Tran-SET

Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Development of a Machine Learning-Based Model to Determine the Optimum and Safe Restriping Timing of Thermoplastic Pavement Markings in Hot and Humid Climates

Project No. 21BLSU11

Lead University: Louisiana State University

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Disclaimer

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16. Abstract

Due to limited budget, most transportation agencies restripe their thermoplastic pavement markings based on a fixed schedule or based on visual inspection instead of monitoring the retroreflectivity and restriping when the retroreflectivity drops below a pre-determined threshold. These strategies are questionable in terms of efficiency and economy. Therefore, previous studies proposed degradation models to predict the retroreflectivity of thermoplastic markings based on key variables. Yet, most of these studies reported low R^2 (as low as 0.1), which placed little confidence in these models. Therefore, the objective of this study was to evaluate and predict the field performance of thermoplastics and to propose cost-effective restriping strategies for thermoplastics used in hot and humid climate service conditions. To achieve this objective, National Transportation Product Evaluation Program (NTPEP) data were mined and analyzed. Results indicated that the service life (SL) of thermoplastics ranged between 0.4 and 12.1 years (according to the initial retroreflectivity, traffic, and surface type) with an average value of 3.4 ± 0.2 years. Four regression models with relatively high accuracy were developed to predict the SL of thermoplastics based on key variables. In addition, the genetic algorithm was used to develop a model that predicts the future retroreflectivty of these pavement markings. The predicted values were compared against actual retroreflectivity measurements collected from a field experiment at Louisiana State University. The results of this study could be used to make effective decisions related to restriping scheduling. Using the proposed models in restriping scheduling can result in considerable cost savings (up to $8,212 per lane-mile), as compared to the conventional restriping strategy.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Official
LaDOTD	Louisiana Department of Transportation and Development
DOT	Department of Transportation
NTPEP	National Transportation Product Evaluation Program
NCHRP	National Cooperative Highway Research Program
R^2	Coefficient of Determination

EXECUTIVE SUMMARY

Due to limited budget, most transportation agencies restripe their thermoplastic pavement markings based on a fixed schedule or based on visual inspection instead of monitoring the retroreflectivity and restriping when the retroreflectivity drops below a pre-determined threshold. These strategies are questionable in terms of efficiency and economy. Therefore, previous studies proposed degradation models to predict the retroreflectivity of thermoplastic markings based on key variables. Yet, most of these studies reported low R^2 (as low as 0.1), which placed little confidence in these models. Therefore, the objective of this study was to evaluate and predict the field performance of thermoplastics and to propose cost-effective restriping strategies for thermoplastics used in hot and humid climate service conditions. To achieve this objective, National Transportation Product Evaluation Program (NTPEP) data were mined and analyzed. Results indicated that the service life (SL) of thermoplastics ranged between 0.4 and 12.1 years (according to the initial retroreflectivity, traffic, and surface type) with an average value of 3.4 ± 0.2 years. Four regression models with relatively high accuracy were developed to predict the SL of thermoplastics based on key variables. In addition, the genetic algorithm was used to develop a model that predicts the future retroreflectivty of these pavement markings. The predicted values were compared against actual retroreflectivity measurements collected from a field experiment at Louisiana State University. The results of this study could be used to make effective decisions related to restriping scheduling. Using the proposed models in restriping scheduling can result in considerable cost savings (up to $8,212 per lane-mile), as compared to the conventional restriping strategy.

1. INTRODUCTION

Pavement markings are key traffic control devices that control traffic and provide guidance for road users reducing lane departure accidents *(1)*. In general, there are various pavement marking materials available for commercial use including paint (solvent-based and waterborne paints), thermoplastic, preformed thermoplastic, tape, epoxy, etc. Based on a survey from 51 state departments of transportation (DOTs) and local authorities, National Cooperative Highway Research Program (NCHRP) synthesis 306 indicated that thermoplastic is the second most common marking material—after waterborne paints—used throughout the United States *(2)*. It was used by 69% of the responding agencies and it represented 21% of striped lane miles.

The performance of pavement markings is primarily assessed using two key metrics, namely, retroreflectivity (R_L) and durability *(3)*. Under the effect of traffic and climate, these metrics deteriorate over time; and therefore, thermoplastic pavement markings require regular restriping to maintain these metrics. As such, it is essential to monitor the degradation of these metrics, especially the retroreflectivity, to identify pavement marking failure and accordingly plan for future restriping activities. Nevertheless, due to limited budget, most transportation agencies restripe their thermoplastic pavement markings based on a fixed schedule (according to an expected service life) or based on visual inspection instead of monitoring the retroreflectivity and restriping when the retroreflectivity drops below a pre-determined threshold *(2)*. For example, the Louisiana Department of Transportation and Development (LaDOTD) and Texas Department of Transportation (TxDOT) are commonly restriping thermoplastics based on regular visual inspection. There is a general agreement in the literature that these restriping strategies (visual inspection and fixed schedule) are not optimum in terms of both efficiency and economy *(4)*. This is because on many occasions, markings are restriped before or after the end of their service life, misspending funds or jeopardizing user safety, respectively. Additionally, adopting any of these strategies usually results in thermoplastic pavement markings that do not meet the minimum in-service levels of R_L proposed at the federal level *(5)*.

To mitigate the aforementioned challenges associated with conventional restriping strategies (visual inspection and fixed schedule), several research studies *(6-13)* were conducted to assist state agencies make effective decisions for the restriping of their thermoplastics. These studies monitored the retroreflectivity of thermoplastic pavement markings over a specific period of time and proposed degradation models that can predict the future R_L of thermoplastic pavement markings based on key variables. Yet, most of these studies did not report the coefficient of determination (R^2) or reported low R^2 (as low as 0.1), which placed little confidence in these models.

2. OBJECTIVE AND SCOPE

The main objective of this study was to develop cost-effective restriping strategies for thermoplastic pavement markings used in hot and humid climate service conditions. To achieve this objective, the following was accomplished:

- Evaluate the field performance of thermoplastic pavement markings in hot and humid climate service conditions.
- Develop prediction models that could predict the service life of thermoplastic pavement markings based on key project conditions.
- Propose new cost-effective restriping strategies (based on key project conditions) for thermoplastic markings used in hot and humid climate service conditions.

To accomplish these tasks, data from the National Transportation Product Evaluation Program (NTPEP) were mined and analyzed. The findings from this study will provide scientific basis to assist state agencies in hot and humid climates make effective decisions for the restriping of their thermoplastic markings mitigating the drawbacks associated with conventional restriping strategies.

3. BACKGROUND

3.1 State of Practice in Louisiana

In Louisiana, thermoplastic pavement markings are applied on new and existing asphalt concrete (AC) and Portland Cement Concrete (PCC) roads. On new PCC, curing compound should be removed and a two-part epoxy sealer installed prior to the installation of new markings. While 40-mil thermoplastics are only used (sprayed) in Louisiana in some chip seal applications, 90-mil thermoplastics are typically used (extruded) in new and existing roads. Typically, type 4 glass beads are used for the first drop and type 1 glass beads are used for the second drop. After application, one initial R_L measurement is taken within 30 days after installation for acceptance. To be accepted, the measured initial R_L should exceed 375 and 250 mcd/m^2/lux for white and yellow markings, respectively. Throughout the pavement marking service life, the R_L is not monitored. Instead, visual inspection is conducted regularly to determine failed thermoplastics and make restriping decisions.

3.2 Overview of the NTPEP Program

Each year, the American Association of State Highway and Transportation Officials (AASHTO) conducts field and laboratory tests to assess the performance of pavement marking materials (including thermoplastic pavement markings) through the National Transportation Product Evaluation Program (NTPEP). In the NTPEP, test decks (sections of highways in Florida, Minnesota, Wisconsin and Pennsylvania) are utilized to test marking materials from vendors in the field. The tested products are placed on asphalt and concrete pavements according to the NTPEP's work plan *(14)*. For each tested product, four transverse lines (4-inch wide) are applied running from the right edge line to the skip line area. For each line, field R_L measurements are conducted monthly in the first year and quarterly in the second and third years. These measurements are collected in both the skip-line area (defined in the work plan as the first nine inches from the skip-line) and the left wheel path area using LTL 2000 retroreflectometers.

3.3 Empirical Degradation Models for Thermoplastic Pavement Markings

As early as 1997, Andrady et al. *(6)* proposed a degradation logarithmic model to assess the R_L of thermoplastic pavement markings based on the initial R_L as follows:

$$T_{100} = 10^{\frac{(R_0 - 100)}{b}} \quad (1)$$

where,

T_{100} = time (months) for R_L to reach 100 mcd/m^2/lux;

R_0= estimate of the initial R_L (mcd/m^2/lux); and

b = gradient of the semi-logarithmic plot of R_L.

