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Degradation of Retro-Reflectivity of Thermoplastic Pavement Markings: A Review

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Abstract

For an effective thermoplastic pavement marking replacement strategy, the rate at which the marking's retro-reflectivity deteriorates in service must be well established in order to avoid re-stripping that is too soon or too late. Against this background, this paper undertook a review of models that deal with degradation of thermoplastic pavement markings under different traffic and environmental conditions in order to establish service life and the terminal retro-reflectivity levels that have informed re-striping. Service life in the context of this paper is the time taken for a newly-installed marking to degrade to some minimum retro-reflectivity level below which motorists would find it difficult to navigate on the carriageway under night-time and poor visibility conditions. It was established that the minimum retro-reflectivity requiring re-stripping intervention reported varied, although commonly-adopted values tended to range from 50 mcd/m^2/lx to 150 mcd/m^2/lx. A number of empirical models, based on site specific conditions, have been developed by researchers using field data, to estimate marking retro-reflectivity at any time since placement. Whereas some of the models used time as the only independent variable, others used a combination of time, traffic level and a few other parameters to estimate retro-reflectivity. Even though degradation of marking retro-reflectivity is a reflection, among other things of material degeneration impacted by environmental and service conditions, almost all the models reviewed failed to consider environmental factors. Additionally, for some of the models, non-inclusion of the initial retro-reflectivity level and their generally low coefficient of determination statistic erode the confidence in their reliability.

Keywords

Degradation, Re-Striping, Retro-Reflectivity, Service Life, Thermoplastic Pavement Marking

1. Introduction

Retro-reflective pavement markings are used as key visual elements to guide motorists when roadway visibility is compromised by night-time and adverse weather conditions in order to help drivers keep their position on the carriageway and avoid lane departure accidents. The ability of pavement markings to retro-reflect headlamp illumination begins to decline following marking installation due to several factors that operate within the service environment and, with time, may be lost completely. Factors that cause deterioration in marking retro-reflectivity are varied but may include bead loss, loss of base material due to chipping and abrasion, deposition of detritus on the marking, discoloration of paint material and loss of contrast between the base material and its surrounding [1]. In order that they will continue to provide navigation guidance to motorists, pavement markings should be scheduled for maintenance when they reach some minimum threshold in retro-reflectivity [2]. This pre-supposes that the Transportation Department or Road Agency concerned has information about the minimum retro-reflectivity level found acceptable to motorists within its area of jurisdiction and that a methodology exists for establishing the service life of the marking so as to avoid replacement that is too soon or too late. In the context of this paper, service life is the time taken by a newly-placed thermoplastic pavement marking to degrade to a pre-determined minimum retro-reflectivity level below which motorists would find it difficult to navigate on the carriageway under night-time and poor visibility conditions [3].

It is recognized that because of the varied operational environments within which pavement markings function, it may be difficult to find a single deterioration model of universal applicability to guide re-stripping interventions. A simple approach is to estimate the service life of a marking based on the past performance of similar materials or to undertake periodic retro-reflectivity measurements. Under limited budget, the latter approach may make it difficult for the management of pavement markings. There is, therefore, a clear need for a more rigorous methodology to define and predict the service life of a pavement marking [4] within its service environment. Against this background, this paper undertook a review of models that have been used by researchers to deal with degradation of thermoplastic pavement markings under different traffic and environmental conditions and the terminal retro-reflectivity levels that have informed re-striping. The intention was to define a pathway to further studies into pavement marking retro-reflectivity degradation as impacted by the service environment.

2. Minimum Acceptable Retro-Reflectivity

The service life of retro-reflective pavement markings is defined as the time taken for a newly-installed marking to degrade to some minimum retro-reflectivity level below which motorists would find it difficult to navigate on the carriageway under night-time and poor visibility conditions. Even though marking performance may be based on both durability and visibility, it is visibility which defines the lower limit of the acceptable performance range and, hence, the point at which re-stripping intervention is required. Transportation Departments may set their own standards that meet the visibility needs of the range of drivers using their road networks based on driver subjective ratings of pavement markings under night-time conditions. In principle, minimum retro-reflectivity is dictated by driver preview distance requirements which are speed-dependent. At higher speeds, longer viewing distances are required which in turn require higher levels of pavement retro-reflectivity [5]. While control can be exercised on the initial retro-reflectivity level through manipulation of paint characteristics, reflective beads content and material at the marking stage, terminal values are dependent on the minimum found acceptable to motorists under night-time conditions.

