Retroreflectivity and Deterioration Characteristics of Sheeting Used for In-Service Guide Signs*

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Abstract: To determine the deterioration characteristics of the retroreflective sheeting used for guide signs, this study examined 12 - year (1998 - 2010) observation data on 230 guide signs located in a test square. On the basis of the data, the deterioration curves of sheeting materials were calculated and the mathematical deterioration model for retroreflective sheeting was accordingly constructed. In determining the most suitable reference model, we chose among a linear mathematic model, a second - order polynomial model, and a cubic curve regression model. It was then applied to the signs found along Jiangxi Yongwu expressway in China. This research is expected to provide guidance for the maintenance of traffic signs in our country.

Key words: traffic engineering; deterioration model; guide sign; retroreflective sheeting; retroreflectivity

1 Introduction

Traffic signs are one of the most effective traffic management measures, among which guide signs are the most important tools for accurately conveying traffic information to road users[1-2]. For this purpose, drivers should be able to view and comprehend such signs in both daytime and nighttime conditions. Signs that are not equipped with internal illumination have retroreflective sheeting material placed on their surfaces for readability. Retroreflective materials reflect light back to the original source, with minimum scattering of light. For example, light from a vehicle's headlamps is reflected from the sign surface back to the driver, giving the sign an illuminated appearance.

The efficiency of sign materials in reflecting light is quantified by the coefficient of retroreflection (R_A), which is the ratio of reflected light to the light that strikes a defined section of a sign's surface area.

The readability of traffic signs is a crucial factor in traffic management and safety, making scientific maintenance work for such signs a highly important task. This research determined the deterioration characteristics of expressway guide signs by using 12 - year (1998 - 2010) observation data on 230 traffic signs located on a test square. On the basis of the data, we calculated the deterioration curves of the R_A for green, white, and blue retroreflective sheeting [3]. Furthermore, a mathematical model was established, for which we chose among a linear mathematical model, a second-order polynomial model, and a cubic curve regression model to serve as reference. It was then applied to the traffic signs found along Jiangxi Yongwu expressway. Results show that the second order polynomial and cubic curve regression models have better fitting than the linear mathematical model. The mathematical model constructed in this work can serve as guidance for determining the deterioration characteristics of retroreflective sign sheeting and service life of retroreflective guide signs. Our results are expected to facilitate Chinese traffic sign maintenance.

2 Overview

2.1 US standards

To guarantee the effective performance of retroreflective sheeting, relevant standards were established in the United States. In 1993, the US Federal Highway Administration (FHWA) released the Manual on Uniform Traffic Control Devices (MUTCD), which indicates the

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maintenance requirements for retroreflective sheeting[4]. In 2009, the FHWA included the minimum R_A and road management measures in the MUTCD to develop appropriate assessment and management programs that ensure service traffic signs comply with the R_A. Two fundamental approaches to sign maintenance were established: assessment and management. Assessment focuses on the evaluation of individual sign visibility, and management methods include the expected sign method, blanket replacement technique, and control sign method. The service life of signs is defined as the longest exposure to natural environmental conditions, from sign establishment to failure of the R_A[5].

2.2 Chinese standards

In 2002, the Ministry of Transport in China established national standards for retroreflective sheeting [6]. These standards classify retroreflective sheeting into five categories on the basis of American benchmarks. A disadvantage of the national standards is that they specify only the R_A requirement during sign establishment, not that during sign service.

Studies on the deterioration and service life of in-service retroreflective signs under physical environments are limited.

2.3 Literature review

In the 1980s, the US Congress began paying attention to traffic sign service life because of the safety issues raised by old traffic signs [7-9]. The FHWA and Transportation Research Board were commissioned by Congress to carry out relevant studies, among which is that on the minimum retroreflectivity requirements for traffic signs. The results of these studies were published in 1993, and were extended by Paniati, Mcgee, Carlson, and Hawkins in succeeding years until 2007[10-15]. Given the wide range of visual, cognitive, and psychomotor capabilities of the driving population and the complexity of the relationships among drivers, vehicles, signs, and roadways, a mathematical modeling approach was established.

