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Estimating the Effective Life of Pavement Marking Based on Crash History

Prepared by

Brian Bowman, Ph.D., P.E.
Nasser Abboud

Department of Civil Engineering
Auburn University

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1. INTRODUCTION AND BACKGROUND

1.1 ROLE OF PAVEMENT MARKINGS

Traffic control devices are used to direct motorists and assist them in the guidance and navigational tasks required for safe travel. Traffic control devices include signs, signals, pavement markings and other devices placed on, over or adjacent to highways to regulate, warn or guide traffic. To be effective, traffic control devices must fulfill a need, command attention, convey a clear meaning, command respect, and give adequate time for proper response (*1*). Pavement markings are unique traffic control devices, in that they continuously convey critical driving information to the driving public without the need to shift driver attention away from the roadway. Longitudinal pavement markings, such as edge lines and centerlines, provide positive delineation and present drivers with the visual input necessary for proper vehicle positioning on the roadway, including the direction of travel, the boundaries between traffic lanes, and permission and prohibition of passing maneuvers.

Since the inception of the centerline stripe idea by Edward Hines, a road commissioner in Wayne County, Michigan, and the application of the first hand painted centerline stripe by Frederick Basley along one block of University Avenue in Madison, Wisconsin in 1921, interest in pavement markings has grown to an international level (*2*). The use of pavement markings has become widespread, and their importance in traffic guidance and safety has been recognized by highway agencies worldwide. With the increase in highway mileage and traffic volumes, the need for faster application rates and drying times arose, especially where the suitable season for paint application is relatively short. This need gave rise to an evolution of delivery equipment from the original hand powered stripers, which primarily consisted of a wheelbarrow frame, a five-gallon tank, and a canvas-wrapped solid wooden wheel, to modern striping trucks with capacities of up to 1,200 gallons (4,500 liters) of paint and striping speeds of up to 35 miles per hour (mph) or 56 kilometers per hour (km/h)

Pavement marking materials have evolved significantly throughout the last eight decades, from the original plain black paint used for striping the first centerline in 1923 to a variety of marking materials, such as paints, tapes, and field-reacted and field-melted materials. Epoxy paints and thermoplastics are examples of field-reacted and field-melted durable materials, respectively, that enjoy long service life and high resistance to wear. Pavement marking materials have also become more visible at night since the introduction of glass beads into the pavement marking material in 1938 (patented in 1933 by Edwin R. Gill). These spherically shaped micro glass beads help redirect light from vehicle headlamps back in the direction of the driver resulting in improved nighttime visibility of the markings. The phenomenon of redirecting light back in the direction of the source is referred to as retroreflection. Longitudinal pavement marking colors used for delineating travel lanes are limited to white and yellow. White is used to delineate edges of adjacent travel lanes of same-direction traffic as well as right edge lines, while yellow is used to delineate adjacent lanes of opposite-direction traffic and left edge lines of divided highways, and one way streets and ramps.

Positive delineation provided by longitudinal lines contributes to traffic safety, particularly where high speeds, horizontal and vertical curvature, and narrow roadside recovery areas exist. On rural highways, where street lighting and signing are scarce, longitudinal pavement markings become the primary traffic control device available to motorists. National transportation organizations have recognized the important role of pavement markings and have established subcommittees to promote the development and application of improved pavement markings. The involvement of these organizations includes material testing, safety research and specification development. These organizations include the American Association of State Highway and Transportation Officials (AASHTO), the American Society for Testing and Materials (ASTM), the Transportation Research Board (TRB), the Institute of Transportation Engineers (ITE), and the national advisory committee of the Manual on Uniform Traffic Control Devices (MUTCD).

1.2 STATEMENT OF PROBLEM

Positive delineation provided by longitudinal pavement markings is crucial to proper traffic guidance during nighttime driving. At night, visual input available to drivers is minimized and the potential for vehicles to stray off their paths increases. Nighttime crashes constitute a significant portion of highway crashes. Computed on a per-mile basis, the nighttime crash rate at the national level is about three times the daytime rate (*3*). When considering the number of crashes, the ratio of nighttime-to-daytime crashes in Alabama is approximately 0.48 for 1998 (10,938 crashes occurred between dusk and dawn compared to 23,102 crashes during the day) (*4*). Statistics on the proportion of daytime to nighttime miles driven in Alabama are not available. The nighttime crashes have resulted in a significant number of casualties, totaling 15,232 personal injuries and 514 deaths in Alabama in 1998.

Although studies have shown longitudinal pavement marking lines with high retroreflective properties (the ability to redirect light rays back in the direction of the driver) to be an effective means of reducing single-vehicle nighttime crashes, efficacy of longitudinal pavement markings is contingent on their continual ability to retroreflect and effectively convey the necessary traffic control information. As pavement markings age, their reflective qualities deteriorate due to loss of adhesion with the pavement and loosening and detaching of the glass beads embedded in the markings. Glass beads are typically embedded 55% to 60% (vertical height) in pavement markings. Eventually, degradation of the markings reaches a point beyond which they become ineffective in guiding traffic at night. This degradation process is accelerated by extreme weather conditions and vehicle off-tracking where vehicle tires travel directly on the longitudinal lines. The abrasive effect of vehicle tires is most visible around horizontal curves due to off tracking, and in the vicinity of intersections and driveways due to turning traffic. The effects of extreme weather are more complex. In colder climate states, snow removal operations cause the most damage to pavement markings. The abrasive effects of studded tires and chains and the shaving (scraping) effects of snowplows are the primary causes of marking material removal. In addition, the presence of salt and deicing agents on the road surface disintegrates the material chemically and loosens its bond with the pavement. In warmer climate states, marking material damage is caused by expansion and contraction of the marking and pavement at different rates, which results from extreme temperature fluctuations. Also, breakdown of the chemical bond of resins and pigment components of the marking has been attributed to ultraviolet rays. The rate of deterioration can be retarded by using high quality markings. Pavement marking quality depends on its thickness, method of application, pavement type and condition, glass beads amount, quality and embedment depth, and pavement and weather conditions at the time of application.

With the absence of national guidelines for identifying the point beyond which pavement markings become ineffective, various agencies have established re-striping schedules based on local experience, engineering judgment, and availability of funds, among other considerations. Adjustments to these schedules are typically made in response to citizen complaints, political pressure and/or excessive or fatal crash occurrences. Setting a fixed schedule, such as re-striping every year for paint and every other year for thermoplastic, for example, would result in having some highways with adequate striping being prematurely re-striped while others with deficient striping being overlooked and not addressed promptly.

1.3 OBJECTIVE OF RESEARCH

The purpose of this research study is to identify a threshold of pavement marking retroreflectivity for use by Alabama Department of Transportation (DOT) Product Evaluation Program for striping material approval, and by maintenance personnel to determine when highway striping becomes ineffective so that re-striping could be scheduled appropriately. In this study, determination of the retroreflectivity threshold is based on the results of a survey of the state of practice in southern States of the U.S., and on the relationship between striping retroreflectivity and crashes along Alabama highways.

The retroreflectivity threshold established in this study is used for determining the useful lifetime of the two most commonly used striping materials: paints and thermoplastics and for cost comparisons between them. As a result of adopting a safety-based retroreflectivity threshold, practitioners can expect reductions in striping-related crashes and an overall improvement in traffic safety and operations. To encourage the use of the study results by practitioners, the study is designed to produce a user-friendly means of predicting striping material useful lifetime, as in a chart format for example. Practitioners should be able to use such a chart to estimate striping-related crash potential of a highway by taking simple retroreflectivity measurements of the stripes, or, when measuring devices are not available, striping useful lifetime and crash potential can be estimated based on the highway average daily traffic and striping date. Therefore, practitioners are provided with the means to make insightful decisions on re-striping scheduling to help them better appropriate their funds and target problem areas in real need of re-striping. This research is based on the premise that prolonged exposure of pavement markings to vehicular traffic reduces their retroreflectivity, which in turn increases the potential for striping-related nighttime crashes. Striping-related crashes are those crashes that involve lane departures.

1.4 SCOPE OF WORK

This study evaluated all striping projects on file with the Alabama DOT for inclusion in the research. A project was included if striping-related information was obtainable, such as type and color of pavement markings, striping date, and project limits. To compile a database of striping projects, field logs of the Alabama DOT paint crews were searched for the years 1996 through 1999. Projects with incomplete information were excluded from further consideration. The total number of projects evaluated in this study was 220 projects totaling 1,275 highway miles (2,050 km) in 32 Alabama counties.

Pavement marking retroreflectivity data included test and field data. The test data included 2 years of retroreflectivity readings collected on Alabama and Kentucky test decks between 1989 and 1995. The total number of pavement marking samples tested was approximately 2,000. The field-collected retroreflectivity data included readings along 520 miles (835 km) of rural highways in nine Alabama counties for evaluation of striping under in-situ conditions. A total of 4,518 retroreflectivity readings were taken at 827 test sites. Highway-related information such as traffic volume and striping details was obtained for these test sites to relate retroreflectivity to pavement marking age and exposure to traffic.

Striping-related crash data were compiled for approximately1,275 miles (2,050 km) of state highways in 32 Alabama counties for the purpose of evaluating the relationship between pavement marking deterioration and crash occurrence. The highways included in this study are located in the Alabama DOT's first, third, fifth and seventh divisions. Striping project details from the remaining divisions could not be obtained. The first division includes Cullman, DeKalb, Jackson, Limestone, Madison, Marshall and Morgan counties; the third division includes Blount, Cherokee, Etowah, Jefferson, Shelby, St. Clair, and Walker counties; the fifth division includes Bibb, Chilton, Fayette, Greene, Hale, Lamar, Perry, Pickens and Tuscaloosa counties; and the seventh division includes Barbour, Coffee, Covington, Crenshaw, Dale, Geneva, Henry, Houston and Pike counties. The 32 counties where crash data were collected are highlighted in Figure 1.1.

Highway-related information such as traffic volumes and striping details was obtained for the crash sites in order to relate crashes to pavement marking type, age and exposure to traffic. The relationships between pavement marking retroreflectivity and crashes that were developed in this study are based on the above data and are representative of the warmer climate of the southern states of the Unites States. Widening the scope of work to include national or regional data may lead to future improvements in the model.

