Technical Report Documentation Page

1. Report No. RES2013-29	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle *Retrace Pavement Marking Retroreflectivity Levels on Tennessee Highways*		5. Report Date November 2015 6. Performing Organization Code
7. Author(s) Onyango, M. (UTC); Chimba, D. (TSU); Owino, J. (UTC)		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Tennessee Chattanooga Engineering, Math & Computer Science (EMCS) 735 Vine St Chattanooga, TN 37403		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 38749 (Contract ID) 041B268 (FHWA Project No.)
12. Sponsoring Agency Name and Address Tennessee Department of Transportation James K. Polk Building 505 Deaderick Street, Suite 900 Nashville, TN 37243		13. Type of Report and Period Covered Final Report March 2013 to November 2015 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This study evaluated the performance of pavement markings in the State of Tennessee and established pavement marking replacement (maintenance) timing for two types of pavement markings used in Tennessee: paints and thermoplastics. Pavement markings provide vital information to road users pertaining to lane restrictions and vehicle movements, which if adhered to, result in improved road safety.

Retroreflectivity is a measurement of how well the markings can be seen by road users, especially at night. The Tennessee Department of Transportation (TDOT) specifies acceptable minimum pavement marking refroreflective properties 45 days from application to be a minimum of 300 mcd/m2 /lux for white stripes and a minimum of 200 mcd/m2 /lux for yellow stripes, (mcd/m2/lux is milli-candela per square meter per lux).

The study established data collection sites, collected data using a handheld retroreflectometer (LTL-X) for a period of two years, and evaluated pavement marking retroreflectivity trends over time. The data collection was performed on two types of pavement markings, paints and thermoplastic, where thermoplastic markings are expected to perform longer than paints. Sixty (60) data collection sited were randomly selected from the four TDOT regions. Data were collected approximately every forty-five (45) days on dry markings.

Pavement markings deterioration models and deterioration rates were established using the collected data. The analysis was performed at statewide and regional levels. The study established statewide pavement marking deterioration rates per month. Further analysis was performed to evaluate the influence of traffic intensity and elevation to marking deterioration rates. The study found no conclusive pattern for pavement marking deterioration rates based on traffic intensity and elevations. The deterioration rates obtained for thermoplastic markings yielded a very low correlation to measured values. It could be that two years is not long enough for thermoplastic markings to fail to the extent of producing a defined pattern that correlates with measured values. For paint markings, the correlation value ranges were acceptable.

17. Key Words **Retroreflectivity** **Pavement Marking** **Road Safety** **Thermoplastic**		18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161; www.ntis.gov.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 102	22. Price $199,526,38

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

This research was funded through the State Planning and Research (SPR) Program by the Tennessee Department of Transportation and the Federal Highway Administration under RES2013-29: *Retrace Pavement Marking Retroreflectivity Levels on Tennessee Highways.*

This document is disseminated under the sponsorship of the Tennessee Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Tennessee and the United States Government assume no liability of its contents or use thereof.

The contents of this report reflect the views of the author(s) who is(are) solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Tennessee Department of Transportation or the United States Department of Transportation.

FINAL REPORT

To: The Tennessee Department of Transportation

Research Development and Technology Program

Retrace Pavement Marking Retroreflectivity Levels on Tennessee Highways

Report Period: 8

For Period: May 15, 2015 to November 14, 2015
Project #: RES2013-29

* Agreement Period
From: August 15, 2013 To: August 15, 2018

* Time Used (100 %)

* Work Completed (100 %)

Disclaimer
This final report is disseminated for review purposes only and as such is regarded as proprietary. The information contained in this document will be shared at the discretion of TDOT management.

EXECUTIVE SUMMARY

This study is a collaboration between the University of Tennessee Chattanooga (UTC) and Tennessee State University (TSU) to evaluate the performance of pavement markings in the state of Tennessee, and to establish pavement marking replacement (maintenance) timing for two types of pavement markings used in Tennessee: paints and thermoplastics. Pavement markings provide vital information to road users pertaining to lane restrictions and vehicle movements, which if adhered to, results in improved road safety. Retroreflectivity is a measurement of how well the markings can be seen by road users, especially at night. The Tennessee Department of Transportation (TDOT) specifies acceptable minimum pavement marking refroreflective properties 45 days from application to be a minimum of 300 mcd/m^2 /lux for white stripes and a minimum of 200 mcd/m^2 /lux for yellow stripes, (mcd/m^2/lux is milli-candela per square meter per lux). Candela is a measurement of light intensity and lux is measurement of luminous light per square meter.

The study established data collection sites, collected data using a handheld retroreflectometer (LTL-X) for a period of two years, and evaluated pavement marking retroreflectivity trends over time. The data collection was performed on two types of pavement markings, paints and thermoplastic, where thermoplastic markings are expected to perform longer than paints. Sixty (60) data collection sited were randomly selected from the four TDOT regions. Data were collected approximately every forty-five (45) days on dry markings.

Pavement markings deterioration models and deterioration rates were established using the collected data. The analysis was performed at statewide and regional levels. The study therefore established the following statewide pavement marking deterioration rates per month:

- White Paints: - 4.19 mcd/m^2 /lux/Month
- Yellow Paints: - 3.90 mcd/m^2 /lux/Month
- White Thermoplastics: - 3.82 mcd/m^2 /lux/Month
- Yellow Thermoplastics: - 2.39 mcd/m^2 /lux/Month

The rates were also narrowed per TDOT region; however, the deterioration rates were not uniform across regions, with no clear patterns to differentiate one region from the other. Further

analysis was performed to evaluate the influence of traffic intensity and elevation to marking deterioration rates. The study found no conclusive pattern for pavement marking deterioration rates based on traffic intensity and elevations.

The deterioration rates obtained for thermoplastic markings yielded a very low correlation to measured values. It could be that two years is not long enough for thermoplastic markings to fail to the extent of producing a defined pattern that correlates with measured values. For paint markings, the correlation value ranges were acceptable. TDOT Region 2 had the lowest coefficient of determination (R^2) values especially for yellow markings.

SYNOPSIS OF THE PROBLEM BEING RESEARCHED

Pavement markings are affected by traffic, pavement surface type and environment, and sometimes they don't meet the required retroreflectivity levels after a certain time of usage. Determining how long a pavement marking will stay within acceptable limits after application has been a challenge. This research study is geared at determining a correlation between pavements marking reflectivity with time. The scope of this research project includes:

- Selecting testing sites from 2013 TDOT retracing program locations within the state of Tennessee.
- Grouping selected sites as per geographical location and traffic (High, Medium and low) and pavement type.
- Collecting data using the handheld LTL-X Retroreflectometer on the selected sites for a period of two years in about 45 days intervals. The team used traffic management procedures and relevant signs when collecting data.
- Developing a relationship between time and pavement marking retroreflectivity measurements collected in a period of 2 years.

Project Objectives

The objectives of this proposed study focus on the efficiency of pavement markings on Tennessee roadways by:

1) Monitoring the retroreflectivity performance of retraced pavement markings in Tennessee in a 2 year period, beginning in 2013,

2) Tracking the pavement marking retroreflectivity with time and developing correlation curves.
3) Evaluating the time it takes for the pavement markings to stay within the acceptable retroreflectivity limits.

ACTIVITIES THIS QUARTER (QUARTER 8)

Listed below are activities completed from May 15th 2015 to November 14th 2015.

1. Updates of activities performed in this quarter

- A project progress meeting with TDOT was conducted on 05/12/2015. UTC and TSU presented the progress and data analysis so far; TDOT was pleased with the progress and was not going to extend the project (phase II). It was then agreed that the month of May 2015 was the last month for data collection, data analysis and report writing will follow.

2. Recommendations from the last progress meeting:

a. Thermoplastic markings readings are still high, close to acceptance readings, two years after application, it was recommended to end the project at this point and that TDOT expect the thermoplastic markings to fail in about 4 years. Linear models could not well predict thermoplastic markings because long data collection period was required for a much better correlation.

3. Pavement markings trends and deterioration rates:

- Data trends for pavement marking retroreflectivity are as shown in appendix B.
- The analysis of pavement marking deterioration rates are categorized by traffic and by altitude. The data was mixed for all regions before categorizing. The rates were computed as average regardless of fluctuations observed in the retroreflectivity readings. Tables 5.1 to 5.6 on the final report attached, give a summary of the deterioration rates per category and overall statewide.
- Literature shows in some cases retroreflectivity values reads are above the initial application values after one year. An explanation could be due to more exposure of beads for thermoplastics.
- The same trends similar to those found in the literature are observed in some locations in this study as shown in the figures in appendix B. Most of these data hikes occurred in March –

May 2014 data collection period. This was after snow and rain season, it could be pavement markings were clean, with less dust and debris or more exposure of beads.

4. Data Analysis

Statistical data analysis was performed to relate retroreflectivity deterioration with increase in pavement marking age and AADT. Degradation models could be developed for paint markings but not for thermoplastic markings (because of low correlation between measured and predicted values of thermoplastic markings). For all thermoplastic markings, the effect of pavement marking age and AADT was found to be statistically insignificant at a confidence level or 95%. The degradation model for all paints markings was developed and is given in equation 1.

$$RL_{fut} = RL_{INI} - D * DR/30 \quad (1)$$

Where:

RL_{fut} = Future pavement marking retroreflectivity

RL_{INI} = Initial pavement marking retroreflectivity

D = number of days to the estimated future pavement marking retroreflectivity

DR = Monthly deterioration rate.

5. Final Report

Final report is attached to this report. It was found that paint markings will last for at least two years for all regions except region 2 yellow markings which had higher deterioration rate and on average lasted for less than two years.

FINAL REPORT

RETRACE PAVEMENT MARKING RETROREFLECTIVITY LEVELS ON TENNESSEE HIGHWAYS

A COLLABORATIVE RESEARCH BETWEEN UTC AND TSU

A Proposal Submitted to TDOT in March 2013

By:

Dr. Mbakisya Onyango, UTC (PI)

Dr. Deo Chimba, P.E., PTOE; TSU (Co-PI)

Dr. Joseph Owino, P.E., UTC (Co-PI)

November 2015

EXECUTIVE SUMMARY

This study is a collaboration between the University of Tennessee Chattanooga (UTC), and Tennessee State University (TSU) to evaluate the performance of pavement markings in the state of Tennessee, and to establish pavement marking replacement (maintenance) timing for two types of pavement markings used in Tennessee: paints and thermoplastics. Pavement markings provide vital information to road users pertaining to lane restrictions and vehicle movements, which if adhered to, results in improved road safety. Retroreflectivity is a measurement of how well the markings can be seen by road users, especially at night. The Tennessee Department of Transportation (TDOT) specifies acceptable minimum pavement marking refroreflective properties 45 days from application to be a minimum of 300 mcd/m^2 /lux for white stripes and a minimum of 200 mcd/m^2 /lux for yellow stripes, (mcd/m^2/lux is milli-candela per square meter per lux). Candela is a measurement of light intensity and lux is measurement of luminous light per square meter.

The study established data collection sites, collected data using a handheld retroreflectometer (LTL-X) for a period of two years, and evaluated pavement marking retroreflectivity trends over time. The data collection was performed on two types of pavement markings, paints and thermoplastic, where thermoplastic markings are expected to perform longer than paints. Sixty (60) data collection sited were randomly selected from the four TDOT regions. Data were collected approximately every forty-five (45) days on dry markings.

Pavement markings deterioration models and deterioration rates were established using the collected data. The analysis was performed at statewide and regional levels. The study therefore established the following statewide pavement marking deterioration rates per month:

- White Paints: - 4.19 mcd/m^2 /lux/Month
- Yellow Paints: - 3.90 mcd/m^2 /lux/Month
- White Thermoplastics: - 3.82 mcd/m^2 /lux/Month
- Yellow Thermoplastics: - 2.39 mcd/m^2 /lux/Month

The rates were also narrowed per TDOT region; however, the deterioration rates were not uniform across regions, with no clear patterns to differentiate one region from the other. Further analysis was performed to evaluate the influence of traffic intensity and elevation to marking deterioration rates. The study found no conclusive pattern for pavement marking deterioration rates based on traffic intensity and elevations.

The deterioration rates obtained for thermoplastic markings yielded a very low correlation to measured values. It could be that two years is not long enough for thermoplastic markings to fail to the extent of producing a defined pattern that correlates with measured values. For paint markings, the correlation value ranges were acceptable. TDOT Region 2 had the lowest coefficient of determination (R^2) values especially for yellow markings.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Pavement Markings

Pavement markings are lines drawn on a pavement surface that convey information to road users pertaining to lane uses and restrictions, especially at night. This information if adhered to, leads to improved road safety. Pavement markings indicate lane direction, the center and edges of the road, and passing or no passing zones; following this information allows drivers to know they are in the correct lane [Debaillon et. al.., 2007]. Pavement markings are characterized by their ability to retroreflect to the driver the light coming from the headlamps of the vehicle. Safety depends on efficiency and performance of the markings' retroreflectivity.

1.2 Retroreflectivity

As defined by Debaillon et. al.., "Retroreflectivity is a measure of an object's ability to reflect light back towards a light source along the same axis from which it strikes the object" [2007]. In other words, a pavement marking has retroreflective properties if it reflects light back towards the vehicle's headlamps and ultimately towards the driver's eyes, thus making the markings visible at night.

Glass beads are mixed into the pavement marking material, or binder material, to make it retroreflective. The beads prevent incoming light from scattering and refract it back towards the vehicle's headlamps, as illustrated on Figure 1.1. Retroreflectivity is typically measured as the coefficient of retroreflected luminance (R_L), which is "the ratio of the luminance of a projected surface of retroreflective material to the normal illuminance at the surface on a plane normal to the incident light" [Austin and Schultz, 2009]. In measuring the ability of pavement markings to retroreflect the light from headlamps, retroreflectivity can be used to assess marking efficiency.

The FHWA in the Manual on Uniform Traffic Control Devices (MUTCD) recommends minimum retroreflectivity levels on different types of pavements (FHWA Table 3A-1). For instance for a road with speed limit > 55mph, MUTCD recommends a retroreflectivity level of 250 mcd/m2/lux [MUTCD, 2009].

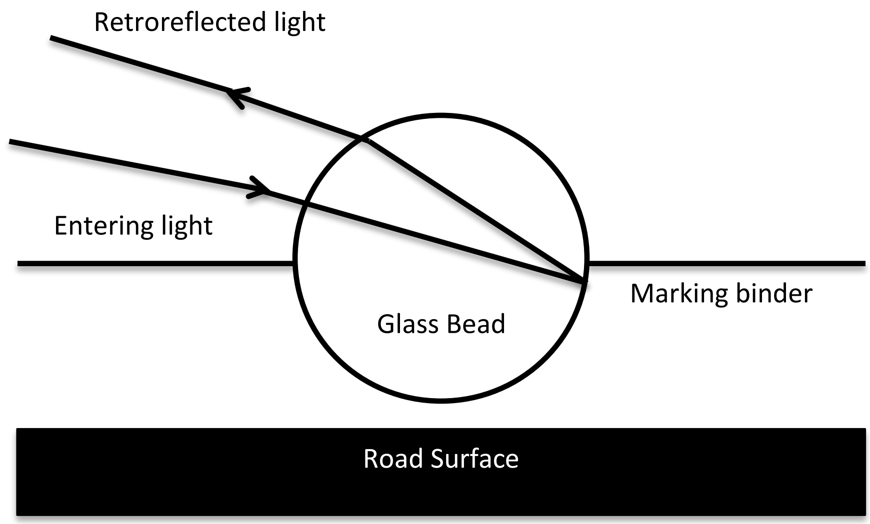


Figure 1.1 Pavement marking retro-reflection

1.3 Problem Statement

According to previous studies, pavement markings are affected by traffic, pavement surface type, environment, and age. Determining how long a pavement marking will stay within acceptable limits after application has been a challenge. The state of Tennessee's Department of Transportation (TDOT), in an effort to increase road safety, funded this project to evaluate the performance of pavement markings on Tennessee highways and establish replacement (maintenance) timing for two types of pavement markings used in Tennessee (paints and thermoplastic). This research study is geared towards determining a correlation between pavement markings retroreflectivity over time.

This study used the handheld LTL-X retroreflectometer to measure pavement marking retroreflectivity levels on selected highways in TDOT regions 1 through 4 for a period of two years and developed a correlation between time and retroreflectivity levels. The results of this study map how long these types of pavement markings can be expected to stay within the acceptable limits.

1.3.1 Objectives

The objectives of this study were to determine the efficiency of pavement markings on Tennessee roadways by:

1) Monitoring the retroreflectivity performance of retraced pavement markings in Tennessee in a 2-year period beginning in 2013.
2) Tracking pavement marking retroreflectivity over time and developing retroreflectivity – time (age) correlation curves.
3) Evaluating the time it takes for the pavement markings to fall below acceptable retroreflectivity limits.

1.3.2 Scope

The scope of this research project included:

- Selecting test sites from the 2013 TDOT retracing program.
- Grouping selected sites as per geographical location and traffic (High, Medium and Low) and pavement type.
- Collecting data using the handheld LTL-X retroreflectometer on the selected sites for a period of two years in a feasible frequency (approximately forty five (45) day intervals).
- Attending traffic management training for traffic safety when collecting data. The team used a big vehicle (van) and traffic signs when collecting data at selected sites.
- Developing a relationship between time and pavement marking retroreflectivity measurements collected over a period of two years.

1.3.3 Deliverables (Milestones)

Upon acceptance of this final report, the research team will have provided TDOT with:

- Results of retroreflectivity data collection on the 2013 TDOT retracing program.
- A correlation between pavement marking retroreflectivity levels over time in terms of deterioration rates and curves.
- A final report documenting test results, analyses, and findings.

2. LITERATURE REVIEW

A literature review was performed in order to obtain published information related to the minimum acceptable pavement marking retroreflectivity on highways and to establish a threshold for paint and thermoplastic markings. Pavement marking deterioration models were also reviewed to assist in the establishment of a reliable deterioration model for Tennessee highways.

2.1 Minimum Pavement Marking Retroreflectity

In 1999, FHWA hosted three regional workshops on pavement marking retroreflectivity. At this time, participants set recommendations for minimum pavement marking retroreflectivity values for both white and yellow marking colors at various speed limit levels. The recommended threshold of acceptable retroreflectivity fell between 80 to 100mcd/m^2/lux for white markings and 65 to 80mcd/m^2/lux for yellow markings. Hawkins, et al (2000) prepared a report summarizing FHWA pavement marking retroreflectivity.

In 2007, Debaillon, et al (2007) conducted retroreflectivity research for the FHWA. This work used a window-based deterministic computer model (TarVIP) developed in Matlab for evaluating nighttime visibility of refroreflective objects from a driver's perspective. The TarVIP model allows the user to calculate approximate detection distances for pavement markings, legibility distances of traffic signs, and pedestrians seen under automobile headlamp illumination. Suggested minimum retroreflectivity values were 40mcd/m^2/lux for fully marked roadways (with centerline, lane lines and/or edge lines) and 90mcd/m^2/lux for roadways with centerlines only for speeds under 50 mph.

FHWA (2007) reports a study by the 3M Company conducted in 1986 where subjects drove on a test road marked to resemble one side of a four-lane freeway. The retroreflectivity of the pavement markings ranged from 30 to 1,700 mcd/m^2/lux and were viewed from distances of 30 m (98.4 ft.) and 100 m (328.0 ft.). Participants then rated the markings on a scale of one (very poor) to seven (superior). Three was considered the minimum acceptable rating. After fitting a regression curve to establish a relationship between the average rating and the retroreflectivity of the pavement markings, researchers found that the retroreflectivity value most frequently given the minimum acceptable rating was 90 mcd/m^2/lux. Due to instrument variability, therefore, the researchers recommended a minimum value of 100 mcd/m^2/lux.

The 1989 Attaway study used two evaluation measures to analyze thermoplastic and tape markings for the North Carolina Department of Transportation. The first measure analyzed longitudinal markings according to zones; the second took multiple readings from each special marking. Each marking held a minimum acceptable retroreflectivity level of 100 mcd/m^2/lux. The study found thermoplastic markings to be more durable than preformed tape.

In 1991, the University of North Carolina asked 59 participants to drive a 32-km (20-mile) test course and evaluate 20 pavement markings embedded with various retroreflectivity levels as less than adequate, adequate, or more than adequate. The participants were also presented with markings in a laboratory setting and asked to make subjective evaluations. Ninety percent of participants rated markings with a retroreflectivity value of 93 mcd/m^2/lux as adequate or more than adequate. As the majority of participants were younger drivers, however, the researchers conducted a similar study on older drivers in 1996. They found that the adequate or more than adequate retroreflectivity value of pavement markings increased to 100 mcd/m^2/lux for 85 percent of drivers aged 60 or older [FHWA, 2007].

A 1998 study for the Minnesota Department of Transportation (MnDOT) recruited 200 drivers whose age distribution reflected that of the state. Participant were asked to rate the quality of the pavement markings along a designated route on existing roads. Markings rated as acceptable were found to be those with a retroreflectivity of 100 mcd/m^2/lux. In analyzing the ratings, researchers also found that as retroreflectivity increased from 0 to 120 mcd/m^2/lux, the acceptability of pavement markings increased dramatically. Acceptability increased less perceptibly as the retroreflectivity increased from 120 to 200mcd/m^2/lux. Little to no increase in acceptability accompanied increases of retroreflectivity beyond 200 mcd/m^2/lux. These findings led researchers to recommend that MnDOT adopt 120 mcd/m^2/lux as the minimum acceptable level of retroreflectivity [FHWA, 2007].

Similarly, a 2002 study for the New Jersey Department of Transportation (NJDOT) asked 64 participants to rate the quality of the pavement markings along a designated route on existing roads (Parker and Meja 2003). The study indicated the retroreflectivity threshold of an acceptable pavement marking was between 80 and 130 mcd/m^2/lux for drivers younger than 55 years of age and between 120 and 165 mcd/m^2/lux for drivers older than 55. In order to achieve "a greater relative increase in driver satisfaction," however, researchers suggested that NJDOT adopt a retroreflectivity less than 130 mcd/m^2/lux.

Omar Smadi et. al (2010) conducted a research study sponsored by the Iowa Highway Research Board and Iowa Department of Transportation to analyze the relationship between crash occurrence probability and longitudinal pavement marking retroreflectivity, based on road and line types, retroreflectivity measurement source and range, and high crash routes. The study concluded that retroreflectivity was significant in crash occurrence probability in reference to interstate, white and yellow edge line, and yellow center line data. In fact, for white edge line and yellow center line data, a decrease in retroreflectivity marked an increase in crash occurrence probability.

In a 2009 study conducted for TDOT, Clarke et. al. analyzed the retroreflectivity of several marking materials (including 40 and 90 mil spray thermoplastic, rumble stripe, wet reflective tape and patterned reflective tape) used on Tennessee highways and the retroreflectivity behavior of the materials (including color (white or yellow), pavement type (ACC or PCC) and traffic volume). Measurements were taken at 121 test sites using handheld LTL-X Retroreflectometers. The data suggested that after 500-600 service days, all markings met the minimum retroreflectivity standards when measured dry but when measured wet exhibited low retroreflectivity. The study also found that yellow markings had a lower dry reflectivity than white markings.

The FHWA 2007 Pittsburg Workshop recommended minimum retroreflectivity as reported in Table 2.1 [Clarke et. al., 2009 and Debaillon et. al., 2007].

Table 2.1 Suggested Minimum Retroreflectivity values, FHWA 2007

Roadway Marking Configuration	Without RRPM			With RRPM
	≤ 35 mph	55 – 65 mph	≥ 70 mph	
Fully marked roadways (with center line, lane lines, and/or edgeline, as needed)*	40	60	90	40
Roadways with center lines only	90	250	572	50

* Applies to both yellow and white pavement markings
RRPM = raised retroreflective pavement markers

2.2 Pavement Marking Retroreflectivity Deterioration models

In a 1997 study sponsored by the NCHRP, Andrady developed one of the first deterioration models for pavement marking retroreflectivity. The focus of Andrady's study was twofold: 1) to determine the environmental impact of volatile organic compounds and 2) to identify alternative pavement marking materials. This required Andrady to also evaluate the performance characteristics of pavement markings in terms of retroreflectivity, and in doing so created the following logarithmic model for thermoplastics:

$$T_{100} = 10^{(R_0 - 100)/b}$$

Where:

T_{100} = Time in months for the retroreflectivity to reach 100 mcd/m^2/lux

R_0 = Estimate of the initial retroreflectivity value

b = Gradient of the semi-logarithmic plot of retroreflectivity

A retroreflectivity value of 100 mcd/m^2/lux marks the end of service life for this model; however, no goodness of fit measures have yet been published.

A 1999 study conducted by Lee, et al. at Michigan State University (MSU) determined deterioration rates for four major marking materials (paints, thermoplastics, thermosets, and tapes) from 50 sample sites throughout Michigan by using the Mirolux 12, a 15-meter geometry device. A minimum threshold value of 100 mcd/m^2/lux was used as the satisfactory performance baseline. The study found considerable variability in the Mirolux 12 measurements. Researchers concluded that future studies should employ other data collection equipment and methods. Of significant note, however, was that snowfall and consequently snow plowing was strongly correlated to retroreflectivity deterioration. Such a correlation was not found with Annual Average Daily Traffic (AADT), speed limit, or percent commercial traffic. The study concluded that of the four pavement marking types, water-borne markings were the most cost-effective, with a service life of 445 days, or about 15 months. The model for thermoplastics used by Lee, et al. is as follows:

$$R_L = -0.3622X + 254.82, \qquad R^2 = 0.14 \qquad \textbf{2.1}$$

Where:

R_L = Retroreflectivity of pavement marking ($mcd/m^2/lx$)

X = Age of the pavement marking in days

A retroreflectivity value of 100 $mcd/m^2/lx$ marks the end of service life for this model.

A large-scale study conducted by Migletz et. al. (2000) used regression analysis to evaluate the durability of various pavement markings and to establish a predictive deterioration curve of material performance over time. Data was drawn from 362 longitudinal pavement markings from 85 sites that spanned 19 states. The analysis indicated considerable performance variation for identical materials at different sites, resulting from differences in region, roadway type, marking specifications, quality control, and winter maintenance. While yellow lines were shown to perform better than white lines, they were not proven to be more durable.

In a follow-up study, Migletz (2001) calculated deterioration rates for each material type (by color) and organized it into a service life matrix arranged by cumulative traffic passages (the cumulative sum of the AADT over time) and months elapsed that provides average service lives, standard deviations, and service life ranges (in months). The study concluded the following for the two most common marking materials:

- The average lifespan of waterborne white paint markings was 10.4 months
- The average lifespan of white thermoplastics was 26.2 months and 27.5 months for yellow thermoplastics.

In Abboud and Bowman’s 2002 study for the Alabama DOT, the application cost, service life, and crash-related user cost of pavement marking retroreflectivity was analyzed. An exponential regression model was used to determine the relationship between pavement marking retroreflectivity and vehicle exposure (VE) (a function of time and AADT). Notably, this study did not analyze marking color and surface material as independent variables. These have been established as dependent variables for pavement marking deterioration in the other studies cited here.

The deterioration model presented for paint was:

$$R_L = -19.457 \ln(VE) + 26.27, \qquad R^2 = 0.31 \qquad \textbf{2.2}$$

The model for white thermoplastic edge lines was:

$$R_L = -70.806 \ln(VE) + 150.55, \qquad R^2 = 0.58 \qquad \textbf{2.3}$$

Where: R_L = Pavement marking retroreflectivity (mcd/m^2/lux)

ln = Natural logarithm

VE = Vehicle exposure = AADT x PM age x 0.0304

AADT = Annual average daily traffic

PM age = Age in months

Abboud and Bowman also evaluated cost and longevity of paint and thermoplastic markings (using a minimum retroreflectivity threshold of 150 mcd/m²/lux, notably higher than in other studies) and determined that a useful paint lifetime is 22 months for low-AADT (<2500 vehicles per day) highways; 7.5 months for mid-AADT (2500 to 5000 vpd) highways; and 4.5 months for high-AADT (>5000 vpd) highways (2002).

A 2003 study conducted by Sarasua et. al., developed predictive models to estimate the rate of pavement marking deterioration that could be applied to an overall pavement markings management plan. Researchers collected data using 30-meter geometry (the geometry identified in ASTM E 1710-97) a total of six times during a 28-month period at more than 150 sites along South Carolina’s interstate system. Eleven measurements taken with an LTL-2000 at each site provided the average retroreflectivity value. The study used regression analysis to analyze the retroreflectivity performance of each sample based on surface type, marking material, marking color, and maintenance activities, as compared to the differences in retroreflectivity values and the percent differences in retroreflectivity values.

Sarasua, et al. developed linear and non-linear (break-in period) models for each combination of marking material (thermoplastics and epoxy), surface material, and color to pinpoint the deterioration of marking retroreflectivity after the break-in period. The models for thermoplastics on asphalt are as follows:

Model for white thermoplastics:

$$\text{Diff} = -0.06(\text{Days}) - 6.80, \quad R^2 = 0.47 \tag{2.4}$$

$$\%\ \text{Diff} = -0.03(\text{Days}) - 3.29, \quad R^2 = 0.39 \tag{2.5}$$

Model for yellow thermoplastics:

$$\text{Diff} = -0.03(\text{Days}) - 3.63, \quad R^2 = 0.21 \tag{2.6}$$

$$\%\ \text{Diff} = -0.02(\text{Days}) - 2.35, \quad R^2 = 0.24 \tag{2.7}$$

Where:

Diff = Difference in retroreflectivity over time

% Diff = Percentage of difference in retroreflectivity over time

Days = Time in days

A retroreflectivity value of 100 mcd/m^2/lux marks the end of service life for this model.

Thamizharasan et al. (2003) identified four patterns of retroreflectivity change over time, as shown in Figures 2.1 (a - c). In the first pattern, retroreflectivity increases for a short time, then gradually decreases (Figure 2.1(a)). This pattern is seen in newly placed markings as the glass beads begin to wear. In the second pattern, retroreflectivity decreases gradually over time (Figure 2.1 (b)). This pattern is seen in well-established markings that have passed the initial increase period. The third and fourth patterns show the impacts of remarking and snowplowing, respectively (Figure 2.1 (c)).

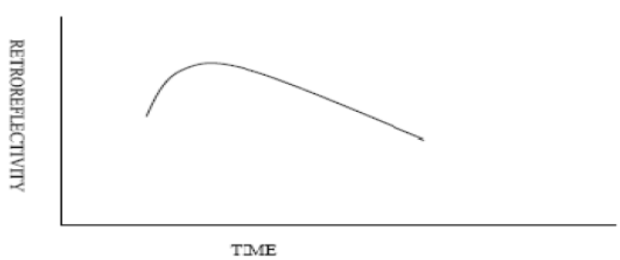


Figure 2.1 (a) Pattern representative of newly placed pavement markings

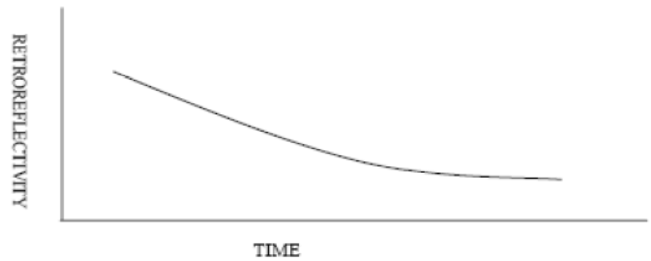


Figure 2.1 (b) Pattern for established sites – markings older than about 300 days

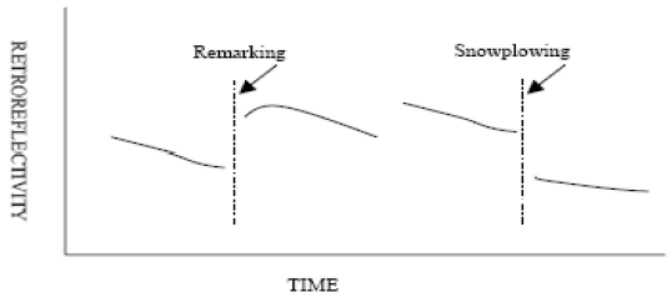


Figure 2.1 (c) Patterns showing sudden change due to maintenance operations

Figure 2.1 Observed retroreflectivity patterns over time [Thamizharasan et al., 2003]

Thamizharasan et al. also developed a non-linear model to predict the time over which the retroreflectivity increases when applied and a linear model to predict the time retroreflectivity decreases to a minimum value. Marking color (white or yellow), surface type (AC or PCC), and marking material (thermoplastic or epoxy) were incorporated into the model. ADT was found not to be significant in the analysis.

An example of Thamizharasan et al.'s model:

Difference in Retroreflectivity = – 0.06Days – 6.80 **2.8**

In order to calculate retroreflectivity as a function of age, Bahar et al. (2006) employed the following inverse polynomial model:

$$R = \frac{1}{\beta_0 + \beta_1 * Age + \beta_{2*} Age^2} \quad \textbf{2.9}$$

Where:

R = retroreflectivity of pavement markings (mcd/m^2/lux)

Age = age of marking in months, and

β_0, β_1, β_2 = model parameters to be estimated.

Bahar et al. also analyzed color, material, traffic volume, pavement surface type, climatic region, and snow removal and developed other models based on combinations of these variables. ADT was not used in the models due to its inconsistent effects on different materials.

Dale (1988) concluded that there was a linear relationship between the service life of markings and ADT. Figure 2.2 depicts his findings for preformed tape by degree of snowfall. As ADT increases, the service life decreases in a linear fashion; similarly, as snowfall increases, the service life also decreases.

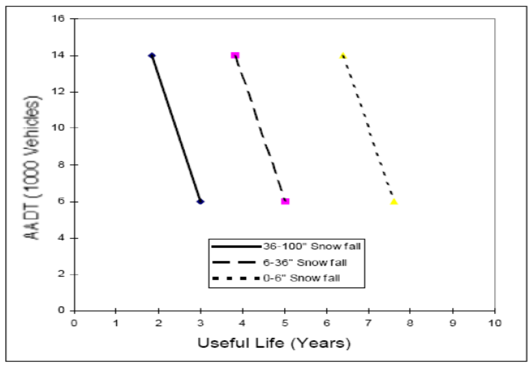


Figure 2.2 Life expectancy of preformed tape on both AC and PCC [Dale, 1998]

Perrin et al. (1998), however, construct the relationship between service life and ADT as a hyperbolic curve, given the product of ADT and service life is a constant. Figure 2.3 illustrates the relationship for epoxy by surface type and compares this model with Dale's. The relationship is shown in the following equation:

$$U = \frac{K}{V} \qquad \textbf{2.10}$$

Where:

U = useful life (months)

V = ADT/lane, and

K is a constant defined as:

$$K = \frac{I-M}{D} \qquad \textbf{2.11}$$

Where:

I = initial retroreflectivity ($mcd/m^2/lux$),

M = minimum acceptable retroreflectivity ($mcd/m^2/lux$), and

D = average deterioration rate ($mcd/m^2/lux/month/ADT/lane$).

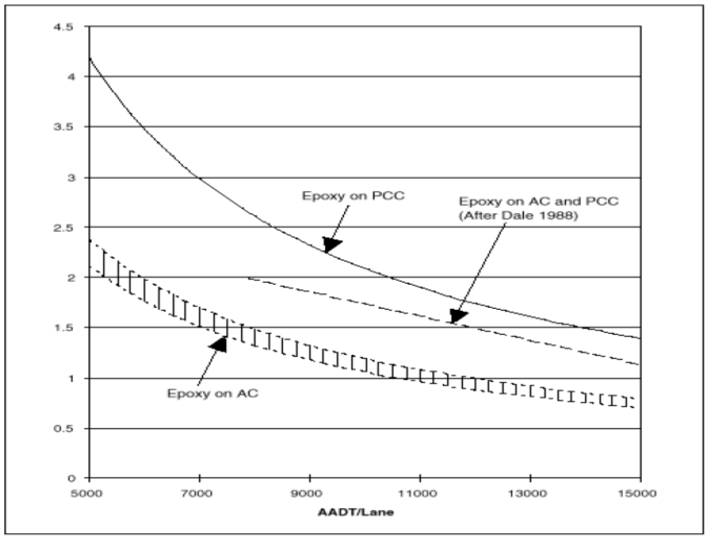


Figure 2.3 Service lives and ADT/lane for epoxy on PCC and AC [Perrin, 1998]

Many recent studies represent the combined impact of time and ADT by forming a new variable, the cumulative number of traffic passages (CTP) to which the marking has been exposed since installation, expressed in terms of millions of vehicle passages per lane. For example, the CTP of a lane is given by:

$$CTP = \frac{ADT * Age\ of\ marking\ in\ months * 30}{1{,}000{,}000 * number\ of\ lanes} \qquad \textbf{2.12}$$

In a 2003 study, Lindly et al. tested linear, exponential and logarithmic regression models in order to determine whether marking age or ADT made a better primary variable. The study found that CTP better correlates with retroreflectivity than marking age and that, other variables (road type, speed limit, geographic location, etc) were not statistically significant. The study also found that linear and exponential models produced more accurate R^2 values than logarithmic and power models.

These two model forms are:

Linear model; $R_L = a + b*CTP$ **2.13**

Exponential model; $R_L = a*exp\ (b*CTP)$ **2.14**

Where:

R_L is the pavement marking retroreflectivity, and a, b are model coefficients.

Other studies have tested models using CTP as the primary variable. Magletz et al. (2000) tested linear, quadratic, and exponential regressions while Abboud and Bowman (2002) tested linear and log-linear regressions. In these cases, CTP is estimated so that it corresponds to the minimum reflectivity, then the equation is used to find the service life (in months). The following is an alternate equation:

$$SL_{months} = \frac{SL_{CTP}}{\left[\frac{CTP_{final}}{date_{final} - Date_{install}}\right]\left[\frac{365.25days}{12months}\right]} \quad \textbf{2.15}$$

Where:

SL_{months} = service life in elapsed months;

SL_{CTP} = service life in cumulative traffic passages (millions of vehicles), corresponding to CTP values when R_l equals to the minimum retroreflectivity.

CTP_{final} = cumulative traffic passages (millions of vehicles) at final field measurement date;

$Date_{final}$ = date of final field measurement; and

$Date_{install}$ = installation date of pavement marking.

Levels of road ADT are used to calculate service life Lindly et. al. used 2,500, 5,000, 7,500, and 10,000 vpd per lane, while Abboud and Bowman used low-ADT (<2,500 vpd), mid-ADT (2,500 to 5,000 vpd), and high-ADT (>5,000 vpd). Kansas DOT used <5,000 vpd, 5,000-50,000 vpd, and >50,000 vpd to calculate the benefit cost ratio [Haoqiang, 2008].

Sitzabee, et al. (2008) developed linear pavement marking deterioration models for paint and thermoplastic markings. Researchers strapped a mobile laselux Reflectometer (model LLR5) to a Chevy Suburban and used a standard 30 meter geometry to collect data from 56 thermoplastic and 37 paint segments. The models yielded a coefficient of determination (R^2) of 0.6 for thermoplastic and 0.75 for paints. The study determined a 2.09 mcd/m^2/lux deterioration rate per month for thermoplastic and 4.17 mcd/m^2/lux per month for paints.

In a 2004 study, Kopf tested 80 sections of waterborne and solvent pain markings on Washington state roads for deterioration trends, using a Laserlux retroreflectometer with a minimum of

100mcd/m^2/lx as a retroreflectivity threshold value. The study found considerable variability in the data and therefore concluded that there was no strong correlation between retroreflectivity deterioration rates and time.

