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ENHANCED DECISION MAKING FRAMEWORK FOR THE SOUTHERN STATES TO COMPLY WITH THE NEW FEDERAL RETROREFLECTIVITY PAVEMENT RULE

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Sam Houston State University

Momen Mousa

Enhanced Decision-Making Framework for the Southern States to Comply with the New Federal Retroreflectivity Pavement Rule

Momen Mousa- mxm363@shsu.edu (Engineering Technology Department)

ABSTRACT

Retroreflectivity plays a crucial role in pavement markings as it enhances nighttime visibility for drivers. Yet, due to budget constraints, many state U.S agencies including the Texas Department of Transportation (TxDOT) rarely monitor the retroreflectivity of their markings, and instead, restripe their markings based on visual inspection or fixed schedule (every two years). Such a strategy is questionable in terms of safety as markings are usually restriped after the end of their service life. To address this issue, in August 2022, the Federal Highway Administration (FHWA) announced a new final rule that requires state agencies to implement a method within four years for maintaining pavement marking retroreflectivity at or above minimum levels. Hence, the key objective of this study was to develop a simple tool for TxDOT and other Southern state and local agencies to help them comply with the new federal rule. To do so, pavement marking data from the National Transportation Product Evaluation Program (NTPEP) were retrieved and analyzed. Results indicated that the service life of standard water-borne paints varies significantly from 0 to 3.9 years according to the project conditions. Hence, a performance prediction model was developed with superior accuracy to predict the expected service life of standard waterborne paints based on the initial retroreflectivity value, traffic level, and marking color. This model can be used by TxDOT and other southern state agencies to determine the expected restriping time before the retroreflectivity drop below the minimum threshold, and hence, comply with the new federal rule.

INTRODUCTION

Pavement markings play a significant role in the highway system by providing guidance and conveying regulations and warnings to road users (MUTCD 2009). In the U.S., the traffic road marking coatings market size was valued at $5.18 Bn in 2021, and the market is projected to be worth USD 8.23 Bn by 2030 (Market Research Community 2023). In states like Texas, there are more than 78,000 centerline miles of highway for pavement marking (Timothy et al. 2003). The performance of pavement markings is primarily evaluated using nighttime retroreflectivity (R_L) and durability (Dwyer et al. 2013).

The term "Nighttime retroreflectivity" refers to the ability of pavement markings to reflect light back to its source, such as the headlights of vehicles at night. Retroreflective materials used in pavement markings are designed to enhance visibility and improve driver awareness in low-light conditions. These materials contain tiny glass beads or prismatic elements that redirect the incoming light back toward its origin, making the pavement markings appear brighter and more visible to drivers. On the other hand, the term "Durability" refers to the ability of the markings to be present on the pavement and retain their structural integrity throughout the expected lifespan. Typically, the R_L is measured using a device called a hand-held or mobile retroreflectomer, see Figure 1, while the durability is quantified through visual inspection and ranked on a scale of 1 to 10 (with 10 being the highest durability rating), see Figure 2.

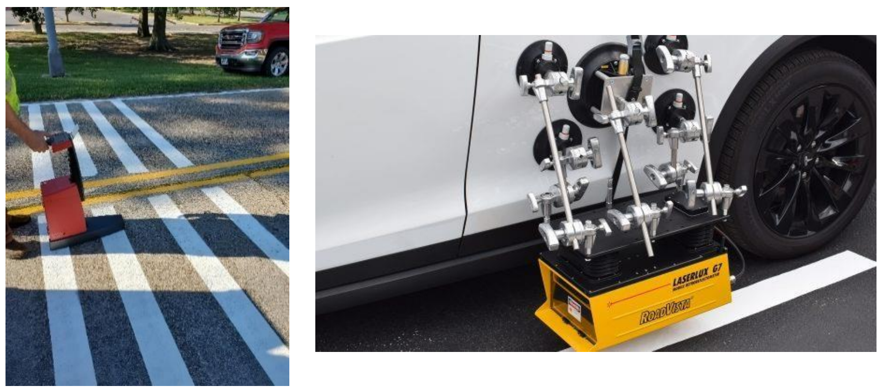

Figure 1. Handheld retroreflectometer (Left) and mobile retroreflectometer (Right)

