORED DATA SAMPLE

For durable marking materials with longer evaluation durations, problems like missing inspections and censored values are often encountered because of unexpected situations, weather constraints or work plan. Also, data points with regular intervals are often desired by statistical analysis and prediction methods. This study developed an imputation technique handling the missing points that aids in designing a more economical alternative work plan. The following sections give an overview of data, field evaluations and their classification to elucidate the problem of censored data in the field of pavement markings.

Current Practices in Field Evaluation

Effective and efficient evaluation tests are required to produce meaningful data to aid in decision making efforts. Currently most of field tests involve transverse test deck, while there are many advantages associated with it they work as accelerated test deck to some extent. Contrary to the long line test decks these are exposed to more number of traffic hits resulting in accelerated degradation. Also as these materials are not designed to be installed in transverse direction, the results may not represent the actual field performance. On the other hand testing materials longitudinally involves huge amount of time, money and resources. Therefore usually long line test decks are installed with a collaborative effort between the industry and state to evaluate the performance under real time conditions of traffic and climate. It also requires multiple years to monitor the performance of markings till the end of their service-life. As there is no defined procedure for conducting long line testing the duration and inspection interval for performance evaluation may vary across different testing agencies. As for NTPEP, field testing is conducted according to ASTM D 713. Evaluations are carried out within seven days of application and then monthly (30 days) for the first year. Subsequently materials are evaluated quarterly (120 days) and half-yearly (180 days) for the second and third years respectively (6, 10).

TEST DECK AND DATA

Test Deck Locations and Characteristics

Three year retroreflectivity data were obtained from the NTPEP data mine facility. NTPEP provides information of performance of pavement marking materials by conducting field tests according to ASTM D 713 (10). Test deck locations were also selected according to the procedures and guidelines of ASTM D 713. Some of the characteristic guidelines were, to have a minimum average annual daily traffic (AADT) of 5000, uniform traffic wear, uniform and adequate drainage movement, minimal braking and turning movements, complete exposure to sun, open to traffic for at least one year with free-rolling and with no grades.

The data in this study was from bituminous asphalt site from Mississippi test deck on U.S. Highway 78 westbound, located west of Tupelo, Lee County, MS. The test deck was installed in June 2004 on a four lane divided highway, with an average daily traffic (ADT) of 24,000 vehicles with about 30% trucks.

Data

The test set-up involved placing the marking materials in a transverse direction across the traffic lanes. The data may not represent the actual performance of the markings as the products were not installed in longitudinal fashion for which they are intended and developed for (6). But this does not influence the present study as the focus is not to evaluate the actual field performance but instead is aimed to present the methodology of imputation and time series. Also, the data set from NTPEP serves as a suitable example to implement the imputation technique as the performance measurements were based on a work plan in which the data was collected with irregular inspection intervals. The inspection intervals spanned over a period of three years with monthly, quarterly and half-yearly gaps. The first year data set was complete with all the 12 month data points and this set was considered as *observed series*. The second year data set was taken as *missing series* with four observed and eight missing values.

Evaluations included color, nighttime retroreflectivity, durability and weather conditions. Retroreflectivity measurements were obtained both in the skip line and left wheel-path areas using an LTL2000 retroreflectometer for a period of three years from June 2004 till June 2007. For analysis and application purposes through out this chapter only retroreflectivity data from four white colored products on bituminous asphalt surface from skip-line area were used. Measurements from the skip-line area were considered as the traffic condition is more similar to that of actual skip-line stripes in contrary to the wheel-path area which often exhibits an accelerated degradation (6). However, the developed method can also be extended to other surface types, products and different external conditions.

IMPUTATION TECHNIQUE

The main objective of this section is to develop an effective imputation technique to estimate the missing values and thereby, and to forecast the censored values using time series models. It should be noted that imputation technique is based on ARMA models which can only handle stationary processes (without any trend) with equally spaced points, therefore the first step was to examine the data for any trend. The imputation technique was used to estimate missing values before forecasting the censored points. There were several steps involved in the process which will be explained in the following sections starting with preliminary analysis.

PRELIMINARY ANALYSIS

As stated previously data from four white colored products (thermoplastic, preformed thermoplastic, methyl methacrylate, and durable others) were used for analysis. The application part of the present study is to predict the retroreflectivity measurements until the end-of-service-life of marking products. Taking this into consideration analysis was carried out on individual product samples rather than focusing on a particular product group. A preliminary investigation was carried out with scatter plots to examine any trend, changes in behavior and outliers in the observations. Figure 7 illustrates the scatter plots of skip retroreflectivity over a period of three years for four different individual product samples. Graphically it appears that there exits a general degradation trend over time across all the products. However to further validate this observation a classical regression analysis was carried out by fitting three different models.

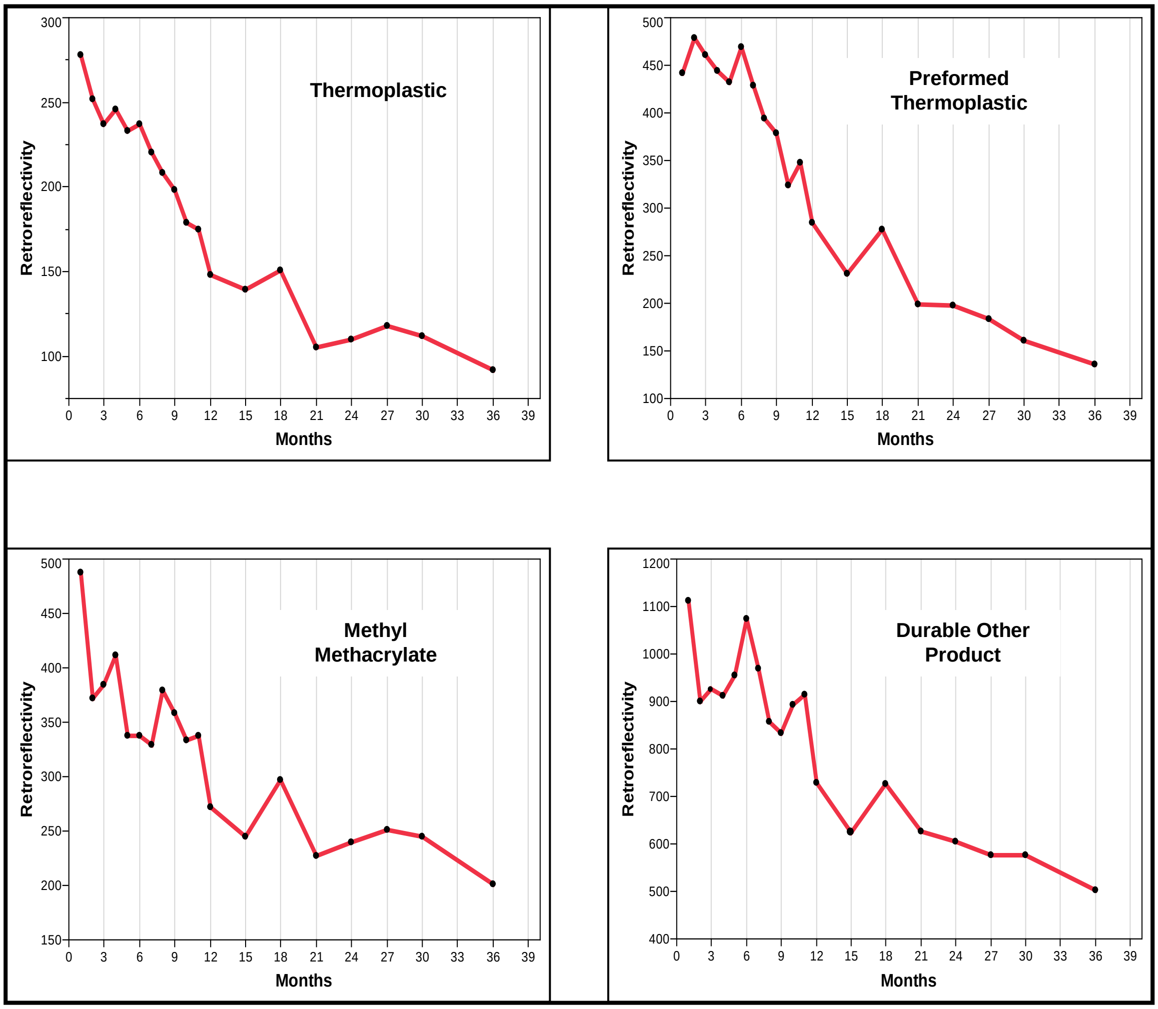


Figure 7 Retroreflectivity Degradation Curve for Different Individual Products.

Classical Regression Analysis

Three different models were chosen and checked for goodness of fit to estimate the best regression parameters. Linear, quadratic and exponential decay models were considered to model pavement marking retroreflectivity as a function of time. Here the purpose of regression analysis was to examine the existence of any trend in the data series. This information obtained was used to perform detrending (elimination of trend)

— meaning if the existence of any trend was identified, the series was made stationary to eventually develop imputation technique.

The data series was univariate with retroreflectivity varying with time making retroreflectivity as dependent variable and time as the only independent variable. Based on the existing literature, other external factors do play a significant role in retroreflectivity degradation of pavement markings, but in the present study the data set was taken as a case study to show the development and application of statistical techniques. Scatter plots in Figure 7 shows different patterns from fairly linear to clearly non-linear relationships. Therefore one model type may not fit all the four different materials under study, three different models were considered to obtain a better fit based on type of degradation. Linear, quadratic and exponential models were examined given by Equation (1), Equation (2) and Equation (3).

Model 1:

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad \textbf{(1)}$$

Model 2:

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \varepsilon \quad \textbf{(2)}$$

Model 3:

$$ln(Y) = \beta_0 + \beta_1 X + \varepsilon \quad \textbf{(3)}$$

where

X = elapsed time in months

Y = retroreflectivity in mcd/m^2/lux

Significance of the model and goodness of fit were analyzed to compare above three models. In total, 13 products (five thermoplastic products, three preformed thermoplastic products, one methyl methacrylate products, and four durable others) were analyzed from four different product groups. One sample from each group was selected for further analysis and illustration purposes. Therefore the analysis and performance prediction was limited to that particular product sample selected and cannot be generalized in any way. Table 2 summarizes the model adopted for each product sample selected that best explains the relationship and intensity of the degradation with time. The coefficient of determination (R^2) is a measure of variability in a data set explained by the linear regression model. The JMP® software was used to perform the classical regression analysis (40).

Table 2 Summary of the Classical Regression Models Adopted

Product	**Best Fit Model**	**Regression Equation**	**R^2 -value**
Thermoplastic	Exponential	$ln(Y) = 6.552 - 0.028X$	0.925
Preformed thermoplastic	Exponential	$ln(Y) = 6.267 - 0.043X$	0.909
Methyl methacrylate	Exponential	$ln(Y) = 6.054 - 0.026X$	0.783
Durable others	Exponential	$ln(Y) = 6.971 - 0.024X$	0.783

From the regression analysis it was evident that retroreflectivity data series for each product is not stationary (do not exhibit a fixed mean). Such non-stationary series are not suitable for description by ARMA models. As the imputation method and further analysis were based on ARMA models, these series were made stationary by detrending the values in the series. The next step in analysis was to develop imputation technique to estimate the missing values.

IMPUTATION METHOD

The retroreflectivity measurements were characterized by irregularities like missing and censored data. These irregularities are common in field evaluations because of various factors like weather constraints, unexpected situations or due to the actual work plan. In this research effort an imputation technique was presented to estimate the missing values based on a class of Gaussian autoregressive and moving average (ARMA) models. In the present case data were collected quarterly in the second year leading to eight missing points from months 13, 14, 16, 17, 19, 20, 22 and 23 (Figure 8). The second year data set was considered as *missing series* with four observed and eight missing values. This method is an extension of the technique developed by Park et al. for handling autocorrelated censored data (41).

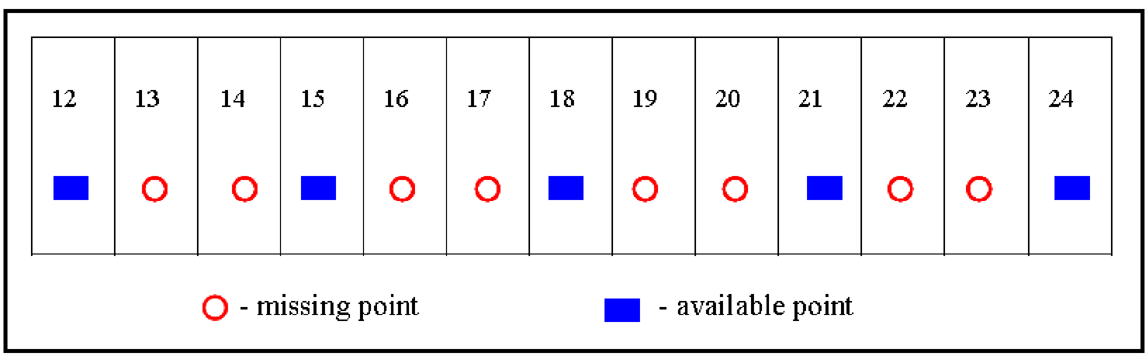


Figure 8 Available and Missing Points from the Second Year Evaluation.

Imputation Algorithm

The algorithm is based on the idea that observed values follow a multivariate normal distribution. Following which the missing series were then imputed using the conditional multivariate normal distribution given the observed part (41). In other words it captured the trend of the observed set in the first year and estimated the parameters based on which the missing values were also estimated. The following section gives a brief outline of the algorithm in a step-wise manner. The R software was used for programming.

Step 1. 1

The entire series Y was considered as an n-dimensional multivariate normal distribution with mean μ and $n \times n$ co-variance matrix $\boldsymbol{\Sigma}$ whose elements are given by, $\{\Sigma\}_{ij} = \gamma(|i-j|) = \gamma(h)$,where $\gamma(h)$ is the autocovariance function at lag h.

$$\mathbf{Y} \sim N_n(\mu, \Sigma)$$

The two-year sample data series has sixteen observed points and eight missing points (Table 3). The data series was then separated as observed $\mathbf{Y_o}$ and missing $\mathbf{Y_m}$ by using a permutation matrix P given by,

$$\mathbf{P} = \begin{pmatrix} \mathbf{P_o} \\ \mathbf{P_m} \end{pmatrix} \qquad \mathbf{Y} = \begin{pmatrix} \mathbf{Y_o} \\ \mathbf{Y_m} \end{pmatrix}$$

Table 3 Sample Data (Y), Observed (Y_o) and Missing (Y_m) Series

Months	Y	Y_o	Y_m
1	687	687	0
2	644	644	0
3	640	640	0
4	637	637	0
5	584	584	0
6	638	638	0
7	598	598	0
8	556	556	0
9	531	531	
10	507	507	
11	541	541	
12	475	475	
13	0	401	
14	0	444	
15	401	359	
16	0	378	
17	0		
18	444		
19	0		
20	0		
21	359		
22	0		
23	0		
24	378		

Step 1. 2

Using **P** and **Y** matrices, the series was made stationary obtaining a zero mean component. It was evident from regression outputs that all the four products followed a trend of degradation (Table 2). Therefore, exponential smoothing technique was used for detrending, where in for any fixed $\alpha \in [0, 1]$, the one sided moving averages $\hat{m}_t$, $t = 1,\ldots, n$, was defined by the recursions

$$\hat{m}_t = \alpha Y_t + (1-\alpha)\hat{m}_{t-1}, \qquad t=2,\ldots, n,$$

$$\hat{m}_1 = Y_1$$

Here m_t is the trend component and Y_t is the population data. The value of alpha (α) was obtained using ITSM software depending on the data from individual products (42). Later the stationary process is obtained by,

$$X_t = Y_t - \hat{m}_t$$

This is given by **X** with observed and missing matrix. Further analysis and estimations were carried out on this matrix given by,

$$\mathbf{X} = \begin{pmatrix} \mathbf{X_o} \\ \mathbf{X_m} \end{pmatrix}$$

Step 1. 3

The parameters $\widehat{\mu}$ and $\widehat{\Sigma}$ of the separated observed series were then estimated. Based on these, the corresponding conditional mean $\widehat{\nu}$ and variance $\widehat{\Delta}$ of the missing series were calculated.

Step 1. 4

An imputed sample for the missing series was constructed based on these estimated parameters. The previous steps were repeated until the tolerance converges to a set limit.

Step 1. 5

Complete stationary series was built using the estimated detrended missing values. Finally the entire population data set **Y** was recalculated resulting in the completed series for two years.

Step 1. 6

The entire algorithm was repeated until the obtained series **Y** has a root mean square error (RMSE) less than that of the original data series.

The output of imputation technique was series **Y**, with all the eight imputed points estimated from the second year. Figure 9 shows all the twelve data points from the second year for months thirteen to twenty-four. Data series **Y** with all the 24 points that are equally spaced across two years was called *complete series*. In the later part of this chapter this complete series was used to predict and validate retroreflectivity values from the third year using ARMA *(p, q)* model.

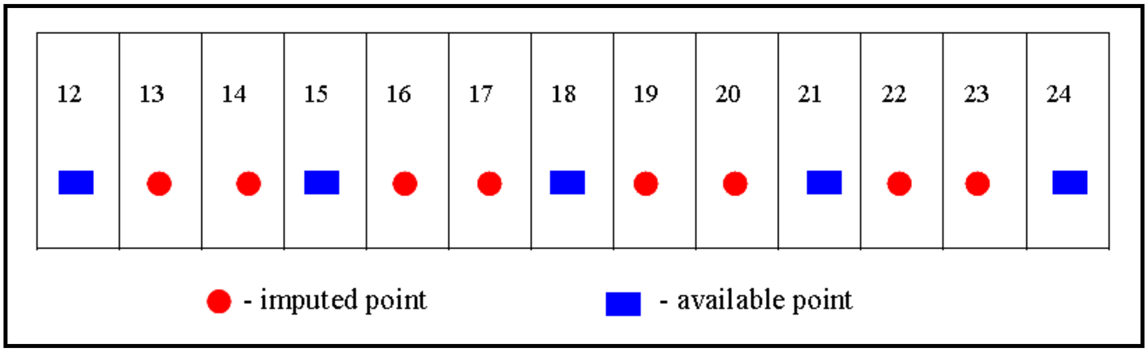


Figure 9 Available and Imputed Points from the Second Year Evaluation.