Sarasua, et al. (2012) investigated the lifecycle of 126 waterborne and nine high-build pavement markings samples on primary and secondary roads in South Carolina. Data were collected every 3 months (11 rounds total) using a handheld retroreflectometer and a threshold retroreflectivity of 100 mcd/m^2/lux. The research findings are shown in Table 2.1:-

TABLE 2.1 Average pavement markings life for NC (Sarasua, et. al., 2012)

Material	Model	R-Squared	Average Initial Value	Estimated Marking Lives	
White Edge HB	DIFF = -57.8900 (C)	0.32	390	5.01 CTP	
	% DIFF = -15.6744 (C)	0.35		4.74 CTP	
White Edge WB	DIFF = -0.1317(D)	0.22	315	1632 Days	4.47 Years
	% DIFF = -0.0537(D)	0.34		1271 Days	3.48 Years
White Edge T	DIFF = 54.142 – 0.0403 (D)	0.01	426	6745 Days	18 Years
	% DIFF = 13.699 – 0.0079 (D)	0.01		9279 Days	25 Years
Yellow Solid WB	DIFF = -0.0721 (D)	0.37	141	569 Days	1.56 Years
	% DIFF = -0.0569 (D)	0.47		511 Days	1.40 Years
Yellow Skip WB	DIFF = -0.0594 (D)	0.34	150	879 Days	2.41 Years
	% DIFF = -0.0366 (D)	0.33		911 Days	2.50 Years
Yellow Solid T	DIFF = -0.0764 (D)	0.05	260	2094 Days	5.74 Years
	% DIFF = -0.0270 (D)	0.04		2279 Days	6.24 Years
Yellow Skip T	DIFF = -0.1123(D)	0.09	290	1691 Days	4.64 Years
	% DIFF = -0.0364(D)	0.06		1800 Days	4.93 Years

In a three-year study, Fitch and Ahearn (2007) evaluated the performance of epoxy paints, thermoplastic and polyurea markings on Vermont roads using a logarithmic model and the minimum acceptable retroreflectivity of 100 mcd/m^2/lux. The study found a significant correlation between traffic volume and retroreflectivity life-cycle: as AADT increased, the deterioration rate increased. The coefficient of determination (R^2) was 0.4339 for paint and 0.8046 for thermoplastic. The study also found that warmer regions had lower deterioration rates than colder regions.

For their 2012 study, Mitkey et al. evaluated the durability of rumble stripes and standard paint markings in various weather conditions. Data for wet conditions were gathered using the LTL-X retroreflectometer; data for dry conditions were gathered using the LTL-2000. The threshold retroreflectivity was 100 mcd/m^2/lux for white markings and 65 mcd/m^2/lux for yellow markings. The study found that in dry conditions the retroreflectivity for a white rumble stripe with glass beads performed 95% better and a yellow rumble stripe performed 80% better. The study also found that in a corridor containing paint with blended elements, the white rumble stripe exceeded the edge line by approximately 90% and the yellow by 260%.

In a four-year study, Lee (2011) evaluated the life cycle of inlaid tape and thermoplastic markings on roads in Maryland. Waterborne paint was used as a control paint for its non-durability. A linear function model was determined to best evaluate the markings. The study found that while yellow inlaid tape had a higher retroreflectivity initially, it deteriorated faster than yellow thermoplastic.

A 2011 Karwa and Donnell study used a mobile reflectometer to collect data on 11 segments of thermoplastic markings across three districts in North Carolina over a period of 7 months. The segments varied by initial retroreflectivity, age of markings, traffic flow and route location. Researchers used an artificial neural network with a nonlinear relationship to predict retroreflectivity. Some of the findings from this study are shown in the following figure:

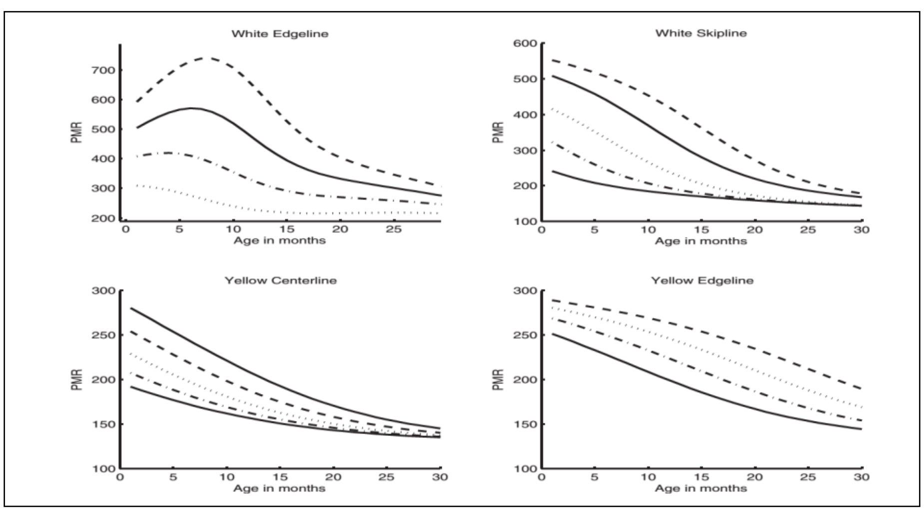


Figure 2.4 Effect of initial retroreflectivity on deterioration pattern (Karwa and Donnell, 2011)

The study found the deterioration pattern of retroreflectivity to be nonlinear and that it differs by marking type. The study did not find a significant correlation to traffic volume.

In their 2006 study, Zhang and Wu developed a model that applied the smoothing spline method and time series modeling to marking material retroreflectivity in order to predict the service life of various materials. Both methods yielded similar results, a difference of only two months. The study used the pavement marking material test deck from the 2002 National Transportation Product Evaluation Program (NTPEP) in Mississippi for validation.

Pike, et al. (2011) analyzed the impact of stepping distance on the average dry retroreflectivity measurements of profiled and rumble stripe pavement markings. Researchers compared the measurements taken from a portable handheld retroreflectometer to those from a mobile retroreflectometer. The study found that when measured according to ASTM, stepping distance does not have a significant impact on averaged retroreflectivity measurements. The study further found that in the hands of an experienced user, a properly calibrated mobile retroreflectometer will provide dry retroreflectivity measurements almost identical to handheld retroreflectometer measurements. This finding proves profiled and rumble stripe pavement markings may be accurately measured with a handheld retroreflectometer.

In their 2003 study, Narci and Lindly analyzed the service and cost life cycles of flat thermoplastic edge markings (FTM) and rumble stripes on Alabama highways. Researchers measured the nighttime dry and wet retroreflectivity with a mobile retroreflectometer. The initial dry retroreflectivity of newly installations were 320 mcd/m^2/lux for FTM and 236 mcd/m^2/lux for rumble stripes. The study found that a rumble stripe's dry retroreflectivity decreases at a lower rate than an FTM with the same cumulative traffic volume (ADT). The study also found that the average wet retroreflectivity of a new rumble stripe was higher than the average wet retroreflectivity of a new FTM.

Sitzabee and Dowining (2012) conducted a five-year study in which they collected data on polyurea pavement markings 30 days after installation on North Carolina roadways. The Ordinary Least Squares (OLS) model was used to analyze the data. Time, initial retroreflectivity, lateral line location, and annual average daily traffic were used to construct the performance models. The study found that the polyurea marking deterioration rate was significantly impacted by the type of glass bead embedded in the marking and that the retroreflectivity decay rate follows an exponential decay pattern that varies by bead type.

3. METHODOLOGY

This study was conducted to establish pavement marking performance time for the state of Tennessee. Pavement marking retroreflectivity measurements collected from selected highways were used to evaluate the performance of the pavement markings. The study comprised of retroreflectivity data collection from TDOT 2013 pavement markings retrace projects on (1) thermoplastic markings on high volume roads and (2) paint markings on medium to low volume roads. The data collection locations (sites) were selected randomly from the TDOT pavement marking retrace project locations. A total of sixty-two locations were selected from four TDOT regions as shown in Table 3.1 and on the map in Figure 3.1. The list of the selected sites is provided in Table 4.7 and Appendix 1. The pavement marking's retroreflectivity acceptance reading was performed 45 days after application. TDOT requires an initial minimum retroreflectivity level of 200 mcd/m^2/lux for yellow markings and 300 mcd/m^2/lux for white markings. This study collected retroreflectivity data from the selected locations for a period of two years (August 2013 - June 2015) at approximately 45 days intervals. A minimum acceptable retroreflectivity of 100 mcd/m^2/lux for white markings and yellow markings was adopted for this study.

Retroreflectivity data were collected using a handheld LTL-X Retroreflectometer (Figure 3.2). Data were collected on white and yellow, solid and skip lines, with an average of 10 tests on a 50 ft. section, and on rumble stripes with an average of 30 tests on a 50 ft. section. A data collection frequency of forty-five (45) days was adopted. The collected data were used to evaluate the performance of pavement markings over time. Pavement deterioration rates and pavement marking deterioration curves and equations that correlate longevity and performance of pavement markings were developed. Prior to data collection, the team members attended traffic safety training to prepare for effective data collection. During data collection, the crew wore safety gear and used traffic signs for traffic management to maintain safety for road users and data collection crew.

Data were collected at an interval of 45 days except during periods with heavy rain, snow or severe cold. On these days, data collection was postponed. Data analysis was performed using MS Excel database. Deterioration rates were calculated using raw data and three point moving averages. Excel plots of retroreflectivity vs. number of days were used to obtain linear equations that also could estimate the life and/or remaining life of a pavement marking.

TABLE 3.1: Summary of selected sites per pavement marking type and region

	Year 2013		Total
Region	Paint	Thermoplastic	
1	7	8	15
2	7	8	15
3	10	10	20
4	7	5	12
Total number of sites			**62**

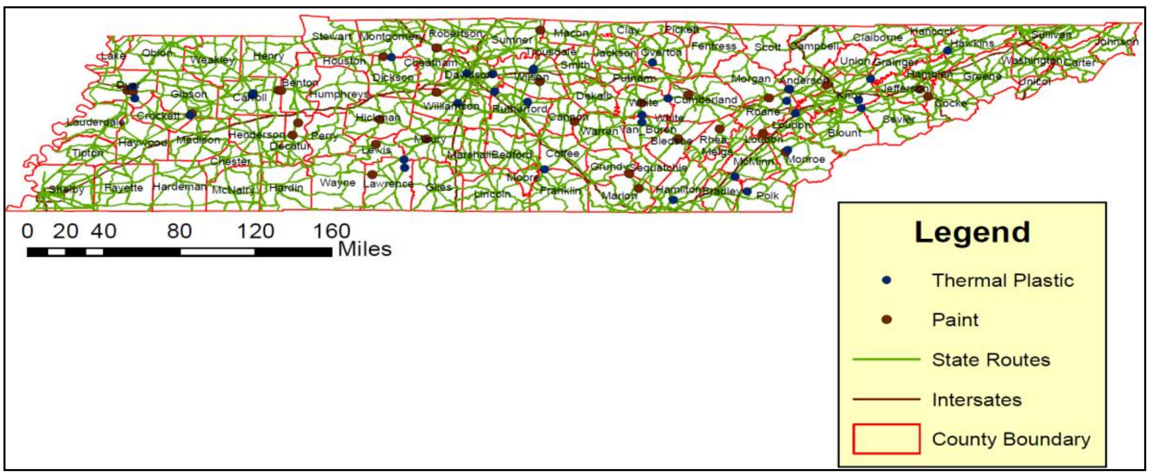


Figure 3.1 GPS map of selected locations

Figure 3.2 LTL-X Retroreflectometer

3.1. Tasks

The tasks listed below were performed during the course of the project.

Task 1: Literature Review

A comprehensive literature search was conducted to uncover both on-going or previous published and unpublished reports and papers on Retrace Pavement Marking Retroreflectivity. Resources such as library holdings, databases, and gateway services; and external database services, such as TRB, ASCE, ITE, NCHRP, TRIS, Elsevier Science, and others were accessed as reported in Chapter 2.

Task 2: Training and Review of TDOT Existing Information on Pavement Markings

The project team attended TDOT training on the use of a handheld LTL-X Retroreflectometer for data collection. In addition, a comprehensive review of pavement marking retrace projects in the state of Tennessee was performed. The purpose of the review was to randomly select data collection locations statewide. The locations having 45-day acceptance readings were targeted for first readings. As listed in Table 4.1, 62 locations were randomly selected.

Task 3: GPS mapping of project locations

The selected data collection locations from the TDOT retracing program were mapped on a GPS map (Figure 3.1).

Task 4: Data collection

Retroreflectivity data were collected from the study locations using the LTL-X retroreflectivity for a period of two years at an interval of approximately 45 days. During data collection, the study team performed traffic control at the sites, as well (Figure 3.2).

Task 5: Evaluation of the Pavement Retroreflectivity through Descriptive Statistics

Descriptive statistics of factors (traffic, elevation and age) associated with pavement retroreflectivity were performed. Pavement marking deterioration rates and models were developed to correlate pavement marking performance with respect to marking type (yellow or white color), age, traffic, elevation and region.

Task 6: Developing Time – Retroreflectivity correlation

Pavement marking correlation curves (models) were developed as shown in section 4.2. Curves were developed to correlate the pavement marking retroreflectivity measurements with time, statewide and per age, traffic and elevation. Statistical analysis tools from Excel software were utilized.

Task 7: Quarterly Project Progress Reports

Quarterly reports were submitted at the end of each quarter with updated information on activities performed during that quarter. Meetings with the TDOT project manager were called to discuss progress and address any queries raised. A comprehensive final report will be submitted to TDOT at the end of the project.

4. DATA COLLECTION

4.1. Overview

Pavement marking retroreflectivity readings collected from selected highways were used to evaluate the pavement markings life cycle, or deterioration rates. The study used retroreflectivity data collection from TDOT 2013 pavement makings retrace projects on (1) thermoplastic markings on high volume roads and (2) paint markings on medium to low volume roads. The data collection locations (sites) were selected randomly to account for variability among factors such as high and low traffic volumes, number of lanes, high and low elevations, rural and urban areas and TDOT regions. The pavement marking's retroreflectivity acceptance reading was performed 45 days after application. The initial acceptance readings were based on TDOT required minimum retroreflectivity levels of 200 mcd/m^2/lux for yellow markings and 300 mcd/m^2/lux for white markings. This study collected data from the selected locations for two years (from August 2013 to June 2015) at approximately 45 days intervals.

4.2. Number of Data Collection Sites

Initially, a total of sixty-two locations were selected from the four TDOT regions as shown in Figure 4.1; however some sites were dropped as the study progressed due to factors such as traffic control difficulties and pavement resurfacing or marking retracing. At the end of the study, only forty-five sites were retained with complete rounds of data collection. Table 4.1 shows the breakdown of the number of sites per TDOT region. Table 4.2 summarizes the mean, minimum and maximum length of the sites per TDOT region and shows an average of 5.16 miles in length for initial sites and 6.07 miles for the final 45 retained sites.

Table 4.1: Initial and Final Study Sites per TDOT Regions

Region	Initial Sites				Final Study Retained Sites		
	Paint	**Thermoplastic**	**Total**		**Paint**	**Thermoplastic**	**Total**
Region 1	7	8	15		4	8	12
Region 2	7	8	15		5	7	12
Region 3	10	10	20		5	8	13
Region 4	7	5	12		3	5	8
Total	**31**	**31**	**62**		**17**	**28**	**45**

Table 4.2: Study Sites by Length per TDOT Regions

	Initial Sites (Length, in Miles)				Final Retained Sites (Length, in Miles)		
	Mean	Min	Max		Mean	Min	Max
Region 1	8.16	0.78	21.48		9.57	1.46	21.48
Region 2	5.31	0.82	13.60		7.18	0.82	13.60
Region 3	3.47	0.16	16.28		4.64	0.31	16.28
Region 4	3.71	0.10	14.25		2.88	0.10	7.26

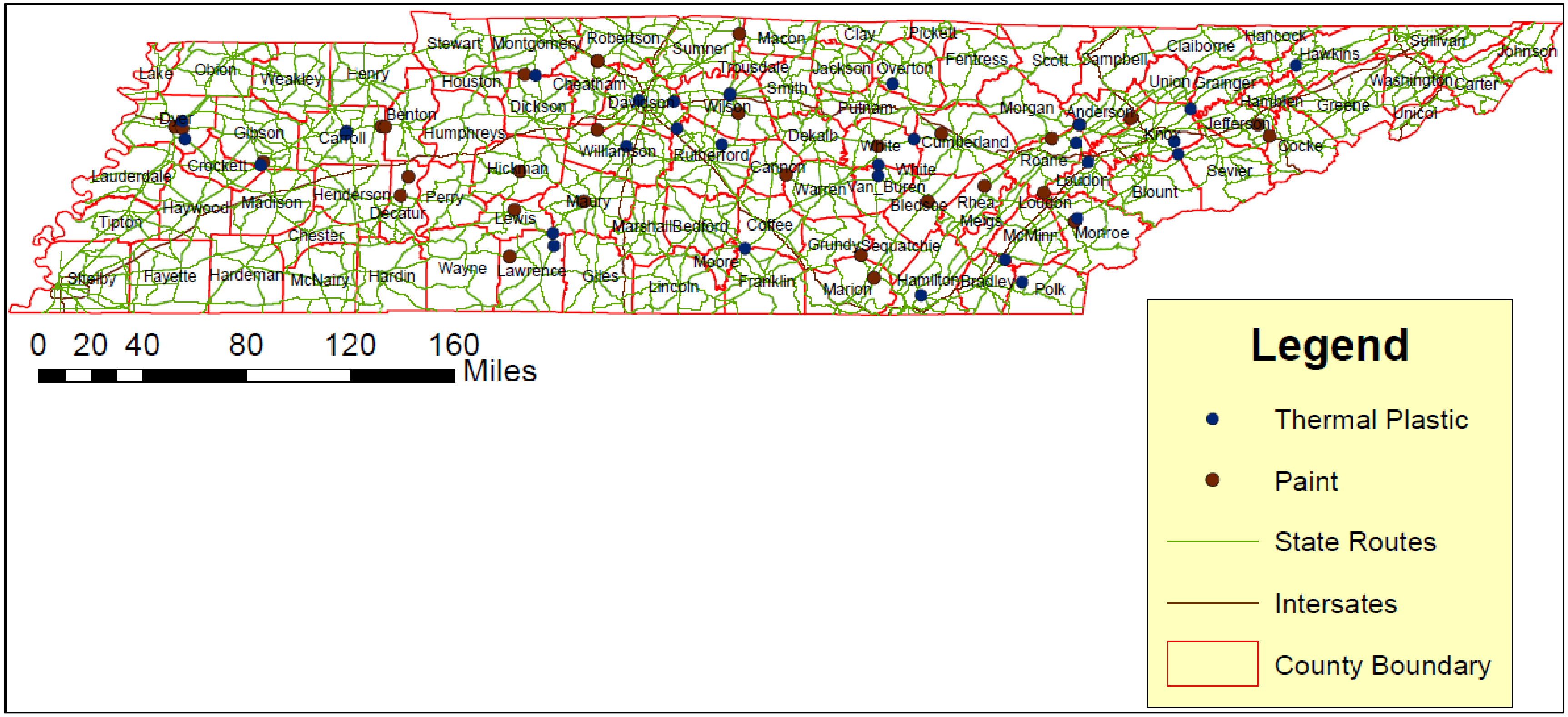


Figure 4.1: Initially 62 Selected Data Collection Sites

4.3. Distribution of Study Sites with Number of Lanes and Traffic Volume

Data collection sites were selected to account for variations in the number of lanes, which indirectly reflects traffic intensity, as shown in Table 4.3. The paint pavement markings were mostly from 2-lane segments while thermoplastic markings were from 4-lane segments. The data collection sites were also varied in order to capture the impact of undivided, divided and two-way left turn lanes (TWLT). Table 4.4 shows variation of traffic volume per site averaged per TDOT regions. The sites with the highest average daily traffic volumes (13,070 vpd) as well as the highest variability (as observed in standard deviation) were in Region 1. In contrast, Region 4 sites had the lowest daily traffic volume levels (6,320 vpd). The 2-lane sites, which mainly contained paint pavement markings, were shown to have low traffic intensity while TWLT and 4-lane sites had slightly higher traffic volumes, as depicted in Table 4.5.

Table 4.3: Study Sites by the Number of Lanes

	Initial Sites				Final Retained Sites		
	2-Lanes	**≥4-Lanes**	**Total Sites**		**2-Lanes**	**≥4-Lanes**	**Total Sites**
Region 1	9	6	**15**		5	7	**12**
Region 2	10	5	**15**		7	5	**12**
Region 3	11	9	**20**		10	3	**13**
Region 4	7	5	**12**		5	3	**8**
Total	**37**	**25**	**62**		**27**	**18**	**45**

Table 4.4: Final Study Sites by Traffic Volume (AADT)

Region	**AADT for the Final Retained Sites**			
	Mean	Min	Max	SD
Region 1	13,070	1,097	32,500	9,522
Region 2	8,143	1,268	30,850	8,145
Region 3	8,183	900	25,830	6,408
Region 4	6,320	5,110	9,405	1,886

Table 4.5: Correlation between Sites AADT and Number of Lanes

Number of Lanes	**AADT for the Final Retained Sites**			
	Mean	Min	Max	SD
2-Lanes	5,241	900	11,300	2,993
3-Lanes (TWLT)	9,513	4,210	14,370	5,095
4-Lanes	14,287	2,700	32,500	9,131

4.4. Distribution of Study Sites with Elevation

The study attempted to correlate the deterioration of retroreflectivity with terrain and topographic alignment, which may directly or indirectly be linked to weather and climate variations. This was achieved by ensuring the retroreflectivity data collection sites were varied by elevations. As shown in Figure 4.2, Tennessee topography aligns well with TDOT administrative regions, which correlate well with the spectrum of elevations above sea level. Table 4.6 summarizes the mean and range of elevations found at the data collection sites. The highest elevation site was 1,990 ft. above sea level (in Region 2) while the lowest was 192 ft. (in Region 4). Overall the mean elevation across all sites was 809 ft. above sea level.

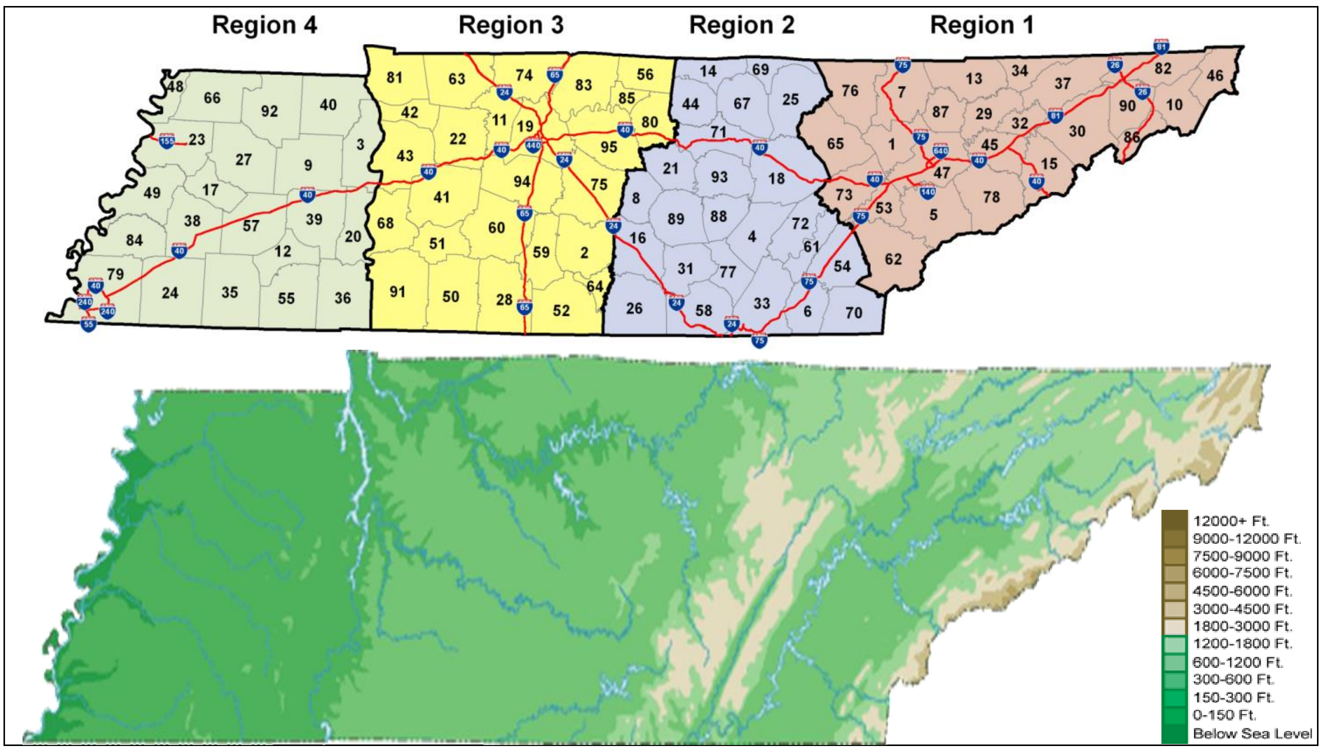


Figure 4.2: Tennessee Topographic Map and Correlation to TDOT Regions

Table 4.6: Average Elevations (in feet) for the Final Study Sites

Region	**Average Elevations for the Final Retained Sites**			
	Mean	Min	Max	SD
Region 1	1,003	763	1,313	184
Region 2	1,165	667	1,990	455
Region 3	602	355	866	156
Region 4	321	192	652	145

4.5. Retroreflectivity Data Measurement Process

Retroreflectivity measurements were taken according to TDOT testing methods. As shown in Figure 4.3, for study sites with two-lane segments, there was a minimum of 30 readings taken, including 10 on the white lines and 5 on each skip or solid yellow line. For study sites with more than 2 lanes in one direction that were undivided, there was a minimum of 40 tests, including 10 on each white line and 5 on each skip or solid yellow line. For study sites with 2 or more lanes separated by a median, there was a minimum of 30 tests, including 10 tests on the white edge lines, 5 on each of skip lines, and 10 additional tests on the yellow line on the opposite side.

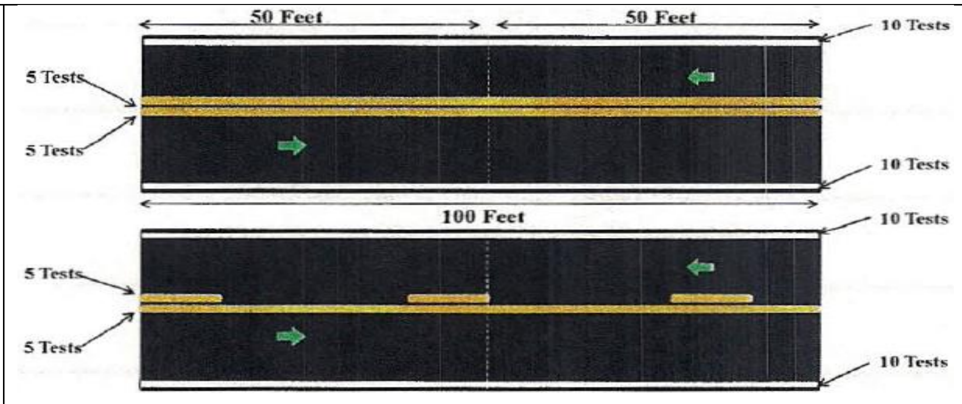
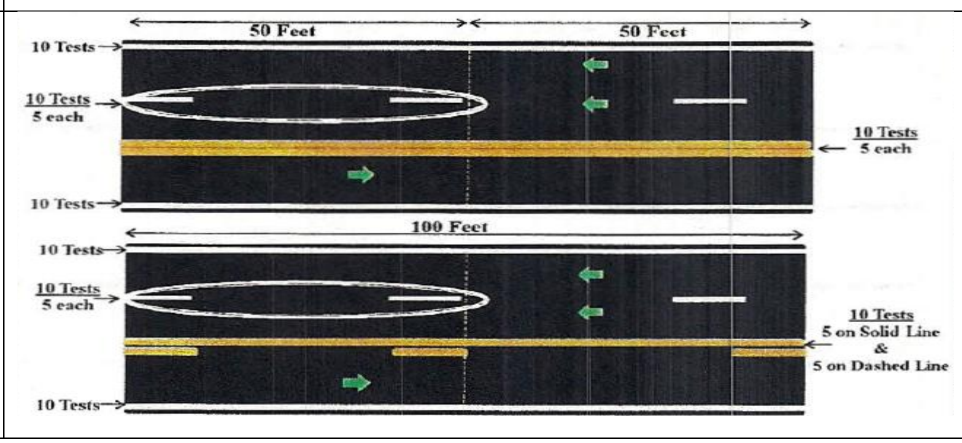
<table>
<tr><td>Two Lane Roads</td><td>
</td></tr>
<tr><td>Two or More Lane Traffic Not Separated by Median or Barrier</td><td>
</td></tr>
</table>

Figure 4.3: TDOT Retroreflectivity Measurement Procedures

Retroreflectivity data were collected using a handheld LTL-X Retroreflectometer (Figure 4.4) in a forty five (45) days data collection frequency. During periods with heavy rain, snow or severe cold, data collection was rescheduled. The data shown in Table 4.7 was used to evaluate the performance of pavement markings over time. Pavement deterioration rates and pavement marking deterioration curves and equations that correlate longevity with performance of pavement markings were developed. Data analysis was performed using an MS Excel database.

Deterioration rates were calculated using raw data, and two- or three-point moving averages. Excel plots of retroreflectivity vs. number of days were used to obtain equations that could estimate the remaining life of a pavement marking.

Figure 4.4: LTL-X Retroreflectometer

4.6. Retroreflectivity Deterioration Curves and Models

Using the data in Table 4.7, retroreflectivity curves and graphs correlating the number of days with other variables were generated. The study used these data to develop models with tractable deterioration rates. Figure 4.5 shows the average retroreflectivity deterioration trends calculated per number of months since application. The magnitude of deterioration is characterized by the change in retroreflectivity values. The retroreflectivity deterioration rates were then calculated from the plots of readings taken after marking application, readings take after the markings have undergone the intermediate time, and the readings after two years. For instance, in Figure 4.5 the deterioration rates for white paints, yellow paints, white thermoplastics and yellow thermoplastics are -7.36, -5.10, -4.83 and -3.00 mcd/m^2/lux per month, respectively. The established rates are expected to give TDOT opportunity to maintain and replace the pavement markings.

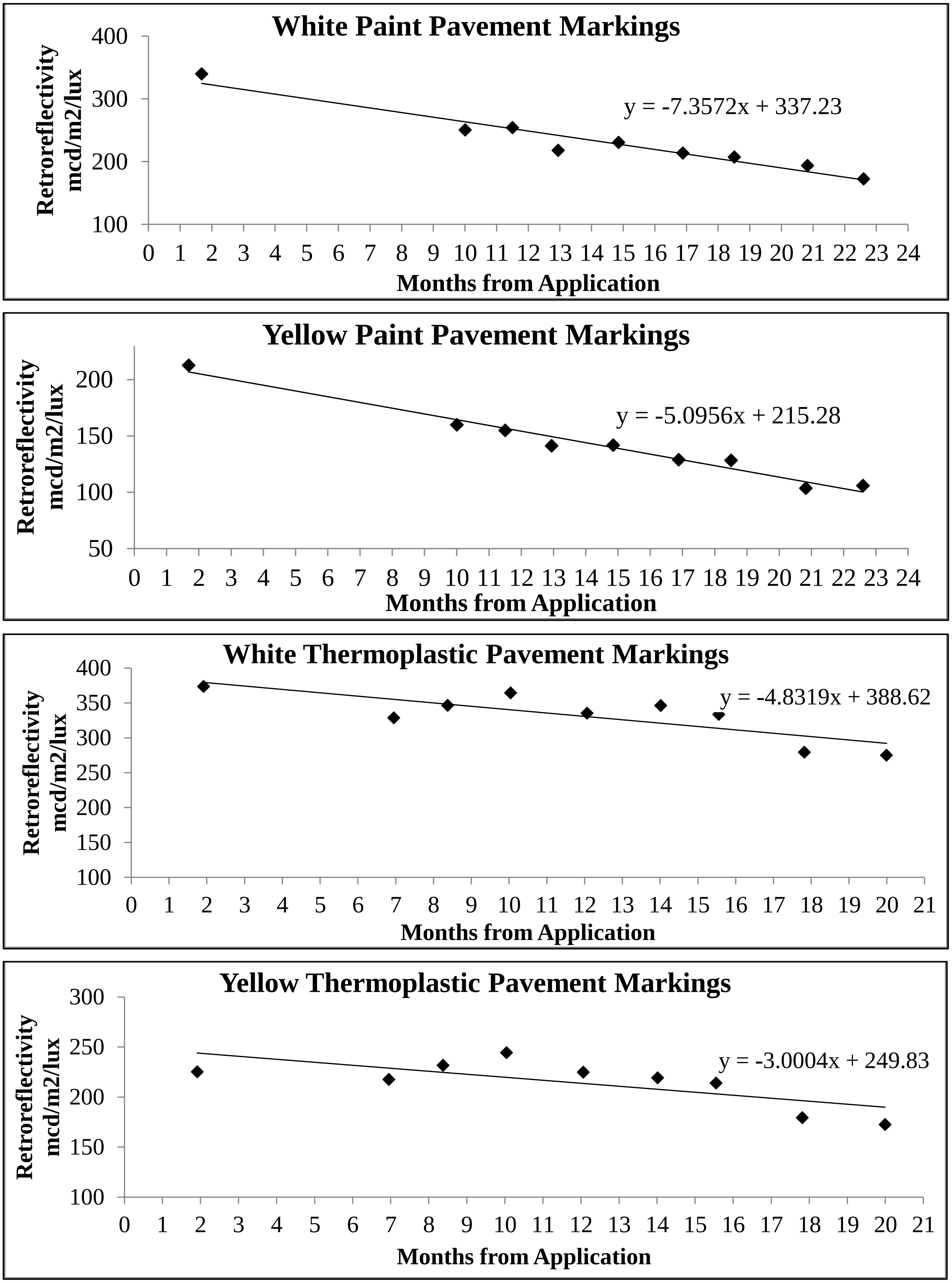


Figure 4.5: Retroreflectivity vs. Number of Months since Application

Table 4.7: Summary of Pavement Marking Retroreflectivity Data Collected

Region	County	Route	Type	Acceptance Reading			Data Reading Round1			Data Reading Round2			Data Reading Round3			Data Reading Round4			Data Reading Round5			Data Reading Round6			Data Reading Round7			Data Reading Round8		
				Days	White	Yellow	Days to R1	White R1	Yellow R1	Days to R2	White R2	Yellow R2	Days to R3	White R3	Yellow R3	Days to R4	White R4	Yellow R4	Days to R5	White R5	Yellow R5	Days to R6	White R6	Yellow R6	Days to R7	White R7	Yellow R7	Days to R8	White R8	Yellow R8
1	Cocke	SR009	Paint	67	403	225	320	215	134	362	293	208	401	201	142	456	184	138	522	152	118	572	144	118	642	124	113	692	135	122
1	Loudon	SR322	Paint	59	367	220	321	235	179	362	252	208	401	265	182	456	276	182	522	246	161	572	268	132	642	211	130	692	214	145
1	Monroe	SR068	Paint	50	330	218	320	176	154	362	206	151	401	142	135	456	164	125	522	135	122	572	123	108	642	127	94	692	115	100
1	Morgan	SR116	Paint	50	359	201	326	304	102	363	295	129	402	277	127	457	271	112	525	231	110	573	231	101	652	209	71	693	184	59
1	Anderson	SR061	Thermo	22	473	286	275	337	319	317	379	374	356	342	402	411	304	377	479	250	281	527	233	236	606	213	152	647	218	165
1	Blount	SR033	Thermo	47	393	247	125	330	179	167	397	247	206	404	269	261	394	254	327	423	278	377	413	241	447	364	153	497	434	177
1	Hamblen	SR034	Thermo	62	450	285	235	201	160	277	252	191	316	193	161	373	219	182	437	208	178	487	190	182	557	184	170	607	199	171
1	Hawkins	SR001	Thermo	58	534	312	232	317	286	273	760	596	312	481	355	369	423	331	436	375	292	483	422	228	553	356	222	603	217	234
1	Knox	SR168	Thermo	66	418	246	168	434	244	210	441	269	249	516	220	305	514	180	370	610	159	420	563	141	490	434	120	540	457	132
1	Monroe	SR033	Thermo	55	463	342	289	210	153	331	223	139	370	232	136	425	230	145	491	234	140	541	204	141	611	194	133	661	203	129
1	Savier	SR035	Thermo	42	375	230	117	292	194	159	369	239	198	372	239	253	368	242	319	363	232	369	318	212	439	294	181	489	194	183
1	Sulivan	SR001	Thermo	75	464	301	226	391	315	267	745	505	306	447	338	363	463	328	430	463	349	477	385	305	547	264	307	597	250	286
2	Bledsoe	SR028	Paint	52	387	224	314	222	209	361	268	142	402	227	157	455	228	160	521	237	127	571	214	153	641	226	110	691	187	94
2	Cannon	SR146	Paint	50	329	128	324	263	165	359	261	153	401	248	155	453	266	127	519	253	130	569	249	123	639	214	91	689	202	82
2	Cumberland	SR024	Paint	50	378	174	326	198	96	363	237	128	402	208	118	455	233	147	521	231	127	573	240	169	652	229	160	693	226	120
2	Grundy	SR108	Paint	50	278	163	312	182	141	359	170	122	401	159	124	453	187	128	519	151	98	569	155	100	639	129	51	689	76	43
2	Marion	SR027	Paint	52	353	235	314	215	65	361	213	63	403	129	66	455	106	66	521	107	58	571	92	45	641	108	49	691	122	55
2	Cumberland	SR001	Thermo	67	451	240	232	234	157	269	412	178	308	391	237	361	433	227	427	401	201	479	392	174	558	366	159	599	280	154
2	Hamilton	SR153	Thermo	72	360	225	145	307	192	192	328	202	234	342	211	286	341	201	352	338	209	402	354	181	483	337	183	522	322	163
2	Overton	SR111	Thermo	51	379	196	202	358	205	239	374	218	278	371	223	333	375	233	401	393	244	449	383	251	528	230	202	569	290	160
2	Rhea	SR029	Thermo	49	346	197	166	322	196	213	330	195	253	343	189	307	341	189	373	370	201	423	357	210	493	283	198	543	396	247
2	Sequatchie	SR008	Thermo	48	334	163	143	297	165	190	277	174	232	520	298	284	271	170	350	333	170	400	328	152	470	240	130	520	242	110
2	Van Burren	SR111	Thermo	46	356	222	183	251	149	218	258	185	259	298	195	312	246	161	378	244	147	428	273	174	498	178	99	548	131	63
2	White	SR111	Thermo	49	376	188	193	303	174	228	346	211	269	373	207	322	334	198	388	363	212	438	394	211	508	264	169	558	246	201
3	Lawrence	**SR240**	Paint	47	341	255	282	333	222	331	302	200	381	278	187	447	276	181	492	289	190	541	273	183	618	209	92	694	206	163
3	Maury	**SR099**	Paint	60	220	245	285	316	199	334	245	217	384	261	184	450	275	169	495	280	165	544	261	161	621	259	115	697	197	140
3	Montgomery	**SR235**	Paint	45	462	242				199	418	247	249	426	240	314	408	227	359	365	222	410	424	220	469	397	222	544	378	210
3	Robertson	**SR049**	Paint	45	267	216	208	278	208	271	280	222	320	224	195	386	271	202	431	252	186	481	247	197	540	281	193	615	198	160
3	Wilson	**SR265**	Paint	58	240	230				306	335	223	377	337	227	442	306	205	503	332	209	538	323	214	598	324	199	671	245	202
3	Davidson	**SR265**	Thermo	51	397	221	165	329	176	199	362	201	270	382	219	335	348	186	380	385	151	430	364	164	490	325	142	564	316	134
3	Lawrence	**SR006**	Thermo	52	364	235	243	297	260	292	331	273	342	291	258	408	251	234	453	225	233	502	200	225	579	116	151	655	165	110
3	Maury	**SR006**	Thermo	58	346	176	190	303	216	244	287	201	294	288	169	360	244	136	405	249	129	454	224	140	531	157	116	607	178	134
3	Montgomery	**SR048**	Thermo	48	432	302				276	365	230	326	321	204	391	344	185	436	340	171	487	322	168	546	315	156	621	259	139
3	Rutherford	**SR001**	Thermo	70	355	231	293	483	312	327	494	291	397	479	298	463	465	286	523	471	301	558	551	351	635	438	275	691	213	170
3	Rutherford	**SR266**	Thermo	63	436		286	321	206	320	432	232	390	424	265	455	360	240	500	342	227	550	302	206	628	231	110	684	426	224
3	Williamson	**SR096**	Thermo	49	343	207	261	345	290	294	373	321	365	341	379	430	296	297	475	294	285	525	263	255	584	240	209	659	230	204
3	Wilson	**SR010**	Thermo	50	323	218	265	403	262	298	418	293	369	470	300	434	388	275	479	391	264	529	351	248	589	350	232	663	325	198
4	Benton	SR001	Paint	25	406	261	251	320	203	300	284	69	350	216	64	416	263	104	476	211	80	512	197	78	569	190	75	664	179	92
4	Carroll	SR001	Paint	61	405	235	289	303	248	338	293	189	388	240	166	454	280	168	499	223	166	549	221	159	605	211	139	702	167	119
4	Dyer	SR104	Paint	76	381	218	192	332	177	242	320	171	Flooded	Flooded	Flooded	Flooded	Flooded	Flooded	328	250	144	377	309	157	434	289	149	605	194	142
4	Carroll	SR022	Thermo	71	320	238	153	332	216	203	276	237	252	300	250	319	316	293	378	311	306	415	282	321	471	287	311	566	220	253
4	Carroll	SR022	Thermo	71	320	238	153	232	141	203	242	128	252	238	147	318	281	154	378	267	154	415	287	160	471	268	148	566	185	143
4	Dyer	SR020	Thermo	92	354	223	229	298	166	279	287	148	328	262	157	395	245	140	453	246	116	490	235	121	546	211	124	642	210	172
4	Dyer	SR020	Thermo	92	340	215	229	236	203	279	272	208	328	296	204	395	279	187	454	298	187	491	283	192	547	272	183	642	202	80
4	Gibson	SR076	Thermo	45	407	205	298	457	316	348	385	297	398	429	333	464	433	332	522	460	341	559	448	346	615	398	325	711	375	305

5. RESULTS AND DATA ANALYSIS

As explained in Chapter 4, data collection was performed for a period of two years at approximately 45 days intervals. Pavement deterioration rates and models were developed from the collected data. The analysis also predicted retroreflectivity using the established pavement marking deterioration rates. Linear prediction models were developed by averaging the data collected during each round. The established rates and models could be used to predict the time it will take for the pavement marking to deteriorate past the acceptable retroreflectivity limits. The deterioration rates were obtained by dividing the change in retroreflectivity readings by the number of days (or months) between the two readings, preferably the acceptance reading and the last reading (round 8). It should be noted that the deterioration rates form a linear deterioration model of retroreflectivity when plotted against pavement marking age in days. This is different from the actual reading that fluctuates over time, but it is a quick method to predict the longevity of a pavement marking. Correlations were established between the actual retroreflectivity readings collected and the retroreflectivity values predicted using different pavement marking deterioration rates in order to determine the coefficient of the goodness of fit, or the coefficient of determination (R^2).