Figure 1.1 Alabama counties where crash data were collected

2. REVIEW OF LITERATURE

To obtain information relevant to pavement marking performance, an in-depth review of the literature was conducted. Needed information included pavement marking types, properties, efficacy, service life, rate of deterioration, impact on traffic safety, and means of measurement. It also includes past and current practices of pavement marking use, and the standards governing their application and acceptance. This review of the literature gives special emphasis to the retroreflective property of pavement markings. Information sources searched included Auburn University civil engineering library, which contains the Transportation Research Records (TRR), Institute of Transportation Engineers (ITE) Journals, National Cooperative Highway Research Program (NCHRP) reports, Transportation Research Circulars (TRC), and Public Roads journals. Other sources included the Transportation Research Board (TRB) annual meeting preprint CD-ROMs for the years 1995 through 1999, the University of Alabama Critical Analysis Reporting Environment (CARE) computerized database, manufacturers and suppliers of pavement marking material and measuring devices, and the World Wide Web. The number of relevant documents cited in this study totaled 46.

2.1 TYPES OF PAVEMENT MARKINGS

Several types of pavement marking (PM) materials are currently in use on U.S. highways. These PM types can be categorized into four broad classes (*5*):

- Traffic paints: This group involves applying a solution or latex of a polymer binder with necessary additives, and the subsequent evaporation of volatiles to obtain the marking. It includes solvent-borne and water-based paints.

- Preformed materials: This group involves applying a preformed plastic or other material onto the pavement using an adhesive. It includes cold-applied plastics, raised pavement markers, and temporary and permanent tapes.
- Field-reacted systems: involves reacting monomers and other compounds in the field immediately prior to application on the pavement to synthesize a resin or polymer directly onto the pavement. It includes epoxy, polyester and methacrylate paints.
- Field-melted polymers: involves melting a solid polymer resin in the field and applying the melt directly onto the pavement. It includes hot-applied plastics and thermoplastics.

The most commonly used materials for longitudinal markings in Alabama are solvent-borne and water-based paints and alkyd and hydrocarbon-based thermoplastics. These materials are also the most commonly used nationwide, with solvent-borne paints, water-based paints and thermoplastics constituting 42%, 36% and 14% of all pavement markings used, respectively (*5*).

2.1.1 Paints

The primary components of pavement marking paints are a binder resin, pigments or fillers, and solvents/additives. The polymeric binder provides integrity and is the film-forming material. The pigments are used for desired optical properties such as high reflectivity as in the case of titania, and color as in the case of lead chromate or Hansa Yellow. Fillers such as calcium carbonate are used to extend the paint composition. A very important additive in all traffic paints is the glass beads. To impart retroreflectivity, these beads are premixed or dropped on fresh markings at a rate of 16 pounds (lb) per gallon (gal) of paint (or 1.62 kilogram per liter) as recommended by ASTM D 713 (*6*).

Other additives such as anti-settling agents, anti-skinning agents and stabilizers may also be included in the formulation. To enable paint to be brushed, sprayed, or rolled onto a surface, its viscosity must be suitably adjusted with a solvent. The amount and type of solvent used control the drying (no-track) time of paint, an important property used to classify paints. *Conventional* paints dry in at least 7 minutes, *fast-dry* paints dry in 2 to 7 minutes, *quick-dry* paints dry in 30 to 120 seconds, and *instant-dry* paints dry in less than 30 seconds. Solvents that are slow evaporating are not usually used in paints because they tend to dissolve tar and asphaltic-type substrates and cause bleeding (discoloration). Paint application film thickness typically ranges from 15 to 20 mils with the ASTM D 713 Standard recommending a wet film thickness of 15 mils for test stripes (1 mil = 0.001 inch = 0.0254 mm). ASTM D 868 specifies the use of photographic reference standards for evaluating the extent of bleeding in a laboratory setting.

2.1.2 Thermoplastics

A thermoplastic stripe is produced when a binder resin, compounded with pigments, fillers and additives, is melted and coated, sprayed, or extruded as a ribbon onto the pavement surface. The resin is either alkyd-based or hydrocarbon-based. Alkyd-based stripes are marginally higher in cost, but are more durable and more petroleum oil resistant than hydrocarbon-based thermoplastic markings. Thermoplastic stripes are 60-90 mils thick when sprayed, and about 125 mils when melted and extruded or curtain-coated. Hot-sprayed thermoplastic stripes can be expected to last from 3 to 15 times longer than conventional paint stripes. Because of their thickness, however, they are subject to scraping by snowplows in colder climate northern states.

2.2 PROPERTIES OF PAVEMENT MARKINGS

Quality evaluation of pavement marking materials is usually based on their nighttime visibility, daytime visibility, service life, and cost. The performance variables commonly used to evaluate these properties are retroreflectivity, appearance, durability, and application cost.

2.2.1 Retroreflectivity

Retroreflectivity is a proxy measure of nighttime visibility of pavement markings. Retroreflectivity is the ability to redirect light rays back in the direction of the light source. When light rays originating from vehicle headlamps strike the surface of a pavement marking, it is the retroreflectivity property of the marking that allows the light rays to be redirected back into the direction of the driver, thus giving the marking its bright appearance.

Two components of a pavement marking make retroreflection possible: glass beads and pigments. Glass beads cause the incident light to refract downwards towards the marking, and the pigments in the marking scatter the light allowing portions of it to reflect back in the direction of the incident light. A description of the retroreflection phenomenon is presented schematically in Figure 2-1.

2.2.2 Appearance

Appearance is a measure of the contrast between the pavement marking stripe and the pavement background, and is the performance measure used for evaluating daytime visibility. Daytime visibility is easily achieved on newer bituminous concrete (asphalt) pavement since white or yellow lines are more discernable against the black background

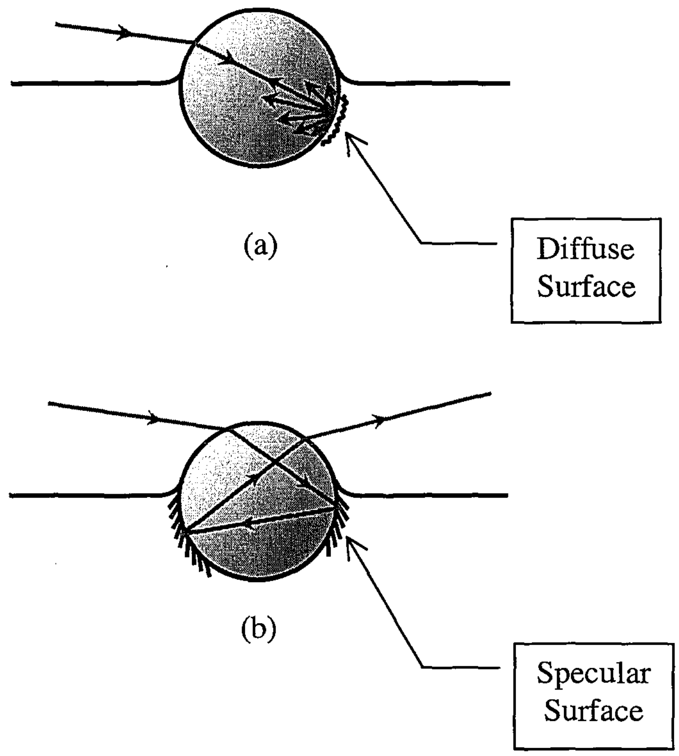


Figure 2-1 Behavior of light against diffuse pavement marking surface (a) versus specular pavement marking surface (b) at back of glass bead

of new asphalt. The appearance property is less critical on most rural highways, since they normally have asphalt surfaces. Appearance is of more importance on newer Portland cement concrete (concrete) surfaces, where the contrast of the pavement markings against the gray concrete surface is not as stark. Ideally, evaluating this property requires measurement of photometric contrast between the marking and thepavement, but in practicality, this variable is usually measured subjectively with experienced personnel visually inspecting the stripes and grading the contrast according to their professional judgement.

2.2.3 Durability

Durability is a measure of the pavement marking resistance to weather and abrasion, and the extended ability to adhere to the pavement surface. This property is dependent on the quality of the pavement marking, its composition, thickness and application workmanship, and externally, on environmental and traffic conditions as well as pavement surface condition. Durability is generally understood in terms of the marking service life. Field-reacted and field melted materials, such as epoxy paints, methacrylate paints, and thermoplastics have higher durability than traffic paints due to their increased thickness. Most agencies consider reasonable re-striping cycles of 6 to 12 months for paints and 3 to 7 years for thermoplastics (7). The difference in striping material thickness is the main reason for the durability difference. Traffic paints are typically 15 to 20 mils in thickness compared to 60 to 90 mils for sprayed thermoplastics. Durability is typically measured on a scale of 1 to 10, as one tenth of the percentage of the pavement marking material retained on the pavement.

2.2.4 Cost

Cost is an important consideration in the selection of pavement marking materials. Longitudinal pavement marking cost varies by type, width and color of the markings. Pavement marking lines are typically measured per-mile, with the exception of dotted lines which are measured in feet. In Alabama, the cost of longitudinal thermoplastic markings is three to four times that of paint for same width and color markings. Cost information is used to compare the average annual cost of paint and thermoplastic striping based on their expected service lives.

2.3 RETROREFLECTIVITY STANDARDS

2.3.1 ASTM standards

The ASTM publishes a number of industry standards relating to retroreflectivity, its measurement, and retroreflective materials (*6*). Following is a brief description of these standards.

ASTM E 808-98 provides the standard practice for describing retroreflection. It provides terminology, specifications for retroreflector performance, and measurement of retroreflection. ASTM E 808-94a describes the standard practice for measuring photometric characteristics of retroreflectors. This comprehensive guide to the photometry of retroreflectors describes the general procedures and parameters required for photometric measurements. ASTM D 6359-98 provides the standard specification for minimum retroreflectance of newly applied pavement marking using portable hand-operated instruments. Several other relevant standards relate to testing of the materials used in the traffic markings, such as the paint and glass bead requirements. ASTM D 1155-89 (re-approved 1994) and ASTM D 1214-89 (re-approved 1994) provide the testing method for roundness and sieve analysis of glass beads, respectively. ASTM D 913-88 (re-approved 1993), ASTM D 868 (re-approved 1993), and ASTM D 1309-93 (re-approved 1998) describe the testing method for evaluating the paint resistance to wear, degree of bleeding, and settling properties during storage, respectively. The standard practice for conducting road service tests on traffic markings is the standard used in the AASHTO testing of transverse lines as described in ASTM D 713-90 (re-approved 1998).