PROBLEM OF UNCERTAINTY AND LIMITED VARIABLE SAMPLE DATA

In this section the problem of uncertainty and limited variable sample data in the PMMs context was explained and addressed using Bayesian regression. In general although performance measurement variables include color, durability and retroreflectivity, in this study the analysis is not exhaustive as it is limited to retroreflectivity. This is just one example of why the problem of uncertainty creeps into prediction models. The main objective of developing a performance prediction model is to predict the behavior of markings by modeling the relationship between performance variable (dependent variable) and precursor variables (independent variables). Thus, data collected from field evaluations should pertain to all the factors that explain the degradation of retroreflectivity. But as observed from the data, the independent variable was only time and other factors that may be related to pavement marking retroreflectivity degradation were not considered. Thus both the limited analysis and data with inadequate precursor variables might result in increasing the uncertainty in prediction models which may not represent the actual behavior of markings. This problem is statistically discussed and addressed by adopting a Bayesian approach in this section.

Generally, retroreflectivity acts as dependent variable (y) and the factors affecting degradation are independent variables (x_i). Statistically this can be represented as

$$y = f(x_i) \tag{4}$$

The subject of the matter is to examine the changes in quantity y (the dependent variable) as a function of other quantities x_i (independent variables). PMMs display varied performance because of external factors such as climate, traffic conditions, roadway surface type and installation quality. Data from field evaluations may not include information related to all the external variables that affect the degradation of retroreflectivity. Also in uncontrolled testing environment (field evaluations) it is difficult to completely understand and quantify the effect of these external factors. Therefore, to account for this uncertainty an error term (ε) is introduced in the above equation. This error term is a random variable, which could explain the influence of other factors that are not considered at the time of evaluation. As a result the degradation of retroreflectivity can be explained by the combination of both measured independent variables and unmeasured random variables, thus the Equation (4) becomes

$$y = f(x_i) + \varepsilon \tag{5}$$

However, when asked if the phenomenon of degradation can be completely explained and attributed to the above discussed variables (external factors), the answer would be *no*. This can also be statistically explained from Equation (5). Right hand side of the Equation (5) has two components – independent systematic part ($f(x_i)$) and random part (ε). Because of the random element involved, the left hand side of the equation also becomes random variable. In other words there always exists a bit of uncertainty no matter how controlled the field evaluations are carried out for high quality data. In statistical terms predicted models depends on probability distribution over performance variables which in turn depend on independent variables ($f(x_i)$) (43).

So are there any solutions for this problem? Ideally this can be achieved in many ways, for example collecting *large amount of data* under carefully controlled conditions till the point of failure or evaluating the performance by considering *all* the factors that effect the retroreflectivity degradation as independent variables. However, these tasks involve huge amount of time and resources. Therefore going a step back to minimize uncertainty in prediction models, this study developed a pragmatic approach using Bayesian theory to deal with the uncertainty in the performance prediction.

BAYESIAN THEORY

Typically the field evaluation process is limited to evaluating limited number of samples of a particular product for a limited time. In addition to this, data collected from these evaluations only pertain to limited number of external variables. Hypothesizing a prediction model based on this limited data can lead to erroneous results, which is also typical in the case of the classical regression analysis discussed in the earlier section (14, 15, 17). On the other hand, state agencies have great deal of information from the past experiences from the behavior of PMMs though limited amount of field data was collected. Hence instead of resorting to a more expensive and intense long term field evaluation plan a Bayesian statistical method can be adopted to use this valuable prior information to reduce the uncertainty in performance prediction. The Bayesian linear regression is an extension to classical linear regression in which additional information is used in the form of prior probability distribution to supplement the existing data.

Analysis Methodology

For the purpose of Bayesian regression, same data from four products were used for the prediction purpose similar to that of regression models for comparison. The data analysis has two parts, method development (estimation) and application (validation and prediction). The data available were divided into two periods for analysis purpose — estimation and validation. The NTPEP data set spanned across three years; the first two year data points were used to select the model and for parameter estimation. The model fitted was then tested with the available data points from the validation period, i.e. the third year, to identify the best model. Once the best model was selected, it was then used to forecast the future data points beyond the evaluation period till the end-of-service-life of PMMs. Here the estimates of coefficients from the classical linear regression were taken as prior additional information. As all the four products followed an exponential trend of degradation, identical models were used for the Bayesian regression. The following section gives a brief outline of the algorithm in a step-wise manner (44).

Step 2. 1

Equation (5) was considered as a linear model as in the classical regression for $i = 1,..., n$ with $1 \times k$ predictor vector for x_i and the equation is given by,

$$y_i = \beta x_i + \varepsilon_i \tag{6}$$

where, the coefficient of performance parameter β is a $k \times 1$ vector. It was assumed that error term was governed by independent, identically distributed normal distribution with mean zero and variance σ^2

Step 2. 2

Likelihood function for Equation (5) can be written as

$$\rho(y | X, \beta, \sigma^2) \propto (\sigma^2)^{-n/2} exp\left(-\frac{1}{2\sigma^2} (y - X\beta)^T (y - X\beta) \right)$$

where X is the $n \times k$ design matrix, each row of which is a predictor vector x_i; and y is the column n-vector $[y_1 ... y_n]^T$. But as the likelihood is quadratic in $(\beta - \hat{\beta})$ it was modified into normal functional form as

$$\rho(y|X,\beta,\sigma^2) \propto (\sigma^2)^{-\upsilon/2} exp\left(-\frac{\upsilon s^2}{2\sigma^2}\right)(\sigma^2)^{-(n-\upsilon)/2} exp\left(-\frac{1}{2\sigma^2}(\beta-\hat{\beta})^T(X^T X)(\beta-\hat{\beta})\right)$$

where

$\upsilon s^2 = (y - X\hat{\beta})^T (y - X\hat{\beta})$, and $\upsilon = n - k$ with k as the number of parameters to estimate.

Step 2. 3

A joint density function which was of the same functional form as the likelihood was considered; this is also the conjugate prior with υ_0 and ${s_0}^2$ as the prior values of υ and s^2, respectively. Therefore,

$$\rho(\beta,\sigma^2) = \rho(\sigma^2)\rho(\beta|\sigma^2)$$

where $\rho(\sigma^2)$ is an inverse-gamma distribution given by,

$$\rho(\sigma^2) \propto (\sigma^2)^{-(\upsilon_0/2+1)} exp\left(-\frac{\upsilon_0 {s_0}^2}{2\sigma^2}\right)$$

and $\rho(\beta|\sigma^2)$ is a normal distribution given by,

$$\rho(\beta|\sigma^2) \propto (\sigma^2)^{-k} exp\left(-\frac{1}{2\sigma^2}(\beta-\overline{\beta})^T(A)(\beta-\overline{\beta})\right)$$

Step 2. 4

Later posterior distribution was expressed as

$$\rho(\beta,\sigma^2|y,X) \propto \rho(y|X,\beta,\sigma^2)\rho(\beta|\sigma^2)\rho(\sigma^2)$$

To express posterior mean $\tilde{\beta}$ in terms of the least squares estimator and the prior mean, with the strength of the prior indicated by the covariance matrix A, the above equation was modified as a quadratic in $(\beta - \tilde{\beta})$ (same as in *Step 2. 2*)

$$\rho(\beta, \sigma^2 | y, X) \propto (\sigma^2)^{-k/2} exp\left(-\frac{1}{2\sigma^2}(\beta - \tilde{\beta})^T (X^T X + A)(\beta - \tilde{\beta}) \right)$$
$$\times (\sigma^2)^{-(n+\upsilon_0)/2+1} exp\left(-\frac{(\upsilon_0 s_0{}^2 + ns^2}{2\sigma^2} \right)$$

Step 2. 5

Finally the coefficients were obtained from weighted average of the prior coefficients described by $\tilde{\beta}$ and the standard estimates $\hat{\beta}$. The estimated coefficients from regression models (Table 2) are used as prior coefficients.

The MATLAB was used for programming (45). Table 4 shows the comparison of retroreflectivity predictions from the third year using the Bayesian regression to that of actual field measurements from 27th, 30th and 36th months. The deviations ranged from -4.12% to -24.38% for retroreflectivity estimates and actual field measurements from the third year. In the later section the prediction accuracies were compared with the classical linear regression and ARMA models. Table 5 presents the end-of-service-life forecasts of products, and the degradation curves are shown in Figure 10.

Table 4 Comparison of Retroreflectivity Predictions from Bayesian Regression Models and Actual Field Measurements

Product / Months	Thermoplastic			Preformed Thermoplastic			Methyl Methacrylate			Durable Other		
	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy
25		342			182			218			581	
26		333			174			213			567	
27	397	323	-18.46%	183	167	-8.87%	251	207	-17.57%	577	553	-4.12%
28		314			160			202			540	
29		305			153			196			527	
30	393	297	-24.38%	161	147	-8.84%	245	191	-22.04%	577	514	-10.81%
31		288			141			186			502	
32		280			135			181			490	
33		272			129			177			478	
34		265			124			172			467	
35		257			119			167			456	
36	319	250	-21.54%	136	114	-16.17%	201	163	-18.91%	503	445	-11.50%

Table 5 Bayesian Regression – End-of-Service-Life Forecasts for Different Products

Product	Service-life (in months)
Thermoplastic	67.8
Preformed Thermoplastic	39.1
Methyl Methacrylate	54.3
Durable Others	97.5

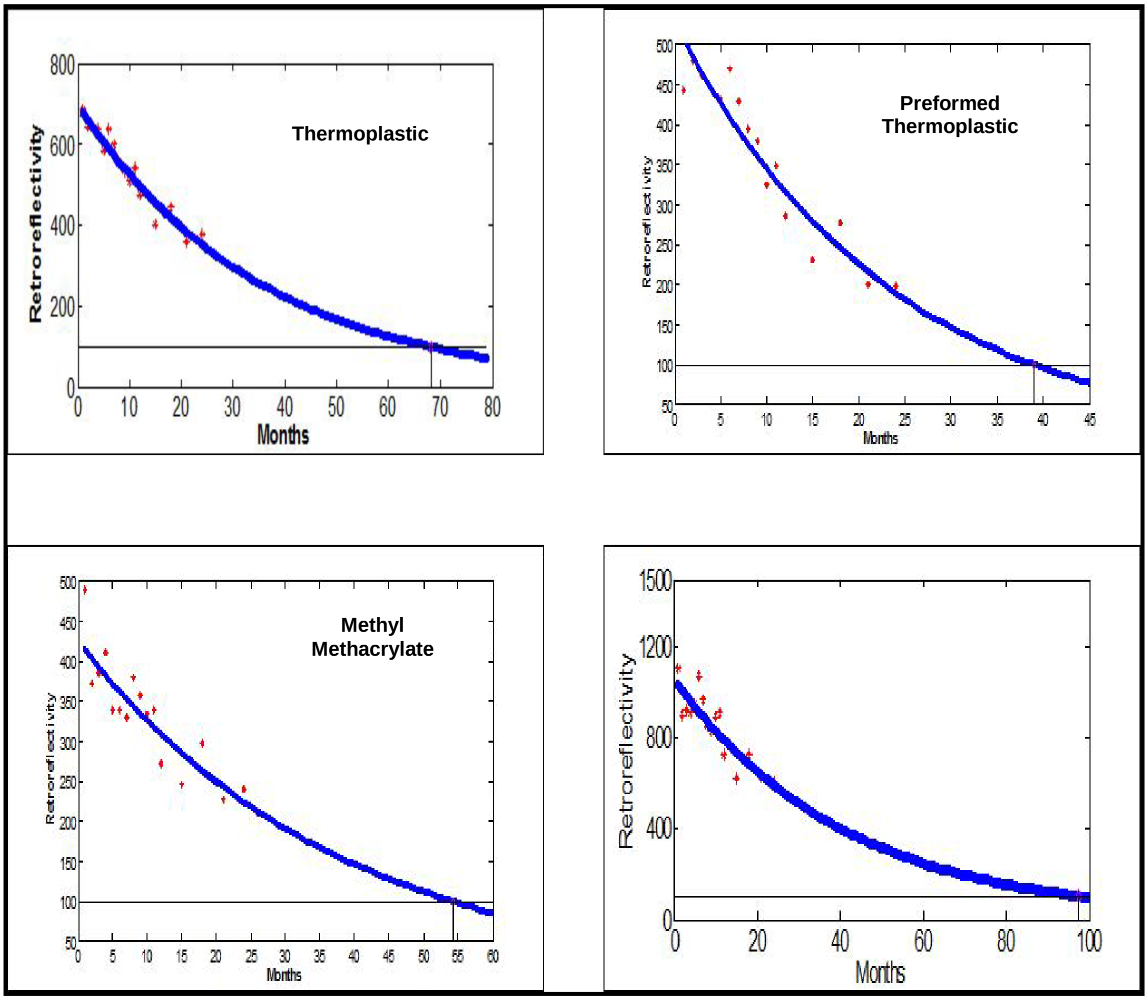


Figure 10 Bayesian Regression – Service Life Forecast Curves for Different Individual Products.

COMPARISON OF THREE ANALYSIS METHODS

In this section three analysis methods used to model the degradation of pavement markings over time were compared. Several research efforts were carried out to estimate the service life and to determine end-of-service-life of pavement markings. These studies used several graphical, statistical techniques and concepts of failure to model the degradation of retroreflectivity (15 – 19). The conclusions were driven from simple visual analysis to complicated analysis techniques. The Bayesian regression, classical linear regression and ARMA model were considered to compare based on predictions from the third year. Also end-of-service-life of four products was predicted by assuming a threshold limit of 100 $mcd/m^2/lux$. It should be noted that these end-of-service-life predictions are just an illustration of these analysis methods for application purposes. As the Bayesian regression was analyzed in the previous section, the other two analysis methods were presented before comparing all the three methods.

Classical Regression Analysis

As discussed in the literature review, classical regression analysis was the most common statistical modeling method used. Three models linear, quadratic and exponential were used given by Equation (1), Equation (2) and Equation (3). Models were developed based on two year retroreflectivity data as shown in Table 2. These same models are used to predict the retroreflectivity measurements from the third year. Table 6 shows the comparison of retroreflectivity predictions of regression analysis and actual field measurements from 27^{th}, 30^{th} and 36^{th} months. The prediction accuracies ranged from -4.5% to -24.94% for the estimated values and actual field measurements from third year. Table 7 presents the service lives of products and the degradation curves are shown in Figure 11.

Table 6 Comparison of Retroreflectivity Predictions from Classical Regression Models and Actual Field Measurements

Months \ Product	Thermoplastic			Preformed Thermoplastic			Methyl Methacrylate			Durable Other		
	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy
25		340			181			217			579	
26		331			174			211			565	
27	397	321	-18.97%	183	166	-9.27%	251	206	-18.06%	577	551	-4.50%
28		312			159			200			538	
29		303			153			195			525	
30	393	295	-24.94%	161	146	-9.29%	245	190	-22.57%	577	512	-11.21%
31		286			140			185			500	
32		278			134			180			488	
33		270			129			175			476	
34		262			123			171			464	
35		255			118			166			453	
36	319	248	-22.27%	136	113	-16.62%	201	162	-19.62%	503	442	-11.98%

Table 7 Classical Regression – End-of-Service-Life Forecasts for Different Products

Product	Service-life (in months)
Thermoplastic	67.7
Preformed Thermoplastic	40.3
Methyl Methacrylate	54.4
Durable Others	96.8

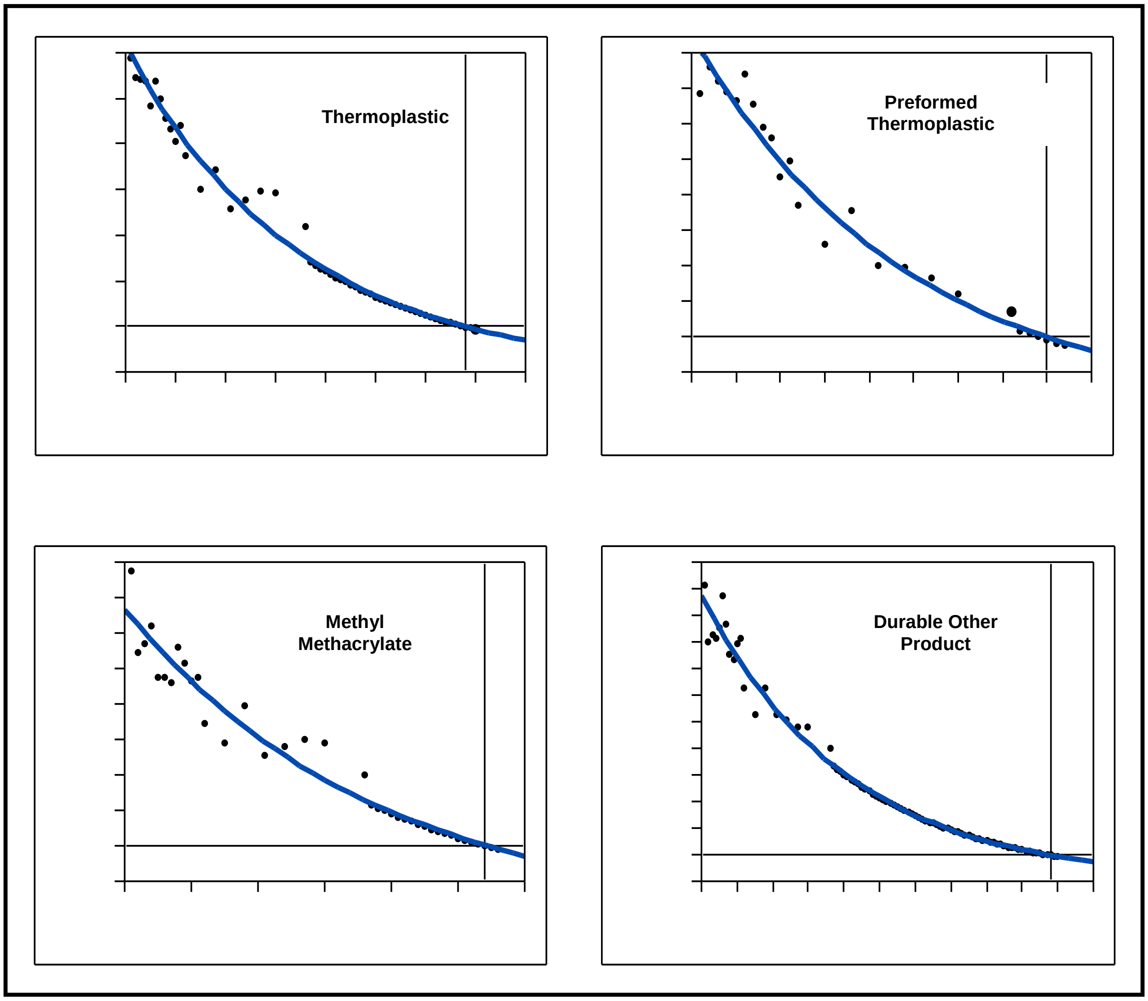


Figure 11 Classical Regression – Service Life Forecast Curves for Different Individual Products.

