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16. Abstract Historically the prequalification or selection of pavement marking materials (PMMs) is mainly based on product specifications and lab testing, which do not correlate well with the field performance of the products. On the other hand, there is no consensus on recommended procedure to design test deck and conduct field performance test. The objective of this project is to investigate field evaluation plans and procedures and develop field performance-based evaluation procedures for PMMs. Field decks are designed incorporating regular long lines, long line in the travel lane, and transverse lines for accelerated testing, while also considering different installation procedures. Three different test field deck sites are selected across the state considering area climate, roadway surface type, and traffic condition. Carefully selected PMM products are installed and monitored for their field performance over time. The relationships between transverse and longitudinal test decks are evaluated with correlation analysis. Analysis results indicate that the points on transverse lines have high correlation with the corresponding five or seven longitudinal long lines in the travel lane when retroreflectivity values of all products on a test deck are averaged. For individual products, the correlations between transverse line locations and corresponding long lines in the travel lane exist, albeit at a lower level. A tracking database is developed and can record and interactively query all relevant data, track individual jobs and products, and graphically display performance changes over time.			
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**DEVELOPMENT OF FIELD PERFORMANCE EVALUATION TOOLS
AND PROGRAM FOR PAVEMENT MARKING MATERIALS:
TECHNICAL REPORT**

by

Yunlong Zhang
Assistant Research Scientist
Texas Transportation Institute

Hancheng Ge
Graduate Assistant Research
Texas Transportation Institute

Adam Pike
Assistant Research Engineer
Texas Transportation Institute

and

Paul Carlson
Division Head, Operations and Design Division
Texas Transportation Institute

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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views and policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation. The objective of this project is to evaluate and recommend field test procedures for pavement marking materials for the Texas Department of Transportation. The project does not endorse or recommend individual pavement marking manufacturers or brands.

The United States Government and the State of Texas do not endorse products or manufactures. Trade or manufactures' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1 INTRODUCTION

Pavement markings play a critical role in maintaining a safe driving environment for road users, especially at night time. The primary function of these traffic control devices is to convey continuous information to the motorists about the roadway path. This includes information related to passing, direction, lateral lane position, and boundaries of a roadway segment. It was estimated that in 2000 over \$1.5 billion were spent on pavement markings for over 3.8 million center line miles of highways in the United States and Canada [1]. The Texas Department of Transportation (TxDOT) spends millions of dollars each year for installation and maintenance of pavement markings. In fact, many TxDOT districts let routine maintenance contracts for pavement markings for over \$1 million. Pavement markings retroreflectivity deteriorates over time as they are continuously exposed to traffic and environment. It is essential to maintain and preserve the functional quality of pavement markings to provide operational safety. In order to ensure that pavement markings remain effective the highway agencies maintain them regularly by replacing the old marking. Therefore, selecting proper pavement marking materials (PMMs) that can maintain an acceptable level of functional performance over a longer period of time can lead to significant cost savings while maintaining safety.

PROBLEM STATEMENT

Historically, the prequalification or eventual selection of PMMs for a job is based on material specifications from lab testing and from American Association of State Highway and Transportation Officials (AASHTO) specifications. However, those specifications do not correlate well with the field performance of a PMM. Also they do not address the aspects of effective field evaluation procedures. In recent years, TxDOT has increased the use of performance based specifications such as the requirements of a minimum, initial performance. However, the same product may display different field performance because of external factors such as climate, traffic condition, roadway surface type, and installation quality. In addition, new PMM types and products have become available at a faster pace and their field performance is mainly unknown. It is also reported by TxDOT districts that performance problems are common in the field, especially at locations such as intersections, ramps, and auxiliary lanes where vehicle turning and stopping frequently occur. It is critical, therefore, to develop procedures to evaluate

the field performance of PMM products and provide guidance and data to TxDOT districts so that high quality PMM products will be used and good, long-term performance ensured.

TxDOT should use all practical and cost effective means to ensure it is getting the best performance. Performance demands continue to increase for PMM, this is partly due to a significant increase in overall traffic and specifically truck traffic in many parts of the state. It is also partly due to other factors such as:

- Changes in pavement design; i.e., the increased use of surface treatments.
- Increased work load for TxDOT employees; i.e., reduction in inspection.
- Variety of factors in the industry; i.e., increased competition and increase in costs.

It is becoming more critical that these materials be field tested in addition to the prequalification, quality assurance, and quality monitoring testing done on samples in the lab. It is also becoming more difficult to do field testing because of the impact on traffic when applying test materials, the high cost of traffic control, and limits on personnel and budgets. It could also help improve the field performance of PMM if the performance of specific marking types used for specific applications is systematically measured and tracked over the performance period when the information is available. Currently, field test procedures vary and there is a consensus on recommended procedures.

This includes specifying initial minimum performance values for some jobs and specifying performance values over a designated period for other jobs. There is a need to evaluate the current performance specifications used by TxDOT and other users and to develop improved performance specifications reflecting the performance capabilities of materials currently available.

RESEARCH OBJECTIVES

The overall objective of this project is to develop a field performance evaluation program and to identify effective field evaluation methods and tools to improve the performance of PMMs. The tasks and deliverables include:

1. Assess state-of-the-art for specifying and evaluating PMMs.
2. Develop field evaluation plan and select field deck locations.
3. Install field decks.
4. Design tracking PMM database.

5. Evaluate PMM field performance.
6. Code and populate prototype database, analyze field data, and research prediction model.
7. Evaluate and improve specifications and recommend performance evaluation procedures.
8. Test and finalize database components.
9. Prepare research reports.

The research reviews the current evaluation techniques in the field of pavement markings. Advantages and disadvantages of different evaluation procedures are studied to conceive an effective program for evaluating and testing PMMs taking into account of different external conditions, specifications, material selection criteria, and performance measures.

RESEARCH BENEFITS

The project will facilitate TxDOT to maximize the benefit from the money spent on PMMs and to meet the increasing performance demands of PMM. Field tests conducted will provide guidelines for field test site selection and optimum test site design and to monitor the field performance with recommended evaluation procedure. The tested PMM products on different decks will provide TxDOT with valuable data regarding their respective performance in different external conditions and their relative performance in a similar environment. Performance of PMMs can be predicted with the forecasting procedures developed. The tracking program allows monitoring the field performance of markings and to store data. Improved specifications, guidelines, and procedures are developed by implementing the research products into practice.

REPORT ORGANIZATION

The report is divided into five chapters beginning with introduction chapter followed by a comprehensive review of the state-of-the-art and state-of-the-practice in [Chapter 2](#). This literature review includes basic knowledge of pavement markings, the previous studies related to field test methods and results of PMMs performance, the service life estimates and life-cycle costs, and current testing practices at different agencies. [Chapter 3](#) presents details about the test deck design and the different configurations implemented. The benefits and rationale behind the design and location are explained with information of different test deck locations. [Chapter 4](#) provides details about the developed of a Pavement Marking Management System (PMMS), a

database to track PMM performance on test decks and real-world projects. [Chapter 5](#) summarizes the final recommendations and conclusions of the report.

CHAPTER 2 STATE-OF-THE-ART AND STATE-OF-THE-PRACTICE

In an effort to review the state-of-art and state-of-practice in PMM performance the team studied the recent and ongoing research activities related to PMM performance evaluation, testing, and specifications. Current issues within TxDOT districts on PMM performance was carried out by the team by contacting TxDOT traffic engineering division and materials division to gather state-level information on PMM performance and testing. The comprehensive summary of the review is provided below.

INTRODUCTION

Pavement markings play a very important role as delineators for older drivers particularly in the nighttime. According to the Manual on Uniform Traffic Control Devices (MUTCD) [2] “pavement markings on highways have important functions in providing guidance and information for the road user” such as:

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

For markings to be visible at night they should be retroreflective unless ambient illumination ensures adequate visibility [1]. Transportation agencies spend huge amounts on pavement marking each year. In 2000, the estimated total money spent on pavement markings by the 50 state transportation agencies, 13 Canadian provinces and territories, U.S. counties, and U.S. cities was \$1,548,616,821 on 3,818,688 center line-miles of highways [1]. The agencies are finding it difficult to maintain the good retroreflectivity over a longer period of time. Some of the other factors that directly or indirectly influence the total cost of pavement markings are the new and diverse materials with new technologies, increased number of older drivers, shortage of skilled labor, and increase in traffic. With the wide variety of new products and with no widely accepted standard test for the performance of the pavement markings the evaluation of these products is getting more complicated.

Different Types of PMMs and Their Characteristics

Pavement markings include longitudinal lines, transverse lines, words, and symbols. Different types of pavement are in use with waterborne paint being the most common type followed by thermoplastic, tapes, and epoxies [1]. Traffic paints are the most commonly used marking type in the U.S. Common problems associated with these are bonding and discoloration. Traffic paints also have the shortest life and have poor night time visibility [3]. Solvent based paints are cheaper than other type of materials. Most of the agencies found that the waterborne are cost-effective as compared to other material types. Thermoplastics generally have more retroreflectivity than that of the traffic paints especially under night and wet conditions. They have an average service more than that of the paints [4]. They have faster drying times and good durability. The preformed thermoplastics usually have high initial retroreflectivity as they are manufactured at factories with better quality standards. Thermoplastics often performed poorly on Portland Cement Concrete (PCC) surface as compared to asphalt surface with the problems of adhesion and chipping. A study was carried out to access the best method of application of thermoplastics and their bonding strengths on PCC surface [5]. ASTM: D 4541-95 (Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers) was used to evaluate the pull-off strength of the coating. Failure in adhesion is attributed to the weak tensile forces between the marking and the pavement surface. Four surface treatment methods, sandblasting, wire-brushing, grinding or scarifying, and water blasting, are used on four different strips installed for the test purpose. Failure of adhesion between epoxy glue and thermoplastic coating and separation of thermoplastics from pavement surface are the two kinds of failures that were identified on PCC surface. Grinding or scarifying treatment was found out to be the best technique both for the asphalt and PCC surfaces. Some durable and experimental markings like preformed tapes, epoxies, polyester, and methyl methacrylate (MMA) also have some problems and advantages. Major problem associated with the preformed tapes is that the retroreflectivity deteriorated drastically even though they have good initial retroreflectivity values. The major advantages are easy installation and good adhesion [4]. Tapes also have higher initial retroreflectivity as they are manufactured at factories with better quality standards. Epoxies are generally applied to PCC pavement type; they have better visibility and are durable. They have longer drying time but often times they are difficult to apply [6]. Polyester performs better than paints but have longer drying times; they have an average service life of two to three years [7].

MMA's are more suitable to the cold climatic conditions as it can be applied at lower temperatures, which in the case of the other marking types reduce the service life. It was also found to have longer service life and good reflectance in the colder regions as compared to the other products, which also makes it cost-effective [4].

Material Selection Criteria

The materials for the pavement markings are selected based on the factors like retroreflectivity, durability, life-cycle cost, type of line, pavement surface, climatic conditions, traffic volume, and type of street and highway. Recently the level of volatile organic compound (VOC) is also taken in to account to meet the environmental regulations.

PERFORMANCE-BASED SPECIFICATION

Rumar and Marsh conducted a study to evaluate the driver's behavior and their reliance on pavement markings in night driving [8]. Some of the important conclusions were:

- Drivers mostly rely on the pavement marking for guidance and information in nighttime and adverse weather conditions.
- Driver characteristics are very important in determining the performance of the markings.

In recent years transportation agencies are relying more upon the performance of the markings for maintenance activities. But different agencies require different specifications for color, durability, and retroreflectivity. Performance-based specification is a method where the agency accepts the material only when it undergoes test-deck evaluation for a period of one or more years and maintains a minimum level of retroreflectivity, durability, and color. ASTM specifies that a new marking is required to a minimum retroreflected luminance (RL) of 250 mcd/m²/lux for white markings and 175 mcd/m²/lux for yellow markings [1]. Some agencies have their own minimum values for performance-based specification.

Performance Evaluation Factors

Retroreflectivity, durability, contrast, and color are the main performance factors that are considered for the performance evaluation of PMMs. In addition to these some European national standards also require luminance coefficient under diffuse illumination and skid resistance as additional performance measures [9].

Retroreflectivity

The most important performance measure of all PMMs is the retroreflectivity, or nighttime visibility. Retroreflectivity is a phenomenon in which “light rays strike a surface and are redirected directly back to the source of light.” The source of light being headlamps, the reflected light should be entirely directed to the headlamps, but due to fact that the markings are not perfect (ideal) reflector bodies light is scattered allowing the driver to identify the markings. Retroreflectivity is quantified by the coefficient of RL, measured in the units of millicandelas per square meter per lux ($\text{mcd}/\text{m}^2/\text{lux}$). Retroreflected luminance is defined as the ratio of the luminance of a projected surface to the normal illuminance at the surface on a plane normal to the incident light according to the American Society for Testing and Materials (ASTM) (ASTM E1710-97) [10].

Measurement

ASTM established standard measurements for pavement marking retroreflectivity by adopting the 30-meter geometry that is also used by the European Committee on Standardization (CEN), which is referenced in ASTM standard specifications (ASTM E1710-97, ASTM D6359-98) [4]. This is designed to measure the retroreflectivity at a point 30 meters ahead of a vehicle in a way to replicate the driver’s observation of the roadway at night. Figure 1 shows the basic geometry with an entrance angle of 88.76° measured from the reference axis perpendicular to the pavement surface. The reflected light is measured at an observation angle of 1.05° . It should be noted that 15 meter is no longer accepted under ASTM standards for retroreflectivity measurement.

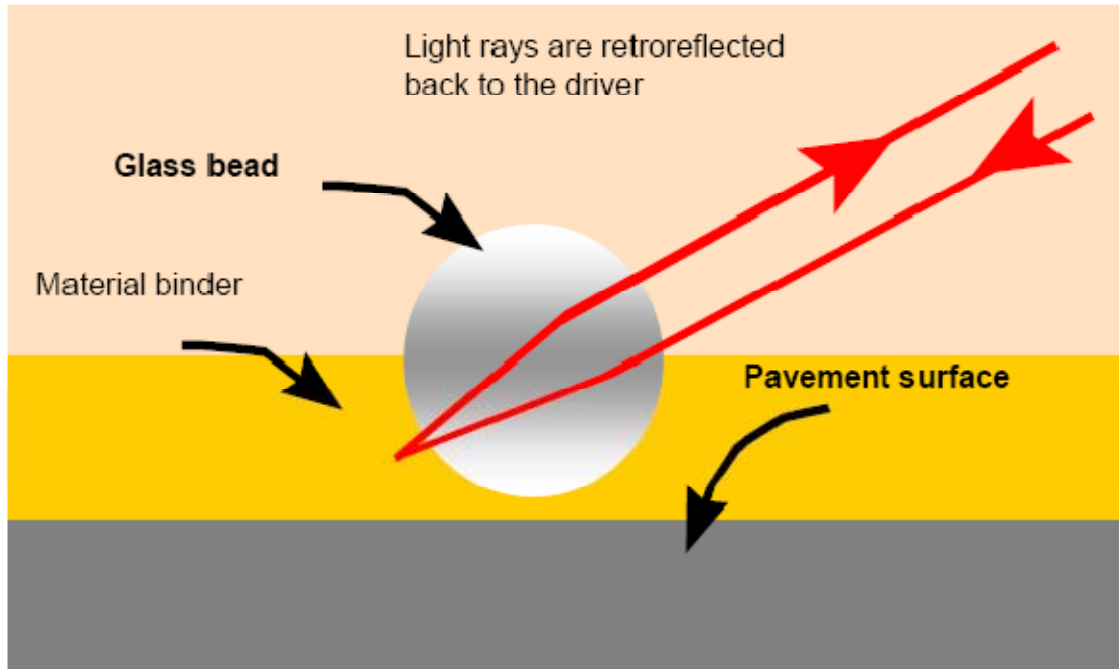


Figure 1. Principles of Pavement-Marking Retroreflectivity [11].

The U.S. Congress, in 1992, required that the MUTCD set minimum requirements for the retroreflectivity of highway pavement markings. The threshold values for retroreflectivity are not yet standardized by MUTCD; several studies and field researches are being carried out by FHWA to have consensus to standardize these values. Table 1 shows an update in this direction has the recommended and the values.

Table 1. Minimum Retroreflectivity Guidelines for Pavement-Marking Materials Recommended by FHWA ($\text{mcd}/\text{m}^2/\text{lux}$) [12].

Roadway Marking Configuration	Without RRPMs			With RRPMs
	≤ 50 mi/h	55–65 mi/h	≥ 70 mi/h	
Fully marked roadways (with center line, lane lines, and/or edge line, as needed)*	40	60	90	40
Roadways with center lines only	90	250	575	50

Aktan and Schnell conducted a study for evaluating the performance of the same type of markings in three conditions (dry, wet, and rainy) [13]. Regression models were developed with detection distance and retroreflectivity. The study recommends higher retroreflectivity during wet and rainy conditions. With these different requirements under different conditions, threshold values for minimum retroreflectivity, and various guidelines, it becomes complicated for the transportation agencies to meet the safety requirements. Moreover, the agencies have to increase

their budgets to maintain the threshold values by frequently maintaining and not get into legal complications. In this regard there is a necessity to come up with standard field evaluation procedures and programs, which acts as a common platform for the maintenance of pavement markings.

Durability

The durability of a PMM describes its presence and physical condition. Durability is typically represented by the percentage of the marking material that is still remaining. It is commonly rated subjectively. The durability of a marking is also considered as the expected life of a particular marking given factors such as traffic volume, roadway geometry, pavement type, and climatic conditions. Durability and retroreflectivity directly affect the service life of a pavement marking. The factors that affect the durability are [14]:

- Type of material (i.e., thermoplastic, plural component, tape).
- Method of application.
- Configuration (i.e., marking thickness, bead rate, surface application, or recessed).
- Type of pavement (i.e., asphalt cement concrete, Portland cement concrete, old surface, new surface, open coarse surface, previously marked).
- Conditions during application.
- Location (i.e., stop bar, horizontal curve, edge line, lane line).
- Annual average daily traffic (AADT).
- Percentage of heavy vehicle traffic.
- Pavement maintenance cycle (i.e., crack sealing, overlays).
- Regional climate (i.e., rain, snow, humidity).

Contrast

Contrast is the property that enables the driver to distinguish the markings from the pavement surface. Contrast is of two types, color and luminance. For the markings color contrast is the degree of difference between marking and pavement surface. Luminance contrast is the ratio of luminance between the marking and pavement surface [1]. The main factor that effects the contrast is the retroreflectivity of markings; other factors such as headlights, windshields, street lighting systems, and ambient light conditions also affect contrast [4]. It is usually

measured in contrast ratio (CR), which is given by the Equation 1. Evaluation of contrast is very critical for PCC surface as drivers often find it difficult to distinguish between an old marking and pavement surface. Color and luminance contrast are important factors that determine the performance of the markings as delineators. A higher contrast ratio enables driver to clearly distinguish the markings from the pavement background. The contrast depends on the retroreflectivity of the markings, which is represented by the coefficient of RL, measured in units of millicandelas per square meter per lux ($\text{mcd}/\text{m}^2/\text{lux}$).

$$CR = \frac{R_L(\text{marking}) - R_L(\text{pavement})}{R_L(\text{pavement})} \quad (1)$$

According to the CEN or the European standard luminance coefficient under diffuse illumination (Q_d) and skid resistance are also evaluated used performance specification [8].

Color

Color coding is used to provide directional and lane information to the users; also service life of markings varies by color. The color of a PMM is defined by the Yxy coordinates of the International Commission on Illumination, or CIE. The Y coordinate refers to how light or dark the object is while x and y plot the color on the chart. The color units and can be measured by devices such as BYK-Gardner Spectrophotometer Color-Guide.

Luminance Coefficient under Diffuse Illumination (Q_d)

It represents the brightness of a pavement marking as seen by a driver in typical daylight or street lighting conditions [8]. Q_d is the quotient of the luminance of the pavement marking and the illuminance on the pavement marking expressed in $\text{mcd}/\text{m}^2/\text{lux}$. It is measured by taking the luminance factor of the marking (β) when illuminated at an angle of $45^\circ (\pm 5^\circ)$ and measured at an angle of $0^\circ (\pm 10^\circ)$.

Skid Resistance

Skid resistance of pavement markings is measured on wet pavement markings by the friction of a rubber slider with the surface. British Skid Resistance Tester (SRT) is the equipment used and is expressed in SRTs [8]. The performance of PMMs varies widely, which manifests

the significance of quality control. To ensure satisfactory performance, PMMs are routinely required to meet certain specifications in the lab, and field evaluations have been conducted at the national, regional, and local levels. Most of the agencies are reported to be using specifications that are based on ASTM test methods.

ASTM test methods for testing pavement markings are:

- Standard Practice for Conducting Road Service Tests on Fluid Traffic (ASTM D 713 - 90) (ASTM 1990).
- Standard Test Method for Measuring Retroreflectivity of Pavement Markings in a Standard Condition of Continuous Wetting (ASTM E 2176) (ASTM 2002).
- Standard Test Method for Measuring Retroreflectivity of Pavement Markings in a Standard Condition of Wetness (ASTM E 2177) (ASTM 2002).
- Standard Specification for Minimum Retroreflectance of Newly Applied Pavement Markings Using Hand-Operated Instruments (ASTM D 6359) (ASTM 1998).

Some agencies use locally customized evaluations depending on the local traffic, environment, and pavement conditions. TxDOT uses its own in-house testing procedures supplemented by research [14]. In addition to this there are no guidelines for minimum retroreflectivity (threshold values) for nighttime visibility as many factors color, speed, driver age; visual acuity can affect the minimum acceptable levels. With no standard minimum retroreflectivity levels, transportation agencies resort to untimely stripping and laying new pavement markings. As all the marking materials have different service lives, it is not rational to use a common replacement time. The untimely replacement leads to the replacement of marking even before its service life is reached, which is uneconomical, or in another case replacing the marking way after it has reached its service life causing a safety hazard. This inefficiency adds an unnecessary financial burden on the maintenance of pavement markings to provide better safety for users. The current maintenance procedures include scheduled stripping of markings based on the AADT values and field inspection, which includes the objective and subjective rating by the maintenance personnel.

LIFE-CYCLE COSTS AND SERVICE LIFE

The life-cycle costs include the initial material cost and service life cost of the markings. Service life of the markings is reached when the reflectivity is inadequate to serve the purpose of delineation to the road users. The decision on the loss of retroreflectivity, loss of the base material, and loss of contrast would determine whether the marker need to be refurbished or replaced, which is influenced by the material composition, weather conditions, installation techniques, traffic volume, pavement type, and surface conditions. In colder regions other factors such as studded tires, snow plows, and abrasive materials largely affect the service life of markings [3]. Snowplowing operations have greater impact on service life than the traffic volumes in colder regions [6]. Less service life of the markings increases the maintenance cost even if the initial costs are less. Perrin et al. investigated the relationship between the material age, average daily traffic (ADT), pavement type, and retroreflectivity. They came up with a cost analysis that gives the cost per month based on the useful life of the marking [15, 16]. Cost per month is obtained by dividing the initial installation cost by useful life in months as in [Equation 2](#)**Error! Reference source not found.**. Useful life was the period in which the retroreflectivity of the marking deteriorates from the initial minimum value to the threshold value.

$$C = \frac{C_i}{U} \quad (2)$$

where,

C = cost per month (\$).

C_i = installed cost per linear meter (\$/meter).

U = useful life (months).

Service life of a longitudinal pavement marking is the time or number of traffic passages required for its retroreflectivity to decrease from its initial value to a minimum threshold value. Threshold values also vary depending on the conditions like the presence of RRPMs and roadway lighting and color. Service life is calculated in cumulative traffic passages (CTP) and then converted into months that is the time elapsed [1]. Here the marking material, type and color of line, and the type of roadway were considered as the key factors in calculating the service life of longitudinal pavement markings. Yellow lines have more service life than that of white as the threshold values for white markings is 50 percent more than that of yellow markings. Winter

temperatures have no significant effect on the service life in hot climatic regions in contrast to the cold climatic regions that have a significant effect because of the snow removal equipment, studded tires, and abrasive materials. The factors that are assumed to have significant effect on the retroreflectivity of the markings are passage of time, action of traffic, exposure to ambient weather conditions, snowplow operations, marking material specifications, pavement surface preparation, and quality control at the time when markings are placed [1]. Equation 3 gives the service life in months. Migletz et al. in their study estimated the service life of durable pavement markings by fitting a regression model with coefficient of RL as a function of time and CTP by collecting the data for a period of four years [4].

$$SL_{Months} = \frac{SL_{CTP}}{\left[\frac{CTP_{Final}}{Date_{Final} - Date_{Install}} \right] \left[\frac{365.25_{days}}{12_{months}} \right]} \quad (3)$$

where,

SL_{Months} = Service life in elapsed months.

SL_{CTP} = Service life in cumulative traffic passages (millions of vehicles).

CTP_{Final} = Cumulative traffic passages (millions of vehicles) at final field measurement date.

$Date_{Final}$ = Date of final field measurement.

$Date_{Install}$ = Installation date of pavement marking.

Many models and methods were developed for the prediction of service life or the life cycle of the markings. Most of the studies used the regression models to estimate the service life, but the study by Zhang and Wu used the smoothing spline method and time series modeling to estimate the service lives of markings [17]. Both these models are used to predict retroreflectivity behavior. The smoothing spline has an advantage of flexibility (e.g., data in months were not equally spaced) but the extrapolation beyond the available data were not reliable, so the time series modeling was used to predict the retroreflectivity values. The end results from both the methods were very close, but both the methods predicted low service life values for non-paint products that were accounted on the test deck setup. Finally based on these predicted values the life-cycle costs were calculated taking into account the installation and delay costs.

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) [18]. The data were collected for a 28-month period on interstate system, which included retroreflectivity based on pavement type, marking type, and log of maintenance activities. The change in the trend of retroreflectivity values with time is presented in three different patterns. These three patterns are based on the time of installation and effect of maintenance operations shown in Figures 2, 3, and 4.

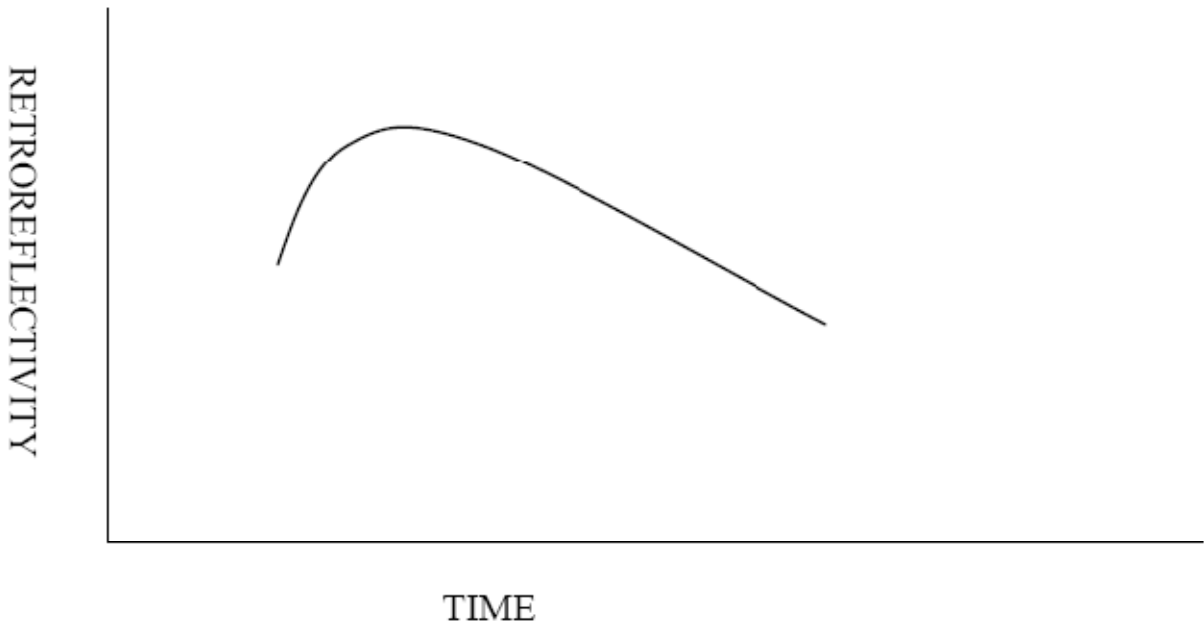


Figure 2. Pattern Representative of Newly Placed Pavement Markings [18].

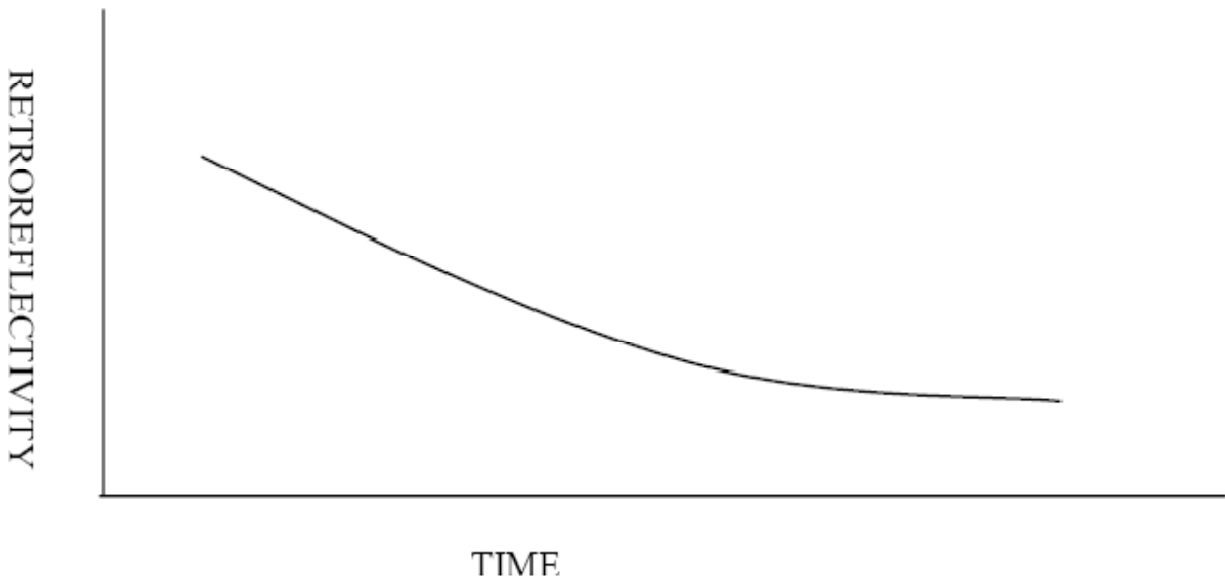


Figure 3. Pattern for Established Sites – Markings Older than about 300 Days [18].

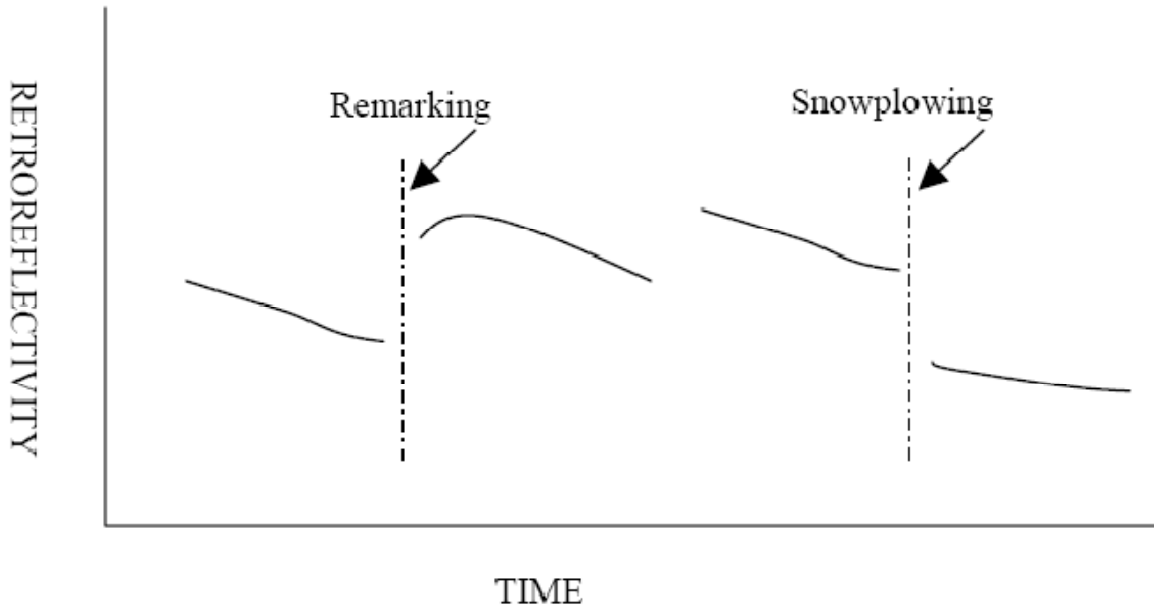


Figure 4. Pattern Showing Sudden Change due to Maintenance Operations [18].

