
Methodologies to Predict Service Lives of Pavement Marking Materials
Author(s): Yunlong Zhang and Dongfeng Wu
Source: *Journal of the Transportation Research Forum*, Vol. 45, No. 3 (Fall 2006), pp. 5-18
Published by: Transportation Research Forum
Stable URL: http://www.trforum.org/journal

Methodologies to Predict Service Lives of Pavement Marking Materials

by Yunlong Zhang and Dongfeng Wu

This study focuses on developing methodologies to predict the service life of a pavement marking material based on its retroreflectivity. Data from the 2002 National Transportation Product Evaluation Program (NTPEP) pavement marking material test deck in Mississippi are used for model development and model validation. The smoothing spline method and time series modeling are applied to estimate the service lives of different types of materials based on the assumption of a required minimum retroreflectivity value. The same models can also predict the retroreflectivity values at future times for a pavement marking product based on its retroreflectivity values in the past. The validation of the models shows satisfactory accuracy. As demonstrated in a case study, the predicted service lives of the marking materials can be used in life-cycle cost comparisons for selecting pavement marking material.

INTRODUCTION

Pavement marking materials are important traffic control devices that provide essential guidance and safety for motorists on all highways. For guidance and safety to be maximized, pavement marking materials must exhibit adequate retroreflectivity and color visibility throughout their service lives. Retroreflectivity is the portion of incident light from a vehicle's headlights reflected back toward the eyes of the driver. Retroreflectivity is provided in pavement marking materials by glass beads. An adequate level of retroreflectivity from pavement marking materials is vital to the safety of night-time driving.

Different pavement marking materials have different costs and service lives, and they require different equipment and different lane closure durations for installation. States spend millions of dollars every year on pavement marking materials. For example, in fiscal year 1998, the Virginia Department of Transportation spent $16.8 million on pavement markings on the interstate and primary systems (Cottrell and Hanson 2001). Because of the high costs of marking materials for states, the selection and use of pavement marking materials that meet all specifications and also have lower life-cycle costs can lead to large cost savings, which will be of great interest to state DOTs.

The selection of pavement marking materials for highways of different classifications, pavement surface types, and traffic conditions is not an easy task. There are many categories of materials including paint, thermoplastic, tape, and epoxy, and they exhibit different performances and have different service lives. Some may work better on asphalt surfaces, while others may serve better on concrete; some may be less expensive but do not last as long as others and need to be replaced at shorter intervals, incurring more installation costs and resulting in more motorist delay costs.

The selection of marking materials is typically experience-based and not based on a detailed life-cycle cost analysis. With vendors manufacturing new products, and with the increasing budgetary concerns of state DOTs, development of a rigorous procedure to select optimal pavement marking materials based on life-cycle cost becomes essential. For highway sections with markings showing deteriorating performance, the question of when restriping is needed must be addressed.

This paper concentrates on developing advanced statistical methodologies and models to explore the relationship between retroreflectivity values and the ages of the markings.[1] It also explores predicting the service life of an existing pavement marking material at various stages of service based on the history of its retroreflectivity values. Since no consensus or standard has been developed on the required minimum value of retroreflectivity, a value of 100 is used for analysis purposes. Toward the end of the paper, a case study of life-cycle cost comparison between waterborne paint and thermoplastic is presented.[2]

Literature Review

In the past, the estimated service life of a pavement marking material was based primarily on the past performance of similar products. This experience-based approach is inaccurate because so many factors affect a pavement marking material's performance. In addition, new products may perform considerably different from their predecessors or their counterparts of the same types. There is a clear need for a more rigorous methodology to define and predict the service life of a pavement marking material.

There are two very critical issues involved in determining the service life of a pavement marking material: the need to determine when a pavement marking material is no longer serviceable. Given a quantified terminating condition of a pavement marking material, how can the remaining service life be forecasted?

Traditionally, the performance of a pavement marking material has been judged based primarily on its retroreflectivity. Retroreflectivity has been used extensively in past studies as an important factor in analyzing the performance and cost-effectiveness of a pavement marking material. For example, Cottrell and Hanson (2001) used retroreflectivity, along with installation cost and service life, to determine the cost-effectiveness of pavement marking materials. The American Society of Testing and Materials (ASTM) established standard retroreflectivity measurements for pavement markings by adopting the 30-meter geometry that is also used by the European Committee on Standardization. This geometry simulates the performance of a marking that is located 30 meters in front of a vehicle and approximates the distance illuminated by the vehicle's headlights (Highway Innovative Technology Evaluation Center 2000). Retroreflectivity for pavement marking materials is commonly measured as millicandela per square meter per lux ($mcd/m^2/lux$) using a retroreflectometer (Thomas and Schloz 2001, Cottrell and Hanson 2001).[3] In the study detailed in this paper, the service life of a pavement marking material is determined by the duration that a certain level of retroreflectivity is maintained.