Research works on marking retro-reflectivity reported in literature have used different minimum values in dealing with marking degradation. Minimum values which ranged from 85 to 150 mcd/m^2/lx were used by Migletz *et al.* [6] in some parts of the United States to study white and yellow thermoplastic marking degradation. Sarasua and Bell [1], Andrady [7] and Fitch and Ahearn [8] used 100 mcd/m^2/lx as the minimum to guide marking degradation model development. Others, such as Abboud and Bowman [9] and Chimba *et al.* [10] have used a much higher value of 150 mcd/m^2/lx in retro-reflectivity degradation studies.

To improve road safety in the United States, the Federal Highway Administration (FHWA) has proposed updates to minimum retro-reflectivity values contained in the Manual on Uniform Traffic Control Devices (MUTCD) that set 50 mcd/m^2/lx and 100 mcd/m^2/lx for posted speed limits of 35 mi/h (56.4 km/h) or greater and 70 mi/h (112.7 km/h) or greater, respectively [11]. In some transportation jurisdictions, for example [12], markings having retro-reflectivity levels less than 60 mcd/m^2/lx are considered bad and require immediate renewal and in Ghana, Salifu and Owusu [13] established a minimum standard of 150 mcd/m^2/lx for highways in the country based on subjective ratings of markings by drivers during nighttime driving.

3. Empirical Marking Degradation Models

Development of models to track the life expectancy of retro-reflective pavement markings originated in the United States of America (USA) in the 1990s. Since then, several empirical studies have focused on pavement marking performance but only a handful has attempted to develop life-cycle models [14]. This could be attributed to the fact that the field of pavement marking service life is relatively new, with the majority of work having been undertaken mostly during the past decade [15]. An early degradation model was developed by Andrady [7] to evaluate the performance of pavement markings in terms of retro-reflectivity using a logarithmic model shown below for thermoplastics:

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

where,

T_{100} = time in months for retro-reflectivity to reach 100 mcd/m^2/lx;

R_0 = estimate of the initial retro-reflectivity (mcd/m^2/lx);

b = gradient of the semi-logarithmic plot of retro-reflectivity (a value whose determination was not sufficiently explained).

For this model, the end of the service life of the marking was reached when retro-reflectivity degraded to a value of 100 mcd/m^2/lx. Andrady [7] used the equation to predict the life time of thermoplastic markings to be in the range of 7.8 to 40.6 months. However, the major limitation of the model was the fact that, other than the initial retro-reflectivity of the marking, no variable associated with the operational environment featured in the model. Moreover, neither the goodness of fit measure required to assess the explanatory power of the model nor the degree of variation in the predicted dependent variable was provided.

Subsequent to the work of Andrady [7], Lee *et al.* [16] studied the performance of pavement marking materials in Michigan, USA using several sample sites involving a number of marking materials including thermoplastics. A linear model was developed for thermoplastics as;

$$\text{RL} = 254.82 - 0.36X \quad \left(R^2 = 0.14\right) \quad (2)$$

where,

RL = retro-reflectivity (mcd/m^2/lx);

X = age of marking in days.

The study reported a very low coefficient of determination (R^2 = 0.14) and large variances in the service life of the markings which place little confidence in the model.

Migletz *et al.* [6] evaluated the durability of a variety of marking materials over a four-year period throughout some States in the USA with minimum retro-reflectivity threshold values ranging from 85 to 150 mcd/m^2/lx for white and yellow thermoplastic lines. The service life was modelled as a function of time and traffic in terms of cumulative daily traffic. A linear model was developed by regression techniques but variations were found in the performance of identical materials at different sites which were attributed to differences in roadway type, region of the country, marking specifications, quality control and winter maintenance. The average lives of white and yellow thermoplastic markings were established to be 26.2 months and 27.5 months, respectively. The study, however, failed to report the coefficient of determination (R^2) and the nature of the linear model developed, thus making it difficult to establish its reliability.