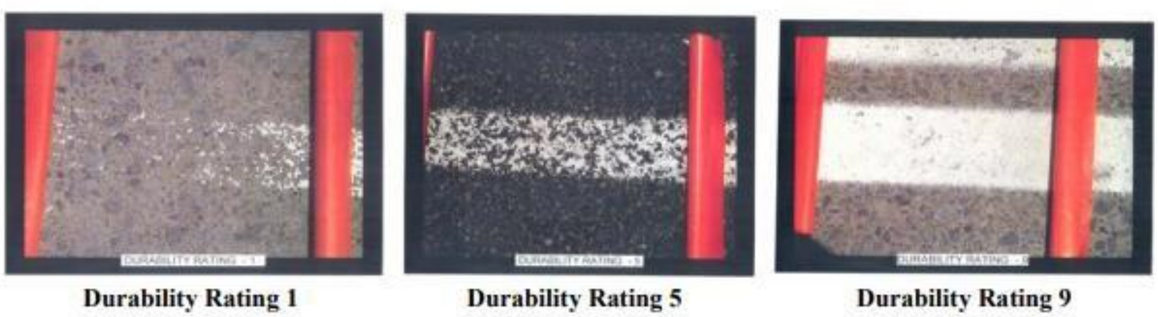

Figure 2. Durability Rating of 1 (Left) and Durability Rating of 9 (Right)

Under the effect of traffic and environment, these metrics (retroreflectivity and durability) deteriorate over time; hence, pavement markings need to be restriped regularly to maintain these metrics. Therefore, it is crucial to monitor the degradation of these metrics (i.e., retroreflectivity and durability) to identify pavement marking failure and subsequently plan for future restriping activities. The durability of pavement markings is easily monitored through visual inspection, while retroreflectivity is more challenging to monitor because it needs equipment (retroreflectometers) for taking field measurements. For this reason, and due to budget constraints, many U.S. agencies do not systematically monitor the retroreflectivity of their markings. Instead, only the initial retroreflectivity is measured within 30 days of marking installation to ensure compliance with specified standards (Wang 2010). After that, the installed markings are replaced based on visual inspection or a fixed schedule rather than continuously monitoring the retroreflectivity and restriping when retroreflectivity falls below a specified threshold. There is a general agreement that these two restriping strategies (fixed schedule or visual inspection) are not optimized as they result in markings that are either restriped before the end of their service life leading to a waste of monetary resources or restriped after the end of their service life resulting in safety hazards for road users at night.

To address the aforementioned issues, in August 2022, the Federal Highway Administration (FHWA) announced a new final rule to ensure that pavement markings are made more visible in dark or low-light conditions (FHWA 2022). Under this rule, the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) provided a new minimum standard for pavement marking retroreflectivity effective September 6, 2022. Table 1 presents these minimum values set by the new federal rule.
The final rule requires state and local agencies or officials to implement a method within four years (before September 6, 2026) for maintaining pavement marking retroreflectivity at or above minimum levels. As such, there is an urgent need to develop a practical decision-making tool that can help the Texas Department of Transportation (TxDOT) and other local agencies in the Southern States comply with this new rule at a minimum cost.

Table 1. Summary of Minimum Values for Pavement Markings Set by the New FHWA Rule

	Sta dard		Guidance
Speed Limit	<35 mph	≥35 mph	≥70 mph
Retroreflectivity Level	n/a	50 mcd/m^2/lux	100 mcd/m^2/lux

There are several pavement marking materials available for commercial use including paint (solvent-based and waterborne paints), thermoplastic, profiled thermoplastic, tape, epoxy, etc. Based on a survey from 51 state departments of transportation (DOTs) and local authorities, waterborne paint is the most common marking material used throughout the United States. It was used by 78% of the responding agencies constituting 58% of striped lane miles (Migletz and Graham 2002). For this reason, this research paper will focus only on waterborne paints.

OBJECTIVE AND SCOPE

The ultimate goal of this paper was to help southern state agencies, including TxDOT, comply with the new FHWA final retroreflectivity rule by providing them with a simple decision-making framework that can determine the restriping time for the retroreflectivity of pavement markings to be above the minimum values set by the new federal rule (Table 1). To accomplish these objectives, data from the National Transportation Product Evaluation Program (NTPEP) were mined and analyzed. The following section provides a brief background about the NTPEP. The analysis conducted in this paper will provide the scientific basis to help TxDOT update its current state of practice in maintaining the retroreflectivity of waterborne paints on district roads and comply with the new federal rule.

BACKGROUND

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 waterborne paints) 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 (NTPEP 1997).