ARMA

Times series ARMA models were third method used for comparison of three analysis methods. This method was previously used and compared with smoothing spline technique (18). However, the degradation trend was assumed to be constant and a same order ARMA model is used across all the product types irrespective of the trend. But, from initial scatter plots and regression analysis it was evident that PMMs are behaving differently with quadratic and exponential degradation (Table 2). Therefore these issues were addressed by assuming different trends and order of ARMA depending on the information obtained from regression analysis.

The output of imputation technique that is the complete series with all the 24 points is used for the prediction purpose. Retroreflectivity data were considered as discrete-time series that is a set of observations Y_t recorded at a specific time t. These observations were assumed to be autocorrelated and not to have any seasonal or periodic variations. A sequence of time-based values $\{Y_t, t=0,1,2,3,\ldots\}$ can be modeled in the form

$$Y_t = X_t + m_t \quad \textbf{(7)}$$

where

Y_t = population data

X_t = zero mean component or noise

m_t = trend component.

Here m_t is a slowly changing function known as the trend component or the drift of the data and X_t represents a stationary process with mean zero plus some white noise (42). Initially the complete series was detrended as only stationary processes with equally spaced points can be modeled using ARMA. The JMP® software was used for time series ARMA model of order *(p, q)* on X_t (40). The order was decided based on minimizing Akaike's information criterion (AIC). The obtained model was validated with the actual field measurements from the third year data. Table 8 shows the comparison of retroreflectivity predictions from ARMA models to that of actual field measurements from 27th, 30th and 36th months. The retroreflectivity estimates exhibited deviations ranged from -0.16% to -17.71% compared to actual measurements.

Table 8 Comparison of Retroreflectivity Predictions from ARMA Models and Actual Field Measurements

Product / Months	Thermoplastic			Preformed Thermoplastic			Methyl Methacrylate			Durable Other		
	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy	Actual	Predicted	Accuracy
25		361			190			233			560	
26		356			188			232			587	
27	397	350	-11.67%	183	183	-0.16%	251	226	-9.99%	577	585	1.45%
28		344			179			222			583	
29		338			173			216			581	
30	393	332	-15.43%	161	168	4.12%	245	211	-13.93%	577	578	0.27%
31		326			161			205			576	
32		320			155			198			573	
33		314			147			190			569	
34		308			139			183			566	
35		301			131			174			562	
36	319	295	-7.35%	136	122	-9.98%	201	165	-17.72%	503	559	11.17%

Finally the application part of analysis is to predict the end-of-service-life of different products. Once the models are validated from the above step, the same models are used to forecast the service lives by assuming a threshold limit of 100 mcd/m^2/lux. Table 9 presents the service lives of products and the degradation curves are shown in Figure 12. The predictions are reasonably accurate and justify the idea of assuming variable trend and ARMA order for different products.

Table 9 Time Series – End-of-Service-Life Forecasts for Different Products

Product	Service-life (in months)
Thermoplastic	68.2
Preformed Thermoplastic	38.3
Methyl Methacrylate	42.6
Durable Others	86.8

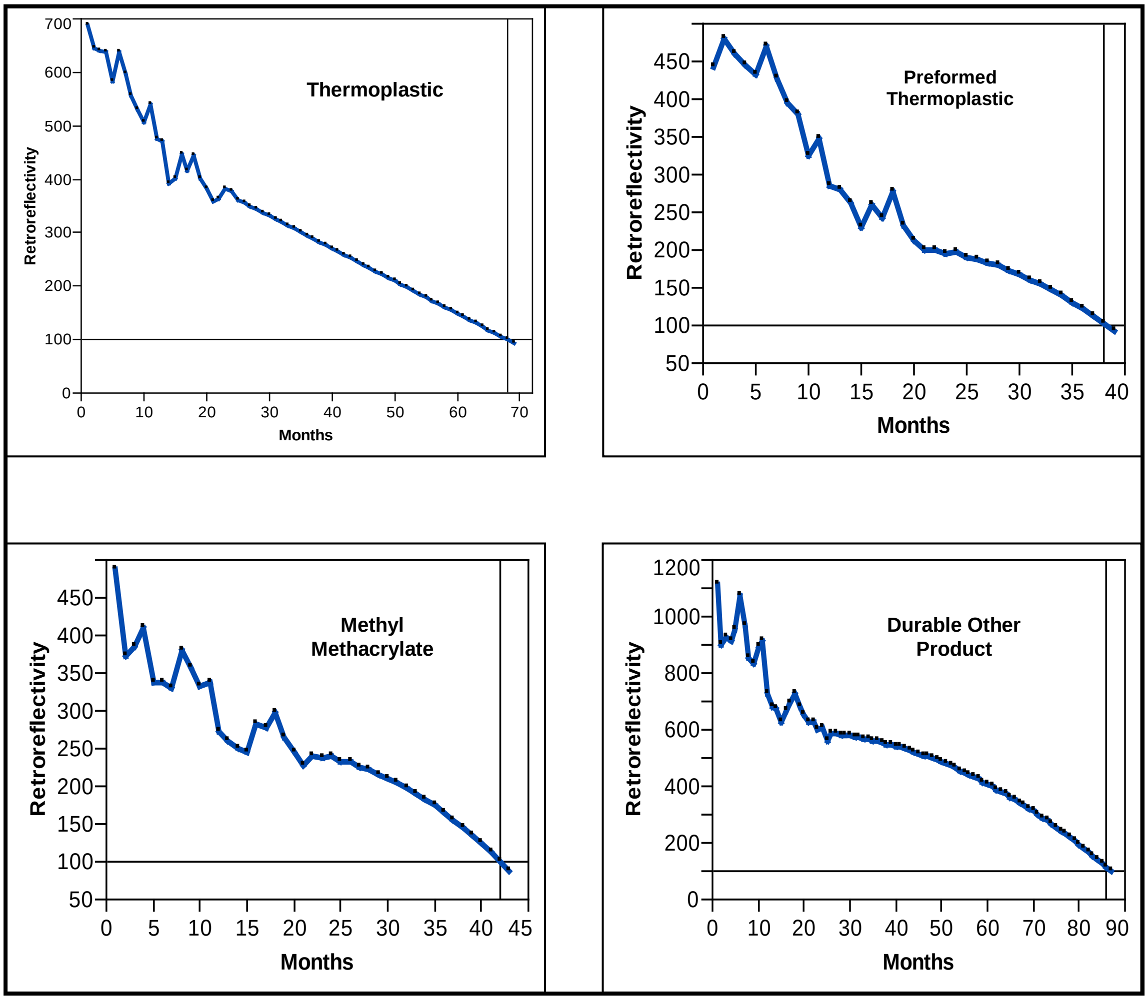


Figure 12 Time Series – Service Life Forecast Curves for Individual Products.

Discussion on ARMA Model

Figure 12 also supports the fact that products have different degradation trend and service lives. In the previous research based on time series ARMA models the mean service-lifetime ranged between 24 and 32 months (18). This is not true in case of durable pavement markings and is verified by the actual observations from the third year evaluation. This problem can be attributed to the trend and order, which is addressed and solved in this study. Therefore a clear improvement was observed by adopting a varying trend and order according to the regression inputs. It should be noted that the predicted service lives may not accurately represent the actual degradation on field due to the following reasons:

- Forecasted values were solely based on retroreflectivity degradation while there are combinations of internal and external factors that affect the degradation of retroreflectivity.
- Degradation trend of skip-line area of the transverse test decks data from NTPEP may not truly represent the actual longitudinal degradation.

However one of objectives of the section is to demonstrate the importance of the developed imputation technique which can be a valuable aid to handle the unexpected situations and data irregularities during field evaluations. Although the technique was demonstrated only on retroreflectivity data, it could be extended to other similar parameters with necessary modifications to design a more economical work plan. The developed imputation technique currently handles only missing values but could be extended to censored data based on the on technique developed by Park et al. (41).

DISCUSSION OF RESULTS

The three statistical techniques (classical regression, ARMA model and Bayesian Regression) analyzed were compared based on the retroreflectivity prediction for the months 27, 30 and 36. All these techniques were analyzed by taking two year data and validated with that of actual retroreflectivity measurements from field data that were know from the third year of evaluation. It should be noted that this comparison is not based on service life predictions beyond the third year as there is no data to support that a particular marking product lasted for predicted number of years.

The prediction accuracy was reasonable considering the variability and abnormality of the measurements from field as variance of over 10% to 20% in measurements of a same product is usual (46). Table 4, Table 6, and Table 8 present the retroreflectivity predictions for individual techniques and their prediction accuracies. These prediction accuracies across the products from three techniques were compared in Table 10. It is definite that ARMA models have a better prediction across all the products, though there was a wide variation in the prediction accuracies they were small when compared to the other two methods.

Table 10 Comparison of Retroreflectivity Prediction Accuracies by Three Methods

Month	**Thermoplastic**			**Preformed Thermoplastic**			**Methyl Methacrylate**			**Durable Other**		
	Classical Regression	ARMA	Bayesian Regression	Classical Regression	ARMA	Bayesian Regression	Classical Regression	ARMA	Bayesian Regression	Classical Regression	ARMA	Bayesian Regression
	Prediction Accuracy %			Prediction Accuracy %			Prediction Accuracy %			Prediction Accuracy %		
27	-18.97	-11.67	-18.46	-9.27	-0.16	-8.87	-18.06	-9.99	-17.57	-4.50	1.45	-4.12
30	-24.94	-15.43	-24.38	-9.29	4.12	-8.84	-22.57	-13.93	-22.04	-11.21	0.27	-10.81
36	-22.27	-7.35	-21.54	-16.62	-9.98	-16.17	-19.62	-17.72	-18.91	-11.98	11.17	-11.50

The advantages of ARMA models are their flexibility and the ability to describe wide variety of data sets. Also they are optimal (under certain assumptions) and are comprehensive in describing a model (42). But on the down side, they are time consuming when compared with other techniques such as regression analysis that are simpler to implement. Implementation of ARMA models desires points with regular intervals or the use of imputation techniques. Also, ARMA models must be completely rebuild and identified each time with a new data set.

Another interesting observation is that the prediction accuracies have improved with the Bayesian regression compared to the classical regression. The explanation behind this improvement could be the use of prior information. The parameter estimates from the classical regression were taken as prior information to obtain the coefficients using the Bayesian regression. As mentioned earlier the Bayesian technique can be used to reduce the uncertainty in the service life prediction. Advantages of Bayesian models are their ability to handle unobserved variables by the use of prior probability distributions by combining information from previous studies. But a wrong choice of prior can affect the posterior inference, particularly for small datasets. For example, if information from PMMs installed in colder regions is used as prior information to analyze same products installed in hot climatic regions this might result in faulty results. Moreover, regressions techniques are simple and easy to apply as compared to ARMA models. In conclusion each model has its own advantage and disadvantages, but by evaluating the prediction accuracies it is found that ARMA models are more reliable when compared to the other techniques. But for application purpose the Bayesian regression seems more practical as it is simple and at the same time gives an opportunity to utilize the valuable prior knowledge and expertise of personnel that are available.

The good accuracy in predicting the third year values and service life based on two-year data raises an interesting question: is it always necessary to test durable markings over their entire service lives? Certainly better data would be obtained with longer test durations but that comes with significant costs. The good results in this section demonstrated that predictions beyond the second year could be fairly reliable with a proper method. This should be considered when developing evaluation programs for durable pavement marking materials.

CHAPTER IV
PRACTICAL RESTRIPING METHODOLOGY

INTRODUCTION

Over time transportation assets age, deteriorate, fail and needs maintenance to be functional at required level of service. Definition of *failure* varies depending on asset category — failure in one category may mean that the asset is completely ineffective, or in another it might indicate the time to replace or repair. Figure 13 illustrates the typical performance cycle of an asset from installation to failure (37).

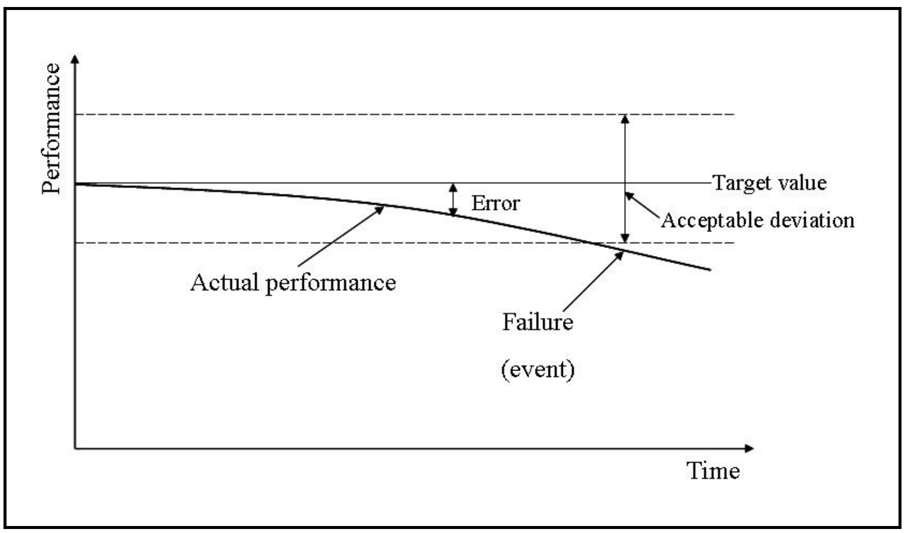


Figure 13 Typical Performance Cycle of an Asset (37).

PROBLEM STATEMENT

In the similar lines performance of pavement markings deteriorates over time loosing their key property of retroreflectivity. Although there is no significant evidence that reduced pavement marking performance causes more crashes road users feel comfortable driving at night with brighter markings (47, 48). Therefore it is the responsibility of the concerned agencies to maintain pavement markings in serviceable condition. But what can be considered as a *failure* for pavement marking assets to take up a restriping decision and how the cost-effective restriping programs needs to be taken up are some of the questions encountered. This chapter attempts to address these issues by developing a practical restriping methodology and an application in GIS to effectively implement the maintenance program.

RECOMMENDATIONS FOR MINIMUM LEVEL OF RETROREFLECTIVITY

Pavement markings can be classified as non-repairable items, overall performance degrades with time from target value to failure with acceptable deviation. But defining a failure as an event is complicated for pavement markings compared to assets such as signs or pavements. Although Congress directed to revise the MUTCD to include a standard for the minimum level of retroreflectivity for signs and pavement markings, there are no specific performance requirements regarding initial or maintained retroreflectivity levels for pavement markings. But, FHWA proposed to follow minimum retroreflectivity values for traffic signs with the second revision of the 2003 Edition of the MUTCD, effective January 22, 2008. These values were developed and revised after several research efforts, the literature of which can be found elsewhere (49). These minimum retroreflectivity levels do not imply that every sign should be inspected but is intended for agencies to help in establishing and implementing a management practice to maintain good visibility of signs. Based on these guidelines FHWA developed maintenance methods that can be followed by agencies to comply with required minimum retroreflectivity levels (50). Similar is the case with pavement assets, where management practices are well established and have one the most commonly used management systems across all transportation assets.

Over the years, there have been several research efforts that addressed the issue of recommending minimum levels of retroreflectivity in field of pavement markings (51). These efforts were based on computer models such as Computer-Aided Road-Marking

Visibility Evaluator (CARVE) developed by Ohio University and Target Visibility Predictor (TARVIP) by the University of Iowa. It was found minimum retroreflectivity recommendations depend on vehicle speed (longer detection distance for same preview time), pavement surface type, pavement marking type, pavement marking configuration (center and edge lines), presence of retroreflective raised pavement markers (RRPMs), preview time, type of vehicle, driver population (51). The calibration of computer models were limited by simplified assumptions and idealized conditions. Other conditions such as wet weather, curved roadway segments, marking width, roadway lighting may influence the minimum retroreflectivity levels which were not thoroughly analyzed. All the above considerations make the process of maintaining pavement marking minimum retroreflectivity levels complicated under various conditions. Also it was found that there is a significant difference between sign and pavement marking assets. Following are some of the major differences that were identified which can also be considered as impediments to implement guidelines for minimum retroreflectivity levels (7):

- Retroreflectivity life cycle of pavement markings is much shorter and relatively variable.
- Many factors influence the retroreflectivity and durability of markings making the prediction of service life highly unreliable.
- Performance of typical markings is much less in wet conditions as compared to dry conditions.
- Restriping or replacement cycles are restricted by seasonal cycles and winter maintenance activities such as snow ploughing for agencies in cold and snowy climates.
- A standard procedure does not exist for field performance evaluations of in-service markings using manual or mobile retroreflectometers.

In the wake of above difficulties and other safety and financial aspects that were considered, AASHTO projected that “it will not be possible to maintain pavement marking minimum retroreflectivity levels for all markings at all times under all conditions." Also it proposed that conformance with the 1993 Appropriations Act "would be satisfied if all agencies have a reasonable, systematic, statistical, and localized assessment and/or management method in place to maintain pavement marking retroreflectivity."

ASSESSMENT AND MANAGEMENT METHODS

This chapter attempts to develop a procedure for assessment and management that assists an agency to maintain pavement marking assets in good serviceable condition. For maintenance purposes both pavements and pavement markings are linear in nature but the similarities end there as pavement assets are considered as repairable systems as against pavement markings which are non-repairable items. In other words pavements can be repaired/ rehabilitated using several maintenance and repair (M&R) techniques before they are completely replaced/ repaved. Nevertheless, principles of management and maintenance from pavement assets were studied for possible adoption into pavement markings. Pavement management is mainly taken up at project level for selecting suitable M&R techniques and at the network-level for determining priorities across different projects (52). But this study focuses on section (project) level management which deals with an assessment of a single roadway section. The following section presents a method for retroreflectivity evaluation of a roadway section based on procedures adopted in maintaining pavement assets.

Section Assessment Method (SAM)

Field evaluation techniques of pavement markings are both subjective and objective in nature as discussed in literature review. This section provides a systematic procedure to perform objective evaluation of retroreflectivity measurement. AASHTO mentioned that, "there is no accepted standard sampling protocol for measuring pavement marking retroreflectivity using either hand-held or mobile units and especially designed for assessing the condition of in-service markings (not newly applied markings)" in identifying the differences between signing and pavement marking systems (7). Signs are evaluated individually unlike markings which are evaluated longitudinally along a travelled way. Evaluation of the entire road section requires commitment of time and resources, demanding effective data collection. Moreover to effectively manage database it is important to collect data in a systematic and consistent method. Thus it is important to have a standard procedure that facilitates field evaluation of section performance conveniently.