Figure 2 illustrates the pattern of newly placed markings and shows a combination of non-linear and linear plots. The initial rise in the pattern is accounted for the gradual exposure of the beads after some amount of wear, and after the trend is linearly decreasing. Figure 3 represents the trend in older markings that follows a gradual decreasing linear pattern. Figure 4 shows two separate patterns due to the maintenance activity that is either the restriping or the snowplowing. The study also points out that the volume does not have any significant effect on the retroreflectivity values and that the variable time can be used as a substitute for the traffic volume in a time based statistical model. The effect of volume is significant at the intersections and curves where the tires roll over the markings as compared to the straight sections of roads that were considered for the present study. A study from Lee et al. also supports this argument that the traffic volume does not have a significant effect on retroreflectivity values [6]. Finally the deterioration pattern for the retroreflectivity values is split into two models. The first model is a combination of linear and non-linear curves that is applied to the newly placed markings. The non-linear portion corresponds to the time from which the initial retroreflectivity of the marking rises and comes back to the initial value and the linear portion corresponds to the time when the retroreflectivity degrades from the initial values to threshold value. The second model follows a gradually degrading linear model that is suitable to the old markings. These models are applied to get the service life or the life-cycle of the markings. The study also attributes the longer life of

the yellow markings to less truck volume on the left lanes as compared to the white edge markings.

FIELD EVALUATION TEST DECK DESIGN

Pavement markings are evaluated for the visibility and durability under different conditions that affect their performance. Performance of the markers depends on various factors such as the marking type, traffic volume, roadway geometry, surface type, climatic conditions, and installation method and conditions. According to a study by Martin, the life expectancy is a function of pavement type, type and volume traffic, and climate [15]. Most of the transportation agencies use similar tests conducted under the National Transportation Product Evaluation Program depending on the local conditions and requirements. There are two main types of on-the-road pavement marking evaluations: transverse test decks and longitudinal (long line) test decks. Transverse test decks are applied perpendicular to the traffic flow. Long line test decks are applied in the normal locations of pavement markings, consistent with the traffic flow. Both transverse and long line test decks may consist of several marking types to allow comparative analysis.

Transverse Test Deck

Transverse test decks are the field method used by the National Transportation Product Evaluation Program (NTPEP). NTPEP test decks are located around the country to evaluate the performance of the pavement marking materials under four different climate conditions such as a cold-humid climate, a hot-humid climate, a cold-dry climate, and a hot-dry climate, and the data are pooled to be used by any transportation agency. Moving traffic can be allowed to go through the transverse lines constantly in contact with the lines along the right and left wheel paths, leading to more excessive wearing at these locations. Transverse test decks are installed using the protocol established in ASTM D 713 and by the NTPEP standards and best practices [19, 20]. This protocol indicates the design of the test deck, appropriate installation conditions, and when and how to collect data after installation.

Many researchers adopted the transverse test deck to evaluate the performance of different pavement markings. Ida Van Schalkwyk [21] applied the transverse test deck to evaluate the performance and durability of pavement marking materials and make recommendations to enhance the pavement marking testing and selection process for the Oregon

Department of Transportation (ODOT) in 2010. Kimberly B. Kosto and Donald C. Schall [22] evaluated the performance of low-VOC solvent-borne acetone paints under cold temperature with the transverse test deck. In addition, some researchers focused on the studies of the characteristics of the transverse test deck in order to more accurately evaluate the performance of the pavement markings. For example, Rasdorf et al. [23] found that directionality of measurement affects retroreflectivity measurements for paint pavement markings. It has not been established whether transverse lines accurately simulate accelerated wear of longitudinal lines.

Some of the advantages of the transverse test decks that were identified in the study by Carlson et al. [12] are as follows:

- The most common example of on-the-road testing.
- Used by AASHTO-NTPEP program.
- Markings can be placed close together in a relatively short length of roadway, which helps minimize biases and provide reasonably uniform abuse (i.e., traffic load, plowing, weaving, etc.).
- The close proximity of the materials on a transverse deck allows data to be quickly collected.
- Materials in wheel track receive many more hits than traditional long line (center line, lane lines, or edge lines) and therefore act as an accelerated test deck to some degree.
- Transverse test decks are easier to organize and implement than long line tests.
- Conditions and application of materials can be closely controlled.

Meanwhile, disadvantages of the transverse test decks identified in the study by Carlson et al. [12] are as follows:

- The results may be good for comparing products with each other but not representative of how the materials will perform in the field.
- The criteria used to evaluate markings are not the same as the criteria used to evaluate long lines, especially the criterion used to assess nighttime visibility (which is one of the key interests in this study). Nighttime visibility is assessed using measured retroreflectivity of the marking. Neither mobile nor handheld retroreflectometers can measure the retroreflectivity of transverse lines in the direction that they are worn and as drivers would view them at night. Therefore, the nighttime visibility criterion for markings on a transverse test deck is specified by ASTM D713 with a subjective rating,

creating undesirable levels of variability leading to unreliable estimates of durability (service life).

- The transverse test deck requires a lane closure to place and evaluate the material.
- Correlation between test decks is difficult due to traffic and environmental conditions and the subjective measures used to judge durability.
- Long lines are installed by a large truck, essentially a factory on wheels. Installation across travel lanes is not feasible with such large trucks and therefore the markings are installed with handheld applicators that do not provide the same consistency and quality of the large trucks.

Long Line Test Deck

Long line test decks are installed in the same location and direction as standard pavement markings. This allows the markings to be placed under typical circumstances and subjected to normal traffic conditions. Long line test decks can provide realistic installation conditions and realistic wear conditions for the markings. Various configurations such as different material thickness, different bead rates, various mixes of bead size/type, etc. can be tested and evaluated in long line test deck. These conditions provide an environment where durability can be accurately measured and monitored.

Because long line test decks are capable to evaluate and simulate the actual performance of a pavement marking material in the real world, some researchers and agencies successfully applied long line test decks to evaluate the performance of pavement marking materials. For instance, Washington Department of Transportation (WDOT) [24] designed the long line test decks on I-90 within Snoqualine Pass mountain region. The whole evaluation process was conducted during a dry condition with handheld retroreflectometers used to measure retroreflectivity and ASTM D913 used to assess the durability. By using long line test decks, the final conclusion and recommendation provided by WDOT are useful and valuable to direct the future studies on the evaluation of markings performance.

The method of application would significantly affect pavement marking performance that is very sensitive to the quality of the installation. Long line test decks could more accurately reflect the actual performance of pavement markings due to the same application that is used both in long line test decks and the real-world. However, long line test decks are not used

frequently to evaluate pavement markings performance since they are more complicated than transverse test decks and take a long time to monitor and evaluate.

Long line test decks do not have a protocol for test location, installation conditions, or data collection procedures. This will lead to variations in design from one test deck to another, which may lead to variations in results between studies. These variations though are typical when normal pavement markings are applied to roadways.

Advantages of the long line test decks that were identified in the study by Carlson et al. [14] as follows:

- Marking materials are placed on the test deck with the same equipment that is used regularly to install markings.
- Markings can be evaluated under real climate and traffic conditions.
- Allow measured and actual viewed retroreflectivity to be used as a metric to determine performance and durability.
- The results provide the best indication of how the markings will perform in the field under similar conditions.
- Retroreflectivity can be measured by mobile devices that increase the safety of technicians and minimize lane closures.

Meanwhile, disadvantages of the long line test decks pointed out in the study by Carlson et al. [14] are as follows:

- There is not an established protocol for long line testing like there is for transverse test decks.
- Evaluation with handheld retroreflectometers and/or colorimeters requires lane closures with a best-case traffic control scenario using a mobile operation.
- Environmental conditions vary, not only from state to state, but within the state and on the test deck itself.
- Coordinating successful long line test decks is a significant undertaking that should be reserved for personnel with previous experience and proven successes.

Alternate Test Deck

Kaseko et al. performed a comparative evaluation of the field performance results between NTPEP test deck and the alternate test deck setup [25]. The alternate test deck setup

was designed for evaluating the products that are used for transverse intersection applications. The products at the intersections are installed in such a fashion that all the products are exposed to similar traffic conditions. Figure 5 illustrates the arrangement. The results from this comparison have clearly shown that the durability of the marking materials is poorer at intersection test decks as compared to the NTPEP test deck setup. It was also observed that the performance was better on the Portland Cement Concrete (PCC) surface than on Asphalt Concrete (AC) surface due to the dirt accumulation on AC surface. The markings at the intersection set up had the poor performance since the greater forces were experienced by the markings due to the traffic leading to heavy bead removal.

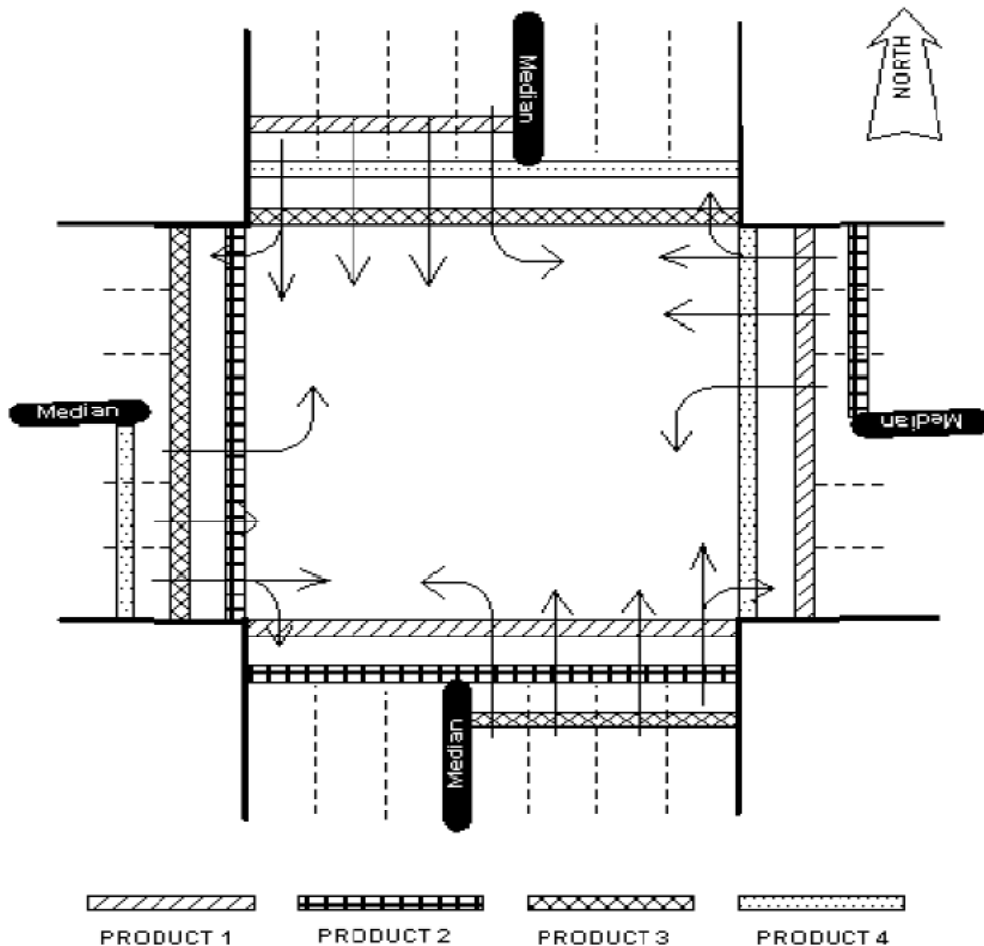


Figure 5. Arrangement of Test Markings at Intersection [25].

Other Accelerated Tests

Attempts are in progress to develop new and improved techniques to lessen the evaluation time and to have more effective specification. A high pressure water blaster or sand

accelerated wear test is one such test that is proposed based on the method used to remove the pavement markings using hydroblasting equipment [14]. The likely disadvantage of this test would be that it favors materials with hard surface and integrated structure over those that have weak bonded material [14].

TXDOT PERFORMANCE SPECIFICATIONS AND EVALUATION

TxDOT's primary material specifications for the furnishing of traffic paint and thermoplastic pavement markings fall within Departmental Material Specification (DMS)-8200 [9] and DMS-8220 [26]. DMS-8200 specifies manufacturer material requirements for the raw products and finished materials, including pigmentation, approved emulsions, and standard formulae for both white and yellow paint. DMS-8220 specifies manufacturer material requirements for pigments, binder, and silica (glass beads) and formulation thereof, as well as requirements for the finished product before and after installation, such as viscosity, toxicity, color, and abrasion, before and after its application for hot applied thermoplastic. The basic placement and performance of hot-applied thermoplastic (Type I) and traffic paint (Type II) products are outlined in several different standard or special construction specifications, as well as standard test methods for durability, color, and retroreflectivity.

Construction Specifications

The two primary specifications for placement of PMMs, developed by TxDOT's Construction Division, are Item 666 [27] and Special Specification (SS) 6110 [28]. These two performance specifications govern equipment requirements, construction techniques, and application requirements (types, colors, sizes, widths, and thicknesses) of Type I and Type II markings. TxDOT's common construction practice is to use Item 666 for temporary markings during construction and for all transverse, word, and symbol markings (temporary and final), and SS 6110 for all final long line pavement markings.

Some districts have modified the above placement specifications to account for performance-based contracts. The San Antonio District has essentially expanded upon Item 666 and SS 6110 to develop a comprehensive performance-based pavement marking specification, most notably, to add a five-year maintenance requirement for all pavement markings and raised reflective pavement markers for all highways in three urban counties. This specification,

referred to as Special Specification (SS) 7201, Performance Based Pavement Marking Maintenance, requires the contractor to adhere to the basic performance language of TxDOT's Departmental Material Specifications related to pavement markings (such as DMS-8200 and DMS-8220) and SS 6110. Furthermore, SS 7201 [29] mandates two independently-conducted and regularly scheduled evaluations:

- Contractor-conducted evaluations for color, retroreflectivity, and presence on the roadway, with retroreflectivity conducted with a mobile retroreflectometer. The frequency and scope of these evaluations vary depending upon the type of highway.
- TxDOT-conducted evaluations on a monthly basis for a fixed percentage of the lane miles in the contract, for color, retroreflectivity, and presence following the basic criteria established by the Texas Traffic Assessment Program, or TxTAP.

Inspection Test Methods

TxDOT's Construction Division has also developed comprehensive procedures for testing in-place PMMs, including in-field evaluations and test decks. The in-field evaluations follow some of the 800-B series of test methods, most notably:

- Tex-828-B: Determining Functional Characteristics of Pavement Markings [30].
- Tex-839-B: Determining Color of Reflective Materials [31].
- Tex-842-B: Measuring Retroreflectivity [32].

Construction Division staff also construct a limited number of field test decks to evaluate the performance of a sample of similar products, such as long lines and symbol markings, or new products that have not yet been widely implemented in TxDOT districts. These test decks have used transverse markings or markings placed in the wheel paths to test for accelerated wear, or markings placed under normal traffic conditions.

Problems with the Existing Evaluation Methods

With the advent of new technologies, it has become difficult to verify the results with the existing methods. The existing methods evaluate the requirements and specifications but do not focus on the installation and configuration that plays a significant role in the performance of the markings [14]. With the non-existence of threshold values, results from the existing tests have a wide variability in acceptance. There is a need to modify the existing techniques depending on

the strengths and weaknesses of each method to match with that of the field performance of each material. In the view of the above listed problems six tactics were stated as a part of the strategy to evaluate durable marking materials [14]:

- Tactic 1 – Familiarization.
- Tactic 2 – Review NTPEP results.
- Tactic 3 – Review on-going research and published research results.
- Tactic 4 – Lab testing and certification requirements.
- Tactic 5 – Conduct field test using transverse lines.
- Tactic 6 – Conduct long line field testing.

This strategy provides combined information on practices and the results involved along with the performance of each product that is of great use in developing a management program for the maintenance of pavement markings.

Field Evaluation

Carlson et al. conducted a study to develop strategies for evaluating durable marking materials that reveals many recommendations from the state agencies regarding the evaluations, such as, to develop testing methods that give both short term (requires less than 6 months of testing) and long-term results (requires 2 or more years of testing). Field evaluations are done based on the above performance evaluation factors. Many parameters are considered for the evaluation such as pavement marking material type, pavement type, color, type of line (edge line, center line). Some studies have even considered the roadway type where in six roadway types (rural freeways, rural multilane highways, rural two-lane highways, urban freeways, urban multilane highways, and urban two-lane highways) were considered along with the six marking material type to get 36 combinations to have an adequate sample for evaluation [33]. Other factors like the season of data collection, bead size, and mixes also influence the field evaluations results to certain extent [3]. Field measurements are made in the direction of travel depending on the type of line, in a case where markings are meant for both the directions such as the yellow center line; measurements are taken in both the directions or in one direction depending on the study and the convenience of the data collection process [4, 33].

PARAMETERS CONSIDERED IN FIELD EVALUATION

Color

Color is an important parameter for field evaluations as the markings of white have greater retroreflectivity values and contrast ratios compared to yellow markings. Zhang and Wu analyzed white and yellow pairs of the same products that resulted in the higher retroreflectivity from white colored markings [34].

Type and Location of Line

Thamizharasan et al. attributed the longer life of the yellow markings to less truck volume on the left lanes as compared to the white edge markings [18]. Craig et al. concluded that the center lines degrade faster than edge lines [35]. This study focused on the thermoplastic markings on asphalt pavement for a period of five years. They suggested incorporating a different maintenance strategy depending on the location of the line. As the edge lines degrade at a slower rate, these can be replaced less frequently than the skip lines resulting in efficient use of the resources.

Pavement Marking Material

Field evaluations vary with the type of marking materials. There are separate work plans for field evaluations depending on the material by NTPEP [19, 20].

Pavement Surface

Pavement surfaces asphalt and PCC have distinct effects on the markings depending on the marking material. The difference in adhesion, stresses, and color affect the field performance of marking materials. No particular trend in the decay of retroreflectivity was observed as there was no standard answer from the previous studies. Some studies indicated that decay was faster on PCC surface due to the stresses and poor adhesion as compared to asphalt [18] in contrary to another study [16], but again several other factors influence the results.

Installation Conditions

Installation methods and conditions depend on the pavement marking types that are suggested by the manufacturer. A study conducted by Arizona Department of Transportation (ADOT) focused on the effects of varying traffic paint application procedures. In the long line

test deck evaluation it was found that the application procedures, quality control, thickness, and bead application have a significant effect on the quality of the markings [36]. Some of the installations conditions that affect the performance of the marking materials are listed below:

- Relative humidity.
- Relative temperature.
- Pavement moisture content.
- Pavement temperature.
- Pavement texture (open coarse surface versus smooth continuous surface).
- Material temperature.
- Application rate.
 - Vehicle speed.
 - Bead rate.
- Material thickness.
- Material mix ratio.
- Wind velocity.
- Cure time.

Ambient application temperatures for different marking types are given in Table 2 [3].

Table 2. Ambient Application Temperatures [3].

Marking Materials	Ambient Application Temperature (°C)
Traffic Paints	93
Thermoplastics	204–218
MA	-1
Preformed tapes	21

Performance Evaluation

Performance evaluations are gaining importance to reduce the maintenance costs and also meet the specifications and guidelines. This is also supported by organizations like American Traffic Safety Services Association (ATSSA), which gives training courses and seminars at transportation agencies. Evaluations are done both before and after the installations. Materials are evaluated standardized, in-house, or a combination of both to check their compliance with the requirements before placement, for scheduled maintenance, and service life after the placement. Recently evaluations are done for the performance-based and warranty provisions contracts.

Evaluation techniques generally include inspection of line quality—line thickness, bead distribution, quantity of material, and measurement of the initial retroreflectivity. The general practice with most of the agencies in the country is to evaluate new markings from three days or less to more than 1 month after installation [1]. Performance evaluation was carried out by the Transportation Research Center of the University of Alaska Fairbanks (TRC/UAF) researchers by taking the performance score, which is an average of the performance factors for expected service life, visibility, durability, and overall costs [4]. One of the recommendations provided by researchers and TxDOT staff (at a conference for pavement marking performance) is to establish a single statewide retroreflectivity performance specification and to use threshold values of 250 mcd/m²/lux for white colored and 175 mcd/m²/lux for yellow colored markings [37]. Evaluations can be mainly divided into objective and subjective techniques.

Objective Evaluation

Objective evaluations are carried out scientifically by using measuring instruments such as retroreflectometer, etc. These instruments measure the retroreflectivity of the markings. Conventional 30 m (98.4-ft) hand-held retroreflectometers were more commonly used but in recent years transportation agencies are looking forward to using a 30 m mobile retroreflectometer unit (MRU). MRUs offer multiple advantages of less number of person-hours, faster data acquisition, reduced risk to the workers, and less traffic control (for examining longer section of roads) [7]. All these benefits results in lower cost for a unit data collected as compared to handheld units. On the other hand errors in measurement and lack of experienced personnel were identified as some of the disadvantages on their effective usage. Apart from these several other safety and economic benefits and functional issues were also reported in the study made for the Florida DOT [7].

Most of the agencies frequently use dry performance evaluations compared to the wet evaluation that is carried out only by few agencies. A special technique was developed for the wet pavement evaluations [1]. The retroreflectivity is measured for dry sections of 1.22 m (4-ft) and then these sections are wetted by application of five back-and-forth passes of a paint roller saturated with water. Wet retroreflectivity was then measured after allowing the water to drain off from the sections for 1 min. Some of the recommendations for objective evaluations are to measure retroreflectivity at least 1 month after striping for long-term pavement marking

performance and to measure retroreflectivity for center lines of undivided two-way roadways in both directions [18]. Variability in the objective measurements is a serious problem that should be avoided by taking necessary action. Significant variability was observed in the retroreflectivity data that were collected even though the AADT and environmental conditions were similar between different roadways. There can be several potential causes for the inconsistency; some of them are differences in the application and installation methods of markings, variability in the Lasexlux® device, faulty calibration of the device, orientation of the laser reflection off the beads, misalignment of the Laserlux® device, percentage and depth of the glass beads in the paint, dirt on the markings, background color of the pavement, and difference in the environmental conditions at the same test deck location during different data collection trips [38].

Subjective Evaluation

Subjective evaluations are more popular than objective evaluations. These evaluations depend upon the experience of the personnel involved. The ratings are made on a scale of zero to 10 and then judged with the standards and guidelines. Most of the studies were reported to use subjective ratings to indicate the minimum retroreflectivity and visibility (daytime and nighttime) [4]. Previous studies have taken a minimum reflectance of 100 mcd/m²/lx as a threshold for determining the subjective ratings that were given from one indicating very poor or not adequate reflectance to more than adequate or superior reflectance. Lower threshold values were considered for yellow in some studies as compared to white colored markings. Subjective evaluations include durability, bead retention, color scale, wet performance pocket microscope test, and color chart. NTPEP test deck setup is used for the evaluating the general performance and bead retention based on retroreflectivity and durability [1]. The ratings were given from one indicating very poor or inadequate reflectance to more than adequate or superior reflectance. Lower threshold values were considered for yellow in some studies as compared to white colored markings.

Minnesota DOT (MnDOT) and New Jersey DOT (NJDOT) sponsored studies for subjective evaluations depending on the real life road driving evaluations. Both the studies involved the public from different age groups to determine the acceptable level of brightness to determine the threshold values of retroreflectivity above which the drivers are comfortable. The

public are allowed to drive vehicles on the selected courses to determine their comfort zone depending on the retroreflectivity. Some of the results from the studies [14]:

- Driver satisfaction increased significantly with the increase in the level of retroreflectivity (0 and 120 mcd/m²/lux for MnDOT study and 0 and 125 mcd/m²/lux in NJDOT study).
- Driver satisfaction increased slightly as the retroreflectivity increased 200 mcd/m²/lux.
- Driver satisfaction remained constant as the retroreflectivity rose above 200 mcd/m²/lux.

Photometric-Based Evaluation

This evaluation is a part of a study sponsored by Virginia DOT and the FHWA to find the minimum retroreflectivity levels. It is a kind of objective evaluation as it involves measurement of visibility distances. Dosage factor was used to calculate minimum retroreflectivity levels, which were calculated as the product of the apparent marking size and the retroreflectivity at threshold. It represents a measure of the total light energy from the individual markings on the road supporting lower threshold values for wider lines. Table 3 gives recommended minimum retroreflectivity values based on this dosage factor and preview time.

Table 3. Recommended Minimum Retroreflectivity.

Speed (mph)	Preview Time = 2.0 sec	Preview Time = 3.65 sec
65	117.0	711.5
55	70.9	431.0
45	38.8	236.1
35	18.3	111.1
25	6.6	40.5

Pavement Marking Management and Assessment Programs Currently in Use

Pavement Marking Assessment System (PAMAS) is a decision-making methodology that considers engineering and environmental goals in selecting a marking material [1]. The engineering performance goals such as high visibility, high durability, convenience, and low cost; environmental performance goals such as the low VOC level; and health and safety considerations are taken for the assessment by this system with the inputs empirical parameters, historical data, and cost.

Performance can be assessed manually or through a software program that can be downloaded from the NCHRP website under Project 4-22 [1]. Solvent-borne paints, waterborne paints, epoxy, thermoplastics, polyester, and preformed tape are the products that can be evaluated using the PAMAS methodology.

GIS Marking Program

At South Carolina DOT, GIS was used by researchers to process, manage, and display the enormous amount of data collected by mobile and handheld instruments. They have also developed an application, Multi-criteria Dynamic Segmentation (MDS), to manage the data more efficiently. The actual distances measured by the mobile instrument are calibrated into GIS route distances. These 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 segmentation into smaller sections. These segmented lengths are binned to produce thematic maps. Maps are 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.

Statistical Replacement Criteria

Statistical replacement criteria are used to determine the time for replacement of markings and also to estimate the required budget [33]. A set of reliable readings (15 sample points in this study) are taken from a defined stretch from the field data and the threshold values for retroreflectivity are specified. If the mean of these sample points collected are less than specified threshold values or if the median of these sample points fell below the established threshold values, the markings for that stretch are replaced. This is also used to estimate the budget that goes into the pavement markings.

Pavement Marking Management System

Pavement marking management system is a management tool developed for Iowa DOT that uses retroreflectivity data to manage the pavement marking performance through the state [39]. This marking management system uses the information on 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 them to integrate the safety with operations and maintenance activities.

The retroreflectivity data were 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/m²/lux for white and 100 mcd/m²/lux for yellow is used to replace the markings. This information is 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 6 shows the GIS map for spring 2004 yellow center line retroreflectivity where black color theme was used to indicate locations below minimum level of retroreflectivity.

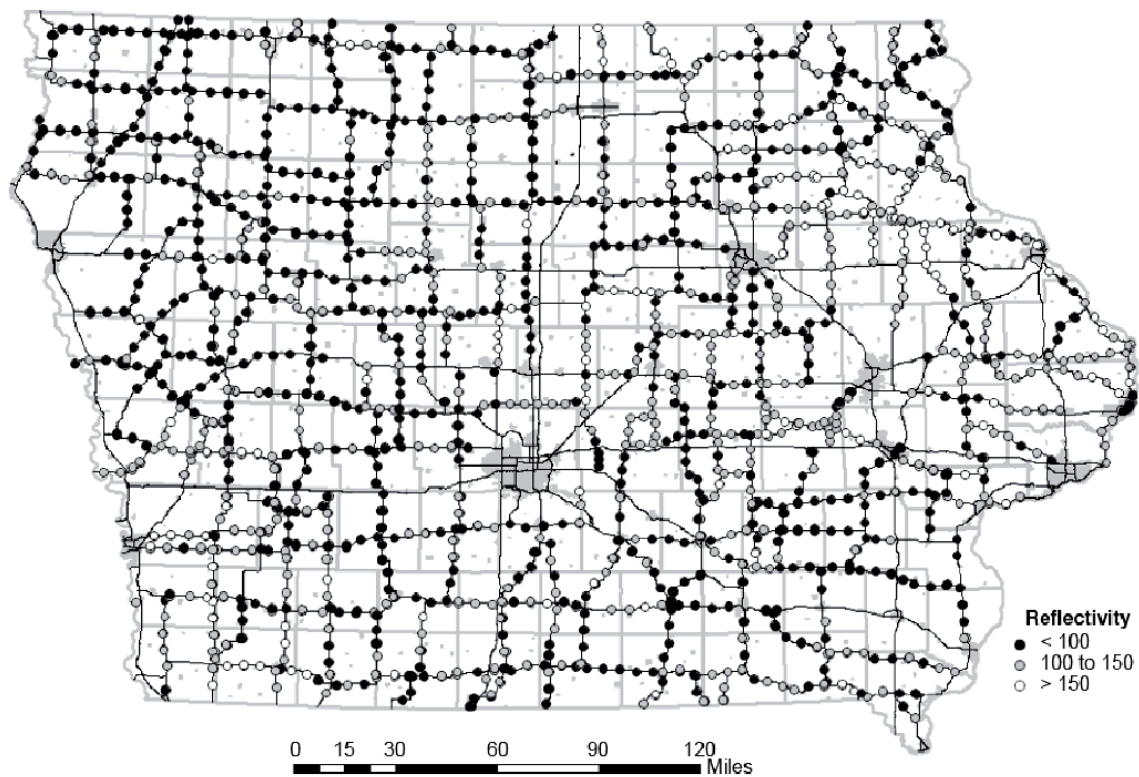


Figure 6. GIS Map for Spring 2004 Yellow Center Line Retroreflectivity (Black Color Theme for Locations below Minimum Level of Retroreflectivity) [39].

GPS units are used to get the coordinates for each measurement from the field. They are referenced through route and milepost. Initial retroreflectivity values were also taken into the database 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 7 illustrates the comparison of yellow center line retroreflectivity and crash frequency and type. The PMMS systems 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.

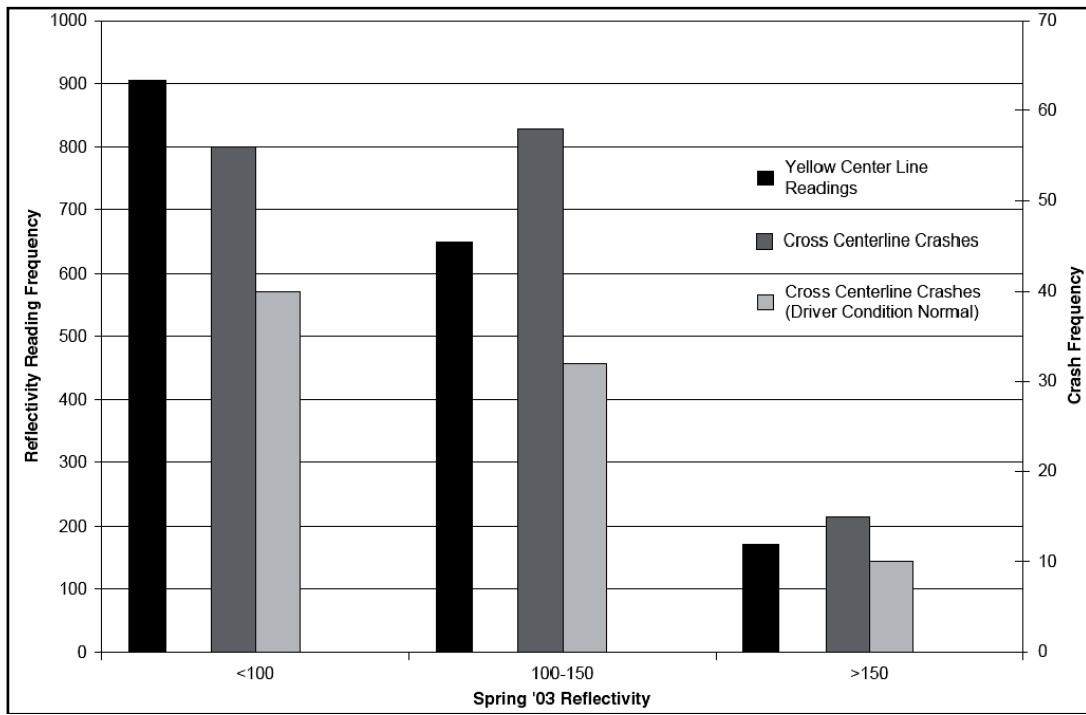


Figure 7. Example Comparison of Yellow Center Line Retroreflectivity and Crash Frequency and Type [39].

Multi-Criteria Decision Making Model

Davis and Campbell developed the multi-criteria decision making (MCDM) model for assessing the utility of pavement markings based upon different input variables [40]. This model stores the data related safety, cost, and convenience of each pavement marking as shown in Figure 8. This model is in turn used as an input for a Decision Support System (DSS), which enables engineers to select the best suitable marking material.