2.3.2 Measurement of retroreflectivity

Understanding the coefficient and units used in describing retroreflectivity requires some understanding of light measurement terminology used in visibility research. The coefficient used for measuring pavement marking retroreflectivity is the coefficient of retroreflected luminance, R_L. ASTM E 808 defines this coefficient as the ratio of the luminance, L, in the direction of the observation to the normal illuminance, $E_\perp$, at the surface of a plane normal to the incident light, (i.e. $R_L=L/E_\perp$). R_L is expressed in candelas per square meter per lux (cd/m^2/lx), where candela is the base unit in light measurement. Definitions of L, $E_\perp$, and other light measurement terms can be found in many light measurement books (8).

The R_L coefficient is measured in the field using retroreflectometers. It can also be calculated per the following equation (ASTM E 808):

$$R_L = \left(\frac{L}{E_L}\right) = \left(\frac{R_I}{A\cos v}\right) = \left(\frac{I}{E\,A\cos v}\right) = \left(\frac{R_A}{\cos v}\right) \qquad (2)$$

where A = surface area of the sample,

v = entrance angle between the *Reference* and *Illumination Axes*,

where *Reference Axis* is the axis normal to the sample, and

Illumination Axis is the axis from the light source to the sample.

2.3.3 Testing geometry of retroreflectivity

Determination of the photometric characteristics of retroreflective material that are associated with the observer's visual perception of retroreflected light is dependent on the light source (headlamp) illumination, the observer's eye response and field of view, and the distances separating the pavement marking, the headlamp, and the driver's eye.

Figure 2-6 illustrates the measurement geometry used in describing pavement marking retroreflectivity. In this diagram, the *reference axis* is normal to the pavement marking (or road surface) at the *reference center*, the *illumination* (or *incident light*) *axis* extends from the center of the headlamp to the reference center, and the *observation axis* extends from the reference center to the driver's eye position. The *illumination distance*, D, is the distance between the center of the headlamp and the reference center and the *observation distance*, D', is the distance between the reference center, and the driver's eye. The *entrance angle*, β, is the angle between the illumination axis and the reference axis. For pavement markings illuminated by automobile headlights, β is quite large, reaching approximately 90°. The *observation angle*, α, is the angle formed by the illumination axis and the observation axis. The distances D and D' are very long compared to either the eye height or the headlamp height, making α extremely acute. Typically, nighttime visibility of pavement markings is determined using a surrogate method of photometric measurement in an attempt to replicate real-life conditions. Devices called retroreflectometers are used to measure the pavement marking retroreflectance by employing an internal light source and illumination and observation angles consistent with those occurring during nighttime driving conditions.

Pavement marking retroreflectivity measurements have traditionally been taken using portable (handheld) retroreflectometers. These devices are placed directly on the markings to be tested. Until recently, these devices were exclusively based on 15-meter (m) geometry. The 15-m refers to a viewing distance of 15 meters (50 feet) from the light source (vehicle headlamps) to the retroreflective object being tested (pavement marking). This corresponds to an observation angle of 1.5 ° and an entrance angle of

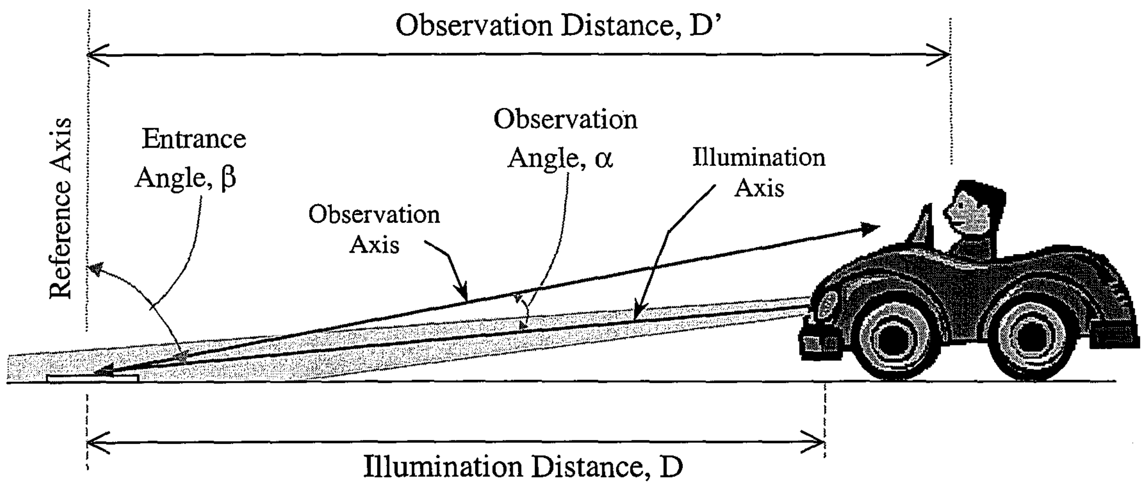


Figure 2-6 Retroreflectivity Measurement Geometry

86.5°. In 1997, however, a new 30-m standard geometry was prescribed by the European Committee for Normalization or *Committee European de Normalisation* (CEN) and later adopted by the ASTM.

The 30-m geometry corresponds to an observation angle of 1.05° and an entrance angle of 88.76°. These angles correspond to headlight and eye heights of 0.65 and 1.2 m, respectively. Note that AASHTO design standards specify headlight and eye heights of 0.6 and 1.07 m, respectively. Research performed by the Federal Highway Administration (FHWA) indicates that using the 30-m observation distance established by the CEN closely approximates the driver view of the pavement surface, and, therefore, is regarded as a more realistic viewing distance. No means of converting the 15-m geometry data into 30-m geometry was found in the literature, and no minimum acceptable retroreflectivity level is established based on either the 15-m or 30-m geometry measurements. In an effort to develop minimum standards based on 30-m geometry, the Transportation Research Board Committee A3C12: Signing and Marking

Materials, has recently disseminated a research problem statement titled: "*Correlation of Thirty-Meter Retroreflectometer Values to Drivers' Needs for Retroreflectivity of Pavement Markings*", and an ongoing project by the FHWA (Project TE-29) promotes the use of 30-m geometry retroreflectometers. The Highway Innovative Technology Evaluation Center (HITEC), an independent entity operating under the American Society of Civil Engineers (ASCE)'s Civil Engineering Research Foundation (CERF), has just completed an evaluation and a comparison of a number of handheld and mobile retroreflectometer.

2.3.4 Minimum acceptable value of retroreflectivity

Due to exposure to traffic and weather conditions, pavement markings disintegrate and retroreflectivity diminishes with time. The average retroreflectivity of newly installed pavement markings is approximately 250 and 500 $mcd/m^2/lx$, for paint and thermoplastic, respectively, with a maximum initial retroreflectivity reaching 450 or 850 $mcd/m^2/lx$ for paints or thermoplastics, respectively. These average and maximum initial retroreflectivity values were derived from a database of over 2100 test samples of paint and thermoplastic markings discussed in a later section titled "Variables Affecting Retroreflectivity". As pavement markings age, however, the marking material disintegrates, the color fades, and the glass beads embedded in the marking become dirty, scratched, or dislodged. As a result, the pavement marking retroreflectivity is reduced, making it difficult for drivers to discern the edges of travel lanes at night.

Currently, there are no minimum pavement marking retroreflectivity requirements specified in the Manual on Uniform Traffic Control Devices (MUTCD) (*1*). Several researchers, however, have recommended establishing minimum levels based on PM types and colors. In 1991, Graham and King reported that 90% of test subjects rated a retroreflectance of 93 mcd/m^2/lx as adequate or more than adequate (*9*). Graham et al reported that 85% of test subjects aged 60 years and above rated marking retroreflectance of 100 mcd/m^2/lx as adequate or more than adequate (*10*). In another study, Migletz et al found a retroreflectivity range of 80 to 130 mcd/m^2/lx to be adequate under favorable dry driving conditions (*11*). A Minnesota DOT study recommended the use of 120 mcd/m^2/lx based on data collected using a mobile retroreflectometer (*12*). A recent research study by Zwahlen and Schnell derived a speed-related set of minimum retroreflectivity values using the human visual luminance contrast threshold data collected by Blackwell in 1946 (*13*). The authors used a driver preview time of 3.65 seconds for roads without raised pavement markers (RPMs) and 2.0 seconds for roads with RPMs. The resulting retroreflectivity minimum values were found to be highly speed-dependent encompassing a huge range of values. For example, the retroreflectivity minimum values for fully striped two-lane highways (edge lines and centerline) unsupplemented by RPMs ranged from 30 to 620 mcd/m^2/lx for speeds of 25 mph (40 km/h) to 75 mph (120 km/h), respectively. For a speed range of 45 to 75 mph (72 to 120 km/h), which encompasses all rural highways, the minimum value doubles for every 10 mph (16 km/h) increment. For example, the minimum retroreflectivity of 45 mph (72 km/h) and 55 mph (88 km/h) highways is 85 and 170 mcd/m^2/lx, respectively. In a previous study, the same authors found no evidence that driving speed influences longitudinal preview distance, and opted to omit the driving speed factor from their study (14). Some researchers chose a minimum retroreflectivity of 100 mcd/m^2/lx in their evaluation of pavement marking retroreflectivity without validation (*5,15*).

2.4 PAVEMENT MARKING PERFORMANCE

2.4.1 Effects of pavement marking color on retroreflectivity

Pavement marking color has been reported to affect the retroreflectivity properties of PM materials. It is commonly accepted that yellow markings have retroreflectivity values equivalent to about 70 to 80% of white marking retroreflectivity. Retroreflectivity readings collected on test decks in Alabama and Kentucky consistently showed yellow paint, thermoplastic and tape markings to have lower retroreflectivity levels than white markings of the same type (*16*). Scheuer et al found that yellow paint has less retroreflectivity than white paint, although both have the same decay rate (*15*). Studies by Zwahlen and Schnell found the average detection distance of white taped longitudinal lines to be 35-38 meters longer than that of yellow taped lines (*17*), although they reported in a later study that there was no increase in the detection distance as a result of substituting white centerlines for yellow centerlines (*18*). They also found that supplementing a yellow centerline with white edge lines doubled the detection distance (*19*).