5.1. Pavement Marking Retroreflectivity Deterioration Rates

5.1.1 Determination of Deterioration Rates

Data analysis was performed on the collected data to develop statewide and regional deterioration rates for yellow and white, paint and thermoplastic markings (Table 5.1). The deterioration rates were developed using raw data, presented in Table 5.1, and with a 3-interval moving average (Table 5.2). A three-interval moving average smooths the data better than a two-interval moving average. Table 5.2 shows the regional and statewide deterioration rates developed using the three-interval moving average. These deterioration rates were lower than those presented in Tables 5.1 (without moving average). The rates calculated from this study are comparable to the rates obtained from a study conducted for North Carolina DOT by **Sitzabee, et al.** (2008), which estimated the deterioration rate of pavement marking to be 2.09 mcd/m^2/lx per month for thermoplastics and 4.17 mcd/m^2/lx per month for paints. Differences may be a result of the study sample size. The deterioration rates presented in both tables are based on data collected from the acceptance date to May 2015.

Table 5.1 Statewide and Regional Pavement Marking Deterioration Rates

	Paint (Rates per month)		Thermoplastic (Rates per month)		Number of sites	Number of observations
	White	Yellow	White	Yellow		
Statewide	**-8.00**	**-4.83**	**-7.36**	**-3.70**	**45**	**405**
Region 1	-9.55	-5.17	-9.96	-5.49	12	108
Region 2	-8.55	-4.96	-5.99	-2.87	12	108
Region 3	-3.09	-3.17	-6.08	-2.64	13	117
Region 4	-10.81	-5.99	-7.42	-3.81	08	72

Table 5.2 Deterioration Rates by Pavement Marking Type and Color (3 pt. moving ave.)

	Paint (Rates per Month)		Thermoplastic (Rates per Month)		Number of sites	Number of observations
	White	Yellow	White	Yellow		
Statewide	**-4.19**	**-2.90**	**-3.82**	**-2.39**	**45**	**405**
Region 1	-5.30	-3.28	-5.81	-4.88	12	108
Region 2	-4.02	-2.38	-2.05	-1.27	12	108
Region 3	-1.46	-2.29	-4.72	-2.67	13	117
Region 4	-6.01	-3.65	-2.71	-0.73	08	72

Further analysis was performed to evaluate the impact of traffic and elevation on pavement marking retroreflectivity by establishing pavement deterioration rates based on elevation and AADT. The statewide deterioration rates for yellow and white pavement markings within these categories are presented in Tables 5.3 to 5.6. Retroreflectivity levels by elevation or altitude for white paint pavement markings located below 550 ft. elevation (Table 5.3) showed a high deterioration rate; however, the sample size (one point) is not strong enough to draw further conclusions. Markings at elevations greater than 1000 ft. also showed high deterioration rates, -5.89 mcd/lux/m^2/month for white paints and -6.93 mcd/lux/m^2/month for thermoplastic. On average, yellow pavement markings at this altitude have deterioration rates below -5.0 mcd/sq. m/lux/month. Yellow paint seems to be consistent regardless of elevation, while yellow thermoplastics have lower deterioration rates, -1.9 mcd/sq. m/lux/month at lower elevations (less than 500 ft.); -3.34 mcd/sq. m/lux/month for pavement markings located between 500 and 1000 ft.; and 3.18 mcd/sq. m/lux/month for pavement markings above 1000 ft. altitude. Table 5.5

presents pavement marking deterioration rates per traffic (AADT). There is no specific pavement markings deterioration pattern that can be drawn in relation to traffic. In both analyses, however, white markings deteriorate faster than yellow markings. Increased deterioration could be caused by traffic crossing the skip lines.

These rates are used to predict deterioration rate over time (age), as explained in section 5.3. Elevation and traffic rates without moving averages were used for analysis because they yielded more accurate results.

Table 5.3 Deterioration rates by elevation (without moving average)

		White Deterioration Rate per Month	Yellow Deterioration Rate per Month	Number of sites	Number of observations
less than 550ft	Paint	-11.65	-5.27	1	9
	Thermo	-5.02	-2.67	8	73
550-1000ft	Paint	-4.95	-4.03	7	63
	Thermo	-6.15	-3.62	13	117
greater than 1000ft	Paint	-9.22	-5.24	8	73
	Thermo	-13.35	-5.13	5	45

Table 5.4 Deterioration rates by elevation with 3-point moving average

		White Deterioration Rate per Month	Yellow Deterioration Rate per Month	Number of sites	Number of observations
less than 550ft	Paint	-5.88	-3.42	1	9
	Thermo	2.46	1.24	8	73
550-1000ft	Paint	-2.43	-2.79	7	63
	Thermo	-3.51	-2.91	13	117
greater than 1000ft	Paint	-5.81	-2.74	8	73
	Thermo	7.53	-4.35	5	45

Table 5.5: Deterioration rates by AADT levels (without moving average)

AADT	Marking Type	White Deterioration Rate per Month	Yellow Deterioration Rate per Month	Number of sites	Number of observations
Below 5000	Paint	-4.10	-3.28	11	99
	Thermo	-7.58	-3.49	3	27
5000-10000	Paint	-6.23	-3.96	7	63
	Thermo	-4.13	-2.16	11	99
>10000-20000	Paint	-1.74	-1.88	1	9
	Thermo	-4.44	-3.76	9	81
Above 20000	Paint	N/A	N/A	N/A	N/A
	Thermo	-4.15	-1.69	4	36

Table 5.6: Deterioration rates by AADT levels (3-interval moving average)

AADT	Marking Type	White Deterioration Rate per Month	Yellow Deterioration Rate per Month	Number of sites	Number of observations
Below 5000	Paint	-3.24	-2.58	11	99
	Thermo	-5.70	-2.35	3	27
5000-10000	Paint	-5.06	-1.70	7	63
	Thermo	-3.56	-2.11	11	99
>10000-20000	Paint	-1.74	-1.70	1	9
	Thermo	-3.19	-3.40	9	81
Above 20000	Paint	N/A	N/A	N/A	N/A
	Thermo	-4.35	-1.92	4	36

5.2. Pavement Marking Retroreflectivity Monthly Deterioration Models

The linear deterioration models plotted in Figures 5.1 to 5.4 were developed by taking the average of statewide retroreflectivity readings per round of data collection. These plots can be used to estimate future pavement marking retroreflectivity at various months as the models can be extrapolated linearly for months that are not shown in the Figures.

For example, if a statewide retroreflectivity prediction reading for white paint markings at 20 months is required, Figure 5.1 is used. On the horizontal axis at 20 months, a vertical line can be drawn until it touches the curve (model) on the graph, then a horizontal line is drawn to the vertical axis. The value on the vertical axis (~230 $mcd/m^2/lux$) is approximately the retroreflectivity reading at that number of days. This is a quick method to predict the number of months it will take to reach a certain retroreflectivity reading (threshold). Section 5.3 shows how the deterioration rates in Section 5.1 can also be used to predict retroreflectivity. From these models, equations can be used to obtain y values (predicted retroreflectivity) when x is the number of months.

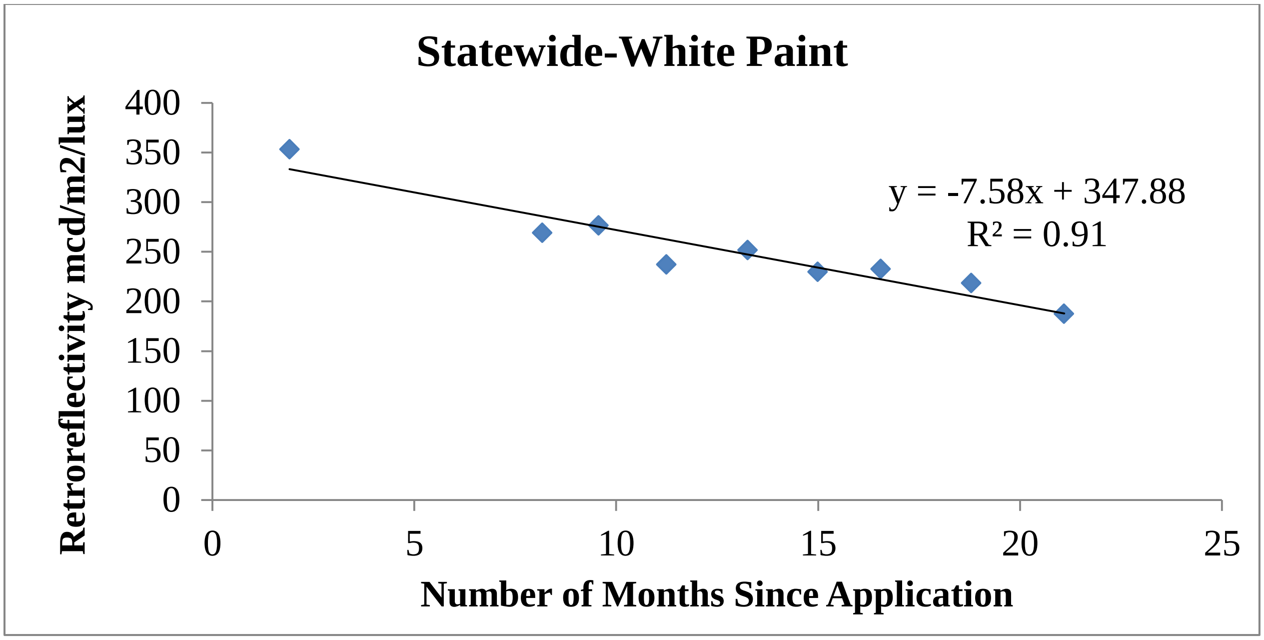


Figure 5.1 Statewide deterioration models for white paint pavement markings

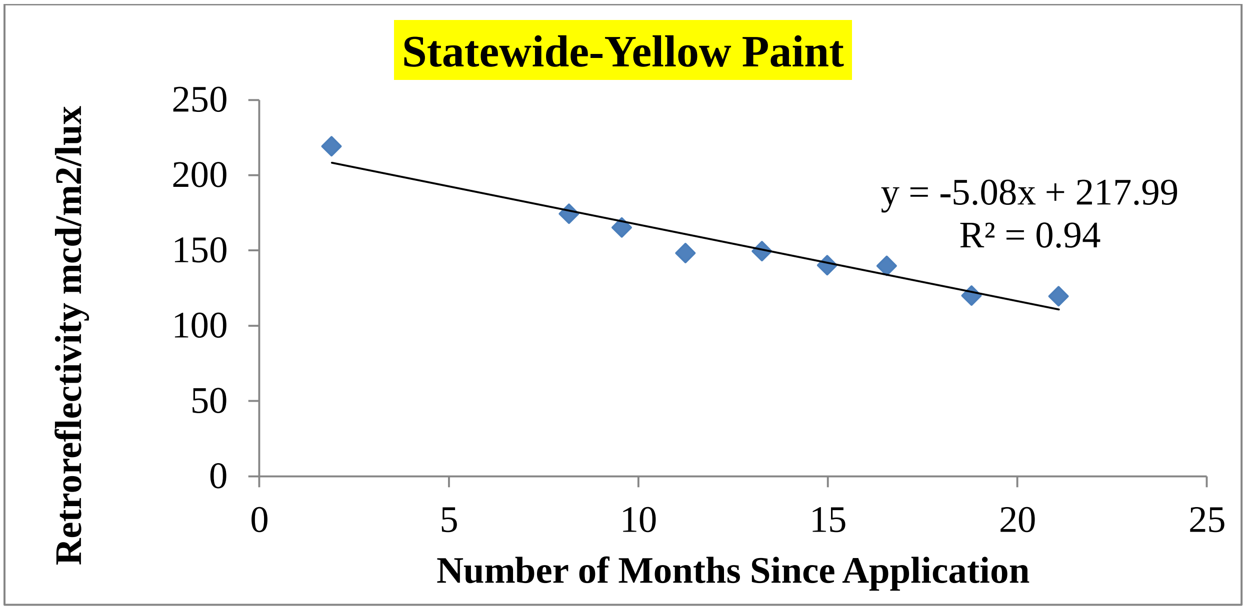


Figure 5.2 Statewide deterioration models for yellow paint pavement markings

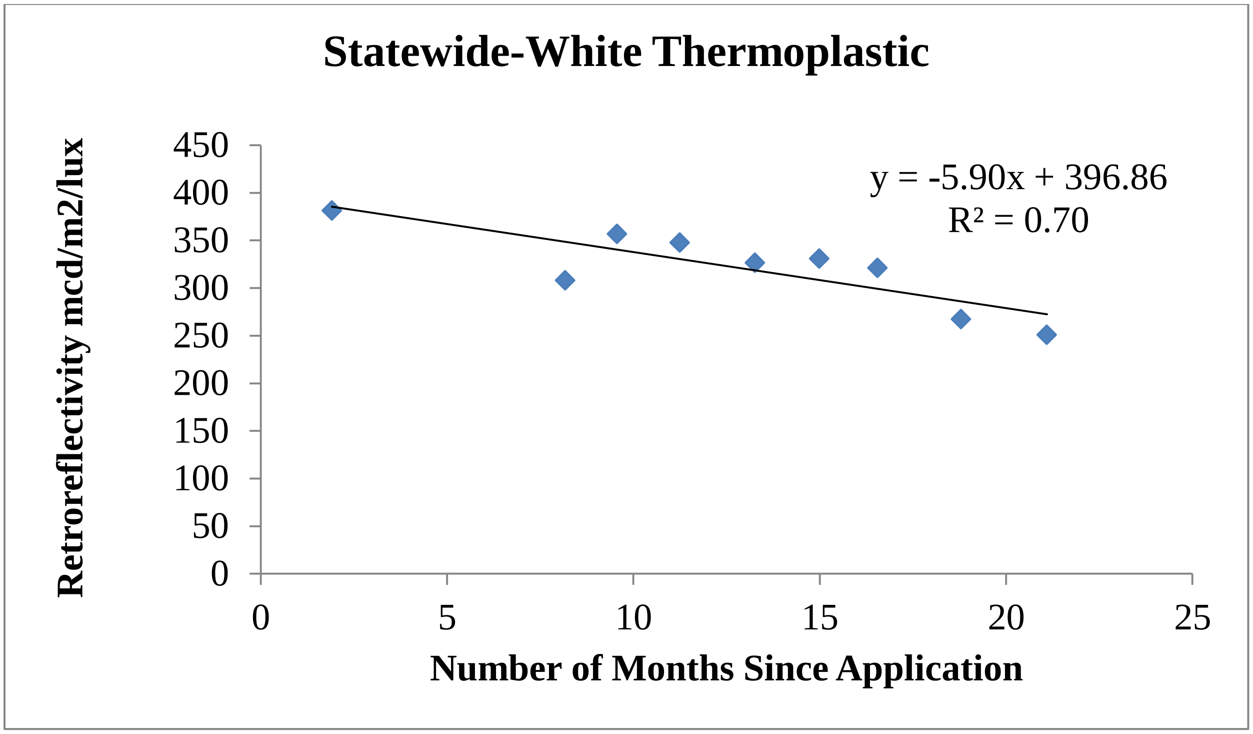


Figure 5.3 Statewide deterioration models for white thermoplastic pavement markings

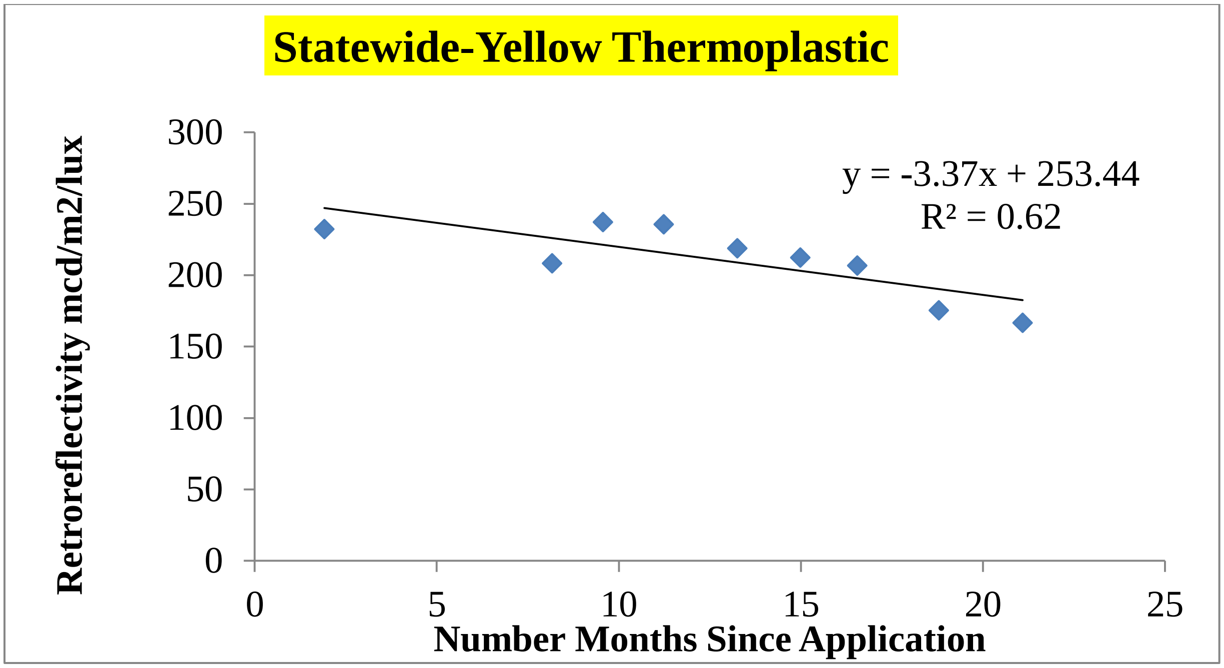


Figure 5.4 Statewide deterioration models for yellow thermoplastic pavement markings

5.3. Prediction of Pavement Marking Retroreflectivity using Deterioration Rates

The deterioration rates per month (Tables 5.1 to 5.6) can be used to predict future pavement marking retroreflectivity at a required number of days (Eq. 5.1) or the time it will take for the retroreflectivity to go below the set threshold (Eq. 5.4).

Equation 5.1 is used to predict retroreflectivity at a predetermined number of days. This equation forms a linear deterioration model of retroreflectivity.

$$RL_{fut} = RL_{INI} - D * DR/30 \qquad 5.1$$

Where:

RL_{fut} = Future pavement marking retroreflectivity

RL_{INI} = Initial pavement marking retroreflectivity

D = number of days to the estimated future pavement marking retroreflectivity

DR = Monthly deterioration rate.

Pavement marking retroreflectivity data from Cocke County SR 009 (TDOT Region 1) is used to illustrate Equation 5.1. The acceptance (initial) reading for yellow paint pavement markings at this location was 224.4 mcd/ m^2/lux. The final reading after 692 days (23 months) was 121 mcd/ m^2/lux. The statewide deterioration rate is 4.83; Region 1's deterioration rate is 5.17 (Table 5.1). Utilizing Equation 5.1, the predicted final retroreflectivity reading is calculated using the statewide rate as 113.05 mcd/m^2/lux (Eq. 5.2) and using Region 1's deterioration rate as 105.1 mcd/m^2/lux (eq. 5.3).

$$\text{Final reading} = 224.4 - 692 * (4.83/ 30) = 113.0 \text{ mcd/m}^2\text{/lux} \qquad 5.2$$

$$\text{Final reading} = 224.4 - 692 * (5.17/ 30) = 105.1 \text{ mcd/m}^2\text{/lux} \qquad 5.3$$

The actual final reading was 121.8 mc/lux/m^2, which is 7 % higher than the projected values using statewide deterioration rates and 13.7% higher than the projected values using deterioration rates for Region 1.

If the pavement marking threshold (RL_{th}) is known, say 100 mcd/m^2/lux for yellow paint markings, the number of days it will take for the pavement marking to deteriorate to threshold level can be calculated using equation 5.4. Using the same location, SR 009 in Cocke Co., the acceptance reading was RL_{INI} = 224.4, and the monthly deterioration rates are 4.83 and 5.17 for statewide and TDOT Region 1 yellow paint markings (Table 5.1). The number of days it will take for the pavement marking to deteriorate to the threshold level, therefore, will be estimated using Equation 5.4:

$$D = (RL_{INI} – RL_{th}) * 30/DR \qquad 5.4$$

Where:

D = number of days to the estimated future pavement marking retroreflectivity

RL_{INI} = Initial pavement marking

RL_{th} = Pavement marking retroreflectivity threshold

DR = Monthly deterioration rate.

Using data collected for SR 009 in Cocke Co., as given above, the estimated life of the pavement marking will be:

$$D = (224.4 – 100) * 30/4.83 = 772.7 \text{ days} \qquad 5.5$$

The number of days it takes for yellow paint pavement markings to deteriorate to 100 mcd/m^2/lux is 772.1 or 25.8 months (a little over two years). This is just one point used to illustrate the interpretation of the results. For this point, the actual results are 7% higher than the prediction. This is due to fluctuations in pavement marking retroreflectivity readings. The estimation of the model also did not take into account other factors like elevation and traffic simultaneously.

Similar analysis can be performed using elevation. The same site, SR 009 in Cocke Co., is used for this illustration. The average elevation of SR 009 in Cocke County site is 1124 ft. (>1000 ft.). Taking this into account, the deterioration rate of yellow paint markings at > 1000 ft. above sea level is 3.58. Using this information with Equation 5.1:

$$\text{Final reading} = 224.4 – 692 * (3.58) / 30 = 141.8 \text{ mcd/m}^2\text{/lux} \qquad 5.6$$

The actual final reading was 121 mc/lux/m^2, which is 17.2 % lower than the projected retroreflectivity. For this location, the statewide deterioration rates predicted closer retroreflectivity values than regional and elevation rates.

5.3.1 Comparison of the Deterioration Rates

The deterioration rates presented in Tables 5.1 to 5.6 and Equation 5.1 were used to predict retroreflectivity. The predicted retroreflectivity data were plotted against actual retroreflectivity data to evaluate how close the predicted retroreflectivity readings are to the measured values. For this analysis, statewide rates were used for white and yellow, paint and thermoplastic markings with and without a moving average. Thermoplastic markings at Hamilton (Region 2) and paint markings at Dyer (Region 4) were used to illustrate the analysis. Table 5.7 and Table 5.8 present the input data for these two sites for white and yellow markings. The deterioration rates extracted from Tables 5.1 to 5.6 for the two sites in Hamilton and Dyer Counties are shown in Table 5.8. "Statewide" and "regional" reflect the deterioration rates generated without a moving average (Table 5.1). "Statewide 3-pt" and "regional 3-pt" reflect the deterioration rates calculated after a three-point moving average (Table 5.2). "Elevation" reflects statewide rates computed per average elevation of the selected site without a moving average (Table 5.3) and "Traffic" reflects statewide rates calculated per traffic AADT without a moving average (Table 5.5).

Table 5.7 Summary of selected sites for verification using deterioration rates

Region	County	Route	BLM	ELM	Length (mi.)	No of lanes	Traffic	Ave. Elev. (ft)	Type
2	Hamilton	SR 153	11.66	12.48	0.82	4	30,850	667.3	T
4	Dyer	SR 104	16.76	19.20	2.44	2	5,340	192.2	P

T = thermoplastic and P = Paint

Table 5.8 Deterioration rates by color for the selected sites

Region	County	Route	Marking	Statewide 1	Statewide 2	Regional 1	Regional 2	Elevation	Traffic
2	Hamilton (T)	SR 153	White	7.36	3.82	5.99	2.05	3.51	4.15
			Yellow	3.70	2.39	2.87	1.27	2.91	1.69
4	Dyer (P)	SR 020	White	8.00	4.19	10.81	6.01	7.68	4.13
			Yellow	4.83	2.90	5.99	3.65	4.50	2.16

T = thermoplastic and P = Paint

5.3.1.1 Analysis of Thermoplastic Markings using Deterioration Rates

State route 153 in Hamilton Co. was used to evaluate the computed deterioration rates for thermoplastic markings. The input values and deterioration rates for thermoplastic and paint, white and yellow pavement markings are presented in Tables 5.7 and 5.8 for the selected sites. Tables 5.9 and 5.10 present the actual retroreflectivity (in column 2), and the computed (predicted) retroreflectivity using different deterioration rates (columns 3 to 8) for white and yellow thermoplastic pavement markings.

Table 5.9 Predicted retroreflectivity values for Hamilton Co. SR 153, white thermoplastic

		Retroreflectivity predictions per deterioration rates					
Age	White	Statewide	Statewide 3-pt	Region 2	Region 2 3pt	Elevation	Traffic
Days	mcd/lux/m^2	3.89	2.38	5.39	5.48	3.51	4.15
47	393.08	386.99	389.35	384.64	384.49	351.58	350.04
125	330.1	376.87	383.16	370.62	370.25	343.04	339.94
167	397	371.43	379.83	363.08	362.57	337.54	333.44
206	404.4	366.37	376.74	356.07	355.45	332.62	327.63
261	393.58	359.24	372.37	346.19	345.40	326.54	320.44
327	422.7	350.68	367.14	334.33	333.35	318.82	311.31
377	412.55	344.20	363.17	325.35	324.21	312.97	304.39
447	363.5	335.12	357.62	312.77	311.43	303.61	293.32
497	434.4	328.64	353.65	303.79	302.29	298.93	287.79

Table 5.10 Predicted retroreflectivity values for Hamilton Co. SR 153, yellow thermoplastic

		Retroreflectivity predictions per deterioration rates					
Age	Yellow	Statewide	Statewide 3-pt	Region 2	Region 2 3pt	Elevation	Traffic
Days	mcd/lux/m^2	3.7	2.39	2.87	1.27	2.91	1.69
72	225	216.12	219.26	218.11	221.95	218.02	220.94
145	191.9	207.12	213.45	211.13	218.86	210.94	216.83
192	202.1	201.32	209.70	206.63	216.87	206.38	214.18
234	211.4	196.14	206.36	202.61	215.09	202.30	211.82
286	200.5	189.73	202.22	197.64	212.89	197.26	208.89
352	208.75	181.59	196.96	191.33	210.10	190.86	205.17
402	180.65	175.42	192.97	186.54	207.98	186.01	202.35
482	183.1	165.55	186.60	178.89	204.60	178.25	197.85
522	163.4	160.62	183.41	175.06	202.90	174.37	195.59

The measured (original) and predicted pavement marking retroreflectivity values in Tables 5.9 and 5.10 were plotted as retroreflectivity versus pavement marking age in days to establish the relationship between retroreflectivity and age for predicted and measured values. Figures 5.5 and 5.6 show the deterioration plots of the measured and predicted retroreflectivity for white and yellow markings, respectively.

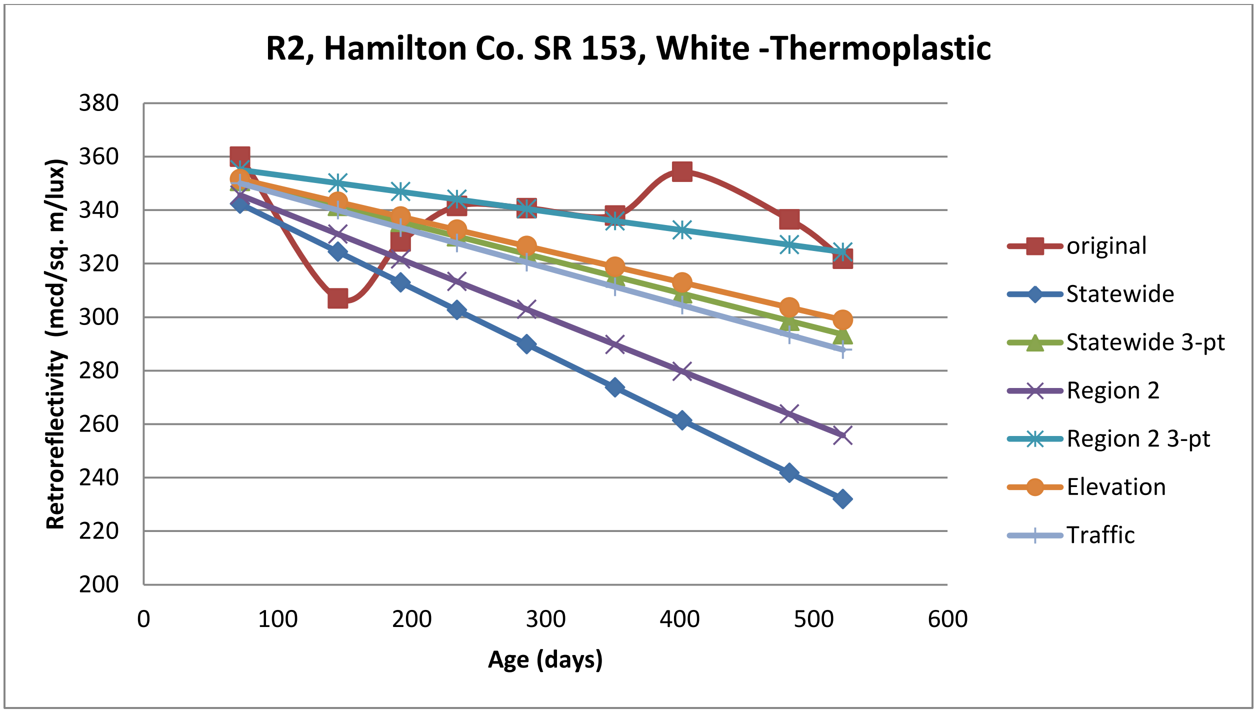


Figure 5.5 Measured and predicted retroreflectivity for SR 153, white thermoplastic.

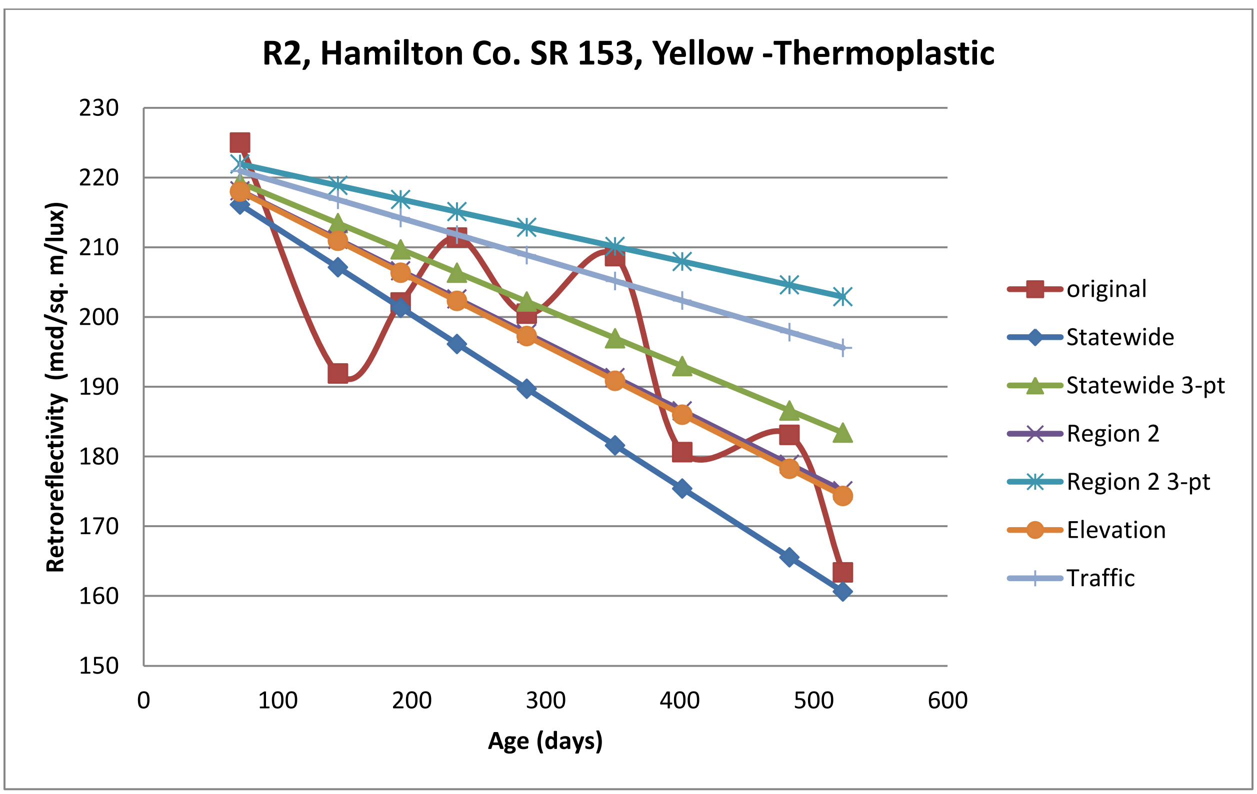


Figure 5.6 Measured and predicted retroreflectivity for SR 153, white thermoplastic**.**

As seen in Figures 5.9 and 5.10, the measured (original) retroreflectivity values fluctuate. This is a common trend in retroreflectivity measurements. Studies from South Carolina and Vermont show similar trends. Due to the fluctuating trends, it is difficult to pinpoint the most accurate deterioration rate. As such, an evaluation of the goodness of fit (R^2) between measured and predicted retroreflectivity values was performed.

The analysis was performed using a three-interval moving average to smooth the collected retroreflectivity readings. The smoothed retroreflectivity values were plotted against pavement marking age in days to evaluate its deterioration trends. The rates computed using 3-point moving average were also used to predict retroreflectivity. Figures 5.7 and 5.8 show the plots for white and yellow markings, respectively. The three point moving average plots are smoother than the original data, although the rates for thermoplastic markings under-predict the retroreflectivity of white markings and over-predict the retroreflectivity of yellow markings.

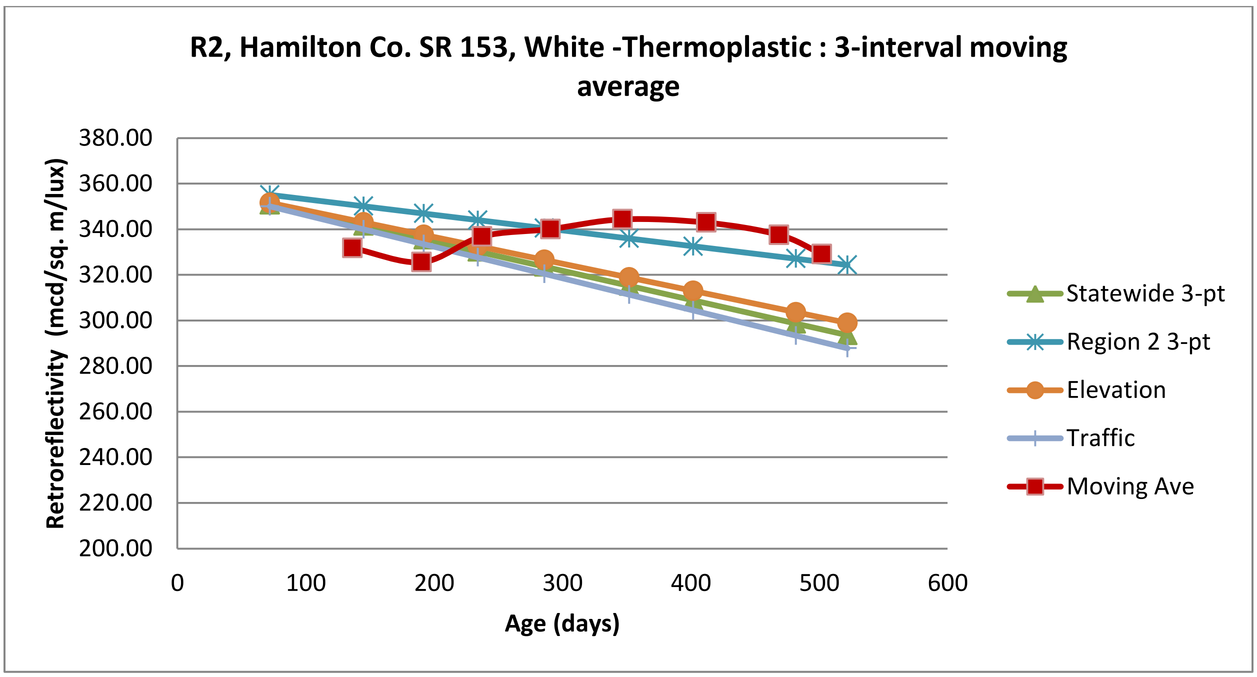


Figure 5.7 Measured and predicted retroreflectivity for SR 153, white thermoplastic, using 3-pt moving average data.