The minimum retroreflectivity value represents the terminating condition of a pavement marking material. Inadequate retroreflectivity leads to reduced safety to motorists. In 1992, the U.S. Congress required that the *Manual of Uniform Traffic Control Devices* (MUTCD) set minimum requirements for the retroreflectivity of highway pavement markings. Several studies have been conducted in this area and the Federal Highway Administration (FHWA 2004) has been developing guidelines for determining minimum retroreflectivity. The FHWA has sponsored field evaluations to develop minimum retroreflectivity requirements for pavement markings. Zwahlen and Schnell (2000) also conducted a study using the Computer Aided Road Marking Visibility Evaluator to determine the amount of retroreflectivity required to support driver performance. A wide variety of factors, noticeably the marking color, driver age and visual acuity, and travel speed, can affect the subjective minimum acceptable retroreflectivity level. A consensus minimum on pavement marking materials has yet to be reached, and standards have not yet been established. However, many researchers seemed to agree that a minimum acceptable level of retroreflectivity is around 100 to 120 $mcd/m^2/lux$ (Fish 1996).

The service life of a pavement marking product varies with traffic, surface, and weather conditions. The average service lives of pavement marking materials also vary significantly between types, from an average of one to two years for waterborne paints to four to five years for extruded thermoplastics. The prediction of service life using statistical methods based on collected historical data after installation has attracted some interest. Thamizharasan et al. (2002) developed regression models to forecast the retroreflectivity life-cycle by analyzing the collected retroreflectivity over time of thermoplastic and epoxy marking materials. A similar study was conducted by Perrin et al. (2001). Migletz et al. (2001) developed regression models to establish relationships between retroreflectivity values and cumulative traffic passages (CTPs). All these regression models, however, typically had R^2 values that were too low to be considered statistically valid, and they also did not give confidence interval bounds. In addition, assuming a certain function type of the regression (such as negative exponential, logarithmic, or parabolic) throughout the life span lacks theoretical and practical support and may have over-simplified the issue.

The life-cycle cost of a pavement marking project consists of many potential costs, such as installation cost, delay cost, and safety crash cost. Several studies have attempted to address life-cycle cost analysis in order to select the most appropriate marking material type. For example, Abboud and Bowman (2002) considered application cost and safety cost to compare the life-cycle costs between waterborne paint and thermoplastic material. Cottrell and Hanson (2001) compared installation cost and delay cost over the service lives of different materials. However, due to limited data availability, a thorough life-cycle cost comparison for the purpose of pavement marking material selection has not been found in the literature.

There have been studies conducted for determining the replacement schedule of traffic signs based on night-time visibility (Rasdorf et al. 2005). Models to determine restriping schedules based on night visibility and future retroreflectivity level prediction have not been reported in the literature.

Data

The data used in this study are from the 2002 National Transportation Product Evaluation Program (NTPEP) pavement marking material field test deck in Mississippi. Each year the American Association of State Highway and Transportation Officials (AASHTO) sponsors field and lab tests to evaluate the performance of pavement marking materials through NTPEP. Test decks, which are sections of highways in selected locations in different regions, are used for testing of marking materials in the field. The Mississippi test deck is located on U.S. Highway 78 near Tupelo, Mississippi. The average daily traffic (ADT) of that section of U.S. Highway 78 is about 20,000 vehicles, with about 30% trucks. Marking stripes from vendors were placed on the pavement in the right lane next to each other across the travel lane in the transverse direction (running in a crosswise direction), perpendicular to the existing horizontal (running in a lengthwise direction) edge line (white line defining the right edge of the pavement) and the skip-line (lane line delineating the separation of adjacent lanes in the same direction). Stripes were placed on both Portland cement concrete (PCC) and bituminous concrete (asphalt) surfaces according to NTPEP's work plan (American Association of State Highway and Transportation Officials 1997). Field measurements of retroreflectivity for each material were taken monthly in the first year and quarterly in the second year for all materials.

Retroreflectivity readings were taken 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. In this study, only the retroreflectivity values from the skip-line area are used. The wheel path retroreflectivity measurement is for the purpose of accelerated testing. It typically has a much faster deterioration rate and will reach the minimum threshold value much earlier and is thus not representative of the actual service life of an actual longitudinal marking stripe. The skip-line area has a traffic condition more similar to that of the actual skip-line stripes, so it is appropriate to use skip-line data for model development.

EMPIRICAL ANALYSIS

There are 95 products in the 2002 study dataset, including 12 durable tape products, 13 two-year waterborne paints, 26 three-year waterborne paints, 8 experimental products, 10 preformed thermoplastic products, and 26 thermoplastic products.[4] To predict the average service life for each product type, a smoothing spline method and a time series method were applied separately. Only the data on asphalt surfaces were used to demonstrate the methods. The same methods can also be applied to collect data on a concrete surface or, indeed, on any specific type of surface, traffic, and climate condition in exactly the same way. These two methods and the models used are discussed in the following sections.

Smoothing Spline

The smoothing spline is widely used in nonlinear regression analysis and additive models (Hastie and Tibshirani 1990). If there are n pairs of data (x_i, y_i) to describe the relationship between x_i and y_i, a smoothing spline minimizes a compromise between the fit and the degree of smoothness of the form:

$$(1) \quad \sum [y_i - f(x_i)]^2 + \lambda \int (f''(x))^2 dx$$

over a twice-differentiable function *f*. We chose to fit a cubic spline with knots (turning points) at the x_i. On the $[x_i, x_{i+1}]$ interval the spline is a cubic polynomial. The degree of fit is controlled by λ, where λ can be chosen by cross-validation automatically in the software package S-PLUS. Confidence curves of 95% can be constructed as well.