For each tested product, four transverse lines (perpendicular to the direction of traffic) are applied running from the right edge line to the skip line area. For each line, field R_L measurements are taken 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 handheld retroreflectometers. Figure 3 presents an example of white and yellow waterborne paints applied in Florida after installation (left) and three years after installation (right).

Figure 3. White and yellow paints after installation (left) and after 36 months (right) for one of the waterborne paints applied in Florida

DATA COLLECTION

Since Texas and Florida have similar climatic conditions, data in this paper were retrieved from the 2012 and 2015 Florida NTPEP test decks. The measured R_L values, durability ratings, and inspection date were retrieved for a total of 184 waterborne paint lines (112 lines were collected from the 2012 test deck and monitored till 2015, and 72 lines were collected from the 2015 test deck and monitored till 2018). These lines included 46 products, 7 manufacturers (A to G), 2 paint colors (white and yellow), 1 surface type (asphalt), and 2 paint types (standard paints with 15 mils thickness and high-build paints with 25 mils thickness). Out of the total 184 paint lines, 128 lines were standard paints, while the remaining 56 lines were high-build paints.

To determine whether the waterborne paints applied in Florida test decks could represent the waterborne paints applied in district roads in Texas, a district survey was conducted in Texas. Table 2 presents the actual conditions in Texas district roads based on these surveys in comparison to the conditions in Florida test decks. As shown, the difference is due to differences in:

1. Marking orientation: Pavement markings are installed on test decks in the transverse direction (perpendicular to traffic) as shown in Figure 3. In real life, pavement markings are installed in the longitudinal direction. The difference in the orientation of marking significantly affects the retroreflectivity values. As such, in this paper, the transverse retroreflectivity collected from the NTPEP was converted to equivalent longitudinal retroreflectivity using prediction models developed in a previous study in Texas (Zhang et al. 2011). 2. Average Daily Traffic (ADT)
3. Bead type.

The differences in ADT and bead type were addressed at the end of the analysis.

Table 2. Comparison of variables in Florida test decks and district roads in Texas

Variable	Florida Test Decks	Texas District Roads	Similarity
Marking Orientation	Transverse	Longitudinal	Not Similar
Manufacturer	A, B, C, D, E, F, G	C	Representative
Paint Thickness	Standard (15 mils) and High Build (20-25 mils)	High Build (20- 25 mils)	Representative
Paint Width	4 inch	4 inch	Representative
Paint Color	White and yellow	White and yellow	Representative
Number of drops	Single (for all standard paints and some high build paints) and double (for the rest of the high build paints)	Single	Representative
Bead type	Single drop: type 1 beads Double drop: types 1 and 3 or types 1 and 4	Type 3 beads	Not Similar
Average Daily Traffic (ADT)	42,764 vehicles per day (vpd) and 17,333 vpd	Variable. In the range of 500 to 50,000 vpd	Not Similar
Average relative Humidity	74.5%	74.0%	Representative
Average temperature	72 °F	67 °F	Representative
Inches of rain per year	52 inches	61 inches	Representative

DATA ANALYSIS

After the transverse retroreflectivity measurements and durability ratings were retrieved for all the 184 waterborne paint lines from the NTPEP, the durability ratings were analyzed. For all the paint lines in this paper, the durability ratings did not show a significant reduction throughout the 3-year monitoring period. Almost all the paints had at least a durability rating of 8 at the end of the three years. Hence, it was concluded that the service life of waterborne paints is controlled by retroreflectivity rather than durability, which agrees with the results of previous studies (Dwyer et al. 2013). Therefore, throughout the remainder of this paper, all service life calculations were based on retroreflectivity, rather than durability.

First, the transverse retroreflectivity of each paint line (as collected from the NTPEP database) was plotted versus time. Figure 4 shows an example of the transverse retroreflectivity (blue dots) for one standard paint line (with a thickness of 15 mils). Second, the transverse retroreflectivity was converted to equivalent longitudinal retroreflectivity using prediction models developed in a previous study (Zhang et al. 2011) in Texas (red dotted line in Figure 4). Third, this degradation curve (red dotted line in Figure 4) was used to determine the service life of the paint line as the time for the R_L to drop from its initial value to 100 mcd/m^2/lux. This threshold value was selected because it is the minimum value set by the FHWA for roads with a speed limit greater than or equal to 70 mph, see Table 1. In Figure 4, the paint line service life (time for the R_L to drop to 100 mcd/m^2/lux) was about 506 days which is equivalent to 1.39 years. These steps were repeated for the other standard paint lines (with 15 mils thickness) and high-build paints (with 25 mils thickness) and their corresponding service lives were determined. These results are presented in the following sections.