Recently, there has been an increased interest in the U.S. in the advantages of all-white pavement marking systems, as used in Europe, particularly with recent moves by countries such as Australia and Norway to adopt an all-white pavement marking system. A recent report by a U.S. team of traffic engineers who visited four European countries concluded that an all-white system could work in the U.S. (*20*). Currently, proposals are being solicited by the National Cooperative Highway Research Program (NCHRP) for a feasibility study of an all-white marking system in the U.S. (*21*).

Edge line brightness is reported to play a larger role in driver perception of pavement marking visibility than does centerline brightness. Exploratory driver eye scanning experiments indicate that drivers have the tendency to fixate almost exclusively on the right edge line when asked to detect the end of pavement markings along a fully-marked road (*22*).

Reasons for retroreflectivity differences - Discussion

The primary reason for the difference in retroreflectivity of white and yellow markings is the type of pigments used in the marking material. Different pigments have different hiding power and tinting strengths, two optical properties used to describe the light scattering efficiency of pigments. The hiding power of paint is a measure of its ability to obscure a background of contrasting color. It results from interactions between incident light and the pigments present in the paint film. White pigments provide opacity by scattering incident visible light at all wavelengths, while color pigments provide opacity by absorbing incident visible light at characteristic wavelengths. In other words, color pigments, such as yellow, absorb light of all wavelengths except that corresponding to yellow, thus only the yellow portion of the light spectrum is reflected and becomes visible. Titanium dioxide (TiO_2) is the most widely used white pigment in the world for paints, coatings, plastics, paper, fibers, cosmetics, and many other commercial uses. This white powder is used in pavement markings primarily because of its ability to scatter light efficiently, thereby imparting brightness, whiteness and opacity. Dry compacted TiO_2 samples exhibit reflectance properties approaching that of the perfect reflecting (Lambertian) diffuser. The high refractive index of TiO_2 ($n = 2.7$) is what gives it this high performance. The refractive index is a measure of the ability to bend light, thus giving the product its opacity. The larger the difference between the refractive index of the pigment and that of the medium in which it is dispersed, the greater the refractive light scattering. It should be noted that only diamonds have a higher refractive index than TiO_2, and only magnesium oxide (MgO) is whiter than TiO_2. Obviously using diamonds in pavement markings is not an economical alternative, but neither is MgO. Although MgO is whiter than TiO_2, it has a much lower refractive index, and thus larger quantities of MgO would be required in pavement markings to achieve opacity.

To make pavement markings reflect back a yellow color, yellow pigments are used in the coatings instead of TiO_2. Unfortunately, yellow pigments are not as efficient in diffusing light as TiO_2, and recent movement towards the use of organic pigments has only led to making this problem worse. Traditionally, lead chromate ($PbCrO_4$) yellow pigments were used in the coatings. Although less reflective than TiO_2, the $PbCrO_4$ pigments were considered efficient and cost-effective, producing good nighttime yellow retroreflected color. Lead and chromium have since been classified as health risks to users of the markings (workers) and to the environment. In mid-1994, the Office of Health and Environmental Assessment published the Interim Final Rule for Lead Exposure in Construction, which reduced the permissible exposure level for lead from 200 to 50 micrograms per cubic meter of air. Lead chromate was banned from use, and replaced by new organic lead-free yellow pigments. The new organic yellow pigments in pavement markings are inferior to lead chromate, and much more expensive. Efficient organic yellow pigments are up to 12 times more expensive than silica-encapsulated lead chromate. The result is an expensive alternative with a worse nighttime yellow retroreflection. Concerned with the lack of a good alternative, Transportation Research

Board Committee A3C12: Signing and Markings Materials, has recently disseminated a research problem statement to determine the efficacy of changing from lead chromate pigmentation to heavy metal-free pigments in pavement markings. Efforts to improve the retroreflection of yellow markings included mixing TiO_2 with the organic pigments. The mixture improved retroreflection, but resulted in a poorer yellow color. There is a serious interest in evaluating the possibilities of substituting yellow markings with white markings as mentioned earlier (*20*). Bids were recently solicited by the NCHRP for evaluating the feasibility of an all-white pavement marking system in the U.S. (*21*).

2.4.2 Performance variations of retroreflectometers

The coefficient of retroreflected luminance, R_L, is measured in the field using devices called retroreflectometers. Retroreflectometers use either 15-meter (m) or 30-m geometry for measuring pavement marking retroreflectivity. These devices fall under two broad categories, either portable (handheld) or mobile (vehicle mounted). There are variations in the performance of portable and mobile units, as well as between different brands in the same category.

Portable versus mobile units

Portable retroreflectometers are sample-based units. They operate in a stationary setting in a controlled environment. The operator selects the specific testing location and ensures that the testing surface is free of debris, that no deep cracks exist that would allow ambient light to enter the unit, and that no interference by other reflective devices exists. This controlled environment enhances the accuracy of the collected data. Portable retroreflectometers, however, require traffic control to allow the field crews to be physically present on the road. This increases testing time per sample, thus allowing fewer sites to be tested, and exposes the crewmembers to potential risk of being struck by vehicles. Mobile units, on the other hand, are capable of collecting continuous retroreflectivity readings at traffic speeds. This makes them ideal for large-scale data collection, and since the crewmembers remain in the vehicle during data collection, the safety risk to the field crew is practically eliminated. The accuracy of the readings collected by mobile units, however, is negatively affected by various factors, including the changing measurement geometry, and the presence of other reflective devices. As the unit continuously collects the readings, the measurement geometry changes as a result of the roadway roughness (bumpiness), the vehicle suspension and braking, and the number and weight of the passengers in the vehicle. In addition, since the mobile unit is continuously collecting data, some of the data collected belongs to segments of the road where no pavement markings exist, such as the road surface between the dashes of a lane line or RPMs. The data are usually screened at a later time and those readings considered to be too low or too high are usually attributed to the absence of markings or the presence of RPMs, respectively, and are discarded. This process, however, can eliminate valid data simply because they are outside the expected range. Having too many low readings discarded may falsely inflate the retroreflectance levels and lead to erroneous PM replacement decisions. Also, retroreflectance levels from older RPMs may be accepted if their levels are closer to typical (expected) PM retroreflectivity levels, making the validity of the data questionable.

Variations within portable units

It is important to recognize that portable units of different brands do not necessarily produce similar readings even when they employ the same measurement geometry. It is also important to note that employing the same geometry does not necessarily mean that the entrance and observation angles used by the different retroreflectometers are identical. Hodson compared the performance of four different types of 30-m geometry retroreflectometers (*23*). The units compared were: an LTL 2000 by Delta Light & Optics; a Mechatronic FRT 01 by Mechatronic GmbH; a Mirolux 30 by Potters Industries; and a Retrolux 1500 by Advanced Retro Technology. The testing was done on multiple panels of different retroreflectivities by four different laboratories under near-ideal conditions. Hodson found that the different retroreflectometers gave similar results when reading higher retroreflectance panels (300, 800 and 1400 mcd/m^2/lx), but substantially differed at lower retroreflectance levels (0, 50 and 100 mcd/m^2/lx panels). The 100-mcd/m^2/lx panel was read by two of the units as approximately 30% and 65% higher. The 45-mcd/m^2/lx panel was read by one of the units as 100% higher and by another unit as 80% lower. The zero-panel had readings ranging from below zero to over 35 mcd/m^2/lx. Another recent study reported that the MP-30 retroreflectometer consistently read higher retroreflectivity than did the LTL 2000 by approximately 20 mcd/m^2/lx (*24*).

Note that it is at lower retroreflectivity levels that the accuracy of the readings is most important, since lower retroreflectivity levels are indicative of the need for marking replacement. Establishing a minimum retroreflectivity requirement may not be meaningful without a correlation between the readings of different brands of retroreflectometers. Because of the variability in retroreflectivity readings even among units of the same geometry, use of the same instrument is considered essential to consistently track the performance of pavement markings over time.

2.4.3 Effects of weather on pavement markings

Weather conditions are reported to have a significant effect on PM durability and retroreflectivity. The PM rate of deterioration is affected by such climatic factors as the ambient temperature and precipitation.

Effects of temperature

The only research found in the literature that studies the effects of weather on pavement temperature was that done by Bosscher et al (*30*). The authors found pavement temperature to be consistently higher than ambient temperature for all hours of the day. This phenomenon is especially important in the southern United States, where warmer temperatures prevail. The authors developed the following equation for calculating the maximum pavement temperature at a specified depth.

$$T_{d(MAX)} = T_{PAV@6.4mm(MAX)} - 2.68 \times 10^{3} (d - 6.4)\, T_{PAV@6.4mm(MAX)} + 4.25 \times 10^{-4} (d - 6.4)^2 \qquad (5)$$

where:

$T_{d(MAX)}$ = maximum pavement temperature at a depth d, °C

d = depth from surface, mm

$T_{PAV@6.4mm(MAX)}$ = maximum pavement temperature @ probe depth of 6.4 mm

$$= -8.428 + 0.716 \sqrt[4]{Solar_{\_0} * T^2{}_{AIR(MAX)}} + 0.489 T_{AIR\_01} + 0.261 \sqrt[4]{Solar_{\_0} * MS_{\_0}} \qquad (6)$$

where:

$Solar\__0$ = daily total solar radiation intensity, W*hr/m^2

$T_{AIR(MAX)}$ = Maximum air temperature, °C

$T_{AIR\text{-}01}$ = Average air temperature 1 day before the day of $T_{AIR(MAX)}$, °C

To calculate the temperature at the pavement surface, a value of d = 0 can be used in the equation. This model had a coefficient of determination of 0.94, but it requires excessive amounts of data collection using pavement monitoring and climatological monitoring systems, making it difficult to apply.

Effects of rain

Heavy rain submerges pavement markings and diminishes their retroreflective properties. Light from vehicle headlamps strikes the water film covering the pavement marking and reflects off the water surface without reaching the pavement markings or the glass beads embedded in them, and does not get redirected back in the direction of the driver. As a result of this phenomenon, the highway centerline and edge lines are said to "disappear", as described by the average motorist. To counteract this phenomenon, profiled material, large beads, waffle tapes or raised pavement markers are conventionally used. The expectation behind using such devices is that a portion of the retroreflective material would remain above the water surface during heavy rain, thus retaining retroreflectivity. Evaluation of such devices is not included in this research.