The smoothing spline method is applied to the data, with x_i representing the service time in months and y_i representing the retroreflectivity value of the corresponding month. For each type of product, the average value monthly in the first year and quarterly in the second year is calculated; then a smoothing spline model is fit as shown in Figure 1. Based on these spline curves (one of mean, one for the 95% confidence interval lower bound, and one for the 95% confidence interval upper bound), the mean and the range of the service life for each type of product can be predicted. The termination of service life is determined by a minimum retroreflectivity value of 100; the results of service life prediction are listed in Table 1, also with 95% confidence interval bounds.

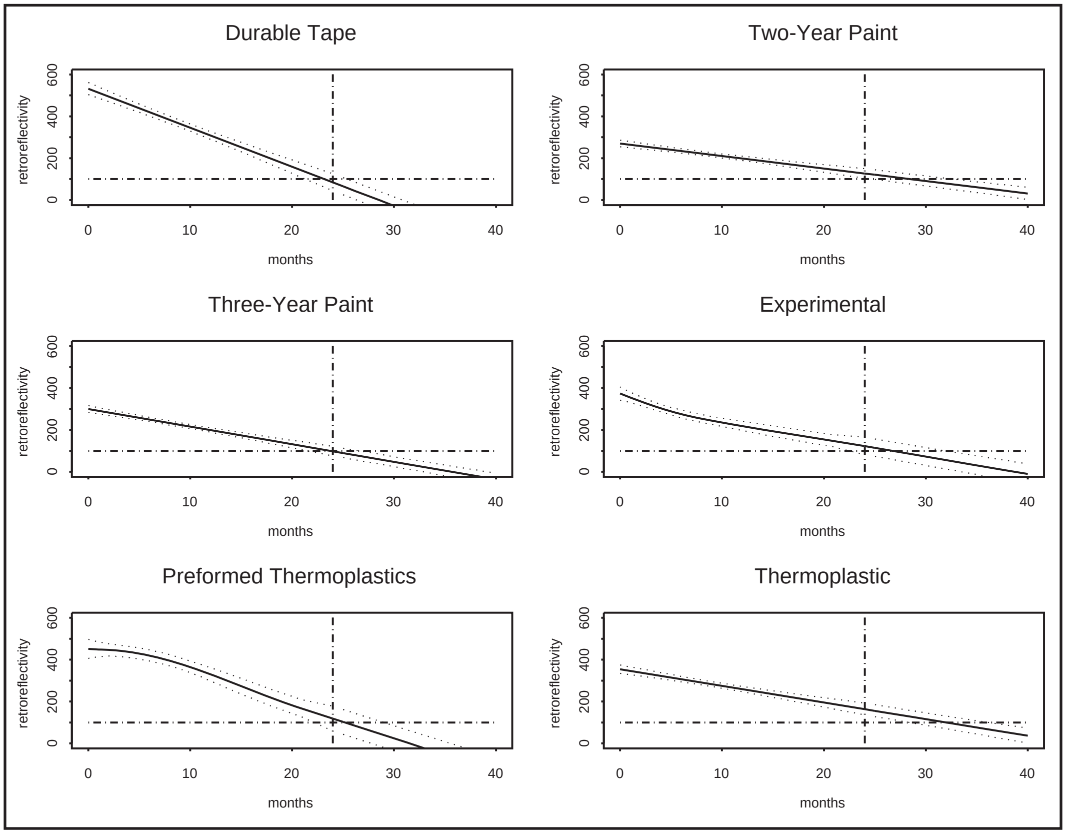
In Table 1, the estimated average service lives of the six groups of materials are between 23 months and 32 months. The service lives of non-paint products are somewhat lower than the commonly expected values, but that is probably due to the fact that the data from the NTPEP deck are not collected from the actual (longitudinal) skip-line stripes and are not an issue of model deficiency. Interestingly, three-year paints (with thicker film) do not appear to have any advantage over two-year paints; however, this outcome is what the data indicate and has nothing to do with the model.

Table 1: Smoothing Spline: Effective Lifetime with 95% Confidence Interval Bound (in Months)*

Product Type	Lower Bound	Mean Lifetime	Upper Bound
Durable Tape	21.33	23.21	25.67
Two-Year Paint	24.79	28.54	32.68
Three-Year Paint	21.42	24.09	26.76
Experimental	22.71	27.16	32.18
Preformed Thermoplastic	22.00	25.25	29.17
Thermoplastic	28.19	32.02	36.15

* Confidence intervals are for the averages (means) of all products in the same product group.

Figure 1: Smoothing Spline: Mean Values of Transient Retroreflectivity by Material Type at Skip-Line Area



The smoothing spline has an important advantage in model fitting, namely, its flexibility. It is not required that *x* be equally spaced. The data collection interval is monthly in the first year and quarterly in the second year; the time intervals are not equally spaced, but the smoothing spline can be directly applied effectively. However, the smoothing spline also has some limitations in prediction. All regression methods are safe for interpolation predictions and may lead to unrealistic outcomes in extrapolation predictions. As with regression-based models, results from the smoothing spline model may not be reliable for predictions beyond the range of recorded data. With this in mind, another model, the time series method, is proposed to predict the service time of the pavement marking material beyond the two-year period. Later in the paper, the prediction accuracies of these two methods are compared.