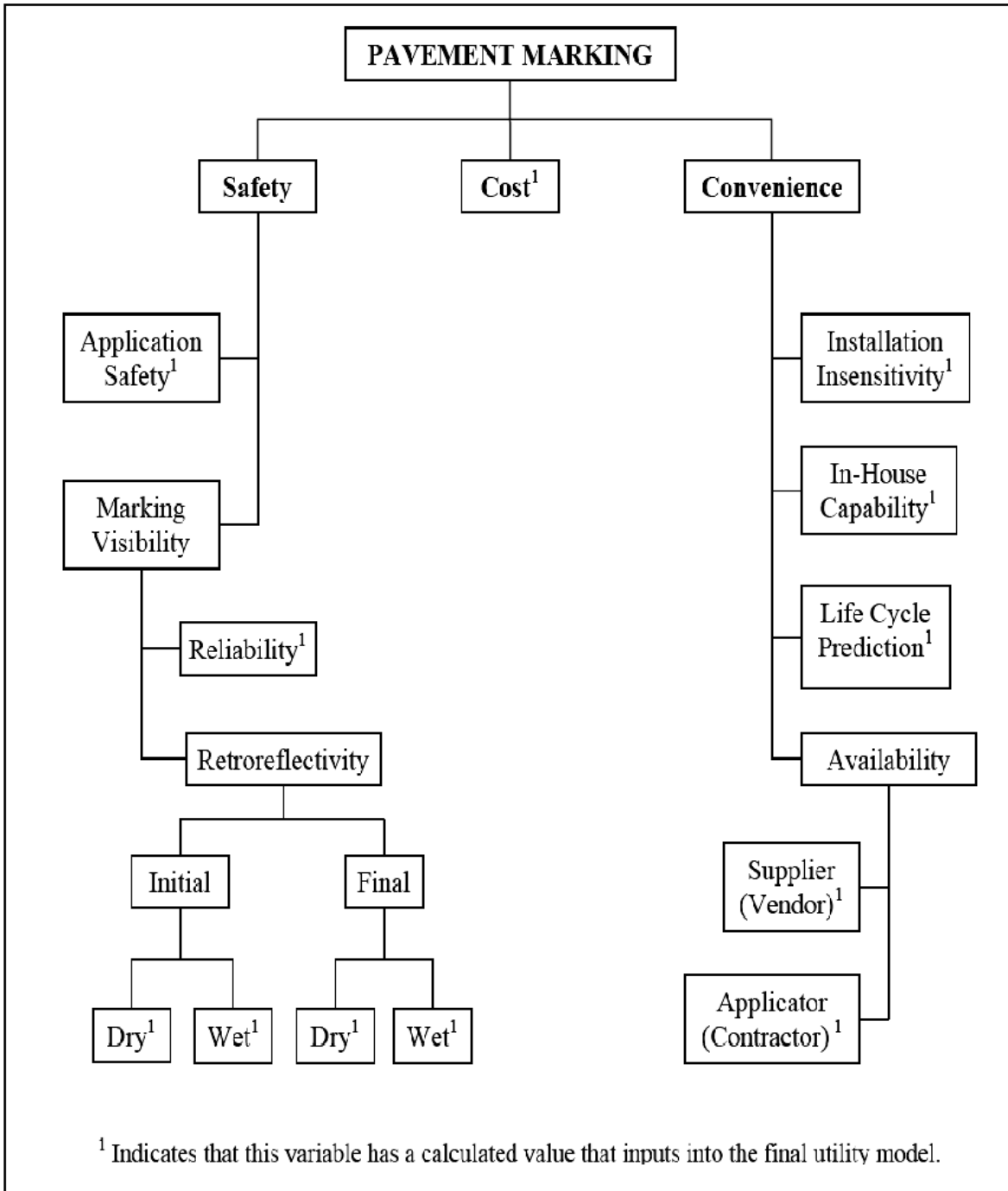


Figure 8. Multi-Criteria Decision Making Utility Model [40].

CHAPTER 3 TEST DECK DESIGN AND FIELD STUDY

TEST DECK DESIGN

Researchers came up with an indigenous test deck design to tackle the deficiencies in the design of previous test decks (as indicated in the past literature). The final design is a combination of stripes installed in transverse and longitudinal directions. With this design, the test decks will not only have the element of accelerated testing to shorten the evaluation duration and to save resources, but also provides data for correlating field performance between transverse lines and longitudinal lines. While transverse line testing is done using the protocol established in ASTM D 713, which is also a part of NTPEP test deck plan, there are no standards that exists for the execution of longitudinal line test decks. Therefore, several configurations for the longitudinal lines in the travel lane are investigated to simulate the actual field performance of PMMs and to allow accelerated testing. One other significant feature involved in the design is the flexibility in method of application. This step is aimed to encourage vendor participation; it also gives an added advantage to test multiple pavement marking systems that are defined by a distinct combination of binder, bead type, bead rate, color, or method of application (e.g., single-drop and double-drop application of beads of the same product). In conclusion this setup is arranged to have many added advantages and for an extensive evaluation from all the perspectives with an efficient use of material, labor, and time and to provide data to establish correlations between lines at different locations/orientations. The major subjects of the set up are described below.

Test Deck Configuration

Test deck configuration is designed to maximize the evaluation benefits by efficient use of material, labor, and time. The section shown in [Figure 9](#) is an example of typical configuration of test deck on a right lane with transverse (five and seven lines) and longitudinal lines.

The configurations of longitudinal lines are as follows:

- Longitudinal lines are installed in two patterns (sets) of five and seven lines equally spaced across the right lane as shown in [Figure 9](#).
- The length of the longitudinal lines is 20 ft with a gap of 20 ft between the two sets.

- Longitudinal lines are either applied by truck or handcart on all decks for each marking system.

The configurations of transverse lines are as follows:

- Transverse lines are laid across the deck.
- Six lines are applied for each marking system.
- Transverse lines are laid with handcart on all decks for each marking system.

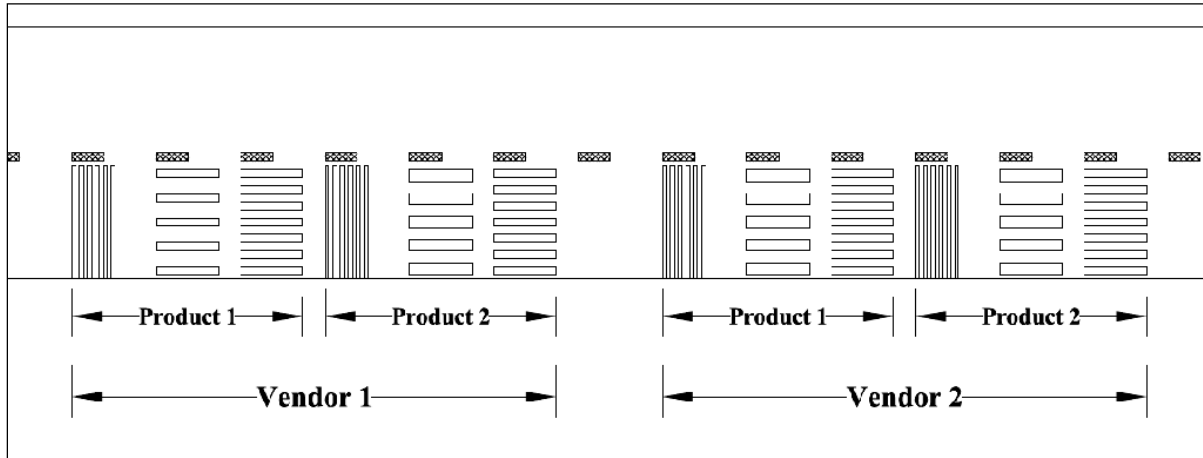


Figure 9. Test Deck Configuration.

Benefits and Rationales for the Deck Configuration

The benefits with this deck configuration are multifold. It will provide data to correlate various results and to recommend efficient testing criteria. The main purposes are as listed below:

- To correlate the results obtained from truck laid longitudinal lines versus hand cart laid longitudinal lines.
- To gather data from different transverse locations: skip line, left wheel path, middle of the lane, right wheel path, and right edge line.
- To correlate the results obtained from wheel path, edge lines and skip line locations both from longitudinal lines and transverse line. The result could potentially invalidate, revise, or approve accelerated performance testing.
- Different configurations for the wheel path longitudinal lines (five equally spaced skips or seven equally spaced skips) are included to assess the influence of the markings patterns on driver's behavior (whether they will maneuver to avoid hitting markings in the wheel path area) and to identify best locations for wheel path lines.

- The configuration will provide data for optimal test deck design in the future. It may potentially provide quantitative performance criteria for test lines under a recommended deck configuration. In the past, material performance evaluation was done in a comparative sense and setting standard was almost impossible without an identified relationship between real-world readings and readings from materials on test decks.

SELECTION OF TEST DECK LOCATIONS

The test deck locations are selected at three sites across the state of Texas shown in [Figure 10](#) to account for the vast environmental and geographical differences of the state and also to evaluate on different pavement surfaces. Selection of test deck locations is based on different factors like region, area type (urban or rural), climate, roadway surface type, traffic composition, and volume level.

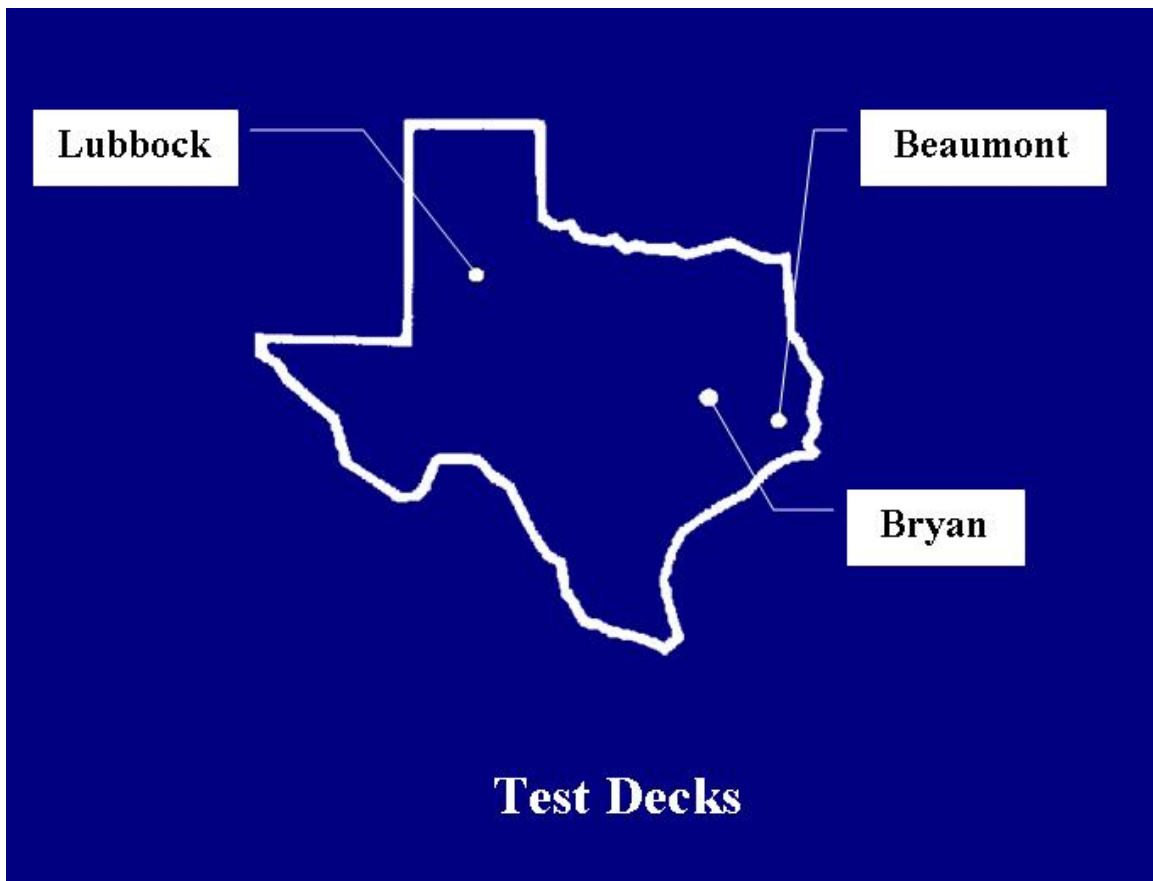


Figure 10. Test Deck Locations across Texas.

Criteria Considered for the Selection of Location

Specific rules for selecting locations to install test decks are as follows:

- Moderate to high ADT, with a speed limit between 50 to 70 mph.
- Multilane or access controlled freeway facility.
- Segment should be generally free of horizontal, vertical curves and significant grades.
- Segment should be away from access points or intersections to avoid excessive braking or turning movements.
- Pavement surface should be representative of the same type in the area and should not require crack sealing or extensive patching during the evaluation period.
- The seal coat locations should not have excessive aggregate loss or flushing.
- The segment will not be resurfaced in the next three years.
- Wide shoulder area is desirable to serve as a staging area for vehicles and equipment during installation.

Test Deck Locations

Based on discussions with the project panel and TxDOT, the following field deck locations are identified.

Beaumont District

The test deck is on a concrete pavement in the city of Beaumont, Texas. The test deck is located between US 90 and I-10 with an ADT of 13,000 as shown in the [Figure 11](#) (marked in red oval). [Figure 12](#) shows the stretch in specific on FM 364 between Walden Road and I-10.

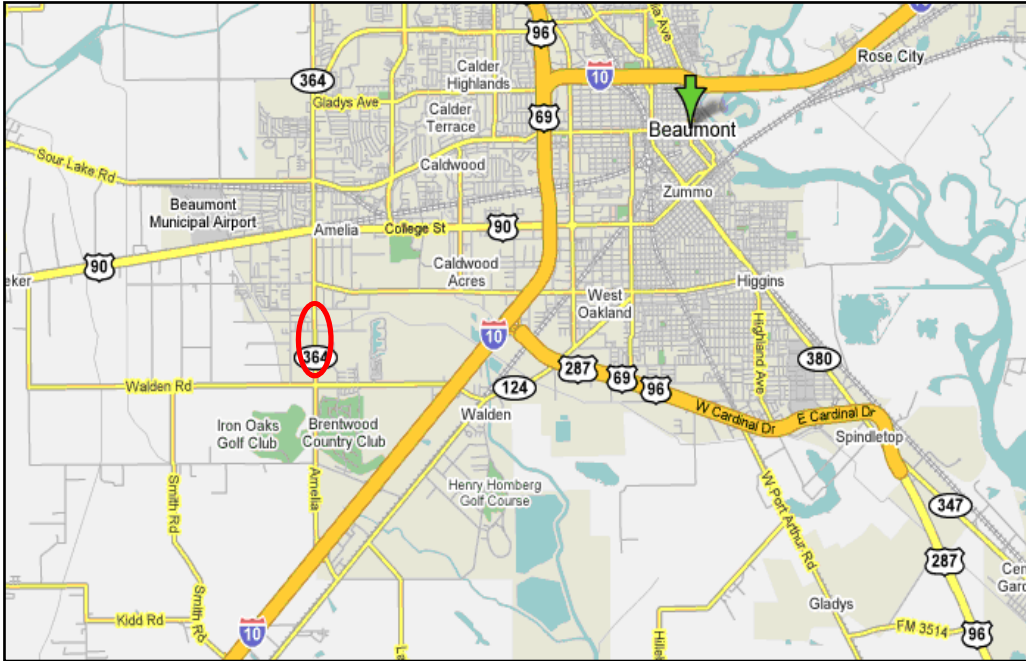


Figure 11. Test Deck Location - Beaumont, Texas.

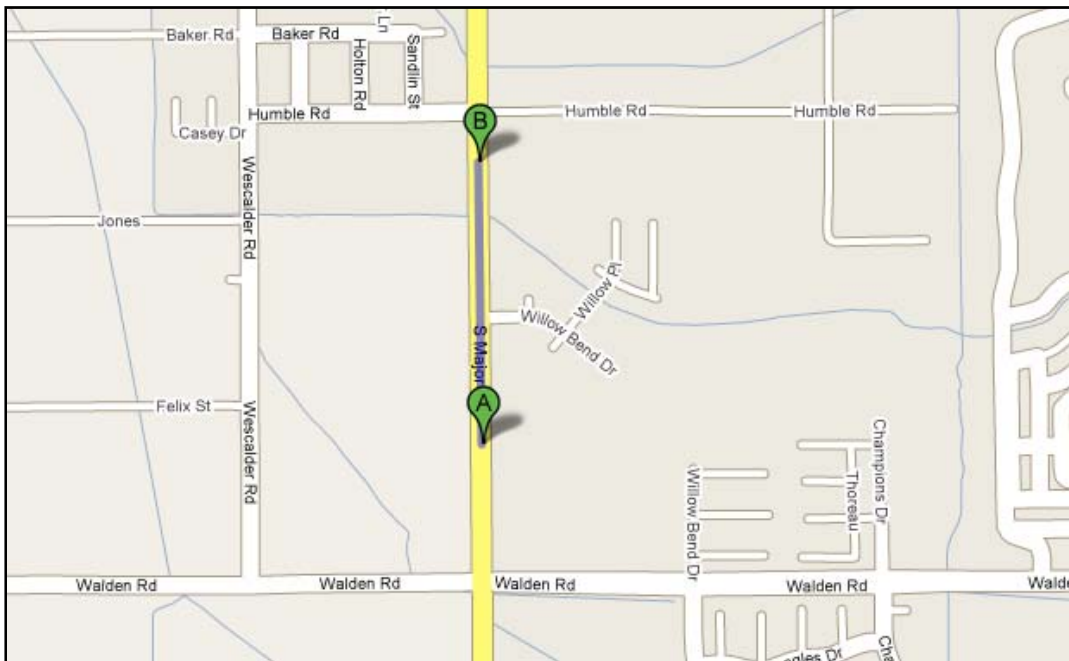


Figure 12. Test Deck Stretch between US 90 and I-10.

Lubbock District

The test deck is on Asphalt pavement in the city of Lubbock, Texas. It is located on US 62/82 Hockley County (Figure 13) with an ADT of 9,000 starting 1000 ft South of County

Rd. Oxen (approx. 2 miles from Lubbock Co. lane) to the south one mile (southbound outside lane) as shown in Figure 14.

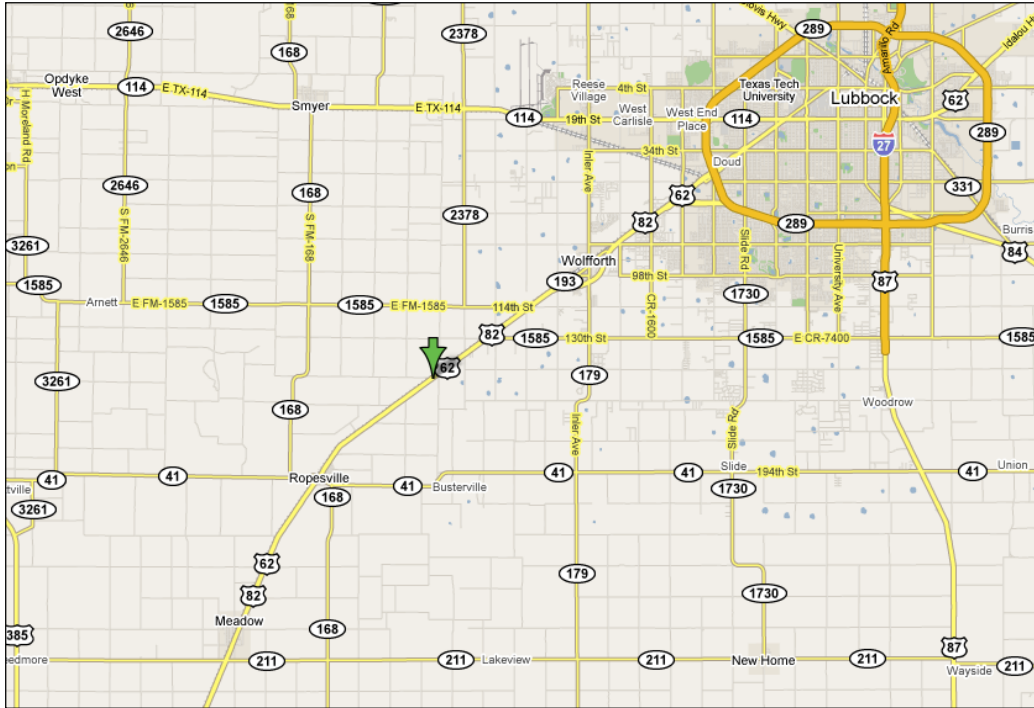


Figure 13. Test Deck Location - Lubbock, Texas.

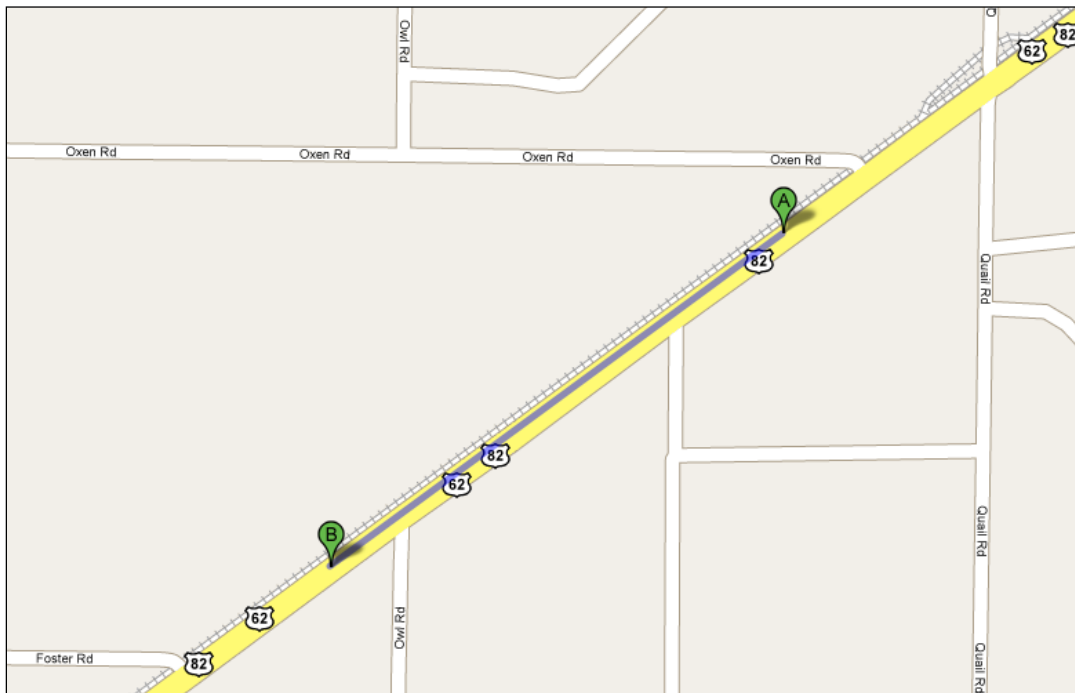


Figure 14. Test Deck on US 62/82, Hockley County.

Bryan District

The test deck is located between Bryan and Caldwell on State Highway 21 with an ADT of 11,000 between County Road 229 and the next turnaround lane heading to eastbound as shown in [Figure 15](#).



Figure 15. Test Deck on State Highway 21.

Bryan Deck's Unique Configuration

The location has a newly paved seal coat pavement. Unlike the usual design a different deck configuration is planned at this site in order to compare the performance with the newly applied existing skip lines and edge lines. The normal skip lines and edge lines are striped as a part of TxDOT's seal coat striping project. Additional skip lines that connect existing ones are also applied. [Figure 16](#) illustrates the test deck configuration at this deck. It has eight sections; the first four sections are striped with Ennis paint thermoplastic and the rest with Dobco thermoplastic. The test deck also consists of a unique feature to compare between spray and extruded type of application as both application methods are used for each of the products installed. The data collection on retroreflectivity and color at this deck will be conducted on the following type of lines:

- Transverse lines (applied by handcart, extruded).
- Longitudinal lines in the travel lane, applied via spraying and extruding.
- Skip lines applied via spraying and extruding.
- Existing edge line and skip lines, applied as a part of TxDOT's seal coat striping project.

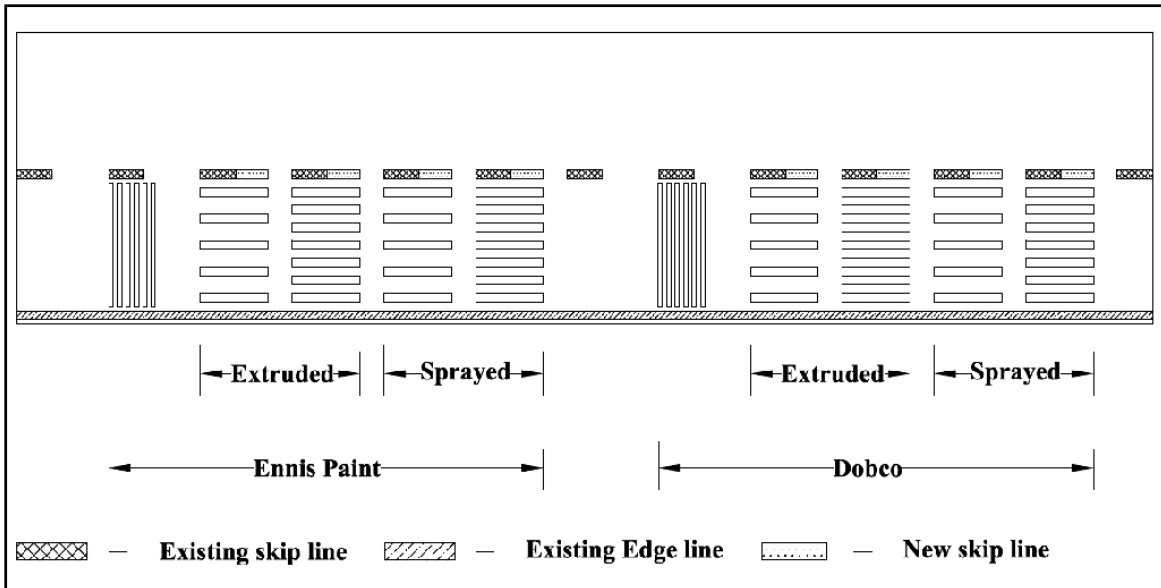


Figure 16. Unique Bryan Test Deck Configuration.

Products Tested

The products to be applied on the test decks are identified after a series of discussions with the advisory panel and other TxDOT personnel. The majority of the materials tested included high performance materials like thermoplastics, Premark preformed tapes, MMA, polyurethane, and polyurea. High build and water based paints were also tested but to a lesser percentage. A detailed list of the materials selected and the manufacturers involved is listed in the technical memorandum submitted to TxDOT.

Test Deck Installation

Test deck installation is crucial in determining the field performance of the products. Various combinations are executed in the installation process to evaluate the performance of the same products, by altering binder, bead type, and the method of installation.

Installation Data by Location

Beaumont

The Beaumont test deck was installed on May 8, 2008, with 10 sections. The installation was carried out by the vendors for their respective products at all the sections. [Table 4](#) gives an overview of the products installed, type and the manufacturer.

Table 4. Beaumont Test Deck Information.

Section No.	Product	Color	Type	Manufacturer
7	Premark Preformed Tape	White	Tape	Flint
8	ATM 300 Tape	White	Tape	ATM
9	MMA	White	MMA	Ennis
10	HPS-4 Modified Polyurethane	White	Polyurethane	Ennis
11	HPS-4 Modified Polyurethane	White	Polyurethane	Ennis
12	HPS-5 Polyurea	White	Polyurea	Ennis
13	HPS-5 Polyurea	White	Polyurea	Ennis
14	MMA	White	MMA	Ennis
15	Thermoplastic contrast marking	White thermo on black thermo	Thermoplastic	Ennis
16	Thermoplastic	White	Thermoplastic	Ennis

Lubbock

The Lubbock test deck was installed on May 20, 2008, with 15 sections. The sections were installed by vendors except for the first six sections with Poly-Carb products for which a contractor was hired. [Table 5](#) gives an overview of the products installed, type, and manufacturer.

Table 5. Lubbock Test Deck Information.

Section No.	Product	Color	Type	Manufacturer
1	MARK 55.5	White	Epoxy	Poly-Carb
2	MARK 55.5	Yellow	Epoxy	Poly-Carb
3	MARK 65.5	White	Epoxy	Poly-Carb
4	MARK 65.5	Yellow	Epoxy	Poly-Carb
5	MARK 70.3	White	Epoxy	Poly-Carb
6	MARK 70.3	Yellow	Epoxy	Poly-Carb
7	R&H HD 21 High Build Paint	White	Paint	Ennis
8	R&H HD 21 High Build Paint	White	Paint	Ennis
9	R&H HD 21 High Build Paint	White	Paint	Ennis
10	R&H HD 21 High Build Paint	White	Paint	Ennis
11	Waterbase DURA SHEEN SEMI-Gloss Waterborne Paint	Yellow	Paint	Ennis
12	Waterbase Paint EP series	Yellow	Paint	Ennis
13	Flametape	White	Tape	Ennis
14	Flametape Alternate	White	Tape	Ennis
15	Premark Preformed Tape	White	Tape	Flint

Bryan

The Bryan test deck was installed on September 9, 2008, with eight sections. A contractor was hired for the installation of all the products. The quality of installation was supervised by a team of researchers and an associate from Ennis paint. [Table 6](#) gives an overview of the products installed, type, and manufacturer.

Table 6. Bryan Test Deck Information.

Section No.	Product	Color	Type	Manufacturer
1	Thermoplastic (extruded)	White	Thermoplastic	Ennis
2	Thermoplastic (sprayed)	White	Thermoplastic	Ennis
3	Thermoplastic (extruded)	White	Thermoplastic	Ennis
4	Thermoplastic (sprayed)	White	Thermoplastic	Ennis
5	Thermoplastic (extruded)	White	Thermoplastic	Dobco
6	Thermoplastic (sprayed)	White	Thermoplastic	Dobco
7	Thermoplastic (extruded)	White	Thermoplastic	Dobco
8	Thermoplastic (sprayed)	White	Thermoplastic	Dobco

Data Collection Plan

The performance of the markings is periodically monitored in intervals of three months from the initial set of readings. [Table 7](#) gives a data collection schedule at different locations. Test deck sections are numbered to identify the individual characteristics and for a better organization in the database tracking system. In an attempt to correlate the performance readings are taken on five different locations in the direction perpendicular to the direction of the traffic on the transverse lines: near skip line, left wheel path, middle of the lane, right wheel path, and near right edge line. For the longitudinal lines readings are taken at one-third and two-third points of a marking irrespective of the marking pattern (five and seven lines). Photos of the sections are also taken for the rating schemes under subjective evaluation.

Retroreflectivity, day color, and night color are the performance parameters that are measured on field. Retroreflectivity is measured using LTL-X (from DELTA), a handheld retroreflectometer based on 30-meter geometry. Color measurements are taken using LTL-Y (night color) and BYK color-guide (day color). All the readings are taken using hand-held devices; a mobile retroreflectometer was not used in the entire data collection process.

Table 7. Data Collection Schedule.

Site	Date of Installation	Initial Readings (first interval)	Regular Readings (second Interval)	Regular Readings (third Interval)	Regular Readings (third Interval)	Regular Readings (fourth Interval)	Regular Readings (fifth Interval)	Regular Readings (sixth Interval)	Regular Readings (seventh Interval)
Beaumont	5/8/2008	5/8/2008	8/15/2008	11/20/2008	02/19/2009	05/26/2009	08/26/2009	01/21/2010	05/04/2010
Lubbock	5/20/2008	5/20/2008	7/30/2008	11/03/2008	02/24/2009	06/03/2009	09/10/2009	03/23/2010	06/22/2010
Bryan	10/9/2008	10/25/2008	1/07/2009	04/08/2009	07/02/2009	10/22/2009	01/22/2010	04/22/2010	08/10/2010

GENERAL PERFORMANCE OF PAVEMENT MARKINGS

Upon completing the retroreflectivity measurements, the researchers extracted the data from the original readings and to obtain various averages. The periodic field evaluations were conducted approximately every three months when the lines were dry. The following subsections provide a summary of the results obtained during the performance evaluation period.

Retroreflectivity measurements are summarized and compared with the initial and current retroreflectivity values between different products. In all, there were over 4000 recorded retroreflectivity measurement values during the testing period. Color data were not analyzed but were recorded for vendor use and potential use in future projects.

Beaumont

In total there were 10 different pavement marking sections installed at the Beaumont test deck. [Figure 17](#) illustrates the average retroreflectivity data of each measurement location for all 10 markings on the deck. Visual inspection of the curves shown in [Figure 17](#) indicates that the measurement points near the wheel path have lower retroreflectivity values than the other measurement areas regardless of being in the transverse, five or seven line measurement sections. The measurement points of the transverse lines have a similar performance trend with the corresponding points of five and seven longitudinal lines over time.