Abboud and Bowman [9] developed an exponential regression model to relate pavement marking retro-reflectivity to vehicle exposure (VE) measured as a function of time and AADT in Alabama. A unique feature of the model was the absence of marking color and surface material, both of which had been established as independent variables for pavement marking degradation by others [9].

The model for white thermoplastic edge lines was;

$$\mathrm{RL} = -70.806 * \ln(\mathrm{VE}) + 150.55 \quad (R^2 = 0.58) \tag{3}$$

where,

RL = pavement marking retro-reflectivity (mcd/m^2/lx);

VE = vehicle exposure = AADT × PM_age × 0.0304;

AADT = annual average daily traffic;

PM_age = age in months.

The study used a minimum retro-reflectivity threshold of 150 mcd/m^2/lx and estimated the useful marking lifetime for low AADT (5000 vpd) highways to be 4.5 months.

Fitch and Ahearn [8] used a logarithmic model and data collected for three years and a minimum acceptable retro-reflectivity of 100 mcd/m^2/lx to evaluate the performance of pavement marking materials in Vermont, USA. The authors studied the effect of traffic volume and geographic regions on retro-reflectivity degradation and established that the higher the AADT, the higher the degradation rate, making traffic volume significant. With respect to geographical regions, warmer regions were found to have low degradation rates compared to relatively colder regions. Though the coefficient of determination (R^2) was 0.80 for thermoplastic markings, the study failed to indicate the nature of the logarithmic model developed.

Sitzabee *et al.* [17] used the performance characteristics of thermoplastic pavement markings on asphaltic roadways to create a general linear degradation model with time, initial RL value, AADT, colour, and lateral location as independent variables. The model was given as;

$$\begin{aligned} \mathrm{RL} = {} & 190 + 0.39\mathrm{RL}_o - 2.09\mathrm{Time} - 0.0011\mathrm{AADT} \\ & + 20.7X1 - 20.7X2 + 19X3 - 19X4 \quad (R^2 = 0.60) \end{aligned} \tag{4}$$

where,

RL = retro-reflectivity (mcd/m^2/lx);

$\mathrm{RL_o}$ = initial retro-reflectivity (mcd/m^2/lx);

Time = time in months since installation;

AADT = annual average daily traffic in vehicles per day;

$X1$ = 1 if edge line, 0 otherwise;

$X2$ = 1 if middle line, 0 otherwise;

$X3$ = 1 if white line, 0 otherwise;

$X4$ = 1 if yellow line, 0 otherwise.

In 2009, Rasdorf *et al.* [18] determined the performance characteristics of paint and thermoplastic pavement markings and considered time, traffic volume, color and lateral line location as the variables known to have impacts on service life. A linear regression was used to model the degradation rates of the materials and the service life of thermoplastics on asphalt with an AADT of 10,000 vehicles per day. The service life was established to range from 5.4 years to 8.5 years depending on the lateral location of the line. The study, however, failed to provide the model as well as the value of R^2 associated thereof, making it difficult to ascertain the predictive power of the model.

Karwa and Donnell [19] collected data in three districts in North Carolina over a 7-month period for predicting thermoplastic pavement marking retro-reflectivity. The data varied by initial retro-reflectivity, age of markings, traffic flow and route location. Retro-reflectivity was predicted using an artificial neural network considered as a nonlinear relationship.

$$\text{Retroi} = \beta Xi + \varepsilon_{ij} \quad \left(R^2 = 0.26\right) \tag{5}$$

where

Retroi = retro-reflectivity at any time (mcd/m²/lx);

β = parameters to be estimated;

Xi = vector of explanatory variables.

Retro-reflectivity degradation was established to follow a nonlinear trend and differed among marking types. White pavement markings were shown to have higher estimated service lives than yellow pavement markings.

Sarasua and Bell [1] used a minimum retro-reflectivity of 100 mcd/m²/lx for white thermoplastic marking to establish the number of days taken for the marking to reach the minimum threshold by the expression;

$$\text{Diff} = -0.06\left(\text{Days}\right) - 6.80 \quad \left(R^2 = 0.47\right) \tag{6}$$

where,

Diff = difference in retro-reflectivity (mcd/m²/lx);

D = number of days.