Time Series: The ARIMA Model

Many systems with time-based data can be modeled and predicted by time series analysis using the ARIMA (*p*, *d*, *q*) model (Brockwell and Davis 2002). Suppose a sequence of time-based values $\{X_t, t=0, 1, 2, 3, \ldots\}$, and assume that

(2) $X_t = M_t + Y_t$,

where M_t represents the trend or the drift of the data and Y_t represents a stationary process with mean zero plus some white noise. Then the trend M_t is eliminated by differencing the data *d* times if M_t is a polynomial of the order of *d*. In our application, it is assumed that the retroreflectivity deteriorates at some constant rate, which means that $M_t = a + bt$. M_t is eliminated by differencing the data once to get:

$$W_t = X_t - X_{t-1} = b + (Y_t - Y_{t-1}) = b + U_t, \quad (3)$$

where U_t is a stationary process with mean zero. Then U_t can be modeled as a ARMA(*p*,*q*):

$$U_t - \phi_1 U_{t-1} - \phi_2 U_{t-2} - \cdots - \phi_p U_{t-p} = Z_t + \theta_1 Z_{t-1} + \cdots + \theta_q Z_{t-q}, \quad (4)$$

where the Z's are uncorrelated white noise with mean zero, and the ϕ's and the θ's are unknown parameters that must be estimated from the data.

According to the property of retroreflectivity, an autoregressive model of order *p* was developed. That is, ARMA(*p*,*0*) =AR(*p*) model for U_t, where *p* is chosen optimally by the Akaike's Information Criterion (AIC), and the Yule-Walker equation is used in estimating the autoregression coefficients ϕ.

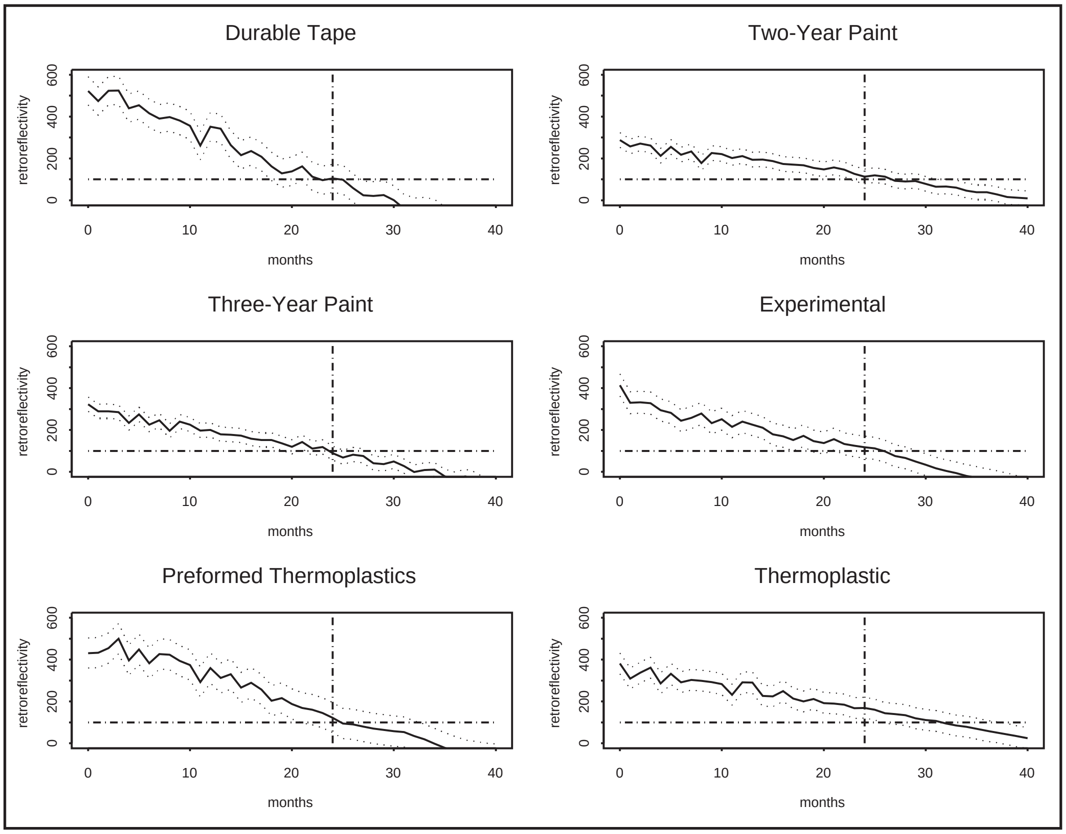
The S-PLUS software (Venables and Ripley 2002) used to conduct the time series data analysis is limited to constant time intervals; however, the data were collected monthly in the first year and quarterly in the second year. So a step-by-step fitting of the missing values for the second year is applied. That is, the first-year data is used to predict the values in months 13 and 14; then after adding these pseudo-data into the dataset, the first 15 months of data is used to predict the values of months 16 and 17, and so on. At the last step, the model was refit using the first two years' data. The model was then used to predict the remaining service time of a pavement marking material and to construct confidence bounds. The results of the time series analysis for all groups are listed in Table 2. The fitting and the prediction curves for each type of product are shown in Figure 2.[5]