The assessment of sheeting deterioration, as reflected by the R_A, is considered a critical component in research on sign maintenance and replacement. In line with examining this factor, one of the first studies conducted was that of Black et al. [8] in 1992 for the FHWA. The objectives of the study were to determine the factors contributing to the degradation of retroreflective signs and to formulate models based on the significant factors to accurately estimate retroreflectivity. The authors collected retroreflective readings from 5 722 signs in 18 different locations throughout the United States and conducted corresponding measurements. The data collected include sheeting color, sheeting type, contrast ratio, sign direction, ground elevation, area type, and sign age. The sheeting colors observed were green, red, white, and yellow. The measurement results revealed that signs performed adequately for up to 12 years. Within the scattered plots, high variability and a large dispersion of data points were observed. For example, the values for white type-III sheeting at five years ranged from 150 cd/lx/m^2 to 390 cd/lx/m^2, while those for red type-III sheeting ranged from 10 cd/lx/m^2 to 90 cd/lx/m^2. The analysis indicated that sheeting age, precipitation level, ground elevation, and temperature are significant factors for sign deterioration. The analysis also showed that sign direction and precipitation variables are unsuitable predictors of the retroreflectivity of in-service signs. With the significant factors, Black et al. [9] created a linear prediction model for each type-III sheeting color. The linear prediction models estimate the retroreflectivity of a specific sheeting type on the basis of sign age. The authors deemed the equations reasonable predictors of retroreflectivity, but model correlation was poor and the R-squared (R^2) values ranged only from 0.20 to 0.50.

In 2002, Wolshon et al. [16] of the Louisiana Department of Transportation and Development (DOTD) analyzed 273 traffic signs with different colors, grades, ages, and orientations. The study was conducted to analyze the performance and deterioration characteristics of retroreflective sheeting materials, with the goal of targeting the compliance of sign groups with DOTD testing requirements. Three other goals were fulfilled: the analysis of the interaction between various sign properties and environmental aspects for the determination of the factors affecting the rate of traffic sign deterioration, the effect of cleaning on sign retroreflectivity, and the development of mathematical models for predicting the retroreflectivity of the traffic signs sheeting.

$$f_a = f_1 - f_{c1} \cdot T_a + f_{c2} d_e + C_k,$$

Where, f_a is R_A of a certain sheeting color or type; f_1 is

R_A during a given service life; f_{c1} is R_A of a given location for installation; f_{c2} is R_A of a given location for installation; C_k is Constant of direction; T_a is service time; d_e is distance between the sign and the highway edge.

The results showed that 92% of the signs under warranty exceeded the minimum performance requirements. For the signs that have aged beyond their respective warranty periods, 43% were in compliance with established standards. The researchers generated a linear degradation model for each type and color of sign sheeting. The analyses showed that sign orientation and offset distance to the road are statistically nonsignificant factors contributing to retroreflective deterioration. The correlation between the models and field data significantly varies; thus, these models should be applied only to local and site-specific data.

Bischoff and Bullock[17] of Purdue University applied an approach similar to that of Wolshon et al., but the main objective of the former were to determine whether Indiana's current type-III 10-year service life requirement should be shortened or extended. The authors analyzed 1 341 sign boards to determine whether they satisfy the proposed minimum retroreflectivity. Only seven of the signs violated the requirement for each color category. The authors also established a deterioration model, which generated a maximum R^2 of 0. 32 for red sheeting and a minimum R^2 of 0. 02 for white sheeting. The service life of regulatory signs with white and yellow backgrounds can be extended to 12 years. Red sheeting, however, should be replaced after 10 years.

In 2006, Rasdorf et al. [18] analyzed the retroreflectivity of 1 057 type-I (high-intensity grade in China) and type-III (engineering grade in China) sheeting of each color category for the North Carolina Department of Transportation. Linear, logarithmic, polynomial, and exponential models were used to predict retroreflectivity deterioration. The models exhibited poor correlations and R^2 ranged from 0. 01 to 0. 48. Red sheeting had the highest R^2, whereas white sheeting showed the lowest R^2. Sheeting should not exceed 10 – year exposure.