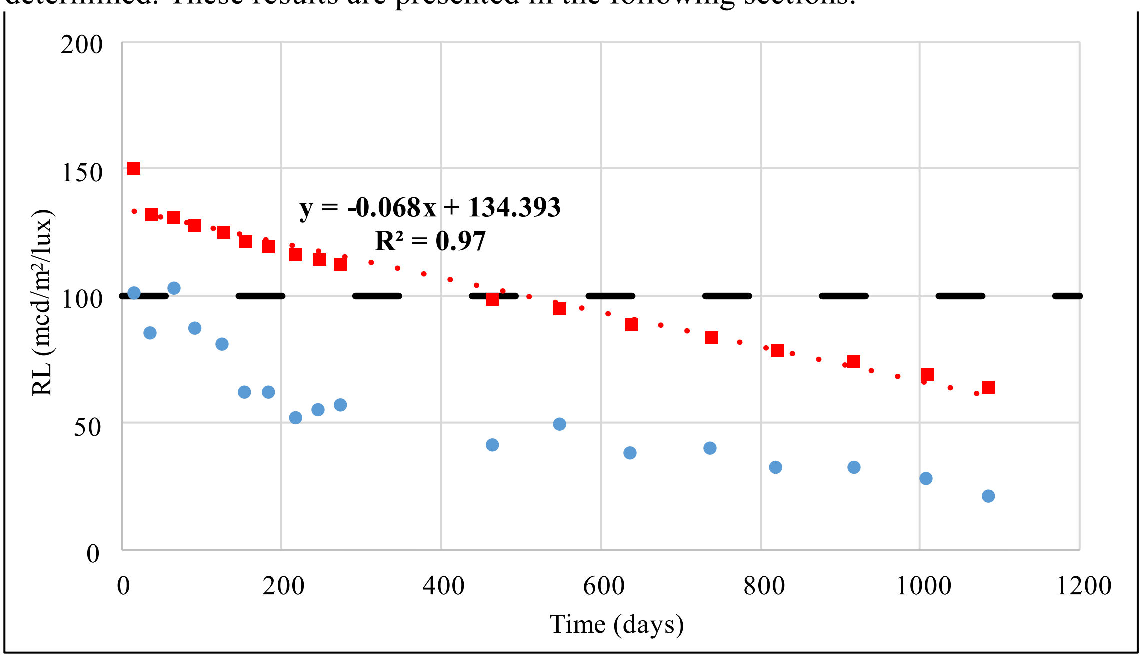

Figure 4. Degradation curve for a standard paint line (15 mils thickness)

Service Life of Standard Waterborne Paints

For all the standard waterborne paint lines (128 lines out of the total 184 lines in this paper), the service life was calculated as discussed in Figure 4 and the results are presented in Figure 5. Since the service life in Figure 5 showed high variability, the values were grouped by manufacturer, line color, and ADT; the average service life was then computed for each group, see Table 3. As shown in this table, the average service life ranged from zero to 3.95 years. A service life of zero was predicted when the initial R_L was less than the threshold value.