Hollingsworth [20] developed the following linear regression model for thermoplastic pavement markings in North Carolina with AADT (average annual daily traffic), bead type, color, initial retro-reflectivity level, lateral line placement and time as the significant variables;

$$\begin{aligned} \text{RL} = {} & 244.9 - 0.0006\text{AADT} - 55.10\text{BeadDV} - 71.17\text{ColorDV} \\ & + 0.28\text{InitialRL} + 44.06\text{LPDV} - 1.28\text{Time} \quad \left(R^2 = 0.53\right) \end{aligned} \tag{7}$$

where,

RL = retro-reflectivity (mcd/m²/lx);

AADT = average annual daily traffic;

BeadDV = bead type [1 = large; 0 = standard];

ColorDV = marking color [1 = yellow; 0 = white];

Initial RL = initial retro-reflectivity (mcd/m²/lx);

LPDV = Lateral line location [1 = edge line; 0 = center line];

Time = number of months since installation.

Ozelim and Turochy [21] studied the modelling of retro-reflectivity performance of thermoplastic pavement markings in Alabama with data collected by the Alabama Department of Transport for 15 projects that had measurements of retro-reflectivity for the same locations. The model considered initial retro-reflectivity, age and annual average daily traffic as independent variables. A correlation coefficient (R^2) value of 0.45 was obtained for white markings while initial retro-reflectivity was insignificant for retro-reflectivity estimation.

Relatively more recently, Malyuta [22] modelled empirically the degradation of thermoplastic pavement marking retro-reflectivity in Tennessee for asphalt concrete highways as:

$$\text{RL} = 234.10 - 0.1985\text{Age} + 0.0013\text{AADT} \quad \left(R^2 = 0.72\right) \tag{8}$$

where,

Age = time since the installation of the markings;

AADT = average annual daily traffic count.

In 2016, Wang *et al.* [23] developed a piecewise multiple linear model to explicitly account for the effect of winter weather events on pavement marking retro-reflectivity. The model developed is as follows;

$$\text{RLi} = \alpha + \beta 1\text{ADTi} + \beta 2\text{Daysi} + \beta 3\text{MaxRetroi} \tag{9}$$

where,

ADT = average daily traffic per lane (veh/day/ln);

Days = elapsed days since installation;

MaxRetro = maximum retro-reflectivity from installation.

The range of R^2 values was between 0.57 and 0.68 with a service life of 24 months.

Table 1 presents a summary of the reviewed models for service life estimation of thermoplastic pavement markings in terms of retro-reflectivity.

Table 1. Summary of the charateristics of the models reviewed.

Source	Model Type	R^2	Independent Variables
Andrady [7]	Logarithmic	Not Provided	RL_o
Lee *et al.* [15]	Linear	0.14	Time
Migletz *et al.* [6]	Multiple Linear	Not Provided	Time, AADT
Aboud & Bowman [9]	Exponential	0.58	AADT
Fitch & Ahearn [8]	Logarithmic	0.81	AADT, Geographical Region
Sitzabee *et al.* [17]	Linear	0.60	RL_o, Time, AADT
Rasdorf *et al.* [18]	Multiple Linear	Not Provided	Time
Karwa & Donnell [19]	Non-Linear	0.26	RL_o, Time, AADT
Hollingsworth [20]	Multiple Linear	Not Provided	RL_o, AADT, bead type, color, lateral line placement, and time
Sarasua & Bell [1]	Linear	Not Provided	Time
Ozelim & Turochy [21]	Not Provided	0.45	RL_o, Time, AADT
Malyuta [22]	Linear	0.72	Time, AADT
Wang *et al.* [23]	Linear	0.57 to 0.68	RL_o, Time, ADT

4. Discussion

Two major issues confront pavement marking re-striping management: 1) the minimum retro-reflectivity level below which marking performance is unacceptable to motorists, and 2) the time taken for a newly-placed marking to reach the minimum retro-reflectivity. The research efforts seen in this review largely focused on the second issue. This is understandable because the first issue, which is primarily associated with drivers' visual acuity levels, is easily addressed by conducting studies on the minimum retro-reflectivity levels found accepted to drivers from different age cohorts within the driver population. As became evident in this review, the minimum marking retro-reflectivity level that defined the point at which re-marking intervention may be required spanned the range 50 - 150 mcd/m^2/lx. In the case of the second issue, researchers have largely attempted to use field data to develop empirical relationships for estimation purposes.