Table 2: Time Series: Effective Lifetime with 95% Confidence Interval Bound (in Months)*

Product Type	Lower Bound	Mean Lifetime	Upper Bound
Durable Tape	17.85	24.76	27.88
Two-Year Paint	22.71	26.65	32.28
Three-Year Paint	21.76	23.70	27.94
Experimental	21.23	25.87	29.12
Preformed Thermoplastic	21.33	24.98	32.58
Thermoplastic	25.97	31.69	37.22

* Confidence intervals are for the averages (means) of all products in the same product group.

Figure 2: Time Series: Mean Values of Transient Retroreflectivity by Material Type at Skip-Line Area



From Table 2, the predicted average service lives of the six groups of materials are between 24 months and 32 months. They are again somewhat lower than expected, and three-year paints are also not as good as two-year paints as far as retroreflectivity is concerned.

Comparison of the Two Methods

Comparing those two methods based on the results in Tables 1 and 2, the predicted service lives of the material groups from the two methods are all very close and the differences are within about two months. This seems to indicate that both methods are reliable.

To further compare these two methods, a single product is randomly selected from each of the four main groups (durable tape, three-year waterborne paint, preformed thermoplastic, and thermoplastic) and both methods use the first 18 months of data to forecast the retroreflectivity values of months 21 and 24. The predicted values are compared to the actual readings. The estimated values of the smoothing spline curve and the time series curve are plotted in the same graph in Figure 3. The resulting curves in Figure 3 show that both methods yield predictions fairly close to actual readings, especially for month 21. The mean squared errors from both methods are calculated, and they slightly favor the time series method. The prediction accuracies of retroreflectivity values for months 21 and 24 are tabulated in Table 3. The percentages in Table 3 show the departure of the estimated value from the actual readings at months 21 and 24. Further investigation shows the accuracy of time series prediction is reasonably good, especially for month 21, for which the difference between the predicted values and actual readings are within 5%. The prediction accuracy for the smoothing spline method is also acceptable, except in the case of product 3 (a preformed thermoplastic) where the difference is large (34.3%). This seems to point toward the drawback of less than desirable accuracy with the smoothing spline method when it comes to extrapolation beyond the recorded data points. The prediction performance for month 24 deteriorates, which is expected. However, the accuracy for month 24 is still mostly reasonable for time series prediction considering the retroreflectivity values are highly variable, and a 10% to 20% or even higher difference in readings at different locations of a same product is not uncommon (Kopf 2004). An accuracy of six-month time series prediction of less than 20% for three out of four products is acceptable. The prediction accuracy from the time series method for Product 1 is at 31.3%, not great but still reasonable considering the significant variability of retroreflectivity values. The prediction errors for the smoothing spline method in month 24 are less than the time series method except for Product 3, which has a very large error of 86.4%.

Figure 3: Comparison of the Smoothing Spline and the ARIMA (*P, 1,0*) for Some Single Products