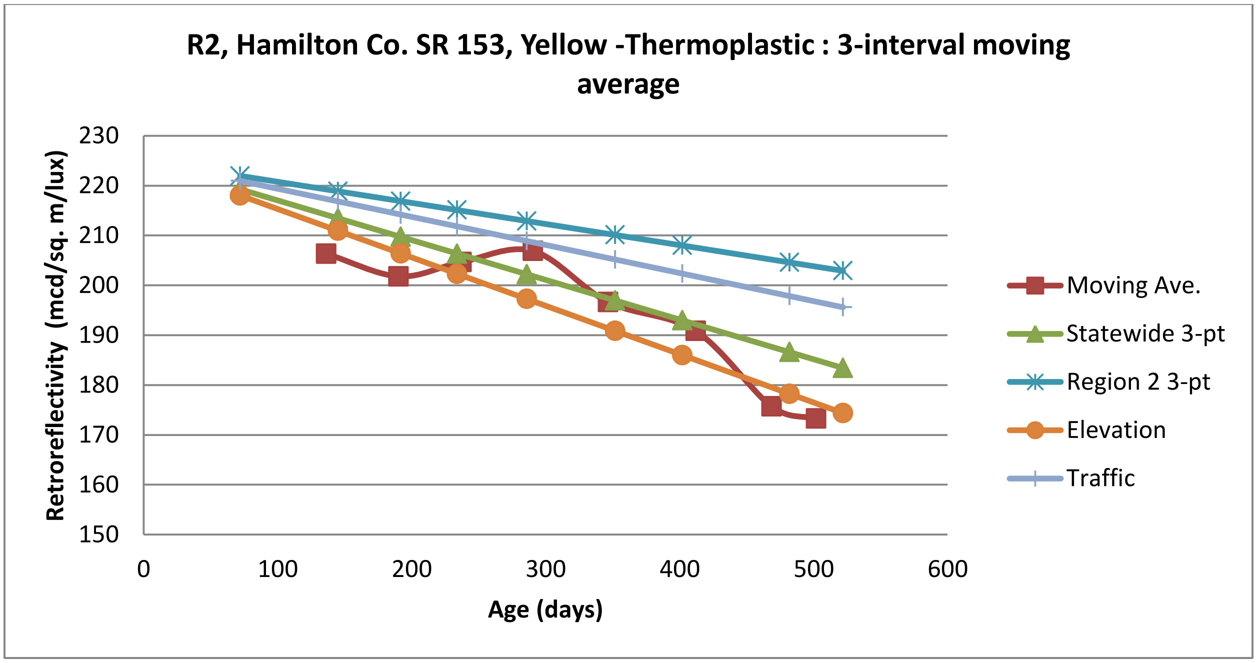


Figure 5.8 Measured and predicted retroreflectivity for SR 153, yellow thermoplastic, using 3-point moving average data.

The correlation between measured and predicted retroreflectivity for white and yellow markings was established by plotting measured versus predicted retroreflectivity in order to establish the coefficient of determination (R^2) value (Figures 5.9 and 5.10). As seen in Figure 5.9, the correlation values between measured and predicted for white thermoplastic are very low (R^2 = 0.06), indicating that there is no correlation between measured and predicted retroreflectivity. The deterioration rates, therefore, may not be a very reliable method to predict future retroreflectivity values for white thermoplastic markings. Yellow thermoplastic markings with 3-interval moving average, however, showed a good correlation between measured and predicted values (R^2 = 0.85). A full analysis using regional and statewide retroreflectivity data is presented in Section 5.4.

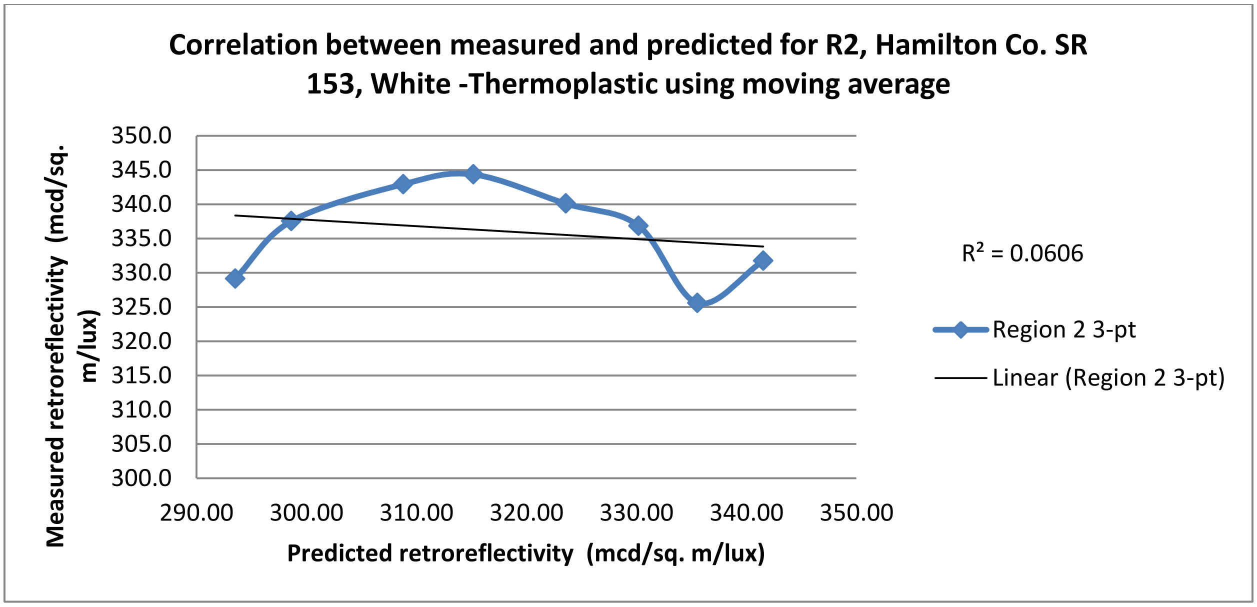


Figure 5.9 Correlation between measured versus predicted retroreflectivity for SR 153, white thermoplastic.

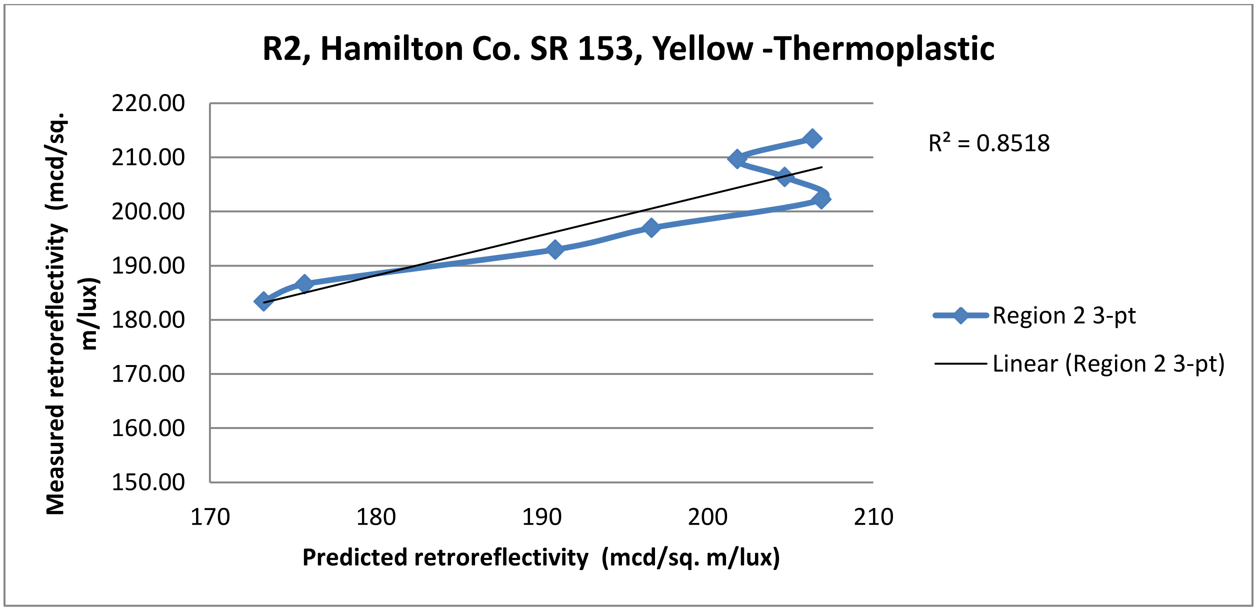


Figure 5.10 Correlation between measured versus predicted retroreflectivity for SR 153, yellow thermoplastic.

5.3.1.2 Analysis of Paint Markings using Deterioration Rates

State Route 020 in Dyer County (TDOT Region 4) was used to evaluate the deterioration rates for paint markings. The input values and deterioration rates for white and yellow paint markings at the selected site are presented in Tables 5.7 and 5.8. Tables 5.11 and 5.12 present the actual (measured) retroreflectivity (in column 2) and the computed (predicted) retroreflectivity using different deterioration rates (in columns 3 to 8) for white and yellow paint pavement markings.

Table 5.11 Predicted retroreflectivity values for Dyer Co. SR 020, white paint.

		Retroreflectivity predictions per deterioration rates					
Age	White	Statewide	Statewide 3-pt	Region 4	Region 4 3-pt	Elevation	Traffic
Days	mcd/lux/m^2	8	4.19	10.81	6.01	7.68	4.13
92	357.4	332.87	344.55	324.25	338.97	333.85	344.73
229	235.9	296.33	325.42	274.88	311.52	298.78	325.87
279	271.8	283.00	318.43	256.87	301.51	285.98	318.99
328	295.7	269.93	311.59	239.21	291.69	273.43	312.25
396	278.8	251.80	302.09	214.71	278.07	256.02	302.88
453	246.3	236.60	294.13	194.17	266.65	241.43	295.04
491	283.2	226.57	288.88	180.62	259.12	231.81	289.86
547	271.5	211.60	281.04	160.39	247.87	217.44	282.13
643	202.2	186.01	267.64	125.82	228.65	192.87	268.92

Table 5.12 Predicted retroreflectivity values for Dyer Co. SR 020, yellow paint.

		Retroreflectivity predictions per deterioration rates					
Age	Yellow	Statewide	Statewide 3-pt	Region 4	Region 4 3-pt	Elevation	Traffic
Days	mcd/lux/m^2	3.7	2.39	2.87	1.27	4.5	3.28
92	214.2	202.85	206.87	205.40	210.31	200.40	204.14
229	203.1	185.96	195.96	192.29	204.51	179.85	189.16
279	208.2	179.79	191.97	187.51	202.39	172.35	183.70
328	204.3	173.75	188.07	182.82	200.31	165.00	178.34
396	186.5	165.36	182.65	176.32	197.44	154.80	170.90
453	116.2	158.33	178.11	170.86	195.02	146.25	164.67
491	192.4	153.69	175.12	167.27	193.43	140.61	160.56
547	182.5	146.77	170.64	161.90	191.05	132.19	154.42
643	80.4	134.93	163.00	152.72	186.99	117.80	143.93

The measured (original) and predicted retroreflectivity values in Tables 5.11 and 5.12 were used to plot retroreflectivity versus pavement marking age in days to establish retroreflectivity deterioration of predicted and measured values. Figures 5.11 and 5.12 show the deterioration plots of measured and predicted retroreflectivity for white and yellow paint markings, respectively. As these figures show, almost any deterioration rate can be used for prediction, but for this site, elevation and statewide deterioration rates are much closer to the measured retroreflectivity.

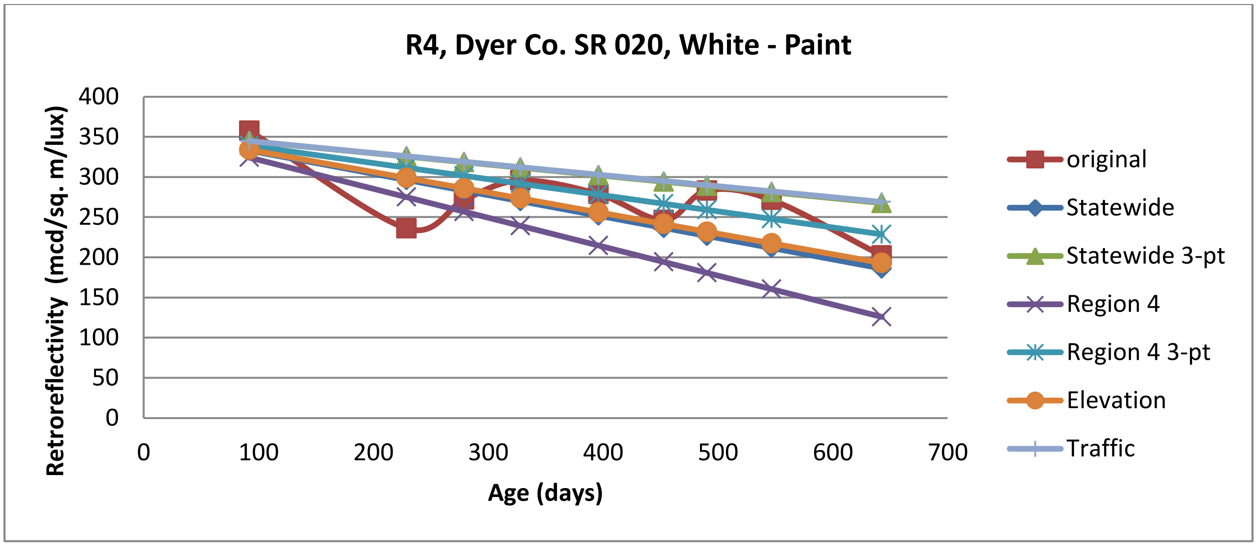


Figure 5.11 Measured and predicted retroreflectivity for SR 020, white paint markings.

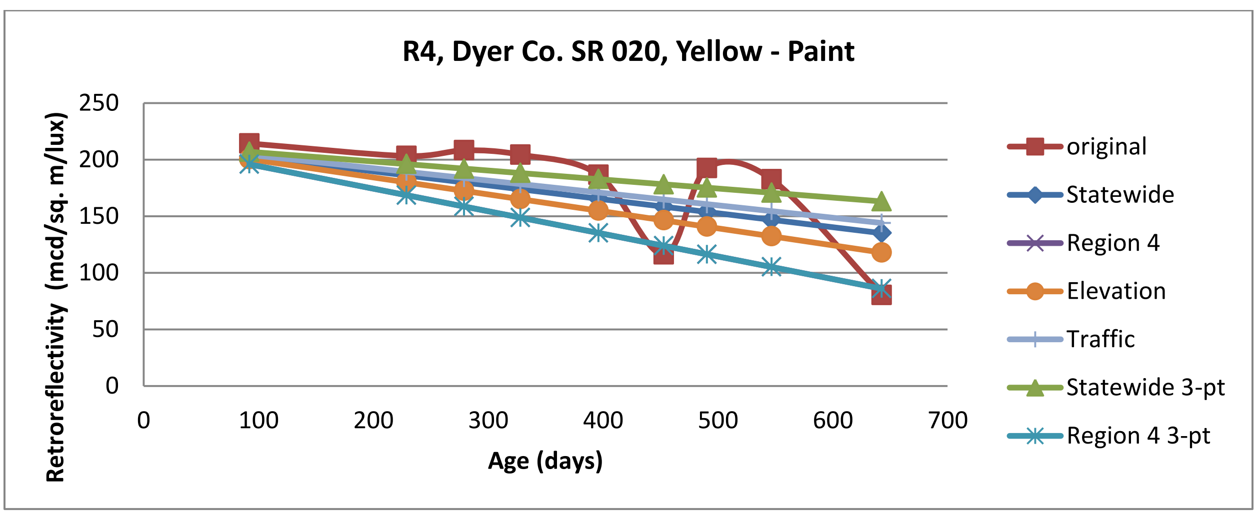


Figure 5.12 Measured and predicted retroreflectivity for SR 020, yellow paint markings.

It can be seen on Figures 2.11 and 5.12 that the measured data fluctuates with increase in pavement marking age (in days). Similar trends have been reported in other studies. The models can be used to estimate retroreflectivity readings, but it is difficult to create a model that will accurately accommodate all of the collected data.

The measured data was smoothed by using a three-interval moving average. Figures 5.13 and 5.14 show the plots of the smoothed measured values and the predicted values for white and yellow markings plotted against pavement marking age in days to evaluate its deterioration rate. The rates computed with the three-interval moving average were used to predict the retroreflectivity corresponding to that deterioration rate. As seen in Figures 5.13 and 5.14, the three-point moving average plots are smoother than the original data plots, although the rates for thermoplastic markings under-predict the retroreflectivity of white markings and slightly over-predict the retroreflectivity of yellow markings.

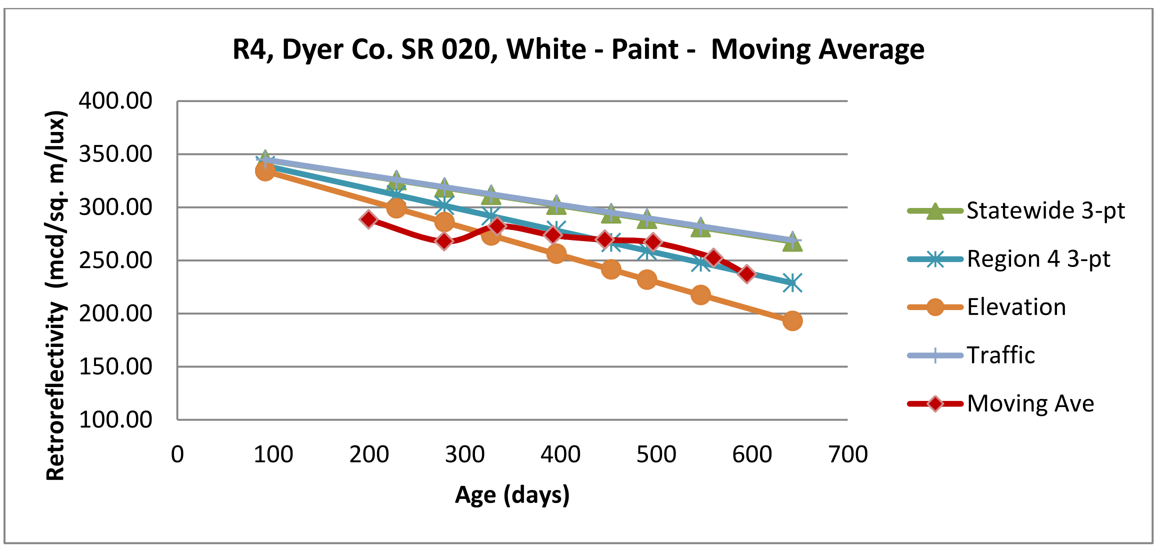


Figure 5.13 Measured and predicted retroreflectivity for SR 020, white paint, using 3-point moving average data.

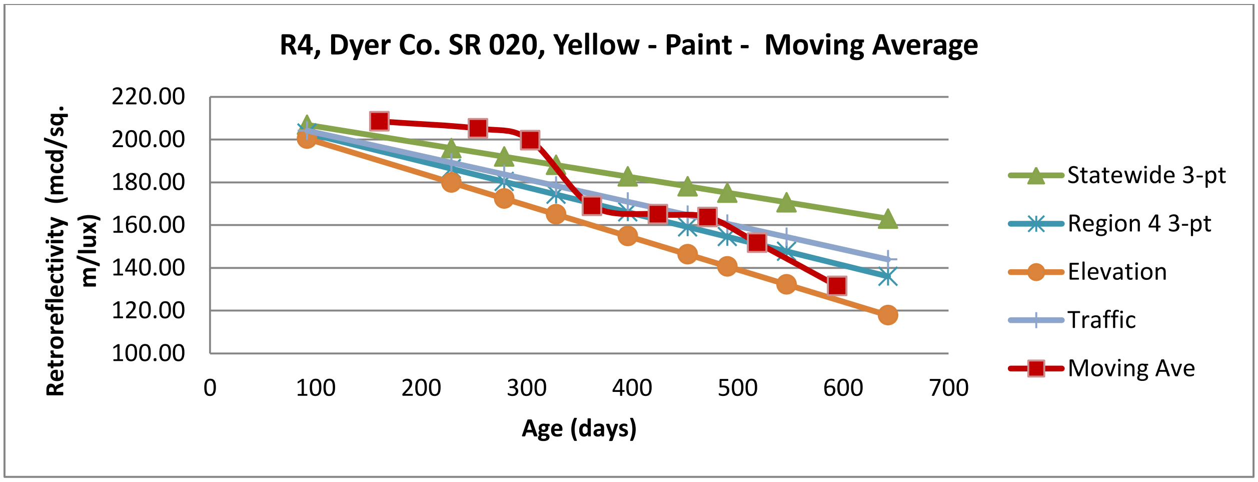


Figure 5.14 Measured and predicted retroreflectivity for SR 020, yellow paint, using 3-point moving average data.

The correlation between measured versus predicted retroreflectivity was established. Figures 5.15 and 5.16 show how the correlation of measured versus predicted retroreflectivity was used to establish the coefficient of determination (R^2) using the statewide deterioration rate. As seen in Figures 5.15 and 5.16, the R^2 of measured vs predicted retroreflectivity values is 0.79 for white paint markings and 0.96 for yellow. Because R^2 is greater than 0.75 for this point, it indicates that statewide deterioration rates could be used to predict retroreflectivity. Regional and statewide correlations were performed (Section 5.4) to further evaluate the usefulness of the rates considering statewide data.

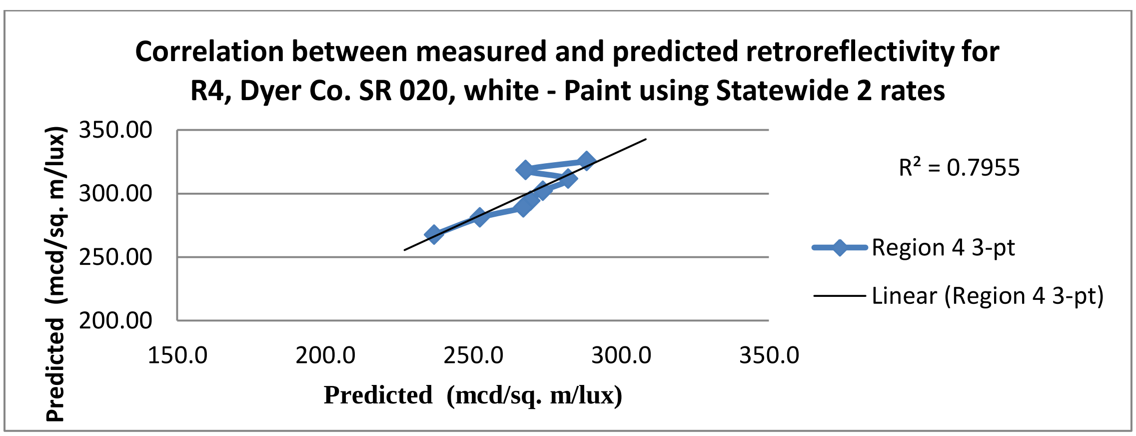


Figure 5.15 Correlation between measured versus predicted retroreflectivity for SR 020, white paint.

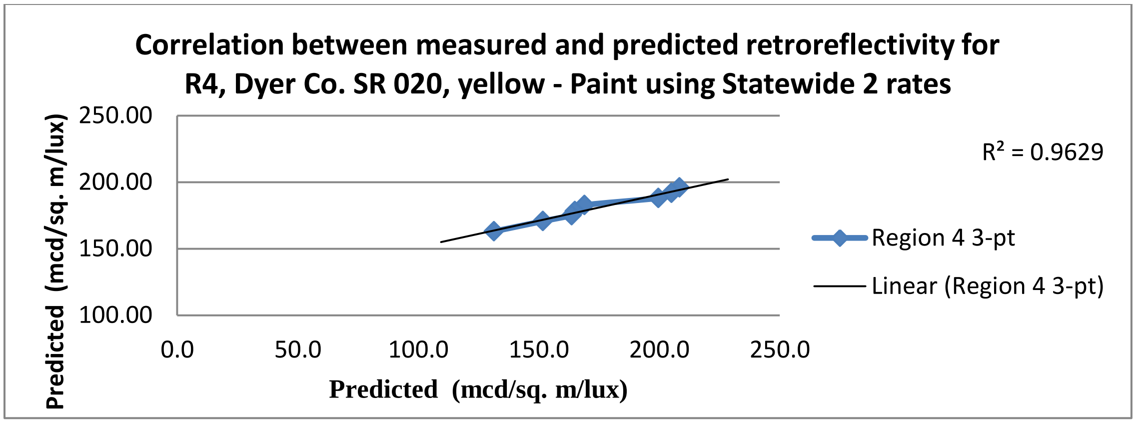


Figure 5.16 Correlation between measured versus predicted retroreflectivity for SR 020, yellow paint.

5.4. Correlation between measured and predicted retroreflectivity

A correlation between measured and predicted retroreflectivity was conducted to determine the coefficient of determination (R^2) between observed and predicted retroreflectivity values. For a good correlation, R^2 of 1 is expected. In most cases it is not easy to get a perfect correlation, but numbers closer to 1 are desired. The predicted retroreflectivity was computed using the deterioration rates in Tables 5.1 to 5.5. Plots of measured versus predicted retroreflectivity and regression analysis were used to determine R^2 values for each region and for white and yellow paint and thermoplastic markings. The computed R^2 values are presented in Tables 5.13 and 5.14. The plots of measured versus predicted retroreflectivity used to obtain R^2 are given in Appendix C.

Table 5.13 R^2 for paint markings using 4 different deterioration rates.

	Region	Statewide 1	Statewide 3-pt	Regional 1	Regional 3-pt
White	1	0.4528	0.3210	0.4771	0.3750
	2	0.5317	0.4014	0.5396	0.3912
	3	0.7381	0.7521	0.7466	0.7287
	4	0.8515	0.7563	0.8774	0,8317
Yellow	1	0.6270	0.5099	0.6375	0.5425
	2	0.2452	0.1453	0.1707	0.0316
	3	0.6449	0.5631	0.5108	0.4548
	4	0.7799	0.8343	0.8177	0.8214

Table 5.14 R^2 for Thermoplastic markings using 4 different deterioration rates.

	Region	Statewide 1	Statewide 3-pt	Regional 1	Regional 3-pt
White	1	0.1389	0.0545	0.183	0.1037
	2	0.2136	0.1926	0.2121	0.1548
	3	0.0553	0.0232	0.0449	0.0321
	4	0.1067	0.2708	0.1577	0.2237
Yellow	1	0.0926	0.0612	0.1259	0.1162
	2	0.0497	0.0305	0.0379	0.0136
	3	0.0227	0.0117	0.0137	0.0139
	4	0.2163	0.3552	0.3272	0.3238

Table 5.13 shows a better correlation between observed and predicted values of retroreflectivity for paint pavement marking data. Regions 3 and 4 have a much better correlation than Regions 1 and 2. Generally, rates without a moving average showed a slightly better correlation than those computed using the 3-point moving average. Region 2 yellow markings show a very low R^2 value, indicating low correlation between observed and predicted pavement marking.

It can be seen from Table 5.14 that the correlation between observed and predicted retroreflectivity for both white and yellow thermoplastic markings is very low, mainly less than 0.214, which indicates that there basically is no correlation between observed and predicted retroreflectivity for thermoplastic markings. The retroreflectivity readings of thermoplastic markings, though fluctuating, were above the suggested minimum retroreflectivity of 100 mcd/m^2/lux. On some locations the readings were higher than the acceptance reading after two years. More time was needed for data collections to reach threshold retroreflectivity values, which would establish a robust prediction model. Nevertheless, the deterioration rates without a moving average provided a somewhat higher correlation.

Further analysis was performed on regions 1 and 2 using elevation deterioration rates without 3-interval moving average (Table 5.15). There was a big improvement on R^2 values of region 2, elevation between 550 ft. and 1000 ft. both yellow and white markings. This is due to a fact that only one point was considered. It was observed that the site in Canon Co. had slower deterioration rave than predicted and Marion Co. had a much faster deterioration rate the predicted. The R^2 in brackets was calculated by eliminating the two points. With this analysis it still can be colluded that statewide and regional deterioration rates can be used to predict pavement marking retroreflectivity of Tennessee highways at a minimum accuracy of 50%.

Table 5.15 R^2 for paint markings using elevation deterioration rates for Regions 1 and 2.

		Elevation	
	Region	550 - 1000 ft.	> 1000 ft.
White	1	0.3726	0.491
	2	0.9449	0.529
Yellow	1	0.3293	0.8474
	2	0.6857	0.075 (0.5668)

6. CONCLUSIONS AND RECOMMENDATIONS

The research project was conducted to evaluate the performance of pavement markings on Tennessee highways. Paint and thermoplastic pavement markings (yellow and white) were evaluated for a period of 2 years from 2013 to 2015. The University of Tennessee at Chattanooga (UTC) in collaboration with Tennessee State University (TSU) collected retroreflectivity readings on selected highways, starting with 62 sites and ending with 45 sites after eliminating some roads due to resurfacing or pavement markings retracing. Retroreflectivity data was collected using a hand-held LTL-X Retroreflectometer. As shown in Appendix B, retroreflectivity trends over time were not linear. This is consistent with the literature; some studies showed an initial upward tick in retroreflectivity values after pavement marking application that lasted for several months before deteriorating. This was also the case at some locations in this study. Retroreflectivity readings fluctuated over time, especially for thermoplastic markings. Most of the locations yielded readings close to acceptance readings even after two years since marking application. This could be the result of increased bead exposure.

The study established pavement markings deterioration rates and deterioration models using statewide and regional data. The following statewide pavement marking deterioration rates per month were established:

- White Paints: - 4.19 mcd/m^2 /lux/Month
- Yellow Paints: - 3.90 mcd/m^2 /lux/Month
- White Thermoplastics: - 3.82 mcd/m^2 /lux/Month
- Yellow Thermoplastics: - 2.39 mcd/m^2 /lux/Month

The established models can be used to predict the performance of retraced markings or to determine the remaining life of a pavement marking by using the initial retroreflectivity readings, deterioration rates and number of days.

From the data analysis, it was determined that the deterioration rates developed for thermoplastic pavement markings had a very low coefficient of the goodness of fit (R^2) between observed and predicted retroreflectivity. This indicates that the models cannot be used reliably to predict retroreflectivity. Malyuta D. (2015) performed a statistical regression analysis of retroreflectivity data collected from Tennessee highways using Minitab software to evaluate factors contributing to retroreflectivity deterioration. He analyzed deterioration as a function of age and traffic simultaneously and determined that for thermoplastic markings, neither marking age nor traffic were statistically significant to deterioration. Neither marking age nor traffic were contributing factors.

The data were collected from thermoplastic sites for an average of 599 days (about 1 year and 8 months), and the retroreflectivity readings were still greater than 350 mcd/m^2/lux for white markings and greater than 160 mcd/m^2/lux for yellow markings. Most scholars recommend longer data collection periods for thermoplastic because the markings last longer than two years. Bowman (1992) reported that in the southern states thermoplastics markings can last up to 10 years (Bowman, Kowshik et al. 1992) before they deteriorate enough to need retracing.

On average, the data were collected on paint markings for 663 days (about 22 months). The average minimum retroreflectivity was 187 mcd/m^2/lux for white markings and 155 mcd/m^2/lux for yellow markings. Given a threshold of 100 mcd/m^2/lux, after 22 months most of the markings were still in acceptable condition. Further analysis was performed. Table 6.1 shows that both white and yellow pavement markings in Region 2 deteriorated faster than the other regions, followed by Region 1. This could be the reason for the lower R^2 values for Region 2 data.

Table 6.1 Average number of days and retroreflectivity for white and yellow per region.

Region	Average days	Months	Average minimum Retroreflectivity	
			White Paint	Yellow Paint
1	692	23	180	106
2	692	23	163	79
3	634	21	226	159
4	632	21	180	118

As reported in Table 5.13, paint markings had much acceptable R^2 values between observed and predicted retroreflectivity. Regions 3 and 4 yielded R^2 values higher than 0.5, which is much higher than many published prediction models. Regions 1 and 2 had lower R^2 values. This could be attributed to the geographic elevation of the locations. An analysis using elevation deterioration rates was used and yielded a R^2 that are comparable to statewide and regional deterioration rates. The retroreflectivity prediction model for deterioration rates is shown below:

$$RL_{fut} = RL_{INI} - D * DR/30 \qquad 5.1$$

Where:

RL_{fut} = Future pavement marking retroreflectivity

RL_{INI} = Initial pavement marking

D = number of days to the estimated future pavement marking retroreflectivity

DR = Monthly deterioration rate.

Deterioration rates in Tables 5.1 to 5.6 can be used in the equation 5.1 for retroreflectivity prediction. From the analysis, it has been established that the rates obtained without a moving average yielded slightly higher R^2 values between measured and predicted retroreflectivity.

6.1. Recommendations for future studies

Longer data collection time is recommended for thermoplastic markings in order to reach the threshold level for both colors. This will establish with certainty the length of time thermoplastic markings can perform within the acceptable retroreflectivity limits. At the time of this study, TDOT used a 4-year limit for thermoplastic markings. Climatic conditions, such as rainfall, snow and temperature, should be considered in future studies. Future studies may also consider using a Laserlux mobile retroreflectometer, which measures retroreflectivity at vehicle speed as opposed to the LTL-X that collects static measurements.

LIST OF REFERENCES

Abboud, N. and Bowman, B. L. (2002). "Cost and Longevity-Based Scheduling of Paint and Thermoplastic Striping," Transportation Research Record 1794, Paper Number 02-2170. http://scholar.utc.edu/cgi/viewcontent.cgi?article=1321&context=theses

Andrady, A. L. (1997). "Pavement Marking Materials: Assessing Environment-Friendly Performance," NCHRP Report 392, Transportation Research Board, Washington, D.C.

Attaway, R. W., 1989. *In-Service Evaluation of Thermoplastic and Tape Pavement Markings Using a portable Retroreflectometer*, Transportation Research Record 1230. Transportation Research Board, National Research Council, Washington D. C., pp. 45 - 55.

Austin, R. L. and Schultz, R. J. (2009)" Guide To Retroreflection Safety Principles And Retroreflective Measurements" VistaRoad, ISBN 0-9710215-0-3. http://www.gamma-sci.com/wp-content/uploads/2012/06/Retroreflectivity-Guide-RoadVista.pdf

Bahar, G., Masliah, M., Erwin, T., Tan, E., and Hauer, E., "*Pavement Marking Materials and Markers: Real-World Relationship between Retroreflectivity and Safety over Time*," NCHRP Web-Only Document 92: Contractor's Final Report for NCHRP Project 17-28, 2006.

Bowman, B., et al. (1992). Determining the Longevity and Service Life of Pavement Marking Materials. Final Report, Auburn University, Alabama, 1992. https://eng.auburn.edu/files/centers/hrc/IR-92-01.pdf.

Bullock M.D., Mitkey S.R., Brennan T. M., Remias S.M., Davis A.D., Grimmer G., Hainen M.A., Morris R. and Michael P., (2012) *Retroreflectivity Durability Comparison of Rumble Stripes vs. Painted Line.* TRB 2012 Annual Meeting, Paper No. 12-0616

Clarke, et al., 2011. *Evaluation of Pavement Marking Materials for Use in Tennessee Highways.* Tennessee Department of Transportation (TDOT) Research Report. Tennessee, 2011. http://scholar.utc.edu/cgi/viewcontent.cgi?article=1321&context=theses

Dale, J.M. "*Pavement Markings: Materials and Application for Extended Service Life*," NCHRP Report 138, Transportation Research Board, Washington, D.C., 1988.

Debaillon, C., Carlos, P., He, Y., Schnell, T., and Aktan, F., 2007. *Update to Research on Recommended Minimum Levels for Pavement Marking Retroreflectivity to Meet Driver Night Visibility Needs*. Report FHWA-HRT-07-059, prepared by Texas Transportation

Institute and the University of Iowa for the Federal Highway Administration, U. S. Department of Transportation.

Federal Highway Administration. *Updates to Research on Recommended Minimum Levels for Pavement Marking Retroreflectivity to Meet Drivers Night Visibility Needs*, Publication No. FHWA-HRT-07-059, United States Department of Transportation, Washington, D.C. Retrieved October, 2007.

FHWA Report (2007) "Updates to Research on Recommended Minimum Levels for Pavement Marking Retroreflectivity to Meet Driver Night Visibility Needs". Publication Number: FHWA-HRT-07-059 Date: October 2007.

https://www.fhwa.dot.gov/publications/research/safety/07059/02.cfm.

Fitch, J. M.V. and Ahearn E.W (2007) *Pavement Marking Durability Statewide*, Vermont Agency of Transportation Materials and Research Section, sponsored by Federal Highway Administration. Report No. 2007-2

Gates, J. T., Hawkins G.H, & Rose, E. R. (2003). *Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways*. FHWA/TX-03/4150-2, Texas Transportation Institute.

Gates, T. J., Hawkins, H. G., and Rose, E. R. (2003). Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways. Report 4150-2, Texas Transportation Institute, College Station, Texas.

Haoqiang F., and Chester G. W., "*Assessing Performance of Alternative Pavement Marking Materials*", Technical Assistance Report No. 08-4TA, Louisiana Transportation Research Center, August 2008.

Hawkins, H. G., et al., 2000. *Minimum Levels of In-Service Retroreflectivity for Pavement Markings:* Summary of workshop findings. Report prepared for the Federal Highway Administration, U. S. Department of Transportation.

Howard, C. (2006). Interview with North Carolina State Department of Transportation Pavement Marking Engineer. October 11, 2006, Raleigh, N.C. http://mutcd.fhwa.dot.gov/knowledge/proposed09mutcdrev1/mutcd2009_pmretro.htm

Jiang, Y. *Durability and Retro-Reflectivity of Pavement Markings (Synthesis Study)*. Publication FHWA/IN/JTRP-2007/11. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2008. doi: 10.5703/1288284313356.

Karwa V. and Donnell E. T. (2011) *Predicting Pavement Marking Retroreflectivity Using Artificial Neural Networks: Exploratory Analysis*. Journal of Transportation Engineering. Vol. 137, No. 2. ASCE, ISSN 0733-947X/2011/2-91–103

Kopf J. (2004) *Reflectivity of pavement markings: analysis of retroreflectivity deterioration curves*. Washington State Transportation Center (TRAC), sponsored by Washington State Department of Transportation. Report no. WA-RD 592.1

Lee Y.J. (2011) *Life cycle and economic efficiency analysis phase II: Durable pavement markings*. Report submitted to Maryland State Highway Administration. Project SP808B4P

Lindly K.J and Narci A. (2003) *Evaluation of Rumble Stripe Markings*. Alabama DOT Research Project. Project No. 930-506R

Lindly, J. and Wijesundera, R., "*Evaluation of Profiled Pavement Markings,*" University Transportation Center for Alabama, Report Number 01465, Nov 2003.

Loetterle, F.E., R.A. Beck, and J. Carlson. *Public Perception of Pavement marking Brightness.* Minnesota Department of Transportation, Roseville, Minnesota, 1998.

Malyuta, Daniel (2015). "Analysis of Factors affecting Pavement Markings and Pavement Markings Retroreflectivity in Tennessee highways". Master's Thesis, University of Tennessee at Chattanooga, Tennessee.

Martin, P., Perrin, J., Jitprasithsiri, S., and Hansen, B., "*A Comparative Analysis of the Alternative Pavement Marking Materials for the State of Utah*," Presented to Utah Department of Transportation, 1996.

McDiarmid, M. (2001). "Mobile Pavement Marking Retroreflectometer Data Collection for TIP Project R-4067," Memorandum for Record March 8, 2001, North Carolina Department of Transportation, Raleigh, North Carolina.

McDiarmid, M. (2007). Interview with North Carolina State Department of Transportation Pavement Marking Manager and Project Engineer, February 2, 2007, Raleigh, N.C.

McGinnis, R.G. (2001). *Pavement Markings Benchmarking*. FHWA-PA-2001-027-97-04(83), Pennsylvania Transportation Institute.

Migletz, J. and Graham, J., "*Long-Term Pavement Marking Practices: A Synthesis of Highway Practice*," NCHRP Synthesis 306, TRB, 2002.

Migletz, J., Graham, J., Harwood, D., Bauer, K., and Sterner, P. *Evaluation of All-Weather Pavement Markings*. Federal Highway Administration, McLean, Virginia,

Mitkey, S., T. Brennan, S. Remias, A. Davis, G. Grimmer, A. Hainen, R. Morris, P. Michael and D. Bullock. Retroreflectivity Durability Comparison of Rumble Stripes vs. Painted Line. Proceedings, *91st Annual Transportation Research Board Meeting*, Washington, D.C., January 2012.