The major limitation of this model was the fact that the R^2 required to assess the accuracy of the model was not reported. Later in 1999, Lee et al. *(7)* evaluated the field performance of thermoplastic pavement markings in Michigan and developed the following linear regression model:

R_L (mcd/m^2/lux) = [-0.3622× age of marking in days] + 254.82 (2)

This research study reported a very low R^2 of 0.14 as well as large variances in the service life of the thermoplastic pavement markings providing little confidence in the developed model. In 2008, Hollingsworth *(8)* studied the rate of R_L degradation of thermoplastic pavement markings in North Carolina. In this study, a linear regression model with R^2 of 0.53 was developed to predict the pavement marking R_L based on the Annual Average Daily Traffic (AADT), bead type, line color, initial R_L, lateral line placement, and time as follows:

$$\text{Ln}(R_L) = 5.5002 - 0.000002 \times \text{AADT} - 0.1861 \times \text{Bead}_{DV} - 0.2975 \times \text{Color}_{DV} + 0.0008 \times \text{Initial } R_L + 0.1528 \times \text{LP}_{DV} - 0.0039 \times T \quad (3)$$

where,

Bead_{DV} = Bead Type [1=large; 0 = standard];

Color_{DV} = Marking color [1 = yellow; 0 = white];

LP_{DV} = Lateral line location [1 = edge line; 0 = center line]; and

T = Number of months since installation.

Similarly, in 2008, Sitzabee et al. *(9)* proposed a linear degradation model for thermoplastic pavement markings on asphalt roads in North Carolina. The independent variables for this model were time, initial R_L, AADT, line color, and lateral location. The model had an R^2 of 0.6 and was as follows:

$$R_L = 190+0.39\,R_{Lo}-2.09\,T-0.0011\,\text{AADT}+20.7\,X1 - 20.7\,X2+ 19\,X3-19\,X4 \quad (4)$$

where,

R_{Lo} = initial retroreflectivity;

T = time since installation (months);

X1 = 1 if edge line, 0 otherwise;

X2 = 1 if middle line, 0 otherwise;

X3 = 1 if white line, 0 otherwise; and

X4 = 1 if yellow line, 0 otherwise.

In 2008, Fu and Wilmot *(10)* evaluated the field performance of thermoplastic pavement markings in Louisiana. A total of eight regression models were developed for 40-mil and 90-mil white and yellow pavement markings on asphalt and concrete roads. The R^2 for these eight models ranged between 0.18 and 0.55. The following equation shows the developed model for 40-mil white thermoplastic markings installed on concrete roads (R^2=0.46):

$$\ln (R_L) = 5.8250 - 0.0079 \times T - 0.0559 \times CTP \tag{5}$$

where,

T = Elapsed time (months); and

CTP = cumulative exposure of the marking to vehicle travel since its installation (millions of vehicles).

In 2009, Rasdorf et al. *(11)* studied the performance characteristics of thermoplastic pavement markings in North Carolina and considered time, traffic volume, color and lateral line location as the key variables. Linear regression was employed to model the degradation rates of thermoplastics on asphalt roads with an AADT of 10,000 vehicles per day. Yet, this study did not provide the R^2 of the model, making it difficult to determine the model accuracy. Later in 2012, Sarasua and Bell *(12)* developed predictive models to estimate the rate of degradation of thermoplastic pavement markings on asphalt roads in South Carolina. The developed models were as follows:

White Edge: $D = 54.142-0.0403\ T$ (R^2=0.01) (6)

Yellow Solid: $D = 0.0764\ T$ (R^2=0.05) (7)

Yellow Skip: $D = 0.1123\ T$ (R^2=0.09) (8)

where,

D = difference in R_L over time;

T= time (days).

As shown in the Equations (6) to (8), the developed linear regression models had very low R^2 to be statistically valid. More recently in 2014, Ozelim and Turochy *(13)* modeled the R_L degradation of thermoplastic pavement markings in Alabama utilizing R_L data collected from 15 projects. The independent variables in the developed model were initial R_L, age, and AADT. Although the developed model was not provided in this study, an R^2 of 0.45 was reported for white thermoplastic pavement markings.

3.4 Service Life of Thermoplastic Pavement Markings

The review of the literature showed considerable debate over the service life of thermoplastic pavement markings. As shown in Table 1, the service life of thermoplastic pavements markings throughout the United States exhibited wide variations to range between 0.65 year *(6)* and 18.4 years *(12)*. These wide variations relate to differences in traffic volume, climatic conditions, marking properties, winter maintenance, etc. Additionally, and as indicated in the previous section, shortcomings in modeling the R_L degradation of thermoplastic pavement markings appear to significantly contribute to these wide variations.

Table 1. Summary of the service life of thermoplastic pavement markings in the literature

Author (reference)	**Year**	**Location(s)**	**Service Life (years)**
Andrady *(6)*	1997	Across the US	Between 0.65 and 3.4 years
Migletz et al. *(15)*	2001	19 States in the US	2.1 years for white markings 2.3 years for yellow markings
Thamizharasan et al. *(16)*	2003	SC	5.4 years for white markings 8.6 years for yellow markings
Rasdorf et al. *(11)*	2009	NC	5.4 to 8.5 years
Zhang and Wu *(17)*	2010	MS	Between 2.1 and 3.1 years
Wang *(18)*	2010	MS and PA	Between 2.84 and 6 years for white markings on AC; between 2.01 and 5.38 years for white markings on PCC; between 1.32 and 1.37 years for yellow markings on AC; and between 1.43 and 2.98 for yellow markings on PCC

Sarasua and Bell *(12)*	2012	SC	18.4 years for white edge markings 5.7 years for yellow solid markings 4.6 years for yellow skip markings
Dawyer et al. *(19)*	2013	IL	Between 3.2 and 6.5 years
Chimba et al. *(20)*	2018	TN	4.0 years for white markings 2.4 years for yellow markings

3.5 Advancements Based on Previous Research

Based on the reviewed literature, there is a general agreement that the service life of thermoplastic pavement markings in dependent on several factors including the initial R_L, traffic level, pavement surface type, etc. This study is expected to address several shortcomings in previous studies as follows:

- Numerous studies calculated the service life of thermoplastic pavement markings based on R_L readings measured at limited time intervals. This contributed significantly to the low R^2 reported in the literature for the R_L degradation models. Therefore, in this study, the service life was predicted using at least 21 R_L readings measured at 21 different time intervals over a 3-year monitoring period.
- To the authors' knowledge, all of the degradation models developed in previous studies considered the R_L as the dependent variable. Based on the relatively low R^2 reported in the literature, it seems that it is not possible to predict the R_L of pavement markings with a high level of confidence. This conclusion was also reported by Kopf *(21).* As such, in this study, the developed models predicted the thermoplastic service life (instead of R_L) with relatively high accuracy based on the relevant project conditions.
- None of the previous studies proposed cost-effective restriping strategies based on the expected field performance of thermoplastics. Therefore, in this study, new cost-effective restriping strategies were proposed based on the pavement marking initial R_L (and the resulting expected service life).

4. DATA COLLECTION

The data utilized in this study were mined from the NTPEP's database. Since this study focused on the field performance of thermoplastic pavement markings under hot and humid climate service conditions, data utilized in this study were retrieved from the 2012 and 2015 Florida NTPEP test decks. A total of 184 thermoplastic pavement marking lines were identified from the NTPEP data mine (116 lines were collected from the 2012 test deck and monitored till 2015, and 68 lines were collected from the 2015 test deck and monitored till 2018). For each line, the following data were collected:

- The skip retroreflectivity (R_s) and durability rating (rating from 1 to 10 with 10 being perfect) at 21 different intervals (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 18, 21, 24, 27, 30, 33, and 36 months). It is worth noting that R_S was used in this study since it is *"considered to represent long line retroreflectivity performance" (22)*. This assumption was fairly done in all the previous studies that employed NTPEP data to assess the performance of thermoplastic pavement markings *(17, 18, 23)*.
- Pavement surface type: collected data included marking lines applied on AC (78 lines) and PCC (106 lines) surfaces.
- Marking color: collected data included 86 white lines and 98 yellow lines.
- Marking thickness: collected data had thicknesses ranging between 60 and 180 mils. Out of the total 184 lines, 97 lines (53%) had a thickness of 90 mils, 35 lines (19%) had a thickness of 120 mils, and 52 lines (28%) had a thickness ranging between 60 and 180 mils.
- Average Daily Traffic (ADT): collected data had two ADT levels; 17,333 and 42,764 vehicles per day (vpd). Out of the total 184 lines, 116 lines were subjected to 17,333 vpd, while the remaining 68 lines were subjected to 42,764 vpd.
- Number of glass bead drops: collected data included single drop (for 75 lines) and double drops (for 109 lines).
- Type of glass beads: for a single drop, Type 1 beads were used; for double drops, Types 1 and 3, Types 2 and 3, or Types 1 and 4 were used.

5. ESTIMATE PAVEMENT MARKING SERVICE LIFE

For all the 184 lines in this study, the durability ratings did not show substantial reduction throughout the 3-year monitoring period. Almost all the thermoplastics had at least a durability rating of 8 at the end of the three years. Hence, it was concluded that the service life of thermoplastic pavement markings is controlled by the R_L rather than the durability, which agrees with the results of previous studies *(19).* This emphasizes that restriping thermoplastics based on visual inspection without considering the marking R_L may yield unreliable decisions. As such, throughout the remainder of this study, all service life calculations were based on the pavement marking R_L.

For each of the 184 pavement marking lines collected in this study, the service life (SL) was calculated. In general, the SL is defined as the time for the pavement marking R_L to drop from its initial value (after installation) to a pre-determined threshold *(3)*. In this study, a threshold value of 100 mcd/m^2/lux was employed since this value is considered acceptable by most state agencies. To predict the SL for each of the 184 lines, the R_S degradation curve (R_S versus time in days) was plotted for each line, and the time for R_S to reach 100 mcd/m^2/lux was estimated and reported as the marking line SL. To minimize the error when estimating the SL for each marking line, one of three techniques was employed according to the corresponding data distribution as discussed in the following sections. These techniques were: (i) linear interpolation, (ii) linear regression, and (iii) piece-wise regression.