In 2010, researchers evaluated 859 type-III retroreflectivity signs in seven different regions of Texas [19]. Among the samples, 99% satisfied the MUTCD requirements, 2% failed between 10 and 12 years from installation, and 8% reached a service life of 12 to 15 years. The linear prediction models revealed differences in deterioration rates among areas. The deterioration of white sheeting ranged from -2 dc/lx/m^2 to -8 dc/lx/m^2, and that of yellow sheeting ranged from -1 dc/lx/m^2 to -12 dc/lx/m^2 per year. The predicted and measured values showed poor correlation, and R^2 ranged from 0. 1 to 0. 3. Despite the weak relationships, the models showed deterioration trends. The prediction models can serve as reference in maintenance programs, but they do not clearly identify the period at which signs should be replaced.

According to previous studies, the deterioration of sign retroreflectivity is affected by factors, such as temperature, humidity, altitude, age, and climate. The models are poorly correlated with the observation measurements. They can be valuable for sign maintenance, but they cannot be considered accurate guidelines for determining the periods at which signs should be replaced. In China, research on the deterioration of sign retroreflectivity is a recently initiated effort.

3 Data collection

In 1998, 230 retroreflectivity traffic signs from the mainstream brands of different manufacturers were installed in the Beijing Proving Ground. Beijing is located in a temperate continental climate zone and has four seasons, with an annual average temperature of 10 ℃ to 12 ℃.

As previously stated, we collected 12 years' worth of retroreflectivity values for this study. A hand-held contact retroreflectometer was used to measure the retroreflectivity of traffic signs in the test area. The observation angle was 0. 2° and the entrance angle was $-4.0°$, as prescribed by Chinese national standards.

According to these standards [3], expressway regulatory signs are made of green and white sheeting. Fifty green and white retroreflective signs installed in the Beijing Proving Ground were evaluated. type – I, – II, and – III sheeting materials were chosen because these variants are widely used.

4 Results

4.1 Theory

To obtain the prediction model of retroreflectivity

Fig. 1 Experimental signs

deterioration, we implemented two steps. First, the model that exhibits the best fit with deterioration was selected. Second, the mathematical model was accordingly established.

Following the literature, we considered time as an independent variable and the R_A as a dependent variable. SPSS 16.0 was used in the computation. Considering the relation between the attenuation of the R_A and the service time, the continuous mathematical function model is chosen. From the time-R_A plot diagrams, we found that the diagram is similar to the decreasing-slope curve. Therefore, we tried the linear model, the quadratic curve model, and the cubic curve model. The model that generates a value most similar to the curve slope was chosen as the prediction model.

4.2 Deterioration model of green sheeting

On the basis of the theory (chapter 4.1), we studied the deterioration model for green sheeting.

(1) Type-III sheeting

Time was considered the independent variable and the difference between two R_A measurements was regarded as the dependent variable. Three models were employed, namely, the linear, quadratic, and cubic models. The fitting of the model and actual curves are shown in figure 2(a).

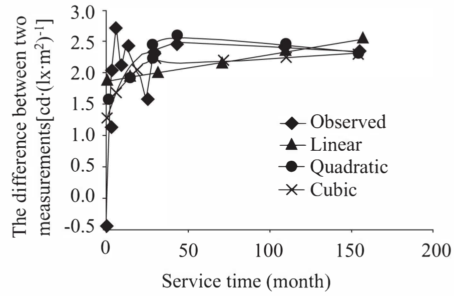
The quadratic and cubic curve models generated a curve significantly closer to the observed curve than that yielded by the linear model. The cubic model generated the highest R^2 (0.516).