MUTCD , 2009. Manual on Uniform Traffic Control Devices.

North Carolina Department of Transportation (NCDOT) (2006). Division 12, Section 1205 of the NCDOT Standard Specification, Raleigh, NC.

Omar Smadi, et al 2010. Pavement Markings and Safety: A performance Perspective. Report prepared by Center for Transportation Research Education, Iowa State University.

Paniati, J.F., and D.J. Mace. *Minimum Retroreflectivity Requirements for Traffic Signs.* Report FHWA-RD-93-077. Federal Highway Administration, United States Department of Transportation, Washington, D.C., 1993.

Parker, N.A. *Evaluation of the Performance of Permanent Pavement markings and Retroreflectors in Snow plowable Raised Pavement Markers.* Report 55657-01-13, New Jersey Department of Transportation, Trenton, New Jersey, 2002.

Perrin, J., Martin, P., and Hansen, B. "*A Comprehensive Analysis of Pavement Marking Materials.*" Presented at 77th Annual Meeting of the Transportation Research Board,

Pike A. M., Ballard D.L. and Carlson P. J. (2011) *Evaluation of Retroreflectivity Measurement Techniques for Profiled and Rumble Stripe Pavement Markings*. TRB 2011 Annual Meeting. Paper no. 11-1293

Report, Minnesota Local Road Research Board, St Paul, Minnesota. TransTech Management Inc. (2001*). Synthesis of Practice for AASHTO's National Transportation Product Evaluation Program*. NCHRP 20-7 Task 143 Draft Report.

Sarasua W., Davis W. and Bell L. (2011) *Estimating the Lifecycle of Pavement Markings on Primary and Secondary Roads in South Carolina*. Report to South Carolina Department of Transportation. Project SPR No. 669.

Sarasua, W. A., Clarke, D. B., and Davis, W. J. (2003). "*Evaluation of Interstate Pavement Marking Retroreflectivity*" Report to South Carolina Department of Transportation, Report Number FHWA-SC-03-01.

Sitzabee E.W., White D.E. and Dowining W.A. (2012) *Deterioration Modeling of Polyurea Pavement Marking.* Journal of Public Works Management Policy, vol. 18 no. 2 185-199

Sitzabee W. E., Hummer E.J. and Rasdorf W. (2008) *Pavement Marking Deterioration Modeling and Analysis*, Journal of Infrastructure Systems. DOI: 10.1061/ (ASCE) 1076-0342

Texas Transportation Institute (2001). *Summary of Evaluation Findings for 30 Meter Handheld and Mobile Pavement Marking Retroreflectometers,* Draft Technical Evaluation Report, Highway Innovative Technology Evaluation Center, Civil Engineering Research Foundation, Washington D.C.

Thamizharasan, A., Sarasua, W., Clarke, D., and Davis, W. "*A Methodology for Estimating the Lifecycle of Interstate Highway Pavement Marking Retroreflectivity.*" TRB Paper Number: 03-3867, Washington, D.C., 82ed Transportation Research Board Annual Meeting, 2003

Turner, J. D., (1998). *Pavement Marking Retroreflectivity: Research Overview and Recommendations*, Unpublished Report to the Federal Highway Administration, Office of Safety and Traffic Operations, McLean, VA.

Turner, J.D. Pavement marking Retroreflectivity: Research Overview and Recommendations. Unpublished report, FHWA, Office of Safety and Traffic Operations Research and Development. 1999.

Washington, D.C., 1998.

Zhang Y. and Wu D. (2006) *Methodologies to Predict Service Lives of Pavement Marking Materials.* Journal of the Transportation Research Forum, Vol. 45, No. 3.

Zwahlen, H. T. and T. Schnell. *Pavement marking Visibility Research and Proposed Values for Minimum Required Pavement marking Retro Reflectivity.* Unpublished report, Department of Industrial and Systems Engineering, Ohio University Athens, Ohio. August, 1998.

APPENDIX A: DATA ON RETROREFLECTIVITY READINGS WITH TIME

Table A1 is comprised of retroreflectivity readings of thermoplastic markings and Table A2 for paint markings for the eight rounds of data collection.

Table A1 Thermoplastic Retroreflectivity readings for Regions 1 to 4

		Acceptance reading			Round 1 Readings			Round 2 Readings		
	County	Time Days	White mcd/lux/m²	Yellow mcd/lux/m²	Time Days	White mcd/lux/m²	Yellow mcd/lux/m²	Time Days	White mcd/lux/m²	Yellow mcd/lux/m²
Region 1	Anderson SR 61	22	472.68	285.7	275	336.83	319	317	378.6	373.6
	Blount	47	393.08	246.9	125	330.1	179.1	167	397.0	247.0
	Hamblen	62	449.7	285.5	235	201.18	159.95	277	251.8	190.5
	Sevier	42	375.28	230.4	117	291.675	194.25	159	369.4	238.8
	Hawkins	58	533.9	312.3	232	317.3	286.35	273	760.5	595.8
	Knox	66	418.37	245.6	168	434	244.4	210	440.6	269.4
	Monroe SR 33	55	462.7	342.3	289	210.275	152.5	331	223.5	138.5
	Sullivan	75	464.3	300.8	226	391.38	314.9	267	744.7	505.2
Region 2	Coffee	60	349	176	173	115.45	70.5	NA	NA	NA
	Cumberland	67	450.7	239.7	232	234.1	156.6	269	412.1	178.3
	Overton	51	379	196	202	358.15	205.2	239	373.7	218.2
	Van Buren	46	356	222	183	251.33	148.7	218	258.3	185.1
	White	49	375.5	188	193	303.3	174.425	228	345.8	211.2
	Rhea	49	345.5	197	166	321.6	195.75	213	329.9	195.0
	Sequatchie	48	334	163	143	297.4	165	190	277.4	173.5
	Hamilton	72	360	225	145	307	191.9	192	328.2	202.1
Region 3	Rutherford	70	355	231.3	293	482.9	311.8	327	494.2	291
	Rutherford	63	436.2		286	321.0	205.8	320	432.0	231.5
	Williamson	49	342.7	206.5	261	344.8	289.6	294	373.4	321.1
	Wilson	50	323.2	218.2	265	402.5	262.4	298	418.0	293.3
	Davidson	51	397.4	221.3	165	329.5	175.6	199	362.2	201.1
	Lawrence	52	363.8	235.3	243	297.3	259.8	292	330.6	272.6
	Maury	58	346.1	175.6	190	303.4	216	244	287.2	200.5
	Montgomery	48	431.7	301.6				276	365.1	229.6
Region 4	Dyer	92	341.1	219.2	229	297.7	166	279	287.1	148
	Dyer	92	357.4	214.2	229	235.9	203.1	279	271.8	208.2
	Gibson	45	407	205.3	298	456.8	315.5	348	384.6	297
	Carroll	71	320.0	204.2	153	232.1	140.9	203	241.6	128.0
	Carroll	71	320.0	204.2	153	332.3	215.5	203	275.8	237.0

Table A1 Thermoplastic Retroreflectivity readings for Regions 1 to 4 Cont. . . .

		Round 3 Readings			Round 4 Readings			Round 5 Readings		
	County	Time Days	White mcd/lux/m^2	Yellow mcd/lux/m^2	Time Days	White mcd/lux/m^2	Yellow mcd/lux/m^2	Time Days	White mcd/lux/m^2	Yellow mcd/lux/m^2
Region 1	Anderson SR 61	356	341.575	402.35	411	304.21	376.55	479	249.65	281.20
	Blount	206	404.4	269.00	261	393.58	253.50	327	422.70	278.30
	Hamblen	316	193.2	161.40	373	218.75	181.95	437	207.90	177.95
	Sevier	198	371.8	239.0	253	368.10	242.00	319	362.70	232.40
	Hawkins	312	480.6	354.9	369	423.40	330.55	436	375.00	292.10
	Knox	249	516.2	220.0	305	513.96	180.43	370	609.50	158.60
	Monroe SR 33	370	231.6	135.6	425	229.98	144.50	491	234.10	140.00
	Sullivan	306	447.0	337.7	363	463.12	327.55	430	462.80	349.40
Region 2	Coffee	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Cumberland	308	390.6	237.0	361	432.52	227.40	427	400.50	201.40
	Overton	278	370.75	222.6	333	374.85	232.70	401	392.70	244.35
	Van Buren	259	297.5	194.65	312	246.36	160.65	378	244.25	146.95
	White	269	372.525	207.05	322	333.70	197.55	388	363.40	211.95
	Rhea	253	342.7	189.35	307	341.30	189.45	373	370.43	201.30
	Sequatchie	232	520.2	297.825	284	270.75	170.25	350	333.20	169.50
	Hamilton	234	341.525	211.4	286	340.75	200.50	352	338.00	208.75
Region 3	Rutherford	397	479.4	298.4	463	465.2	286.2	523.3	471.1	300.8
	Rutherford	390	424.2	265.1	455	359.6	240.3	500.5	341.6	227.2
	Williamson	365	340.6	378.9	430	296	297.1	475.4	294.0	285.5
	Wilson	369	470.3	299.5	434	387.7	275	479.4	390.8	263.6
	Davidson	270	382.2	218.6	335	347.6	185.8	380.4	385.4	151.3
	Lawrence	342	290.8	258.1	408	251.1	233.8	452.7	225.0	233.5
	Maury	294	287.7	169.5	360	243.6	135.8	404.7	248.7	129.4
	Montgomery	326	320.7	203.7	391	343.6	184.7	436.5	339.8	170.8
Region 4	Dyer	329	261.9	156.7	395	245.4	139.6	453.0	246.3	116.2
	Dyer	328	295.7	204.3	396	278.8	186.5	453.8	298.1	186.9
	Gibson	399	429.4	333.2	464	432.8	331.6	522.0	460.4	341.3
	Carroll	252	237.8	147.3	319	280.7	154.2	378.0	266.7	153.9
	Carroll	253	299.9	249.8	319	315.9	293.1	378.0	311.3	305.7

Table A1 Thermoplastic Retroreflectivity readings for Regions 1 to 4 cont. . . .

		Round 6 Readings			Round 7 Readings			Round 8 Readings		
	County/Route	Age Days	White mcd/lux/m^2	Yellow mcd/lux/m^2	White mcd/lux/m^2	Yellow mcd/lux/m^2	Age Days	White mcd/lux/m^2	Yellow mcd/lux/m^2	Age Days
Region 1	Anderson SR 61	527	233.10	236.10	213.30	151.90	606	217.90	164.60	647
	Blount SR 33	377	412.55	241.10	363.50	152.70	447	434.40	177.30	497
	Hamblen SR 34	487	189.90	182.10	184.00	170.30	557	199.40	171.00	607
	Sevier SR 35	369	318.10	211.65	293.67	181.00	439	193.70	183.20	489
	Hawkins SR 01	483	422.25	228.40	355.50	221.95	553	217.00	234.25	603
	Knox SR 168	420	563.30	141.20	433.85	119.77	490	456.75	131.90	540
	Monroe SR 33	541	203.55	141.20	193.60	132.70	611	202.70	129.30	661
	Sullivan SR 01	477	385.19	305.45	264.45	307.30	547	249.70	286.20	597
Region 2	Coffee SR 55	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Cumberland SR1	479	391.85	174.40	366.45	158.70	558	280.10	153.90	599
	Overton SR111	449	382.90	250.80	230.40	202.35	528	289.80	160.40	569
	Van Buren SR111	428	273.10	174.30	177.80	99.40	498	130.90	62.80	548
	White SR111	438	394.43	211.40	263.85	168.65	508	246.30	200.70	558
	Rhea SR 29	423	356.68	210.10	282.80	197.65	493	395.50	247.00	543
	Sequatchie SR 08	400	327.75	152.00	240.40	130.00	470	242.25	109.50	520
	Hamilton SR153	402		180.65	336.50	183.10	482	321.80	163.40	522
Region 3	Rutherford	558.3	550.7	351.2	438.0	275.0	634.6	426.3	223.9	691
	Rutherford	550.4	301.7	206.4	230.9	110.0	627.5	212.5	169.7	684
	Williamson	525.5	263.1	255.4	239.8	209.3	584.4	229.9	203.7	658
	Wilson	529.4	351.1	248.3	350.1	231.7	588.6	325.0	198.2	662
	Davidson	430.3	364.1	163.9	325.0	142.2	489.6	316.2	133.9	563
	Lawrence	502.4	199.8	224.8	116.4	150.7	578.7	165.1	110.3	655
	Maury	454.4	223.8	139.6	157.0	116.2	530.7	177.6	133.7	607
	Montgomery	486.7	322.1	168.1	314.9	155.6	545.6	259.3	138.5	620
Region 4	Dyer	490.6	283.2	192.4	210.8	123.8	546.0	209.6	171.8	642
	Dyer	489.9	235.0	121.3	271.5	182.5	546.7	202.2	80.4	643
	Gibson	558.9	448.1	345.9	398.4	324.9	615.0	375.4	305.2	711
	Carroll	414.9	287.0	159.9	268.0	148.2	471.0	184.8	143.1	567
	Carroll	414.9	281.8	321.3	287.4	311.3	471.0	219.6	253.5	567

PAINT PAVEMENT MARKINGS

Table A2 Paint Retroreflectivity readings for Regions 1 to 4

		Acceptance reading			**Round 1 Research Reading**			**Round 2 Reading**		
	County	Time	White	Yellow	Time	White	Yellow	Time	White	Yellow
		Days	mcd/lux/m^2	mcd/lux/m^2	Days	mcd/lux/m^2	mcd/lux/m^2	Days	mcd/lux/m^2	mcd/lux/m^2
Region 1	Anderson SR 330	57	339.13	219.4	321	198.5	149.6	363	279.7	173.9
	Cocke	67	403.2	224.8	320	214.85	133.7	362	293.2	207.6
	Jefferson	57	277.05	150.7	320	214.7	137.6	362	277.3	158.6
	Knox SR 170	65	306.7	223.4	321	212.35	120.6	363	322.6	157.0
	Loudon	59	366.5	219.6	321	235	179.3	362	252.1	207.8
	Monroe SR 68	50	329.95	218.38	320	175.85	153.7	362	205.5	150.6
	Morgan	45	359.28	201.15	320	303.93	101.7	363	294.7	129.2
Region 2	Bledsoe	52	386.7	224	314	222.45	208.5	361	268.4	142.3
	Canon	50	328.5	128	324	263.45	165.25	359	261.1	153.2
	Cumberland	50	378	174	321	197.63	96.3	363	236.7	128.2
	Grundy	50	278	162.5	312	182.2	141.25	359	170.5	122.4
	Marion	52	353	235	314	214.85	65.25	361	212.5	62.6
	Rhea SR 68	51	327	234	314	243.8	227.6	361	237.7	220.2
	White SR 84	46	NA	162	323	NA	51.3	NA	NA	NA
Region 3	Wilson	58	239.8	229.7				306	334.9	223.4
	Davidson	46	140.7	342.9	300	139.8	256.0	333	143.5	241.0
	Hickman	54	508.1	317.9	188	385.2	255	237	334.5	223.9
	Lawrence	47	341.0	254.7	282	333.1	222.5	331	301.5	200.1
	Lewis				282	310.6	155.3	331	330.3	151.7
	Maury	60	219.6	245.1	285	316.3	199.3	334	244.7	217.2
	Montgomery	45	461.6	242.1				199	418.0	247.3
	Robertson	45	266.8	216.1	208	278.0	208.2	271	279.6	221.8
Region 3	Benton	25	406	261	251	320.2	202.8	300	283.8	168.6
	Carroll	61	405		289	303.4	248.0	338	293.2	188.8
	Decatur	38	309	229	259	188.1	217.9	308		
	Decatur	38	309	229	259	313.3	240.5	308	305.8	165.6
	Dyer	76	381	218	192	331.9	176.6	242	320.1	170.7

Table A2 Paint Retroreflectivity readings for Regions 1 to 4 cont. . . . .

		Round 3 Reading			Round 4 Reading			Round 5 Reading		
	County	Time	White	Yellow	Time	White	Yellow	Time	White	Yellow
		Days	mcd/lux/m^2	mcd/lux/m^2	Days	mcd/lux/m^2	mcd/lux/m^2	Days	mcd/lux/m^2	mcd/lux/m^2
Region 1	Anderson	402	147.2	112.9	457	192.42	140.35		441.35	268.15
	Cocke	401	200.8	142.2	456	183.65	137.75	522	152.30	118.40
	Jefferson	401	188.2	147.65	456	179.10	124.65		413.65	279.80
	Knox	402	175.05	119.85	457	186.24	119.55		363.35	251.30
	Loudon	401	265.05	181.6	456	276.37	181.50	522	245.60	160.75
	Monroe	401	141.55	134.75	456	164.43	124.85	522	135.40	121.85
	Morgan	402	277.35	126.5	457	270.55	112.30	525	230.80	109.90
Region 2	Bledsoe	402	226.95	157.25	455	228.00	159.86	521	237.45	126.60
	Canon	401	247.85	154.60	453	266.35	127.20	519	252.85	130.10
	Cumberland	402	207.75	117.55	455	232.60	147.43	521	231.25	127.45
	Grundy	401	158.58	123.65	453	186.90	128.25	519	151.05	98.30
	Marion	403	128.85	65.95	455	105.50	65.95	521	106.60	58.25
	Rhea	401	196.00	202.30	455	208.72	193.50			
	White	NA	NA	NA	NA	NA	NA	NA	NA	NA
Region 3	Wilson	377	337.3	227.2	442	306.1	204.8	503.3		331.6
	Davidson	404	130.4	213.8						
	Hickman	287	325.7	195.2						
	Lawrence	381	278.3	187.2	447	275.8	181	491.7	288.8	190.2
	Lewis	381	325.3	171.9	447	338.3	179	492.3	332.5	186.7
	Maury	384	261.4	184.4	450	274.6	169.2	494.6	280.5	165.1
	Montgomery	249	426.3	240.3	314	408.1	226.7	359.5	364.6	222.0
	Robertson	320	224.2	195	386	271.1	202	430.6	251.6	186.5
Region 4	Benton	350	215.6	64	416	263	104	476.3	210.9	79.7
	Carroll	388	239.7	166.3	454	280	168.4	499.5	223.0	165.9
	Decatur				Repaved	and	repainted			
	Decatur	358	278.2	168	424	269.8	203			
	Dyer	Rainfall-rumble strip was flooded with water						327.6	250.3	144.2

Table A2 Paint Retroreflectivity readings for Regions 1 to 4 Cont. . . .

		Round 6 Reading			Round 7 Reading			Round 8 Reading		
	County	Age	White	Yellow	White	Yellow	Age	White	Yellow	Age
		Days	mcd/lux/m^2	mcd/lux/m^2	mcd/lux/m^2	mcd/lux/m^2	Days	mcd/lux/m^2	mcd/lux/m^2	Days
Region 1	Anderson SR 330	69	388.10	255.90	300.00	204.60	148	306.95	205.20	189
	Cocke SR 09	572	144.15	117.60	123.85	113.20	642	135.25	121.90	692
	Jefferson SR 113	68	366.75	257.95	239.80	196.30	138	317.35	182.85	188
	Knox SR 170	69	322.65	224.40	220.15	154.15	148	228.30	142.40	189
	Loudon SR322	572	268.30	132.40	211.05	129.60	642	214.20	144.80	692
	Monroe SR 68	572	122.75	108.00	127.40	94.35	642	115.45	99.50	692
	Morgan SR 116	573	231.10	100.85	209.40	71.30	652	184.30	59.30	693
Region 2	Bledsoe SR 28	571	214.00	153.35	226.35	109.50	641	187.15	93.50	691
	Canon SR 146	569	249.15	123.40	214.20	91.25	639	201.55	82.15	689
	Cumberland SR24	573	240.25	168.55	228.70	160.30	652	226.30	120.10	693
	Grundy SR108	569	155.20	99.85	128.85	51.25	639	75.55	43.40	689
	Marion SR 27	571	91.95	44.95	108.35	48.95	641	121.70	55.15	691
	Rhea SR 68	6	304.40	167.35	176.95	147.50	76	178.30	170.70	126
	White SR 84	NA	NA	NA	NA	NA	NA	NA	NA	NA
Region 3	Wilson	542.0	344.9	202.0	323.8	198.8	598	244.9	202.0	671
	Davidson	Repaved and painted								
	Hickman	Repaved and painted								
	Lawrence	541	272.9	183.1	209.4	91.8	618	206.3	162.8	694
	Lewis	542	344.9	202.0	226.9	154.7	619	267.2	148.9	694
	Maury	544	260.5	161.0	258.8	114.5	621	197.1	139.6	607
	Montgomery	410	424.4	220.0	396.8	221.5	469	377.8	209.7	543
	Robertson	481	246.6	196.7	281.0	192.7	540	197.8	160.1	614
Region 4	Benton	512	197.0	77.5	189.7	75.3	569	178.9	91.8	664
	Carroll	549	221.4	158.5	211.2	139.1	605	167.1	118.6	701
	Decatur	Repaved and painted								
	Decatur	Repaved and painted								
	Dyer	377	309.3	156.7	289.2	148.8	434	194.3	142.2	530

Note:

	The brown shaded rows indicate repainted and locations under construction

APPENDIX B: RETROREFLECTIVITY TRENDS WITH TIME

Appendix B 1: Plots of collected data for Region 1

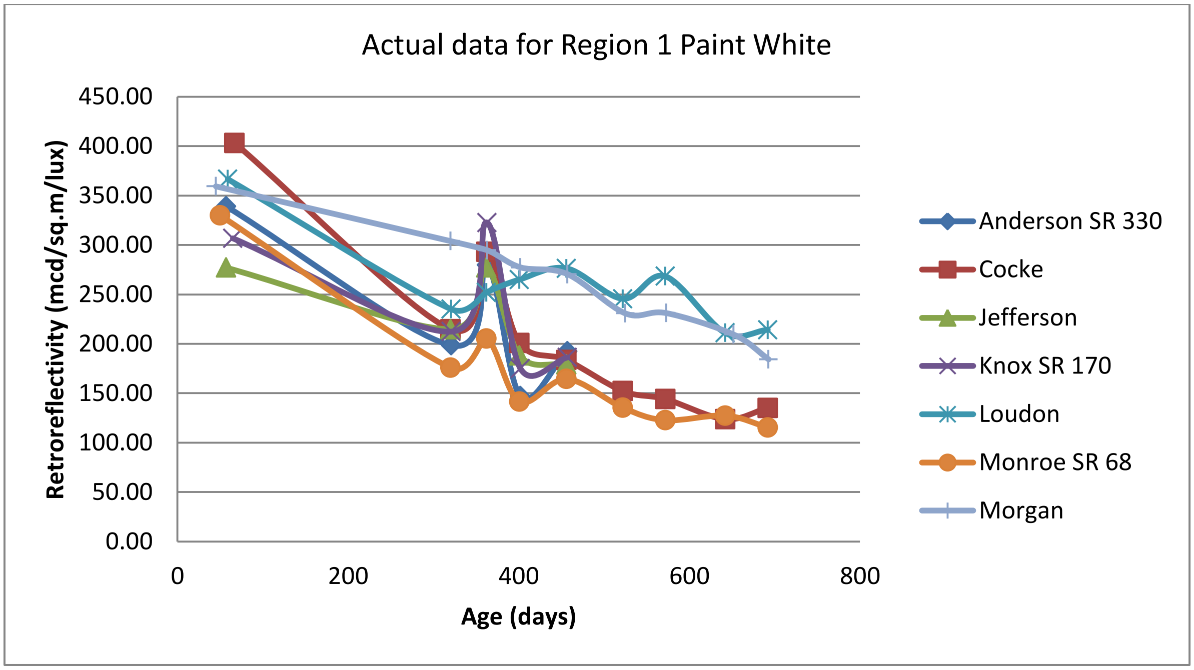


Figure B1.1 Region 1 white paint

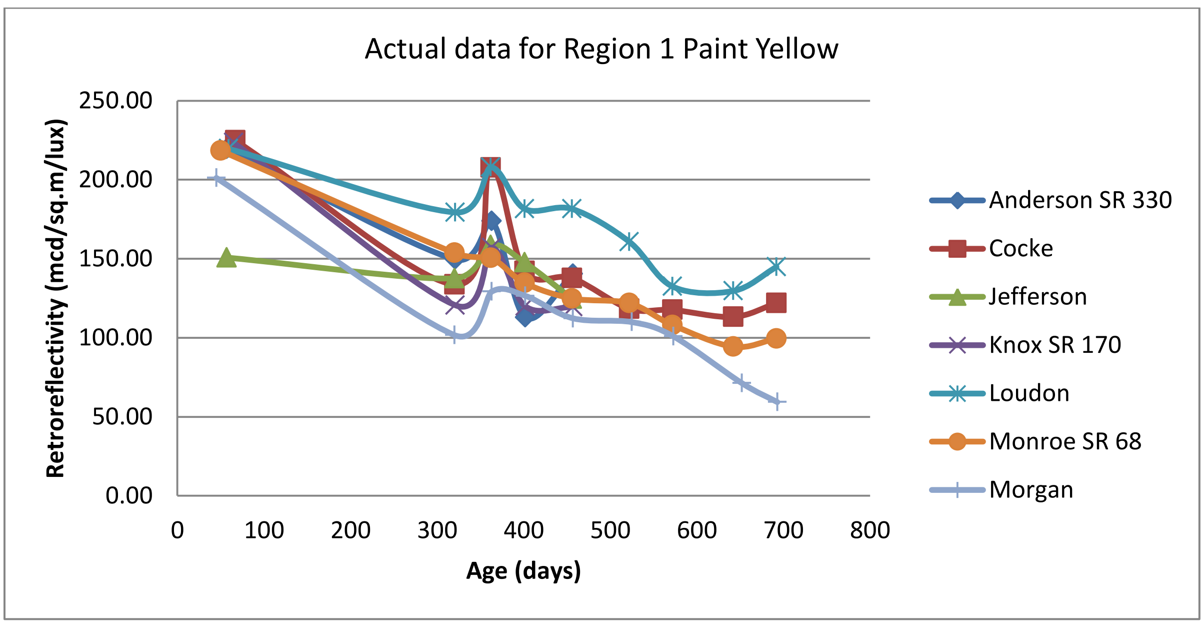


Figure B1.2 Region 1 yellow paint

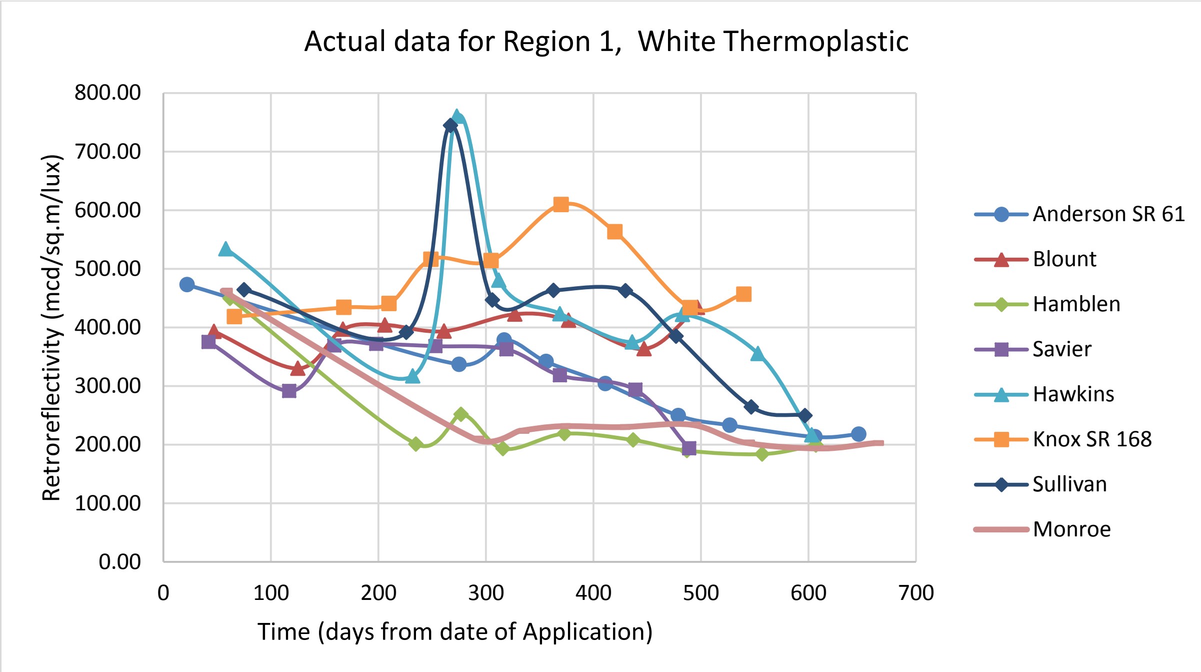


Figure B1.3 Region 1 white thermoplastic

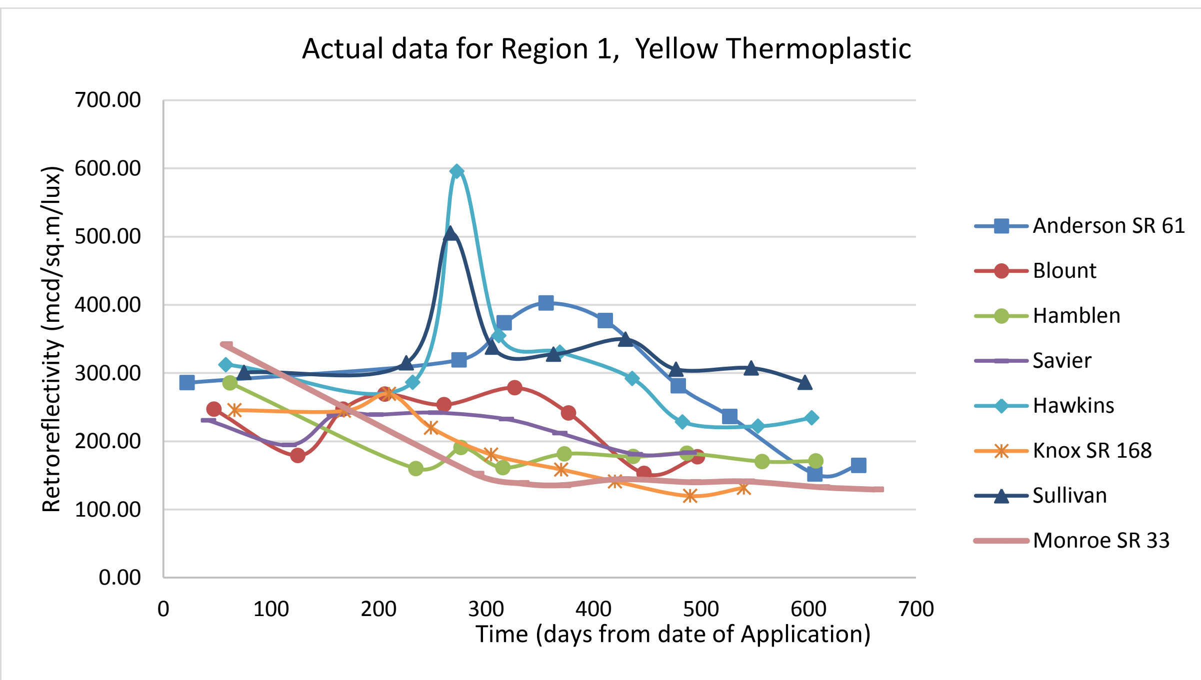


Figure B1.4 Region 1 yellow thermoplastic

Appendix B 1: Plots of collected data for Region 2

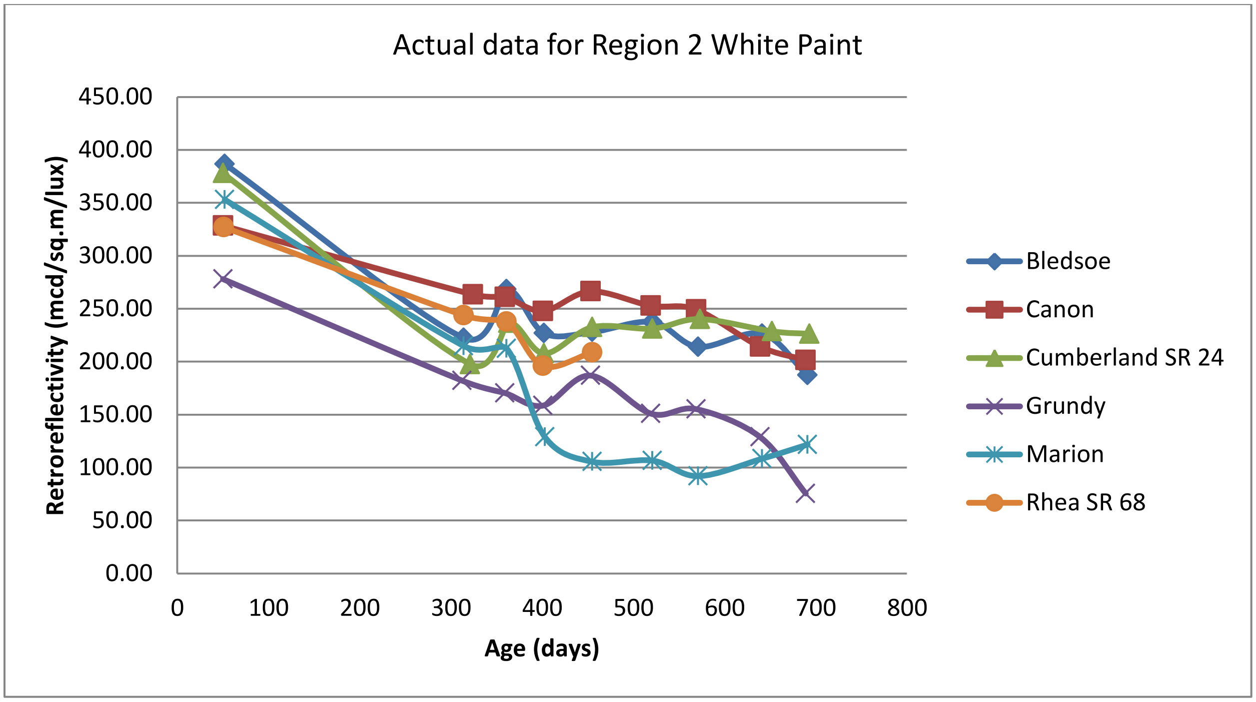


Figure B1.5 Region 2 white paint

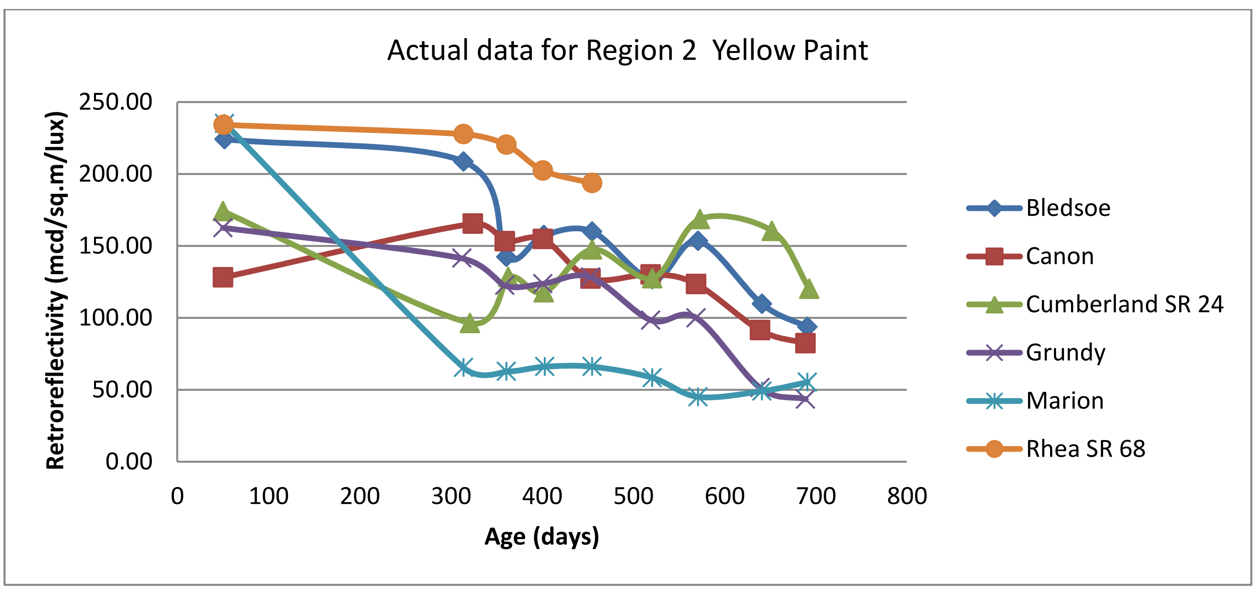


Figure B1.6 Region 2 yellow paint

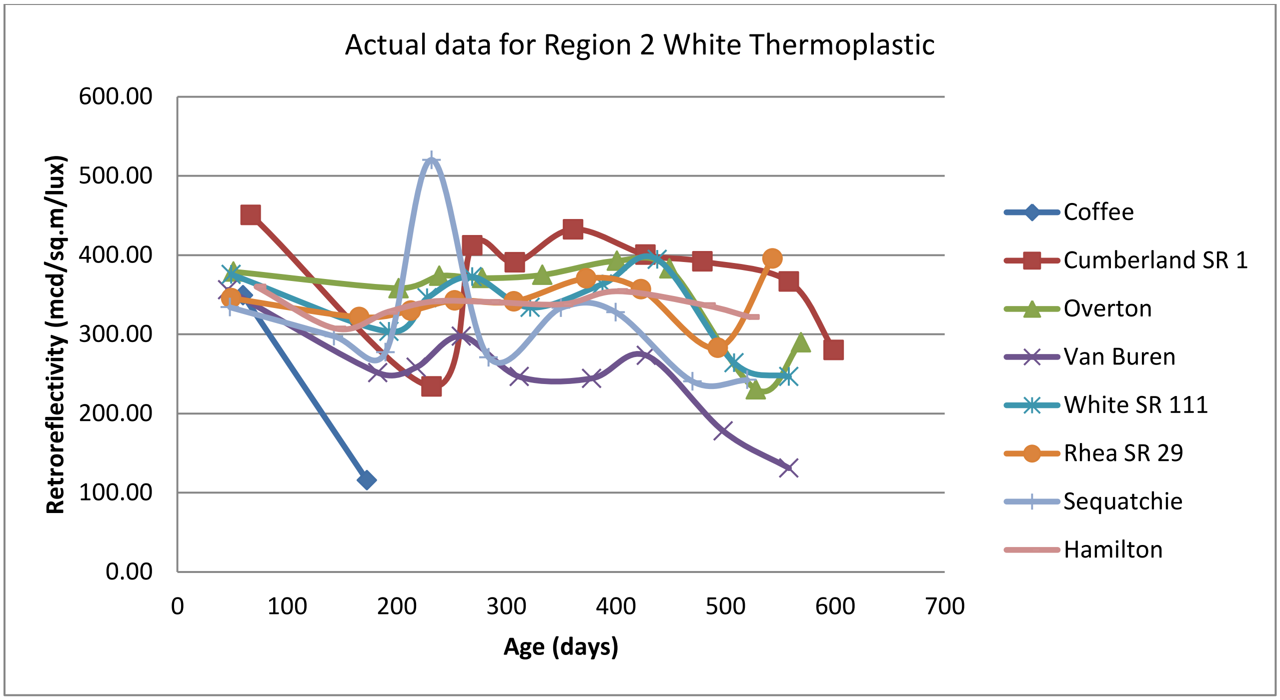


Figure B1.7 Region 2 white thermoplastic

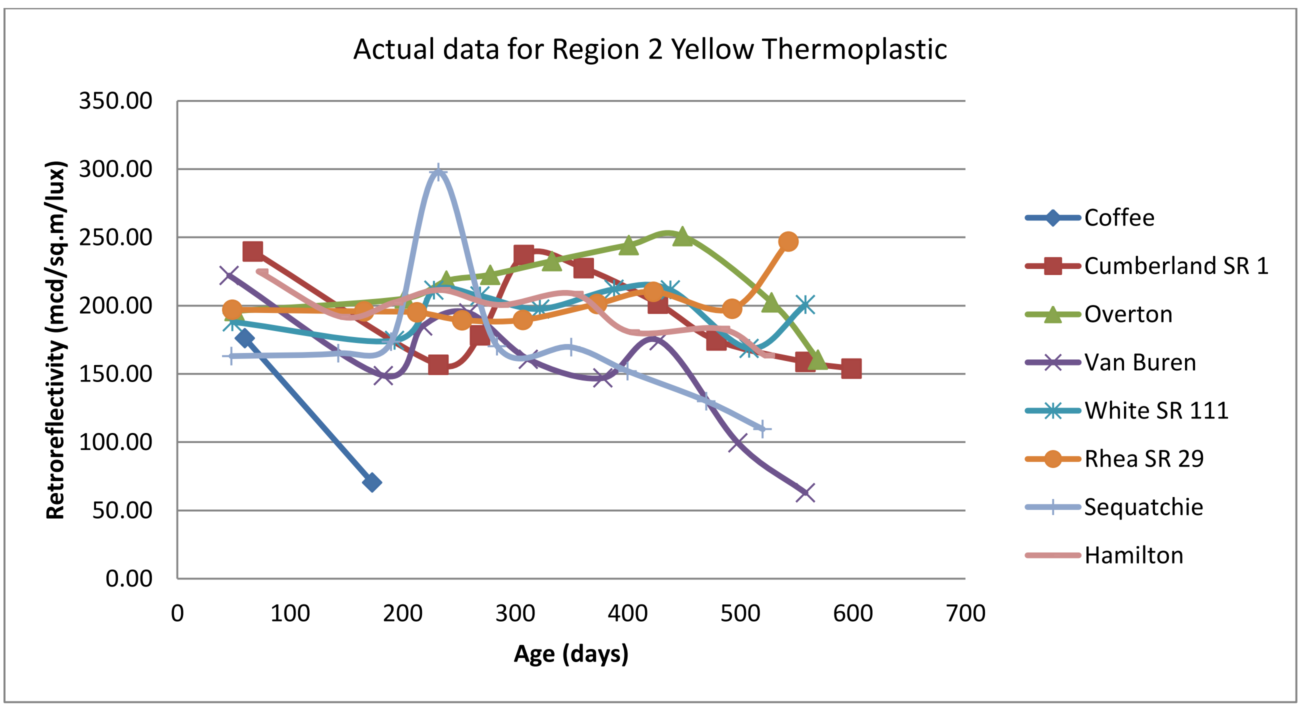


Figure B1.8 Region 2 yellow thermoplastic

Appendix B 1: Plots of collected data for Region 3

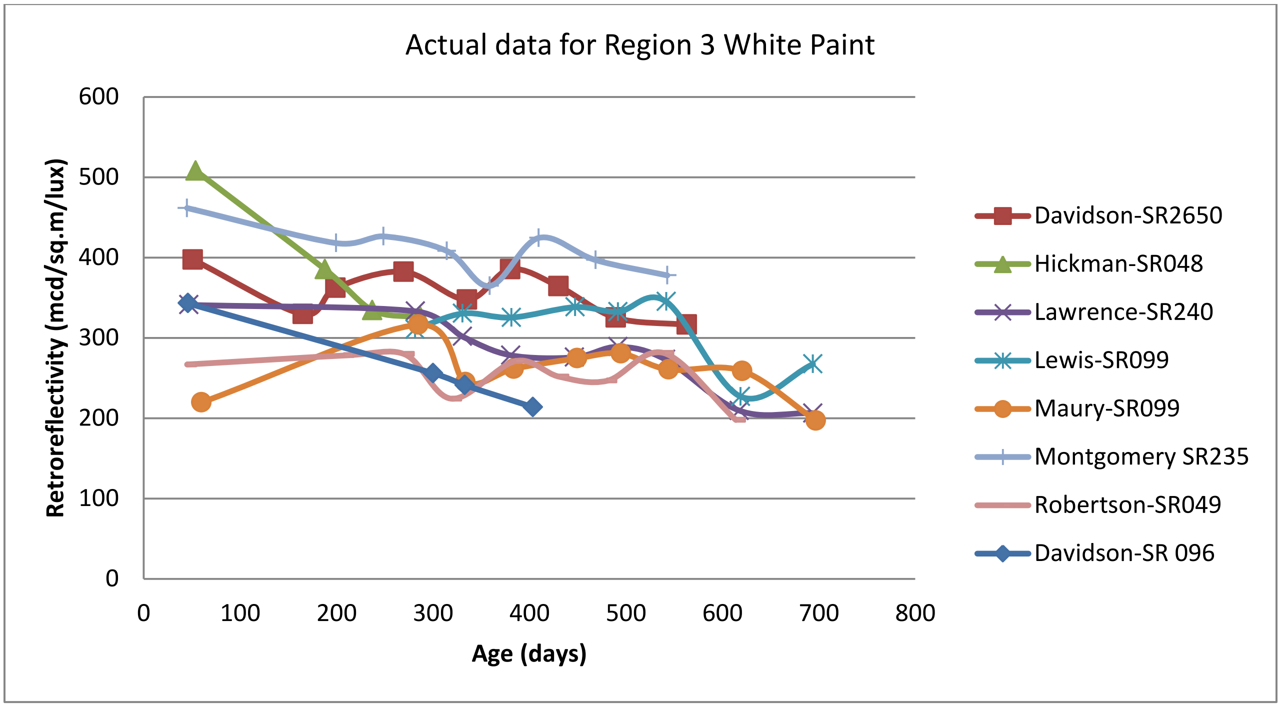


Figure B1.9 Region 3 white paint

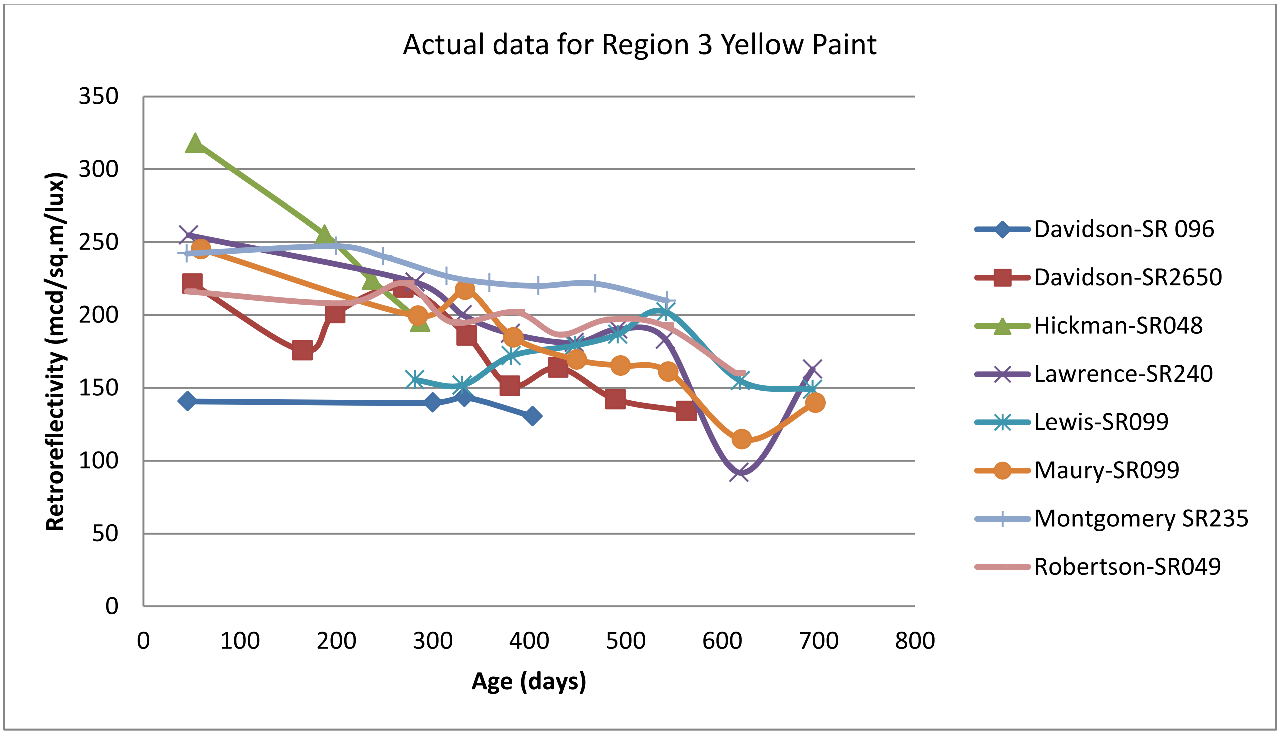


Figure B1.10 Region 3 yellow paint

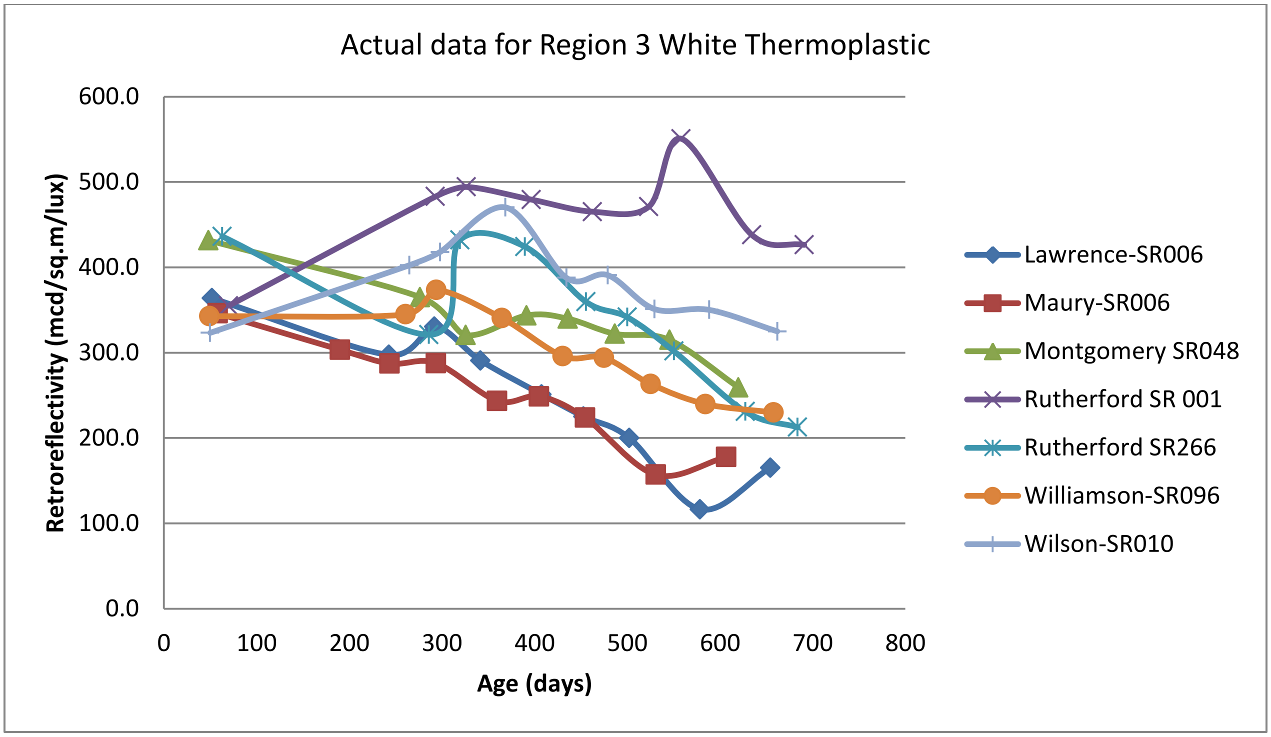


Figure B1.11 Region 3 white thermoplastic

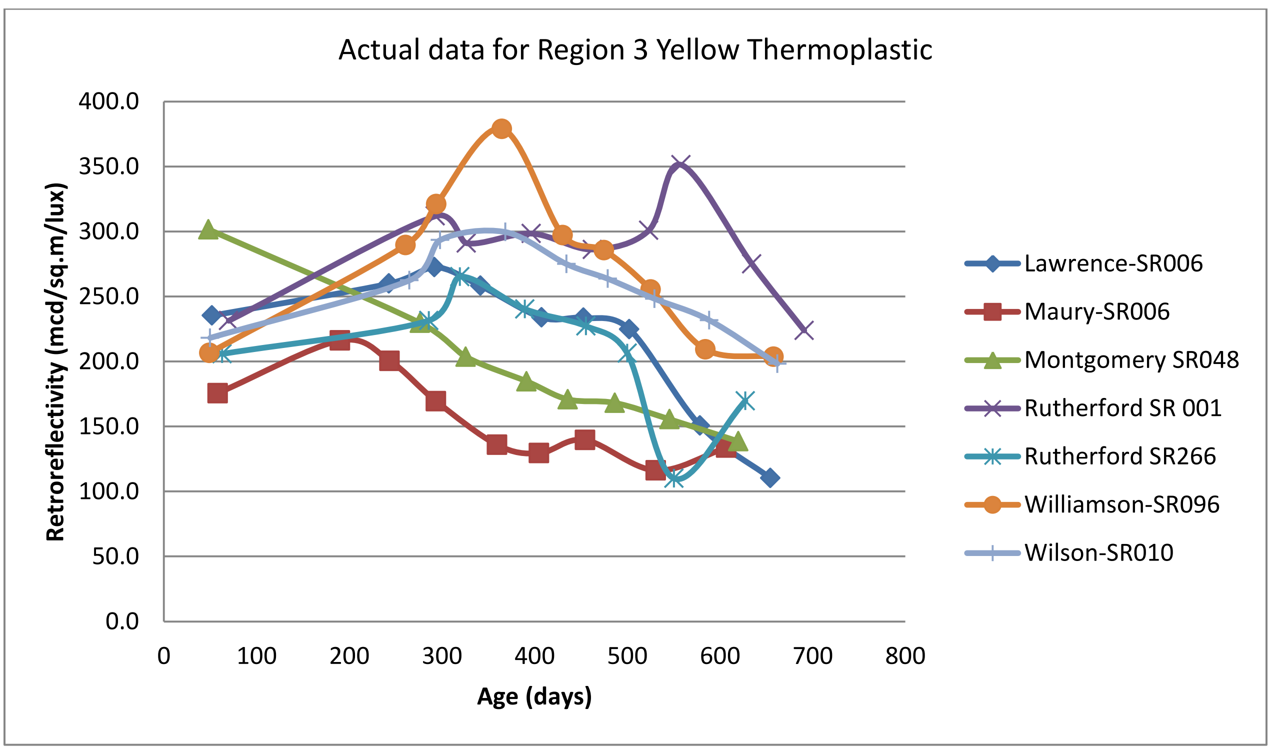


Figure B1.12 Region 3 yellow thermoplastic

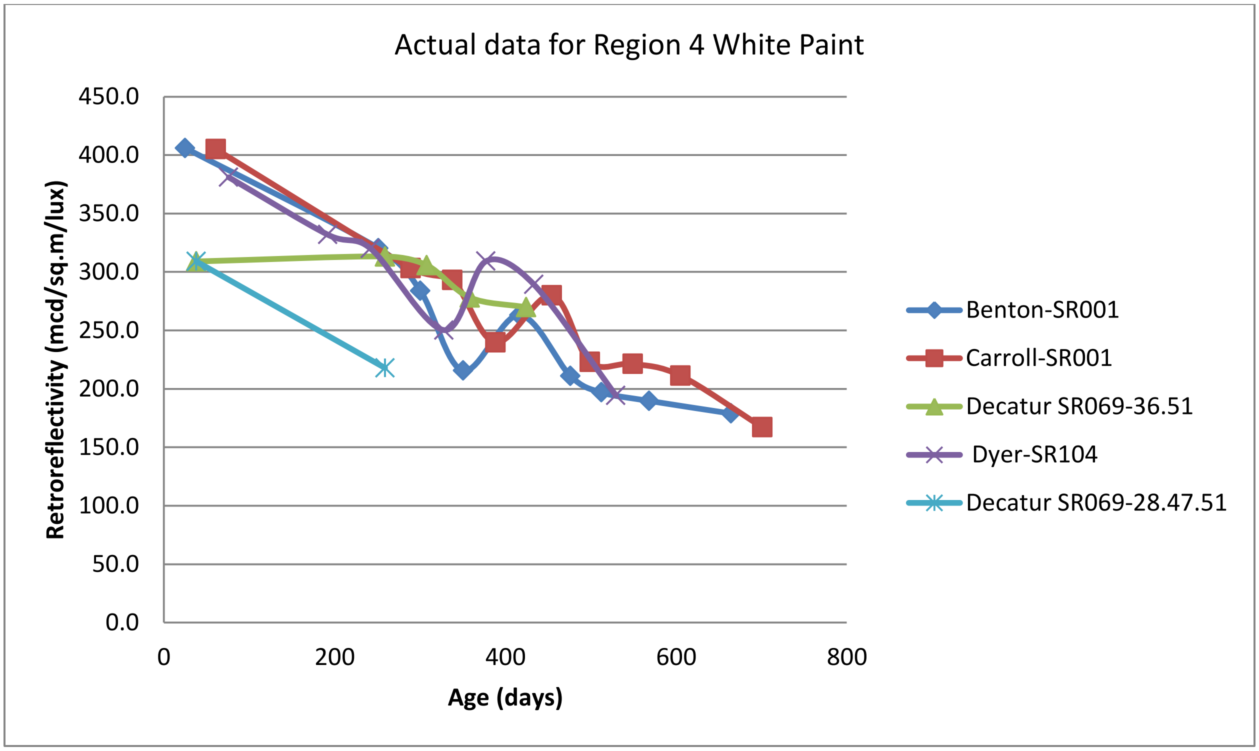


Figure B1.13 Region 4 white paint

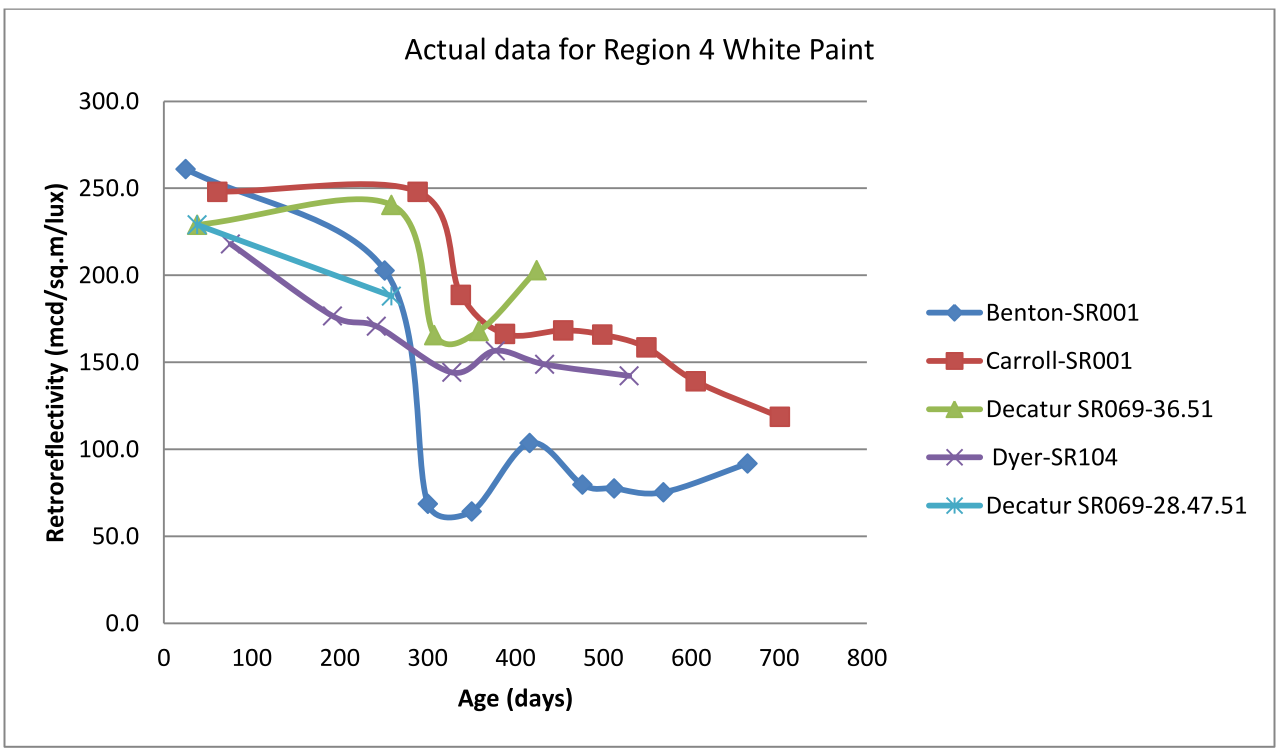


Figure B1.14 Region 4 yellow paint

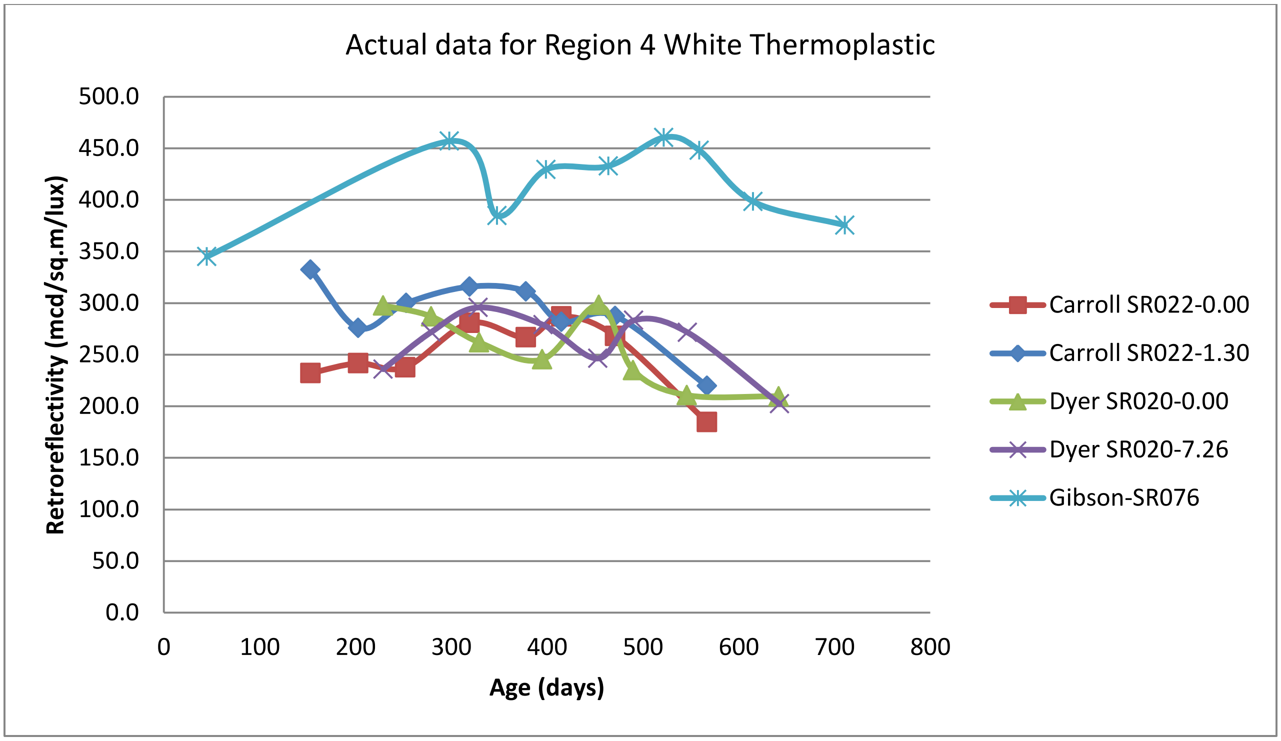


Figure B1.15 Region 4 white thermoplastic

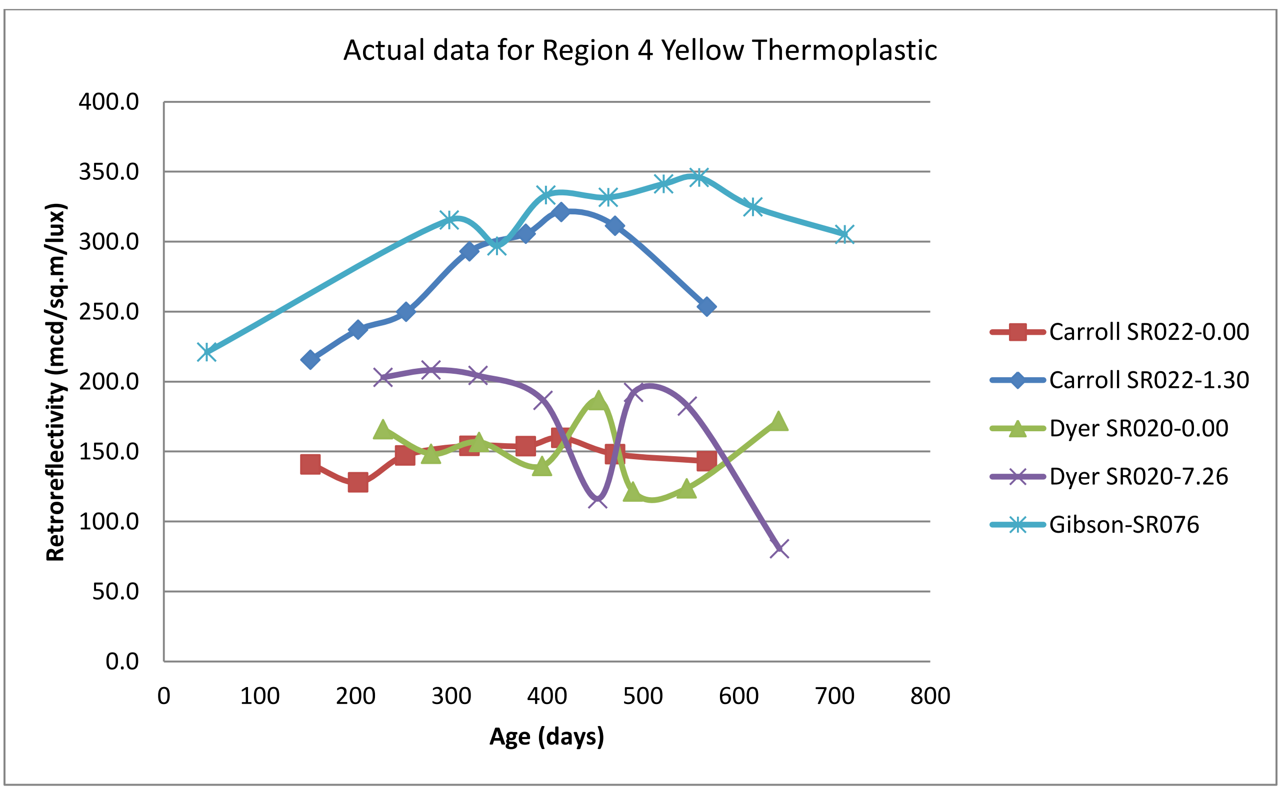


Figure B1.16 Region 4 yellow thermoplastic

APPENDIX C: CORRELATION GRAPHS

C1: Statewide deterioration rates without moving average

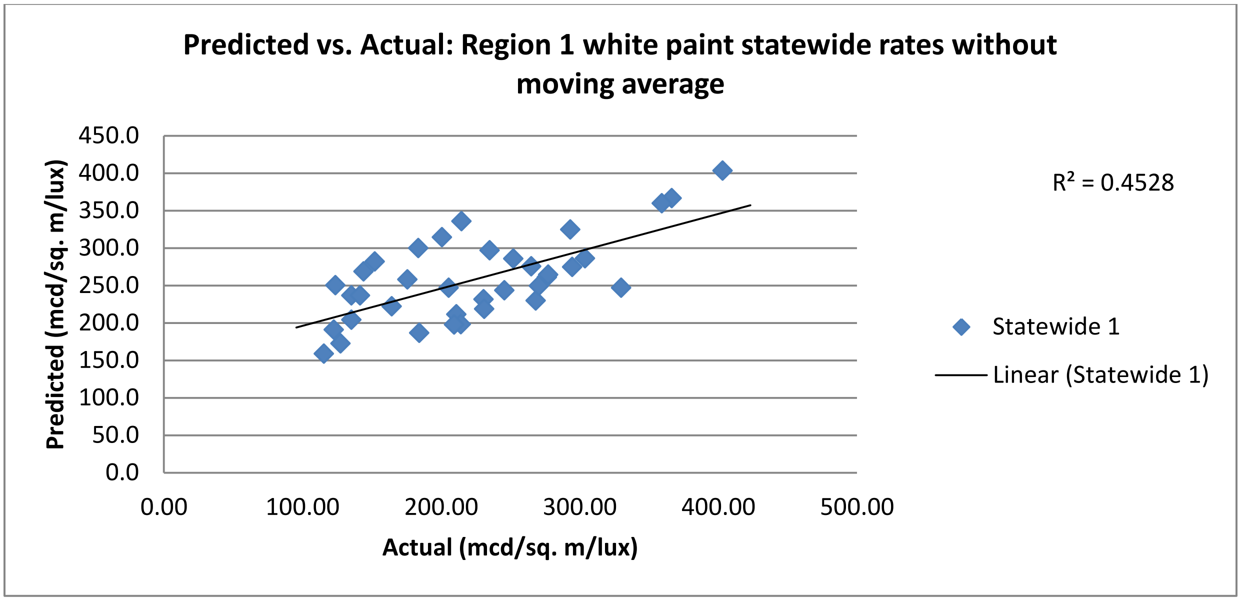


Figure C1.1 Region 1 white paint predicted with statewide rates without moving average

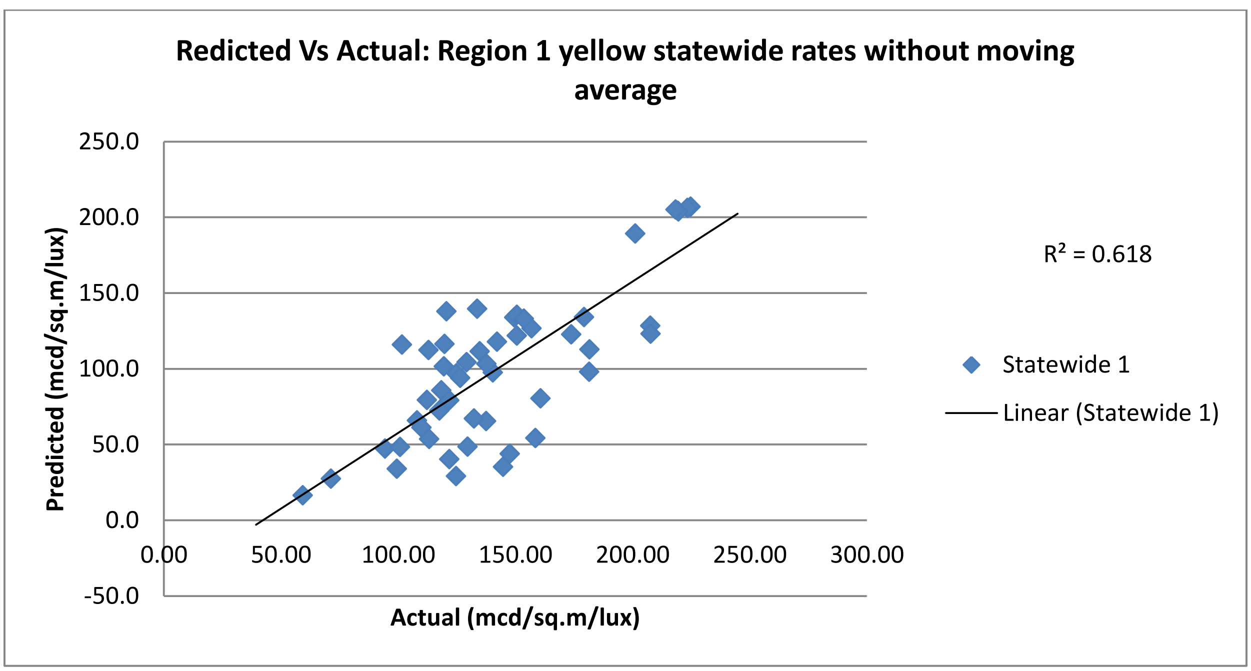


Figure C1.2 Region 1 yellow paint predicted with statewide rates without moving average

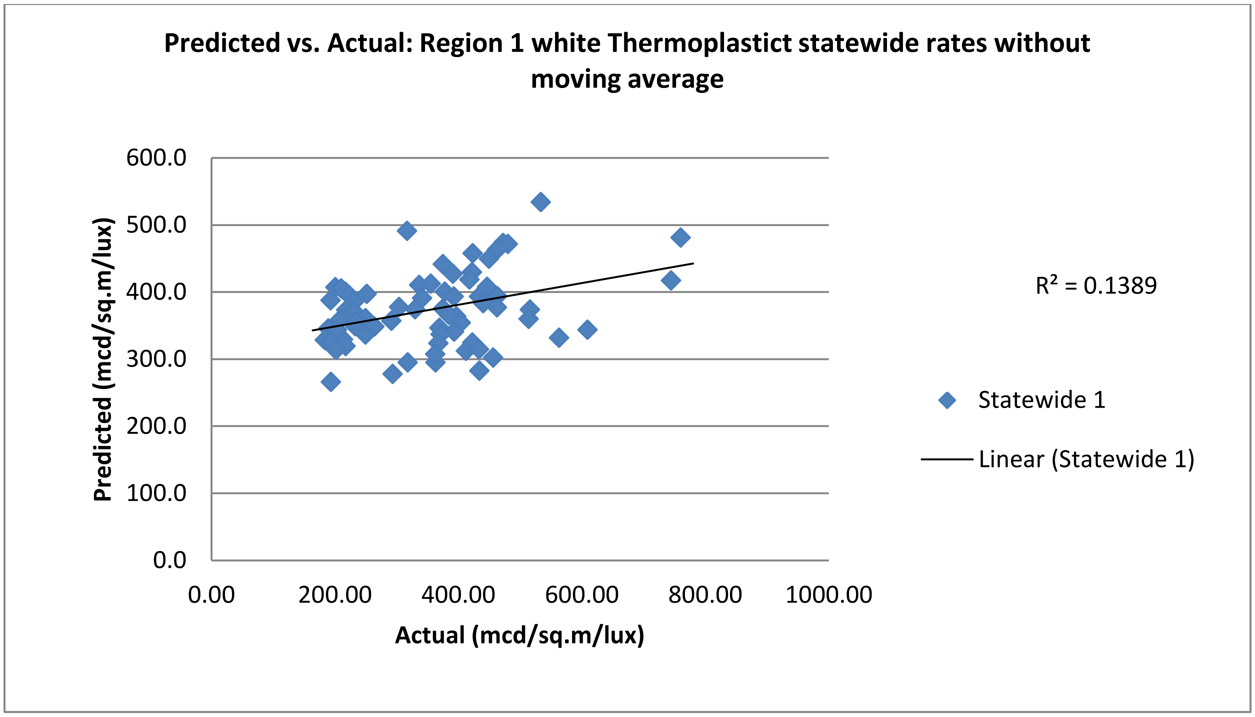


Figure C1.3 Region 1 white thermoplastic predicted with statewide rates without moving average

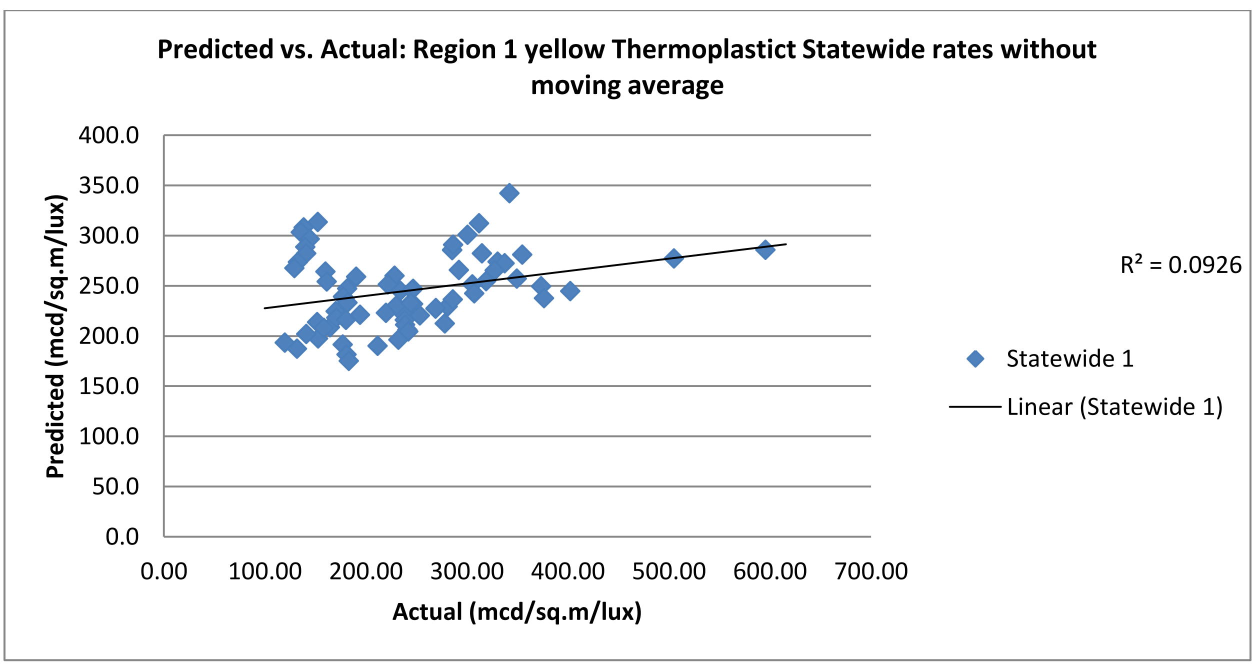


Figure C1.4 Region 1 yellow thermoplastic predicted with statewide rates without moving average

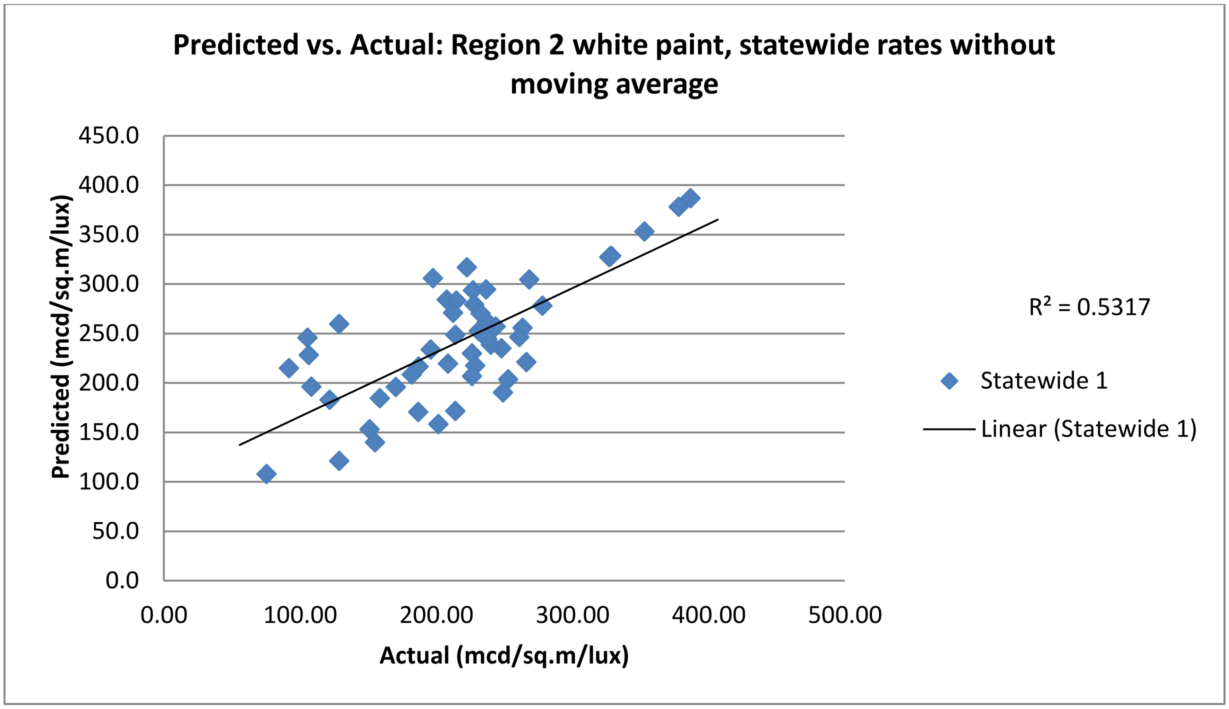


Figure C1.5 Region 2 white paint predicted with statewide rates without moving average