5.1 Linear Interpolation

This technique was employed for a marking line if the corresponding R_S measurements reached 100 mcd/m^2/lux within the three-year monitoring period. In this case, the SL was calculated using linear interpolation as follows:

$$\mathrm{SL} = \frac{(100 - \mathrm{R_{S1}})(\mathrm{ET_2} - \mathrm{ET_1})}{(\mathrm{R_{S2}} - \mathrm{R_{S\,1}})} + \mathrm{ET_1} \tag{9}$$

where,

$\mathrm{R_{S1}}$= The last R_S measurement greater than 100 mcd/m^2/lux;

R_{S2}= The first R_S measurement less than 100 mcd/m^2/lux;

ET_1= Elapsed time since installation (in days) which correspond to R_{S1}; and

ET_2= Elapsed time since installation (in days) which correspond to R_{S2}.

Out of the total 184 lines analyzed in this study, the SL for 43 lines was estimated using this technique (Equation 9). Figure 1 shows an example for one of these lines. According to Figure 1 and Equation 1, the SL was computed as follows:

- R_{S1} = 192 mcd/m^2/lux
- R_{S2} = 26 mcd/m^2/lux
- ET_1= 799 days
- ET_2= 902 days
- SL = $\frac{(100-192)\times(902-799)}{(26-192)}$ + 799 = 856 days (2.35 years)

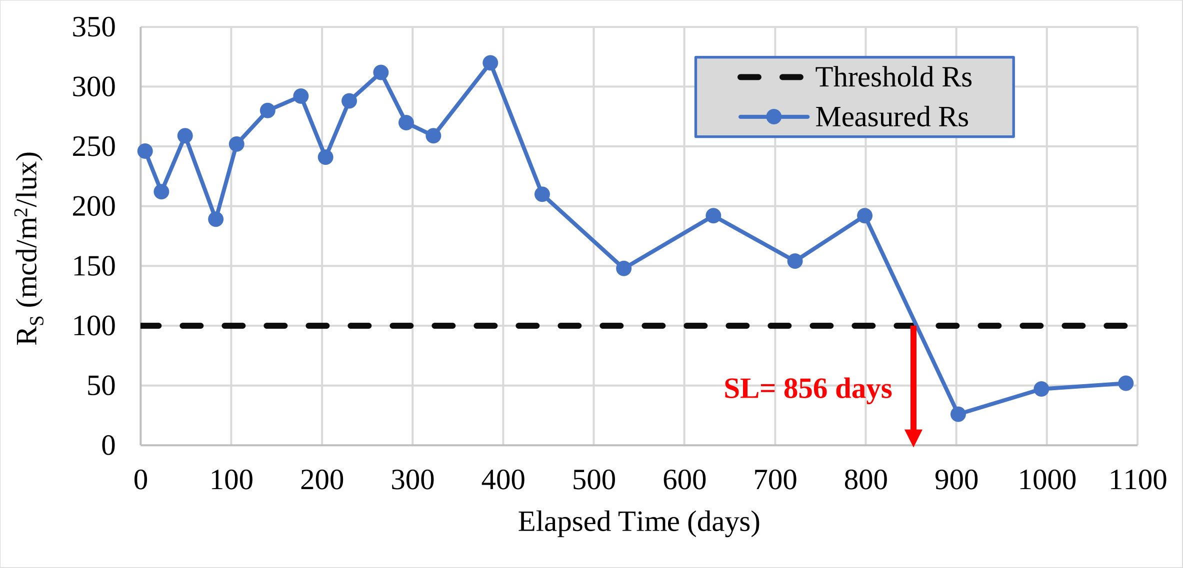


Figure 1. RS versus time for one of the marking lines (line number 35 installed on subdeck number 8 in NTPEP number PMM-2012-01-056)

5.2 Linear Regression

This technique was employed for a marking line if the corresponding R_S measurements fulfilled the following two conditions:

- R_S did not reach 100 mcd/m^2/lux within the three-year monitoring period.
- R_S showed continuous degradation with time without noticeable peaks.

In this case, R_S was fitted to a degradation model using a linear regression equation. This equation was then solved for Y=100 mcd/m^2/lux and the resulting X was reported as the SL. Previous studies indicated that linear regression may be used to fit retroreflectivity data *(3, 9)*. Out of the total 184 lines analyzed in this study, the SL for 80 lines was estimated using this technique. The R^2 for these 80 lines ranged between 0.6 and 0.9 indicating superior accuracy. Figure 2 shows an example for one of these lines.

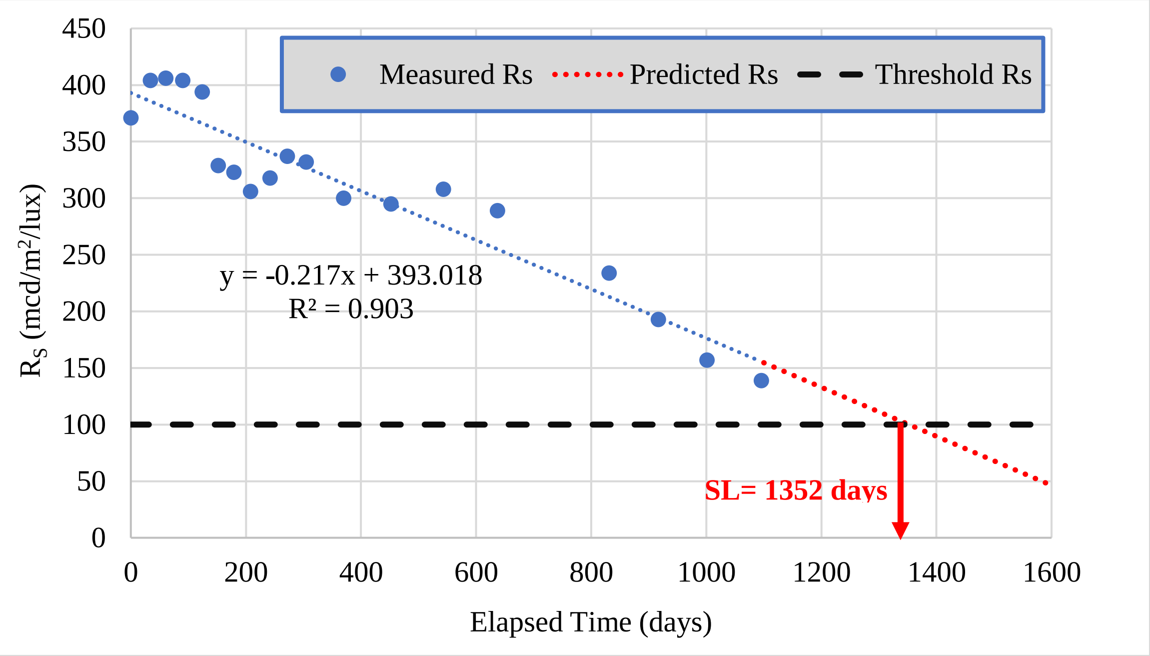


Figure 2. RS versus time for one of the marking lines (line number 35 installed on subdeck number 10 in NTPEP number PMM-2015-01-018)

5.3 Piece-wise Linear Regression

This technique was employed for a marking line if the corresponding R_S measurements fulfilled the following two conditions:

- R_S did not reach 100 mcd/m^2/lux within the three-year monitoring period.
- R_S showed noticeable increase with time. This trend has also been observed in previous studies and generally occurs due to the gradual exposure of beads embedded in the thermoplastic *(18-19)*.

In this case, piece-wise linear regression was employed to estimate the SL of the marking line. It is noteworthy that this technique was successfully employed in a previous study *(23)* to model the retroreflectivity degradation of preformed tape and methyl methacrylate (MMA). In this technique, the dataset was divided into multiple subsets where significant changes in R_S were observed, see Figure 3. Afterwards, a linear regression model was fitted within each subset, and the linear equation of the last subset was solved for Y=100 mcd/m^2/lux to estimate the SL. Out of the total 184 lines analyzed in this study, the SL for 61 lines was estimated using this technique. The R^2 for these 61 lines ranged between 0.6 and 0.98 indicating superior accuracy. Figure 3 shows an example for one of these lines. As shown in Figure 3, the R_S measurements were divided into three subsets and a linear regression model was fitted within each subset, see Equation (10). The R^2 for the three regression models was 0.73.

$$R_S = \begin{cases} 366.94 + 0.10029\mathrm{ET} & \mathrm{ET} < \ 322 \text{ days} \\ 413.7295 - 0.04465\mathrm{ET} & 322 \text{ days} \le \mathrm{ET} \le \ 856 \text{ days} \\ 905.8611 - 0.61957\mathrm{ET} & \mathrm{ET} > \ 856 \text{ days} \end{cases} \qquad (10)$$

Substituting R_s with 100 mcd/m^2/lux in the third segment of Equation 10 yielded a SL of 1,300 days (3.5 years).