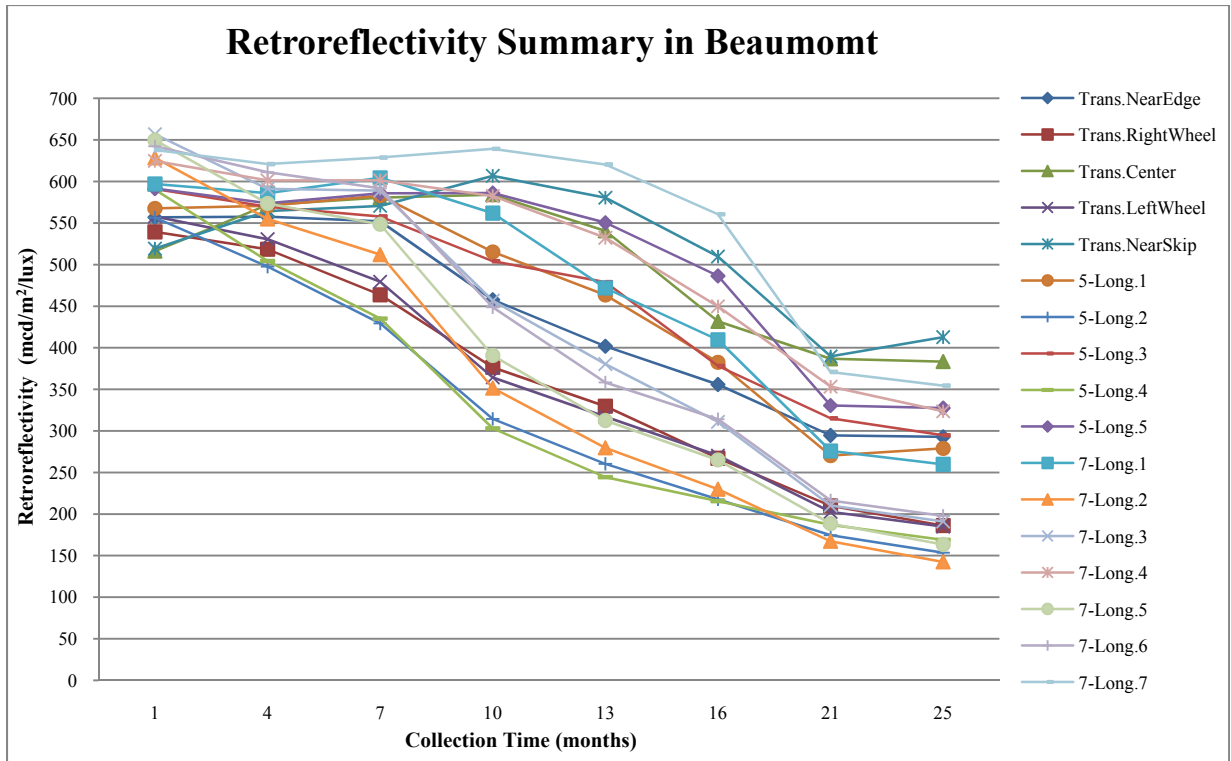


Figure 17. Summary of Retroreflectivity in Beaumont.

Figure 18 illustrated the initial and final retroreflectivity values for all seven products from three vendors at Beaumont. These values correspond to the average of 17 retroreflectivity readings obtained from transverse and longitudinal lines. The product Ennis-MMA has both the lowest initial and final values compared with others. Correspondingly, the product Ennis-Thermoplastic, which is white thermoplastic applied on black thermoplastic, has the highest initial value; however, it deteriorated at a higher rate due to the larger difference between its initial and final values. The products that retained retroreflectivity better are Flint-Tape, Ennis-MMA, and Ennis Thermoplastic with the lower difference between the initial and final values.

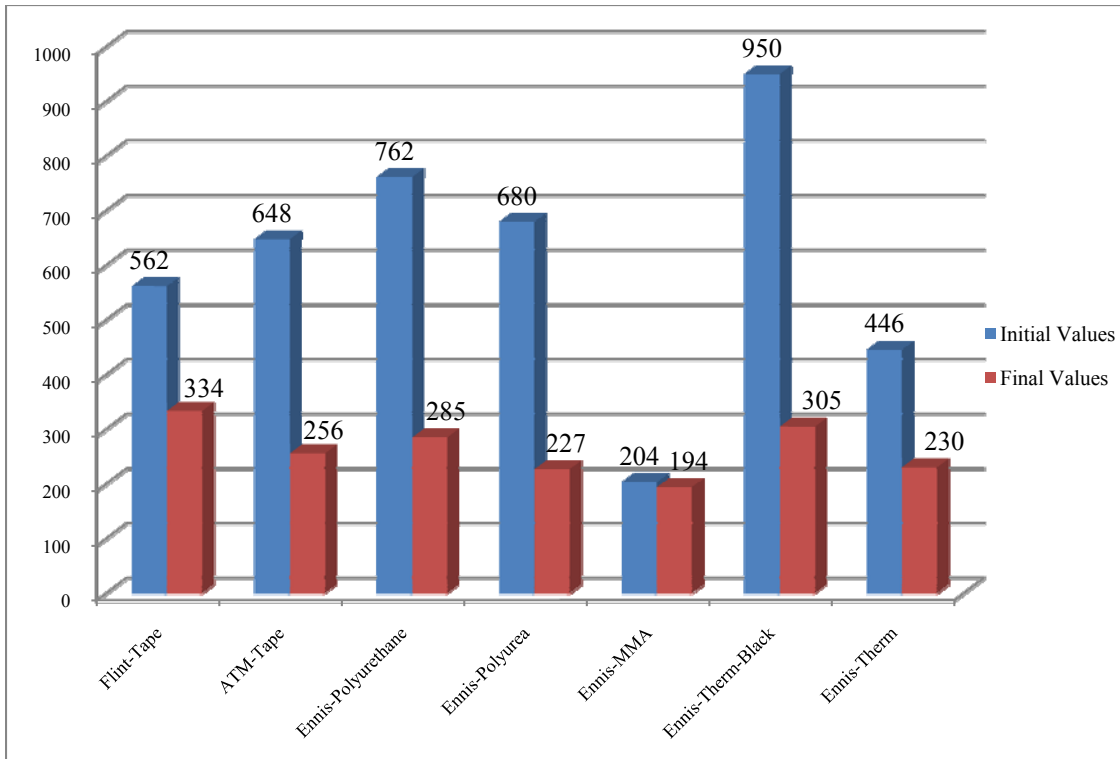


Figure 18. Initial and Final Retroreflectivity Values of All Products at Beaumont.

Lubbock

The Lubbock test deck consists of 15 different pavement marking sections that were installed by vendors except for six sections for which a contractor was hired. Figure 19 illustrates the average retroreflectivity values of each measurement location for all 15 markings on the deck. The measurement points of the transverse lines have a similar performance trend with the corresponding points of five and seven longitudinal lines over time. The average rate of decay at the Lubbock deck is higher than that of the Beaumont deck. The difference in decay rate between the two decks is likely due to a combination of factors, such as the types of pavement marking used, traffic conditions, and vehicle speeds. Moreover, there is a more obvious difference between trend curves of the measurement points in wheel path and those at other positions, as the readings for all the points in wheel path areas have evidently lower values than the readings in other areas. This difference is more pronounced compared to Beaumont deck.

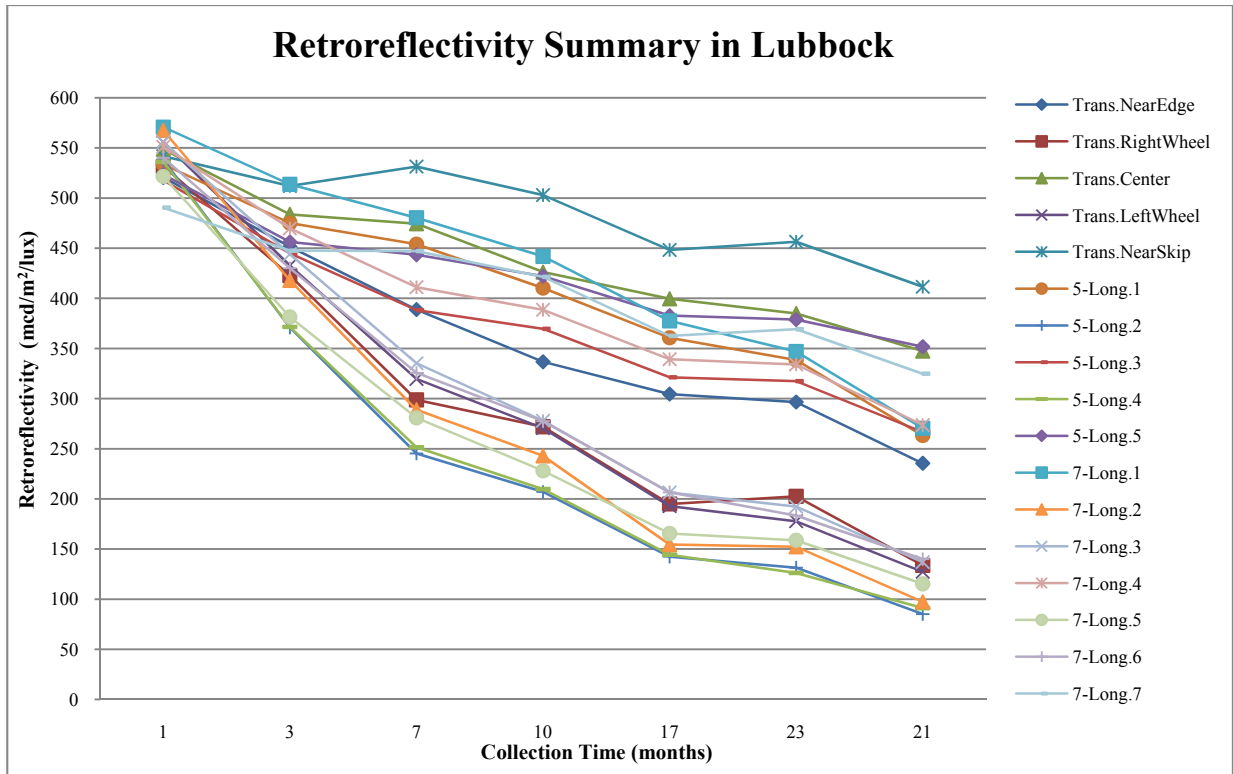


Figure 19. Summary of Retroreflectivity in Lubbock.

Figure 19 illustrated the initial and final retroreflectivity values for products on the Lubbock deck. Based on Figure 20 it is obvious that product WaterDURA-Ennis-Paint has the highest initial retroreflectivity value among all products installed at Lubbock; Product Mark70.3-Poly-Carb-Epoxy has lower final value than all other products regardless of its high initial value, which also demonstrated it had a faster decay rate than other products. It is likely due to the larger bead used in Mark70.3-Poly-Carb-Epoxy. Moreover, the product Flametape Alternate-Ennis-Tape has similar performance with Ennis-MMA with an insignificant difference between the initial and final values. A lower decay rate also showed that Premark-Ennis-Tape was capable of retaining the retroreflectivity.

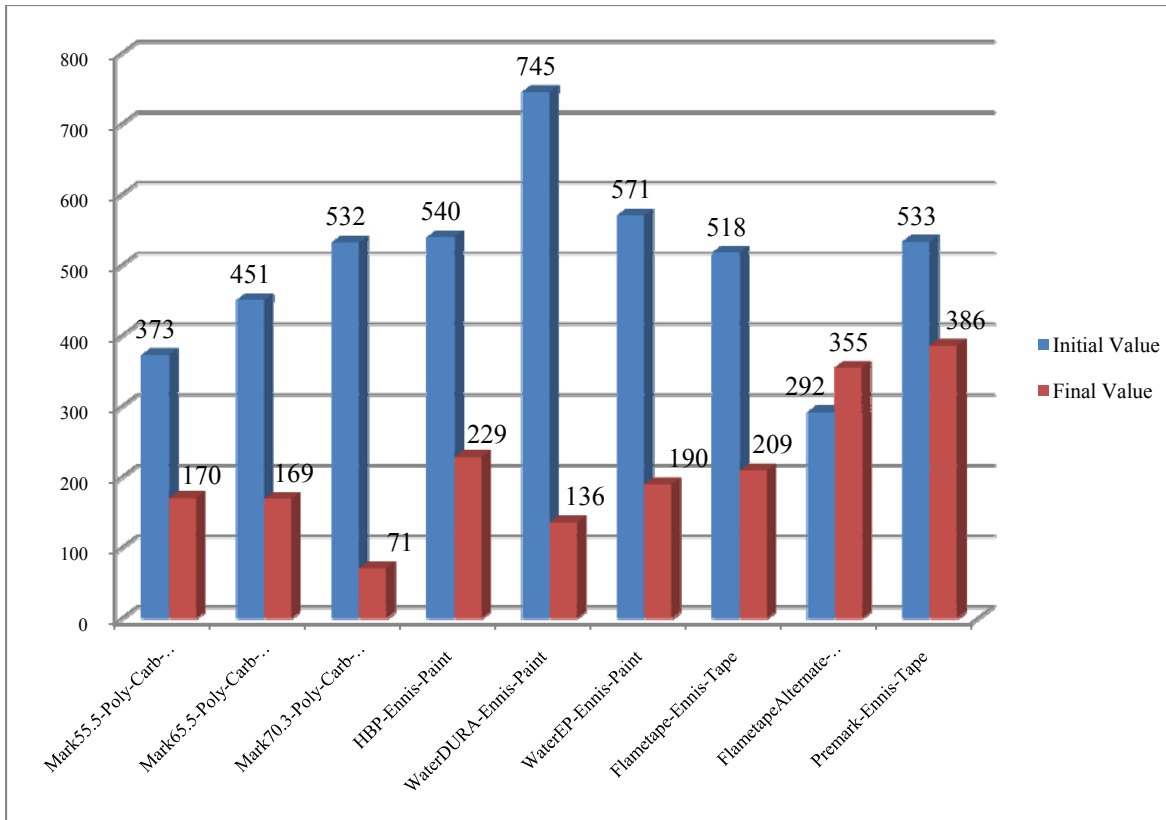


Figure 20. Initial and Final Retroreflectivity Values of All Products at Lubbock.

Bryan

The Bryan test deck consists of two products (Ennis and Dobco thermoplastic) with two different application methods (extruded versus sprayed) that were each repeated, resulting in a total of eight sections. Figure 21 illustrates the average retroreflectivity data of each measurement location for all eight sections on the deck. In general, flat trend curves can be found for all measurement points. There was an exception that measurement points of transverse lines on wheel path had low retroreflectivity performance with a faster decay rate. This rather flat trend is likely due to lower traffic demand compared with Lubbock and Beaumont decks. Similar to the other two test decks it can be seen that the measurement points of the transverse lines have a similar performance trend with the corresponding points of five and seven longitudinal lines. In addition, it is obvious that skip lines did not have a large decay rate compared with other measurement points.

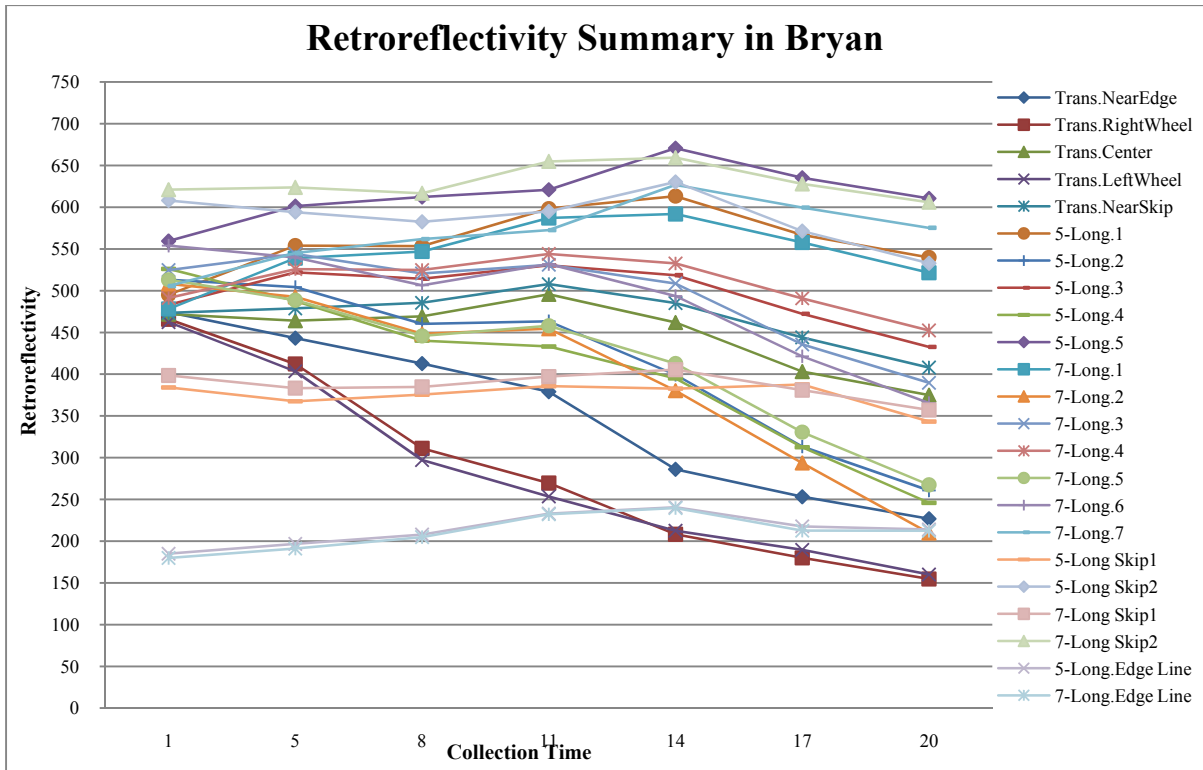


Figure 21. Summary of Retroreflectivity in Bryan.

Figure 22 illustrates the initial and final retroreflectivity at the Bryan test deck. The pavement markings installed at Bryan have similar performance in the retroreflectivity. Relatively, Dobco applied by extruding performed the worst among all products. Though Ennis applied by extruding has the highest initial and final values, it is inconclusive whether it has a better ability to retain the retroreflectivity. In addition, two different kinds of pavement markings applied by spraying performed almost the same in the initial and current values.

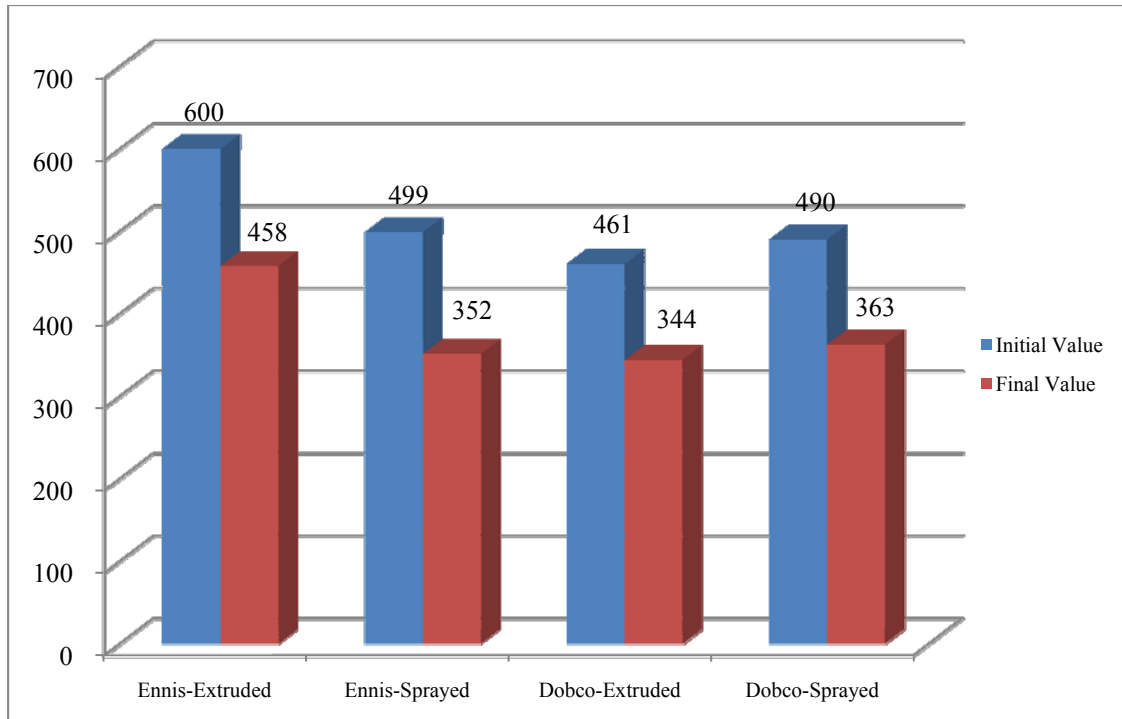


Figure 22. Initial and Final Retroreflectivity Values of All Products at Bryan.

CORRELATION ANALYSIS

One of the objectives of this research was to find the best design of a test deck. The two commonly used configurations of NTPEP style transverse line and long line have both advantages and disadvantages. We conducted a correlation study to investigate the trend change of retroreflectivity between points on different lines. The idea is if a point on a transverse line correlates well with a point on a long line, then we can make a case that using transverse line is valid since it can predict actual performance of a marking in an accelerated manner.

In statistics, correlation means a departure from independence between two random variables. Correlation is useful because it can indicate a predictive relationship that can be used in practice. Pearson correlation coefficient is the most widely used, which is mainly sensitive to a linear relationship between two variables. It is obtained by dividing the covariance of the two variables by the product of their standard deviations as shown in the Equation 4 below.

where,

X, Y =the retroreflectivity data of the time series of two different measurement points.

E = the expected value.

cov = covariance.

μ_X, μ_Y = the mean of time series X and Y .

σ_X, σ_Y = standard deviation of time series X and Y .

The correlation coefficient may take any value between -1.0 and $+1.0$. The positive one means a perfect increasing linear relationship; the negative one means a perfect decreasing linear relationship. The value between -1.0 and $+1.0$ represents the degree of linear dependence between two variables. The closer the coefficient is either -1.0 or 1.0 , the stronger the correlation between two variables. The correlation analysis is used to evaluate and investigate the relationship between different line configurations in this study. In addition to correlation analysis, other statistical techniques are also used. All statistical tests are conducted at 95 percent confidence level.

Beaumont

The data in Beaumont are categorized and averaged by different products and applications. According to the correlation analysis, the measurements on the transverse lines generally have very good correlations with the corresponding measurement points of the five longitudinal lines and seven longitudinal lines as shown in Table 8. The highlighted boxes indicate measurements at similar positions, i.e., right wheel path of the transverse line correlated with the right wheel path of the five line longitudinal section.

Table 8. Correlation between Transverse and Longitudinal Lines.

Beaumont		5 Longitudinal Lines					7 Longitudinal Lines						
		1	2	3	4	5	1	2	3	4	5	6	7
Transverse Lines	Near Edge	0.98	0.97	0.98	0.94	0.88	0.96	0.98	0.99	0.95	0.98	1.00	0.83
	Right Wheel	0.95	0.99	0.98	0.97	0.86	0.94	0.99	0.99	0.94	0.99	0.99	0.82
	Center	0.93	0.71	0.90	0.65	0.93	0.93	0.74	0.83	0.93	0.76	0.81	0.90
	Left Wheel	0.94	0.99	0.96	0.98	0.84	0.93	1.00	0.99	0.92	1.00	1.00	0.79
	Near Skip	0.85	0.56	0.80	0.48	0.93	0.86	0.58	0.70	0.87	0.61	0.68	0.94

In addition, the data were plotted in a scatter plot, which illustrates the degree of correlation between the different test deck designs, as well as providing the regression line. In the scatter plot, an equation for the correlation between the variables can be determined by best fit linear regression. If the data between the transverse lines and longitudinal lines were equal, the correlation would not only be high but the slope of the regression line would be close to 1. Any value for the regression line slope different than one would indicate that the lines were decaying at different rates assuming the initial retroreflectivity values were similar. As shown in Figure 23, the five pairs of the retroreflectivity data between the transverse lines and corresponding five longitudinal line sections are provided. The linear regression equations are also provided in Figure 23 for each pair. It can be seen that all pairs have good correlation in general and with high R squared values. Each regression line has slope not far from 1.0, indicating the retroreflectivity value of the point of transverse lines was very close to one of corresponding point of five longitudinal lines. This further demonstrated that measure points of transverse lines have very good correlation with the corresponding points of five and seven longitudinal lines.

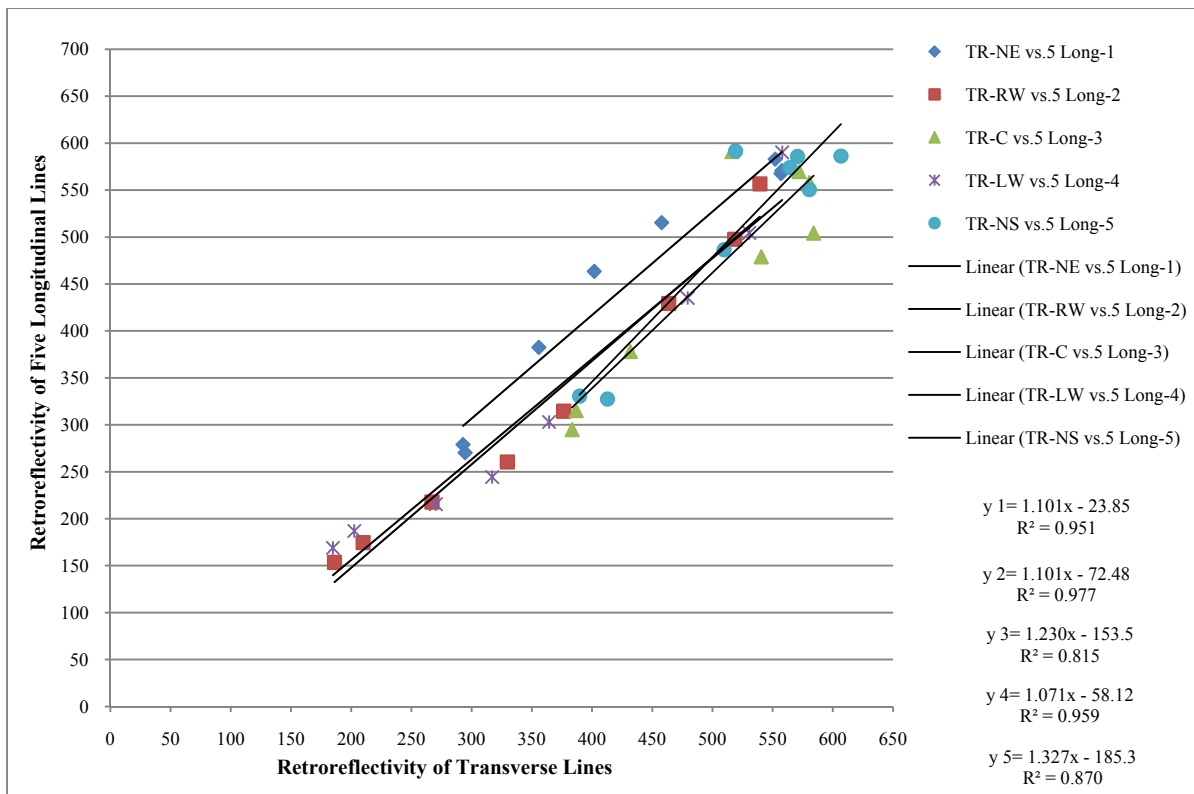


Figure 23. Scatter Plot between Transverse and Five Longitudinal Lines in Beaumont.

Correlation results for individual sections are provided in [Table 1](#) of the [appendix](#). Correlation analysis on a single product produced inconsistent results. The product Flint located in section 1 has the worst correlation between measurement points of the transverse lines and corresponding ones of the five and seven longitudinal lines compared with other products as shown in [Table 9](#). This is probably due to the fact that it was applied by manually heating with handing torch and the fact that when an individual product is studied, the variability of retroreflectivity reading is not averaged, hence the poor correlation. For the product thermoplastic Ennis with black thermo, poor correlation can also be found between measurement points near left wheel path and near skip line on transverse lines and their corresponding points on the five and seven longitudinal lines.

In contrast, the product ATM located in section 2 has perfect correlation between some transverse line points and those corresponding points on the five/seven longitudinal lines as shown in [Table 9](#). Meanwhile, the product polyuria Ennis applied by spraying using a handcart has generally high correlation between measurement points of the transverse lines and corresponding ones of the five/seven longitudinal lines. For the average data of the whole site, the high correlation between measurement points of the transverse lines and corresponding points of the five/seven longitudinal lines can be found as well.

Table 9. Correlation between Transverse and Longitudinal Lines at Section 1 and 2.

Section 1		5 Longitudinal Lines					7 Longitudinal Lines						
		1	2	3	4	5	1	2	3	4	5	6	7
Transverse Lines	Near Edge	0.12	0.96	-0.50	-0.20	-0.63	0.98	0.96	0.96	0.95	0.96	0.96	0.93
	Right Wheel	0.19	0.97	-0.55	-0.37	-0.75	0.96	0.98	0.98	0.97	0.98	0.99	0.98
	Center	0.48	0.13	0.61	0.13	0.21	0.40	0.21	0.24	0.45	0.20	0.18	0.42
	Left Wheel	-0.02	0.97	-0.65	-0.30	-0.79	0.93	0.97	0.98	0.95	0.98	0.99	0.94
	Near Skip	0.76	0.04	0.39	-0.35	0.27	0.33	0.19	0.21	0.36	0.15	0.17	0.36
Section 2		5 Longitudinal Lines					7 Longitudinal Lines						
		1	2	3	4	5	1	2	3	4	5	6	7
Transverse Lines	Near Edge	0.92	0.99	0.98	0.98	0.95	0.93	0.99	1	0.97	0.99	1	0.96
	Right Wheel	0.88	0.99	0.98	0.99	0.94	0.89	0.99	1	0.97	0.99	0.99	0.94
	Center	0.93	0.93	0.97	0.92	0.95	0.94	0.94	0.94	0.97	0.94	0.95	0.97
	Left Wheel	0.87	1	0.97	1	0.91	0.87	1	1	0.95	1	0.99	0.93
	Near Skip	0.85	0.75	0.84	0.74	0.87	0.86	0.77	0.78	0.85	0.76	0.81	0.88

Furthermore, for the entire deck, statistical analysis was made to test whether there is a statistical difference of the retroreflectivity value between transverse and longitudinal test decks. Paired T-test results indicates that at 95 percent confidence level, the retroreflectivity of measure points of transverse lines are not different from corresponding points on five or seven longitudinal lines except for section 1 and just a few of measurement points of the product polyuria Ennis applied by spraying using a handcart. Overall combing the results of correlation and statistical analysis, the points of the transverse lines and corresponding points on five and seven longitudinal lines are highly correlated and are not statistically different.

Based on the retroreflectivity data collected from the five and seven longitudinal test decks in Beaumont, the influence of the markings patterns on driver’s behavior is as follows. The retroreflectivity value of points at wheel path decreased much faster than the points near the edge and skip lines, which demonstrated that drivers did not greatly change their driving patterns in order to avoid the lines since the most wear was seen near the typical driving areas. Furthermore, from the data of the seven longitudinal lines, the retroreflectivity values of points just to the right of wheel paths are lower than ones just to the left of wheel path throughout the evaluation duration. Drivers typically drive slightly to the right of the center of the lane on four-lane divided highways with a large right shoulder.

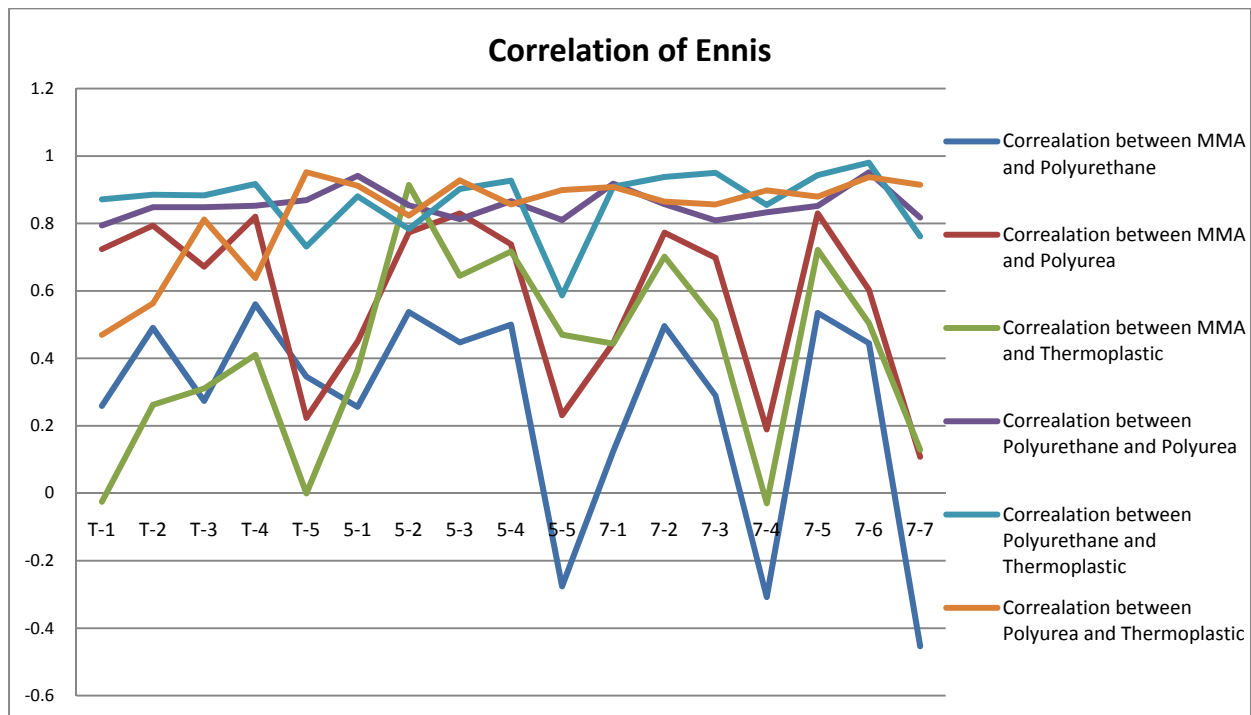


Figure 24. Correlation between Ennis and Other Products.