It has become clear in this review that degradation of thermoplastic marking retro-reflectivity is influenced by a variety of factors including traffic (AADT), pavement surface type, time, weather conditions and initial retro-reflectivity level. Four major types of models which used one or more of the listed factors in estimating the in-service retro-reflectivity level of installed thermoplastic markings were identified: simple linear, multi-linear, exponential, and logarithmic models. For most of the models, the independent variables used included time and traffic (AADT) while for a few they included either time or AADT. Values of the coefficient of determination (R^2) associated with those models for which this statistic was provided ranged between 0.14 and 0.81, suggesting some models to be very poor and others to be fairly good. In addition, models that are linear tend to suggest a constant rate of deterioration but Chimba *et al.* [10] have noted that marking degradation follows an exponential curve rather than linear with degradation rates decreasing with increasing time.

Degradation of marking retro-reflectivity may also be seen as contributed to by chemical changes or aging of the marking material which is impacted by the climatic condition of the environment within which the material operates. This fact appears not to have been captured by virtually all the models reviewed as they did not explicitly include climatic/environmental factors unless it is argued, albeit weakly, that such factors are indirectly encapsulated in the variable called time. In addition, it was noted that some of the models excluded the initial retro-reflectivity of the marking but logically, all things being equal, markings with high initial retro-reflectivity are expected to take a longer time to degrade to a given minimum value than those placed with low initial values. In principle, because degradation simply defines the path of material life or degeneration of the quality of the material with time, it must be characterized by a beginning state which serves as a reference point. This, therefore, enjoined each of the models seen in the review to have been characterized by an initial marking retro-reflectivity value.

In summary, the low values of the coefficients of determination (R^2) associated with most of the estimation models reviewed are indicative of poor explanatory power and suggestive of some degree of paucity in variables used in model formulation. Also, it is not difficult to realize that single variable models, models that fail to include some attributes of the environment within which the markings operate, and those that exclude the initial retro-reflectivity levels have obvious limitations and are not likely to provide reliable in-service estimates of marking retro-reflectivity levels.

5. Conclusions

The field of thermoplastic pavement marking service life estimation has been continuously evolving and improving over time, yet several limitations still exist as most of the empirical models developed for service life estimation tend to be limited in application to other localities and also fall short in reliability. The difficulty in developing suitable estimation models that sufficiently predict the service life of thermoplastic markings limits the cost-effectiveness of re-striping intervention as the intervention may be carried out too soon or too late. It became clear from the review that there does not appear to be a uniform minimum acceptable retro-reflectivity threshold to be used to guide re-stripping, though values in the range 50 - 150 mcd/m^2/lx seem to be common.

In terms of the mathematical form of empirical models developed for retro-reflectivity or service life estimation, differences existed but four major types were identified: simple linear, multi-linear, exponential, and logarithmic models. For some, the explanatory variables used included time and traffic (AADT) while for others they included either time or AADT. However, in all considerations, traffic and time seem to be key factors in most of the estimation models, although the exact role of traffic in affecting marking degradation is not clear. Traffic could be considered significant if it is argued that it contributes to continual deposition of exhaust fumes and detritus from the road surface on the marking which may then diminish bead reflectance and contrast between marking and surrounding.

Without doubt, the service live of thermoplastic pavement markings can vary greatly depending on several factors but more on the retro-reflectivity value achieved at the time of installation. Logically, newly-placed markings with high initial luminance should be expected to take longer to degrade to some minimum threshold under given conditions than those placed with relatively low luminance. Therefore, the level of the initial marking retro-reflectivity must be seen as having significant impact on how long to wait before re-stripping but, surprisingly, some models ignored this parameter.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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