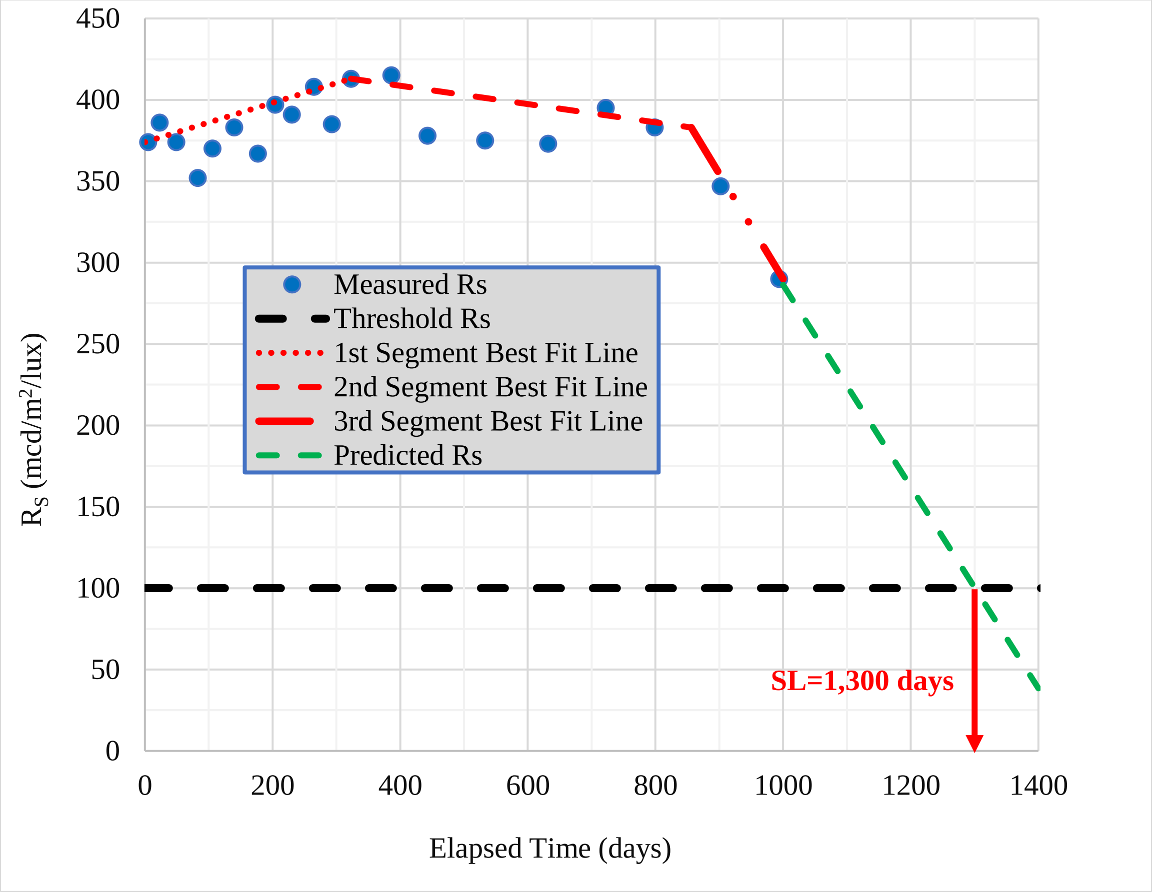


Figure 3. RS versus time for one of the marking lines (line number 24 installed on subdeck number 6 in NTPEP number PMM-2012-01-056)

6. RESULTS AND ANALYSIS

6.1 Service Life of Thermoplastic Pavement Markings

As discussed in the previous sections, the SL of the 184 thermoplastic pavement marking lines was estimated using one of the three aforementioned techniques. Figure 4 presents the SL of these 184 lines plotted against the corresponding initial R_S. Based on Figure 4, the following observations can be made:

- The SL of thermoplastic pavement markings is highly correlated to the initial R_S regardless of the other variables (surface type, ADT, line color etc.). As expected, higher initial R_S yielded higher SL as suggested by previous studies *(9)*.
- For all the 184 lines, the SL ranged between 0.4 and 12.1 years, with an average value of 3.4 years and lower and upper limits of 95% confidence interval (C.I) of 3.2 and 3.6 years, respectively. The upper and lower 95% C.I limits are comparable to the results reported by Zhang and Wu *(17)* who indicated that the SL of thermoplastics in Mississippi (similar climate conditions to Florida) was between 2.1 and 3.1 years. The upper and lower limits are also comparable to Chimba's results in Tennessee *(20)* where the SL ranged between 2.4 and 4.0 years. These values are similar to the industry's expected service life of 3 to 4 years for thermoplastic pavement markings *(19)*.

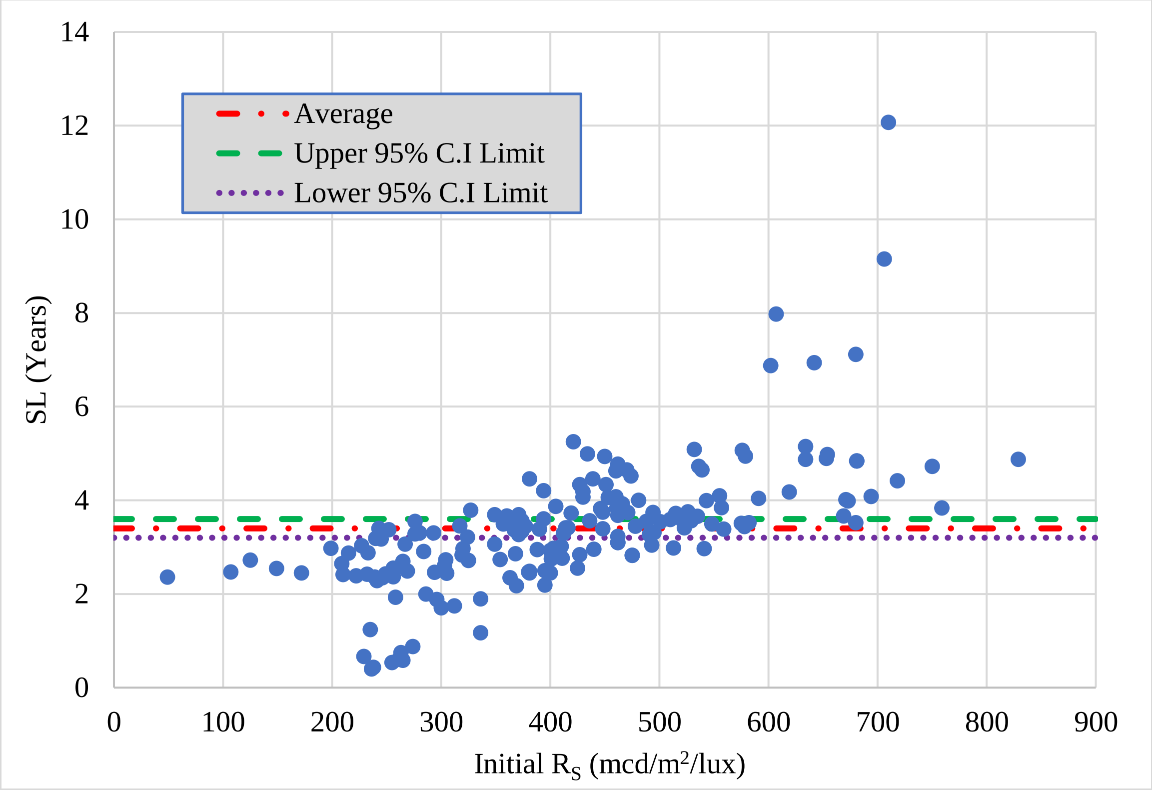


Figure 4. Service life of the 184 thermoplastic pavement marking lines plotted against the initial RS

Since white and yellow lines yield different initial R_S (if all other variables are kept constant), the initial R_S was considered indicative of the line color in this study. Therefore, in this study, the initial R_S, rather than the line color, was considered a key parameter affecting the SL of thermoplastic pavement markings.

To evaluate the effect of road surface type and ADT on the SL of thermoplastic pavement markings, the SL of the 184 lines (presented in Figure 4) were categorized into four groups based on the road surface (AC and PCC) and ADT (medium corresponds to ADT of 17,333 vpd and high corresponds to ADT of 42,764 vpd). The average SL and other descriptive statistics were then computed for each group, see Table 2. Based on Table 2, the following conclusions were drawn:

- Comparing between groups having the same ADT level (group 1 versus group 3 and group 2 versus group 4), the SL (average, upper 95% C.I limit, and lower 95% C.I limit) of marking lines installed on asphalt roads was relatively higher than the SL of lines installed on PCC roads. This could be attributed to the possible de-bonding between thermoplastics and concrete, which is a common problem in states with high moisture/humidity conditions *(24)*.

- Comparing between groups having the same surface type (group 1 versus group 2 and group 3 versus group 4), as expected, the SL (average, upper 95% C.I limit, and lower 95% C.I limit) of marking lines subjected to medium ADT was relatively higher than the SL of lines subjected to high ADT.