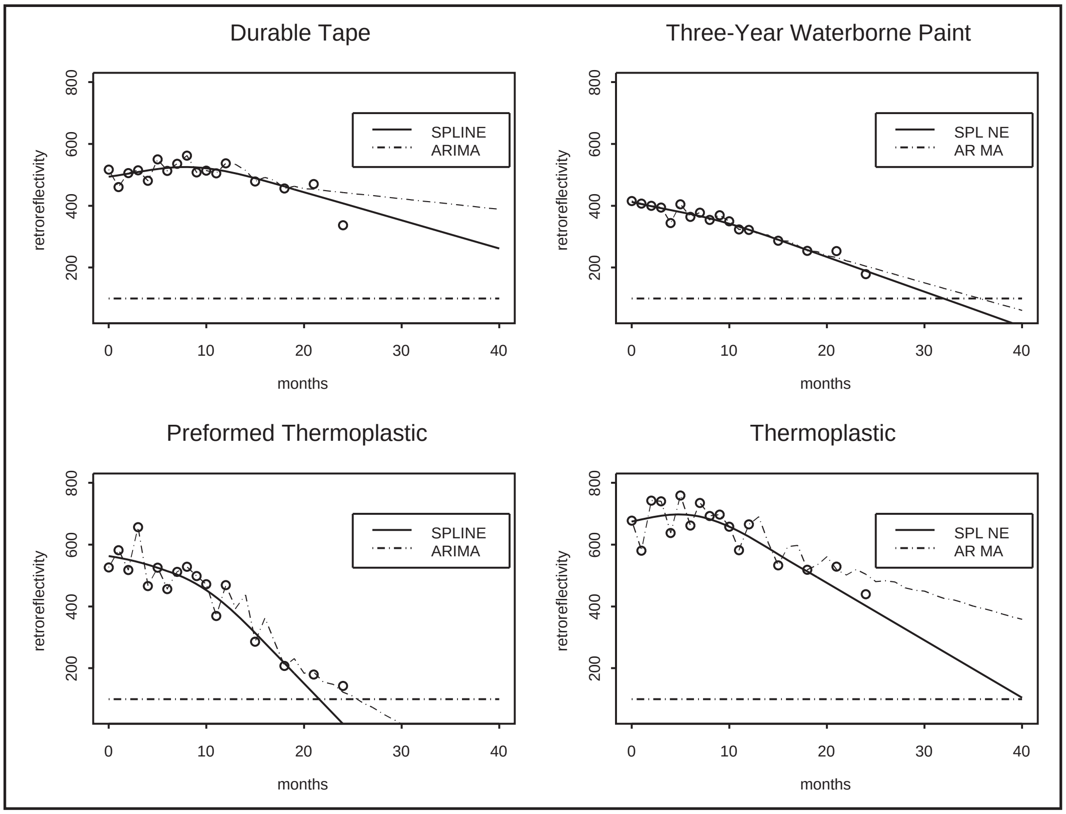


Table 3: Comparison of Retroreflectivity Prediction Accuracies by Two Methods

Product	**Month 21**			**Month 24**		
	Actual	Spline	Time Series	Actual	Spline	Time Series
Product 1 Durable Tape	470.25	434.96	453.44	337.00	407.62	442.55
		-7.51%	-3.57%		21.0%	31.3%
Product 2 Three-Year Waterborne Paint	253.5	222.87	232.15	178.5	189.15	203.48
		-12.08%	-8.42%		5.96%	13.99%
Product 3 Preformed Thermoplastic	179.5	117.89	186.84	142.5	19.36	121.87
		-34.33%	4.09%		-86.41%	14.48%
Product 4 Thermoplastic	528.5	457.58	518.85	439.5	401.82	503.59
		-13.42%	-1.83%		-8.57%	14.58%

APPLICATIONS

Life-Cycle Cost Analysis for Material Selection

Cost is an important factor in determining which pavement marking material to use for a type of highway in a state. With the estimated service lives of marking materials, it is possible to compare the life cycle costs of individual products and product groups. The total life-cycle cost of a striping project includes agency costs such as material, application labor, and removal; it also includes user costs such as operation, accident, and delay cost due to lane closure during striping. Due to lack of data on many of the cost components, a detailed life-cycle cost comparison is often not possible, and only a simplified comparison between two products is presented in the following case study.

In this study, waterborne paint and thermoplastic are compared for a one-mile striping project and the comparison considers all main cost components that are significantly different for different material types and ignores the costs that are generally independent of material type. The considered costs are installation cost, safety cost and delay cost.

Installation Cost. According to a 1996 nationwide survey of striping costs, waterborne paint and thermoplastic cost about \$0.06 and \$0.30 per linear foot, respectively, for materials, labor, and traffic control. A recent study showed the cost per foot has not changed in the years since due to a constant material price resulting from intense competition. However, as the pavement marking material manufacturing industry consolidates, material prices are likely to increase in the future. For one mile of four-lane highway (one direction), the total length of the stripes, including one solid yellow edge line, one solid white edge line, and one broken white center line with 10-foot line segments and 30-foot gaps, is $5,280\times(2+\frac{10}{40})=11,880$ feet, and the installation costs for waterborne paint and thermoplastic at current prices are \$713 and \$3,564, respectively.

Delay Cost. The delay due to marking installation is related to the traffic volume level. At low levels, the delay is negligible, but at high volume levels it could be very significant. This paper uses the delay values calculated in Cottrell and Hanson (2001). The delay costs per mile for a volume of 2,000 vehicles per hour (vph) and 4,000 vph are \$52 and \$736, respectively. The delay is assumed to be the same regardless of material type.

Crash Cost. Thermoplastic materials typically have much higher initial retroreflectivity values than paints; therefore, the average retroreflectivity value for a thermoplastic material is significantly higher than that of a paint product. The higher retroreflectivity value translates to safer driving conditions at night and lower crash costs. The estimation of crash costs for different pavement marking materials is, however, a very complicated process, and there is hardly enough data available to conduct any meaningful calculation. According to Abboud and Bowman (2002), the equivalent annual crash costs per mile related to paint striping is $49,213 for low ADT, $35,525 for moderate ADT and $21,837 for high ADT; the equivalent annual crash costs per mile related to thermoplastic striping is $26,554 for low ADT, $22,301 for moderate ADT and $18,048 for high ADT. Based on those numbers, the crash cost difference between paint and thermoplastic striping ranges from $3,780 to $23,659 per mile per year and is obviously very significant. If crash cost is considered in the life-cycle cost analysis, it will be the deciding factor as its annual values are much higher than those for other costs. Based on the data from Abbound and Bowman (2002), thermoplastic striping will always have a lower life-cycle cost because of significantly lower crash costs.

Life-Cycle Cost Analysis. A life-cycle cost comparison between paint and thermoplastic striping is conducted based on an assumed service life of three years for thermoplastic and two years for waterborne paint. A 30-year life-cycle is chosen and the results are shown in Table 4. Only installation cost and delay cost are considered. The crash cost is not included for several reasons. First of all, the crash cost is difficult to determine due to lack of reliable data. Also, inclusion of crash data will more than likely deem thermoplastic striping a less expensive option as discussed in the previous paragraph, assuming the data are valid. All costs are assumed to increase annually at a rate of 5%, and a discount rate of 4% is used. All the costs in the table are presented in the form of present worth.