Section assessment method (SAM) describes the procedure for retroreflectivity inspections of in-service pavement markings of a road section using a handheld retroreflectometer or MRU. The following are the different steps involved in this method

Step 3. 1 - Dividing section into sample units

Section under evaluation is divided into smaller sample units for the convenience of inspection and to calculate the overall average retroreflectivity. The length of a sample unit is defined based on the driver's preview distances which formed basis for minimum retroreflectivity requirement research. Schnell and Zwahlen suggested that "drivers should be provided with a pavement marking visibility distance long enough to allow for a preview time of 3.65 s at a given vehicle speed." (53) They also proposed that minimum required preview distance can be translated into a minimum required pavement marking retroreflectivity. Another research conducted by University of Iowa also shown that required minimum retroreflectivity was highly sensitive to preview time that can be associated with a detection distance (51). As mentioned earlier the research for calibration of computer models were conducted with assumptions and simplified conditions. The visibility distance may vary depending on the actual conditions which might be different from these testing conditions.

Figure 14 shows a road section divided into ten sample units numbered *i = 1, 2, 3,…, 10* each sample unit with longitudinal length of preview distance (*d*) with a driver positioned at the beginning of the second sample unit. This driver can traverse the second sample unit comfortably if markings in this sample unit are above serviceable limits of retroreflectivity. Conversely, two consecutive sample units (second and third) having retroreflectivity below threshold value may not provide enough visibility distance. Therefore this study proposes that the length of sample unit (*l*) can be equated to the required minimum preview distance (time) at a given vehicle speed that provides enough visibility information for driver at night. Also, this study does not propose any standards regarding the selection of preview distance but the selection can be based on previous research and further investigation of prevailing conditions.

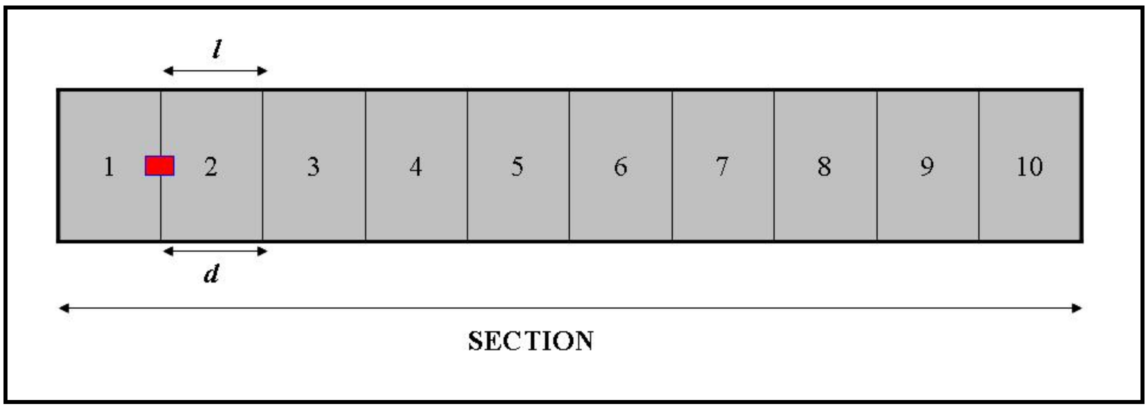


Figure 14 Road Section Divided into Sample Units.

Step 3. 2 - Determining minimum number of random sample units

Once the length of the sample unit is determined from *Step 3. 1*, the next step is to measure retroreflectivity of sample units along the section. Retroreflectivity values are measured using hand-held or MRU. The length of sample unit can be easily programmed in MRUs with chainage or desired inspection interval length. But, MRUs requires high initial investment cost along with continued cost to agencies even though they involve less manual labor (7). Also, Missouri Department of Transpiration (MoDOT) adopted a Pavement Marking Management System (PMMS) which requires only MRUs for retroreflectivity inspections and was considered as one the disadvantages of the system (54). On the other hand measurement of retroreflectivity using hand-held unit on all the sample units along a long road section consumes enormous amount of time and resources. Therefore, a sampling procedure needs to be followed for assessing retroreflective properties of longitudinal pavement markings.

The standard, ASTM 6359 was used to evaluate newly applied pavement marking using portable hand-operated instruments but it was cancelled in 2006 (55). A new standard, WK15655, "Practice for Inspection and Evaluation of the Retroreflectivity of Longitudinal Non-Intersection Pavement Markings" is under development. The proposed new standard can be applied to both new and in-service markings. The sampling as per ASTM 6359 is made based on zone of measurement which is 'the road length containing the marking units to be measured that appear to below specifications.' The zone of measurement is of four types depending on its length and the sampling procedure is different for each type. The detailed procedure is described in detail elsewhere (56).

Currently, there are no standards in place for inspecting and evaluating retroreflectivity of in-service longitudinal pavement markings. Therefore, this study adopted an Equation (8) for calculating minimum number of random samples units (*n*) from pavement management practices with minor modifications given by:

$$n = \frac{N \times s^2}{(e^2 / 4)(N - 1) + s^2} \quad \textbf{(8)}$$

where

N = total number of sample units in the section

e = allowable error in the estimate of the section retroreflectivity

s = standard deviation of retroreflectivity measurements between sample units in the section.

Here the sampling procedure is based on sample unit. Instead of measuring retroreflectivity of all the sample units along a section, Equation (8) can be used to select limited number of sample units. These sample units can be equally spaced along the section by choosing the first sample unit randomly.

Step 3. 3 - Additional Sample Units

It is possible that sample units selected using *Step 2. 2* may not be true representative sample of the section, meaning some sample units that are extremely bad may not be included. Such sample units can be included as additional sample units to calculate the average retroreflectivity of entire section.

Step 3. 4 - Calculating average Retroreflectivity of a section

Depending on the length and location of sample unit selected, each unit includes skip lines or edge line. The retroreflectivity value of each sample unit can be taken as the average of measurements taken over the length of skip/ edge line in that sample. According to ASTM 6359 a total sample size of 20 measurements are taken for approximately 15 ft depending on the length of zone of measurement (56). It is assumed that measurements along markings in a sample unit may not exhibit extreme variations as the length is considerably small compared to the length of a section. Now that retroreflectivity measurement of each sample unit is know, the average of entire section can be calculated using the simple weighted average mean given by Equation (9).

$$R_s = R_r = \frac{\sum_{i=1}^{n} R_i \times l_{ri}}{\sum_{i=1}^{n} l_{ri}} \qquad \textbf{(9)}$$

where

R_s = average retroreflectivity of entire section

R_r = weighted average of retroreflectivity of all random sample units

R_i = retroreflectivity of i^{th} random sample unit

L_{ri} = length of i^{th} random sample unit

n = total number of random sample units

Equation (9) should be slightly modified to obtain average retroreflectivity of entire section if additional sample units are included from *Step 3. 3*. Average retroreflectivity of additional sample units can be calculated using Equation (10) and the overall average of the section with additional sample units is calculated using Equation (11).

$$R_a = \frac{\sum_{i=1}^{na} R_{ai} \times l_{ai}}{\sum_{i=1}^{n} l_{ai}} \tag{10}$$

$$R_s = \frac{R_r\left(l_s - \sum_{i=1}^{na} R_{ai}\right) + R_a \times \sum_{i=1}^{na} l_{ai}}{L} \tag{11}$$

where

R_a = weighted average retroreflectivity of additional sample units

R_{ai} = retroreflectivity of i^{th} additional sample unit

L_{ai} = length of i^{th} additional sample unit

L = total section length

na = total number of additional sample units

Section Management Method (SMM)

Considering section of road segment which has some sample units with pavement marking retroreflectivity less than that of threshold limit. In this case the agency has two alternative choices either to restripe the entire section or to restripe only samples units that are in bad condition. Restriping the entire section may increase the agency's cost as some sample units that are in serviceable condition are also restriped even before the markings reached their minimum retroreflectivity level. Also this option may not be possible because of limited budget or prioritization decision. The second option is to restripe selected sample units that are below serviceable limits. Identification and selection of these units is important and can have a significant impact on practical implementation. Also, marking maintenance activities requires lane closures or detours which compose significant cost along with material costs. Therefore it is important to study the selection of sample units and cost-effective method to maintain the section in serviceable condition. This study proposes a section management method (SMM) that provides information for agencies to take up restriping activity along a section.

In the above example the *bad* sample units are spread across the length of section, these sample units should be combined to form a considerable road length to effectively implement restriping. Restriping of numerous smaller road lengths may lead to higher implementation costs than restriping the entire section. This is considered as space problem where the sample units need to be consolidated using the property of compactness. Compactness is a shape property "has been given the greatest attention due to its potential applicability to a broad range of geographic problem." (57) Taylor performed a set of experiments on different shapes to examine the divergence from compactness (Figure 15) in different shapes from the distribution of distances (58). Conversely different shapes display an extreme case of convergence to a compact shape such as a circle or a square; this forms the basis for selecting a suitable division size in this study (59).

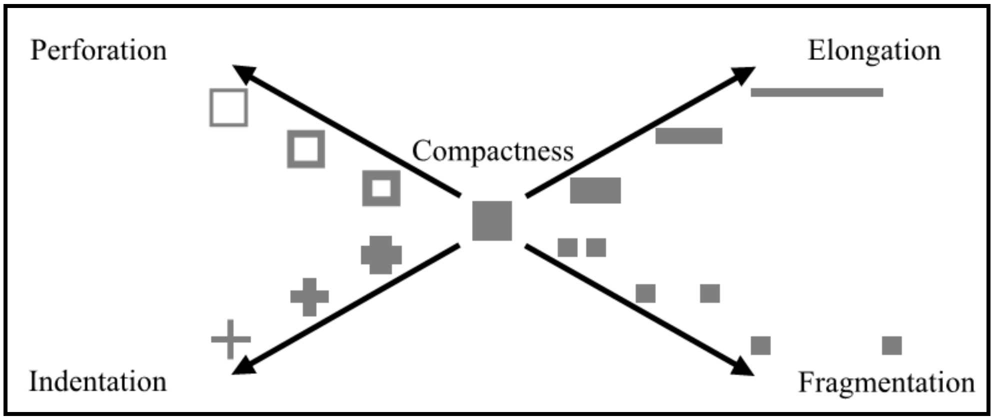


Figure 15 Divergence from Compactness (58).

There exist several methods for interpreting the measure of compactness mathematically, but moment of inertia (MOI) was considered as one of the most accurate compactness measure (57).

Moment of Inertia (MOI) Method

Concept of MOI was widely applied for district apportionment based on population density, size, geographic compactness or other criteria like political/ market analysis (59, 61). It was used by Massam and Goodchild to find optimum location of service center location for a space divided into functional areas or rural operating areas (ROAs) (60). It was either used as measure of geometrical optimality or compactness. In this study MOI is used as a measure of compactness for a set of sample units when calculated with respect to given axis passing through center of gravity.

MOI of an object with finite set of *n* discrete spatial units can be defined the sum over the area of each spatial units multiplied by the square of the distances l_i to the object's gravity center (59, 60). It represents the degree of geometrical optimality of an area, MOI for a set of sample units in a road section can be mathematically represented using Equation (12).

$$I_s = \sum_{i=1}^{n} a_i l_i^2 \tag{12}$$

where

I_s = moment of inertia of set of sample units along axis of center of gravity

a_i = area of sample unit i

l_i = distance from the object's gravity center to sample unit i.

The objective to use MOI is to find centrality of location of a division to perform maintenance cost-effectively. This is further explained in the following example (Figure 16) in a step-by-step procedure;

Step 4. 1

Consider a section divided into 20 sample units (numbered $i = 1, 2, 3\ldots, 20$ and each of length = l) as per section assessment method, retroreflectivity measurements were taken using MRUs. Standard deviation of measurements was calculated to define confidence limits for threshold value, given by:

$$R_{th} \pm Z_{\alpha/2} \times {}^{s}\!/\!_{\sqrt{m}}$$

where

R_{th} = retroreflectivity threshold value

α = significance level

s = sample standard deviation

m= sample size.

Confidence limits were defined so as to include all the sample units in the neighborhood of threshold value. Sample units with retroreflectivity levels within the upper confidence limit of threshold value were identified and are classified bad samples (hatched samples in Figure 16).

Step 4. 2

In this step a sample set is selected. A sample set can be defined as road length which has two or more consecutive bad samples based on the explanation that driver can traverse a single bad sample comfortably. Here three sample sets A – (5, 6), B – (11, 12) and C – (15, 16, 17) were identified as shown in Figure 16.

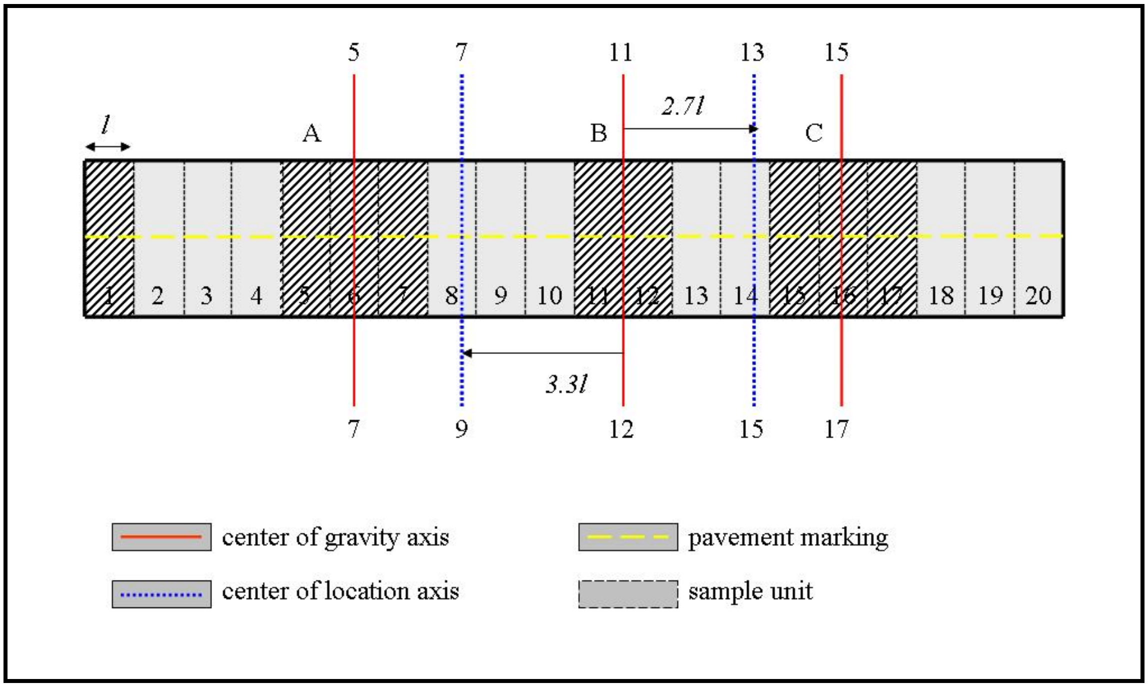


Figure 16 Section with Sample Units and Axes of Rotation.

Step 4. 3

Moment of inertia of each sample set was calculated along axis running through the center of gravity of each sample set with unit area (a_i) and distance (l_i). Larger MOI indicates sample set with more bad samples in other words greater extent of area with retroreflectivity less than threshold limits. In the present example sample sets A and C have large MOI of the magnitude $2l^2$ along axis 5-7 and 15-17 respectively.

Step 4. 4

Entire section was surveyed for sample set with largest MOI to find measure of compactness with adjacent sample set. In this step measure of compactness criterion was used to combine sample set with smaller MOI segments to the adjacent sample sets with larger MOI. The MOI of the sample set system was calculated along the axis passing through the center of gravity of the system termed as center of location axis. In the current example as both A and C have largest MOI, measure of compactness was calculated for sample set system (A, B) and (B, C) along axis 7-9 and 13-15 respectively. Fragments (B, C) have smaller value which can be explained with parallel axis theorem that relates moment of inertia about a displaced axis of rotation to that of the axis through center of gravity given by:

$$I_d = I_s + ax^2$$

where
I_d = displaced moment of inertia of sample sets along center of location
a = total area of sample set
x = displacement.

Here axis of sample set B was displaced by a length of $2.7l$ towards C which was less than that of $3.3l$ making measure of compactness smaller for sample set system (B, C).

Step 4. 5

Measure of compactness of different sample set systems was examined along entire section; systems with smallest value form a *division*. A division is a minimum road length which is viable to perform restriping cost-effectively. Sample sets system (B, C) formed a division as shown in the Figure 17.

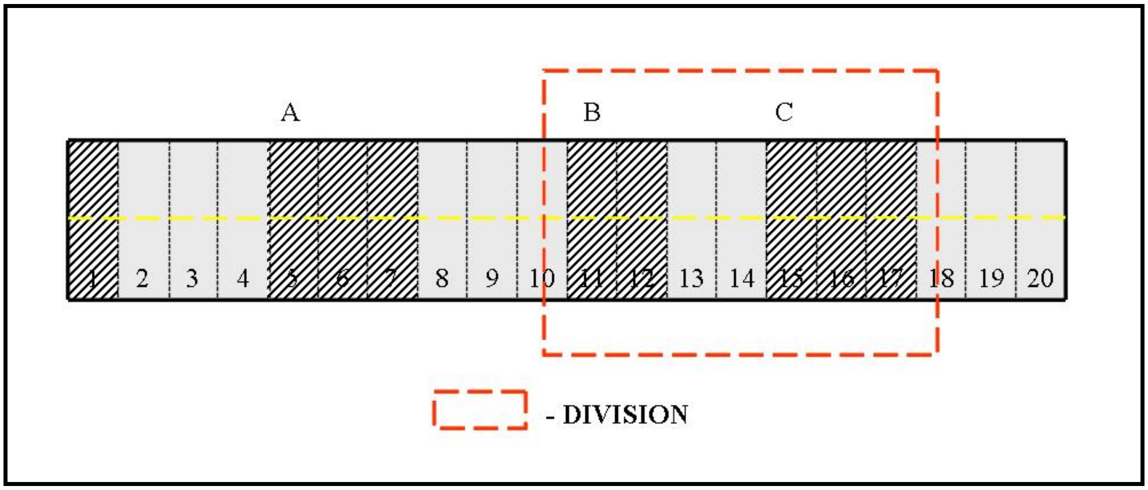


Figure 17 Section with a Division to Implement Restriping Effectively.

Step 4. 6

Finally each division obtained was checked if it is suitable to implement restriping. Else *step 4. 3* to *step 4. 5* are repeated treating each division as a sample set to combine smaller divisions with adjacent larger divisions.

The divisions marked can be used for maintenance activities including traffic control, restriping, budget evaluation, and for prioritization decisions. However there is no set limit for measure of compactness at which the above procedure terminates as the length of section, sample units, and sample sets are variable depending on the road segment chosen. An engineering judgment is required to estimate the length of divisions that are suitable for effective maintenance. Overlooked single bad samples can also be included into the divisions based on measure of compactness. Also it is assumed that there is considerable number of samples within confidence limits whose retroreflectivity is less than that of threshold value. The entire procedure can be modeled as an algorithm for computer modeling that can be very valuable for longer sections of road segments. The above procedure was dealt as a space problem based on property of compactness. This can also be viewed as a time problem or a combination of both by estimating the safety and economic implications of maintenance at different time periods.