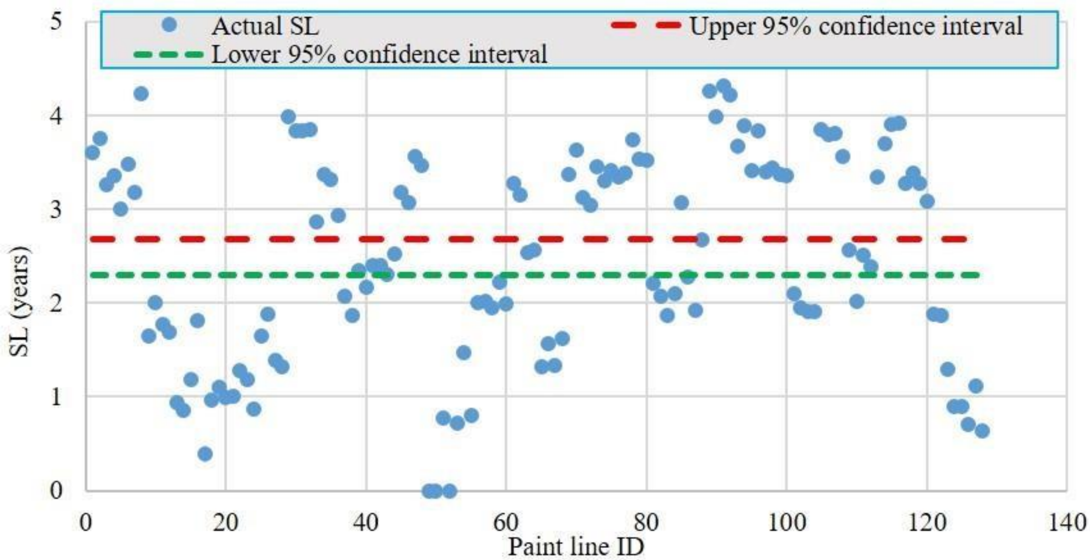

Figure 5. The service life of standard waterborne paints

Table 3. The service life of standard waterborne paints categorized by manufacturer, paint color, and ADT

Descriptive Statistics	Manufacturer	Color= White		Color= Yellow	
		ADT= 17,333	ADT= 42,764	ADT= 17,333	ADT= 42,764
Average (years)	A	1.49	-	0.84	-
	B	3.46	-	-	-
	C	3.95	2.96	2.27	1.30
	D	1.25	-	0	
	E	-	3.47	-	3.49
	F	3.08	-	1.75	-
	G	3.62	-	2.53	-
Standard Deviation (years)	A	0.47	-	0.21	-
	B	0.14	-	-	-
	C	0.31	0.67	0.41	0.42
	D	0.60	-	0.88	
	E	-	0.54	-	0.22
	F	0.38	-	0.34	-
	G	0.23	-	0.58	-
Number of points	A	4	-	4	-
	B	8	-	-	-
	C	8	20	8	20
	D	4	-	4	-

	E	-	4	-	4
	F	8	-	8	-
	G	12	-	12	-

To assess whether the line color and ADT significantly affect the standard waterborne paint service life, three statistical t-tests were conducted as shown in Table 4. T-test 1 was conducted between the service life of all the lines (for all the manufacturers) having ADT of 17,333 vpd categorized by the line color. T-test 2 was conducted between the service life of all white lines for manufacturer C categorized by ADT. T-test 3 was similar to test 2 but it was conducted for the yellow lines. Based on the P-values in Table 4, and as expected, it was concluded that the line color and ADT significantly affect the performance and service life of standard waterborne paints. Therefore, the line color and ADT were considered in the developed regression model in the following sections.

Table 4. Results of t-tests

T-test 1			T-test 2			T-test 3		
ADT	17,333 vpd		Color	White		color	Yellow	
Manufacturers	all		Manufacturer	C		Manufacturer	C	
Color	White	Yellow	ADT	17,333	42,764	ADT	17,333	42,764
Mean (years)	3.1	1.8	Mean (years)	3.9	2.9	Mean (years)	2.3	1.3
Variance (years)	0.88	1.04	Variance (years)	0.09	0.45	Variance (years)	0.16	0.17
Observations	44	36	Observations	8	20	Observations	8	20
P-value	6E-08		P-value	2E-05		P-value	8E-05	

Field Performance of High-Build Waterborne Paints

For most of the high-build waterborne paint lines (56 lines out of the total 184 lines in this study), the retroreflectivity degradation curves did not show consistent degradation with time, see the example in Figure 6. Hence, it was not possible to predict the paint service life with reasonable accuracy. Instead, the research team analyzed the retroreflectivity values at the end of the 3-year monitoring period (R_3) for all the highbuild paint lines (categorized by line color and beads including type and single versus double drop), see Figure 7. As shown, R_3 for almost all the high-build paint lines did not reach the threshold value (100 mcd/m^2/lux) after 3 years. Therefore, it was concluded that the service life of high-build waterborne paints is at least 3 years.