From Table 4, it can be seen that a thermoplastic material is about five times as expensive as the paints if only one-time installation cost is considered. However, because of the longer service life, its 30-year life-cycle cost is about 3.1 times as much as the paint for low volume conditions and only about 2.0 times as expensive at high volume conditions. There have been studies (Thomas and Schloz 2001) that showed the service life of paint can be lower than a year under high volume condition, and that will make thermoplastic more economical. In addition, considering higher crash costs for paints, the thermoplastic materials can easily have lower life-cycle costs if safety costs are also included in the analysis.

Table 4: 30-Year Life-Cycle Cost Comparison Between Paint and Thermoplastic Striping

Year	**Paint**			**Thermoplastic**		
	Installation Cost	Delay Cost (2000 vph)	Delay Cost (4000 vph)	Installation Cost	Delay Cost (2000 vph)	Delay Cost (4000 vph)
1	713	52	736	3,564	52	736
2	0	0	0	0	0	0
3	727	53	750	0	0	0
4	0	0	0	3,668	54	757
5	741	54	765	0	0	0
6	0	0	0	0	0	0
7	755	55	779	3,775	55	779
8	0	0	0	0	0	0
9	770	56	795	0	0	0
10	0	0	0	3,885	57	802
11	785	57	810	0	0	0
12	0	0	0	0	0	0
13	800	58	826	3,998	58	826
14	0	0	0	0	0	0
15	815	59	842	0	0	0
16	0	0	0	4,114	60	850
17	831	61	858	0	0	0
18	0	0	0	0	0	0
19	847	62	874	4,234	62	874
20	0	0	0	0	0	0
21	863	63	891	0	0	0
22	0	0	0	4,357	64	900
23	880	64	908	0	0	0
24	0	0	0	0	0	0
25	897	65	926	4,484	65	926
26	0	0	0	0	0	0
27	914	67	944	0	0	0
28	0	0	0	4,615	67	953
29	932	68	962	0	0	0
30	0	0	0	0	0	0
30 year Total	12,270	895	12,666	40,693	594	8,403
Total LCC*	13,165 (2000 vph) 24,936 (4000 vph)			41,287 (2000 vph) 49,096 (4000 vph)		

* All costs in dollars. LCC is life-cycle cost, computed by adding installation cost to the appropriate delay cost.

Restriping Scheduling

DOTs typically restripe pavement markings in a fixed schedule. However, the actual service lives of markings vary significantly from segment to segment because of different traffic and other factors. Replacing stripes that are still serviceable wastes valuable resources, but a late restriping will compromise driving safety. With the methodologies developed in this paper, DOTs can easily and fairly accurately determine the remaining service lives of markings, which makes it possible to develop optimal restriping schedules that make full use of the marking service life (and thus reduce costs) but also meet safety requirements.

CONCLUSIONS

This paper uses the smoothing spline and time series methods to model pavement marking materials' retroreflectivity changes over time. The results and model comparisons, with a few exceptions, show both methods perform well. It seems that both models can predict retroreflectivity of a pavement marking material for the next six months with reasonably good accuracy most of the time. Between the two methods, the time series model has better prediction accuracy for short-term predictions (three months). This is certainly an improvement over many existing methods in which a constant rate of decrease or a consistent pattern (or function) of decrease for retroreflectivity is assumed but is not supported by field data. The models may also prove to be advantageous over models with vehicle passages as the independent variable since the deterioration of retroreflectivity is due to a combination of factors, vehicle passage being only one of them. In addition, the relationship between vehicle passages on the marking materials and total vehicle passages on that roadway section (determined from ADT and time) is itself a complicated issue, and an assumption of a linear relationship is highly questionable.

The 2002 Mississippi test decks are part of a two-year program, even though many durable products have longer expected service lives. Due to this limitation of having only two-year data, the prediction methodologies of this study may require further validation with future data of longer evaluation periods. The ongoing NTPEP test decks are all three-year decks for nontemporary materials, and they can be used for validation of the methodology once those test decks are completed. The authors again want to point out that the skip-line area data from NTPEP may not be truly representative of actual longitudinal edge line or skip-line stripes since the data collection points slightly deviate from the actual skip-line and may be subject to more wheel passages. This difference may be accounted for by a correlation study of retro values between the NTPEP “skip-line area” and the actual skip-line. Ideally the model development and validation should be conducted using data collected directly from actual longitudinal highway stripes. The service lives estimated in this paper based on NTPEP data may differ from the actual service lives, but this does not discredit the methods presented in the paper.

The authors also want to point out that individual models for different surfaces (asphalt or concrete), colors (yellow or white), and other factors were not constructed, even though these factors may significantly affect the service lives of the marking materials as acknowledged in the paper. The primary purpose of this paper is to develop methodologies, and these methodologies can be applied to any specific application with a set of traffic, roadway, surface, and color conditions.