Case Study

Section assessment method (SAM) and section management method (SMM) were demonstrated with a case study from the Fisher County, Texas. The data in this study was from a section of length 18 miles on FM 57 south bound starting at the boundary line of Fisher County till the intersection of SH 70 was considered (Figure 18). Retroreflectivity data were collected along the solid edge lines of white colored markings using MRU. Size of sample unit was assumed to be 528 feet as retroreflectivity data were collected using MRUs with a chainage of $1/10^{th}$ of mile from single solid edge line. There were 179 total sample units along the section with standard deviation 21.42 $mcd/m^2/lux$.

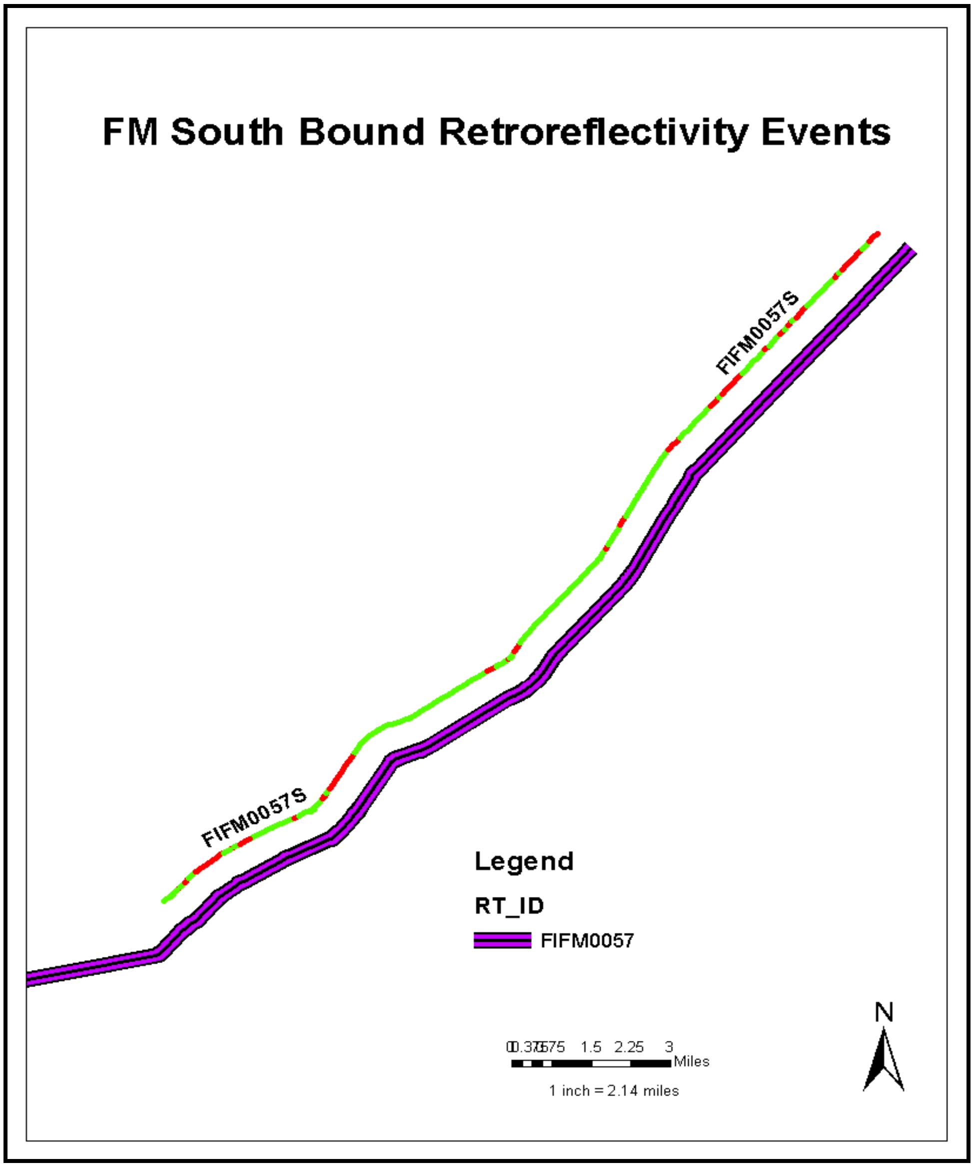


Figure 18 Retroreflectivity Events along FM South Bound.

Retroreflectivity threshold limit was assumed to be 100 mcd/m^2/lux setting the confidence limits at 102.63 and 97.37 mcd/m^2/lux. All the samples having retroreflectivity lesser than upper confidence limit were considered as bad samples (Figure 19).

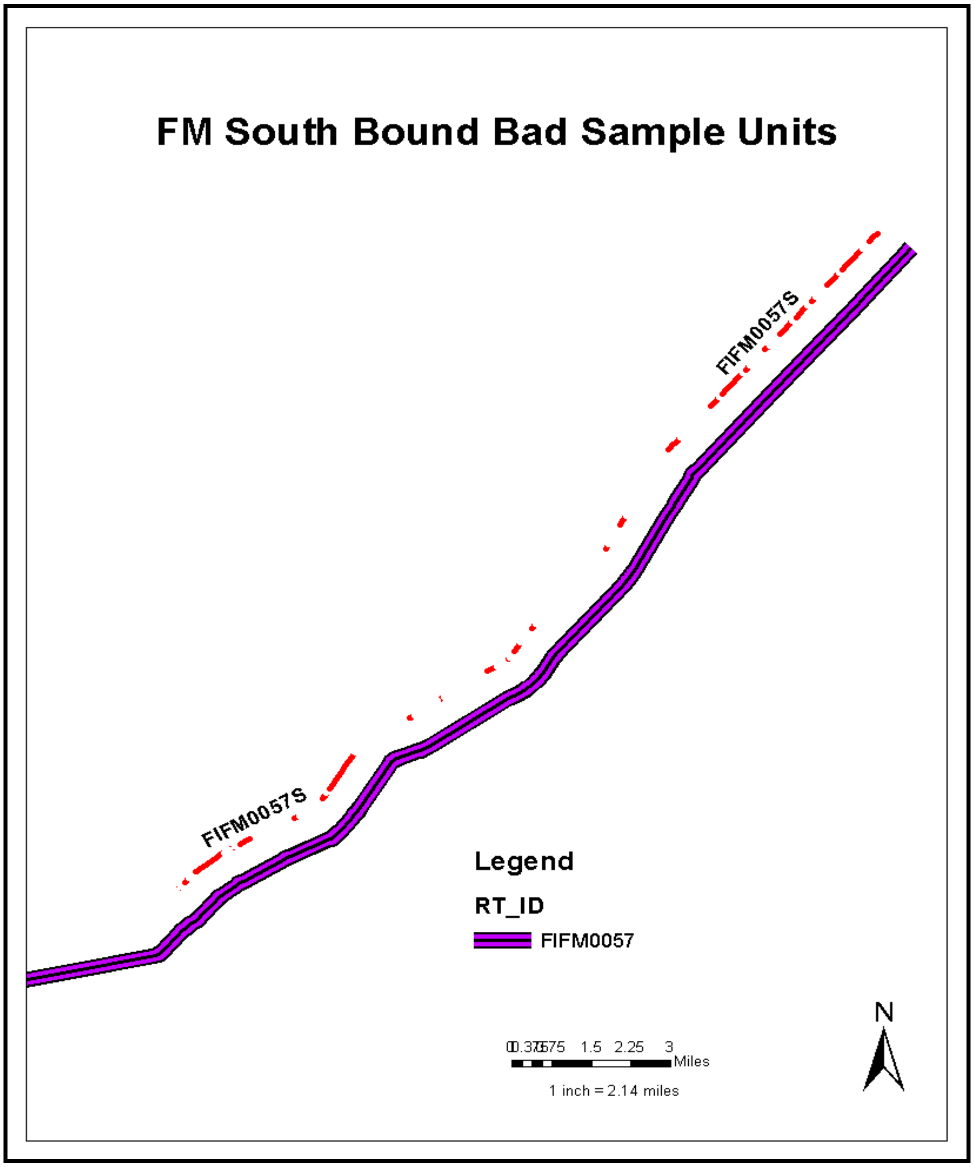


Figure 19 Bad Sample Units along FM 57 South Bound.

Sample sets were identified to calculate MOI, the largest sample set in the entire section was with eight consecutive bad sample units. Divisions were selected based on the measure of compactness calculations. The procedure of merging sample units into divisions was repeated until divisions of at least one mile were obtained. Four divisions were identified with lengths 4.3 m, 1.3 m, 1 m, and 1.3 m with a total of 8 miles of road length along the 18 mile stretch for restriping cost-effectively (Figure 20).

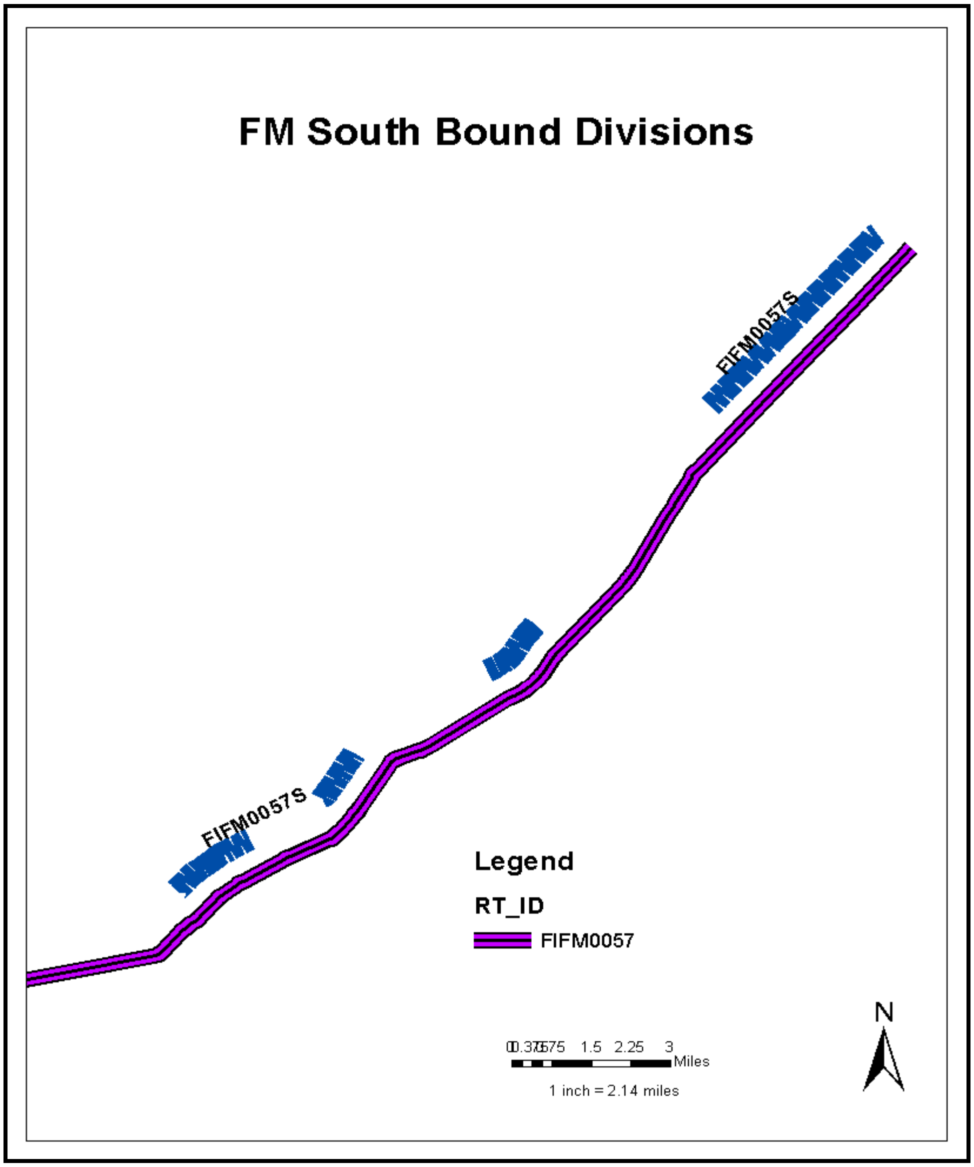


Figure 20 Divisions along FM 57 South Bound.

DISCUSSION

The above section management method was purely analytical where the decision of restriping a section mainly based on retroreflectivity levels. However it was evident from literature that minimum retroreflectivity recommendations depend on vehicle speed, pavement surface type, pavement marking type, pavement marking configuration, presence of RRPMs, preview time, type of vehicle, driver population (51). Therefore a management method should also include information tools so as to integrate information related to other conditions listed above. Also for implementing the assessment and management methods in a systematic and consistent way, a database is required to store information on inventory, location, performance evaluation. For the section-level management it is important to keep track which sample units were evaluated to keep track of the retroreflectivity measurements. Therefore an information tool was devised based on GIS environment which can support pavement marking management program apart from traditional database abilities.

INTEGRATED PAVEMENT MARKING MAINTENANCE (IPMM)

The objective of this section is to demonstrate the use of GIS in the maintenance of pavement marking assets. The procedure developed is a step-by-step process for the implementation of integrated pavement marking maintenance (IPMM). IPMM is designed to be integrated with existing pavement management system (PMS), and hence pavement marking should be referenced in analogous manner as the pavements are referenced. Highway infrastructure is traditionally represented in line features on maps as they are linear in nature. Therefore, instead of locating a point on these linear features using classical geographic coordinate systems it is easy and practical to use relative reference.

METHODOLOGY

The idea of integrating management system for pavement markings with that of pavements emerged from the fact that both the assets can be referenced using the same base linear referencing system. Therefore instead of developing an independent management system the present study conceived an idea to integrate pavement marking management system. The following is a step-by-step procedure for the planning and development of IPMM.

Planning of IPMM

Step 5. 1- Selection of Linear Referencing System

Linear features such as highways and streets are modeled to understand, maintain and analyze information from these features. Linear referencing system (LRS) forms a datum on which this information can be collected. A LRS is “a system where features (points or segments) are localized by a measure along a linear element.” (62) LRS is extensively used to collect information about linear features such as highway/street network, rivers, and pipelines (63). It is popular in transportation field as information about assets and features can be stored with spatial reference along a road section. Mile markers along U.S. highways system is one recognizable example of linear referencing (64). It can be used for analysis purposes of spatial data elements making it more advantageous over conventional database systems. It is also different from conventional reference systems as it does not use the measurement based on geographic coordinate system such as Universal Transverse Mercator or state plane. Therefore any points or locations specified on the field can be easily sited along the linear features. Also linear referencing eliminates overloading database with information from highly segmented networks (65). For example, a network which is segmented based on intersections cannot be effectively used to represent speed limit information as the route between two intersections can have varying speed limits. This means that separate measurement information needs to be recorded from intersection reference for varying speed limits along same route. Thus the implementation of linear referencing eliminates a large and complicated database, reduces redundancy and enables easy and simple cartographic representation of network attribute data. A LRS can include one or more linear reference methods (LRMs).

Linear Reference Methods

A linear method is a technique to identify a single position of an unknown point with respect to a known reference (66). Events are referenced using fixed features such as mileposts, intersections etc. for any network of linear features. In transportation scenario a feature is reference based on a defined path in a network which can also be called as datum.

It is important to have a common reference method to integrate the information collected from different assets. Common reference method also has advantages such as, use of common measurement method, lesser amount of training on the system to users, integration of different database, and effective presentation of output for easy decision making (67). It is advantageous to use a reference system on which the agency has already established its inventory information, but the selected reference system should serve the purpose of smooth integration of data collection on various assets. Some of the common reference methods that can be used in GIS environment are route intersections, mileposts, link/nodes and latitude/longitude (67):

- Route Intersections - In this system the features are referenced by their distance from the intersection of linear features in a particular direction. This system is simple and is more suitable for the areas with closely spaced intersections (urban areas). The measure units are different based on the direction of measurement; also it is subjected to change in the case of relocation of routes.

- Mileposts - This system is typically used in large jurisdictions with established physical markers. Objects are referenced along a linear feature with positive or negative distance from a milepost depending on direction. This system also has a disadvantage due to the relocation of route as all the measures should be reassigned along the route.

- Link/nodes - In this system the network is represented with links and nodes with links numbered using the node numbers at either end of the link. The objects are referenced along a linear feature from the start of a link. This system is complex for cartographic representation as each node needs to have a unique identifier.

- Latitude/longitude - Global Positioning System (GPS) receivers are used to reference objects using geographic coordinates, latitude/ longitudes which acts as events for GIS application. With the advent of economical GPS devices the data collection has becomes cost-effective, simple and accurate. Usually the features are modeled in two dimensions using x, y coordinates. Write more when you come across

Detailed definitions and more information on location reference systems are given in National Cooperative Highway Research synthesis on highway location reference system (68). Each reference system has its own advantages and disadvantages, an agency can choose a reference system based on the type of assets referenced, type of softwares used for database and analysis, extent and type of area and the level of integration across different asset categories.

Step 5. 2 - Selection of Software

Selection of software for information and analysis purpose and selection of a reference system are mutually dependent as some off-the-shelf softwares support only limited reference systems. Agency may select depending on the size, budget, availability of trained personnel and application extent. GIS based databases are being significantly used as they are equipped with cartographic features for spatial representation along with the conventional functions of database software (13).

Step 5. 3 - Database

Design of database is important to effectively store and manage data, which includes database objects and data elements. Database objects are basic components which store, query, analyze and share information. Selection of data elements is based on usefulness of data as it is directly related to cost of data collection (67).

Step 5. 4 - Data Collection

As IPMM system is developed with an idea to integrate the inventory information of markings with that of pavement management system. It is desirable to adopt a reference system that is currently in use for pavements with minor modifications to be consistent in different areas like reference system, data terminology to develop a comprehensive system. This facilitates an easy data collection and integration with the existing database model without additional modifications such as format change etc. But to put the system into practice all the components involved in the management system needs to be standardized under a single platform.

Development of IPMM

The present system is developed based on ArcGIS from ESRI which has the capability to integrate GIS information tools and database. The advantage of this system is that it combines the tabular information with spatial reference. The usual tasks of a typical database system such as data input, update, relations, query, analysis and report generation can also be performed.

Linear Referencing in GIS Environment

The basic function of linear referencing is enhanced with the proliferation of GIS in accurately representing geospatial data, GIS has the unique feature to reference events to features spatially (69, 70). These features are modeled with static events in two dimensions using (x, y) coordinates in GIS environment. But in most of the cases the information about features are dynamic in nature for example; pavement condition along the same route keeps varying. This issue can be addressed using the *dynamic segmentation* functionality.