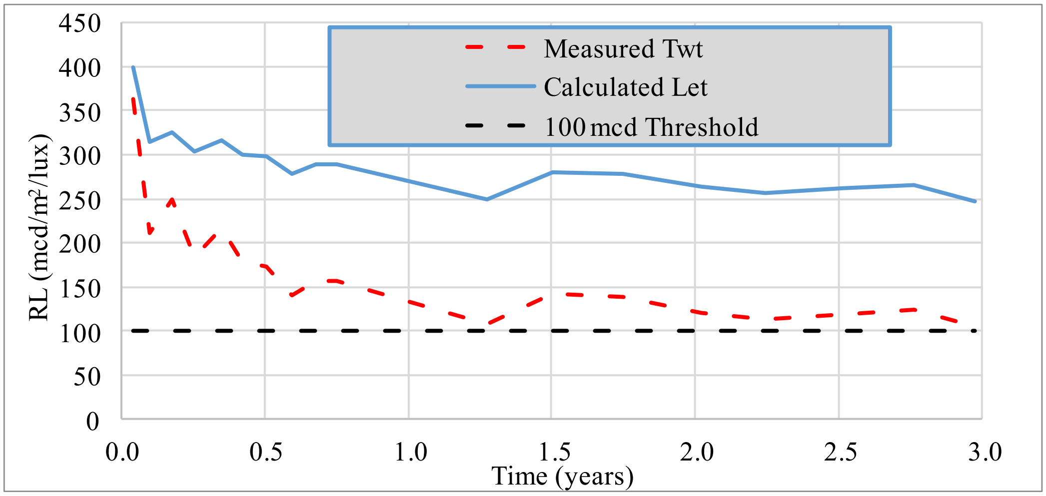

Figure 6 Retroreflectivity versus time for one of the white high-build paint lines (NTPEP number PMM-2015-02-025, sub-deck 4, line 61)

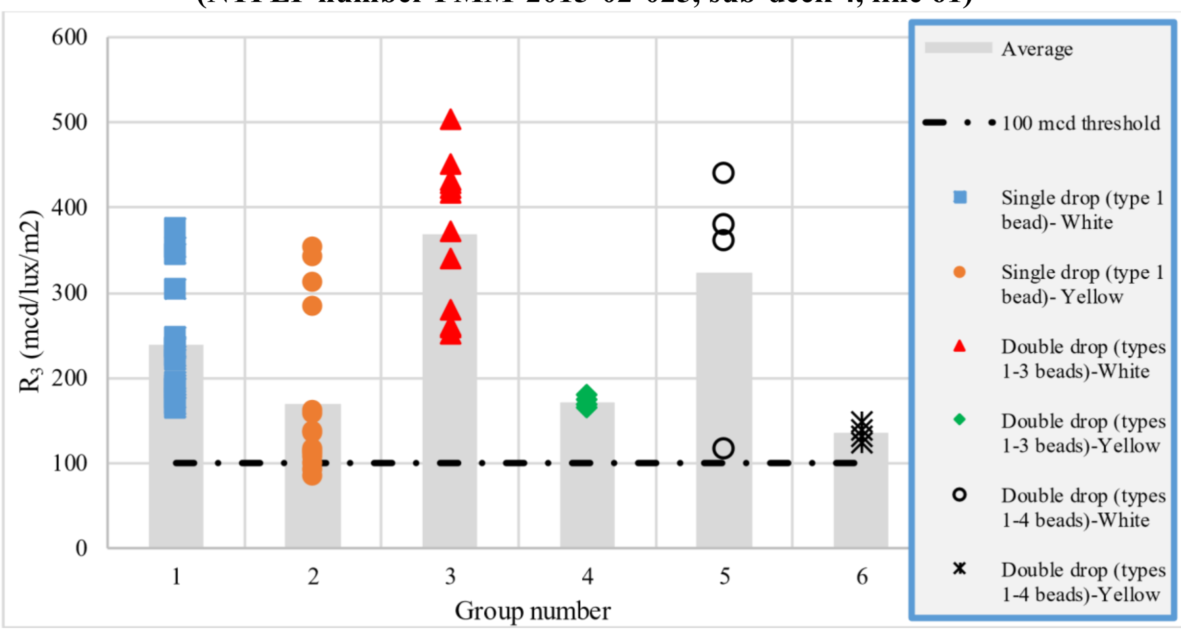

Figure 7 R_3 for all high-build paint lines at the end of the 3-year monitoring period

Model Development for the Standard Waterborne Paints

The service life of the standard waterborne paint lines was analyzed to develop a model that could predict the service life based on the paint color, ADT, and initial R_L (R_{Lo}). A total of 128 lines (or data points) were used in the model development. About 80% of the data (103 points) were used to fit the model and 20% of the data (25 points) were used to validate and test the model. The fitted model developed after performing non-linear regression analyses on the paint service life as a dependent variable, and with R_{Lo}, ADT, and line color as the independent variables, was as follows:

$$SL = 0.0355\ R_{Lo} - 0.0000433 R_{Lo}^2 - 1.75A + 0.3A^2 + 0.14B + 0.13B^2 - 0.9 \qquad (1)$$

where,

SL= Standard waterborne paint service life in years;
R_{Lo} = Initial retroreflectivity of longitudinal marking line.
A = factor representing the ADT. A numerical value of 2 is used if the ADT is 17,333 vpd, while a value of 3 is used if the ADT is 42,764 vpd;
B= factor representing the paint color (0 and 1 are used for white and yellow paints, respectively).