Table 2. SL of thermoplastic pavement markings lines based on the road surface type and ADT level

Variable	**Group 1**	**Group 2**	**Group 3**	**Group 4**
Surface Type	AC	AC	PCC	PCC
ADT Level	Medium	High	Medium	High
Count	54	24	62	44
Average SL (Years)	3.71	3.42	3.35	3.08
SL Upper 95% C.I Limit (Years)	4.21	4.01	3.51	3.52
SL Upper 95% C.I Limit (Years)	3.20	2.83	3.19	2.65

When the SL for the 184 lines (presented in Figure 4) was plotted against the marking thickness, no clear trend was observed probably because the 184 lines had different ADT levels and surface types, which seemed to considerably affect the marking SL. Therefore, to exclude these variables from the analysis, out of the total 184 lines, only lines having thickness of 90 and 120 mils were considered (132 lines). The SL of these 132 lines were categorized into eight groups based on the line thickness (90 mils and 120 mils); road surface (AC and PCC); and ADT (medium and high). The average SL was then computed for each group, see Figure 5. As expected, for all the groups, the 120-mil lines lasted longer than the 90-mil lines.

6.2 Model Development

The service lives of the 184 marking lines (presented in Figure 4) were analyzed to develop regression models that could predict the marking SL knowing its initial R_S, ADT class, and surface type. The 184 lines were categorized into four groups based on the ADT and surface type as presented in Table 2. For each group, a regression equation was developed with SL as the dependent variable and the initial R_S as the independent variable. Figures 6 to 9 present the developed models as well as the corresponding R^2. As shown, the developed models predicted the marking SL with relatively high level of accuracy (R^2 between 0.63 and 0.82) as compared to the R^2 values reported in the literature, which generally ranged between 0.1 and 0.6. It is worth noting that the developed models should only be used when the initial R_S is in the range of the values presented in the corresponding figure, i.e., the model in Figure 6 is valid only for R_S between 209 and 710 mcd/m^2/lux.

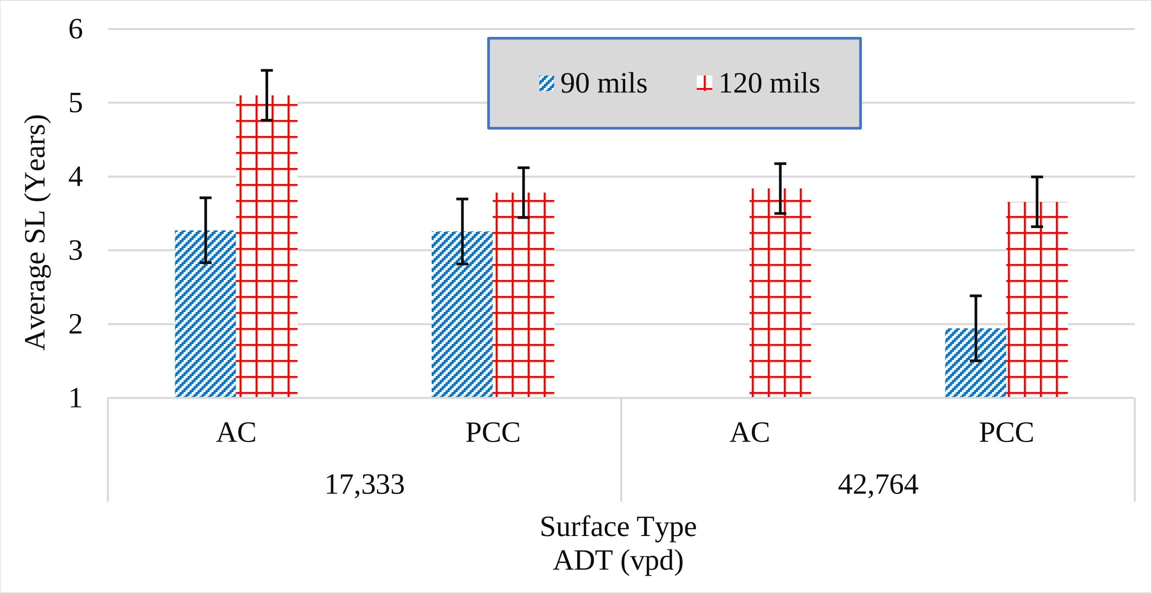


Figure 5. Average SL (and standard error presented by error bars) of the 90- and 120-mil lines categorized by surface type and ADT

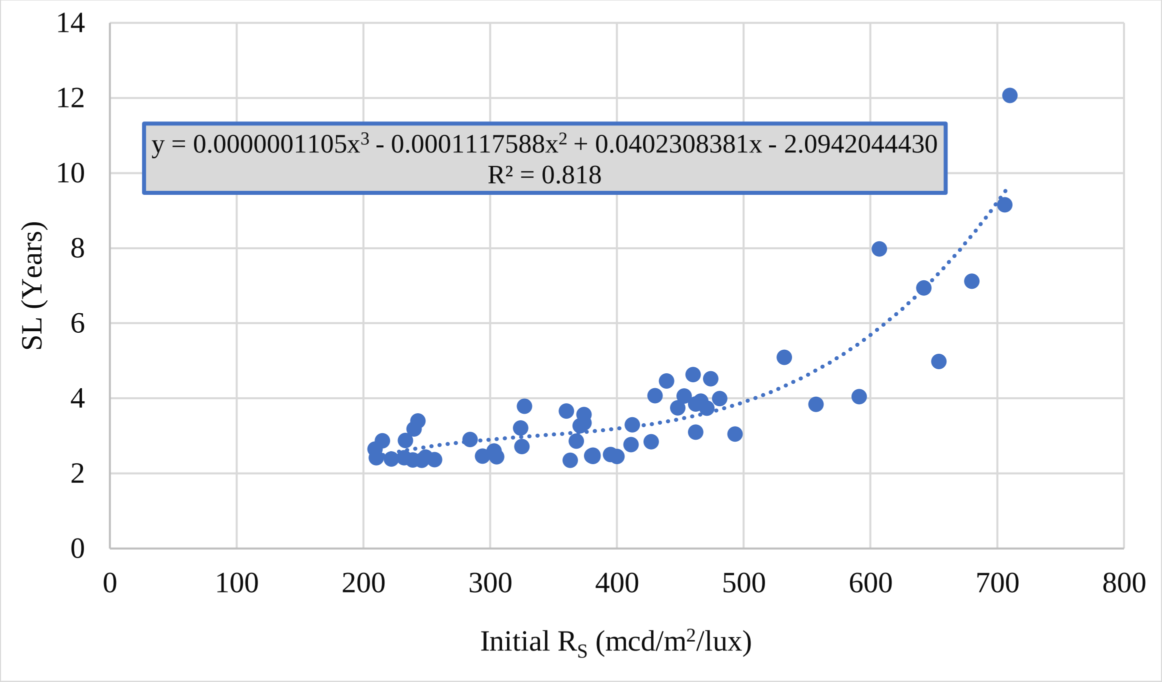


Figure 6. Developed regression model for group 1 (AC surface and medium ADT)

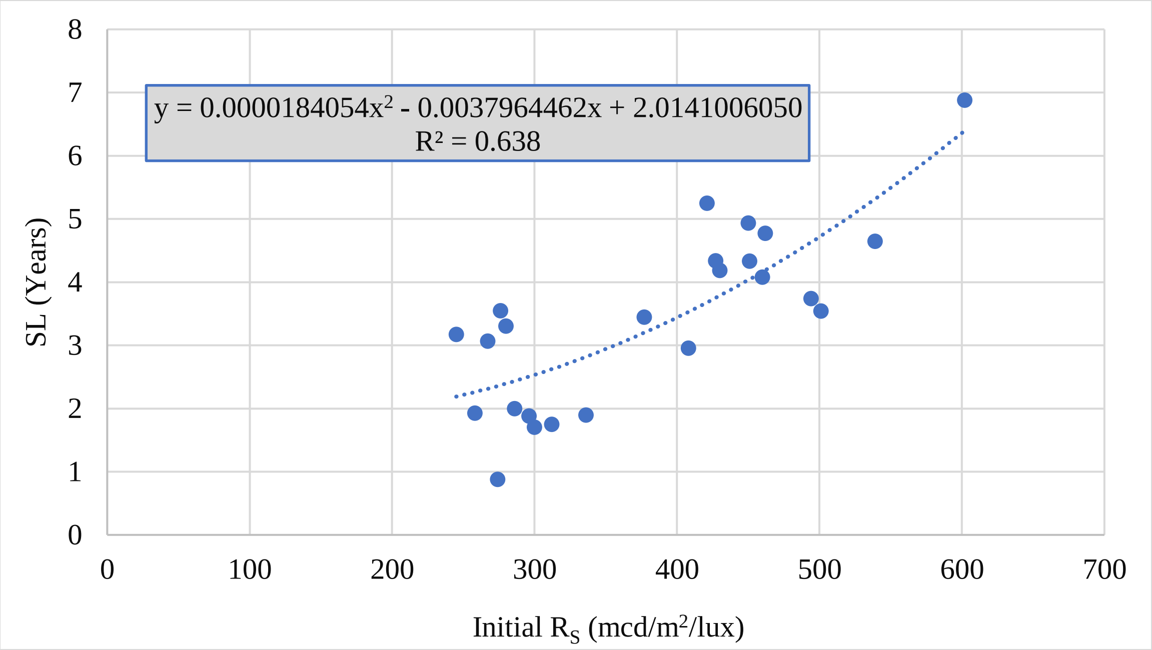


Figure 7. Developed regression model for group 2 (AC surface and high ADT)