Effects of snow

Snowy conditions are very damaging to pavement markings. Accumulation of snow atop pavement markings causes complete visual obstruction. Mechanical abrasion of PM material by snowplows, anti-skid sand, studded tires and chains causes the PM material and glass beads to detach from the surface, and the spreading of salt and deicing agents on the roadway surface causes chemical decomposition of the PM material. This research does not account for these factors since they are insignificant in the southern states where snow is a rare occurrence. For this reason, crashes involving snow were discarded in this study.

2.4.4 Effects of human factors on pavement marking visibility

Retroreflectivity measurement is a surrogate means of quantifying nighttime visibility. Quantitative measurements of PM retroreflectivity are not sufficient to relay how visible the pavement markings appear to the motoring public. In addition to the obvious effects of the marking condition and environmental factors, such as fog and rain, the driver-highway-vehicle system plays an important role in determining how visible the markings appear to drivers. Such driver-highway-vehicle factors include driver condition, driver age, windshield and headlight conditions, and the relative brightness of pavement markings with respect to their background. Adjustments to retroreflectivity readings under ideal conditions and any established minimum levels may be necessary to account for these factors and to better represent the nighttime visibility of pavement markings.

Driver fatigue

Drivers who are fatigued, sleep deprived, or on drowsiness-causing medication suffer from temporary vision weakness that increases their need for greater nighttime PM retroreflectivity. The potential for fatigued/sleep-deprived drivers to run off the road is documented. A study of 12 younger subjects (six men and six women) ages 26 through 35, with normal or corrected vision showed that the lateral placement of vehicles, as well as the number of run-off-the-road types of crashes increased with progressive sleep deprivation (25). Driver fatigue is of special concern to the commercial motor vehicle transportation community, where drivers may drive up to 10 hours continuously before taking a break, often at night when PM retroreflectivity is most critical. The National

Highway Traffic Safety Administration (NHTSA) estimated that between 1989 and 1993, driver drowsiness/fatigue was a contributing factor in 100,000 crashes on U.S. highways annually (*26*). During the same five-year period, an annual average of 1,357 fatal crashes resulting in 1,544 fatalities was attributed to driver drowsiness/fatigue (*27*). Current visibility studies by some intelligent transportation systems (ITS) oriented firms are aimed at developing in-cab detection and warning systems to alert commercial truck drivers of unintentional lane departures and help reduce the large number of drowsiness-related crashes reported by NHTSA.

Driver age

In general, elderly persons suffer from diminished visual and cognitive abilities that negatively impacts their driving-related performance, especially degraded visual acuity and delayed responses (*28*). This suggests that the commonly acceptable minimum retroreflectivity level of 100 $mcd/m^2/lx$ may not be adequate for the elderly driving population. A field experiment conducted by Graham et al on the adequacy of the 100 $mcd/m^2/lx$ retroreflectivity threshold involved rating PM retroreflectivity by 30 male and 35 female drivers (*10*). Of these 65 drivers, 51 were at least 50 years of age and 35 were least 60 years of age. The researchers reported that pavement markings with known retroreflectivity of at least 100 $mcd/m^2/lx$ were rated by about 85% of the test drivers as either adequate or more than adequate, and markings with retroreflectivity of at least 140 $mcd/m^2/lx$ were rated by 95% or more of the test drivers as adequate or more than adequate.

Vehicle condition

Graham et al found in a 1996 research study that an adjustment to the 100 mcd/m^2/lx base value was necessary to account for unclean windshield and headlight conditions (*10*). They recommended increasing the base value from 100 to 121 mcd/m^2/lx.

Background of pavement markings

Driver perception of how "bright" pavement markings are is influenced by how "dark" the immediate background appears. The presence of other light sources and reflections in the background as well as the reflection from the pavement surface adjacent to the markings affect the relative visibility of the markings. The presence of street lighting and signing is typically minimal along rural highways, which reduces background interference. Glare from opposing vehicle headlights, however, is fairly common along undivided rural highways. The specific effect of glare on pavement marking visibility is not part of the focus in this study. Of significant importance is the relative brightness of the PM against the pavement, or the contrast ratio of luminance between the pavement marking and the adjacent pavement surface. The luminance contrast ratio, *LCR* is a measure of effectiveness (MOE) of pavement marking and is calculated as:

$$LCR = \frac{R_L - R_{Pvmt}}{R_{Pvmt}} \qquad (4)$$

where R_L = PM coefficient of retroreflected luminance, mcd/m^2/lx, and R_{Pvmt} = Pavement surface retroreflectivity, mcd/m^2/lx

Retroreflectivity of the pavement surface varies with time. Asphalt surfaces become more polished and their color changes from dark gray to light gray as tire tracks expose the aggregates in the pavement, while concrete surfaces darken with time and their color changes from light gray to dark gray as dirt, grease and tire deposits become embedded in the pavement. In other words, R_{Pvmt} increases on asphalt surfaces but decreases on concrete surfaces. Therefore, all else being equal, *LCR* values will fall faster on asphalt surfaces than they would on concrete surfaces.

Schnell et al calculated the retroreflection values for new and old asphalt and concrete surfaces for various entrance and observation angles (*29*). They reported that the reflectance magnitude of a new concrete surface is equivalent to that of a worn asphalt surface. Using the authors' published results, a comparison of R_{Pvmt} can be made for new and old asphalt surfaces. Interpolating for observation and entrance angles of 1.5° and 86.5°, respectively, which are consistent with the Mirolux 12 retroreflectometer used in this study, R_{Pvmt} for the new asphalt pavement (7-months old) was found to be approximately 19 mcd/m^2/lx, and that of the old pavement (8 years old) to be approximately 33 mcd/m^2/lx. This is equivalent to *LCR* values of 3 to 5 based on a base R_L value of 100 mcd/m^2/lx. Although no minimum acceptable value of *LCR* is established, some research investigated the effects of different *LCR* values. A recent Minnesota study utilized a sample of 200 participants of various age groups to evaluate the perception of longitudinal pavement markings (*12*). In this study, edge lines with *LCR* values of 2.73 to 5.57 were found to be unacceptable by 90% of the participants. Contrary to these findings, another study found that a minimum *LCR* value of 2.0 to be satisfactory for older drivers (*11*). To counteract contrast deficiencies, especially on concrete surfaces, certain jurisdictions use intermittent black contrast lines in the interval between paint stripes.

2.4.5 Relationship between pavement markings and crashes

It is commonly accepted that nighttime crashes increase as highway longitudinal pavement markings become in a poor deteriorated state. However, no such correlation is documented. The types of crashes considered susceptible to poor long line retroreflectivity are nighttime head-on and run-off-the-road crashes. Several research studies have investigated the effects of highway striping on crash occurrence.

Effects of adding longitudinal pavement markings on crashes

Earlier studies by Bali et al investigated the effects of long lines on crash experiences along two-lane rural highways (*31*). Using before and after with control analysis of 500 sites in 10 states, the authors found that adding centerline and edge line markings to unmarked roadways yields 36% reduction in run-off-the-road and head-on types of crashes. These crash reductions were based on at least two years before and two years after the addition of the longitudinal markings.

An earlier study by Musick found that adding edge lines to two-lane rural highways in Ohio resulted in an 11% reduction in the nighttime:daytime crash ratio (*32*). This was in agreement with a subsequent study by Basile, who found significant reductions in daytime as well as nighttime crashes on two-lane rural highways in Kansas after edge lines were added (*33*). A recent study by AlMasaeid et al showed pavement markings to result in crash reductions of 13.5% at hazardous locations (*34*), and a more recent study by Retting et al showed a reduction in rear-end conflicts at commercial driveways after edge lines were added (*35*).

The economic impact of installing long lines was compared in a 1992 study to the estimated costs of injuries suffered in crashes (*36*). The study found that long lines yield far greater benefits than their costs. Three severity levels were used in the cost estimate: fatal, personal injury, and property damage only.

Effects of retroreflectivity levels on crashes

The single study that directly addressed the relationship between PM retroreflectivity and crashes was conducted by Lee et al (*37*). The authors used a linear regression model to describe this relationship. The model was based on data collected over a four-year period from four regions in Michigan, each having distinct highway, weather and traffic characteristics. The authors, however, were unable to establish a correlation between nighttime crashes and long line retroreflectivity. The likely reason for this poor correlation was attributed to the limited data used in the study and to the high level of retroreflectivity retained by the long lines throughout the study period.

Effects of pavement marking color on crashes

A study by Johns and Matthias found an increase in crash rate when the centerline color was changed from white to yellow on two-lane highways in Arizona (*38*).

Effects of pavement marking width on crashes

Effects of wider long lines on crash occurrences on two-lane rural highways were studied by Cottrell and more recently by Loutzenheiser (*39,40*). Neither study found evidence of nighttime safety improvements when wider long lines were used.

2.4.6 Rate of deterioration of PM retroreflectivity

The rate of PM deterioration with age has been described in many research articles. Migletz et al conducted a field survey of PM retroreflectivities throughout the United States (*11*). The retroreflectivity of pavement markings in 32 state and highway agencies was measured with a Model 1500 RetroLux mobile retroreflectometer. Since PM type and age were not determined in the first pass through the measurement sites, the collected data can be used only to provide a general idea of the pavement marking durability, but not to produce specific durability values. Furthermore, no information was provided on the proportions of paint, tape, polyester, and thermoplastic markings within the collected data, making the results too general in nature.

Modeling of pavement marking deterioration

Using linear regression, Dale modeled the retroreflectivity-PM age relationship for solvent-borne and epoxy paints on both asphalt and concrete pavement surfaces (*41*) Dale's findings were contradicted by Perrin et al, who modeled the retroreflectivity-PM age relationship using exponential regression (*42*). Perrin's models showed a substantially higher PM service life than did Dale's linear models.