As an example to show correlations between products, the correlation between different products and Ennis is also analyzed as demonstrated in the [Figure 24](#). It can be easily seen that products of Ennis-Polyurethane, Ennis-Polyurea, and Ennis-Thermoplastic are highly correlated with one another, which demonstrated that they likely have similar performance on the retroreflectivity. Similar correlation analysis was done between other products and the general conclusion is that for all products measure points near wheel path have high correlation with each other and those near center positions usually have low correlation. The low correlation is likely due to the fact that number at center of the lane stayed rather flat, leading to low correlations.

Lubbock

The result of the correlation analysis provided in [Table 10](#) also strongly supports the visual inspection conclusion, which shows that the points of the transverse lines have very good correlations with the corresponding points of the five longitudinal lines and seven longitudinal lines. [Table 10](#) presents the results of the correlation analysis.

Table 10. Correlation between Transverse and Longitudinal Lines in Lubbock.

Lubbock		5 Longitudinal Lines					7 Longitudinal Lines						
		1	2	3	4	5	1	2	3	4	5	6	7
Transverse Lines	Near Edge	0.97	0.98	0.99	0.98	0.98	0.97	0.99	1.00	0.99	0.99	0.99	0.95
	Right Wheel	0.95	0.99	1.00	0.99	0.98	0.95	1.00	1.00	0.99	1.00	1.00	0.94
	Center	0.99	0.96	0.98	0.96	0.99	0.98	0.97	0.98	0.99	0.97	0.98	0.98
	Left Wheel	0.96	0.99	1.00	0.99	0.98	0.96	1.00	1.00	0.99	1.00	1.00	0.94
	Near Skip	0.96	0.83	0.90	0.83	0.92	0.96	0.86	0.88	0.90	0.85	0.88	0.98

The scatter plot ([Figure 25](#)) also supports the same conclusion that good correlation existed between the transverse lines and the corresponding five/seven lines. The level of correlation in the Lubbock deck is very similar to that of the Beaumont deck. In addition, the conclusion about the influence of pavement marking pattern on driver's behavior is the same in Lubbock as it was in Beaumont. The wheel paths showed lower retroreflectivity readings and on average the drivers drove closer to the edge line.

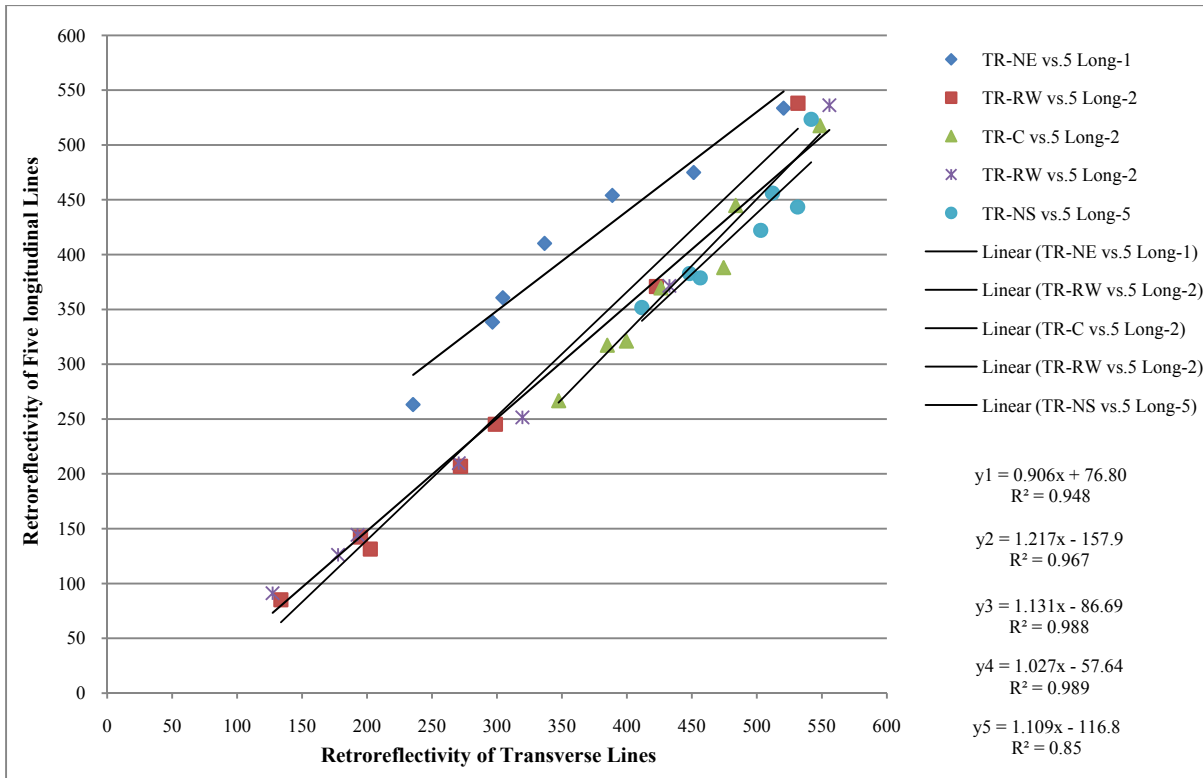


Figure 25. Scatter Plot between Transverse and Five Longitudinal Lines in Lubbock.

Correlation results for individual sections are provided in [Table 2](#) of the [appendix](#). In the same way, the data in Lubbock are categorized and averaged by different products and applications as well. In general, the measurement points of the transverse lines have very high correlation with corresponding points of the five/seven longitudinal lines for all products, and even for the average data of the whole site. Nevertheless, for the product Flametape Alternate Ennis located in section 14, there is inconsistent correlation between measurement points of the transverse lines near edge line and near right wheel path and corresponding points of the seven longitudinal lines. In addition, for the product Premark Preformed tape Ennis, measurement points of the transverse lines near edge line and near skip line have low correlation values with corresponding points of the five/seven longitudinal lines.

Based on the statistical analysis, it can be seen that most measurement points of the transverse lines are statistically different with corresponding points of the five/seven longitudinal lines. For the average data of the whole site, only measurement points of the transverse lines near wheel path are not statistically different with corresponding points of the five/seven longitudinal lines.

Moreover, it can be found that the measure point of the transverse lines near left wheel path is highly correlated and no statistical difference from its corresponding point of the five longitudinal lines for each product.

Bryan

According to the correlation analysis results in [Table 11](#), the points of the transverse line near edge line and near skip line had very poor correlations with the corresponding points of five and seven longitudinal lines. Good correlation could not be found between near skip five/seven lines and lines in the actual skip location, or between near edge five/seven lines and actual edge lines. However, the wheel path readings on transverse lines generally had good correlation with the corresponding five and seven longitudinal lines near the wheel path. The poor correlation is likely due to the fact that the retroreflectivity at skip line and edge line stayed rather flat, and the random fluctuation led to poor correlation. The poor correlation may also be due to the fact that the transverse lines were all hand applied whereas the long lines were truck applied, even though the same issue did not exist for other long lines in the middle of the lane.

Table 11. Correlation between Transverse and Longitudinal Lines in Bryan.

Bryan	5 Longitudinal Lines							7 Longitudinal Lines								
	Edge Line	1	2	3	4	5	Skip Line	Edge Line	1	2	3	4	5	6	7	Skip Line
Near Edge	-0.62	-0.42	0.96	0.56	0.96	-0.66	0.32	0.48	-0.62	-0.39	0.95	0.85	0.46	0.94	0.9	-0.79
Right Wheel	-0.75	-0.56	0.9	0.4	0.92	-0.74	0.25	0.45	-0.75	-0.55	0.88	0.75	0.28	0.89	0.83	-0.85
Center	0.03	0.19	0.91	0.9	0.87	-0.13	0.61	0.78	0.01	0.21	0.91	0.96	0.86	0.91	0.95	-0.29
Left Wheel	-0.77	-0.59	0.87	0.35	0.91	-0.75	0.24	0.45	-0.77	-0.59	0.86	0.72	0.23	0.87	0.81	-0.85
Near Skip	0.18	0.38	0.82	0.96	0.77	0.07	0.69	0.79	0.17	0.41	0.84	0.93	0.95	0.83	0.88	-0.09

The test deck in Bryan also consists of a feature to compare between sprayed and extruded applications as both application methods are used for each of the products installed. The data collected from five longitudinal lines and seven longitudinal lines in the travel lane were used for the comparison between these two types of application. A correlation analysis of the retroreflectivity values of the same product applied with two application methods was made, and the results are presented in [Table 12](#). It can be seen that there is high correlation between different application methods. The correlation values are all above 0.75.

Table 12. Correlation between Products with Different Application at Bryan.

	5 Longitudinal Lines					7 Longitudinal Lines						
	1	2	3	4	5	1	2	3	4	5	6	7
Ennis-E vs. Ennis-S	0.92	0.98	0.97	0.98	0.96	0.70	0.98	0.96	0.75	0.99	0.99	0.86
Dobco-E vs. Dobco-S	0.75	1.00	0.93	0.97	0.91	0.75	1.00	0.99	0.93	1.00	0.96	0.93

Note: E-Extruded, S-Sprayed

However, statistical analysis demonstrated that different application methods affected the performance of pavement markings. After examining the retroreflectivity data in Bryan, it is found that there is a statistical difference between the initial values for the Ennis product applied by spraying and extruded, as shown in Table 13. This significant difference in initial value for Ennis was not observed for the Dobco product.

Table 13. Comparison of Retroreflectivity for the Product Ennis with Different Applications.

t-Test: Paired Two Sample for Means

	<i>Initial Value of the Product Ennis with Extruding</i>	<i>Initial Value of the Product Ennis with Spraying</i>
Mean	613.1	484.6
Variance	2947.175	1171.675
Observations	5	5
Pearson Correlation	0.795664	
Hypothesized Mean Difference	0	
Df	4	
t Stat	8.430082	
P(T<=t) one-tail	0.000542	
t Critical one-tail	2.131847	
P(T<=t) two-tail	0.001084	
t Critical two-tail	2.776445	

At the Bryan deck there are two kinds of skip lines evaluated: skip lines applied by the TxDOT contractor (they are 5-long, skip 1 in the five line section and 7-long, skip 1 in the seven line section) and the vendor-applied ones (they are 5-long, skip 2 in the five line section and 7-long, skip 2 in the seven line section). By examining the retroreflectivity data, the retroreflectivity values of the skip lines applied by the TxDOT contractor one week before the test deck installation are significant. These lines were narrower and thinner, and beads seemed inadequate. This observation signifies the importance of the quality of application.

Correlation results for individual sections are provided in [Table 3](#) of the [appendix](#). Through the examination of the correlation results, it can be seen that, for individual sections, skip 2 lines have relatively higher correlation with lines on wheel path in the sections of pavement markings applied by extruding, and with lines near it (the fifth line of the five longitudinal lines and the seventh line of the seven longitudinal lines) in the sections of pavement markings by spraying. However, after averaging the data by different products, there are no consistent patterns between skip 2 lines and corresponding lines of the five and seven longitudinal lines. Especially for the average data of the whole site, skip 2 line of the five longitudinal lines is highly correlated with lines on wheel paths and skip 2 line of the seven longitudinal lines is highly correlated with the line near edge. However, they all have statistical difference according to the result of pair t-test. There is only one exception: skip 2 line in the five longitudinal line section of Dobco thermoplastic applied by spraying has both high correlation and good t-test results with the line near it (the fifth line of the five longitudinal lines). All measurement points on transverse lines have high correlation with skip 2 lines no matter in the five longitudinal lines or seven longitudinal lines.

CHAPTER 4 PAVEMENT MARKING MANAGEMENT SYSTEM

OBJECTIVE

Pavement Marking Management System is a relational database developed on Microsoft Access® 2003 platform to help TxDOT districts track the performance of the pavement markings. One main consideration for developing PMMS on a Microsoft Access platform is to keep the training requirements to minimal level.

Key Features

Microsoft Access comprises objects such as tables, forms, queries, and reports each with its own function as described briefly below.

- Data storage – Tables to store relevant information about the markings such as product information, vendor, site information, installation date, etc.
- Data entry – Forms enable a user to enter new data or append to the existing data.
- Data view – Existing data can be viewed through forms.
- Data search – Forms and queries enable a user to search for a particular attribute or a combination of attributes.
- Print – Information of a particular product, output of a search or a graphical display can be printed using reports.

Description of Version 1.0

The first release of PMMS was developed to incorporate the parameters that are related to the test deck evaluation, with functions to enter the data and view the existing information pertaining performance of the markings. PMMS is a program designed to store, manage, and manipulate data for monitoring the performance of pavement markings. This program is based on Microsoft Access 2003, taking into consideration that a minimum training is required to operate the application. Access is comprised of different database components called objects that appear on the left side of database window (Figure 26) and are tables, queries, forms, reports, macros, and modules. The following sections explain the basic components and their functions of individual objects.

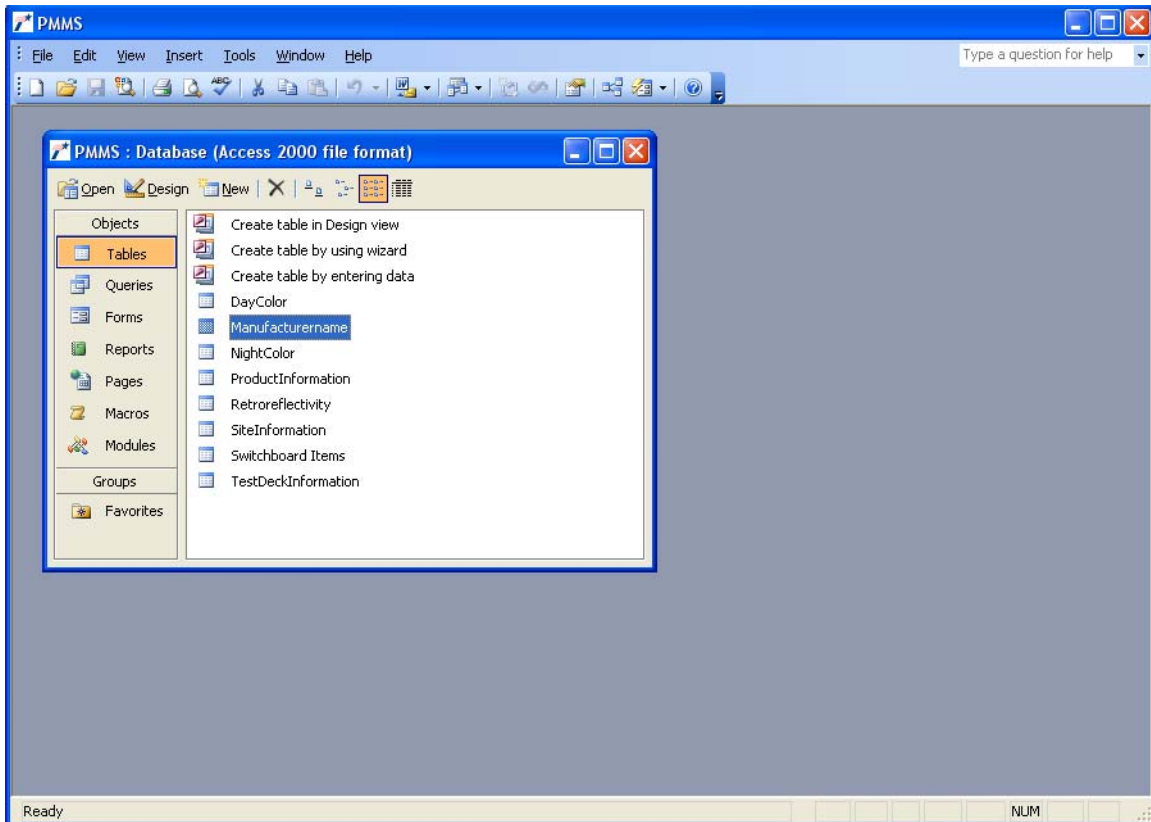


Figure 26. Database Objects.

Tables

Tables are fundamental objects used to store data and designed to accommodate information related to a category. Data entry is made easy by adopting a table format that is similar to Microsoft Excel® spreadsheets. The data going into the tables are arranged in columns called fields based on different data types. [Table 14](#) shows different data types that can be assigned.

Table 14. Data Types.

Text	(Default) Text or text and number combinations, as well as numbers that do not require calculations, such as zip codes (up to 255 characters).
Memo	Text or text and number combinations that is lengthy (up to 65,535 characters).
Number	Numeric data that can be used in mathematical calculations.
Date/Time	Date and time values.
Currency	Numeric data used in mathematical calculations shown as dollars.
AutoNumber	A unique sequential number (incremented by 1) or random number that is assigned by Microsoft Access when a new record is added to a table.
Yes/No	A field containing one of two values (Yes/No, True/False, On/Off).
OLE Object	An object (such as a graphic, or a Microsoft Excel spreadsheet) that is linked to or embedded in a Microsoft Access table.
Hyperlink	Text or text and number combinations stored and used as a hyperlink address. A hyperlink can have up to four parts: <i>text to display</i> – the text that appears in a field or control. <i>address</i> – the path to a file (UNC path) or page (URL). <i>subaddress</i> – a location within the file or page. <i>screentip</i> – the text displayed as a tool tip. Note: Select Insert...Hyperlink to insert a hyperlink address in a field or control.
Lookup Wizard	Creates a field that allows you to choose a value from a list or another table by using a list box or a combo box.

PMMS has seven tables with their titles clearly explaining the information they contain. These tables are:

a. Manufacturer Information:

This is a primary table that contains the manufacturer information of the markings; it has two columns (fields), Manufacturer Name and Manufacturer ID (primary key), as shown in [Figure 27](#). Each manufacturer has a unique ID that is generated by Access and can be used for any further queries or information.

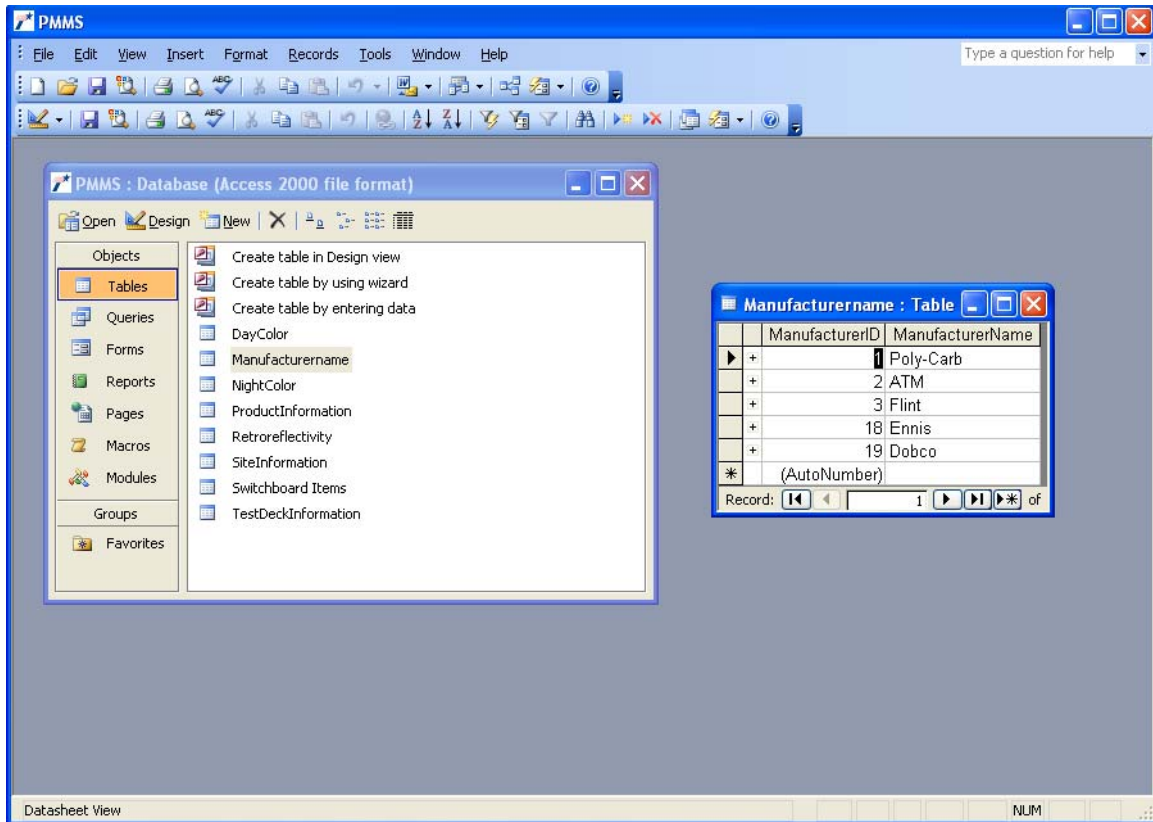


Figure 27. Window with Manufacturer Table and Its Fields.

b. *Product Information:*

This table contains the information of different products from the manufacturers. It also has a one-to-many relationship with the manufacturer table, which allows entering different products information from the same manufacturer. It has five fields namely *Product ID*, *Manufacturer ID*, *Product Name*, *Product Type*, and *Notes* with *Product ID* as primary key and *Manufacturer ID* as foreign key. The final column *Notes* is provided to include any additional information about the product. In addition, the *Manufacturer ID* is populated automatically during the time of entry as the product table has a one-to-many relationship with manufacturer table.

c. *Site Information:*

Site information table acts as a look-up table that is to be separately populated at the time of data entry. It has one-to-many relationship with product information explaining the design that a single location can accommodate many products. This table has 11 fields

namely *Site ID, District, County, Mile Post, Traffic Volume, Truck Percentage, Surface Type, Speed Limit, Pavement Age/Condition, and Notes* with *Site ID* as primary key.

d. *Test Deck Information:*

It is the core table of the entire program that stores the information of test deck and is related to five tables: Site Information, Product Information, Retroreflectivity, Night Color, and Day Color. It has 17 fields with Test Deck ID and Section Number as primary keys and Site ID as secondary key. The table includes entire information related to the test deck with the fields namely: *Test Deck ID, Section Number, Site ID, Product ID, Date of Application, Contractor, Marking Width, Type of Application, Bead Coating, Bead Type, Bead Weight, Binder, Primer, Application Thickness, Material Temperature, Surface Temperature, and Weather Condition.*

e. *Retroreflectivity, Night Color, and Day Color:*

These are tables that contain the retroreflectivity and color measurements from the field comprising of 19 fields with Test Deck ID and Date of Measurement as primary keys. All the tables have same number of fields namely Test Deck ID, Date of Measurement, and 17 other fields for filed measurement on different locations as intended in the design of test decks. Measurements are entered based on the location of readings on the transverse lines and longitudinal lines with five points on transverse lines (near edge line, right wheel path, center, left wheel path, near skip line) and 12 for longitudinal lines (five and seven).

All the tables are related with a one-to-many relationship as shown in [Figure 28](#), illustrating the design of the database. This design is based on the version developed for performance monitoring on test decks. The Manufacturer Information table has a one-to-many relationship with the Product Information table indicating that one manufacturer can have many products that can be tested. Also each product could be installed at several test deck locations leading to a one-to-many relationship between Product Information table and Test Deck Information table. On the same lines each site can have several test deck sections and thereby leading to one-to-many relationship between Site Information Table and Test Deck Information table. Finally each test deck has three sets of readings (retroreflectivity, day color, and night

color) that are collected leading to a one-to-many relationship between the tables Test Deck Information and Retroreflectivity, Night Color, and Day Color.

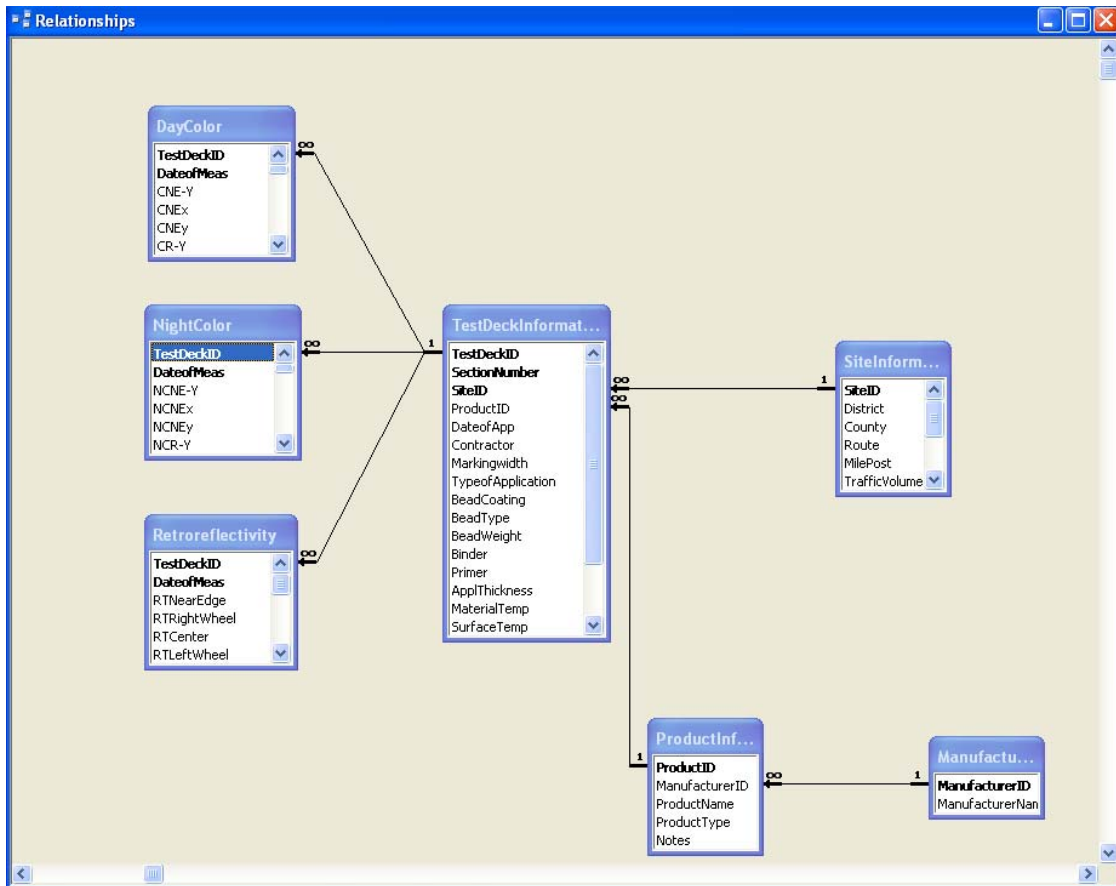


Figure 28. Relationships Illustrating the Basic Design of the Application.

Edit Information

The administrator and the moderators can edit or add the data using the above described tables. Data entry was made simple by adopting the data sheet view as in Microsoft Excel. All the information related to the installation of the test deck and the performance measures can be entered. A safety feature was included based on the user information, for instance the administrator can view all the objects and can delete the unnecessary or obsolete information whereas moderators can only add data to the existing data.

Exploring Information

Users approved with desired security level can search or view existing information depending on the search criteria. The Search tab on the switchboard guides the user to search the

existing information depending on the search criteria. As mentioned the search can be based on a single attribute or a combination of attributes. The search results can be printed or exported into different formats. Graphs can also produce displaying trends of different parameters like retroreflectivity over time in a location, or the values of the same product in a same job at different locations at a given time. Objects like queries and forms are used to explore the existing data.

Queries

Queries are the objects used to view the information or the data present in the tables in a much refined or desired fashion. In the current application the users can design their own queries and access the information based on the requirements. However this requires some knowledge and expertise on Microsoft Access. Queries can be used to view, filter, and print information based on different criteria/requirements. This can be very useful in sharing and exporting only the desired information.

Forms

Forms are objects that act as a user-friendly interface to get the desired information. Unlike queries, users can directly utilize the existing forms to get the desired information without having any knowledge of their design. PMMS has several forms designed to assist the user to access the information easily, more information on the forms, and their description is given below.

Splash Screen and Switchboard

Splash Screen is a type of form that welcomes the users to the application (Figure 29). It provides general information about the application also additional features like disclaimers, copyrights, and help information can be added. A macro is enabled on clicking the close button leading to switchboard. Switchboard is another form that functions as a main menu to the users. It includes two options, one to search for a particular product or location, and the second option is to view charts for performance study or comparison (Figure 30).

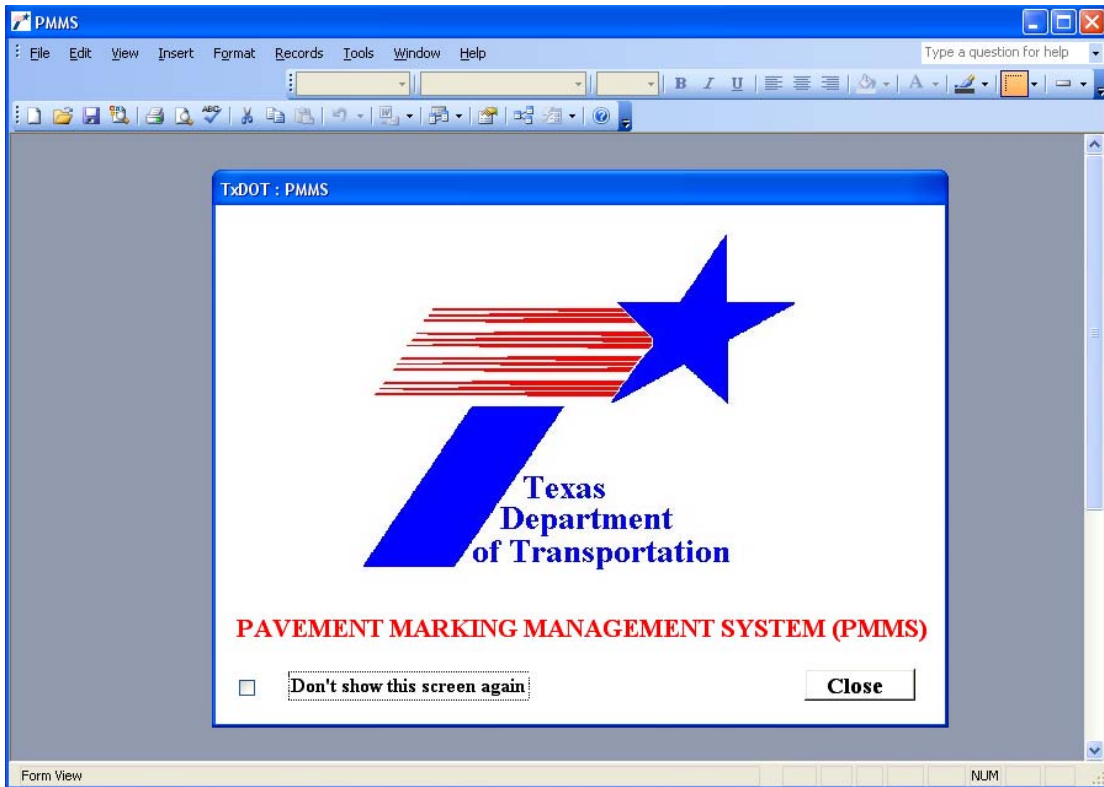


Figure 29. Splash Screen.