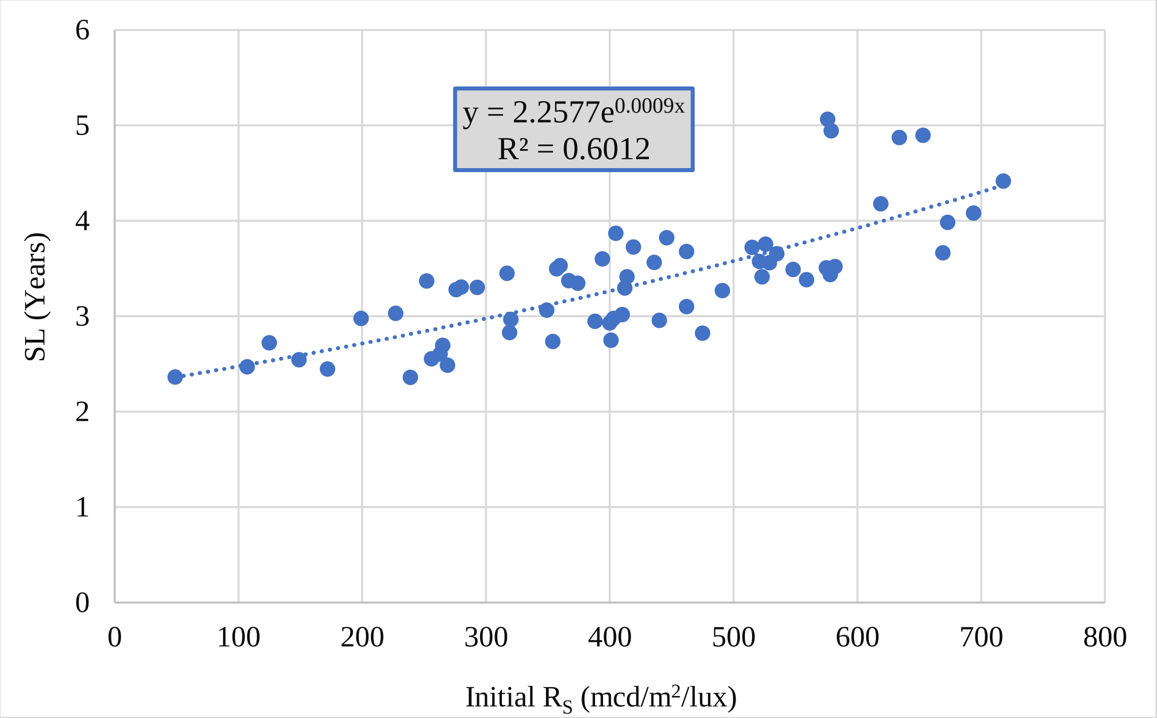


Figure 8. Developed regression model for group 3 (PCC surface and medium ADT)

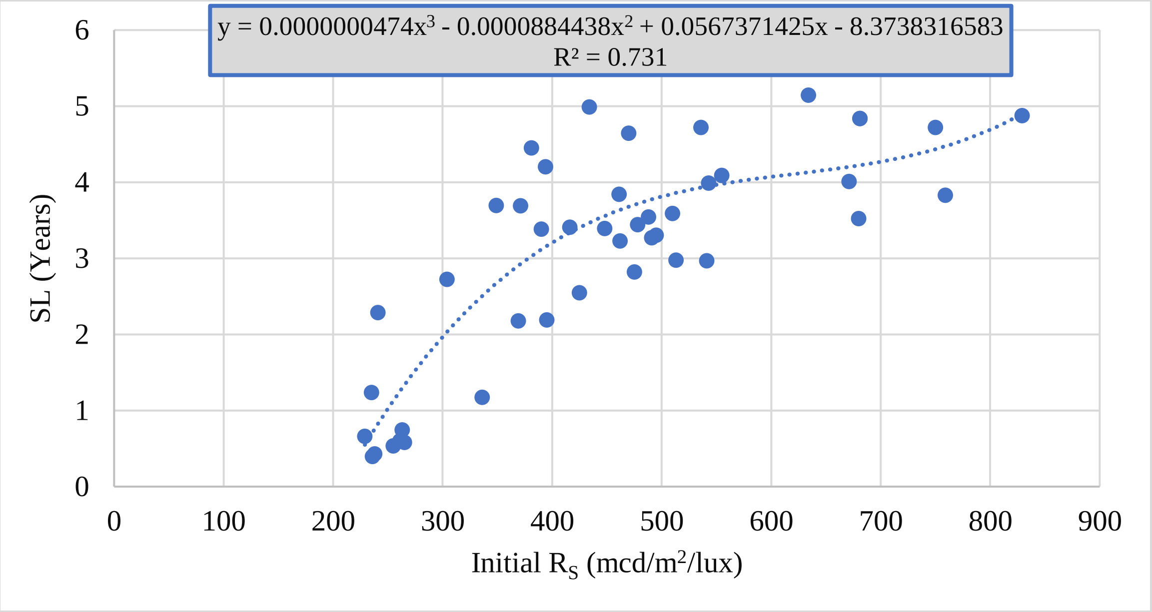


Figure 9. Developed regression model for group 4 (PCC surface and high ADT)

6.3 Illustrative Application of the Developed Models in Restriping Scheduling

After application of thermoplastic pavement markings, state agencies are usually concerned about determining when to restripe the road without jeopardizing the user safety. The proposed models in Figures 6 to 9 are expected to help in this process as shown in the following example.

Example: Determine Restriping Schedule for Thermoplastic Markings Installed on Asphalt Surface and Subjected to Medium Traffic

Given the following variables are known:

- Surface type: asphalt
- Traffic level: medium
- Initial retroreflectivity (measured within the first month after installation)= 460 mcd/m^2/lux

In this case, the SL can be estimated using the Equation shown in Figure 6. That is,

SL= $= 0.0000001105\times(460)^3 - 0.0001117588\times (460)^2 + 0.0402308381\times (460) - 2.0942044430=$ 3.5 years

This indicates that the thermoplastic pavement marking in the example should be restriped after 3.5 years for the retroreflectivity to be maintained above 100 mcd/m^2/lux.

6.4 Life-Cycle Cost Analysis

In this section, a life-cycle cost analysis, in terms on the Net Present Value (NPV), was conducted to compare between three strategies as follows:

- **Strategy 1**: this strategy represents the conventional restriping strategy and is based on the industry's expected service life of 3-4 years for thermoplastics *(19).* As such, this strategy involves restriping using 4-inch-wide thermoplastic markings every four years.
- **Strategy 2:** this strategy involves restriping using 4-inch-wide thermoplastic markings based on the initial R_S, traffic level and surface type and using the equations in Figures 6 to 9 (as discussed in the previous illustrative example).
- **Strategy 3:** this strategy is similar to strategy 2 except that 6-inch-wide thermoplastic markings are used instead of the 4-inch-wide markings. This strategy was considered to address the recent recommendation from the National Committee on Uniform Traffic

Control Devices (NCUTCD) that includes a change to the Manual on Uniform Traffic Control Devices (MUTCD) to use 6-inch-wide pavement markings on all roads with posted speeds of 55 mph and higher, and ADT of 6,000 and higher *(25)*. This recommendation was based on the results of previous studies *(26)* that indicated that wider edge lines are effective in reducing crashes and fatalities.

Recent bid tabulations in Louisiana indicated that the total unit cost of 4-inch-wide thermoplastic pavement markings (90-mils) is about $1.1/lane-feet ($5,808/ lane-mile) including material cost and placement, as of 2021 (base year in this analysis). A 2013 report by Carlson et al. *(27)* reported that state bid prices indicated a 16 to 45% increase for 6-inch pavement markings over 4-inch markings. Therefore, in this study, the cost of the 6-inch markings was assumed as $1.1/lane-feet x 1.45 =$1.56/lane-feet ($8,422/ lane-mile). In this analysis, a 10-year analysis period was assumed. The NPV for strategy 1 was calculated as follows:

- Number of striping cycles within the 10-year analysis period=$\text{quotient }(\frac{10}{4}) + 1 = 3$ cycles
- Remaining service life (at end of analysis period) of the last pavement marking installed= (3 cycles×4 years)-10= 2 years
- NPV (at 2021) of the 3 striping cycles= 5,808×3= $17,424/ lane-mile
- NPV (at 2021) of the salvage value (using the straight-line depreciation method) for the remaining service life of the last installed marking $= -\frac{2\text{ years}}{4\text{ years}} \times 5{,}808 = -\$2{,}904/\text{lane} - \text{mile}$
- Total NPV (at 2021) of strategy 1= $17,424 - $2,904= $14,520/ lane-mile

Similarly, the NPV for strategy 2 was computed for various restriping cycles (instead of the fixed 4-year cycle considered in strategy 1) based on different combinations of initial R_S, ADT level, and surface type and using the corresponding models as discussed in the illustrative example. The NPV of strategy 2 was then subtracted from the NPV of strategy 1 to compute the cost savings, see Figure 10. Similarly, Figure 11 presents the cost savings when adopting strategy 3 as compared to strategy 1. Positive values of cost savings will indicate that strategy 2 (or strategy 3) is more cost-effective than strategy 1. Based on Figures 10 and 11, the following was observed:

- For all the curves in Figure 10 and 11, low values of initial R_S resulted in no cost savings (negative values) when compared to strategy 1, because low values of initial R_S yielded low values of marking SL, hence, increasing the number of required restriping cycles.
- Each curve in Figures 10 and 11 has a specific cut-off value, which is defined in this study as the initial R_S after which positive value of cost savings is expected (point of intersection of the curve with the x-axis). As an example, from Figure10, 4-inch-wide markings installed on AC and subjected to medium ADT has a cut-off value of about 510 mcd/m^2/lux. This suggest that for this category of thermoplastic pavement markings to be cost effective (as compared to strategy 1), the initial R_S should be at least 510 mcd/m^2/lux.
- Cost savings of up to $8,212 per lane-mile and $5,373 per lane-mile could be achieved (as compared to strategy 1) for 4-inch and 6-inch-wide markings, respectively, when applied on AC and subjected to medium ADT.