Using retroreflectivity data from the field measurements by the Northeastern Association of State Highway and Transportation Officials (NASHTO) and the Southeastern Association of State Highway and Transportation Officials (SASHTO), Andrady developed a logarithmic model relating the retroreflectivity and service life of pavement markings (*5*). In developing the model, 93 samples from the NASHTO data and 98 samples from the SASHTO data were used. A minimum acceptable retroreflectivity threshold value of 100 mcd/m^2/lx was assumed in the calculation of pavement marking service life. The following equation describes the resulting relationship.

$$T_{100} = 10^{(R_0 - 100)/b} \tag{7}$$

where

T_{100} = The duration for the retroreflectivity to reach 100 mcd/m^2/lx, in months
R_o = Estimated initial retroreflectivity of the pavement marking, in mcd/m^2/lx
b = Gradient of the semi-logarithmic retroreflectivity-time line

The life cycles of PM materials were calculated according to the above model, and the findings show the service life of PM material to be significantly shorter for yellow stripes than for white stripes. The reported large values of the standard errors of the mean were attributed to the effects of small sample size of each type of material used.

In another study, Lee et al collected retroreflectivity data from 50 test sites in Michigan over a three-year period (*43*). The measurements were taken along polyester, water-borne paint, and thermoplastic long lines using a Mirolux 12 (15-m geometry) portable retroreflectometer. Linear regression models developed for each PM type showed the rate of retroreflectivity loss to be consistent for all four PM types at 0.14 %/day. The coefficients of determination for the regression models were weak ranging from 0.14 to 0.18. The service life ranged from 427 to 445 days (approximately 14 months) for all types of markings tested. A comparison of these findings with Andrady's was not done since separation of retroreflectivity data for white and yellow pavement markings was not done in Lee's research. The authors attributed the primary cause of PM deterioration to be the snow plowing operations.

2.5 EXISTING SOURCES OF RETROREFLECTIVITY DATA

The most extensive source of retroreflectivity data available is that of AASHTO, which was collected as part of AASHTO's Traffic Marking Regional Testing Program. The retroreflectivity data were collected from the northeastern and southeastern regions of the United States by NASHTO and SASHTO, respectively. The data were the results of field tests of various PM materials on both asphalt and concrete surfaces (*16*).

The NASHTO data represent the PM performance in the cold and humid climate of northeastern states. They were collected along eastbound US 22 in western Huntington County, Pennsylvania from 1992 to 1995 (*44*). The PM retroreflectivity measurements were taken by an Erichson Model 710, a portable 15-m geometry retroreflectometer.

The SASHTO data represent the PM performance in the hot and humid climate of the southeastern states. Field testing was conducted in Alabama and Kentucky, originally with identical field installations placed in both states (1989 and 1990). Starting 1991, the field installations were located in one of the two states on alternate years. The Kentucky study sites were on eastbound I-64 near Frankfort, with the installations on the asphalt decks located between milepost (MP) 46 and MP 52, and those on the concrete decks between MP 60 and MP 63. Both sites had an annual average daily traffic (AADT) of 19,000 to 20,000 vehicles per day (vpd) (or an average of 4,500 to 5,000 vpd/lane). The Alabama study sites were primarily along southbound I-65 near Montgomery, except for 1989, where a four-lane arterial in Montgomery with an AADT of 20,000 vpd was used as the asphalt site. The asphalt sites on other years were between MP 140 and MP 149 of I-65, with an AADT range of 8,300 to 9,135 vpd in the southbound lanes (4,150 to 4,567 vpd/lane). The concrete sites were between MP 123 and MP 162 of I-65 with an AADT range of 7,885 to 8,280 vpd in the southbound lanes (3,667 to 4,140 vpd/lane). Retroreflectivity data were collected using Mirolux 12, a 15-m geometry portable retroreflectometer.

The Alabama DOT has participated in the SASHTO Regional Testing Facility (RTF) field testing of pavement marking materials since 1989. The National Transportation Product Evaluation Program (NTPEP) assumed the responsibilities of managing the test facilities in 1994, which were previously managed by SASHTO. The Alabama DOT has been using the SASHTO RTF test results for product evaluation and inclusion in the approved products list. The NTPEP field testing procedures are based on ASTM D 713-90 (re-approved 1998): "Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials". Field testing was conducted in each of the two states on alternate years between 1989 and 1995, and evaluations were made on retroreflectivity, appearance and durability of various PM materials on both asphalt and concrete surfaces. PM materials used included paints, thermoplastics and tapes. SASHTO field measurements were performed at the end of every month in the first year after application, and for Months 15, 18 and 24 in the second year. All pavement marking material tested by NASHTO and SASHTO were placed transversely across the lanes, and tested in the wheel path and center of lane (non-wheel path). Throughout this study, the retroreflectivity data generated by the NTPEP field tests are referenced as the NTPEP data.

2.6 SUMMARY OF LITERATURE REVIEW

A large volume of literature was searched for information on PM types, properties, efficacy, service life, rate of deterioration, impact on traffic safety, and means of measurement, with a special emphasis on the retroreflectivity property. Literature sources included TRRs, TRCs, ITE Journals, NCHRP reports, Public Roads journals, TRB annual meeting preprint CD-ROMs, CARE computerized database, the web, and manufacturers and suppliers brochures.

Pavement marking properties

- Traffic paints and thermoplastics are the most commonly used striping materials.
- Paint is composed of a binder resin, pigments or fillers, and solvents/additives, and applied in 15 mil thickness.
- Solvent content controls drying time of paints. *Conventional* paints dry in at least 7 minutes, *fast-dry* paints dry in 2 to 7 minutes, *quick-dry* paints dry in 30 to 120 seconds, and *instant-dry* paints dry in less than 30 seconds.
- Thermoplastic is melted and sprayed in 60-90 mils thickness, or extruded in 125 mils thickness.

Retroreflectivity

- Retroreflectivity is the ability of a marking to redirect light rays back in the direction of the driver. Measuring retroreflectivity is a surrogate method of measuring nighttime visibility of the pavement markings.
- The coefficient used for measuring pavement marking retroreflectivity is the coefficient of retroreflected luminance, R_L, expressed in $mcd/m^2/lx$.
- Two components of the marking make retroreflection possible: glass beads and pigments. Glass beads bend the incident light downwards towards the marking, and the pigments diffuse the refracted light allowing portions of it to reflect back in the direction of the incident light.

- Higher refractive index for glass beads and pigments provides for better retroreflection.
- Titanium dioxide is a very efficient white pigment with very high refractive index. Organic lead-free yellow pigments have low refractive index and are inferior to titanium dioxide and much more expensive.

Retroreflectivity standards

- The ASTM publishes a number of industry standards relating to retroreflectivity, its measurement, and retroreflective materials, but no national guidelines on minimum retroreflectivity or service life exist.
- Researchers recommend various minimum retroreflectivity levels ranging from 80 to 130 mcd/m^2/lx, with the 100 mcd/m^2/lx being the most commonly used. One researcher used speed-dependent minimum retroreflectivity levels encompassing a wide range of values from 30 to 620 mcd/m^2/lx for speeds of 40 to 120 km/h.

Retroreflectivity measurement

- The R_L coefficient is measured in the field using devices called retroreflectometers, which simulate nighttime driving conditions by employing internal light source and illumination and observation angles similar to those occurring on the road.
- Two different testing geometries are used for testing retroreflectivity, the 15-m and 30-m geometries. The 15-m and 30-m measurements refer to the viewing distances from the vehicle headlamps to the pavement marking tested. The FHWA currently promotes 30-m geometry because it is believed to better approximate driving conditions.

- Portable retroreflectometers require longer testing time per sample than mobile units and expose field crews to possible road hazards, but have high accuracy due to the controlled testing environment.
- Mobile units are ideal for large-scale data collection since they can collect continuous retroreflectivity readings at traffic speeds while eliminating safety risk to the field crew. The accuracy of the readings collected by mobile units is compromised by the changing measurement geometry.
- Laboratory testing has shown same-geometry retroreflectometers to give similar results at higher retroreflectance, but drastically different results at lower retroreflectance. Readings at lower reflectance levels is more critical since they represent the PM deteriorated state, which is a basis for PM re-striping.

Effects of color

- Changing the centerline color from white to yellow on two-lane highways is reported to increase crashes.
- Edge line brightness is reported to play a larger role in the drivers' perception of the pavement marking visibility than does the center line brightness. Driver eye scanning experiments indicate that drivers have the tendency to fixate almost exclusively on the right edge line when asked to detect the end of pavement markings along a fully marked road.
- The U.S. is evaluating the feasibility of implementing an all-white pavement marking system similar to that used in Europe.

Effects of weather

- Quantifying the effect of temperature on pavement markings requires excessive amounts of data collection using pavement monitoring and climatological monitoring systems, making it difficult to determine.
- Heavy rain submerges pavement markings and causes light from vehicle headlamps to reflect off the water surface without reaching the pavement markings or the glass beads embedded in them.
- Mechanical abrasion of the marking material by snowplows, anti-skid sand, studded tires and chains causes the material and the glass beads to detach from the surface, and the spreading of salt and deicing agents on the roadway surface causes chemical decomposition of the material.

Pavement marking qualities

- Appearance is a measure of the contrast between the pavement marking stripe and the pavement background, which is easily achieved on bituminous pavement due to the black background of new asphalt.
- Durability is a measure of the pavement marking resistance to weather and abrasion and the extended ability to adhere to the pavement surface. This property is dependent on the quality of the pavement marking, its composition, thickness and application workmanship, and on environmental and traffic conditions.
- Cost is an important consideration in the selection of longitudinal pavement marking material. It varies by type, width and color of the markings, with the average unit cost of thermoplastic markings being three to four times that of paint.

- Human factors influencing the perception of nighttime marking brightness include driver condition, driver age, and the relative brightness of pavement markings with respect to their background.

Effects of pavement markings on crashes

- Studies found no evidence of nighttime safety improvements when wider longitudinal pavement markings were used.
- No correlation between nighttime crashes and marking condition was found in the literature, although adding centerline and edge line markings to unmarked roadways were found to yield a 36% reduction in run-off-the-road and head-on types of crashes, and adding edge lines to two-lane rural highways was found to result in an 11% reduction in the nighttime:daytime crash ratio, and 13.5% reductions at hazardous locations .
- The single study that directly addressed the relationship between PM retroreflectivity and crashes failed to establish a correlation between nighttime crashes and striping retroreflectivity.
- Linear and exponential regression were used to model the retroreflectivity-age relationship with inconsistent results, with a Michigan study concluding that snow plowing operations to be the primary cause of PM deterioration.