With the methodologies developed in this study, a better understanding of the retroreflectivity life-cycle can be achieved. With a past retroreflectivity history, the remaining service life of a marking material can be estimated with reasonably good accuracy. The methods can certainly help state departments of transportation make informed decisions about pavement marker material replacement schedules, and the methods can also be used in life-cycle cost analysis of different products for material selection.

Endnotes

1. Deterioration of marking materials is affected by many factors such as pavement type, traffic condition, weather condition, vehicle weaving, and marking material type. In this paper, evaluation of a marking material's performance is based on time series analysis of retroreflectivity data, which is the result of all factors noted above.

2. The case study illustrates how state DOTs can use the models in the paper to make informed material selection decisions based on their performance/cost criteria. Recommending a specific marking material for all situations is not possible since so many factors vary from project to project.

3. The *candela* (symbol: cd) is the SI (International System of Units) base unit of luminous intensity. The *lux* (symbol: lux) is the SI unit of illuminance. In photometry, luminous intensity is a measure of the perceived power emitted by a light source in a particular direction, and illuminance is a measure of the perceived intensity of the incident light.

4. Preformed thermoplastic is pre-manufactured and installed on the pavement by heating the pre-cut strip. Thermoplastic strip is installed by melting and mixing materials on site at a set temperature. The materials are applied to the pavement by an extruded method with glass beads being added to the surface through a bead dispenser.

5. Retroreflectivity is highly variable and is affected by many factors. It is common for retroreflectivity to increase one month after installation, possibly due to increased bead exposure from wheel passes. Retroreflectivity also increases on days after rain due to less dusty surface.

References

Abboud, N. and B. L. Bowman. "Cost- and Longivity-Based Scheduling of Paint and Thermoplastic Striping." Preprint of the 81st Annual Meeting of Transportation Research Board. Washington D.C., 2002.

American Association of State Highway and Transportation Officials. National Transportation Product Evaluation Program (NTPEP). *Project Work Plan for the Field and Laboratory Evaluation of Pavement Marking Materials,* August 1997.

Brockwell, P. J. and R. A. Davis. *Introduction to Time Series and Forecasting*, 2nd Edition. Springer-Verlag, 2002.

Cottrell, B. Jr. and R. Hanson. "Determining the Effectiveness of Pavement Marking Materials." Final Report, Virginia Department of Transportation, Charlottesville, Virginia, February 2001.

Federal Highway Administration. "Status of Retroreflectivity Standards Overview." http://safety.fhwa.dot.gov/fourthlevel/retrstat42202 htm. Accessed July 29, 2004.

Fish, J. K. "Evaluation of All-Weather Pavement Markings: Report on Two Years of Progress." Semisequicentennial Transportation Conference Proceedings, Iowa State University, Ames, Iowa, May 1996.

Hastie, T. J. and R. J. Tibshirani. *Generalized Additive Models.* Chapman and Hall, London, 1990.

Highway Innovative Technology Evaluation Center. *Evaluation Findings of the LTL 2000 Pavement Marking Retroeflectometer.* CERF Report No. 40469, January 2000.

Kopf, J. *Reflectivity of Pavement Markings: Analysis of Retroreflectivity Degradation Curve.* Washington State Transportation Center. September 2004.

Migletz, J., J. L. Graham, D. W. Harwood, and K. M. Bauer. "Service Life of Durable Pavement Markings." *Transportation Research Record 1749*, Transportation Research Board, National Research Council, Washington, D.C., 2001, pp. 13-21.

Perrin, P. J., P. T. Martin, and B. G. Hansen. "A Comparative Analysis of Pavement Marking Materials." Preprint of 2001 Annual Transportation Research Board Meeting, Washington, D.C., January 2001.

Rasdorf, W. J., J. E. Hummer, S. C. Vereen, and H. Cai. "A Quantitative Evaluation of the Nighttime Visual Sign Inspection Method." *Journal of the Transportation Research Forum* 44 (1), (2005): 121-140.

Thamizharasan, A., W. A. Sarasua, D. B. Clarke, and W. J. Davis. "A Methodology for Estimating the Lifecycle of Interstate Highway Pavement Marking Retroreflectivity." Transportation Research Board paper, No. 03-3867, 2002.

Thomas, G. B. and C. Schloz. "Durable, Cost-Effective Pavement Markings, Phase I: Synthesis of Current Research." Iowa State University, 2001.

Venables, W. N. and B. D. Ripley. *Modern Applied Statistics with S-Plus*, 4th Edition. Springer-Verlag, 2002.

Zwahlen, H. T. and T. Schnell. "Minimum In-Service Retroreflectivity of Pavement Markings." *Transportation Research Record 1715*, Transportation Research Board, National Research Council, Washington, D.C., 2000, pp. 60-70.

***Yunlong Zhang** is an assistant professor in the Zachry Department of Civil Engineering at Texas A&M University. Zhang got his Ph.D. in transportation from Virginia Tech in 1996. His professional experience includes a Senior Transportation Engineer position at Systems Division of ITT Industries and assistant professor at Mississippi State University. His research interests focus on modeling aspects of transportation systems.*

***Dongfeng Wu** got her Ph.D. in Statistics from University of California, Santa Barbara. She worked as a research associate at University of Texas, M.D. Anderson Cancer Center for a year and a half. She is currently an assistant professor of statistics at Mississippi State University.*