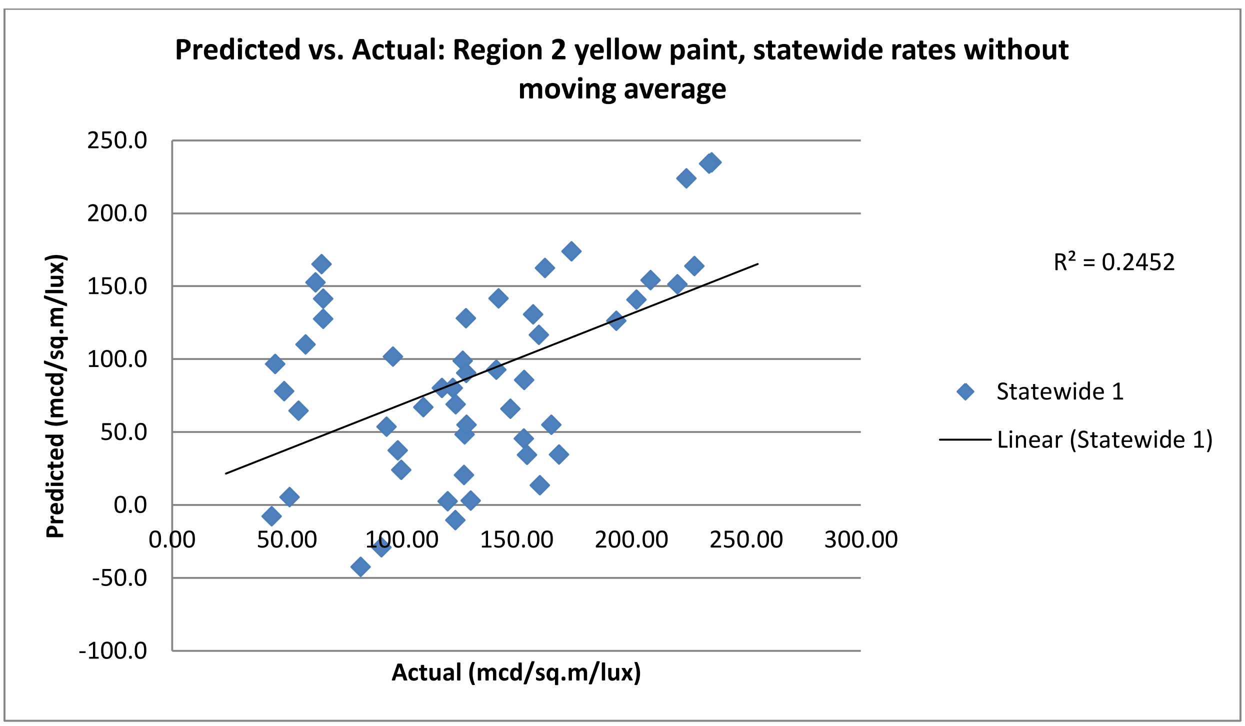


Figure C1.6 Region 2 yellow paint predicted with statewide rates without moving average

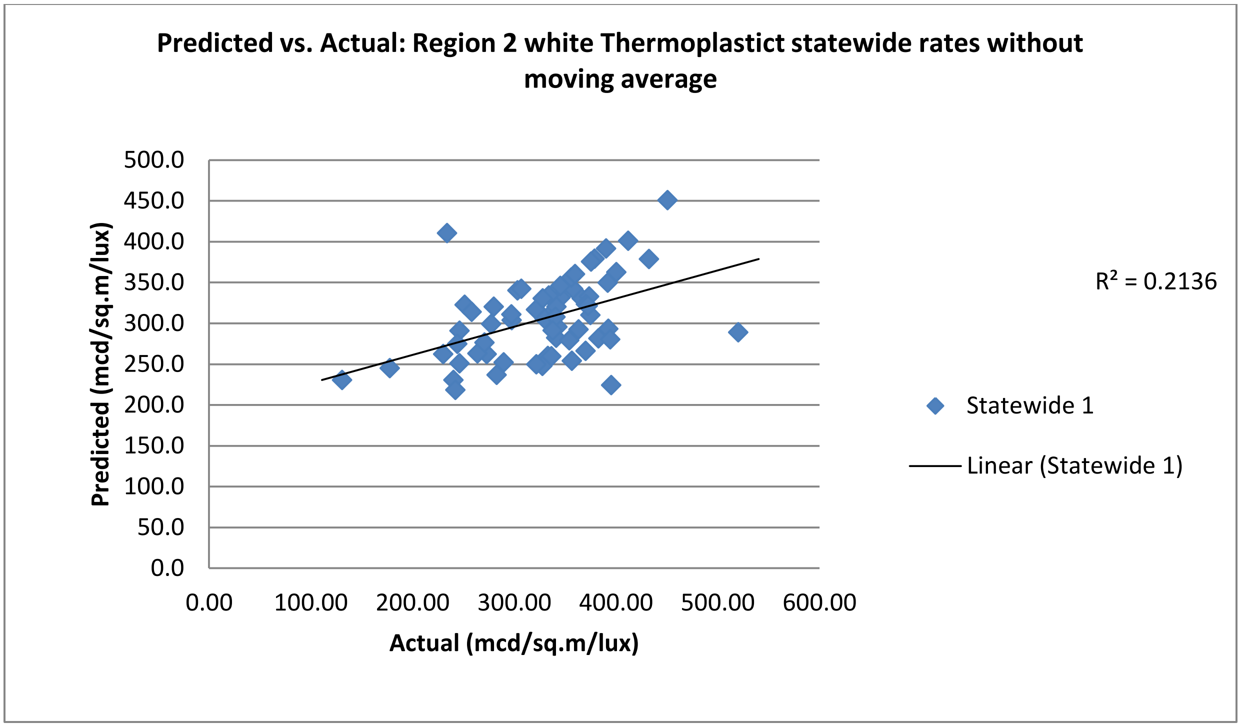


Figure C1.7 Region 2 white thermoplastic predicted with statewide rates without moving average

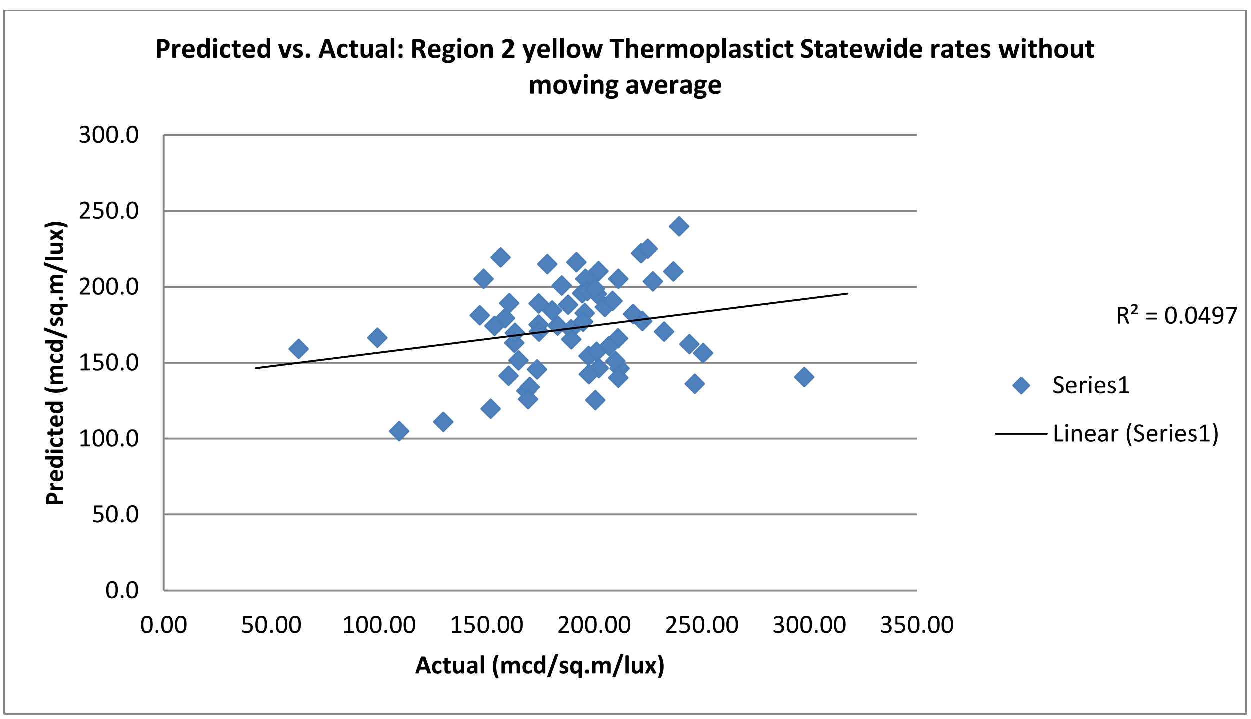


Figure C1.8 Region 2 yellow thermoplastic predicted with statewide rates without moving average

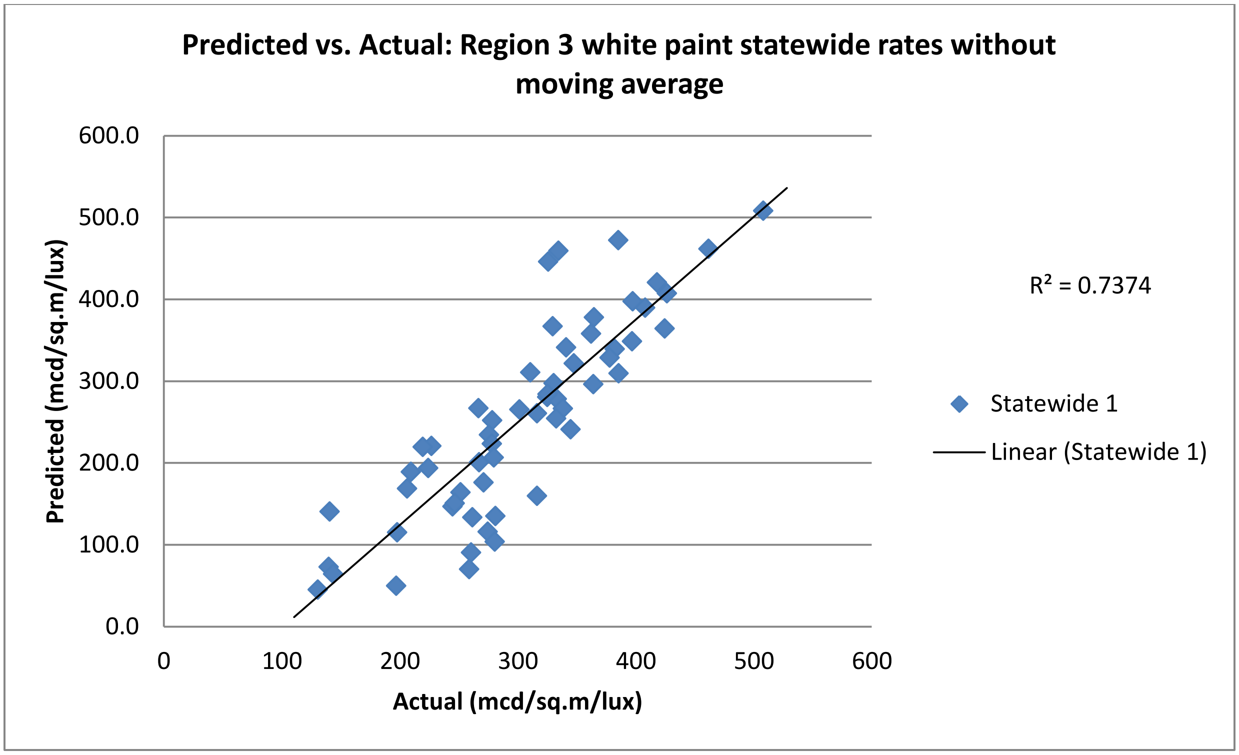


Figure C1.9 Region 3 white paint predicted with statewide rates without moving average

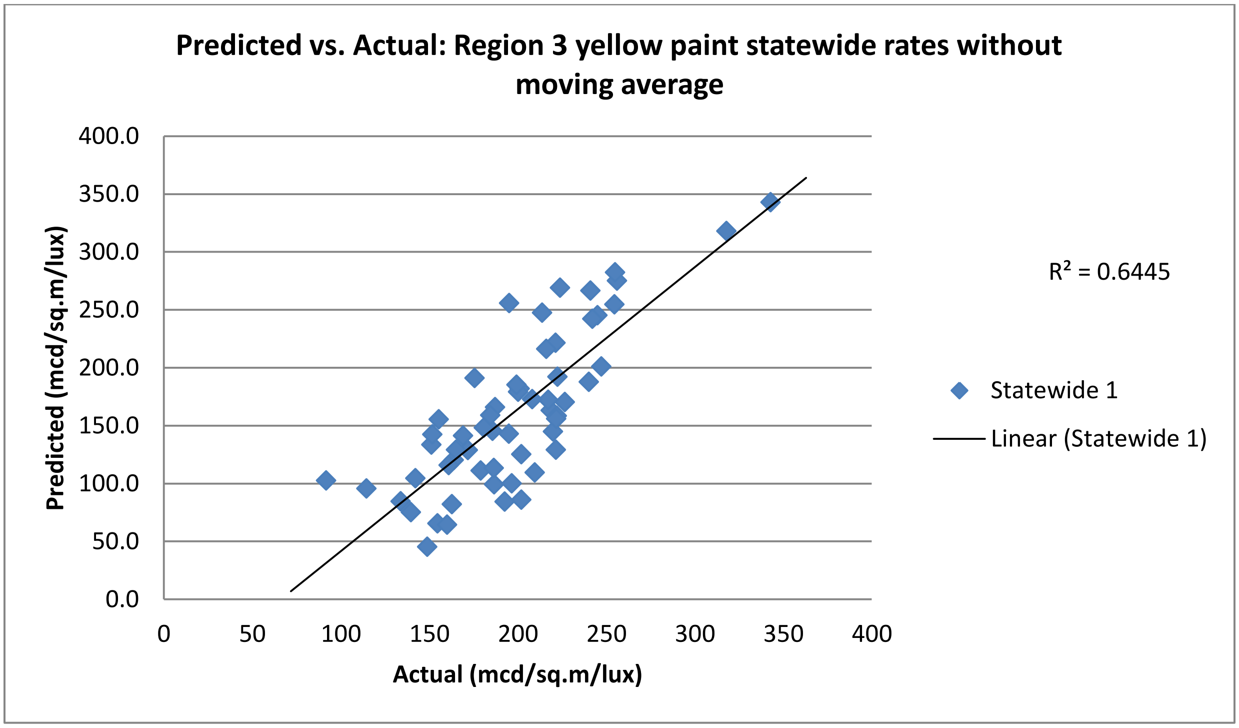


Figure C1.10 Region 3 yellow paint predicted with statewide rates without moving average

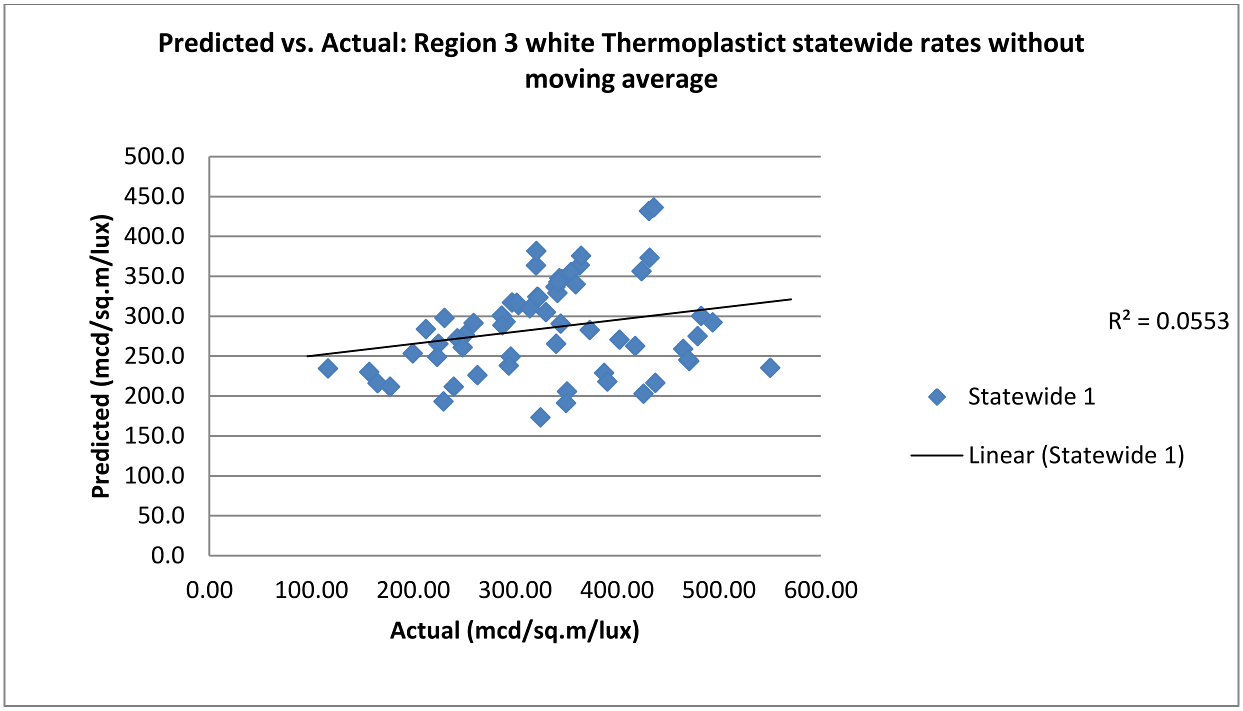


Figure C1.11 Region 3 white thermoplastic predicted with statewide rates without moving average

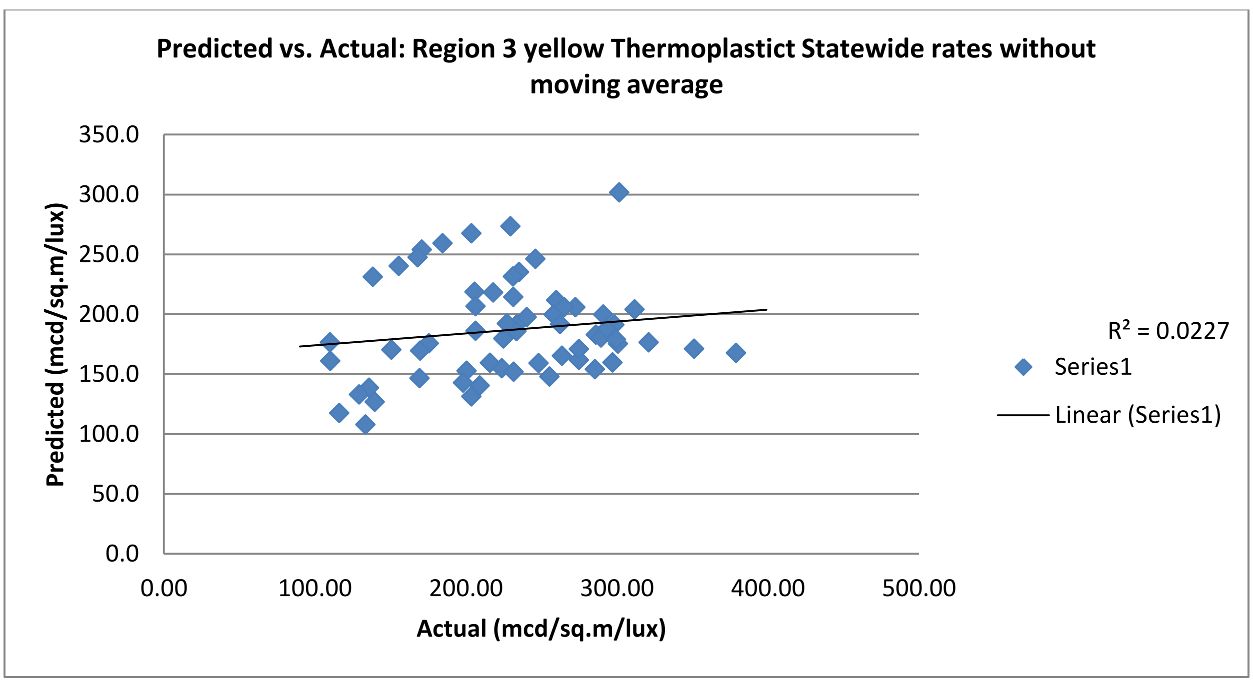


Figure C1.12 Region 3 yellow thermoplastic predicted with statewide rates without moving average

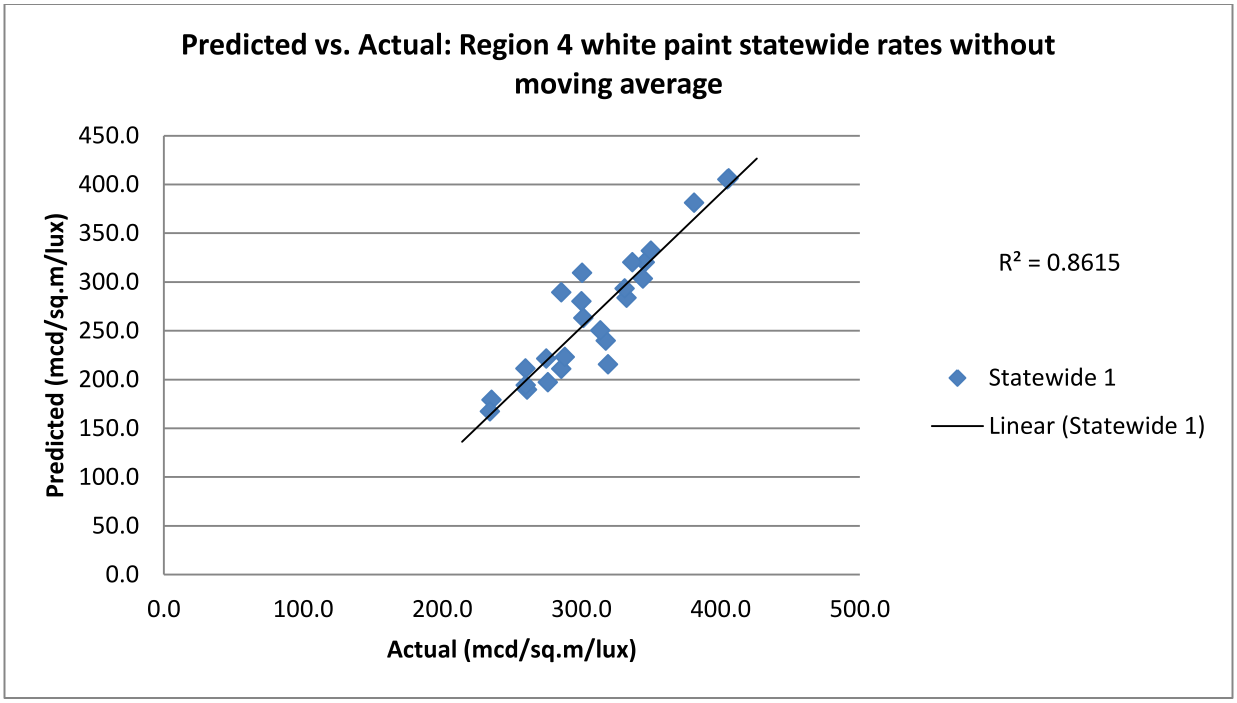


Figure C1.13 Region 4 white paint predicted with statewide rates without moving average

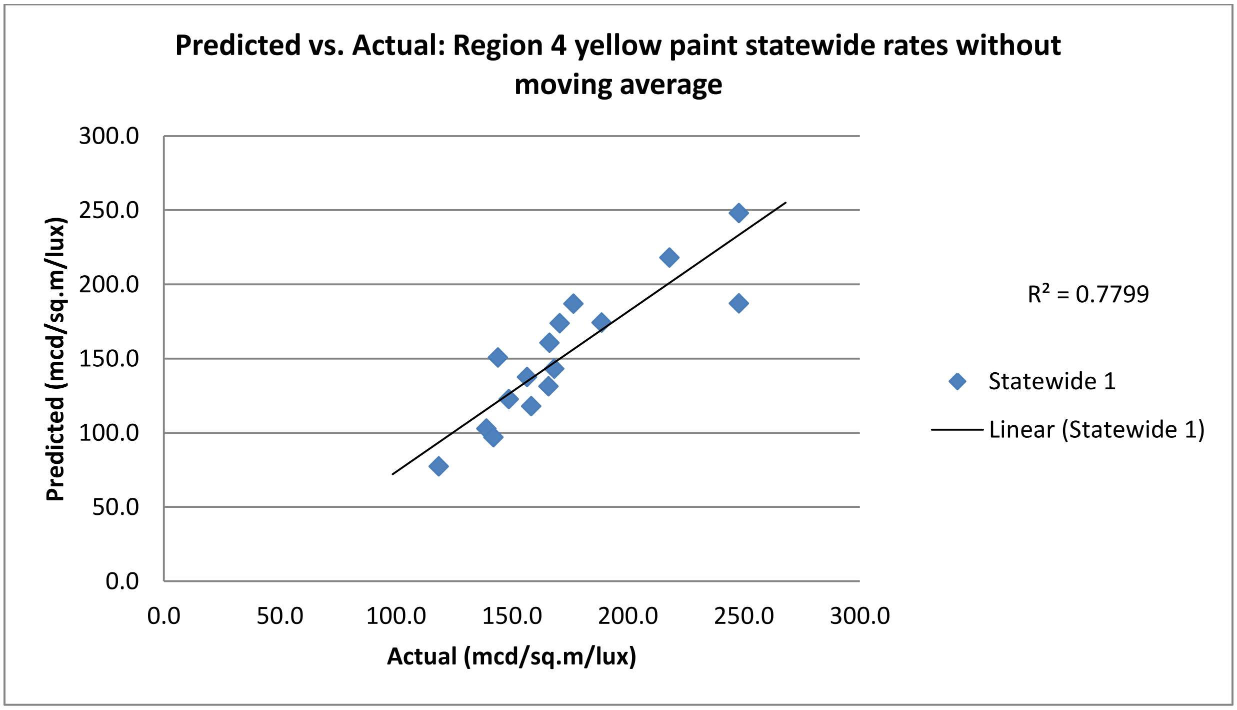


Figure C1.14 Region 4 yellow paint predicted with statewide rates without moving average

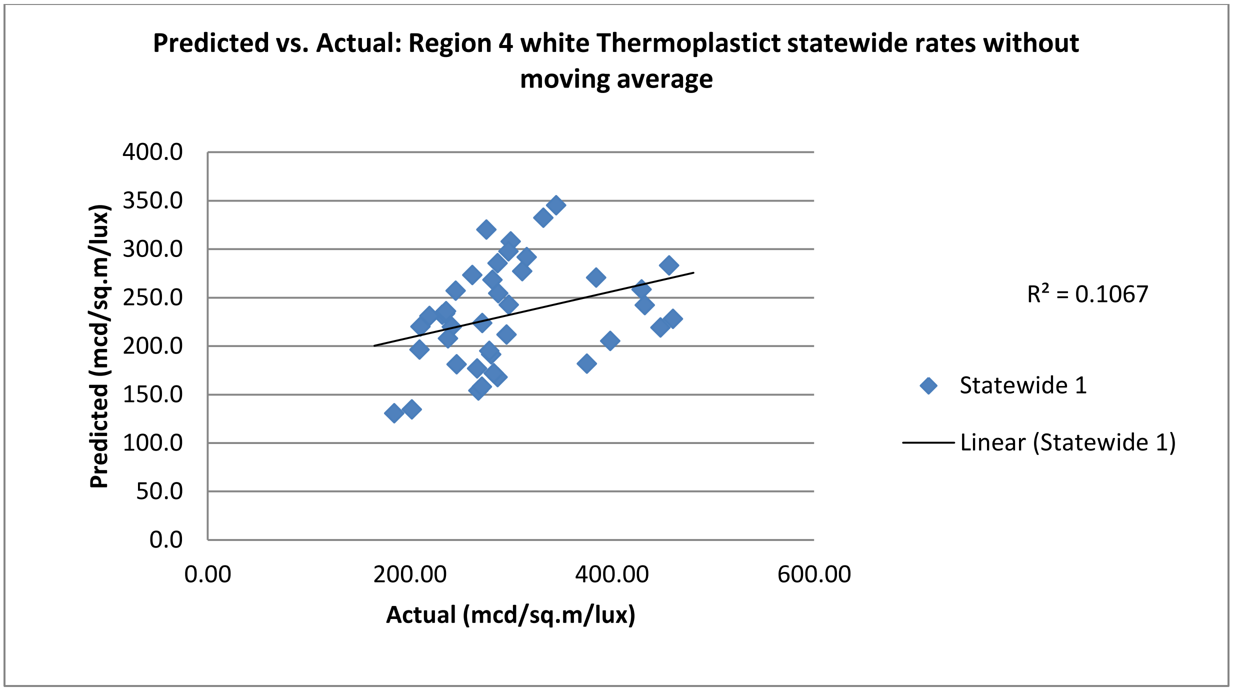


Figure C1.15 Region 4 white thermoplastic predicted with statewide rates without moving average

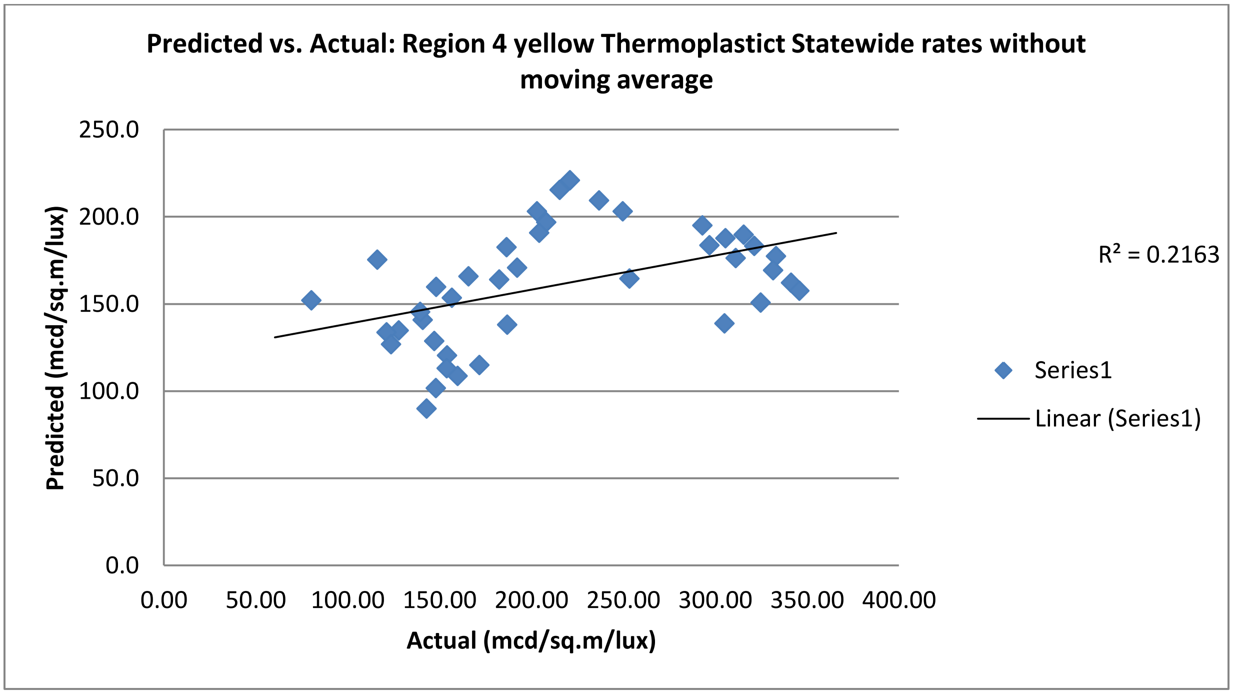


Figure C1.16 Region 4 yellow thermoplastic predicted with statewide rates without moving average

C2: Regional deterioration rates without moving average

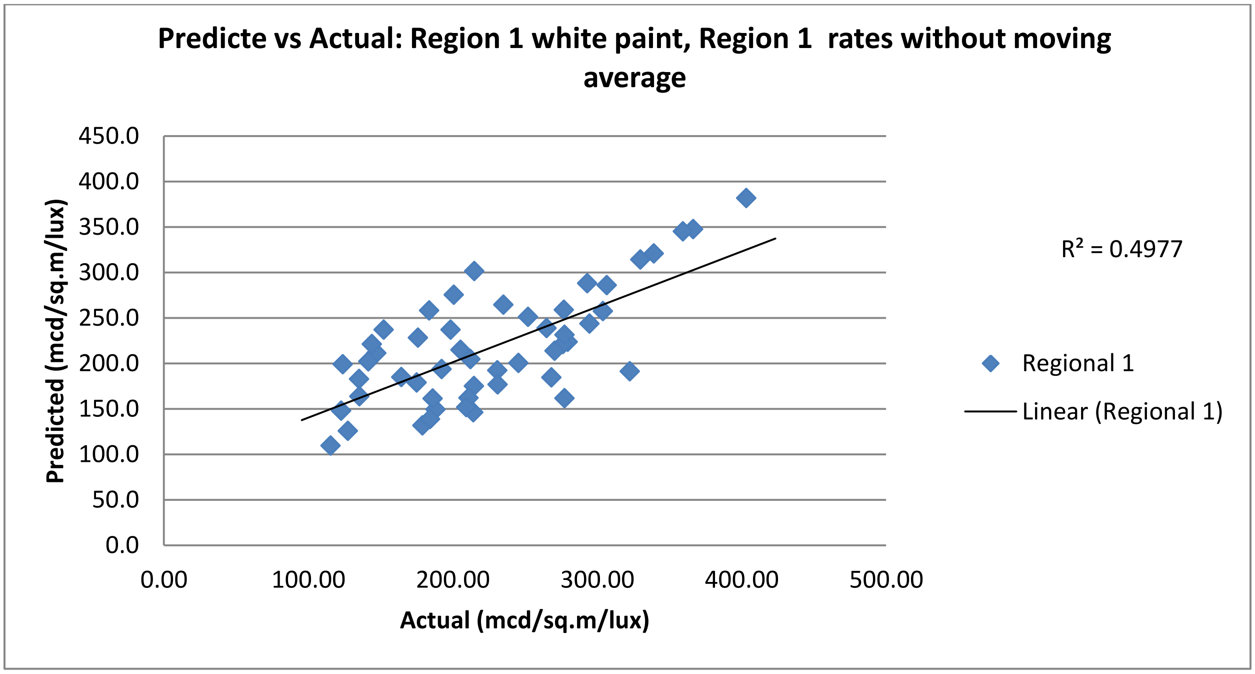


Figure C2.1 Region 1 white paint predicted with Region 1 rates without moving average

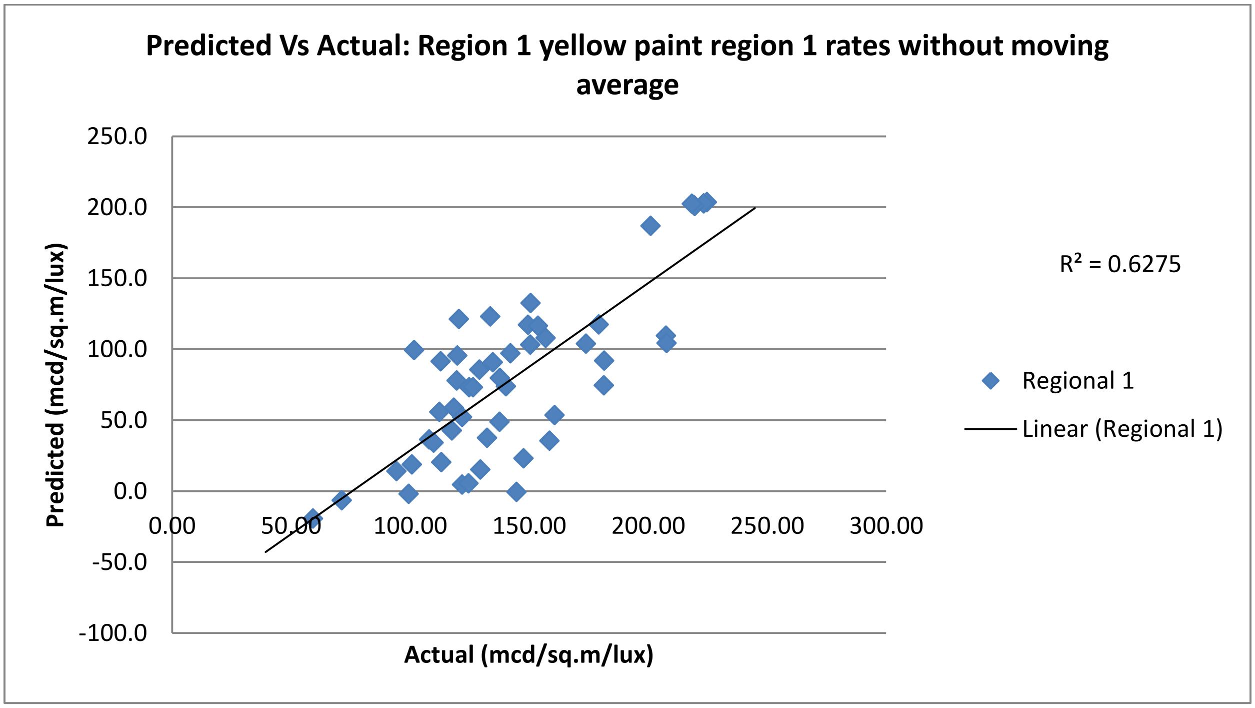


Figure C2.2 Region 1 yellow paint predicted with Region 1 rates without moving average