3. DESCRIPTION OF RESEARCH

This chapter provides a description of the research plan and data used in this study.

3.1 RESEARCH PLAN

This study establishes a crash-based threshold of pavement marking retroreflectivity that allows the prediction of longitudinal pavement marking service life and the potential for striping-related crashes. The retroreflectivity threshold is determined from the relationships between striping retroreflectivity and striping-related crash rate on one hand and the prolonged exposure to vehicular traffic on the other. In this research, vehicle exposure, *VE,* represents the prolonged exposure of pavement marking to vehicular traffic, which accounts for the combined effects of pavement marking age and traffic volumes. Figure 3-1 presents the study plan flow chart.

Pavement marking retroreflectivity threshold, $R_{L(min)}$, is determined from the R_L-VE relationship as the retroreflectivity value that corresponds to the maximum allowable vehicle exposure, VE_{max}. In this research, VE_{max}, is the value of vehicle exposure beyond which crash potential increases, and is equivalent to the highest cumulative number of vehicles a particular pavement marking is subjected to before the corresponding crash rate, *CR*, exceeds a set critical value. This critical value equals the overall average crash rate, CR_{Avg}, and is calculated from the crash experience of all striping projects in this study where this type of marking material was applied. The R_L-VE relationship used in the determination of the $R_{L(min)}$ threshold is the product of the field retroreflectivity data analysis of this study. The *CR-VE* relationship used for determining VE_{max} is the product of the crash data analysis of this study. Regression analysis is used to establish the relationships between R_L, *CR*, and *VE.* The highway ADT, highway segment length,

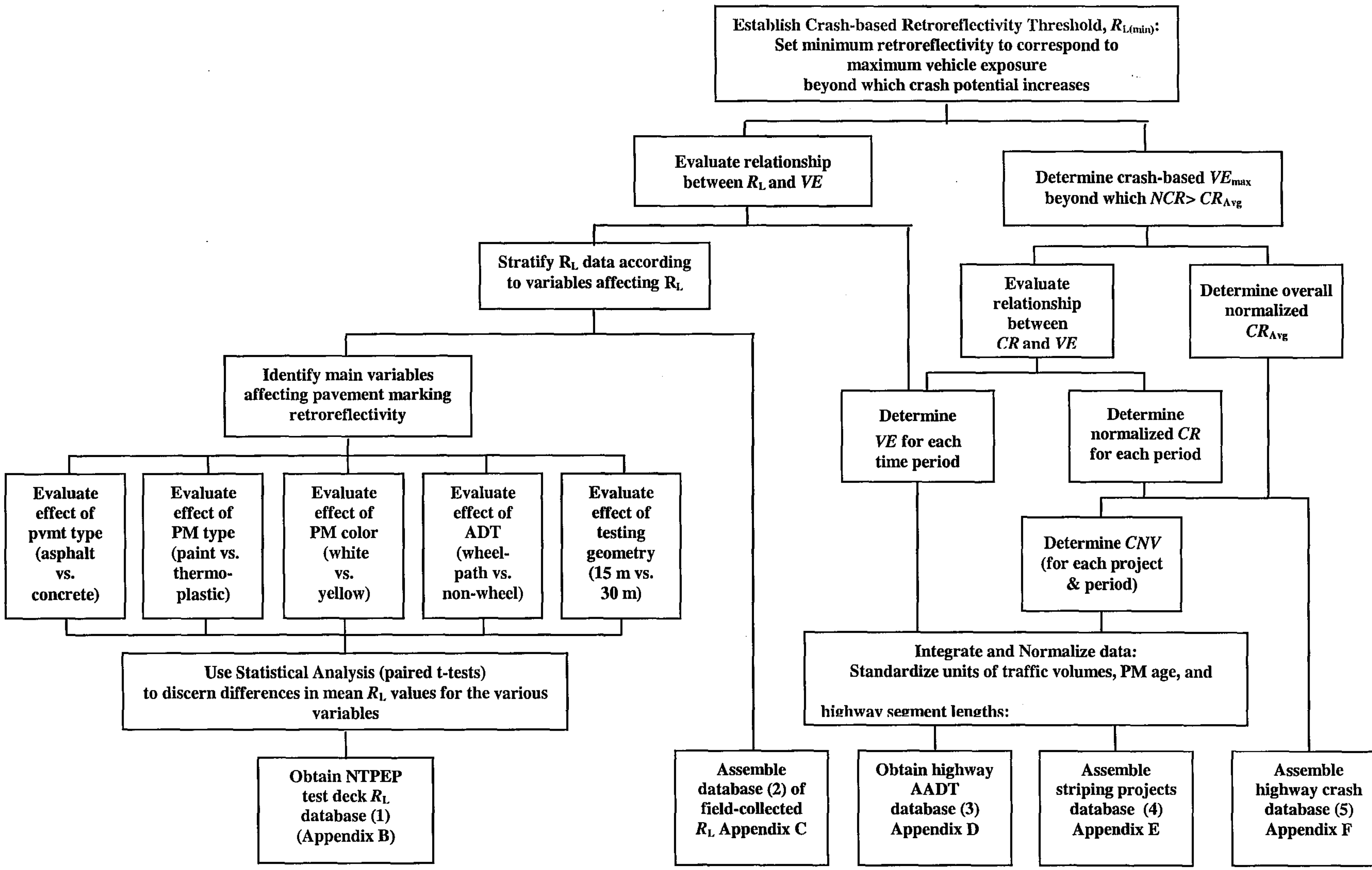


Figure 3-1 Study plan flow chart

number of crashes, and pavement marking age at the time of crash occurrence and at the time of field R_L measurement were used to establish these relationships. To normalize the crash data for highways of different lengths, traffic volumes, and service life, a crash normalization value, *CNV*, is used for each highway. The *CNV* factor converts highway crashes into a crash rate measured in crashes per million vehicle miles (MVM). To identify the highway and marking variables that affect retroreflectivity values, statistical analysis is performed on a large volume of retroreflectivity data. The statistical analysis evaluates if a significant difference exists between pavement marking R_L values when measured 1) on asphalt versus concrete surfaces; 2) for paint versus thermoplastic materials; 3) for white versus yellow marking colors; 4) in the wheel path of vehicles versus away from vehicle path; and 5) by 15-m versus 30-m geometry retroreflectometers. The results of these analyses are used to identify the variables that affect retroreflectivity for the purpose of stratifying the field-collected R_L data according to these variables. These analyses of statistical differences are based on five distinct databases. Databases 1 and 2 document the retroreflectivity values associated with different pavement marking age for transverse and longitudinal markings, respectively. Database 3 documents the traffic volumes along the state highways evaluated in this study. Database 4 documents the particulars of four years of striping projects in nine Alabama counties, and Database 5 documents the crash experience along State highways in 32 Alabama counties.

The two-year accumulation of transverse marking retroreflectivity field tests of Database 1 is used to evaluate the impact of a number of variables on pavement marking retroreflectivity, including pavement marking types and colors, pavement surface types, traffic volumes, and measurement geometries. The field-collected striping retroreflectivity readings of Database 2 are used to evaluate the pavement marking retroreflectivity deterioration under in-situ conditions. The annual average daily traffic (AADT) of Database 3 is used to normalize the crash data to allow for the analysis of highways with different traffic volumes. The striping project particulars of Database 4 are used to identify striping projects and provide information on the pavement markings such as type, color, age and location, and highway details such as number of lane, shoulder width, if any, and pavement surface condition. The crash particulars of database 5 are used to identify the crashes that are striping-related, and to perform crash analysis comparing the difference in crash experiences of highways according to striping age and traffic volumes.

An output of this study is a regression model with predictive properties of the life span of longitudinal pavement markings based on their capabilities to retain an acceptable level of retroreflectivity. Other outputs of this study are regression models that predict striping-related crash rates and the expected retroreflectivity value of markings based on the PM age and vehicle exposure.

3.2 COLLECTION OF DATA

Crashes, in general, are considered rare events. Only 3.5 crashes occur nationwide for every million vehicle-miles of travel (MVMT) or 2.2 crashes for every million vehicle-kilometers of travel (MVKT) (*45*). Establishing a crash-based retroreflectivity threshold involves the analysis of crashes that are considered to be retroreflectivity-related. Retroreflectivity-related crashes are exceptionally rare events since they constitute a small fraction of the total number of crashes. This is because crashes that are not retroreflectivity-related, such as daytime and alcohol-related crashes, are discarded. Therefore, retroreflectivity-related crashes are associated with an even larger vehicle-mileage. To estimate the size of the analysis area needed for data collection, the Alabama State statistics are used. The total number of crashes in Alabama was 137,508 crashes in 1998, of which 37,123 crashes (27%) occurred at night, and only 33,681 crashes (24.5%) were nighttime non-DUI related crashes (*4*). The total number of vehicle-miles traveled in Alabama in 1998 was 55,200 MVMT (88,835 MVKT) (*46*). The nighttime non-DUI crash rate for 1998 is, therefore, calculated to be 0.61 crash/MVMT (33,681 crashes in 55,200 MVMT). Therefore, to obtain a sample of 30 relevant crashes, for example, vehicle-mileage of approximately 50 MVMT (80 MVKT) is needed, which is equivalent to the annual crash experience of 140 miles (225 km) of highways with an average AADT of 1,000 vpd. For this reason, all striping projects available at the Alabama DOT division were evaluated in this study, and all projects with adequate records were included in the analysis. Following is a description of the types of data used in this study, their sources, and the purpose for using them.

3.2.1 Database 1: Test deck retroreflectivity data

Database 1 was obtained from documented field retroreflectivity tests conducted by AASHTO as part of their Traffic Marking Regional Testing Program (*16*). Database 1 includes two years of retroreflectivity measurements of white and yellow pavement marking materials on asphalt and concrete test decks in Alabama and Kentucky (SASHTO data) and one year of retroreflectivity measurements taken on the Pennsylvania test deck (NASHTO data). The PM samples were laid transversely across the travel lane to simulate accelerated wear, and amounted to approximately 2000 PM samples on the Alabama and Kentucky test decks and approximately 375 PM samples on the Pennsylvania test deck. The types of PM materials tested include water-based, solvent-borne, polyester and methacrylate paints; temporary and permanent tapes; and alkyd and hydrocarbon thermoplastics. Despite being performed on transverse markings, this extensive database of field tests constitutes the best available resource for identifying the variables affecting PM retroreflectivity. Database 1 is used to determine the effects PM type and color, pavement surface type, traffic volume, and measurement geometry have on pavement marking retroreflectivity values. Database 1 is presented as Appendix A and Appendix B for the SASHTO and NASHTO data, respectively.