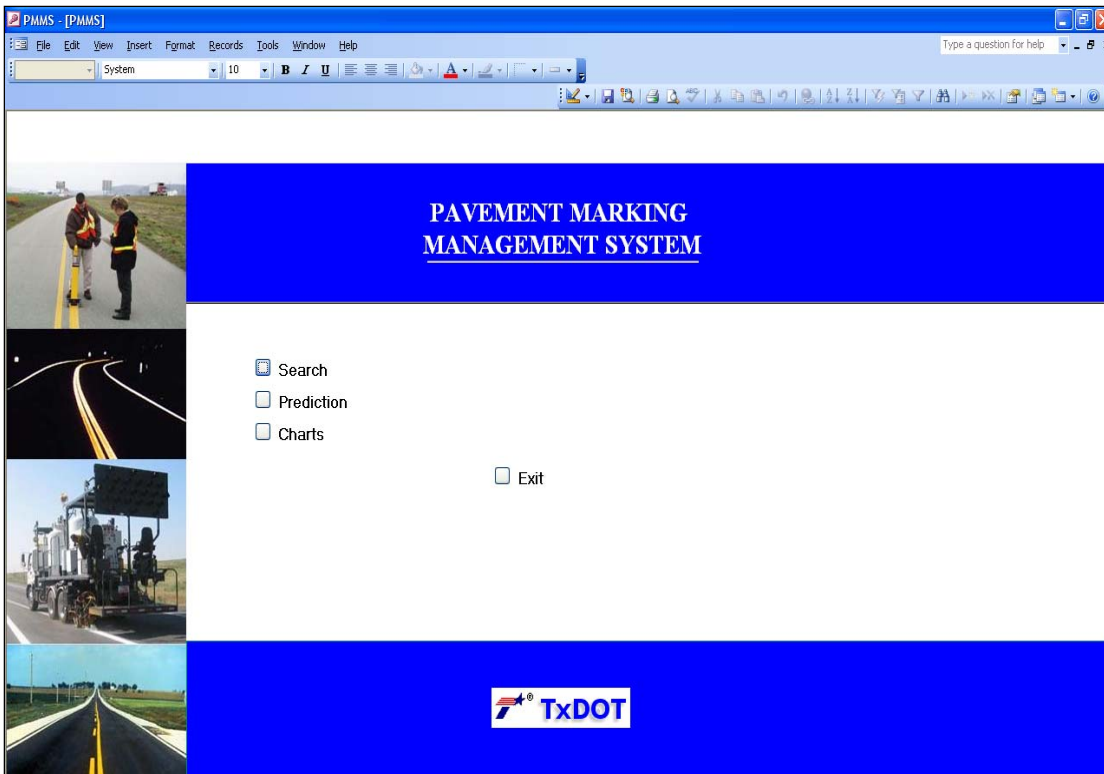


Figure 30. Switchboard or Main Menu.

Search Form

The search form enables users to access complete information regarding a particular product installed or a location. This search selection on the main menu in turn has two options, which are ‘Search by Product’ and to ‘Search by Location’ as illustrated in the [Figure 31](#). The user can choose between these two options to examine the performance of a single product at multiple location or multiple products at a single location. [Figures 32](#) and [33](#) illustrate the Search by Product option, a set of drop-down combo boxes can be used to view the data related to that particular product. These three boxes are a set of cascading combo boxes designed in a way that when a manufacturer is selected the next combo box that is Product fetches all the products installed from this selected manufacturer. Then Date of Application combo box gets refreshed and displays only those dates on which that particular product is installed after selecting the above two combo boxes. Finally on hitting the Search button showed in the [Figure 32](#) test deck, site, measurement, and photo information of that product are displayed on a pop-up form as shown in [Figure 33](#). By clicking Next or Previous buttons, users can examine real photos of that particular product in different collecting times. A similar form is designed for search by location option that presents all the products installed at that location. For editing and managing real photos conveniently there is a form named by Inputimage that helps users manage these photos. After double-clicking the Inputimage form, a pop-up window will appear as shown in the [Figure 34](#). Users can select a particular section in a test location by using these two combo boxes of the pop-up window. Then a pop-up window appears by clicking the Search button as shown in the [Figure 35](#). Next and Previous buttons allow users to view different real photos over time in this particular section. Users also can change and add new photos by clicking Add Image button and selecting the photos users want.

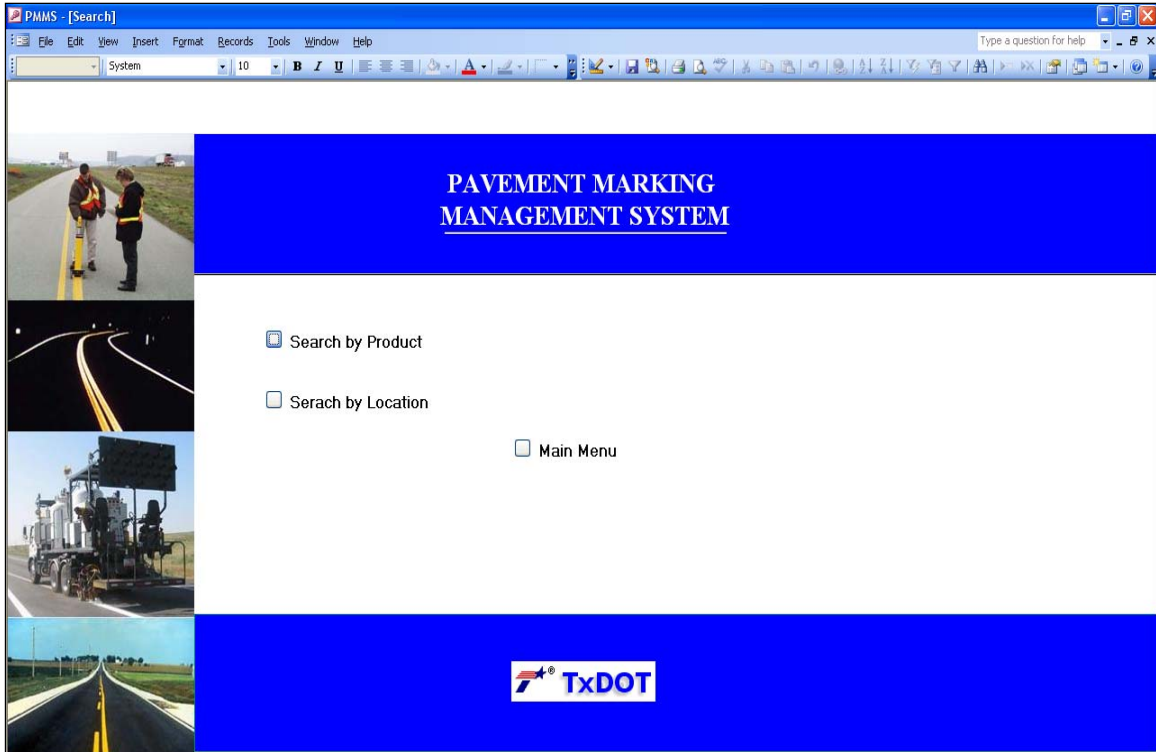


Figure 31. Search Menu with Search by Product and Location Options.

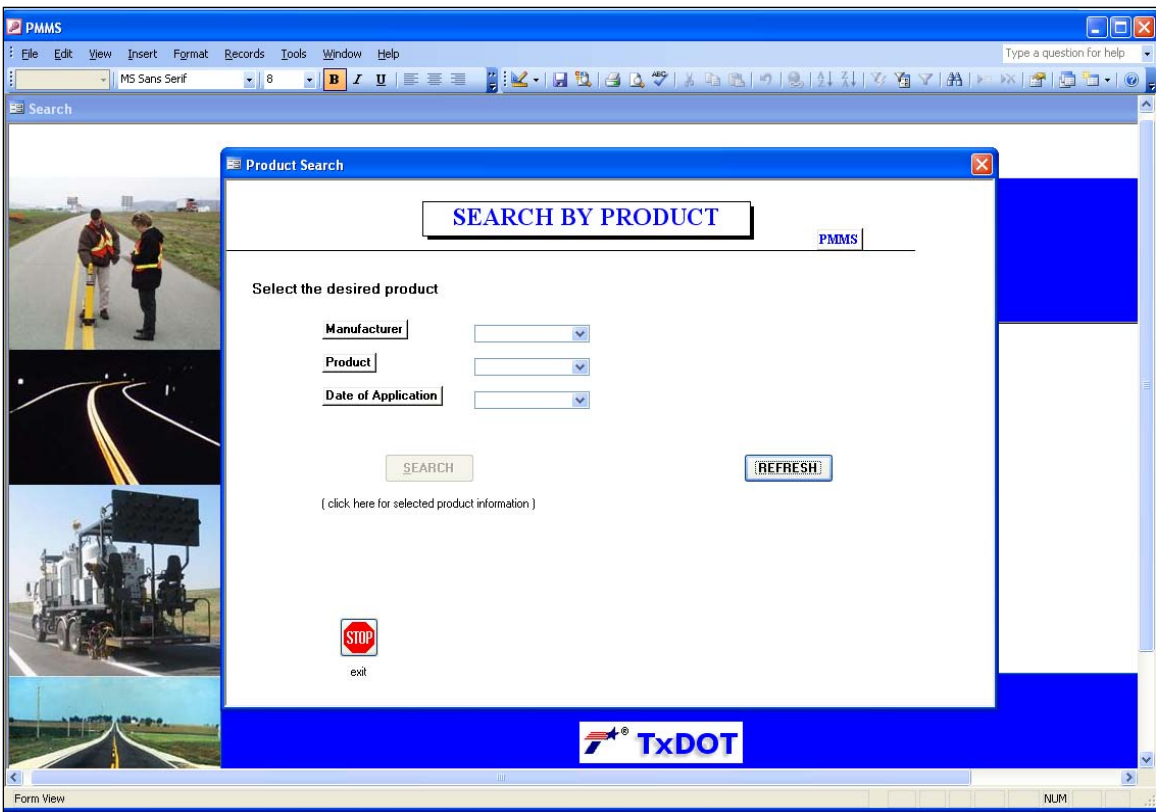


Figure 32. Search Form with Search by Product Drop-Down Combo Boxes.

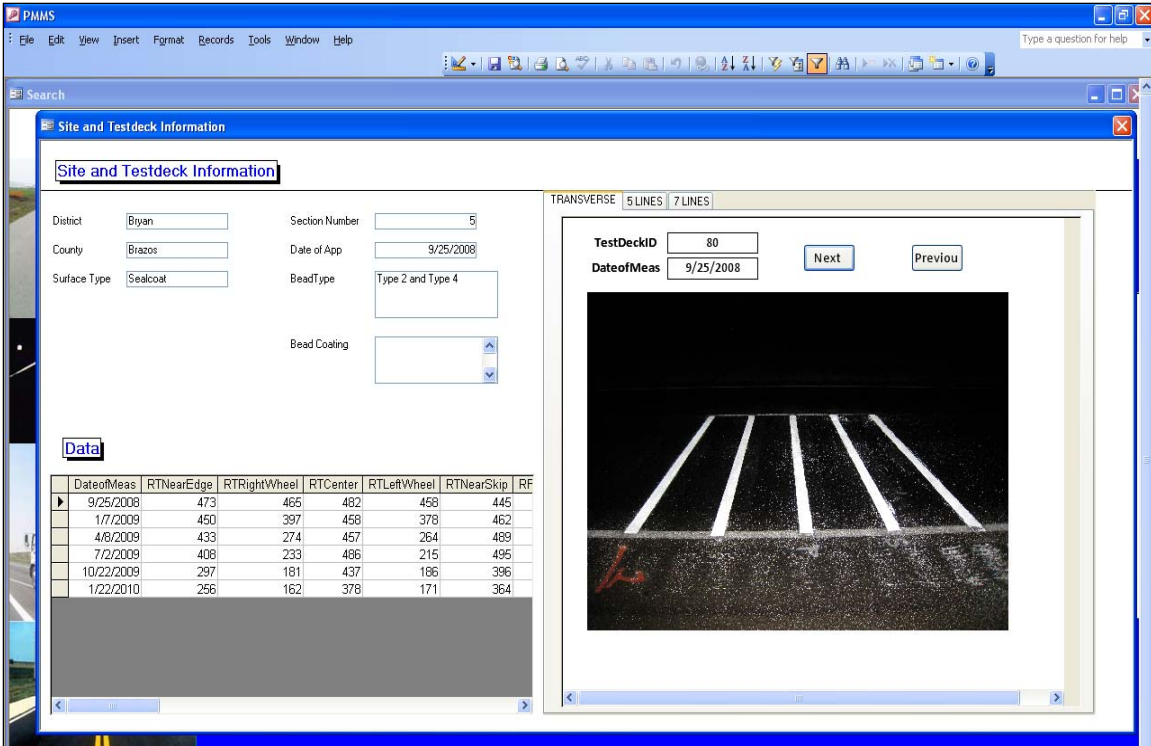


Figure 33. Final Pop-Up Form Displaying Site, Test Deck, and Measurements of a Particular Product.

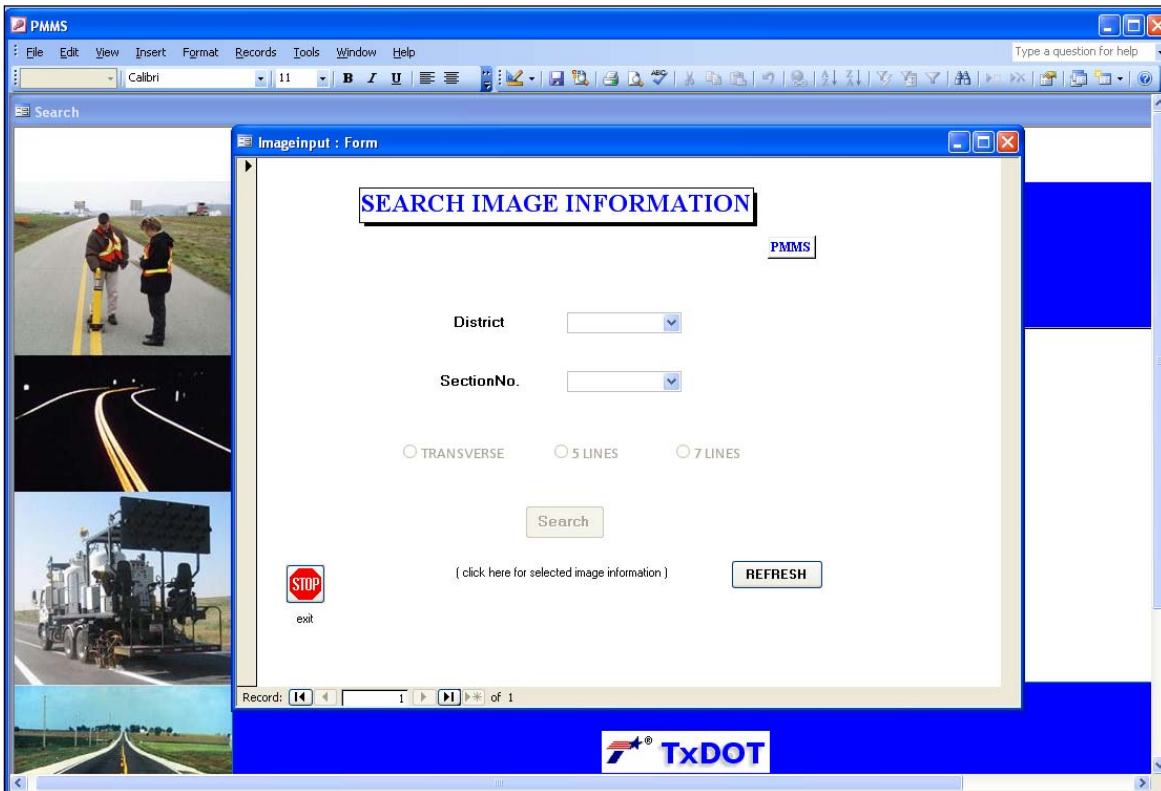


Figure 34. Search Form with Search by a Section of a Particular Location for Inputting Images.

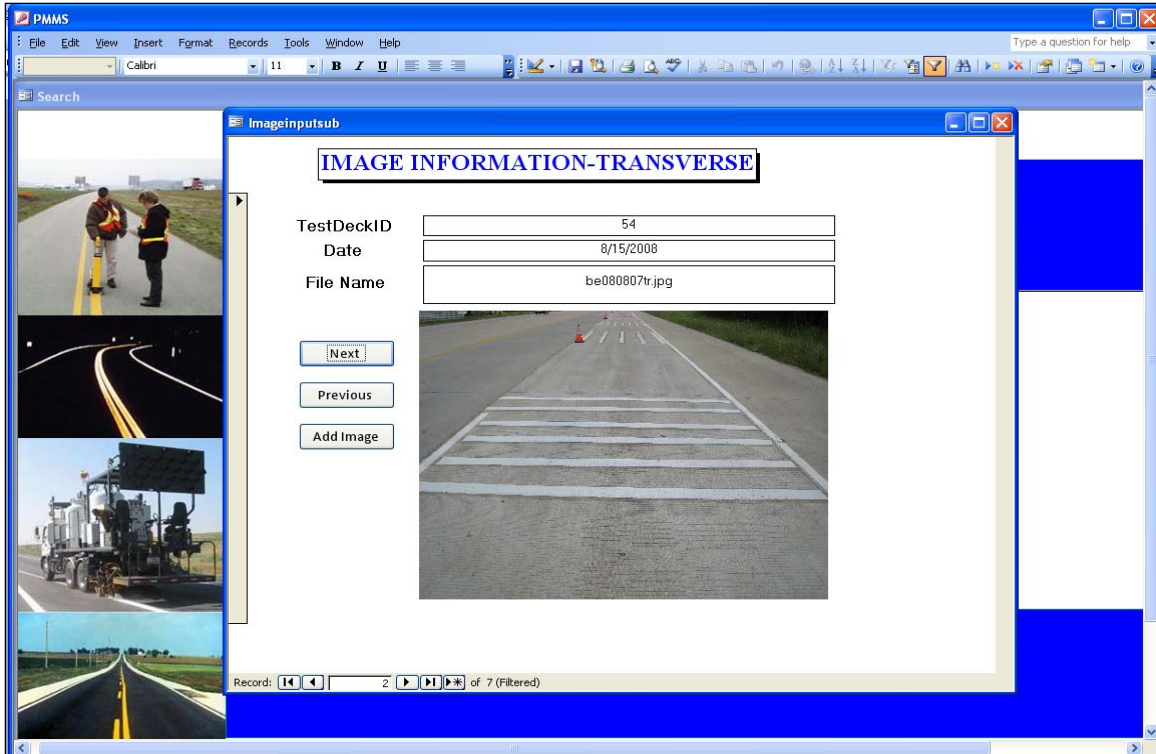


Figure 35. Pop-Up Form Displaying the Image of a Section of a Particular Location.

Chart Form

The charts form allows users to view the performance of the products graphically through interactive charts. This form consists of two options Interactive Chart and Interactive Form shown in [Figure 36](#). The option Interactive Charts can be used to monitor the performance of a single product or a section over a period of time or to compare different products installed by selecting a particular location using the drop-down box as shown in [Figure 37](#). When the desired location is selected, the three buttons located below the drop-down box will be enabled and allow users to choose different marking types. In which transverse represents transverse lines, five represents longitudinal five lines and seven represents longitudinal seven lines. Users can restart their selection by clicking on refresh bottom to clear all the selected records. After the selection of location and marking types, another window with the chart information will pop-up as shown in [Figure 38](#). The most important design feature of this form is its flexibility, charts' form can be modified as desired by the user by hitting the drop-down arrows by the field names as shown in [Figure 38](#). The selection in the fields names 'manufacturer name, product name, product type, section number, and date of measurement' on the chart can be changed using these drop-down

arrows to view only particular information. Buttons on top of the chart represents individual lines shown in the chart. Users can left click on the button and drag it out of the window to delete the selected line. To add the lines to the chart, the users need to right click in the chart field and select the field list option. The option Interactive Form can be used to compare the performance of different products in a measurement point by selecting a particular product type and location using the drop-down box as shown in Figure 39. After selecting District, Manufacturer, Product, and Section Number the toggle buttons become enabled in the sketch map as shown in Figure 40. Users can select the measurement point in which they want to examine the performance of different products in different locations by clicking the corresponding toggle button.

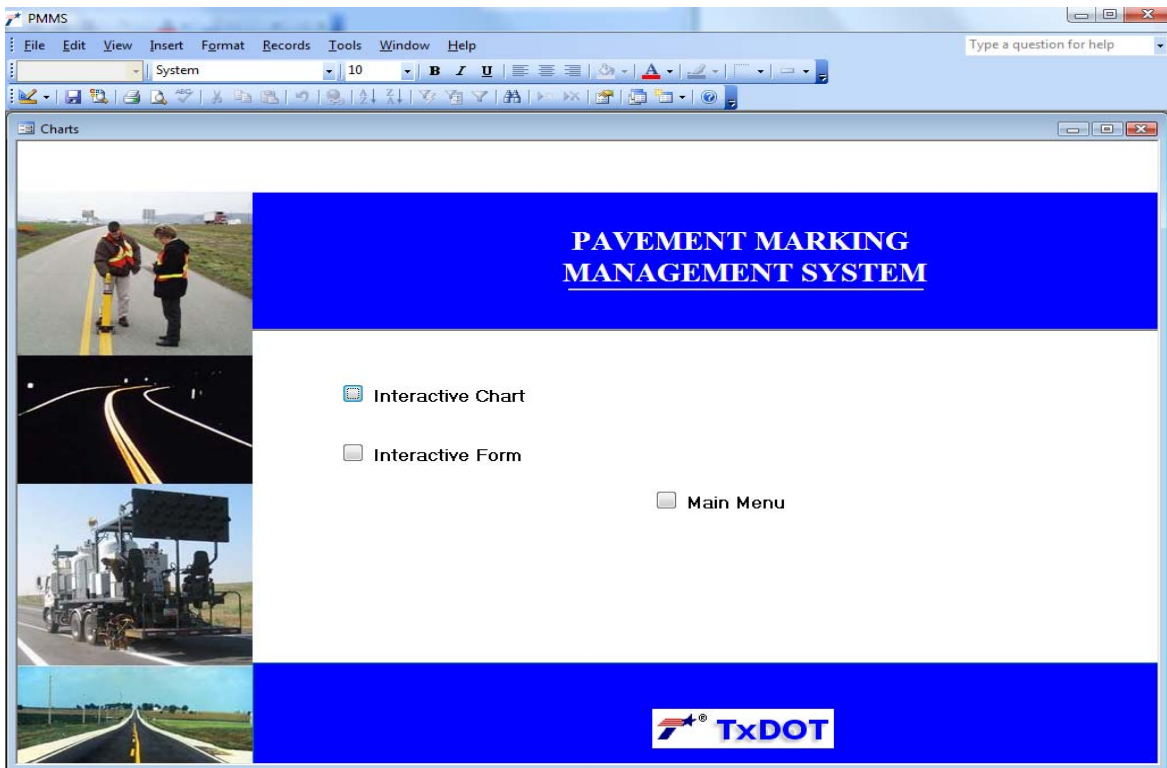


Figure 36. Charts Menu with Interactive Chart and Form Options.

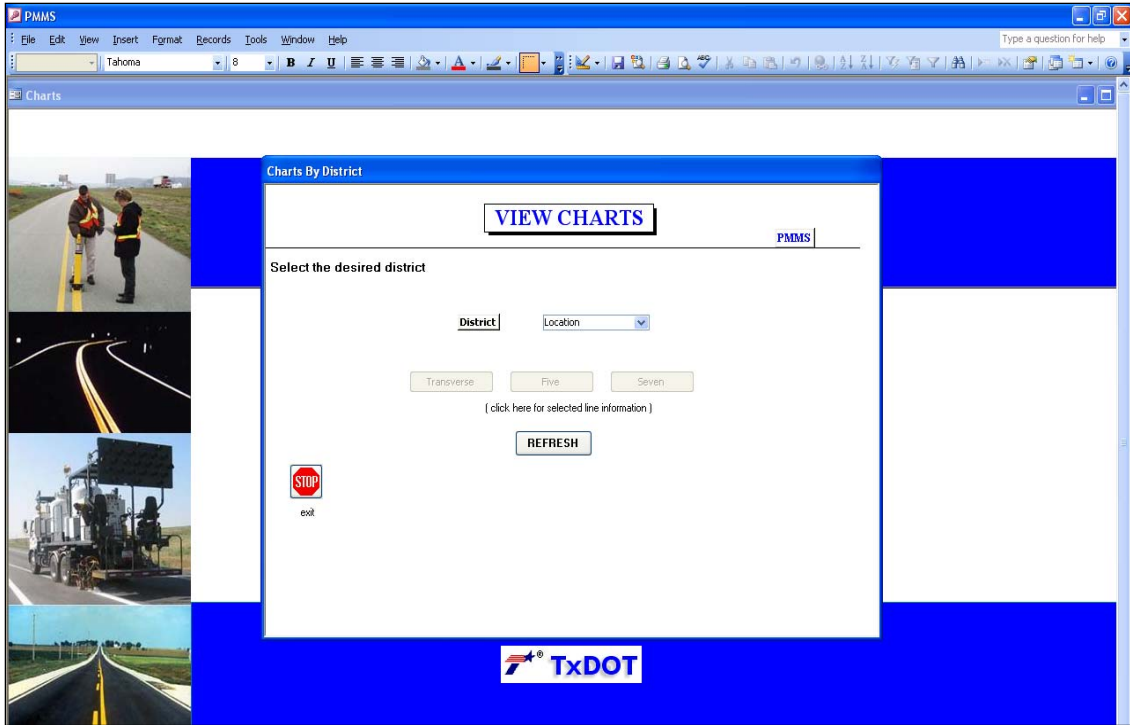


Figure 37. Chart Form to View Graphical Performance.

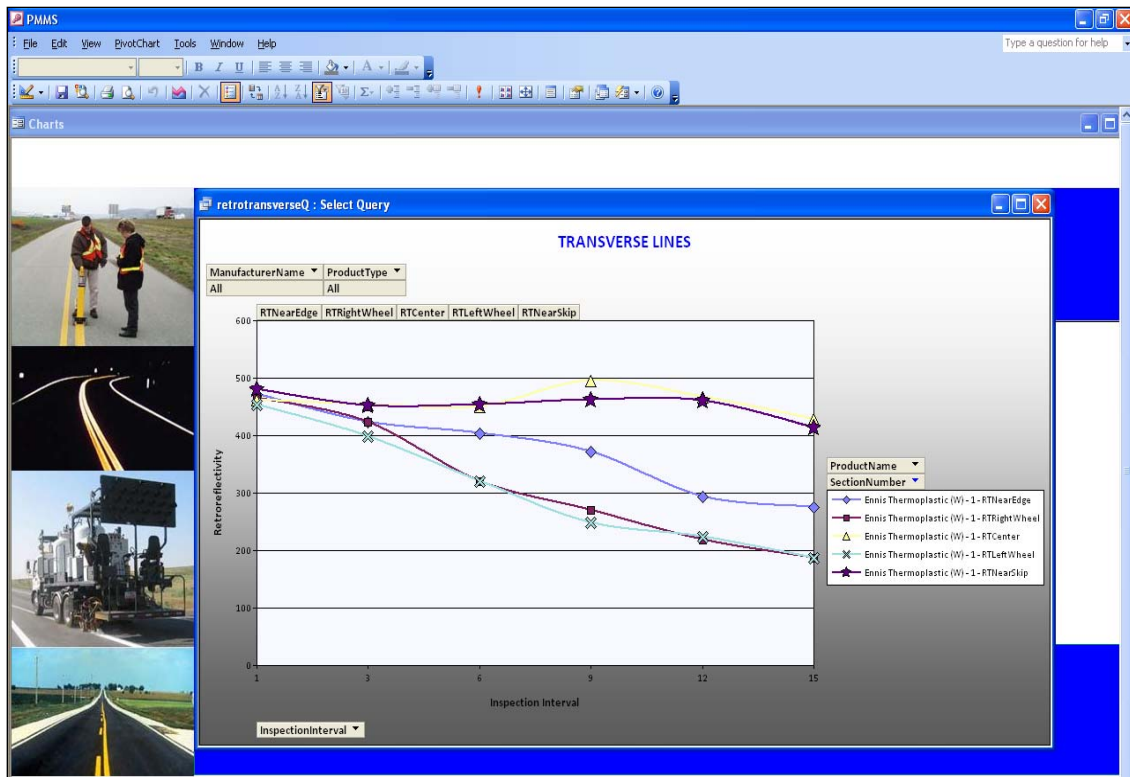


Figure 38. Interactive Chart with Drop-Down Arrows.

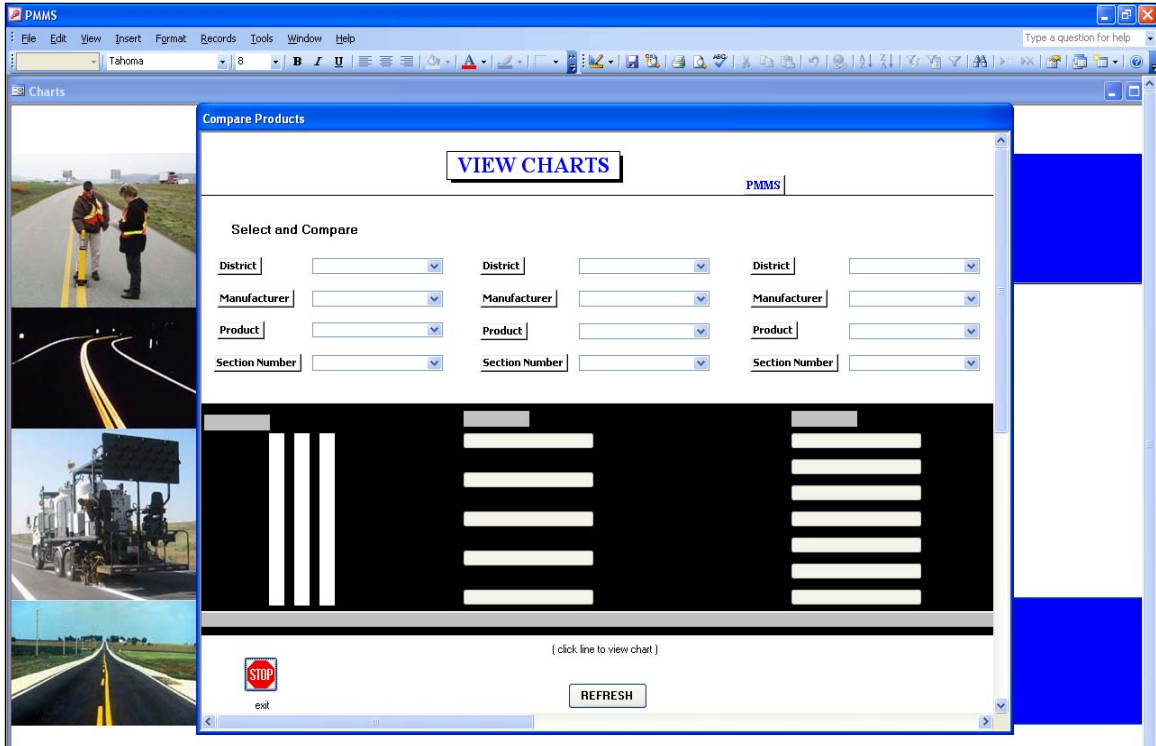


Figure 39. Interactive Chart Form to View and Compare Graphical Performance.

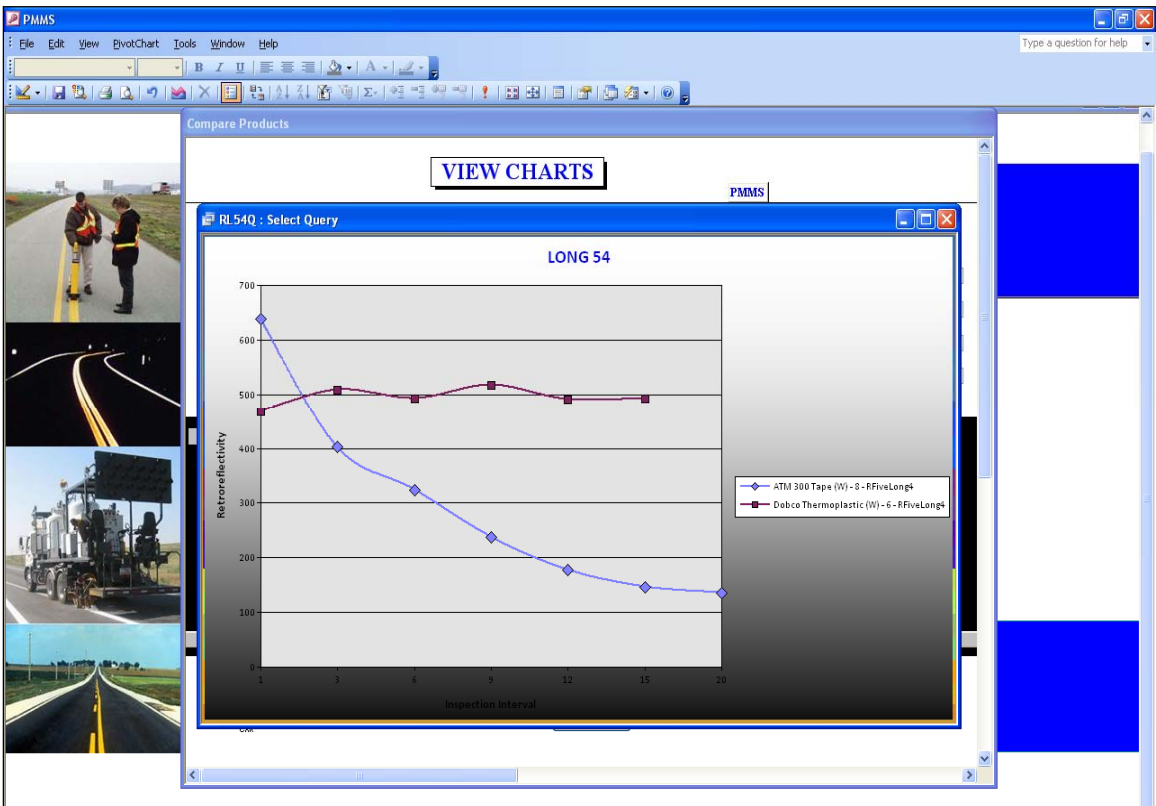


Figure 40. Chart Comparison of Products Installed at Different Locations.