Dynamic segmentation "is the process of transforming linearly referenced data (commonly called events) stored in a table into a feature that can be displayed on a map." (71) Route and event are two required data elements for this functionality and are defined with an example — pavement condition along a street. Here pavement condition is an event based on a route which in turn is based on a polyline (street).

Route – A route is an individual linear feature that can be uniquely identified upon which events can be linearly referenced. A polyline is geometry feature for any linear object like a street with x, y coordinate pairs. Route consists of additional measurement m stored along with each x, y coordinate pair. Figure 21 presents the comparison of polyline and route with events.

Event – An event is a measurement (m values) that can be located along a route (x, y coordinates) stored with a unique identifier.

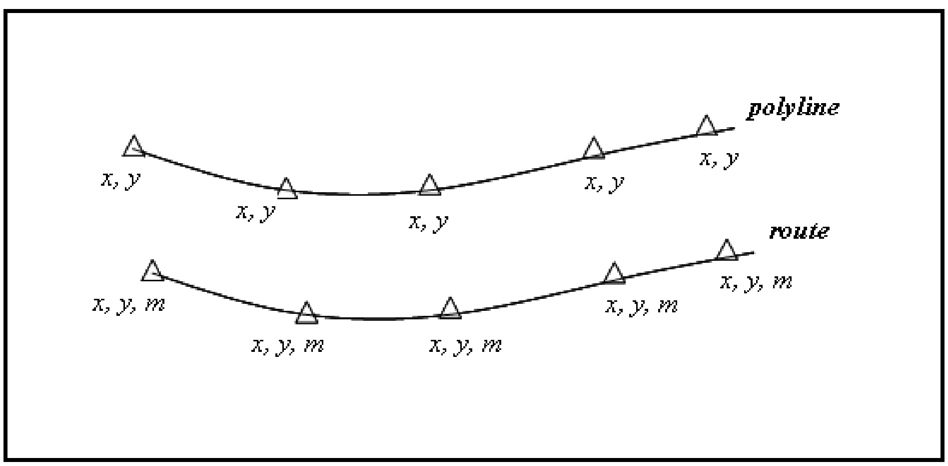


Figure 21 Difference between Polyline and Route Event.

Linear referencing in GIS environment enables the cartographic representation of analytical network database which has been the core basis of linear referencing discipline. But it is not implemented by practitioners even with the readily available hardware and software tools for measurement and execution. Curtin et al. presented a iterative process (Figure 22) as to show how to capture and analyze data using linear referencing in GIS environment (65). The present study uses this process in implementing linear referencing for integrated pavement marking management.

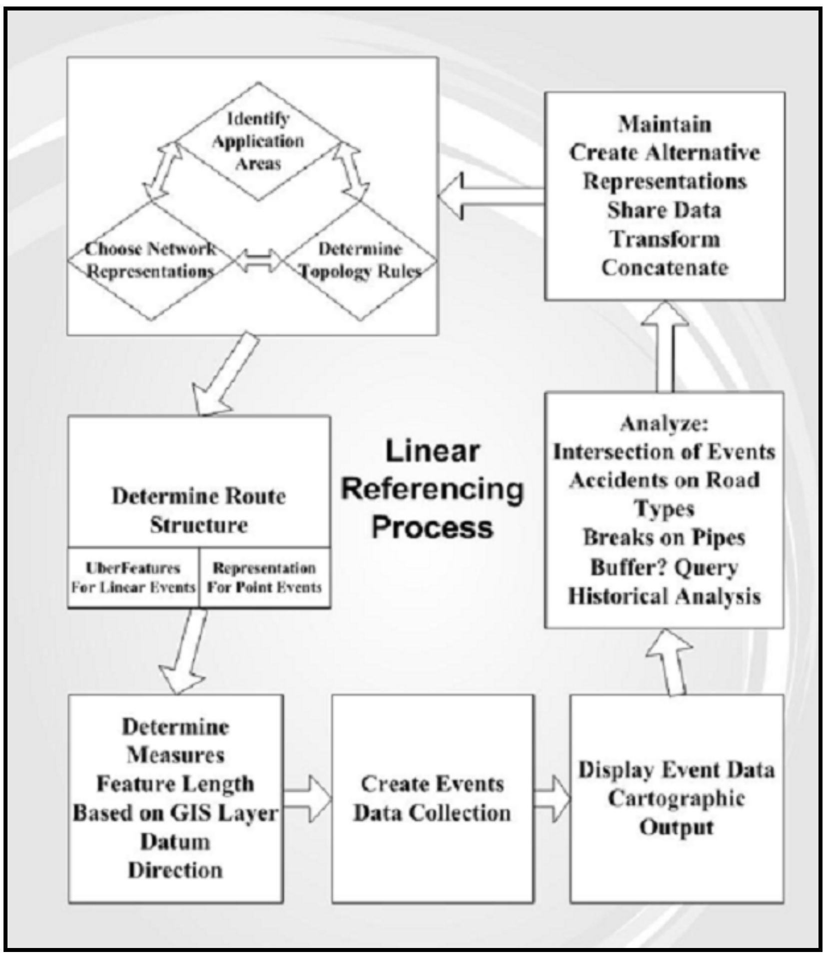


Figure 22 An Iterative Seven-Step Process to Implement Linear Referencing in GIS (65).

Step 6. 1 – Design of Database

As the management system was developed in GIS environment using ArcGIS, a geodatabase was designed to include feature classes and tables. Unique feature of geodatabase is the ability to combine spatial data with that of tabular data. Tables are fundamental objects used to store data and designed to accommodate information related to a category. The data going into the tables are arranged in columns technically called fields based on different attribute data types. Five tables were designed to store attribute data related to manufacturer, product, route, site and location. These tables have common fields so as to establish relationships.

A feature class can be defined "as a group of points, lines, or polygons representing geographic objects of the same kind, like countries or rivers." (72) Shape files with point, line, and polygon features were created to hold the information related to routes, route events and blocks.

Route data were obtained from nine counties from the Abilene district, Texas. Although feature classes (showing different routes) were built based on route information from all the nine counties, tables in the database were not populated because of the limited availability of data. Retroreflectivity data from a section of length 18 miles on both directions of FM 57 were used as a case study. Road network (Figure 23) for these counties was obtained from the maps of TxDOT's onsystem of transportation section available at Texas Natural Resources Information System (TNRIS).

Step 6. 2 – Determine Application, Network Representation, and Topology

Next step in the process was to identify an application, which in the present case was to reference pavement marking assets. This gives a clear picture of the network (datum) and reference method that are to be used for effective implementation. As mentioned earlier the main purpose of this study is to integrate phase 2 of management of pavement marking assets with that of pavement management systems. Pavements and pavements markings are linear and also similar in nature for cartographic representation. Hence, attributes for referencing both the features can be based on same linear referencing specification.

The second sub-step was to identify the network datasets and the representations of those networks. Nine counties from the Abilene district in the state of Texas were selected for this application as a case study — Borden, Callahan, Fisher, Haskell, Howard, Jones, Kent, Mitchell, Nolan, Scurry, Shackelford, Stonewall, and Taylor. These counties were chosen as retroreflectivity data of markings were available from selected road sections using MRUs (with GPS coordinates). Therefore the base network was the selected road sections from these nine counties (Figure 23).

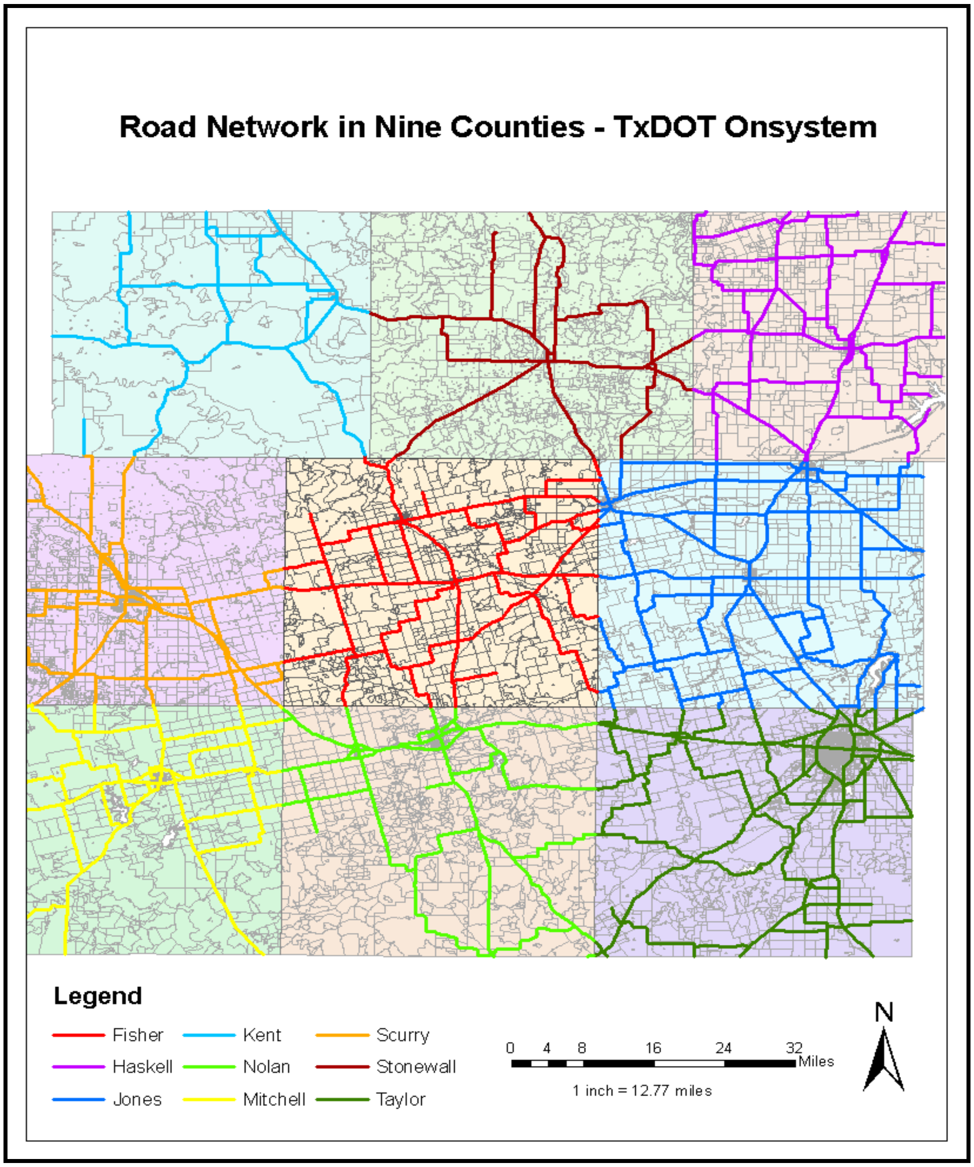


Figure 23 Road Network in Nine Counties – TxDOT Onsystem.

From the entire road network shown in Figure 23, road sections were selected based on the availability of retroreflectivity data. The road sections selected were the base network for application which also acts as datum for linear referencing (Figure 24). These identified road sections are converted into route features which represent the road centerline with attributes shape, route ID and shape length. In linear referencing context the term *route* is an individual feature that can be uniquely identified. Topology for the case study was a simple centerline representation for the reasons mentioned above which does not have any additional details.

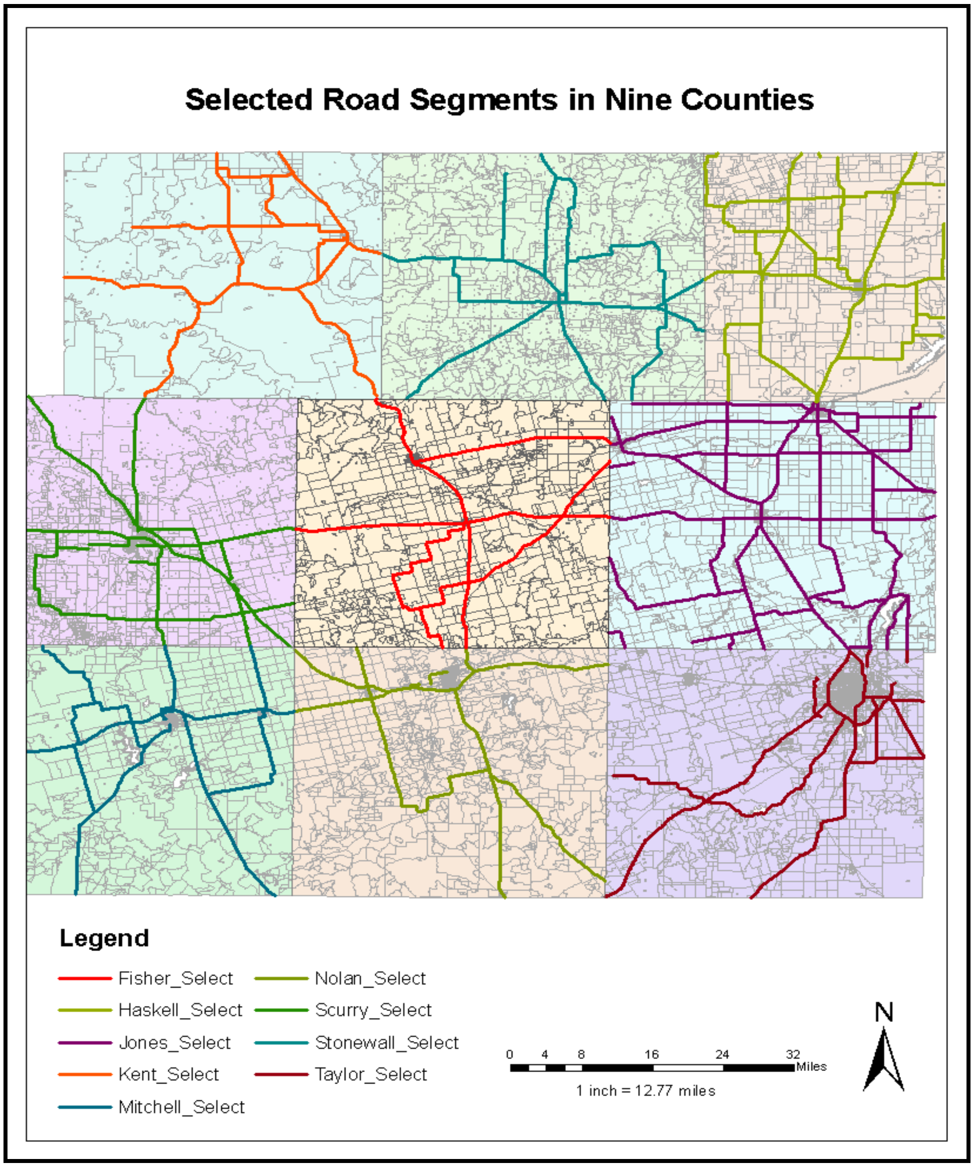


Figure 24 Selected Road Segments in Nine Counties.

It should be noted that the selection of a network dataset and route features may vary depending upon the application for which they are intended for. For example, for pavement management it might be enough to represent a single lane road with a center line, but for pavement marking condition the same road section should represent both centerline and edge lines separately. Therefore the same route should have different attribute features to represent centerline and edge line separately but, this might result in increasing the size of database. To avoid this situation, different route events were referenced along these routes for center and edge lines which will be discussed in the next step.

Step 6. 3 – Determining Route Structure

Now that the route network was determined, the next step was to establish a route structure on which the events can be referenced. The objective of this application is to manage pavement marking retroreflectivity and data were available from road sections from the counties listed in the previous step. Therefore the route structure was determined based on the format of the information available. Retroreflectivity data were collected on road sections based on intersections and county boundaries. For example, in Fisher County for FM 57 the measurement started from the intersection of SH 70 till the Jones County boundary in north direction. The selected road network shown in Figure 24 was segmented into smaller road sections within each county — meaning FM 57 running across Fisher County was identified as route with a unique route ID as FIFM0057 and in Jones County as JOFM0057. Figure 25 presents route structure for Fisher County with unique route IDs.