Figure 8 presents the actual and predicted SL using the fitting data. As shown, the proposed model predicted the SL with a superior level of accuracy as supported by a coefficient of Determination (R^2) of 0.95 and root mean square error (RMSE) of 0.24 years (about 87 days). It should be noted that the developed model is only valid for ADT in the range of 17,333 and 42,764 vpd.

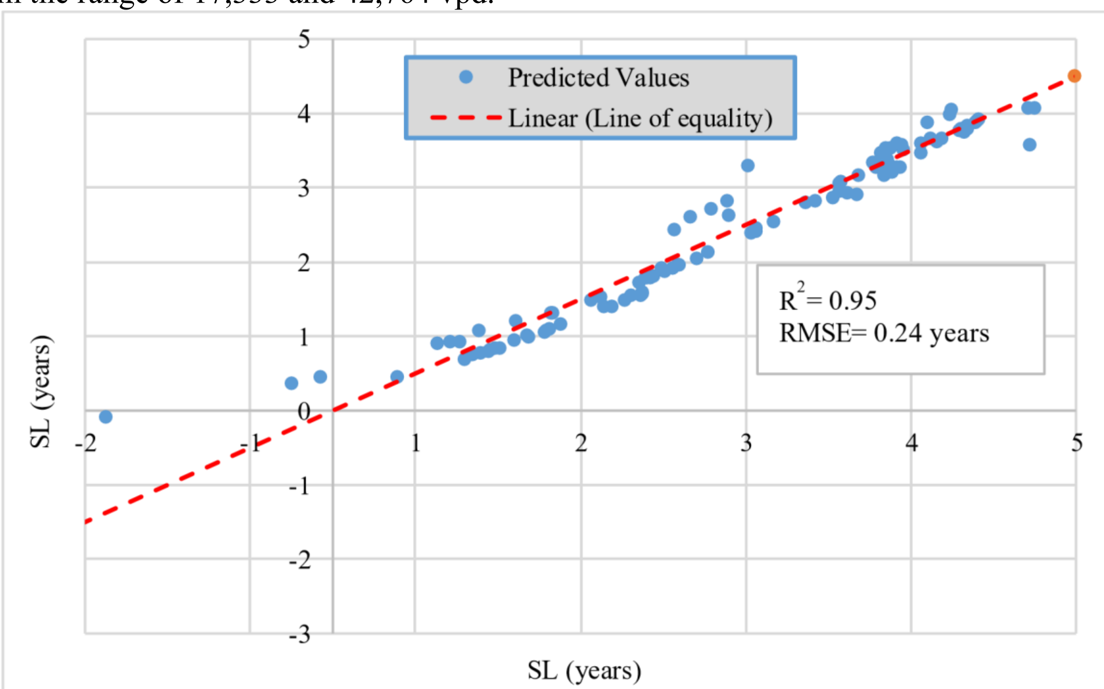

Figure 8 Predicted SL versus actual SL using fitting data Illustrative Application of the Predictive Model

The developed model can be used as a decision-making tool, that a southern state agency can use to determine when to restripe the road. The proposed model is expected to assist in the decision-making process as follows:

1. Once a standard waterborne paint is applied with Type 1 beads, the agency will measure the initial R_L of the edge line within 30 days and report this value as R_{Lo}.

2. Based on the expected ADT on this road and paint color, the agency will use Equation (1) to predict the paint SL.

Table 5 presents the application of the developed model (Equation 1) in estimating SL using the validation data. It is noted that these data points were not used in the model development, and thus would reflect the model accuracy. As shown, the model was efficient in predicting the paint SL with a RMSE of only 0.24 years.