The mathematical model can be expressed as

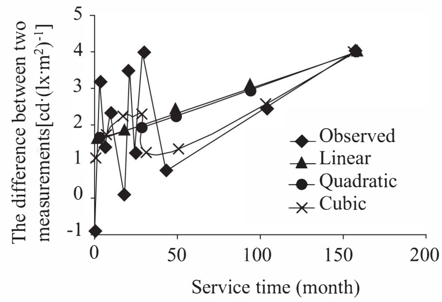
$$y = 19.57 - 0.137t - 0.0008t^2 + 8 \times 10^{-6}t^3. \tag{1}$$

(2) Type-II sheeting

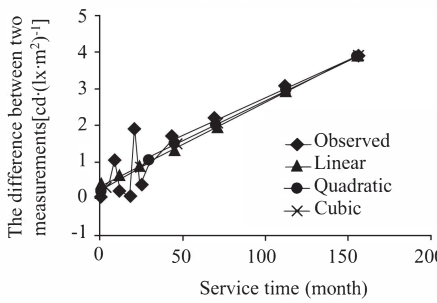
The model fit and actual curves for type-II sheeting are shown in figure 2(b).



(a) Type-III sheeting



(b) Type-II sheeting



(c) Type-I sheeting

Fig. 2 Fitting of model curve and reality curve

The quadratic and cubic curve models generated a curve significantly closer to the observed curve than that produced by the linear model. The cubic model had the highest R^2 (0.853). The mathematical equation can be written as

$$y = 43.54 - 0.63t - 0.0066t^2 + 2 \times 10^{-5}t^3. \tag{2}$$

(3) Type-I sheeting

The model fit and actual curves for type-III sheeting are shown in figure 2(c).

The quadratic and cubic curve models generated a curve significantly closer to the observed curve than that generated by the linear model. The cubic model exhibited the highest R^2 (0.369). The mathematical equation can be written as

$$y = 49.1926 - 0.005t - 0.0066t^2 + 3.8 \times 10^{-5}t^3. \tag{3}$$

4.3 Prediction model results for different colors

The prediction models for blue and white sheeting materials were also obtained (table 1).

Tab. 1 R_A deterioration models of guide signs with different grades of retroreflective sheeting

Color	Type	Prediction model	R^2
Green	III	$y = 19.57 - 0.137t - 0.0008t^2 + 8\times10^{-6}t^3$	0.516
	II	$y = 43.54 - 0.63t - 0.0066t^2 + 2\times10^{-5}t^3$	0.453
	I	$y = 49.1926 - 0.005t - 0.0066t^2 + 3.8\times10^{-5}t^3$	0.369
White	III	$y = 105.271 + 1.5943t - 0.1115t^2 + 0.0006t^3$	0.559
	II	$y = 167.2 - 2.4155t + 0.0452t^2 - 0.002t^3$	0.667
	I	$y = 393.0087 - 2.8453t - 0.0455t^2 - 0.002t^3$	0.581
Blue	III	$y = 8.8 - 0.1373t - 0.0001t^2 - 4.8\times10^{-6}t^3$	0.48
	II	$y = 12.64 - 0.294t + 0.0015t^2$	0.36
	I	$y = 19.3821 - 0.05t$	0.42

4.4 Analysis

Table 1 shows that different levels and colors of regulatory signs require different deterioration models. Such difference may be attributed to sheeting structure and production process.

The prediction models showed poor correlation between the predicted and measured values, and generated a low R^2. These findings are consistent with previous studies. Because of time, light, altitude, temperature, humidity, and other factors, identifying an accurate mathematical model of deterioration is difficult. Nevertheless, the obtained results can serve as reference for traffic sign maintenance. Given the limitation of the data source, more data should be collected from different areas in China to obtain generalizable results.

In previous studies[12], the linear models were commonly used to predic R_A. This paper evaluated varies models for R_A prediction and found quadratic model and cubic model have significant advantages for the R_A prediction. The results can help and guide us the practice in the further.

5 Conclusions

We studied the green, white, and blue retroreflective sheeting materials used for expressway regulatory signs. The prediction results generated by the linear, quadratic, and cubic models were compared to establish the prediction deterioration models of Type -I, -II, and -III sheeting. The quadratic and cubic curve models are better reference models for traffic sign maintenance than the linear model.

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