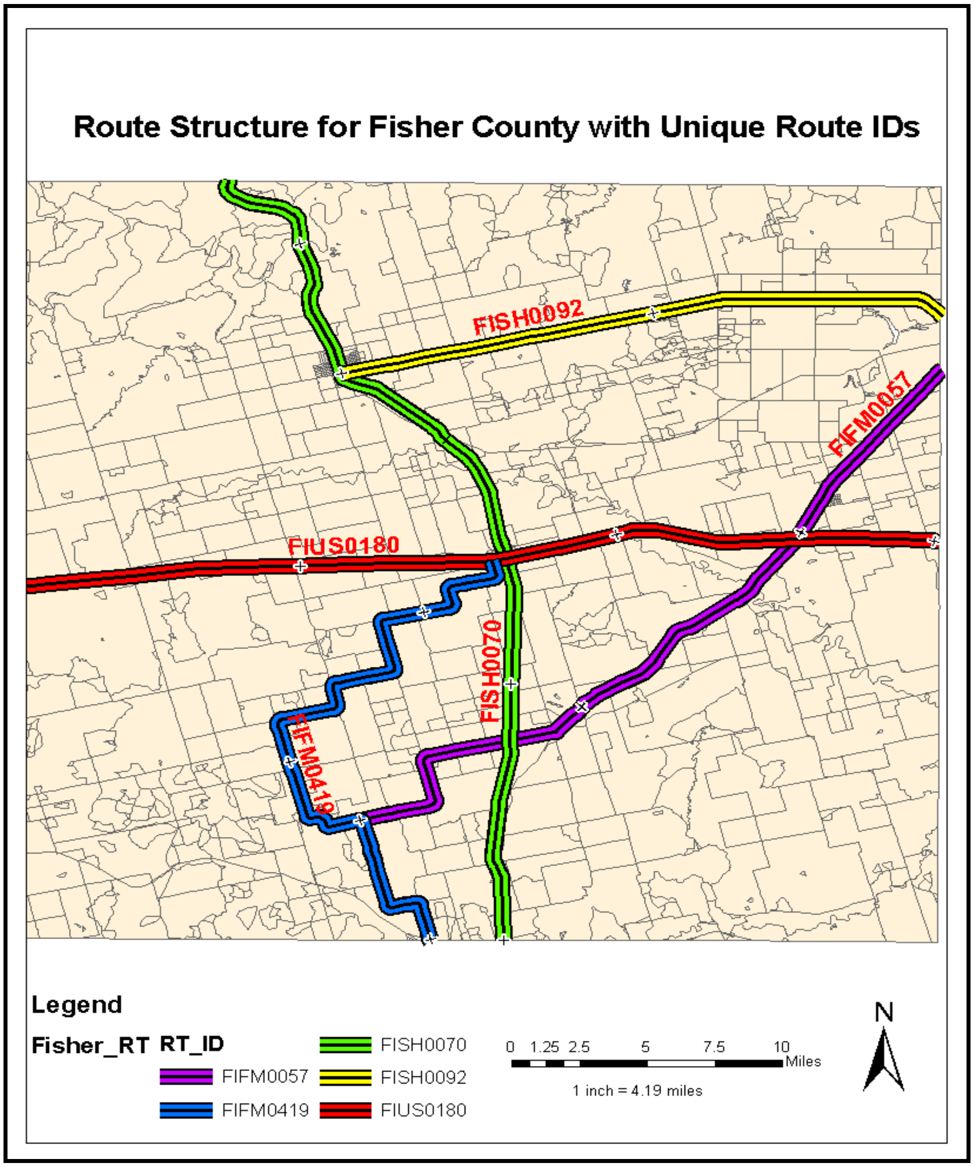


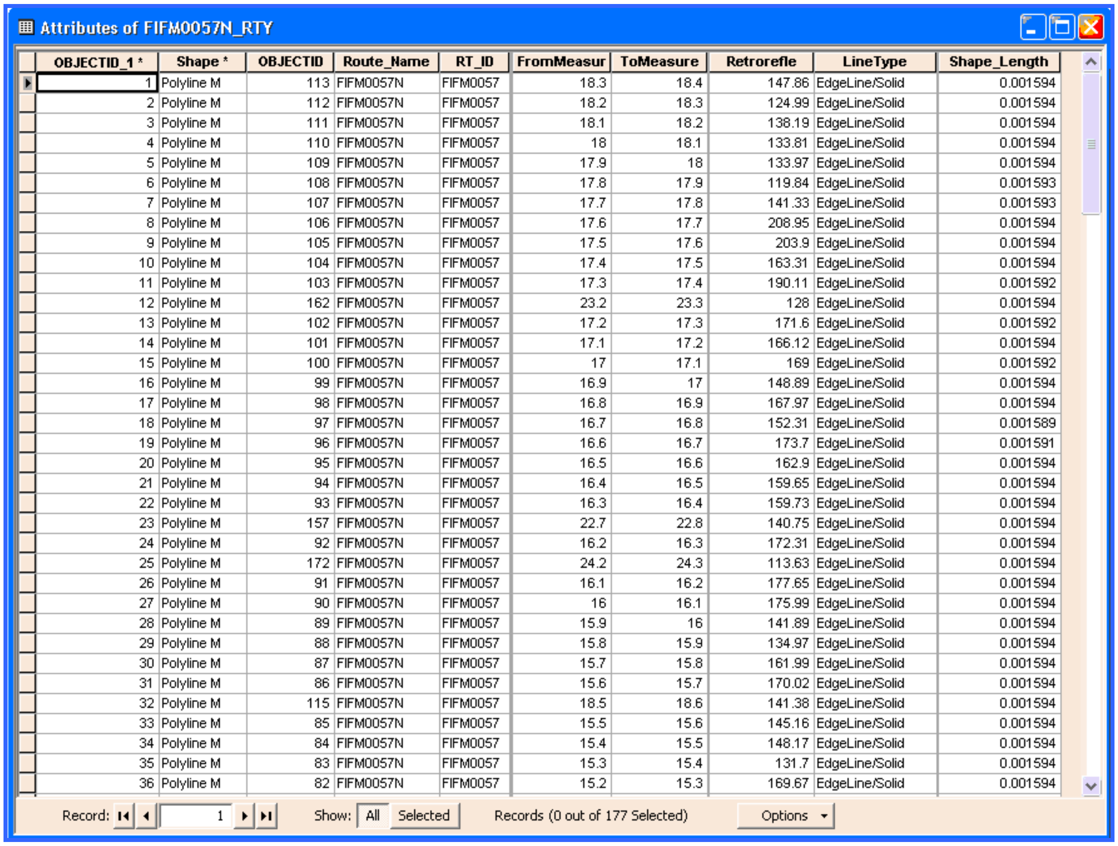
Figure 25 Route Structure for Fisher County with Unique Route IDs.

Step 6. 4 – Determining Measures

Unit and direction of measure is important for route structure as it makes practical sense to the application for which it is intended for. In this application retroreflectivity data were measured along a route with an interval of 0.1 mile in both directions of travel separately, hence the unit of measurement was taken as mile. Also, the route measures obtained from TxDOT onsystem maps were converted into miles. Routes were not differentiated based on direction of travel, meaning same route was not identified differently according to the direction of travel again to keep the size of database small. But to accommodate retroreflectivity data collected separately in different directions, different event features were referenced based on same route which were explained in the next step.

Step 6. 5 – Create Events

Events data in this application is representation of retroreflectivity data. Data from the field have chainage, retroreflectivity value in mcd/m^2/lux and latitude/ longitude. But the events were not referenced using latitude/ longitude (even though they were accurate) as the core principle of linear referencing would be ignored. Instead the events were referenced along the direction of measure from the starting point using the chainage information. Retroreflectivity data were collected using MRUs by dividing the entire route into small segments of 0.1 mile. Event data was represented as line feature, meaning each 0.1 mile segment has same average retroreflectivity. The event attribute table shown in Figure 26 has information regarding route name, route ID, from/ to measures, retroreflectivity, line type and length.



Attributes of FIFM0057N_RTY

OBJECTID_1 *	Shape *	OBJECTID	Route_Name	RT_ID	FromMeasur	ToMeasure	Retroreflе	LineType	Shape_Length
1	Polyline M	113	FIFM0057N	FIFM0057	18.3	18.4	147.86	EdgeLine/Solid	0.001594
2	Polyline M	112	FIFM0057N	FIFM0057	18.2	18.3	124.99	EdgeLine/Solid	0.001594
3	Polyline M	111	FIFM0057N	FIFM0057	18.1	18.2	138.19	EdgeLine/Solid	0.001594
4	Polyline M	110	FIFM0057N	FIFM0057	18	18.1	133.81	EdgeLine/Solid	0.001594
5	Polyline M	109	FIFM0057N	FIFM0057	17.9	18	133.97	EdgeLine/Solid	0.001594
6	Polyline M	108	FIFM0057N	FIFM0057	17.8	17.9	119.84	EdgeLine/Solid	0.001593
7	Polyline M	107	FIFM0057N	FIFM0057	17.7	17.8	141.33	EdgeLine/Solid	0.001593
8	Polyline M	106	FIFM0057N	FIFM0057	17.6	17.7	208.95	EdgeLine/Solid	0.001594
9	Polyline M	105	FIFM0057N	FIFM0057	17.5	17.6	203.9	EdgeLine/Solid	0.001594
10	Polyline M	104	FIFM0057N	FIFM0057	17.4	17.5	163.31	EdgeLine/Solid	0.001594
11	Polyline M	103	FIFM0057N	FIFM0057	17.3	17.4	190.11	EdgeLine/Solid	0.001592
12	Polyline M	162	FIFM0057N	FIFM0057	23.2	23.3	128	EdgeLine/Solid	0.001594
13	Polyline M	102	FIFM0057N	FIFM0057	17.2	17.3	171.6	EdgeLine/Solid	0.001592
14	Polyline M	101	FIFM0057N	FIFM0057	17.1	17.2	166.12	EdgeLine/Solid	0.001594
15	Polyline M	100	FIFM0057N	FIFM0057	17	17.1	169	EdgeLine/Solid	0.001592
16	Polyline M	99	FIFM0057N	FIFM0057	16.9	17	148.89	EdgeLine/Solid	0.001594
17	Polyline M	98	FIFM0057N	FIFM0057	16.8	16.9	167.97	EdgeLine/Solid	0.001594
18	Polyline M	97	FIFM0057N	FIFM0057	16.7	16.8	152.31	EdgeLine/Solid	0.001589
19	Polyline M	96	FIFM0057N	FIFM0057	16.6	16.7	173.7	EdgeLine/Solid	0.001591
20	Polyline M	95	FIFM0057N	FIFM0057	16.5	16.6	162.9	EdgeLine/Solid	0.001594
21	Polyline M	94	FIFM0057N	FIFM0057	16.4	16.5	159.65	EdgeLine/Solid	0.001594
22	Polyline M	93	FIFM0057N	FIFM0057	16.3	16.4	159.73	EdgeLine/Solid	0.001594
23	Polyline M	157	FIFM0057N	FIFM0057	22.7	22.8	140.75	EdgeLine/Solid	0.001594
24	Polyline M	92	FIFM0057N	FIFM0057	16.2	16.3	172.31	EdgeLine/Solid	0.001594
25	Polyline M	172	FIFM0057N	FIFM0057	24.2	24.3	113.63	EdgeLine/Solid	0.001594
26	Polyline M	91	FIFM0057N	FIFM0057	16.1	16.2	177.65	EdgeLine/Solid	0.001594
27	Polyline M	90	FIFM0057N	FIFM0057	16	16.1	175.99	EdgeLine/Solid	0.001594
28	Polyline M	89	FIFM0057N	FIFM0057	15.9	16	141.89	EdgeLine/Solid	0.001594
29	Polyline M	88	FIFM0057N	FIFM0057	15.8	15.9	134.97	EdgeLine/Solid	0.001594
30	Polyline M	87	FIFM0057N	FIFM0057	15.7	15.8	161.99	EdgeLine/Solid	0.001594
31	Polyline M	86	FIFM0057N	FIFM0057	15.6	15.7	170.02	EdgeLine/Solid	0.001594
32	Polyline M	115	FIFM0057N	FIFM0057	18.5	18.6	141.38	EdgeLine/Solid	0.001594
33	Polyline M	85	FIFM0057N	FIFM0057	15.5	15.6	145.16	EdgeLine/Solid	0.001594
34	Polyline M	84	FIFM0057N	FIFM0057	15.4	15.5	148.17	EdgeLine/Solid	0.001594
35	Polyline M	83	FIFM0057N	FIFM0057	15.3	15.4	131.7	EdgeLine/Solid	0.001594
36	Polyline M	82	FIFM0057N	FIFM0057	15.2	15.3	169.67	EdgeLine/Solid	0.001594

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Figure 26 Example of Route Attribute Table.

Also the problem of directionality was addressed in this step; each route was referenced uniquely with a route event depending on direction. For example, on FIFM0057 the same route was used to represent retroreflectivity measures in north bound direction starting from the intersection of SH 70/ FM 57 named FIFM0057N and the measures in south direction were represented with FIFM0057S. Figure 27 illustrates both these event features based on FIFM0057. This step clearly exemplifies the advantages of both linear referencing and dynamic segmentation by displaying the static nature of routes and dynamic behavior of event data.

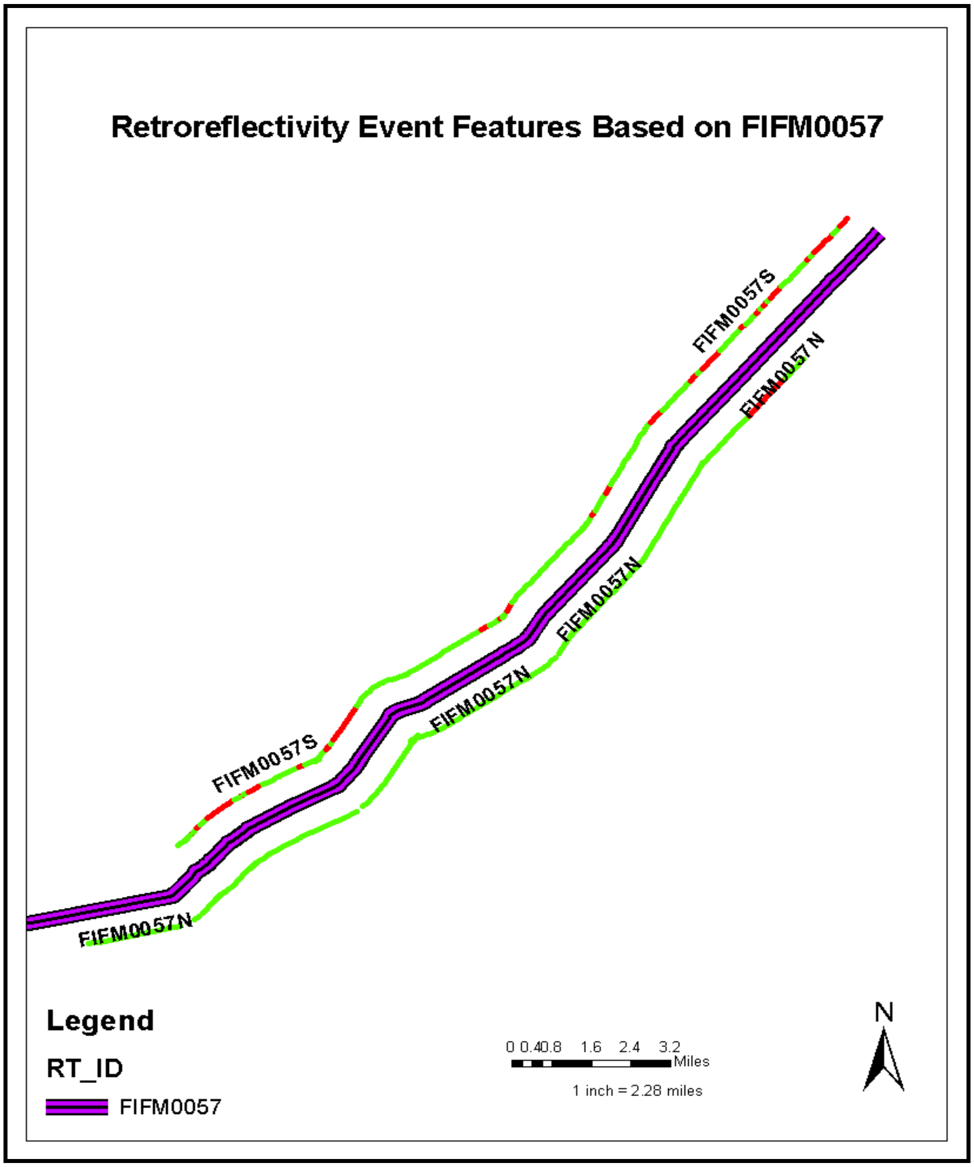

Figure 27 Retroreflectivity Event Features Based on FIFM0057.

Step 6. 6 – Display Event Data; Cartographic Output

Cartographic presentation is one of the powerful features of GIS application among many others functions. Also a good management system should provide right information at right time which helps to communicate among different divisions and to integrate information across different asset categories. In the case study of Fisher County, retroreflectivity data were referenced as event data along the selected routes. A threshold value of 100 $mcd/m^2/lux$ was assumed below which the markings are not serviceable. The segments with value below threshold value were represented in red color with the remaining in green as shown in Figure 28. Figure 29 and Figure 30 illustrates the level of details that can be presented using mile markers as reference, the level of details in map also varies with the level of zoom in ArcMAP avoiding cluttering of information. In addition to markings information, RRPMs were also marked along south bound of FIFM0057 illustrating the integration of information across various asset categories based on same route feature (Figure 28).

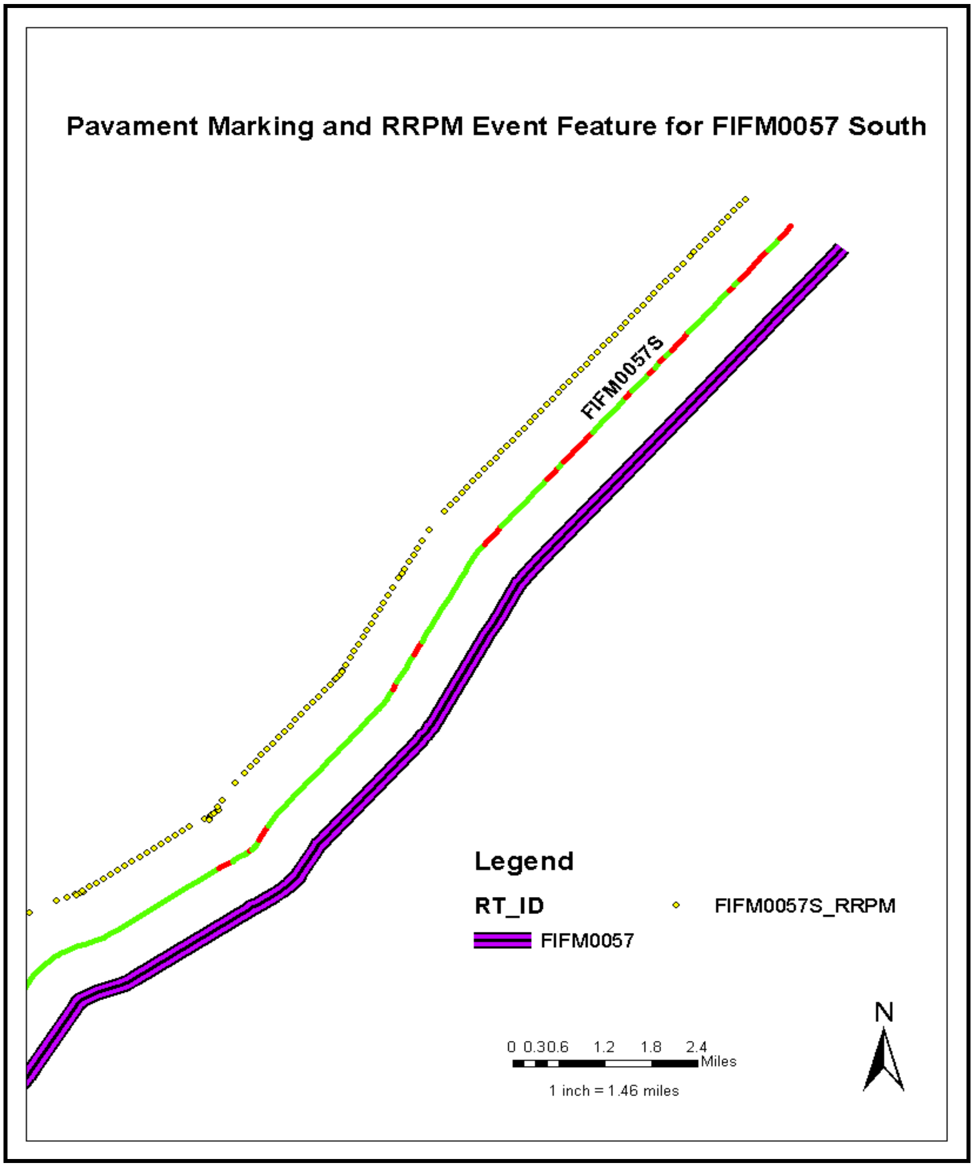

Figure 28 Pavement Marking and RRPM Event Feature for FM 57 South.