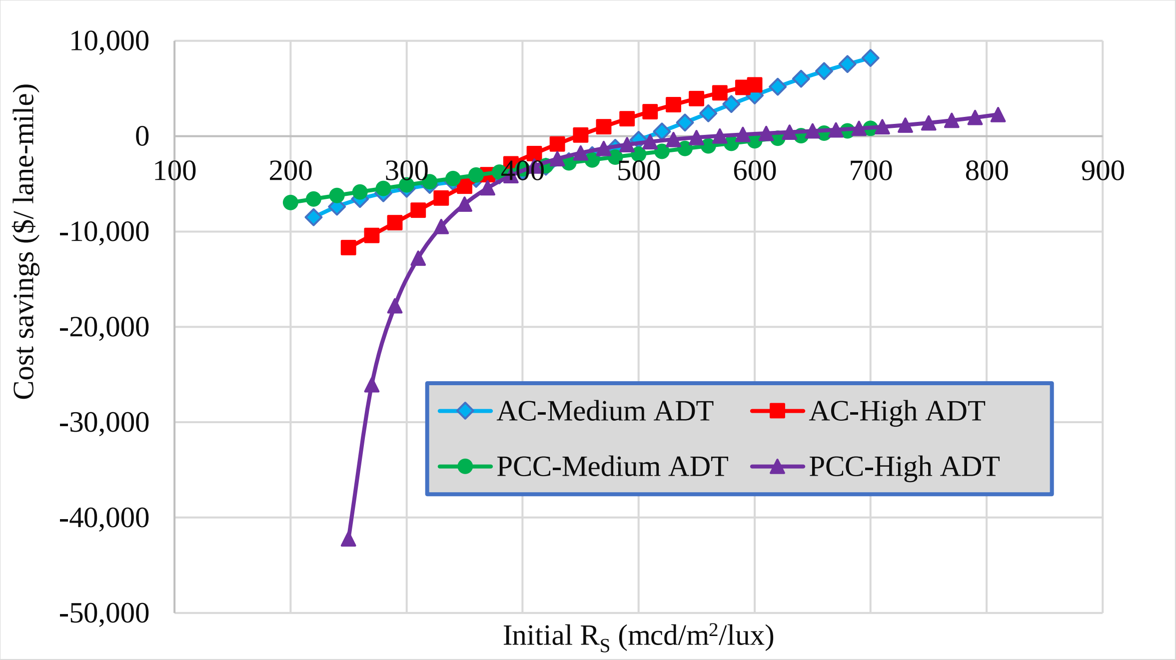


Figure 10. Cost savings when adopting strategy 2 as compared to strategy 1

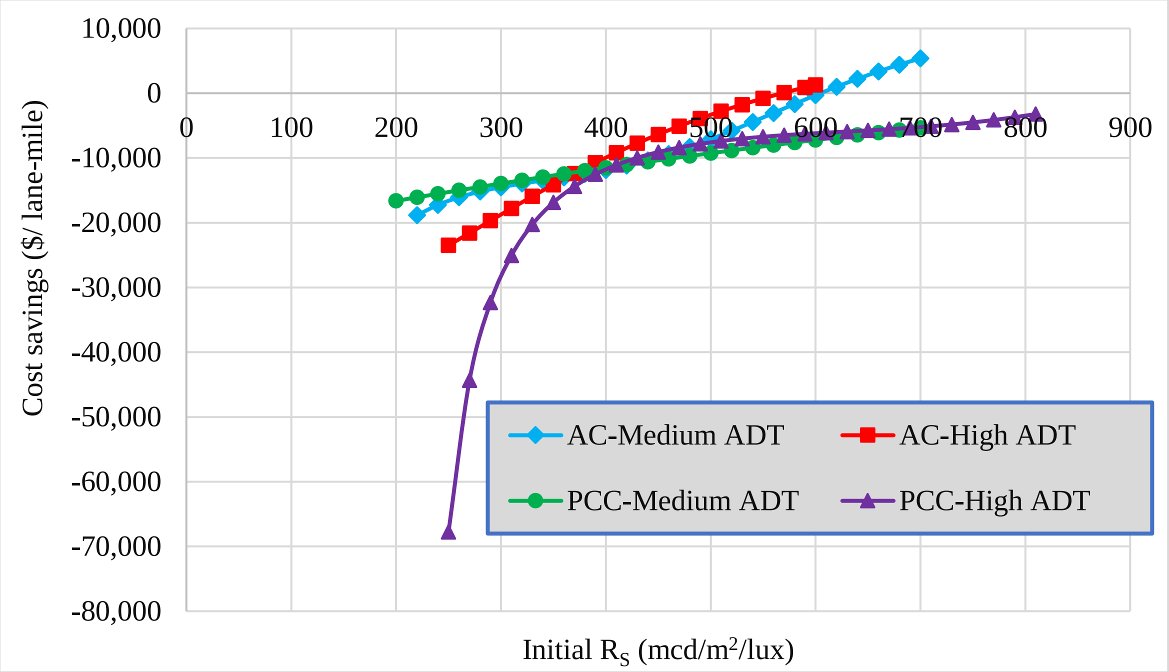


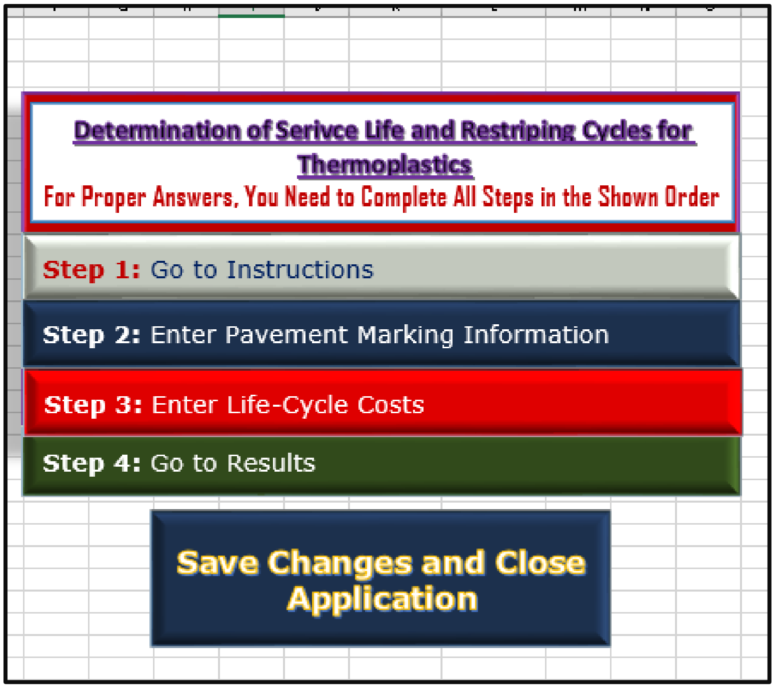
Figure 11. Cost savings when adopting strategy 3 as compared to strategy 1

6.5 Enhanced Decision-Making Tool

The findings of this study were incorporated into an enhanced decision-making tool that can help state agencies (1) determine the SL of their thermoplastics based on the project conditions; (2) select the following restriping year; and (3) determine the expected cost savings ($/lane-mile) if restriping is conducted based on the tool results rather than the conventional restriping strategy. To ensure that the tool is practical and easy to use, it was developed using macros in Microsoft Excel. Once the tool is started, the Master Sheet appears (Figure 12), which controls all the worksheets in this tool. As shown, the Master Sheet consists of four key buttons including four sequential steps that need to be completed in the presented order, and one final button for saving changes and closing the tool.

The first button (Step 1 button) transfers the user from the Master Sheet to a new worksheet, which provides general instructions for using the tool. The second button (Step 2 button) transfers the user from the Master Sheet to a new worksheet to enter the thermoplastic pavement marking characteristics, which include (a) initial retroreflectivity of the marking measured within 30 days after installation; (b) ADT level on the road (medium or high); (c) road surface type (AC or PCC); and (d) conventional restriping period according to the agency’s policy. The third button (Step 3 button) transfers the user from the Master Sheet to a new worksheet to enter the life-cycle parameters, which include (a) base year of the analysis; (b) analysis period; (c) unit cost of 4-inch-wide markings at the base year; and (d) unit cost of 6-inch wide markings at the base year. While most of these inputs could be easily obtained, typical values are provided for each input to aid the user in case of missing information. The fourth button (Step 4 button) transfers the user from the Master Sheet to a new worksheet that presents three outputs as follows:

1. The expected marking SL. The tool utilizes the four equations in Figures 6 to 9 and the provided inputs to compute this output.
2. The following restriping year. The tool utilizes the estimated SL (previous output) and the provided base year to compute this output.
3. The expected cost savings ($/lane-mile) if restriping is conducted in the suggested year (previous output) rather than based on the conventional restriping strategy. The cost savings are presented for the 4-inch and/or 6-inch-wide markings, according to the user's preference.