Table 5. Illustrative application of the proposed model using the validation data

ID	R_{Lo} (mcd/m²/lux)	ADT (vpd)	Color	A	B	Actual SL (years)	Predicted SL (years)	RMSE (Years)
1	127	17,333	White	2	0	0.71	0.61	0.24
2	151	17,333	White	2	0	1.47	1.17	
3	173	17,333	White	2	0	2.00	1.65	
4	284	17,333	White	2	0	3.27	3.39	
5	268	17,333	White	2	0	3.15	3.20	
6	339	17,333	White	2	0	3.53	3.86	
7	348	17,333	White	2	0	3.52	3.91	
8	358	17,333	White	2	0	3.98	3.96	
9	431	17,333	White	2	0	4.31	4.06	
10	175	17,333	Yellow	2	1	2.02	1.96	
11	172	17,333	Yellow	2	1	1.95	1.90	
12	184	17,333	Yellow	2	1	2.22	2.14	
13	199	17,333	Yellow	2	1	2.51	2.42	
14	192	17,333	Yellow	2	1	2.38	2.29	
15	255	17,333	Yellow	2	1	3.27	3.31	
16	267	17,333	Yellow	2	1	3.38	3.46	
17	239	42,764	White	3	0	3.00	2.56	
18	300	42,764	White	3	0	3.48	3.30	
19	402	42,764	White	3	0	3.99	3.82	
20	209	42,764	White	3	0	1.87	2.08	
21	269	42,764	White	3	0	2.35	2.97	
22	283	42,764	Yellow	3	1	3.26	3.40	
23	158	42,764	Yellow	3	1	1.65	1.35	
24	174	42,764	Yellow	3	1	2.00	1.69	
25	133	42,764	Yellow	3	1	0.87	0.78	

RESTRIPING SCHEDULING RECOMMENDATIONS FOR TXDOT

The analysis indicated that all the high-build waterborne paints from the NTPEP Florida 2012 and 2015 test decks had a service life of at least 3 years. However, the high-build waterborne paints used in district roads in Texas (described in Table 1) are expected to live more than three years for the following reasons:

- Paints used in Texas district roads include Type 3 beads (single drop), which provide higher initial R_L than Type 1 beads (single drop) used on the NTPEP test decks.
- Paints in Texas district roads are usually subjected to lower ADT than NTPEP test decks.
- Recently, the FHWA proposed minimum maintained pavement marking retroreflectivity levels for the Manual on Uniform Traffic Control Devices (MUTCD). A value of 50 mcd/m^2/lux was proposed on roadways with statutory or posted speed limits ranging between 35 and 70 miles per hour (mph). Given that all the calculations in this paper were based on a threshold value of 100 mcd/m^2/lux, paints in Texas district roads with posted speeds between 35 and 70 mph, are expected to perform longer than three years.

Based on this analysis and considering the different conditions between Texas district roads and Florida NTPEP Florida test decks, the authors recommend that TxDOT restripe their district roads using the same product (described in Table 1) every three years (instead of the current two-year period). Shifting to this new strategy should include a sampling plan for additional R_L measurements (in addition to the conventional initial measurements) throughout the three-year life cycle to confirm that the R_L values remain above the threshold values.

SUMMARY AND CONCLUSIONS

The goal of this paper was to help southern state agencies, including TxDOT, comply with the new FHWA final retroreflectivity rule by providing them with a simple decisionmaking framework that can determine the restriping time for the retroreflectivity of pavement markings to be above the minimum values set by the new federal rule. To do so, data from the NTPEP database was mined and analyzed. Based on the analysis conducted in this paper, the following was concluded:

- Service life of waterborne paints is dependent on the retroreflectivity rather than durability.
- The service life of standard waterborne paints (with a thickness of 15 mils) applied in the Southern States ranged from 0.1 years to 3.95 years depending on the initial retroreflectivity value, traffic level, and line color.
- A performance prediction model was developed with superior accuracy to predict the expected service life of standard waterborne paints based on the initial retroreflectivity value, traffic level, and line color. This model can be used by TxDOT and other southern state agencies to determine the expected restriping time before the retroreflectivity drop below the minimum 100 mcd/m^2/lux threshold.
- The service life of high-build waterborne paints (with a thickness of 25 mils) is at least 3 years. As such, it is recommended that TxDOT restripe their district roads using the same high-build product every three years (instead of the current twoyear period). Shifting to this new strategy should include a sampling plan for additional

R_L measurements (in addition to the conventional initial measurements) throughout the three-year life cycle to confirm that the R_L values remain above the threshold values.

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