Prediction Form

The database has a main function of predicting the future performance of pavement markings with the basis of the PMM performance prediction model developed by researchers. The prediction model is investigated in order to accurately predict the future performance of pavement markings. Prediction is also a feature in the tracking database that a user can use to estimate future retroreflectivity value based on historical readings. As a univariate model, the time series model is the most widely used in many fields and is easy to implement and understand. In order to investigate the performance of pavement markings the future retroreflectivity is predicted based on the past data. In the time series analysis, three broad classes are the Autoregressive (AR) models, the Integrated (I) models and the Moving Average (MA) models. The Moving Average (MA) model, a common approach for modeling univariate time series model, is selected as the prediction model because it can overcome the sudden fluctuation and make the prediction smooth. The error between every two adjacent measurements is used as the prediction data shown below.

$$Y_{t+1} - Y_t = (Y_{t-4} - Y_{t-5}) + 3 * (Y_{t-3} - Y_{t-4}) + 4 * (Y_{t-2} - Y_{t-3}) + 3 * (Y_{t-1} - Y_{t-2}) + (Y_t - Y_{t-1})$$

Based on the validation with the data from the test deck, this model can predict the performance of pavement markings very well with a good ability to overcome sudden fluctuations. The prediction model is implemented in the tracking database as a database feature. Given the historical retroreflectivity of a marking system, its future values can be predicted. The historical data have a time interval of 3 months (data were collected quarterly), so the prediction horizon is a one time interval (3 months) or multiple intervals, such as 6 months and 9 months. The following figures ([Figures 41](#), [42](#), and [43](#)) illustrate the prediction process of a selected product in the database.

The users can get the prediction information for each measurement point at some section via the prediction form. After clicking the option of prediction, a form named Prediction will pop-up to let users choose a simple product at some section as shown in [Figure 41](#). In the prediction form there are four combo boxes such as District, Manufacturer, Product, and Section Number, which are used to find the correct data constrained by users' selection in the combo boxes. After clicking the Prediction button below the combo boxes, the initial prediction information form will pop-up as showed in [Figure 42](#). Much information about the product users

want to see will appear in the top left area of the prediction information form, and in the top right area there will be specific data about this product at the corresponding section. In order to get the prediction information, users first need to select the prediction time length, which consists of 3 months, 6 months, and 9 months in the middle area of the form. After selecting the prediction time length users can click the toggle buttons corresponding to the measurement points in which they want to examine the prediction performance in the test section to see the prediction value and curve as shown in [Figure 43](#).

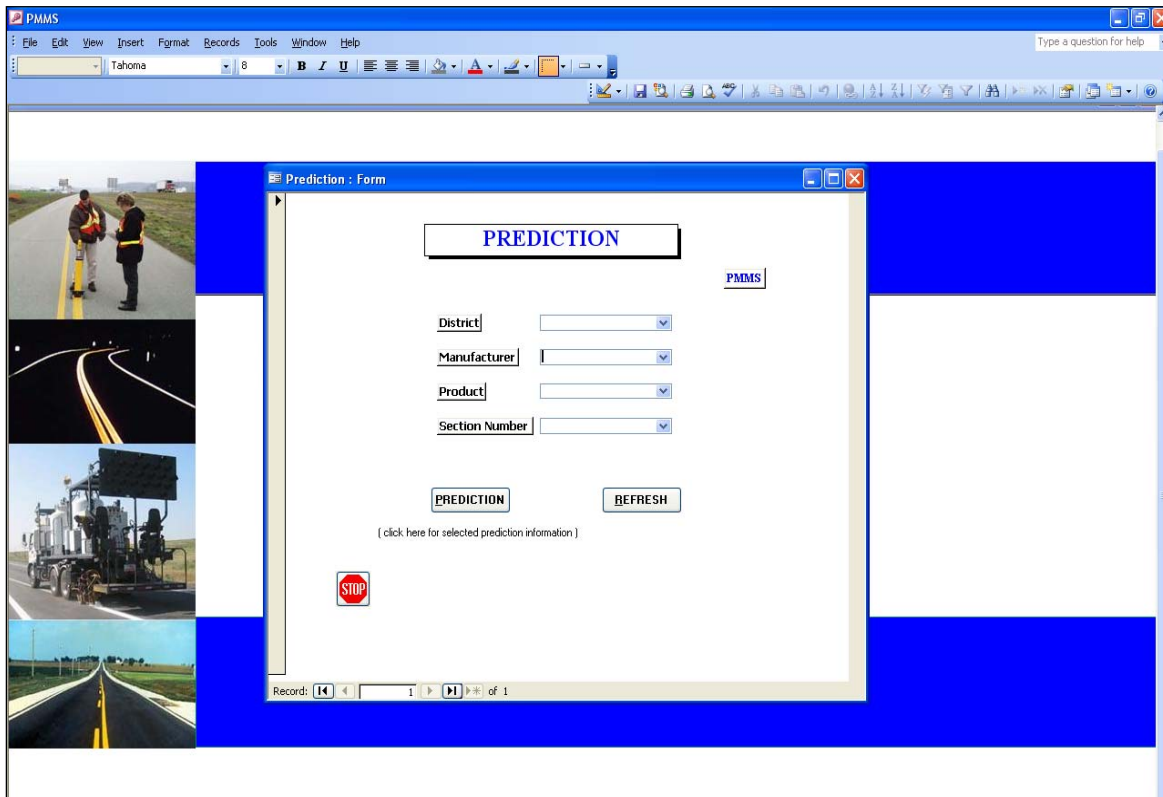


Figure 41. Prediction Form with Search by Product Drop-Down Combo Boxes.

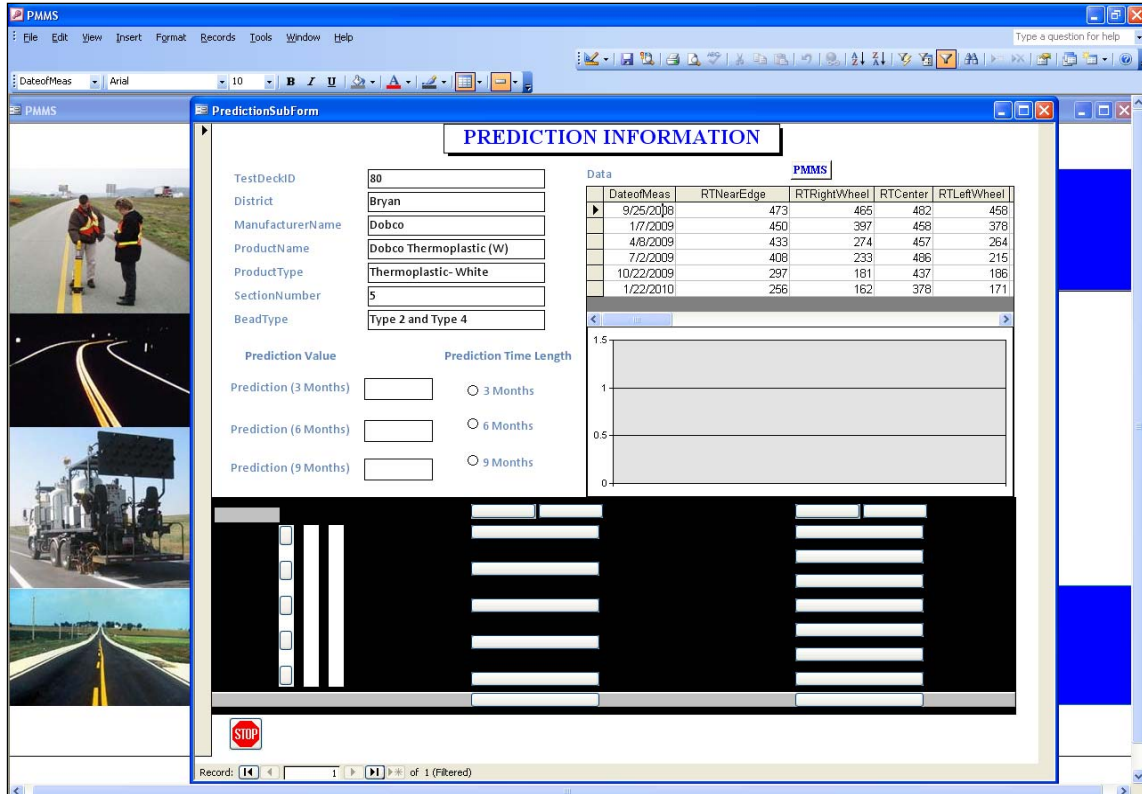


Figure 42. Initial Prediction Information Form.

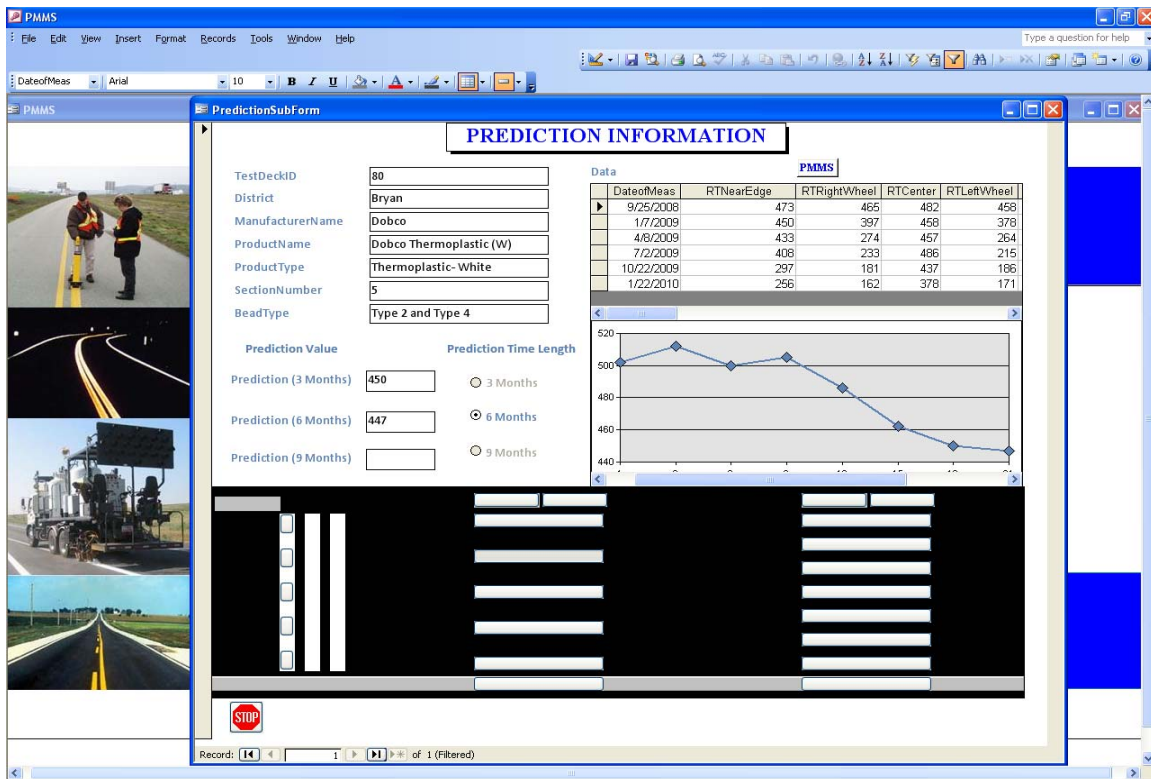


Figure 43. Prediction Information Form.

User Interface and Security

The system includes a user-friendly switchboard that acts as a graphical user interface to access all the functions as shown in [Figure 30](#). The switchboard also acts as a one-point service area for different user groups for multiple applications as the system is enabled with user-level security. This means that the same system can be used as a view/search-only application or view/search/edit-only application depending on the requirement. User-level security enabled to maintain data-integrity by assigning user names and passwords to restrict the data access preventing accidental data loss and at the same time maintaining data integrity.

Description of Version 1.1

This release is based on version 1.0 but deals with real-world data as against version 1.0, which is developed to track the performance of products on test decks installed as a part of the current project. Real-world data from I-27 in Hale and Swisher Counties from the Lubbock District are used to populate the database. This version has a feature to monitor and compare the performance of a product in the form of interactive charts.

Real-World Database

Real-world database is used to track PMM performance of real-world projects. The database is populated with data collected by TxDOT districts with mobile retroreflectometers. Opening the real-world database, a switchboard similar to the test deck database pops-up, which functions as a main menu for the users to start search by products, to compare performance between different products or to view performance charts ([Figure 44](#)).

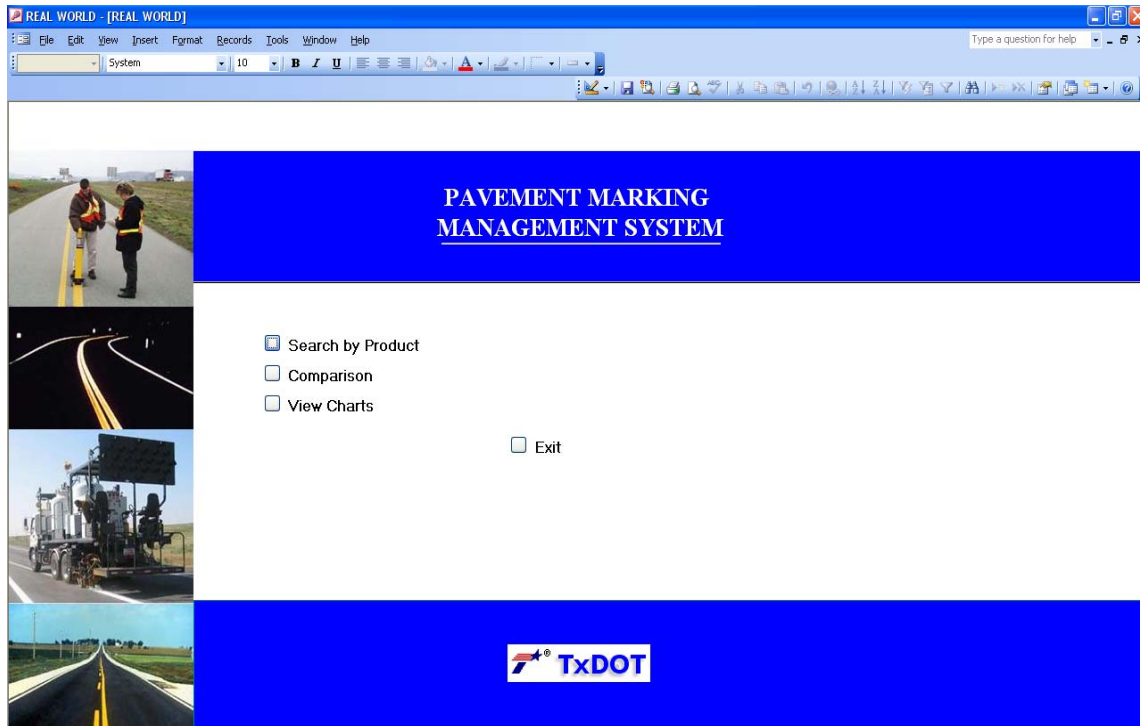


Figure 44. Switchboard in Real-World Database.

Search by Product

Users can check the performance of the product with different colors via using the combo box options. This search option was shown in Figures 45 and 46. In Figure 45, a set of drop-down combo boxes provides multiple options for users to view the data related to that particular product. These are a set of cascading combo boxes designed in a way that when a manufacturer is selected (only one option called Polyurea), the next combo box fetches all the products installed from this selected manufacturer with different colors. In addition, users could change their selection via clicking the button refresh or directly reselecting combo-box options. Finally on clicking the Search button, a pop-up window was activated as shown in Figure 46, which included information such as site, collection time, and measurement record. Users can drag the scroll bar located in the right hand of the pop-up window to see all the record.

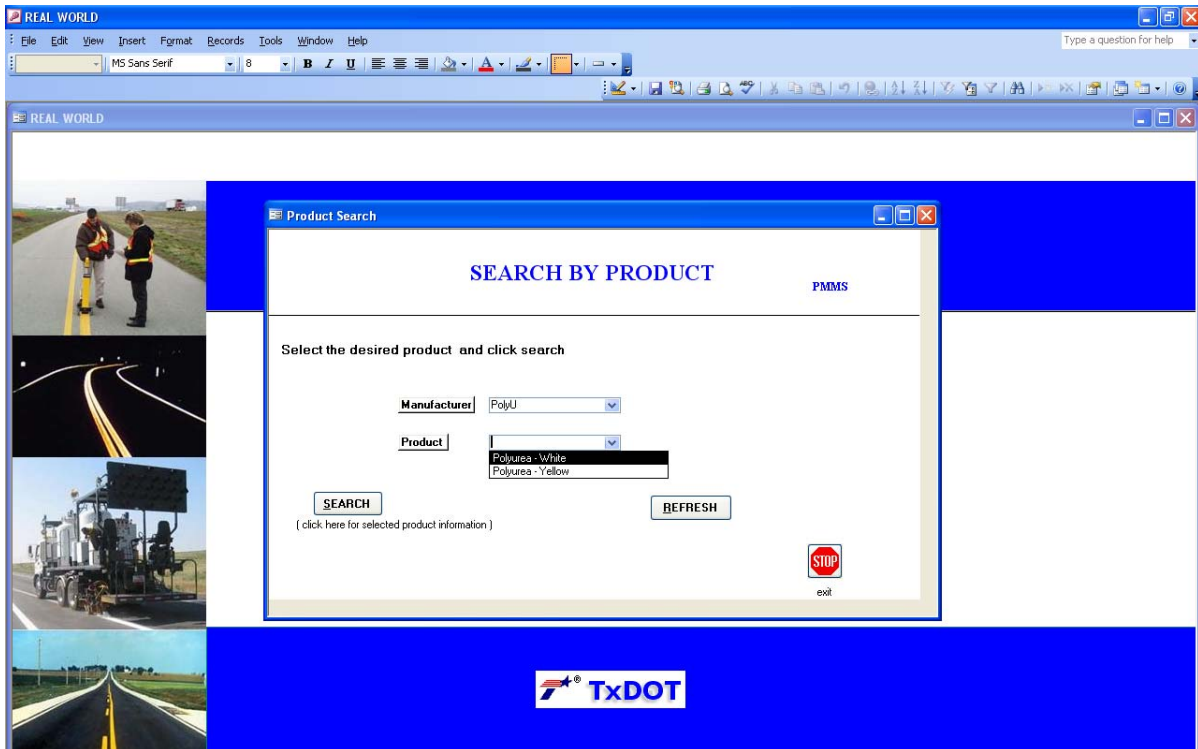


Figure 45. Search Form with Search by Product in Real-World Database.

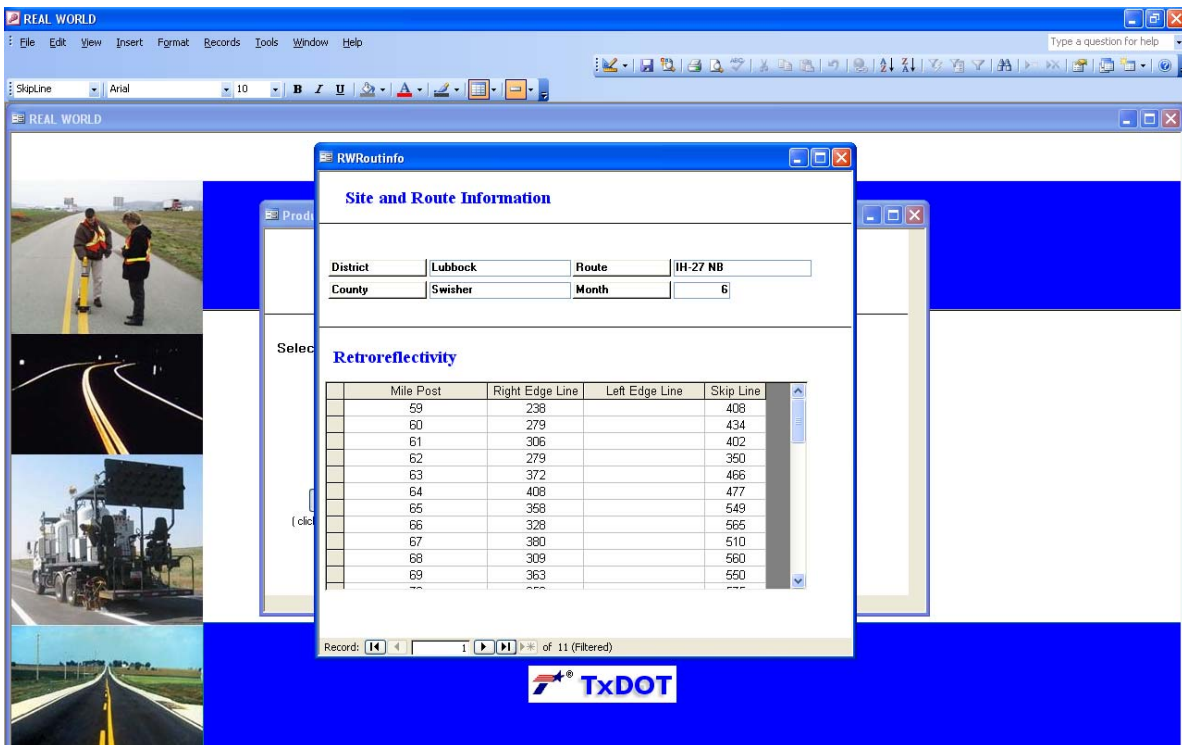


Figure 46. Pop-Up Window of a Particular Product.

Comparison

The option Comparison can be used to compare the performance of different products on different measurement locations by selecting a particular site, a product type, the collection time, a measurement route, and location using the drop-down boxes as shown in Figure 47. After selecting District, Manufacturer, Product, and Month/Route, the toggle buttons become enabled in the sketch map, which can be used to select the exact location, e.g., the right edge of the road, the left edge of the road, or the skip line. As the same way, users can select other products with using the next drop-down boxes. The button refresh can be used to clean all selected options when users want to change their mind. After all options were selected, users can examine the performance of different products in different locations by clicking the button Compare (as shown in Figure 48). However, it should be noticed that at most, three items can be compared once.

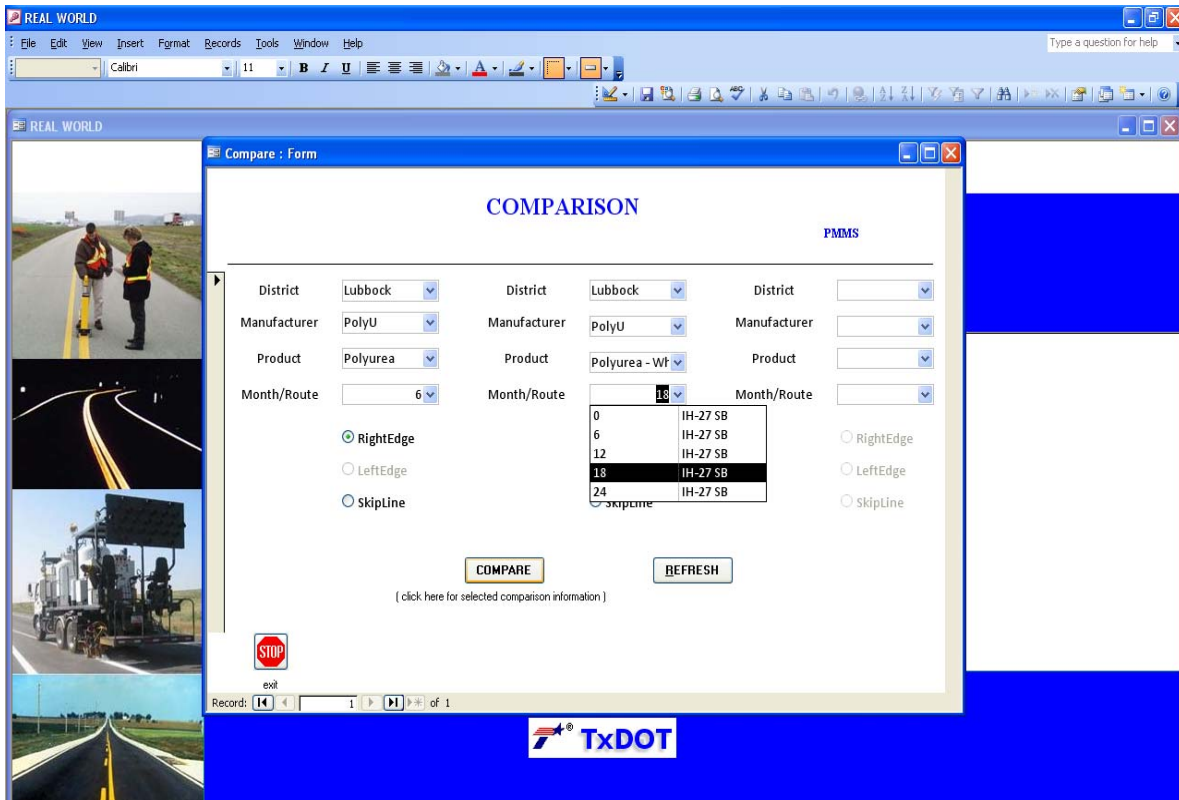


Figure 47. Comparison Form of Real-World Database.

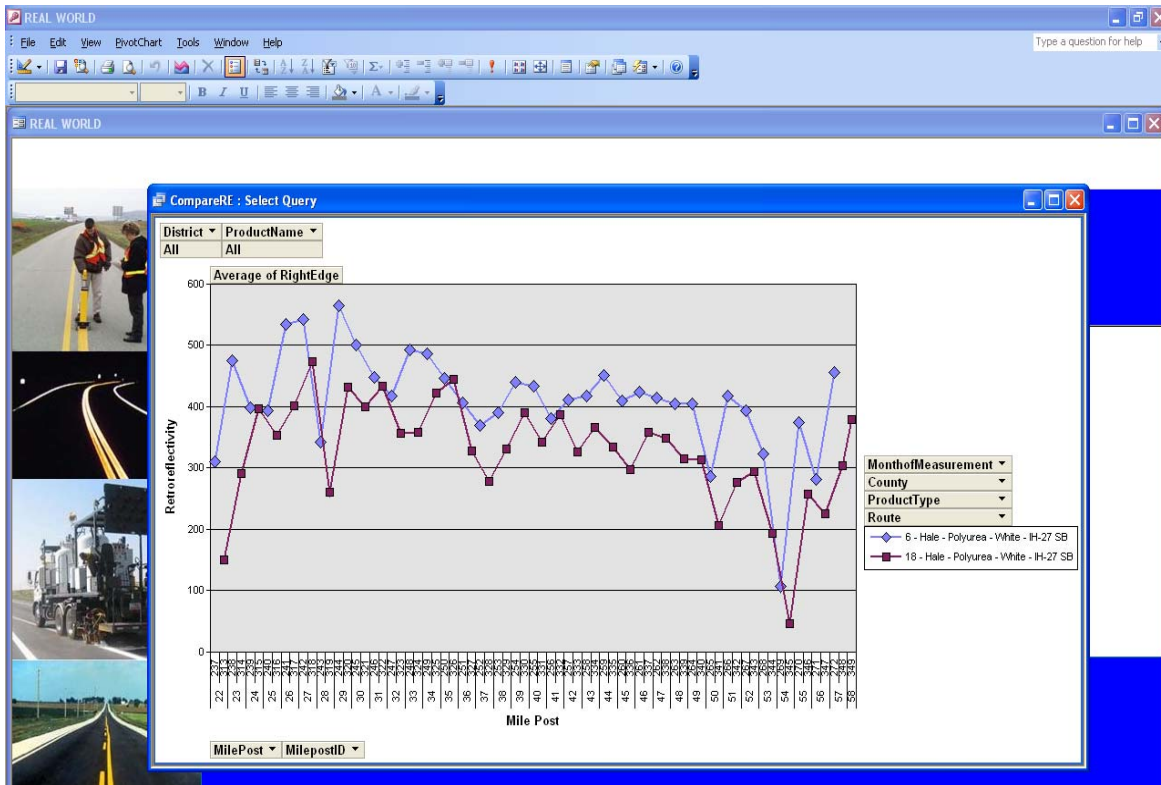


Figure 48. Pop-Up form of Products Comparison in Real-World Database.

View Charts

The option View Charts can be used to monitor the performance of all products over a period of time at a particular mile post or to compare different products or the performance of a product at different time by using the taps on the left top of the window as shown in [Figure 49](#). There were four taps that could be selected to examine the performance of the real-world pavement marking at different locations. The tap by type could make users examine the all products performance at different locations over time. To enhance the flexibility, displayed charts can be modified as desired by the user by clicking the drop-down arrows as shown in [Figure 50](#). The selection in the fields named District, County, Route, Manufacturer Name, Product Name, Product Type, Month of Measurement, and Mile Post on the chart can be changed using these drop-down arrows to view only particular information. The tap right edge line meant that users only can examine the performance of pavement markings located at right edge lines. Similarly, the taps left edge line and skip line only allowed users to inspect the performance at left edge line and skip line, respectively.

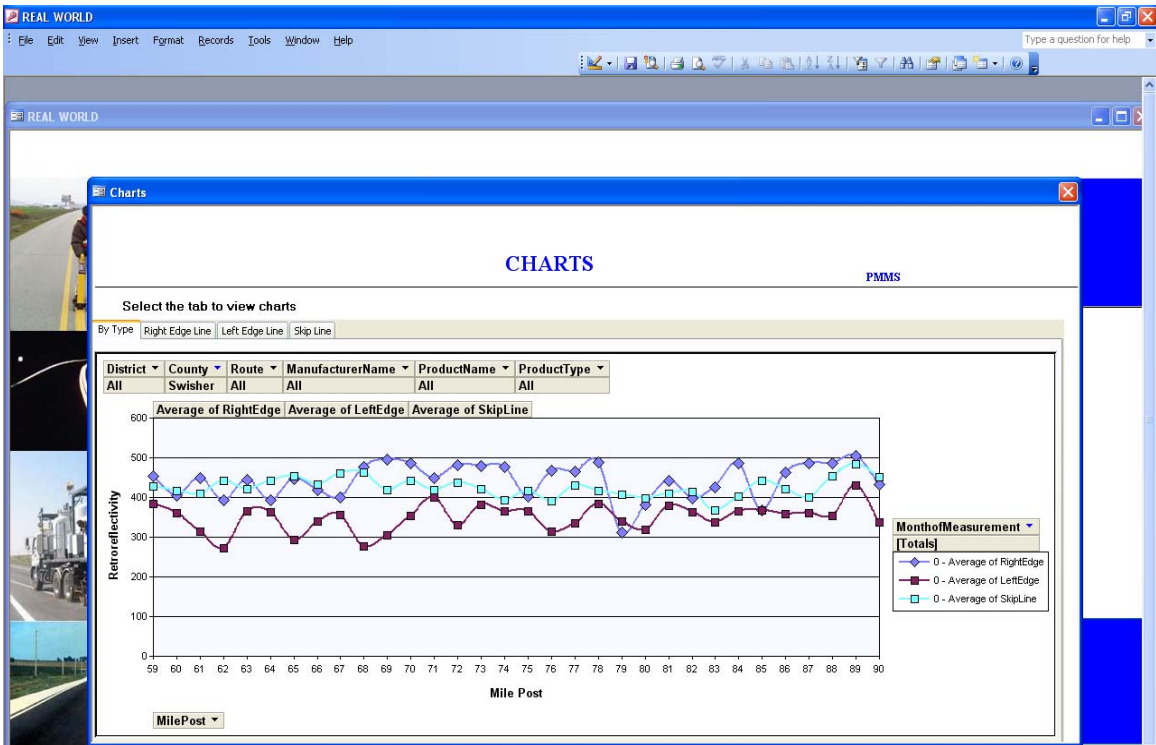


Figure 49. Main Window of View Charts.