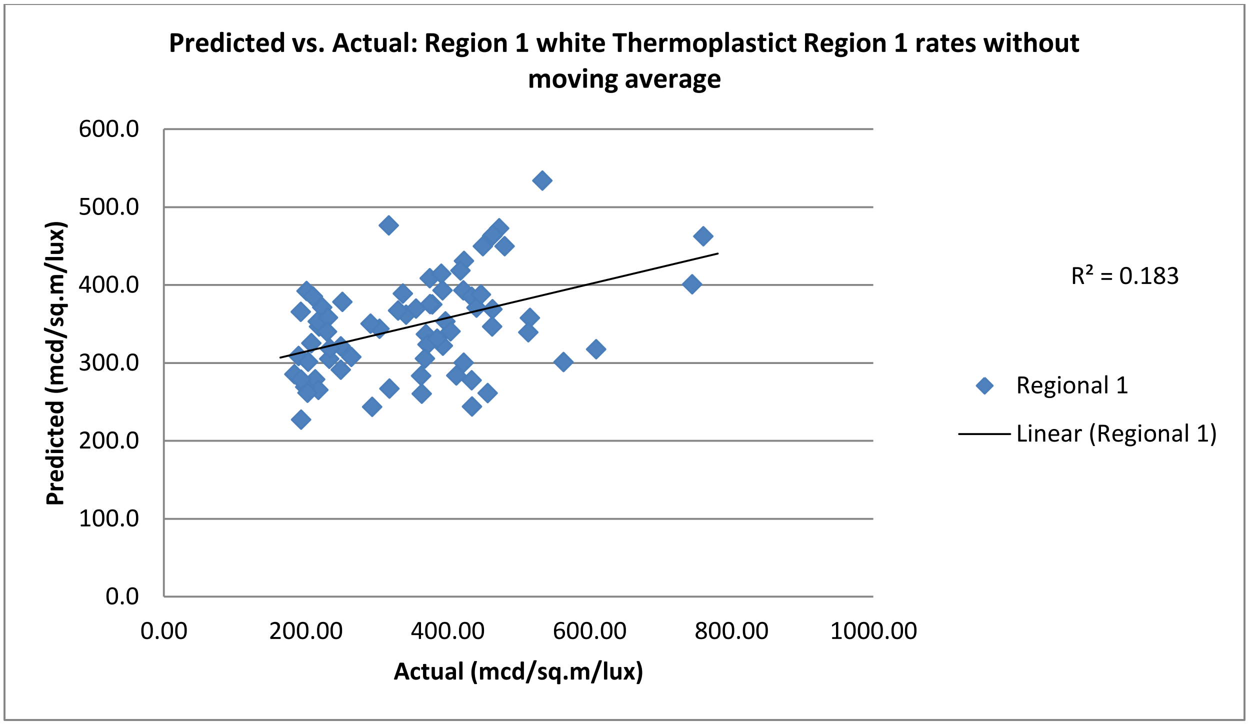


Figure C2.3 Region 1 white thermoplastic predicted with Region 1 rates without moving average

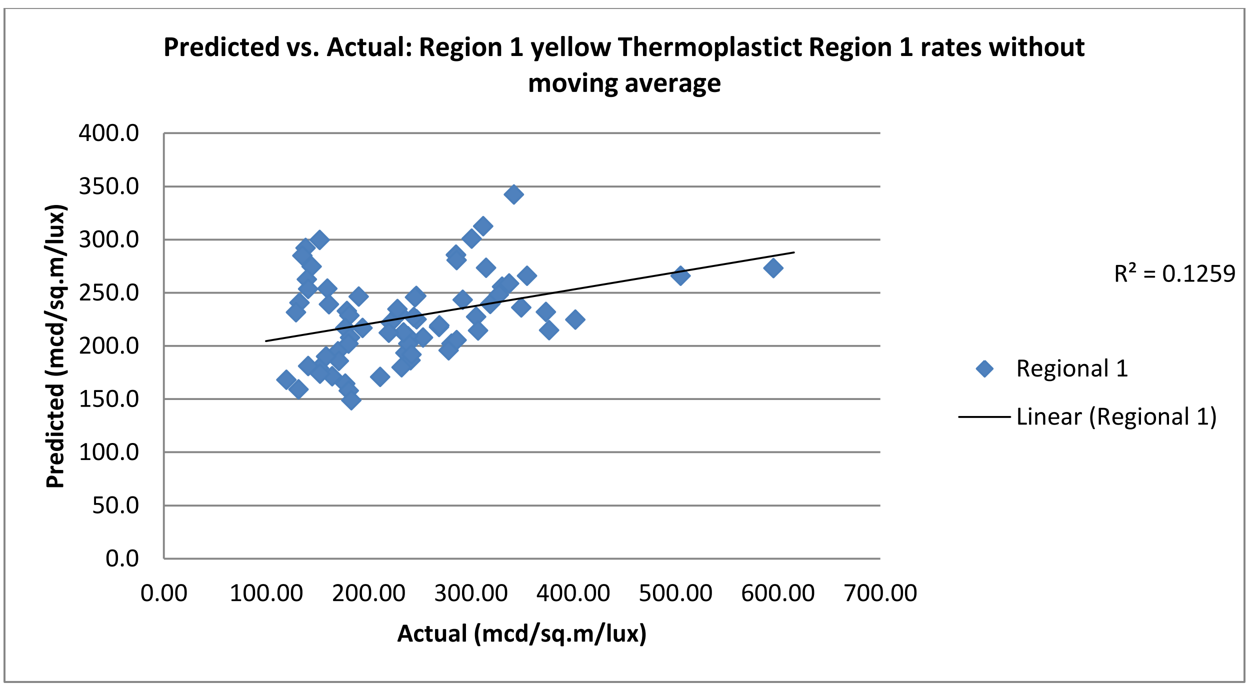


Figure C2.4 Region 1 yellow thermoplastic predicted with Region 1 rates without moving average

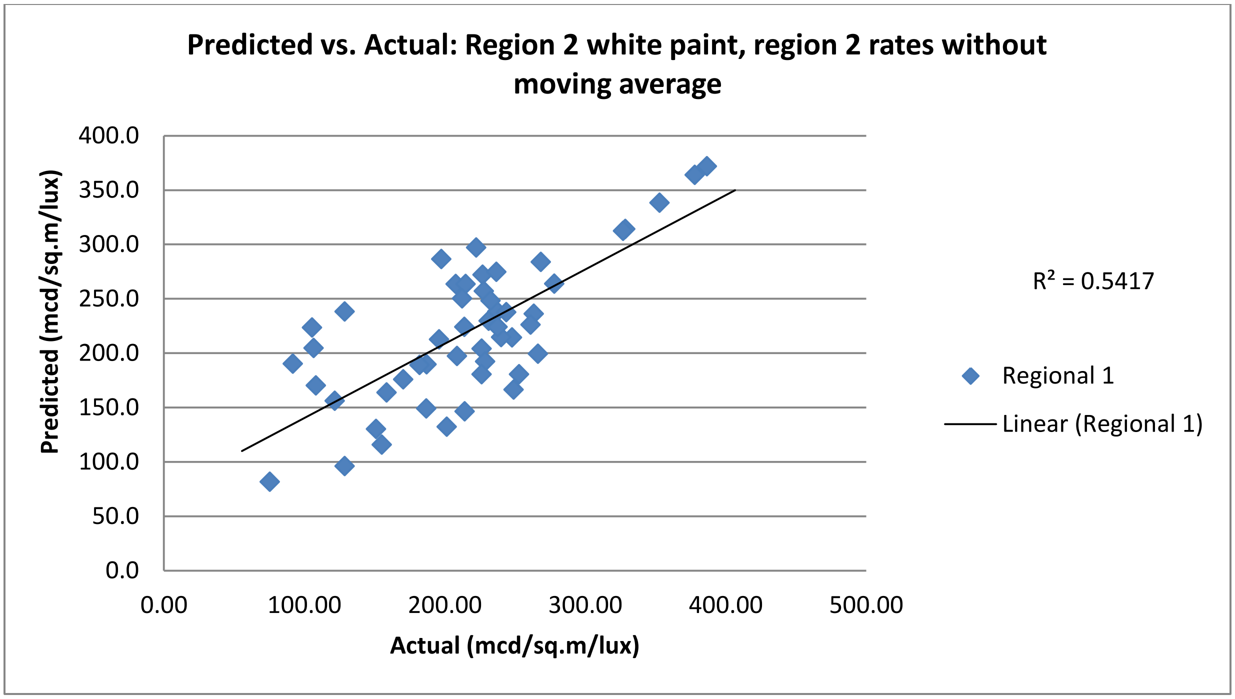


Figure C2.5 Region 2 white paint predicted with Region 2 rates without moving average

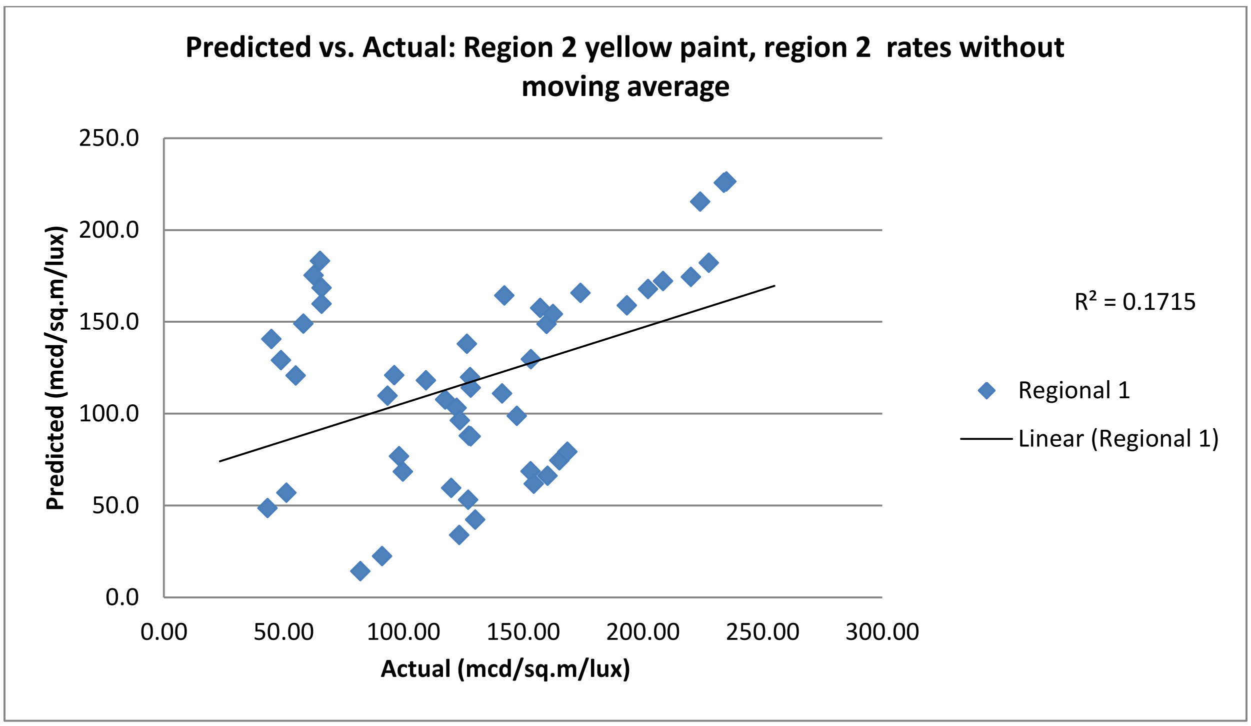


Figure C2.6 Region 2 yellow paint predicted with Region 2 rates without moving average

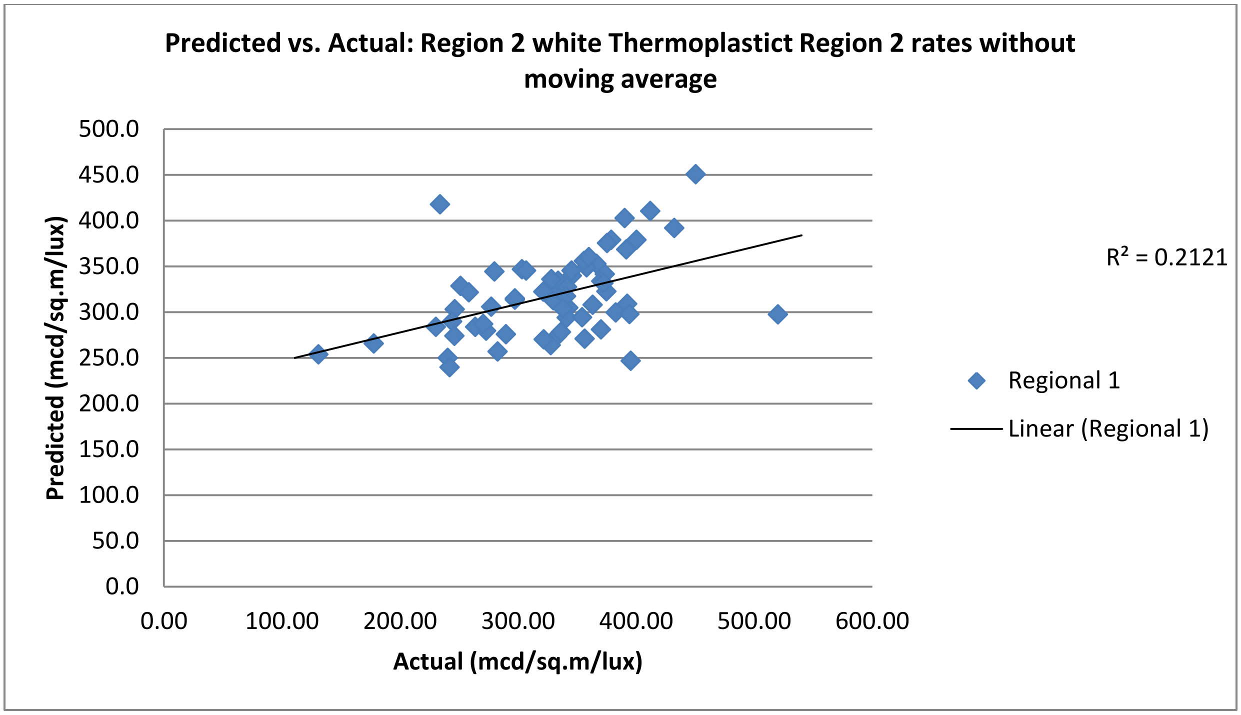


Figure C2.7 Region 2 white thermoplastic predicted with Region 2 rates without moving average

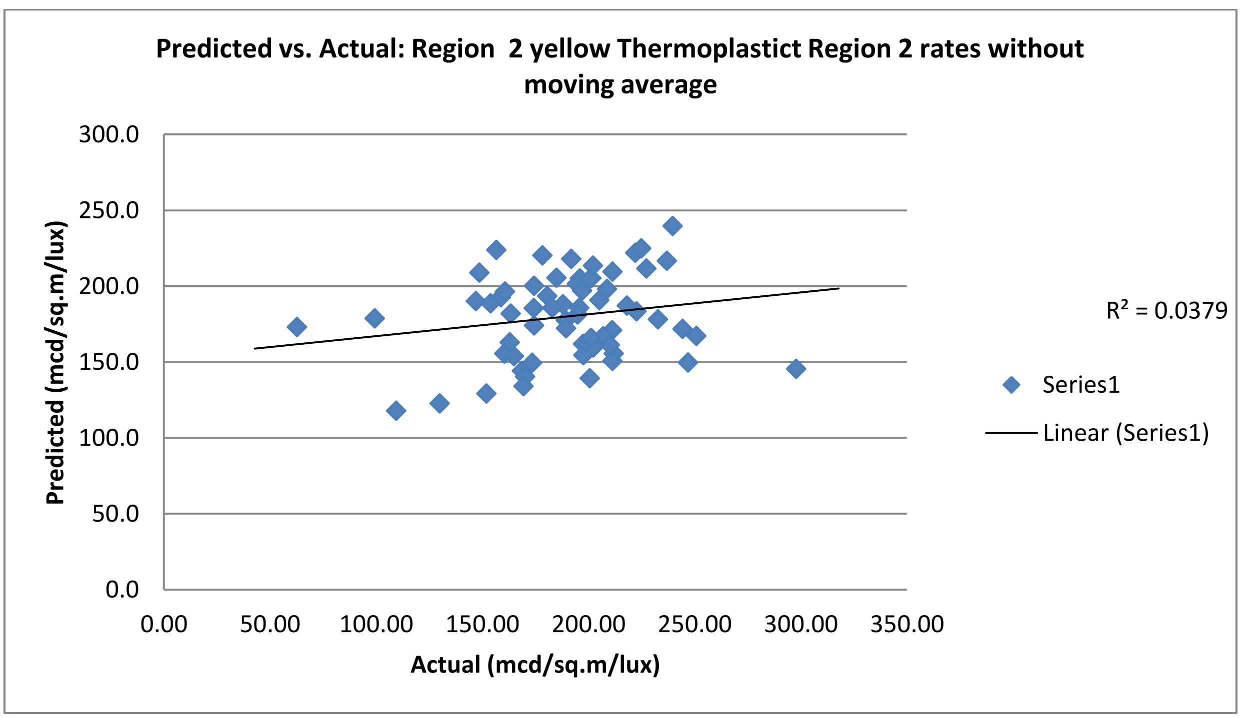


Figure C2.8 Region 2 yellow thermoplastic predicted with Region 2 rates without moving average

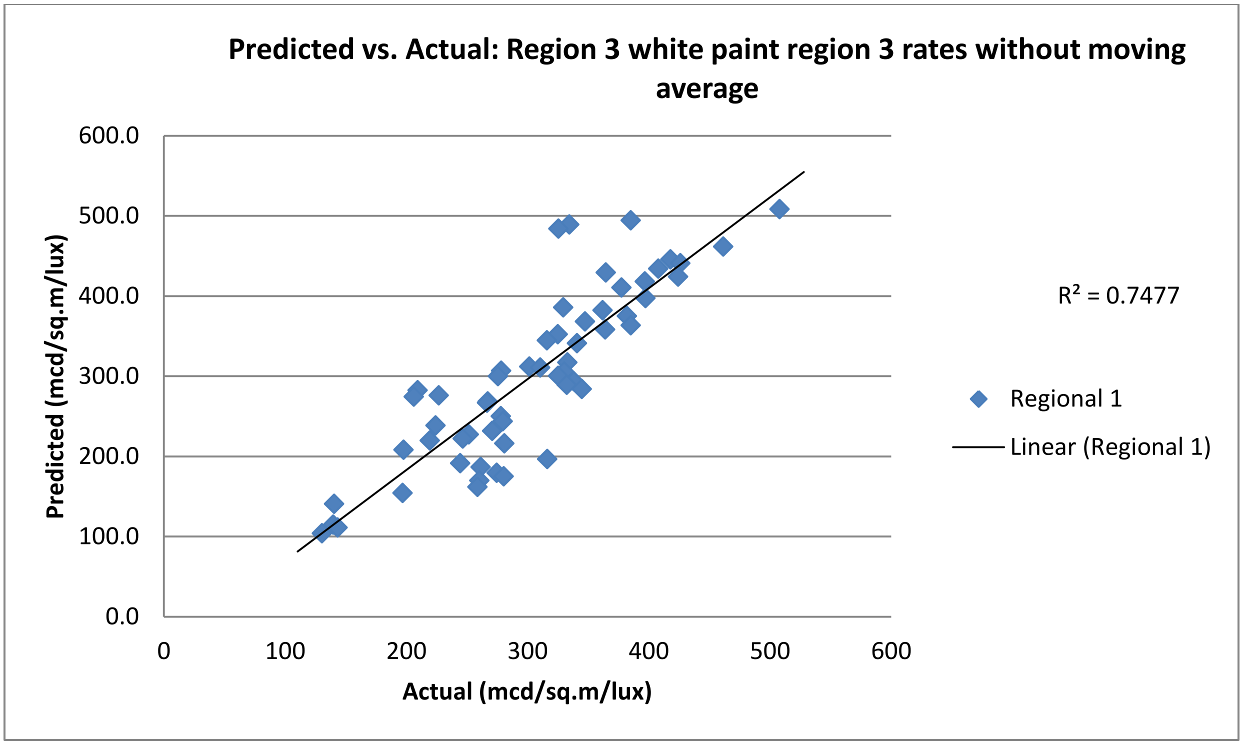


Figure C2.9 Region 3 white paint predicted with Region 3 rates without moving average

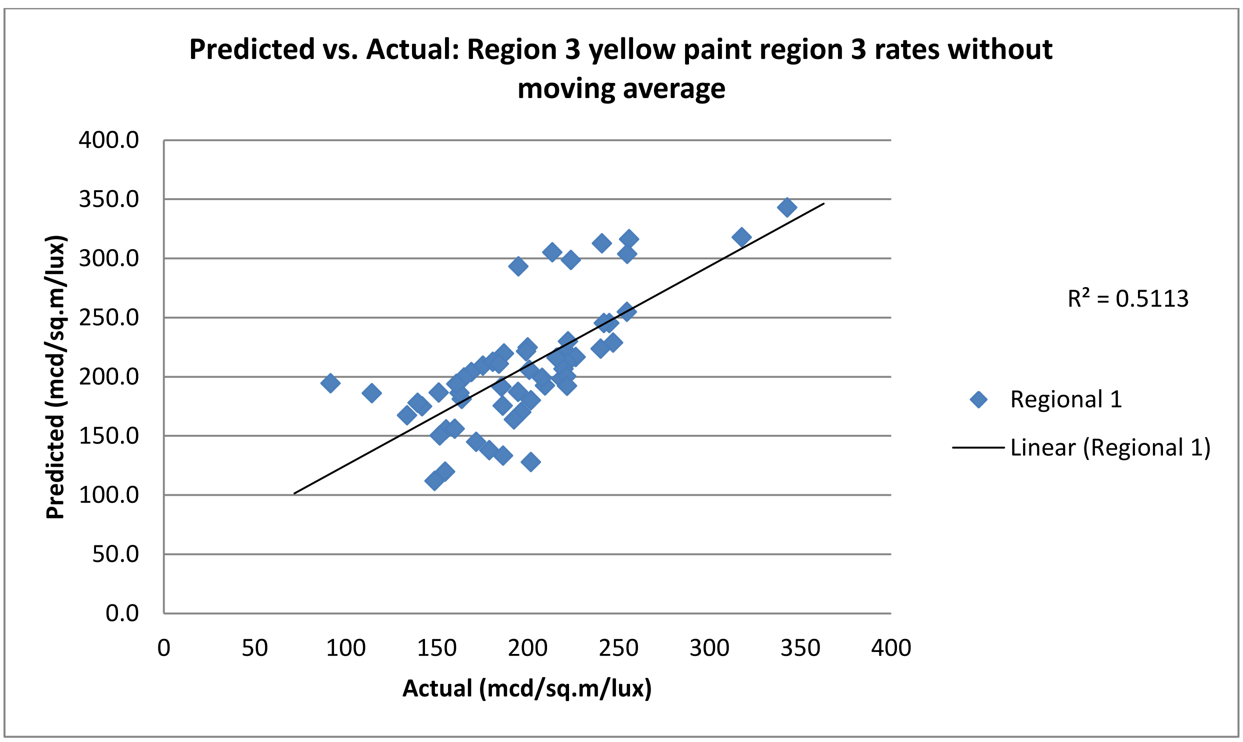


Figure C2.10 Region 3 yellow paint predicted with Region 3 rates without moving average

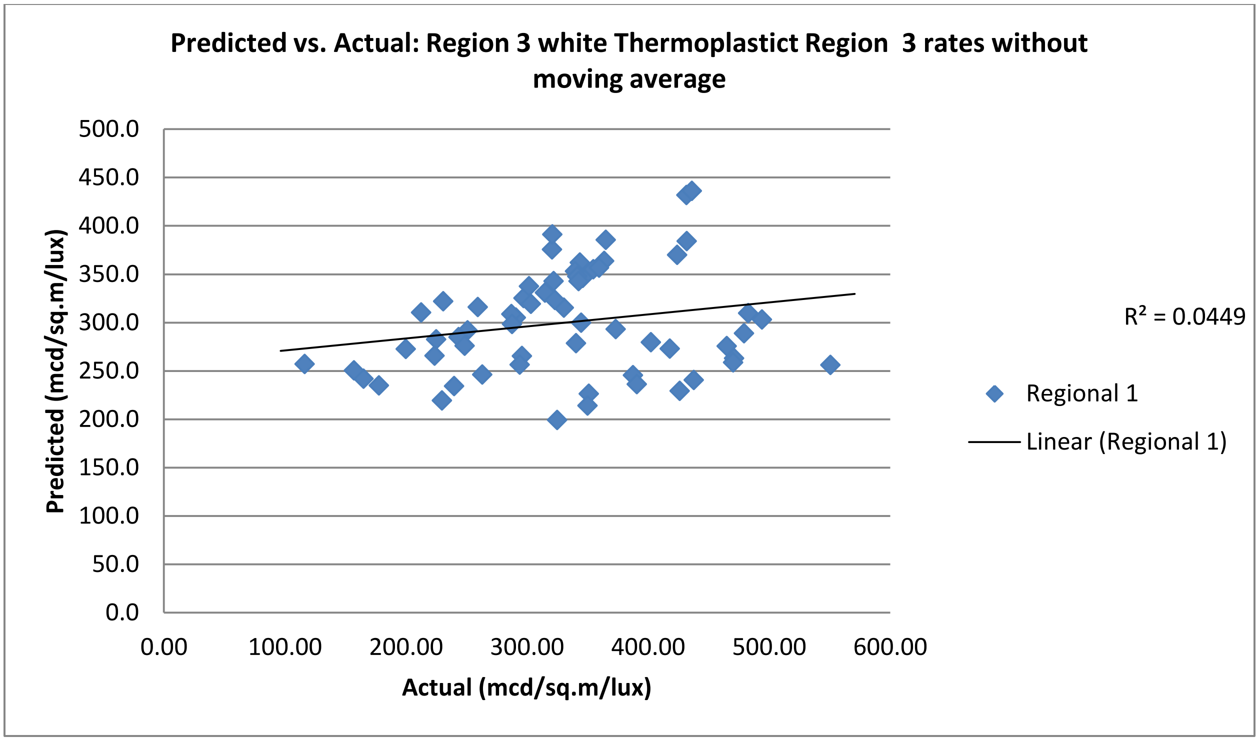


Figure C2.11 Region 3 white thermoplastic predicted with Region 3 rates without moving average

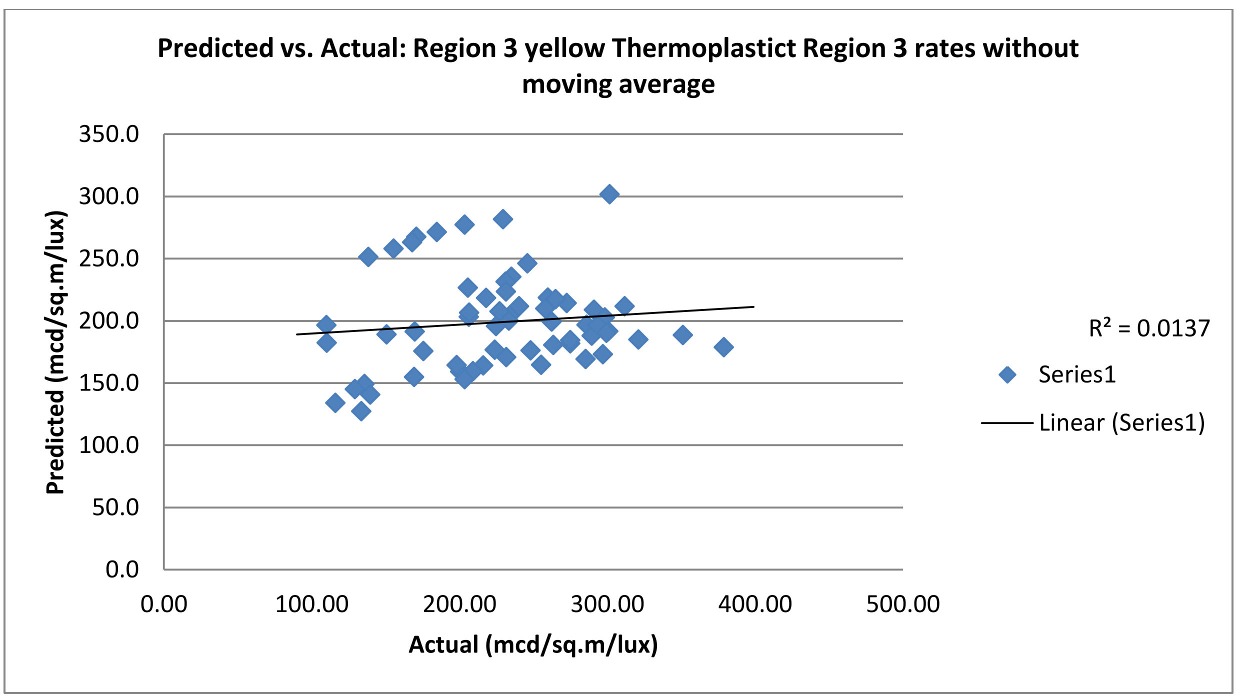


Figure C2.12 Region 3 yellow thermoplastic predicted with Region 3 rates without moving average

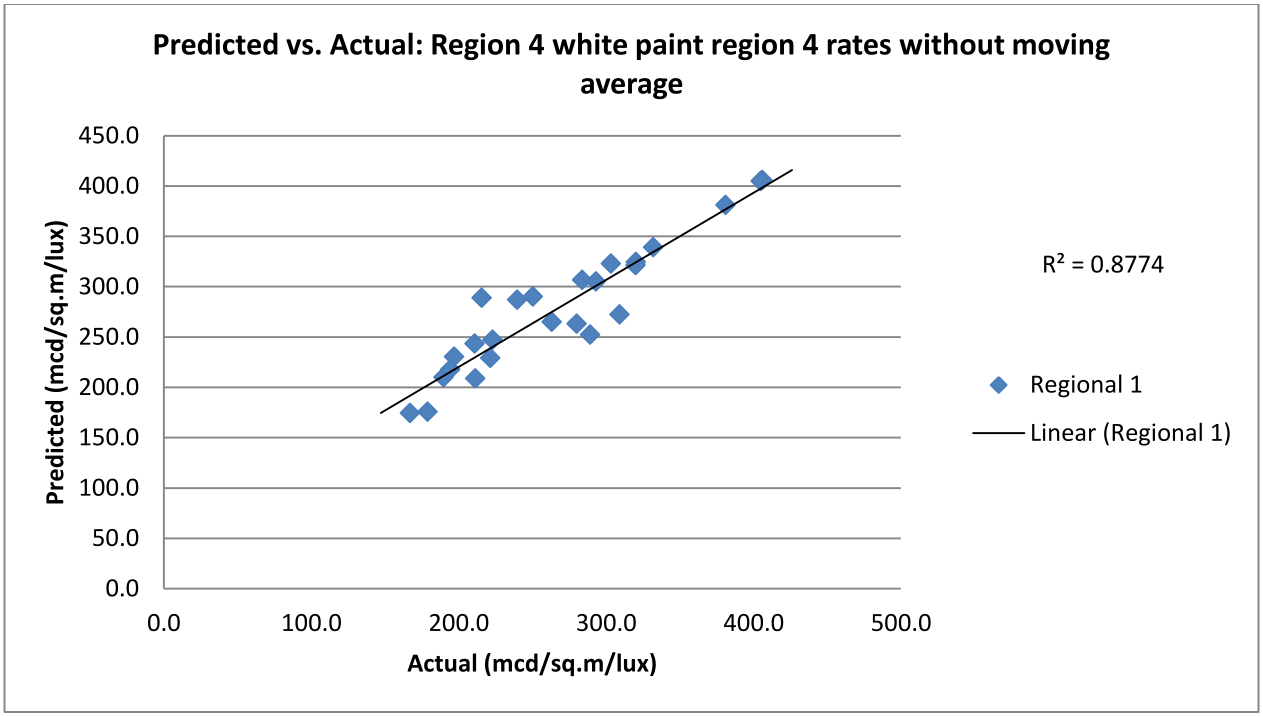


Figure C2.13 Region 4 white paint predicted with Region 4 rates without moving average

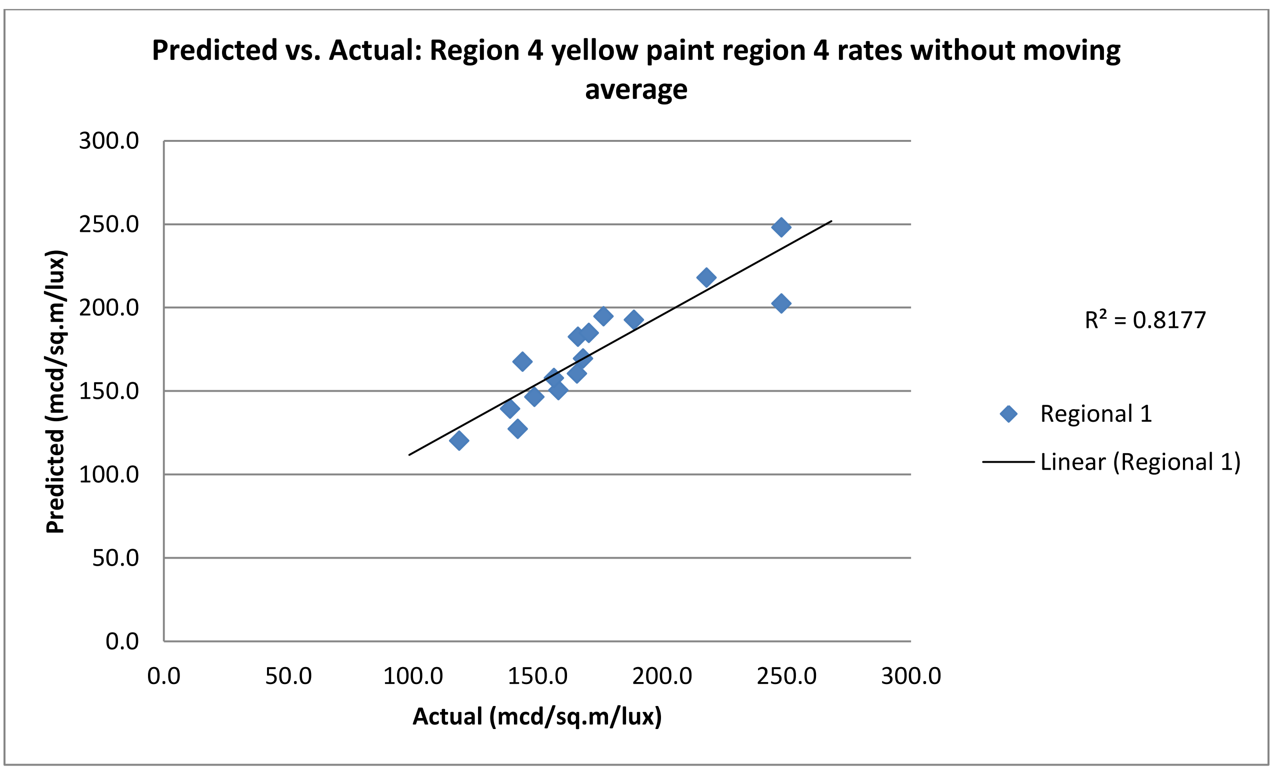


Figure C2.14 Region 4 yellow paint predicted with Region 4 rates without moving average

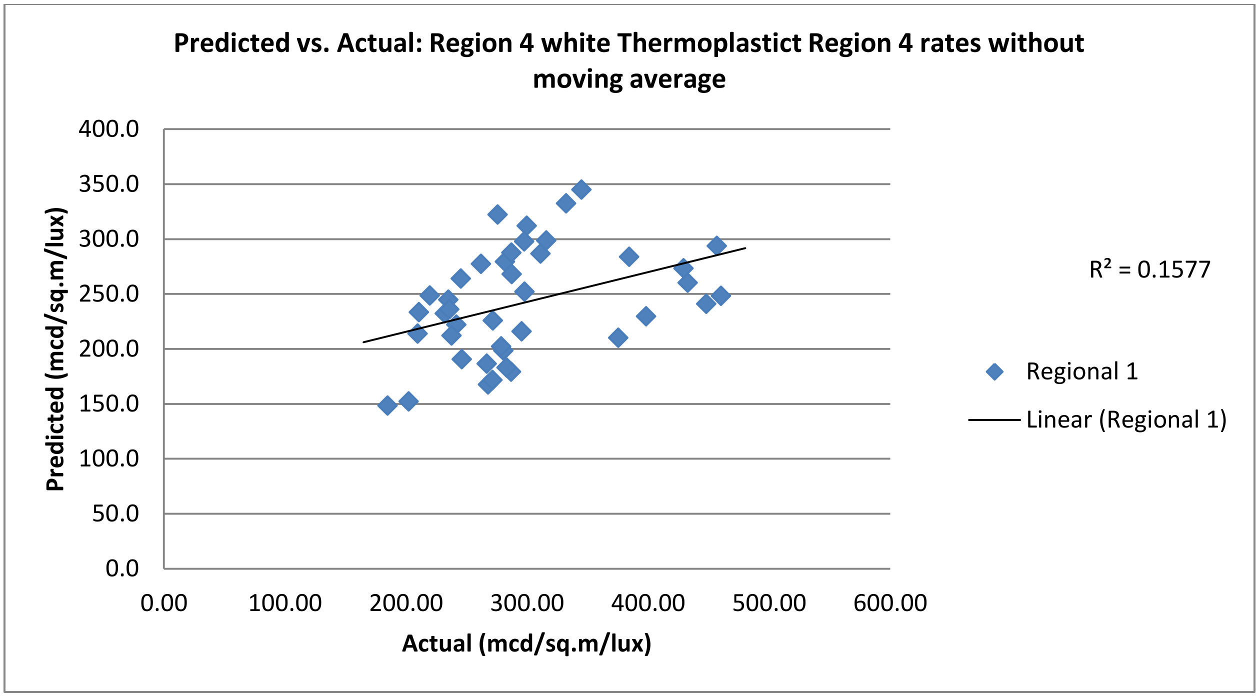


Figure C2.15 Region 4 white thermoplastic predicted with Region 4 rates without moving average

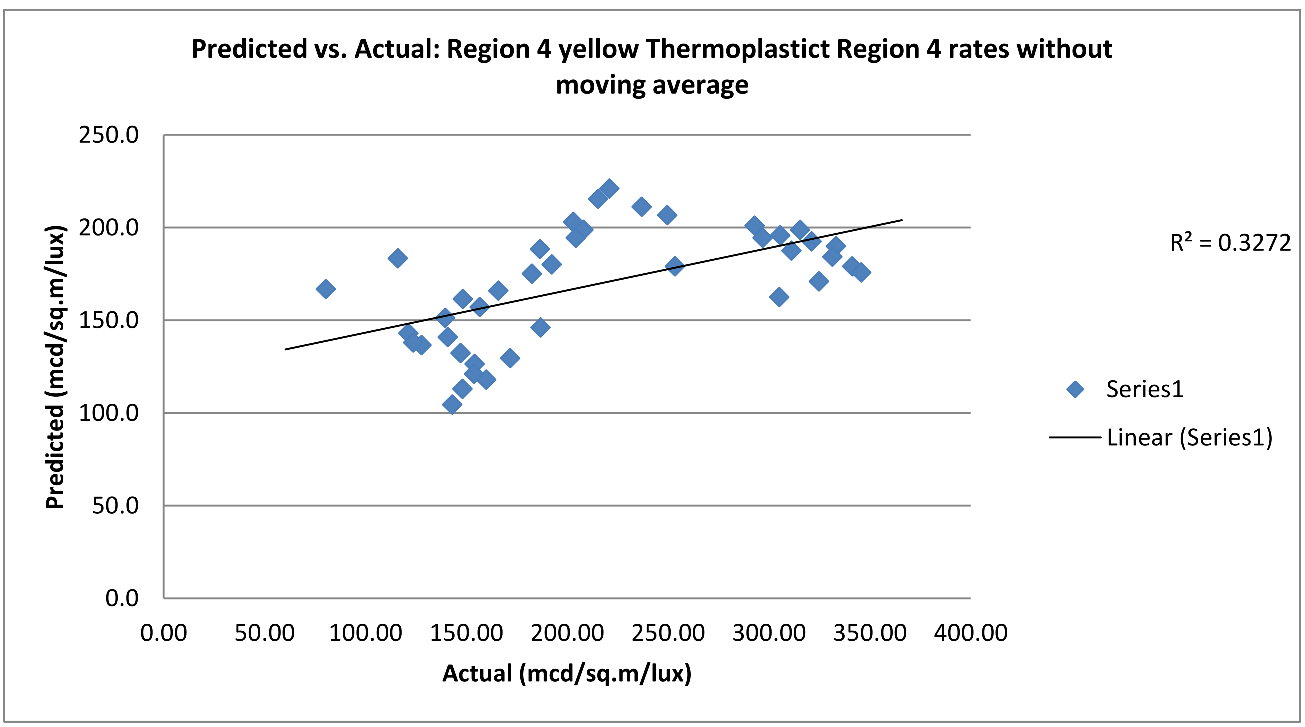


Figure C2.16 Region 4 yellow thermoplastic predicted with Region 4 rates without moving average