Determination of Serivce Life and Restriping Cycles for Thermoplastics

For Proper Answers, You Need to Complete All Steps in the Shown Order

Figure 12. Master sheet of the developed tool

6.6 Prediction of Retroreflectivity Degradation

The genetic algorithm was used to develop 12 different models (A to L) that could be used sequentially to predict the retroreflectivity (Rs) of thermoplastics after one month (PRs1), Rs after two months (PRs2), Rs after three months (PRs3), and similarly till PRS12, based on only the initial measured retroreflectivity and the marking/project conditions (color, manufacturer, thickness, bead type, traffic level, and rainfall). Each of these models was trained using 80% of the collected data and was then tested using the remaining 20% of the data. Figure 13 presents the results of the two models (A and L) as an example using the training and testing data. As shown in Figure 13, the genetic algorithm was effective in predicting the retroreflectivity of pavement markings for up to 12 months as supported by the relatively high R^2 values that ranged between 0.9 and 0.6.

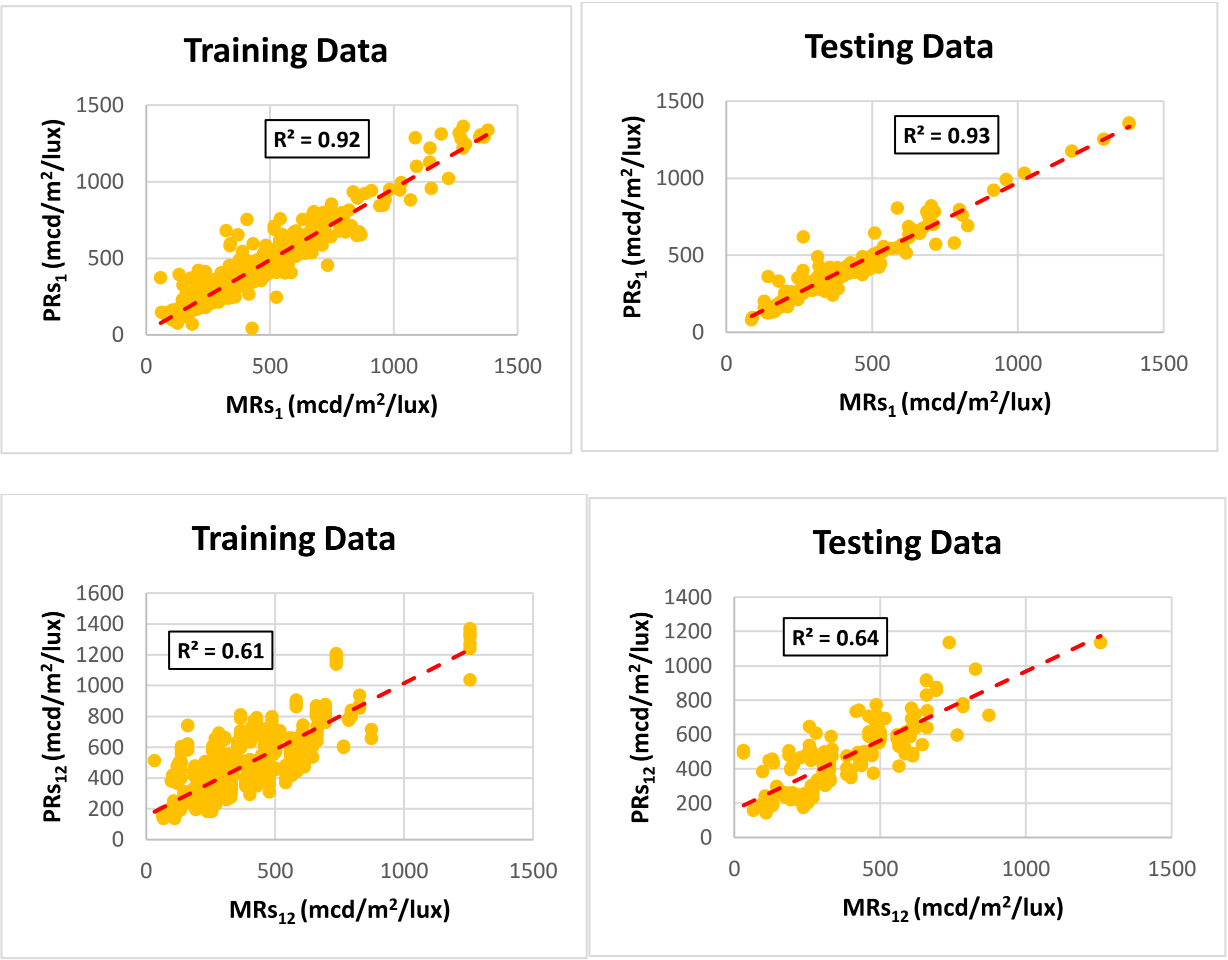


Figure 13. Results of Models A (Top) and L (Bottom) using the Training Data (Left) and Testing Data (Right)

6.7 Field Testing

Field testing was conducted in this study to compare the actual retroreflectivity of pavement markings in the field after 4, 8, and 12 months to the corresponding predicted retroreflectivity using the predictive models developed in the previous section. In the field testing, a thermoplastic pavement marking was applied at Louisiana State University in October 2021. The retroreflectivity of this pavement marking was measured after 0, 4, 8, and 12 months. The measured retroreflectivity at 0 months (after installation) was used along with the project and marking conditions as inputs in the predictive models developed in the previous section to predict the retroreflectivity at 4, 8, and 12 months, as shown in Figure 14. As shown in Figure 14, the predicted and measured values were almost close reflecting the effectiveness of the predictive models developed in the previous section.

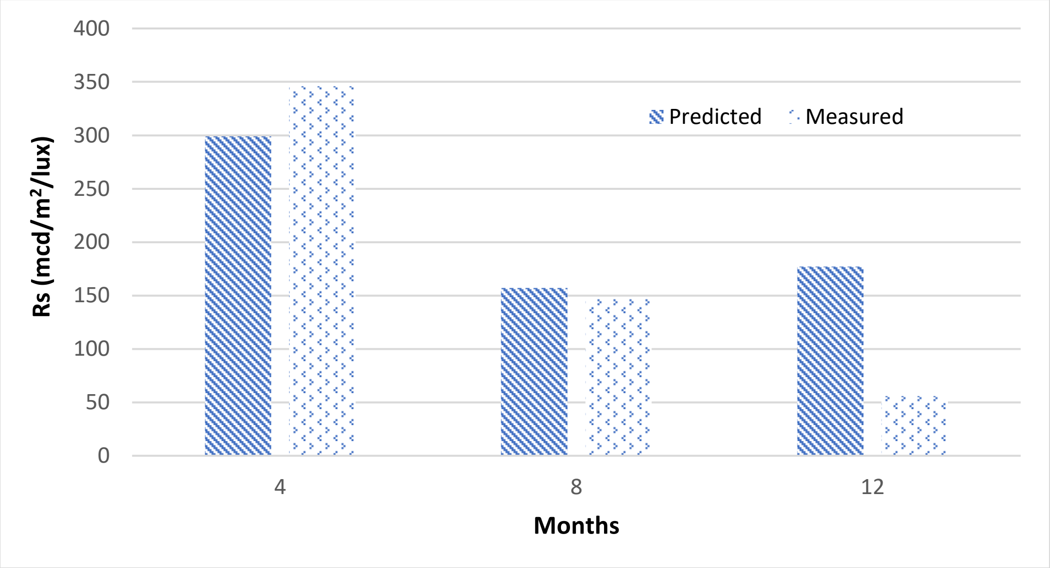


Figure 14. Results of the field testing

7. CONCLUSIONS

The objective of this study was to (1) evaluate and predict the field performance of thermoplastics, and to (2) propose cost-effective restriping strategies (based on the project conditions) for thermoplastic pavement markings used in hot and humid climate service conditions. Based on the analysis, the following key findings were reported:

- For all the 184 thermoplastic pavement marking lines analyzed in this study, the SL ranged between 0.4 and 12.1 years, with an average value and a 95% confidence interval of 3.4 ± 0.2 years.
- The SL of thermoplastic pavement markings is dependent on the initial R_S, surface type, and ADT. Higher SL is achieved with higher initial R_S, lower ADT, and asphalt surface.
- Four regression models with relatively high accuracy (R^2 between 0.62 and 0.82) were developed to predict the SL of thermoplastics based on the initial R_S, surface type, and ADT. These models could be used to make effective decisions related to restriping scheduling.
- Using the proposed models in restriping scheduling can result in considerable cost savings, as compared to the conventional restriping strategy. Cost savings of up to $8,212 per lane-mile and $5,373 per lane-mile could be achieved for 4-inch and 6-inch-wide markings, respectively, when installed on AC and subjected to medium ADT.

The findings of this study were incorporated into an enhanced decision-making tool to assist transportation agencies 1) determine the SL of their thermoplastic pavement markings based on the project conditions; (2) select the following restriping year; and (3) determine the expected cost savings ($/lane-mile) if restriping is conducted based on the tool results rather than the conventional restriping strategy. This will help transportation agencies make effective decisions for the restriping of thermoplastics in hot and wet climate service conditions.

ACKNOWLEDGMENTS

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