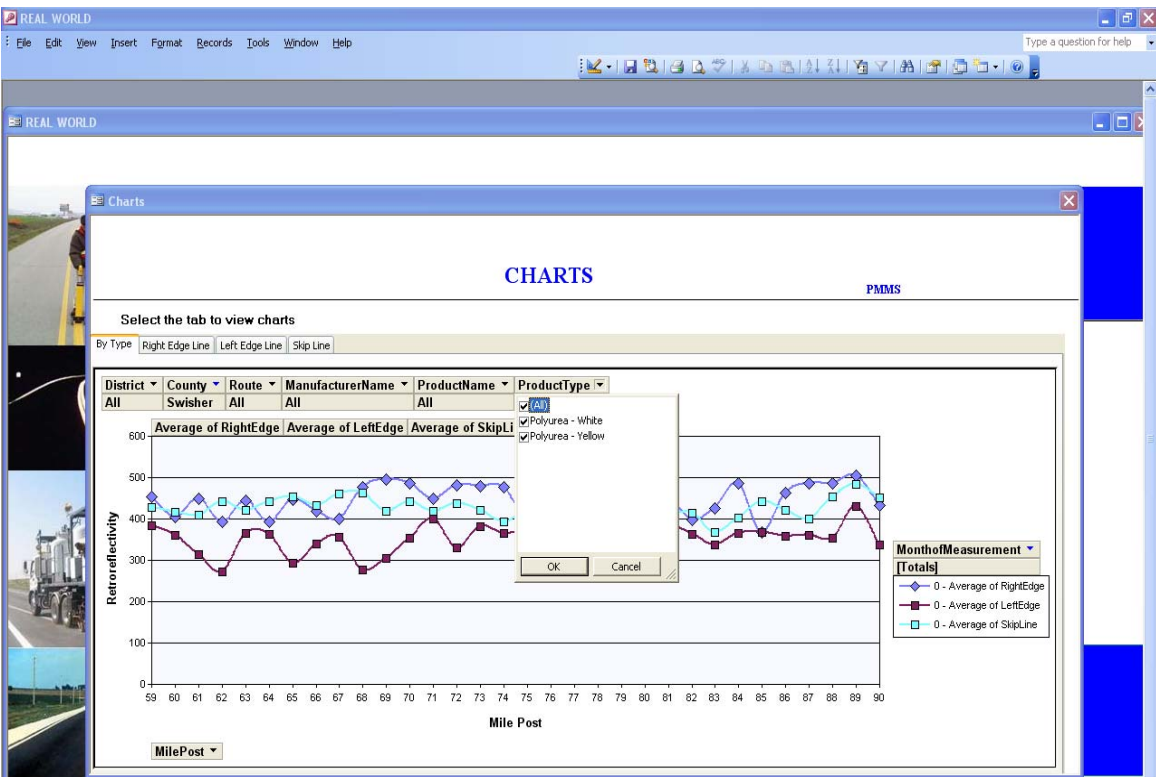


Figure 50. Changing Display with the Drop-Down Arrows.

User's Manual

A separate user's manual of this tracking database is submitted as a separate deliverable (see 0-5548-P1). In the user's manual, both version 1.0 for tracking test deck data and version 1.1, which is a second database designed for storing and tracking performance of PMMs in real-world projects, are described.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This study uses a specially conceived test deck design in order to identify the best design of pavement marking field test decks. Particular, the correlation of transverse lines and long lines are investigated. Additionally, the effects of different application methods are also investigated. A number of findings were obtained through the process of this research described in this report. The statistical analysis results of the retroreflectivity data were obtained based on data collected over a 2-year evaluation period from three pavement marking field test decks specially designed for the purpose of identify the correlation between transverse lines and long lines.

FINDINGS RELATED TO PMM PRODUCTS AND PERFORMANCE

Findings related to PMM products and performance are as follows:

- The retroreflectivity of skip lines applied at the Bryan deck did not have significant changes over the whole duration of evaluation, and the decay rate was rather small. This is likely the outcome of low traffic volume at the test deck location and the fact that the service lives of the installed products are typically longer than the evaluation period of 2 years.
- Skip lines applied by a TxDOT contractor are significantly different with ones applied by vendors. The product applied by regular TxDOT contractor had lower retroreflectivity and a faster decay rate due. The reasons of the poor performance might have been due to narrower and thinner lines with inadequate beads as observed in the field.
- Pavement markings at the Lubbock deck deteriorated at a faster decay rate than the two other test decks, likely due to higher traffic volume and higher truck percentages.
- Retroreflectivity data analysis indicates that the measurement points near the wheel path have lower retroreflectivity values than the other measurement areas regardless of being in the transverse, five or seven line measurement sections for all test decks.
- Different products have markedly different performance, which signify the need of field evaluation. The final retroreflectivity values are related to initial values and the rate of decay, both vary from product to product.

- At the Beaumont deck, Ennis-MMA, had the lowest initial and final values. Ennis-Thermoplastic, white thermoplastic applied on black thermoplastic, has the highest initial value, but with a higher decay rate.
 - At the Lubbock deck, WaterDURA-Ennis-Paint has the highest initial retroreflectivity value among all products; Mark70.3-Poly-Carb-Epoxy had the lowest final value than all other products despite of a rather high initial value, which demonstrated a fast decay rate than others. It is likely due to the fact that the larger bead used in this material was more susceptible to disposure and wear. A lower decay rate was observed for Premark-Ennis-Tape, indicating its good capability of retaining the retroreflectivity.
- Application method may affect pavement marking performance. At the Bryan deck, long lines were applied both by sprayed and extruded. Dobco applied by extruding performed poorer as indicated by the low retroreflectivity values. Ennis applied by extruding had the highest initial and final values, but appeared to have a faster decay rate. In general, the extruding applications at the Bryan deck resulted in better retroreflectivity performance than spraying applications for some of the marking systems. Statistically the method of application appeared to affect the performance of pavement marking to some extent. Two individual sections where the same products were installed with different methods of the application had statistically significant difference in retroreflectivity performance. However for other products (in other two sections) the differences were not statistically significant.
 - The data analysis indicated that when long lines are installed in the travel lane, drivers did not appear to change lateral positions to avoid hitting longitudinal test markings because of the lower retroreflectivity values on wheel path than those on other measurement positions. The setups of seven lines and five lines did not appear to affect the driving path either.
 - Preformed thermoplastics (hot tapes) do not have a consistent performance.

FINDINGS FROM THE CORRELATION ANALYSIS

Findings from the correlation analysis are as follows:

- The average transverse test deck performed similarly to the average longitudinal test deck due to the fact that the points of the transverse lines generally have high correlation with the corresponding points of the five and seven longitudinal lines. This is particularly true when the long lines are also applied with handcarts (transverse lines are all applied with handcarts). When long lines are applied with long-line trucks, the correlation weakens to some degree as found on the Bryan deck.
- At the Bryan deck, the correlation between near edge (both on transverse line or long lines) and actual edge line, or between near skip (both on transverse line or long lines) and actual skip is inconclusive, with a poor correlation. The poor correlation between values from near skip locations and the actual skip location and between near edge and actual edge could be due to the result of the slow decay in retroreflectivity values. A positive correlation may be found when the values further decrease.
- Transverse line points generally have good correlation with corresponding five or seven long lines even though there may be differences in averages. For example, at the Beaumont deck, the good correlation between the transverse lines and five/seven longitudinal lines can be found in product ATM that had statistical difference in values between the two designs (transverse versus long line). The measurement points of the transverse lines from the products Ennis-polyuria and Ennis-thermoplastic were highly correlated with their corresponding points of five/seven longitudinal lines without statistical difference between them.
- At the Lubbock deck, all individual sections demonstrated a good correlation between the transverse lines and five/seven longitudinal lines except the product Ennis-Flametape Alternate installed in section 14. In addition, the measure point of the transverse lines near left wheel path is highly correlated with its corresponding point of the five longitudinal lines, and there was no statistical difference in values for all installed products.
- The correlation between transverse and long lines may be inconsistent when comparing one single product. This is probably due to the generally high variability of retroreflectivity readings.

RECOMMENDATIONS

Based on the results from this research, we make the following recommendations:

- If in-lane long line deck is to be used, the five line design should be used. The seven line design does not provide additional advantages and do not capture wheel path locations as well. This recommendation is based on strong correlation and similar retroreflectivity values between corresponding lines.
- Transverse line decks can in general replace long-line deck in-lane because not only the correlations are strong, the retroreflectivity values between locations on transverse lines and corresponding long lines are similar.
- When a transverse line deck is used, the near skip line readings are typically close to those on actual skip lines. The readings on wheel path locations have a generally strong relationship with the actual readings on skip lines.
- Hot tape field testing typically does not yield consistent results. Caution should be given when evaluating field performance of the hot tape products because the readings are highly influenced by the installation.
- When installing field decks, comparison should be made between products that are installed with the same application methods. This study revealed that different application methods, extruded vs. sprayed, or handcart vs. long line truck, may affect field performance for some PMMs.
- At the Bryan deck, results for some correlation analyses were inconclusive, due to the fact that readings were rather flat during the 2-year evaluation period. When designing a test deck, a higher ADT value is preferred. Otherwise, a longer evaluation period will need to be adopted for durable products.
- Installation quality critically affects field performance of the PMMS. This is very evident when comparing the performance of the same product installed by a regular contract and by the manufacturer. Quality control of installation is highly recommended.

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APPENDIX

Table 1. Correlation between Transverse Lines and Longitudinal Lines for Individual Section at Beaumont.

Section 7 (Flint-Tape)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.12	0.96	-0.50	-0.20	-0.63	0.98	0.96	0.96	0.95	0.96	0.96	0.93
Right Wheel	0.19	0.97	-0.55	-0.37	-0.75	0.96	0.98	0.98	0.97	0.98	0.99	0.98
Center	0.48	0.13	0.61	0.13	0.21	0.40	0.21	0.24	0.45	0.20	0.18	0.42
Left Wheel	-0.02	0.97	-0.65	-0.30	-0.79	0.93	0.97	0.98	0.95	0.98	0.99	0.94
Near Skip	0.76	0.04	0.39	-0.35	0.27	0.33	0.19	0.21	0.36	0.15	0.17	0.36
Section 8 (ATM-Tape)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.92	0.99	0.98	0.98	0.95	0.93	0.99	1.00	0.97	0.99	1.00	0.96
Right Wheel	0.88	0.99	0.98	0.99	0.94	0.89	0.99	1.00	0.97	0.99	0.99	0.94
Center	0.93	0.93	0.97	0.92	0.95	0.94	0.94	0.94	0.97	0.94	0.95	0.97
Left Wheel	0.87	1.00	0.97	1.00	0.91	0.87	1.00	1.00	0.95	1.00	0.99	0.93
Near Skip	0.85	0.75	0.84	0.74	0.87	0.86	0.77	0.78	0.85	0.76	0.81	0.88
Section 9 (Ennis-MMA)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.85	0.17	0.84	0.09	0.85	0.84	-0.05	0.49	0.67	0.72	0.78	0.57
Right Wheel	0.65	0.51	0.93	0.42	0.66	0.57	0.31	0.78	0.40	0.93	0.95	0.27
Center	0.86	-0.59	0.14	-0.60	0.85	0.93	-0.72	-0.25	0.98	-0.02	0.08	0.96
Left Wheel	0.49	0.67	0.93	0.58	0.51	0.40	0.49	0.87	0.22	0.98	0.99	0.07
Near Skip	0.72	-0.77	-0.20	-0.72	0.72	0.74	-0.80	-0.45	0.91	-0.31	-0.21	0.95
Section 10 (Ennis-Poly)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.95	0.90	0.96	0.90	0.98	0.99	0.92	0.91	0.96	0.93	0.98	0.98
Right Wheel	0.88	0.96	0.95	0.95	0.94	0.97	0.97	0.96	0.96	0.97	0.99	0.96
Center	0.97	0.71	0.88	0.71	0.94	0.93	0.75	0.74	0.86	0.76	0.86	0.92
Left Wheel	0.90	0.95	0.96	0.95	0.96	0.98	0.96	0.96	0.97	0.97	1.00	0.97
Near Skip	0.70	0.16	0.42	0.16	0.54	0.52	0.22	0.18	0.36	0.22	0.38	0.51
Section 11 (Ennis-Poly)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.91	0.96	0.91	0.97	0.88	0.94	0.97	0.98	0.91	0.97	0.99	0.71
Right Wheel	0.87	0.98	0.89	0.98	0.84	0.91	0.98	0.99	0.89	0.99	0.99	0.67
Center	0.85	0.40	0.86	0.41	0.86	0.83	0.45	0.59	0.86	0.47	0.62	0.91
Left Wheel	0.85	0.97	0.88	0.98	0.83	0.91	0.99	1.00	0.89	0.99	1.00	0.66
Near Skip	0.80	0.25	0.78	0.26	0.82	0.75	0.30	0.43	0.77	0.31	0.48	0.92
Section 12 (Ennis-Polyurea)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.97	0.93	0.98	0.91	1.00	0.99	0.93	0.97	0.98	0.95	0.94	0.99
Right Wheel	0.99	0.97	0.98	0.95	0.99	0.99	0.97	0.99	0.96	0.98	0.97	0.99
Center	0.70	0.57	0.83	0.51	0.82	0.80	0.55	0.67	0.86	0.60	0.59	0.83
Left Wheel	0.99	0.97	0.98	0.95	0.99	0.99	0.97	0.99	0.96	0.98	0.98	0.99
Near Skip	0.81	0.73	0.88	0.68	0.90	0.88	0.71	0.81	0.89	0.74	0.75	0.91
Section 13 (Ennis-Polyurea)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.96	0.92	0.95	0.92	0.93	0.88	0.95	0.96	0.96	0.96	0.94	0.91
Right Wheel	0.95	0.97	0.98	0.97	0.90	0.89	0.98	0.95	0.99	0.99	0.97	0.87
Center	0.83	0.84	0.96	0.84	0.79	0.71	0.87	0.83	0.94	0.88	0.87	0.77
Left Wheel	0.94	0.97	0.98	0.97	0.88	0.89	0.99	0.94	0.99	0.99	0.98	0.84

Near Skip	0.89	0.88	0.95	0.87	0.89	0.77	0.91	0.90	0.95	0.92	0.89	0.87
Section 14 (Ennis-MMA)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.94	0.77	0.95	0.74	0.65	0.86	0.87	0.95	0.64	0.72	0.64	0.54
Right Wheel	0.69	0.97	0.82	0.96	0.28	0.69	0.96	0.84	0.60	0.94	0.83	0.25
Center	0.96	0.66	0.94	0.63	0.75	0.86	0.78	0.93	0.65	0.62	0.56	0.64
Left Wheel	0.61	0.98	0.77	0.99	0.23	0.62	0.95	0.80	0.63	0.97	0.89	0.24
Near Skip	0.91	0.59	0.93	0.59	0.86	0.90	0.74	0.92	0.83	0.63	0.62	0.84
Section 15 (Ennis-Therm)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.87	0.89	0.88	0.94	0.51	0.82	0.92	0.88	0.73	0.84	0.83	0.66
Right Wheel	0.78	0.88	0.81	0.90	0.48	0.75	0.87	0.81	0.71	0.78	0.76	0.66
Center	0.96	0.80	0.97	0.89	0.82	0.98	0.91	0.96	0.86	0.96	0.97	0.82
Left Wheel	0.89	0.94	0.91	0.97	0.62	0.87	0.96	0.92	0.81	0.90	0.89	0.76
Near Skip	0.90	0.76	0.93	0.85	0.91	0.95	0.89	0.93	0.95	0.91	0.94	0.94
Section 16 (Ennis-Therm)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.09	0.95	0.19	0.96	-0.06	0.09	0.96	0.80	0.40	0.94	0.89	0.12
Right Wheel	0.06	0.91	0.24	0.97	-0.08	0.02	0.91	0.76	0.32	0.91	0.88	0.14
Center	0.94	0.37	0.88	0.19	0.78	0.95	0.28	0.63	0.91	0.31	0.48	0.81
Left Wheel	-0.01	0.89	0.17	0.96	-0.14	-0.04	0.90	0.71	0.25	0.89	0.84	0.08
Near Skip	0.97	0.18	0.94	0.02	0.96	0.93	0.11	0.41	0.65	0.13	0.25	0.97

Table 2. Correlation between Transverse Lines and Longitudinal Lines for Individual Section at Lubbock.

Section 1 (Poly-Carb-EpoxyW)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.95	0.97	0.98	0.96	0.63	0.97	0.97	0.97	0.95	0.97	0.97	0.36
Right Wheel	0.90	0.93	0.95	0.91	0.54	0.96	0.93	0.92	0.97	0.91	0.92	0.32
Center	0.80	0.74	0.80	0.68	0.56	0.88	0.69	0.72	0.92	0.66	0.73	0.72
Left Wheel	0.90	0.89	0.91	0.86	0.61	0.95	0.87	0.87	0.97	0.85	0.87	0.45
Near Skip	0.87	0.78	0.78	0.76	0.79	0.81	0.75	0.76	0.81	0.75	0.79	0.67
Section 2 (Poly-Carb-Epoxy-Y)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.88	0.96	0.94	0.97	0.88	0.90	0.97	0.99	0.92	0.95	0.97	0.81
Right Wheel	0.88	0.98	0.96	0.98	0.89	0.89	0.98	0.97	0.93	0.96	0.98	0.86
Center	0.87	0.95	0.96	0.95	0.93	0.90	0.95	0.94	0.93	0.96	0.93	0.89
Left Wheel	0.92	0.99	0.99	1.00	0.93	0.94	1.00	1.00	0.97	0.99	0.99	0.87
Near Skip	0.76	0.83	0.84	0.82	0.75	0.73	0.82	0.78	0.79	0.81	0.82	0.77
Section 3 (Poly-Carb-Epoxy-W)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.87	0.97	0.78	0.96	0.37	0.89	0.98	0.99	0.72	0.99	0.99	0.44
Right Wheel	0.85	1.00	0.77	0.99	0.34	0.85	0.99	0.98	0.73	0.99	0.98	0.40
Center	0.77	0.43	0.84	0.43	0.87	0.76	0.54	0.56	0.86	0.52	0.57	0.94
Left Wheel	0.95	0.95	0.89	0.94	0.55	0.96	0.99	0.99	0.82	0.98	0.99	0.59
Near Skip	0.90	0.54	0.95	0.54	0.96	0.89	0.66	0.69	0.91	0.63	0.68	0.97
Section 4 (Poly-Carb-Epoxy-Y)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.96	0.96	0.86	0.95	0.80	0.93	0.97	0.97	0.81	0.97	0.97	0.79
Right Wheel	0.99	0.98	0.93	0.98	0.81	0.98	0.99	1.00	0.91	0.99	0.99	0.85
Center	0.95	0.87	0.82	0.86	0.65	0.95	0.89	0.92	0.84	0.91	0.88	0.81
Left Wheel	0.97	0.99	0.92	0.99	0.82	0.94	1.00	0.99	0.88	1.00	1.00	0.77
Near Skip	0.71	0.63	0.71	0.62	0.66	0.78	0.65	0.67	0.71	0.64	0.65	0.94
Section 5 (Poly-Carb-Epoxy-W)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.96	0.87	0.96	0.88	0.79	0.97	0.91	0.95	0.97	0.93	0.92	0.94
Right Wheel	0.93	0.96	0.93	0.96	0.72	0.93	0.98	0.99	0.93	0.98	0.98	0.86
Center	0.98	0.73	0.98	0.75	0.94	0.98	0.78	0.85	0.98	0.81	0.80	1.00
Left Wheel	0.97	0.92	0.97	0.93	0.80	0.97	0.95	0.98	0.97	0.96	0.96	0.93
Near Skip	0.87	0.48	0.87	0.50	0.94	0.88	0.54	0.63	0.87	0.57	0.56	0.93
Section 6 (Poly-Carb-Epoxy-Y)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.88	0.71	0.87	0.69	0.87	0.88	0.69	0.80	0.86	0.73	0.81	0.89
Right Wheel	0.97	0.93	0.95	0.92	0.94	0.97	0.92	0.97	0.97	0.94	0.96	0.95
Center	0.90	0.70	0.92	0.68	0.93	0.90	0.69	0.79	0.87	0.71	0.82	0.92
Left Wheel	0.99	0.96	0.98	0.95	0.97	0.99	0.95	0.99	1.00	0.96	0.99	0.98
Near Skip	0.90	0.70	0.92	0.68	0.93	0.90	0.69	0.78	0.87	0.71	0.82	0.92
Section 7 (Ennis-Paint-White)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.86	0.99	0.79	0.98	0.40	0.71	0.98	1.00	0.59	0.99	0.97	0.37
Right Wheel	0.90	0.99	0.77	0.99	0.39	0.76	0.99	1.00	0.59	1.00	0.99	0.35
Center	0.68	0.84	0.95	0.78	0.77	0.60	0.88	0.87	0.87	0.86	0.89	0.75
Left Wheel	0.85	0.98	0.75	0.98	0.36	0.69	0.98	0.99	0.56	0.99	0.96	0.33
Near Skip	0.38	0.62	0.84	0.56	0.75	0.29	0.68	0.67	0.77	0.66	0.67	0.79
Section 8 (Ennis-Paint-White)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.94	0.98	0.89	0.99	0.83	0.95	0.99	0.99	0.95	0.98	0.98	0.71

Right Wheel	0.84	0.99	0.87	0.99	0.79	0.88	0.99	0.97	0.93	0.99	0.98	0.69
Center	0.71	0.89	0.87	0.87	0.90	0.69	0.88	0.83	0.85	0.85	0.83	0.67
Left Wheel	0.90	1.00	0.89	1.00	0.82	0.93	1.00	0.99	0.95	1.00	0.99	0.69
Near Skip	0.16	0.16	0.56	0.17	0.61	0.12	0.23	0.13	0.39	0.16	0.12	0.74
Section 9 (Ennis-Paint-White)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.99	1.00	0.99	1.00	0.91	0.98	1.00	1.00	0.97	1.00	0.99	0.89
Right Wheel	0.99	1.00	0.99	1.00	0.92	0.98	1.00	0.99	0.97	1.00	0.99	0.90
Center	0.99	0.98	1.00	0.99	0.97	1.00	0.99	0.99	0.99	0.99	1.00	0.95
Left Wheel	1.00	1.00	0.99	1.00	0.94	0.99	0.99	0.99	0.98	1.00	1.00	0.92
Near Skip	0.94	0.88	0.93	0.90	0.99	0.93	0.88	0.90	0.93	0.90	0.93	0.99
Section 10 (Ennis-Paint-White)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.97	0.98	0.87	0.98	0.91	0.98	0.99	0.99	0.94	0.99	0.97	0.95
Right Wheel	0.94	0.99	0.87	0.98	0.88	0.95	1.00	0.99	0.93	0.98	0.97	0.95
Center	0.92	0.77	0.81	0.78	0.96	0.90	0.82	0.81	0.91	0.80	0.71	0.93
Left Wheel	0.96	0.99	0.83	0.99	0.89	0.95	0.99	1.00	0.91	1.00	0.98	0.96
Near Skip	0.76	0.47	0.58	0.49	0.84	0.72	0.53	0.53	0.70	0.53	0.40	0.72
Section 11 (Ennis-Paint-Yellow)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.94	0.99	0.99	0.99	0.95	0.96	0.99	0.99	0.99	0.99	1.00	0.96
Right Wheel	0.89	1.00	0.98	1.00	0.93	0.92	1.00	0.99	0.99	1.00	0.99	0.95
Center	0.97	0.95	0.99	0.97	0.98	0.98	0.98	0.99	0.99	0.97	0.99	0.98
Left Wheel	0.91	1.00	0.98	1.00	0.94	0.94	1.00	0.99	0.99	1.00	1.00	0.96
Near Skip	0.96	0.76	0.86	0.78	0.95	0.95	0.83	0.84	0.84	0.81	0.83	0.92
Section 12 (Ennis-Paint-Yellow)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.94	0.98	0.95	0.96	0.84	0.95	0.97	0.97	0.96	0.98	0.96	0.91
Right Wheel	0.96	1.00	0.97	0.99	0.86	0.97	1.00	0.99	0.98	1.00	0.99	0.95
Center	0.98	0.99	0.98	0.98	0.91	0.99	0.99	0.99	0.98	0.99	0.99	0.97
Left Wheel	0.98	1.00	0.98	0.99	0.90	0.98	1.00	1.00	0.99	1.00	0.99	0.96
Near Skip	0.96	0.90	0.94	0.88	0.91	0.96	0.92	0.92	0.92	0.90	0.93	0.97
Section 13 (Ennis-Tape)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.86	0.92	0.93	0.87	0.76	0.92	0.93	0.97	0.80	0.91	0.97	0.10
Right Wheel	0.54	0.99	0.77	1.00	0.79	0.70	0.99	0.96	0.86	0.99	0.96	-0.20
Center	0.75	0.90	0.81	0.88	0.66	0.83	0.87	0.89	0.70	0.91	0.92	-0.08
Left Wheel	0.46	0.97	0.69	1.00	0.73	0.63	0.97	0.91	0.85	0.98	0.92	-0.30
Near Skip	0.69	0.33	0.73	0.18	0.67	0.59	0.36	0.47	0.13	0.26	0.44	0.79
Section 14 (Ennis-Tape)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.97	0.94	0.99	-0.75	0.98	0.46	-0.85	-0.74	0.87	0.71	-0.64	0.98
Right Wheel	0.63	0.79	0.68	-0.60	0.77	0.22	-0.48	-0.45	0.58	0.77	-0.26	0.73
Center	0.96	0.90	0.99	-0.68	0.95	0.39	-0.82	-0.72	0.95	0.70	-0.69	0.98
Left Wheel	-0.68	-0.29	-0.55	0.80	-0.58	-0.66	0.77	0.76	-0.30	0.05	0.60	-0.53
Near Skip	0.97	0.87	0.98	-0.77	0.96	0.47	-0.82	-0.74	0.93	0.70	-0.66	0.99
Section 15 (Ennis-Tape)	vs. 5 Lines					vs. 7 Lines						
Near Edge	0.64	-0.04	0.58	-0.09	0.79	0.54	-0.01	0.10	0.44	0.00	-0.06	0.53
Right Wheel	-0.14	0.98	-0.22	0.98	0.46	-0.10	0.99	0.99	-0.51	0.98	0.97	-0.67
Center	0.80	-0.72	0.90	-0.72	0.33	0.80	-0.65	-0.53	0.99	-0.68	-0.71	0.97
Left Wheel	-0.26	0.99	-0.36	0.99	0.38	-0.24	0.99	0.97	-0.62	0.98	0.99	-0.75
Near Skip	0.81	-0.74	0.86	-0.74	0.32	0.82	-0.66	-0.54	0.96	-0.68	-0.72	0.95

Table 3. Correlation between Transverse Lines and Longitudinal Lines for Individual Section at Bryan.

Section 1 (Ennis-E)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.72	-0.60	0.92	0.37	0.91	0.00	0.97	0.91	-0.80	-0.63	0.92	0.81	-0.13	0.91	0.86	-0.47
Right Wheel	-0.82	-0.70	0.86	0.22	0.87	-0.05	0.94	0.90	-0.90	-0.71	0.85	0.74	-0.28	0.87	0.81	-0.53
Center	0.07	0.16	0.79	0.81	0.83	0.57	0.71	0.82	-0.09	0.09	0.83	0.83	0.55	0.82	0.88	0.22
Left Wheel	-0.84	-0.73	0.84	0.17	0.85	-0.05	0.94	0.90	-0.91	-0.74	0.83	0.70	-0.32	0.86	0.78	-0.53
Near Skip	-0.29	-0.22	0.92	0.59	0.95	0.48	0.88	0.93	-0.41	-0.29	0.92	0.85	0.21	0.94	0.91	-0.03
Section 2 (Ennis-S)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.86	-0.34	0.97	0.59	0.96	-0.27	0.91	-0.41	-0.73	0.20	0.97	0.88	0.84	0.95	0.92	0.04
Right Wheel	-0.89	-0.45	0.92	0.47	0.90	-0.39	0.89	-0.47	-0.82	0.05	0.92	0.80	0.75	0.89	0.85	-0.05
Center	-0.36	0.24	0.86	0.88	0.87	0.34	0.82	0.20	-0.14	0.69	0.88	0.94	0.95	0.89	0.93	0.56
Left Wheel	-0.90	-0.47	0.90	0.44	0.90	-0.40	0.88	-0.48	-0.84	0.01	0.90	0.79	0.73	0.88	0.83	-0.06
Near Skip	-0.56	0.00	0.94	0.76	0.96	0.14	0.90	0.05	-0.36	0.46	0.94	0.96	0.95	0.96	0.96	0.42
Section 3 (Ennis-E)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.65	-0.49	0.95	0.51	0.91	-0.43	0.46	0.87	-0.49	-0.57	0.90	0.80	0.55	0.94	0.84	-0.69
Right Wheel	-0.70	-0.54	0.93	0.44	0.90	-0.47	0.41	0.88	-0.54	-0.64	0.87	0.76	0.48	0.92	0.81	-0.73
Center	0.22	0.33	0.79	0.89	0.74	0.35	0.80	0.79	0.36	0.19	0.85	0.93	0.89	0.77	0.86	0.02
Left Wheel	-0.74	-0.58	0.89	0.37	0.88	-0.50	0.35	0.88	-0.58	-0.69	0.82	0.70	0.41	0.88	0.77	-0.75
Near Skip	0.41	0.64	0.61	0.95	0.64	0.67	0.76	0.71	0.61	0.47	0.69	0.78	0.88	0.61	0.78	0.41
Section 4 (Ennis-S)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.58	-0.18	0.95	0.80	0.95	-0.05	-0.14	-0.33	-0.34	-0.02	0.96	0.94	0.79	0.95	0.87	-0.41
Right Wheel	-0.61	-0.22	0.95	0.77	0.95	-0.05	-0.14	-0.34	-0.39	-0.06	0.95	0.93	0.78	0.95	0.87	-0.42
Center	0.13	0.25	0.84	0.93	0.83	0.50	0.53	0.37	0.33	0.54	0.84	0.88	0.94	0.84	0.90	0.19
Left Wheel	-0.65	-0.25	0.92	0.71	0.93	-0.07	-0.16	-0.38	-0.46	-0.12	0.92	0.89	0.74	0.93	0.84	-0.45
Near Skip	0.28	0.26	0.72	0.90	0.73	0.75	0.73	0.68	0.30	0.68	0.72	0.77	0.92	0.73	0.84	0.46
Section 5 (Dobco-E)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.48	-0.65	0.96	0.87	0.95	-0.71	0.15	0.83	-0.64	-0.67	0.94	0.91	0.53	0.91	0.98	-0.86
Right Wheel	-0.71	-0.83	0.84	0.71	0.95	-0.88	-0.01	0.82	-0.81	-0.85	0.82	0.76	0.33	0.82	0.88	-0.96
Center	-0.08	-0.35	0.96	0.96	0.85	-0.52	0.57	0.96	-0.26	-0.37	0.97	0.97	0.72	0.94	0.95	-0.65
Left Wheel	-0.72	-0.85	0.81	0.67	0.94	-0.89	-0.03	0.81	-0.82	-0.87	0.80	0.73	0.29	0.80	0.85	-0.97
Near Skip	-0.11	-0.26	0.92	0.93	0.76	-0.35	0.48	0.84	-0.28	-0.29	0.90	0.92	0.76	0.88	0.88	-0.54
Section 6 (Dobco-S)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.65	-0.17	0.92	0.58	0.93	-0.77	-0.29	-0.78	-0.37	-0.36	0.94	0.80	0.32	0.92	0.84	-0.49
Right Wheel	-0.80	-0.31	0.83	0.43	0.90	-0.80	-0.38	-0.74	-0.58	-0.53	0.86	0.69	0.19	0.87	0.80	-0.56
Center	-0.35	0.19	0.98	0.82	0.96	-0.40	0.20	-0.40	0.03	-0.06	0.98	0.97	0.70	0.97	0.97	-0.01
Left Wheel	-0.81	-0.32	0.81	0.39	0.88	-0.79	-0.39	-0.72	-0.60	-0.55	0.84	0.66	0.16	0.86	0.78	-0.56
Near Skip	-0.35	0.17	0.95	0.84	0.89	-0.45	0.08	-0.49	0.00	0.01	0.94	0.93	0.65	0.90	0.88	-0.10
Section 7 (Dobco-E)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.31	-0.63	0.96	-0.36	0.91	-0.75	-0.20	0.60	-0.50	-0.48	0.95	0.66	0.40	0.92	0.80	-0.92
Right Wheel	-0.49	-0.76	0.90	-0.46	0.88	-0.87	-0.14	0.77	-0.63	-0.61	0.92	0.55	0.20	0.85	0.67	-0.94
Center	0.19	-0.21	0.93	0.10	0.90	-0.43	-0.18	0.73	-0.02	-0.01	0.91	0.87	0.78	0.96	0.98	-0.72

Left Wheel	-0.51	-0.74	0.88	-0.44	0.87	-0.85	-0.10	0.66	-0.63	-0.61	0.90	0.54	0.17	0.82	0.63	-0.91
Near Skip	0.97	0.82	-0.03	0.86	0.03	0.56	0.08	0.62	0.93	0.94	-0.06	0.45	0.64	0.06	0.32	0.41
Section 8 (Dobco-S)	Edge	vs. 5 Lines					Skip-1	Skip-2	Edge	vs. 7 Lines						
Near Edge	-0.26	0.30	0.93	0.76	0.92	-0.82	0.52	-0.77	-0.76	0.48	0.92	0.81	0.41	0.92	0.84	-0.88
Right Wheel	-0.41	0.15	0.89	0.68	0.89	-0.87	0.40	-0.84	-0.85	0.35	0.88	0.72	0.29	0.88	0.78	-0.88
Center	0.04	0.67	0.96	0.94	0.96	-0.43	0.37	-0.34	-0.43	0.83	0.96	0.96	0.79	0.97	0.98	-0.52
Left Wheel	-0.43	0.14	0.89	0.68	0.89	-0.84	0.36	-0.83	-0.85	0.34	0.87	0.71	0.29	0.87	0.78	-0.85
Near Skip	0.41	0.82	0.51	0.71	0.53	0.30	0.02	0.39	0.24	0.88	0.53	0.66	0.87	0.55	0.67	0.23