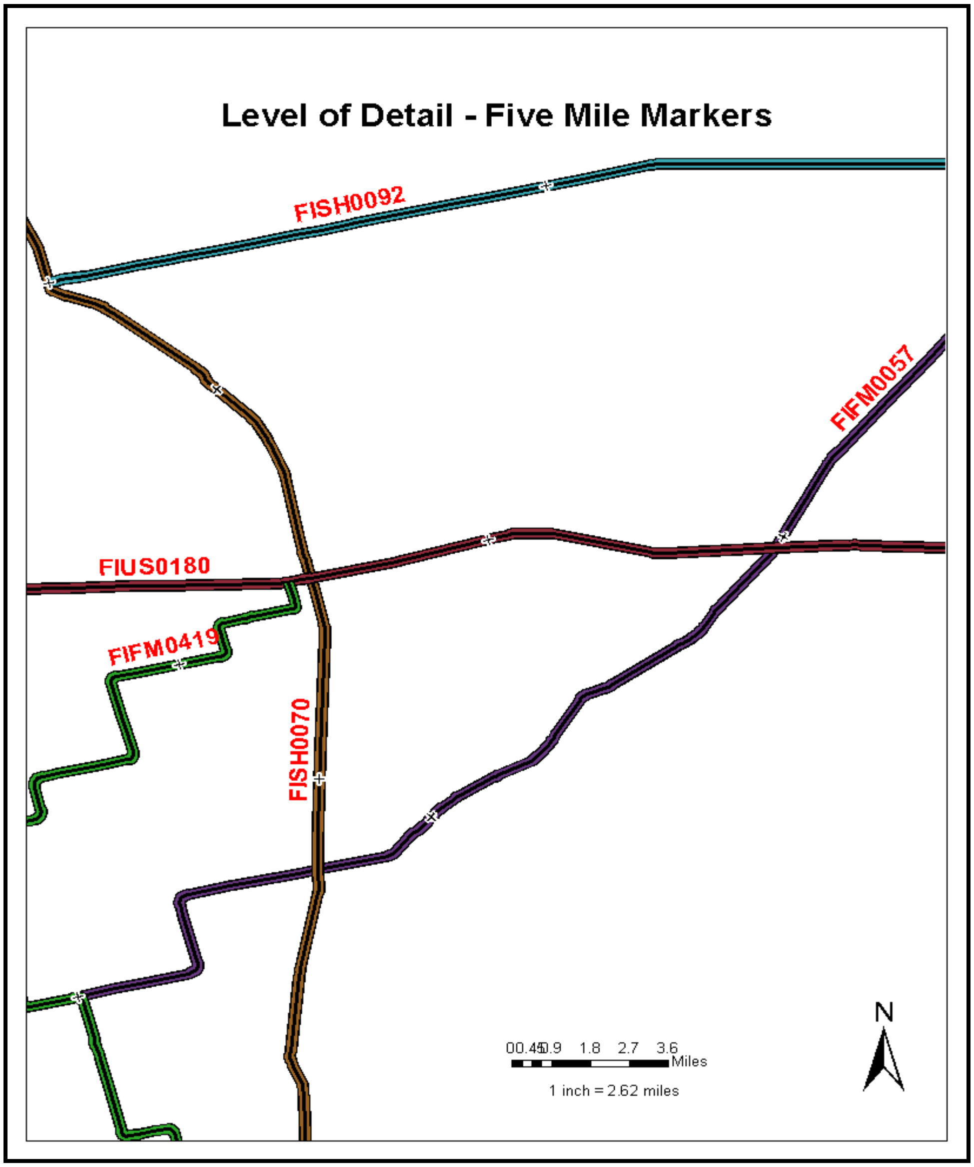

Figure 29 Level of Detail – Five Mile Markers.

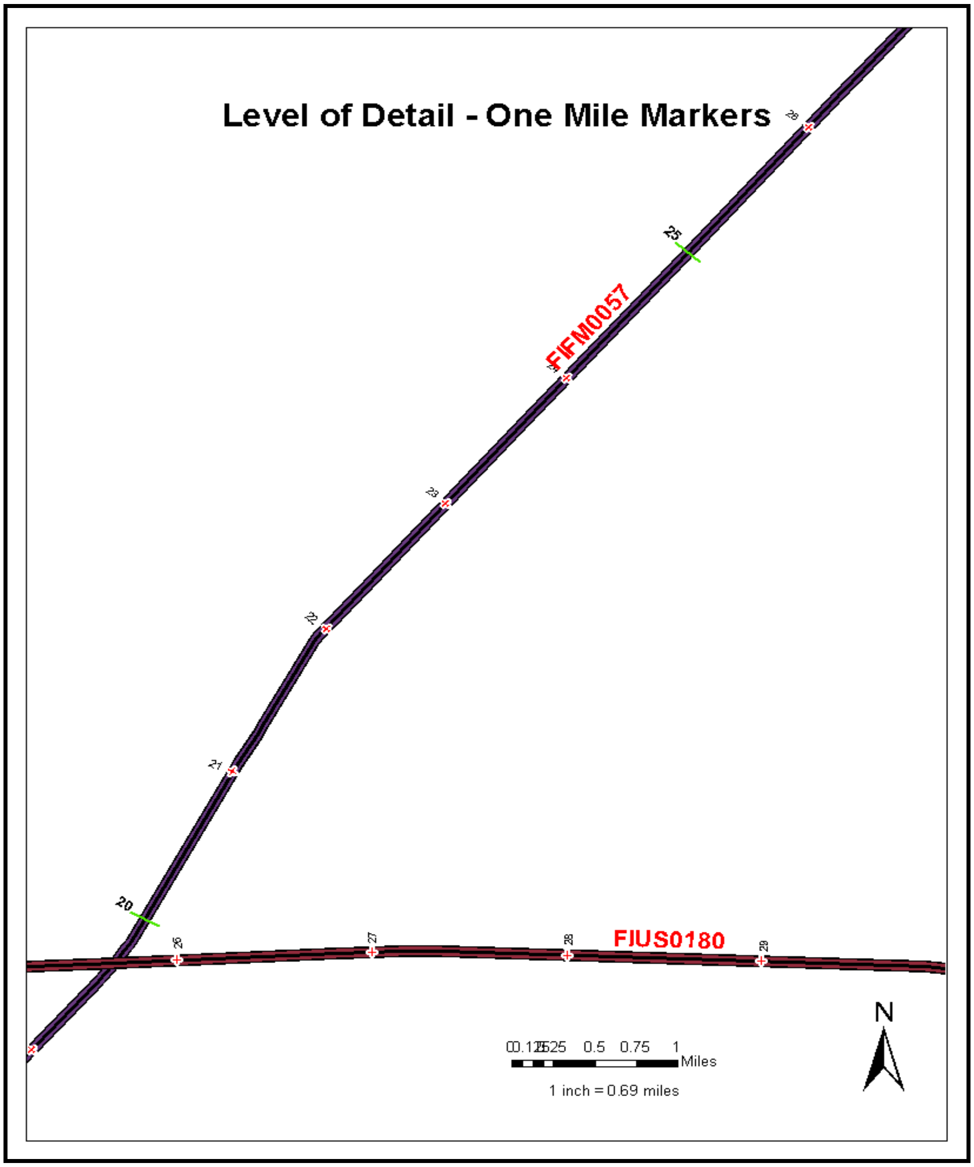

Figure 30 Level of Detail – One Mile Markers.

Step 6. 7 – Analysis with Linear Referencing

One of the main reasons to take up database application in GIS is the ability to perform diverse analyses both in tabular and geospatial formats. Different techniques such as extract, intersect, buffer can be used for spatial queries in addition to the standard functions of a database such as relations between tables (joins and relates), tabular queries, reports. Figure 31 presents a query — the intersection between retroreflectivity data of markings and markers where the retroreflectivity of markings was below 100 mcd/m^2/lux and that of markers above 300 mcd/m^2/lux, this result was also illustrated cartographically in Figure 32.

Selected Attributes of TBL_FIFM0057S_OverlayRouteEv

OBJECTID *	Route_Name *	RT_ID	Retroreflectivity	LineType	Retroreflectivity2
8	FIFM0057S	FIFM0057	88.08	EdgeLine/Solid	305.3
20	FIFM0057S	FIFM0057	82.07	EdgeLine/Solid	303.74
36	FIFM0057S	FIFM0057	98.88	EdgeLine/Solid	306.55
44	FIFM0057S	FIFM0057	98.18	EdgeLine/Solid	302.86
48	FIFM0057S	FIFM0057	98	EdgeLine/Solid	300.43
56	FIFM0057S	FIFM0057	98.03	EdgeLine/Solid	304.75
70	FIFM0057S	FIFM0057	97.54	EdgeLine/Solid	310.92
82	FIFM0057S	FIFM0057	98.02	EdgeLine/Solid	304.8
102	FIFM0057S	FIFM0057	86.54	EdgeLine/Solid	312.33
134	FIFM0057S	FIFM0057	91.88	EdgeLine/Solid	320.17
146	FIFM0057S	FIFM0057	0	EdgeLine/Solid	326.43
194	FIFM0057S	FIFM0057	75.36	EdgeLine/Solid	352.56
204	FIFM0057S	FIFM0057	97	EdgeLine/Solid	319.04
214	FIFM0057S	FIFM0057	87.2	EdgeLine/Solid	345.25
266	FIFM0057S	FIFM0057	99.85	EdgeLine/Solid	318.8
284	FIFM0057S	FIFM0057	96.26	EdgeLine/Solid	314.8
304	FIFM0057S	FIFM0057	97.09	EdgeLine/Solid	324.87
322	FIFM0057S	FIFM0057	86.87	EdgeLine/Solid	311.53
328	FIFM0057S	FIFM0057	97.3	EdgeLine/Solid	311.22
332	FIFM0057S	FIFM0057	90.73	EdgeLine/Solid	337.1
344	FIFM0057S	FIFM0057	87.78	EdgeLine/Solid	311.25
348	FIFM0057S	FIFM0057	85.41	EdgeLine/Solid	312.66

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Figure 31 Query Showing Overlay Analysis.

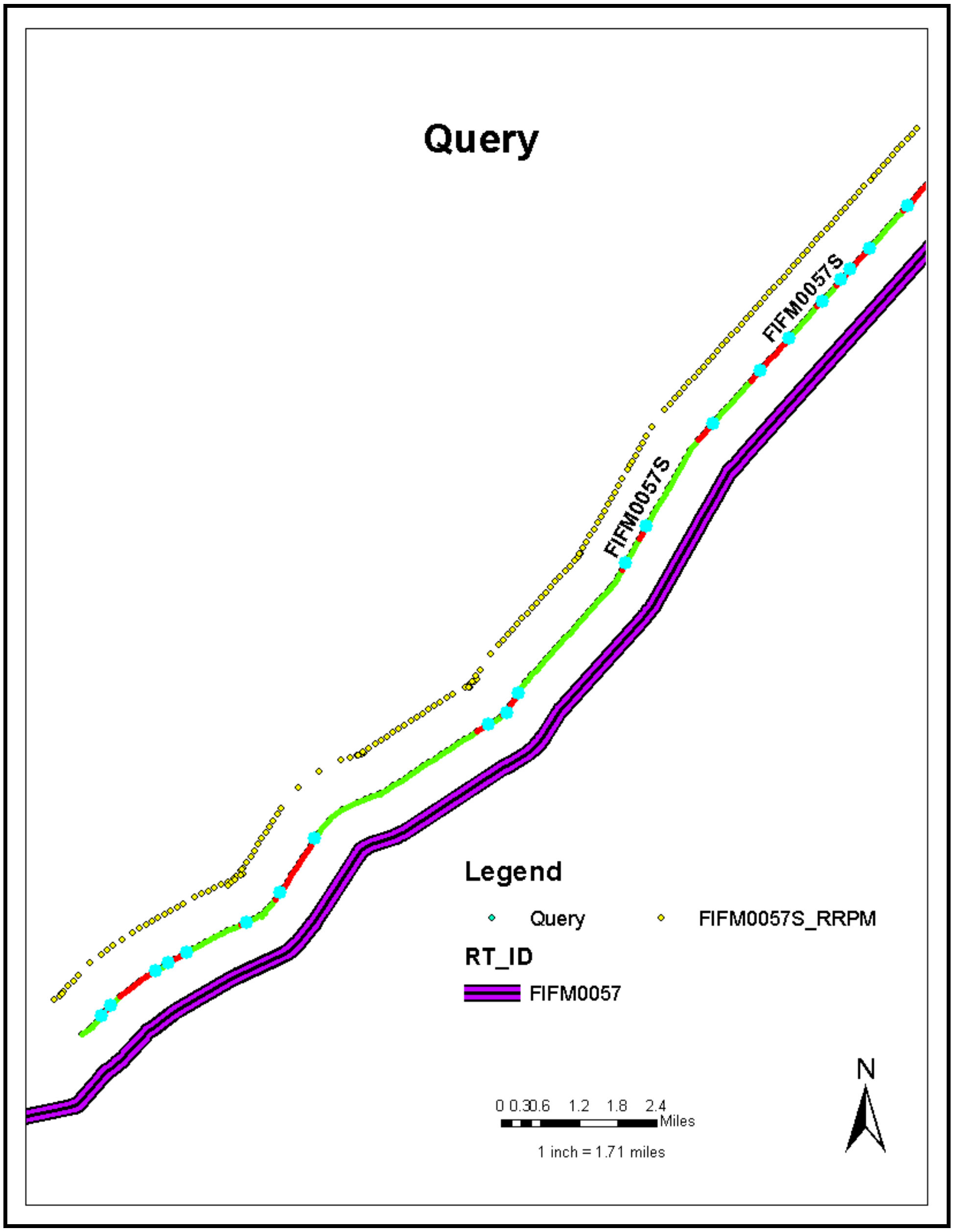

Figure 32 Query Illustrated Cartographically.

CONCLUDING REMARKS

Managing pavement marking assets effectively to maintain a good visibility is complicated as there are no definite guidelines and standards related to failure, sampling protocols, and maintenance methods. Section assessment method (SAM) was proposed as a standard protocol for sampling retroreflectivity on a road section. Section management method (SMM) was developed to practically implement restriping activity at the section-level and was demonstrated using a case study. Also as recommendations for minimum retroreflectivity measurements were based on several other factors, an information tool called integrated pavement marking maintenance (IPMM) based on GIS was developed to collect information based on different features and also to integrate information across different asset categories. A step-wise planning and development of the tool was presented based on a case study.

CHAPTER V
FINDINGS AND CONCLUSIONS

The primary objective of this thesis was to address the issues that were identified in the practical implementation of analytical and information tools of asset management practice in the field of pavement markings. This is put in order by explaining and addressing problems of limited variable data, censored data and uncertainty in field evaluations; developing and comparing statistical prediction models; proposing a section assessment method and a practical maintenance methodology; devising an information tool on a GIS platform. In conclusion, this framework helps in developing a comprehensive pavement marking management program to utilize resources efficiently, lower long-term costs and to maintain markings in serviceable condition. The findings, observations and conclusions from the process are discussed in this chapter.

GENERAL FINDINGS

Problem of Censored Data

In the retroreflectivity evaluations of pavement markings, missing inspections and censored values are often encountered because of unexpected situations, weather constraints or work plan. An imputation technique was developed to handle the missing points using with three-year retroreflectivity data from the Mississippi NTPEP test deck. First two-year data were used to develop this technique; the second year data series had four observed and eight missing values. These missing values were estimated resulting in a data series with all twenty-four points that are equally spaced across two years.

As a part of application, ARMA models were used to forecast the points from third year (27^{th}, 30^{th} and 36^{th} months). These forecasts estimates exhibited deviations ranged from -0.16% to -17.71% compared to actual measurements.

Problem of Uncertainty and Limited Variable Sample Data

PMMs display varied performance because of external factors such as climate, traffic conditions, roadway surface type and installation quality. Data from field evaluations may not include information related to all the external variables that affect the degradation of retroreflectivity. This limited variable data results in increasing the uncertainty in prediction models. The Bayesian linear regression method was used to reduce the uncertainty with the classical linear regression coefficients as prior information. The retroreflectivity predictions for the months 27, 30 and 36 improved with the Bayesian regression compared to the classical regression. The deviations ranged from -4.12% to -24.38% for retroreflectivity estimates and actual field measurements from the third year.

Comparison of Three Analysis Methods

The Bayesian regression, classical linear regression and ARMA model were compared based on predictions from the third year. The retroreflectivity data from four white colored products (thermoplastic, preformed thermoplastic, methyl methacrylate, and durable others) were used for analysis from Mississippi NTPEP test deck. It was found that that ARMA models have a better prediction across all the products but the application of Bayesian regression seems to be more practical as it is simpler and at the same time gives an opportunity to utilize prior knowledge. Lastly, end-of-service-lives were also estimated as a case study.

Practical Restriping Methodology

Assessment and management procedures were developed for restriping a road section to maintain pavement marking assets in good serviceable condition. Both the procedures were based on the driver’s preview distances which formed basis for minimum retroreflectivity requirement research. Also they were demonstrated with a case study from the Fisher County, Texas. Four divisions were identified with lengths

4.3 m, 1.3 m, 1 m, and 1.3 m with a total of 8 miles of road length along the 18 mile stretch for restriping cost-effectively.

Section Assessment Method

Section assessment method describes the procedure for retroreflectivity inspections of in-service pavement markings of a road section using a handheld retroreflectometer or mobile retroreflectometer unit. It was developed based on the principles of management and maintenance from pavement assets.

Section Management Method

Section management method was proposed to take up restriping activity along a section. The moment of inertia method was used to determine a minimum road length which is viable to perform restriping cost-effectively.

Information Tool

To implement the assessment and management methods in a systematic and consistent way, an information tool is required to store information on inventory, location, performance evaluation. An information tool was devised based on GIS environment which can support pavement marking management program. Retroreflectivity data from a section of length 18 miles on both directions of FM 57 were used as a case study. Integration of information across different asset categories was demonstrated. It was found that the tool can be used to perform diverse analyses both in tabular and geospatial formats beyond traditional database abilities

SCOPE FOR FURTHER RESEARCH

Based on the findings and conclusions, this study provides following recommendations so as to improve this effort of developing a framework into a comprehensive pavement marking management program:

- Due to limited data availability only retroreflectivity is considered as a sole performance measure on which all the techniques, methods and tools were developed. Other measures such as color and durability can be included to refine these research efforts.

- The assessment and management methodology developed at the section-level can be extended to the network-level to prioritize between projects in making maintenance decisions.
- The restriping methodology is developed as a space problem based on measure of compactness. There is no set limit mentioned in the study where the procedure terminates. Empirical analysis needs to be carried out depending on the length of the road section.
- In this study, the management methodology is a step-by-step procedure developed based on GIS, but not an automated process that can give a final output to carry out trade-off analysis between different alternatives. As the functions of GIS extend beyond database and cartographic representation, it can be used as a platform to develop an entire management system by additional programming.

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