3.2.2 Database 2: Field-collected retroreflectivity data

Database 2 is composed of retroreflectivity readings collected along Alabama State highways as part of this study. These readings represent in-situ conditions of longitudinal pavement markings along 520 miles (835 km) of rural highways in nine Alabama counties. The literature review has shown that retroreflectometer performance varies by measurement geometry and by brand. Therefore, to ensure consistency in the readings between retroreflectivity data collected on the test decks and those collected on Alabama State highways, the same retroreflectometer was selected. The Mirolux 12 handheld retroreflectometer by Miro-Bran Assemblers of New Jersey was used for retroreflectivity field measurement. The Mirolux 12 is a 15-m geometry based retroreflectometer, with an entrance angle of 86.5° and an observation angle of 1.5°. The retroreflectometer used in this study underwent internal calibration according to the manufacturer's procedures immediately prior to commencement of field data collection

Field measurements along state highways were taken at approximately one to three mile (1 to 5 km) intervals. Selection of test locations was dependent upon the availability of adequate sight distances for field crew safety, and where there were few intersections and driveways to minimize the influence of turning traffic. The measurement procedure according to the manufacturer's instruction manual calls for the collection and averaging of three readings of the same pavement marking. The three readings are to be taken within 10 feet (3 m) of each other and are not to deviate more than 10% from their average. Should any of the readings deviate more than 10% from the average, two additional readings of the same marking are needed. To eliminate the need for decision making in the field and to improve statistical accuracy, the procedure was slightly modified to require a minimum of five readings at all test locations. Also, to minimize the error associated with ambient light, measurements were taken on surfaces free of bumps or deep cracks. Such cracks or bumps allow ambient light to escape from underneath the unit and result in elevated retroreflectivity readings. The retroreflectivity readings are used to relate the condition of the pavement marking to the prolonged vehicle exposure. Similarly, retroreflectivity measurements of the pavement surface adjacent to the markings were also made. The pavement surface retroreflectivity readings are used in the calculation of the luminous contrast ratio. Setting a minimum *LCR* value however, requires that a minimum retroreflectivity value be established. Other means for improving *LCR* values are available, such as using intermittent black contrast lines. This study relates *LCR* to the age of the markings. Database 2 is presented as Appendix C.

3.2.3 Database 3: Traffic volume data

Database 3 is composed of AADTs of all routes included in this study. This database was obtained from the records of the Alabama DOT Bureau of Transportation Planning for the years 1995 through 1998. The 1999 AADTs were not available at the time of this study and were estimated as equal to the 1998 AADTs, since no specific growth rate could be obtained from the 1995 through 1998 data. This database was used to normalize the crash data to obtain rates that are independent of the individual highway AADTs, and to determine the vehicle exposure at time of pavement marking retroreflectivity measurements and at time of crashes. Database 4 is stored in MS Access format and presented as Appendix D.

3.2.4 Database 4: Striping project data

Database 4 includes a tabulation of all available striping records on file with the Alabama DOT. This database was compiled from a search of the daily field logs of the striping crews. It includes all striping projects performed by state and contractor forces in the last two to five years. Striping projects with incomplete information were not considered in this study. Database 4 is provided as Appendix E.

3.2.5 Database 5: Crash data

Database 5 contains the particulars of all striping-related crashes that occurred along the state highway segments of Database 4. These crash histories along these highway segments were requested on July 1, 1999 from the Multimodal Transportation Bureau of Alabama DOT, and entered into a spreadsheet. A new variable specifying the crash type was added to the crash database. This crash type variable was generated from the crash particulars, such as impact points of involved vehicles and their directions of travel. The crash types pertinent to this study were single-vehicle crashes, such as run off the road (*ROR*), fixed object (*FO*) and overturned/jack knifed (*OT/JK*) types, and multi-vehicle crashes, such as head-on (*HO*), same direction sideswipe (*SS*) and opposite direction sideswipe (*ODSS*) types. The single-vehicle crashes are considered to be edge line (EL) related, while the head-on and opposite-direction sideswipe types are considered to be centerline (CL) related, and same-direction sideswipe types are considered to be lane line (LL) related. Crashes with the following characteristics were excluded from the study since the longitudinal line retroreflectivity is not considered to have any impact on them:

- Crash types: rear-end and angle.
- Primary cause: DUI, drugs, animal, and pedestrian.
- Weather conditions: rain, fog, snow, ice, sleet, and hail.
- Road condition: icy
- Light conditions: daytime

The crash database includes the crash histories of 1,302 miles (2,095 km) of state highways in 32 Alabama counties for the period between the striping date of each highway segment and July 1, 1999, the date the crash histories were compiled. This included a total of 244 crashes, the majority of which (220 crashes) were along 734 miles (1,180 km) of two-lane rural highways. Database 5 is provided in MS Excel format as Appendix F.

4. STATE OF THE PRACTICE IN SOUTHERN STATES

A primary purpose of this research study is to identify a threshold of pavement marking retroreflectivity for use by Alabama Department of Transportation (DOT). Since environmental and climatic conditions are similar within states in the southern region of the U.S., a survey was sent to 11 southern states to identify the types and standards of pavement marking used in this region. The states surveyed included Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia.

4.1 PAVEMENT MARKING SURVEY DESIGN

The survey consisted of only four questions with the goal of optimizing the number of responses. The first question provided a list of the types of pavement marking materials and requested the respondent agency to identify the types of markings it uses on its highways. Question 2 and 3 listed the most common criteria used in material approval and requested the agency to select the criteria and the minimum acceptable values it uses, and state if the minimum criteria were based on specific studies or tests. Question 4 dealt with the specific instruments used by the agency in measuring pavement marking properties. A copy of the survey form is presented as Figure 4.1.

4.2 PAVEMENT MARKING SURVEY RESPONSES

All eleven sates surveyed returned the completed surveys. The responses varied from a simple fill-in-the-blanks to elaborate responses with attached documentation. The survey responses were summarized for each question and the results were tabulated. The following Tables 4.1, 4.2, 4.3 and 4.4 present the summarized responses to Questions 1, 2, 3 and 4, respectively. The questions are re-iterated at the top of each table. All additional comments provided on the survey questions are presented in Table 4.5.

PAVEMENT MARKING SURVEY

Responding State and Agency: ______________________________
Responding Individual: ______________________________
Position: ____________________ Telephone Number: __________

This survey applies to both longitudinal (striping) and transverse (stop lines, crosswalks, etc) pavement marking materials. Please include any relevant notes at the end of each question, or attach additional pages if necessary.

1. Which of the following pavement marking materials do you use on your roads?

___Water-based paint	___Solvent-borne paint
___Hydrocarbon thermoplastic	___Alkyd thermoplast
___Temporary tape	___Permanent tape
___Epoxy paint	___Methacrylate paint
___Polyester paint	Other: __________

Notes:______________________________

2. On which of the following factors does your agency base its approval of pavement markings? (check all applicable)

___Retroreflectivity:	Minimum acceptable initial value:	___ mcd/m^2/lx
	Minimum value through service life:	___ mcd/m^2/lx
___Appearance:	Minimum rating: _______ based on a scale of	__________
___Durability:	Minimum rating: _______ based on a scale of	__________

Notes:______________________________

3. Are the minimum requirements of Question 2 based on studies or tests?
___Yes _______No
If yes, please reference the study/test and attach documentation if available.

4. What instrument(s), if any, does your agency use in evaluating pavement marking properties (e.g. LTL 2000 retroreflectometer, etc.)? Please elaborate.

Figure 4-1 Pavement Marking Survey Form

Table 4.1 Responses to Question 1 of the Pavement Marking Survey

Question 1. Which of the following pavement marking materials do you use on your roads?									
State	**WP**	**SB**	**TT**	**PT**	**AT**	**HT**	**EP**	**PP**	**MP**
Arkansas	X	X	X	X	X	X			
Florida	X		X	X	X	X			
Georgia	X			X	X				
Kentucky	X		X	X	X				
Louisiana	X		X	X	X	X			
Mississippi	X		X	X	X	X			
North Carolina	X		X	X	X		X		
South Carolina	X	X	X	X	X	X	X		
Tennessee	X		X	X	X	X			
Texas	X		X	X	X	X			
Virginia	X		X	X	X	X	X	X	
Total	11	2	10	11	11	8	3	1	0

WP = Water-based Paint SP = Solvent-borne Paint AT = Alkyd Thermoplastic
TT = Temporary Tape; PT = Permanent Tape HT = Hydrocarbon Thermoplastic
EP = Epoxy Paint; PP = Polyester Paint; MP = Methacrylate Paint

Table 4.2 Responses to Question 2 of the Pavement Marking Survey

Question 2. On which of the following factors does your agency base its approval of pavement markings?								
State	**Retroreflectivity**				**Appearance**		**Durability**	
	Minimum Initial Value		Min. Service Life Value		Rating	Scale	Rating	Scale
	White	Yellow	White	Yellow				
Kentucky	NO	NO	NO	NO	NO	NO	NO	NO
Georgia	NO	NO	NO	NO	NO	NO	NO	NO
Arkansas	NO	NO	NO	NO	NO	NO	NO	NO
South Carolina	NO	NO	NO	NO	NO	NO	NO	NO
Mississippi	YES	YES	YES	YES	YES	0-10	YES	0-10
Texas	YES	YES	YES	YES	YES	NA	YES	NA
North Carolina	YES	YES	YES	YES	YES	NA	YES	NA
Florida	YES	YES	YES	YES	NO	NO	NO	NO
Virginia	YES	YES	YES	YES	NO	NO	YES	NA
Tennessee	YES	YES	YES	YES	YES	NA	YES	NA
Louisiana	YES	YES	YES	YES	YES	NA	YES	NA

Table 4.3 Responses to Question 3 of the Pavement Marking Survey

Question 3. Are the minimum requirements of Question 2 based on studies or tests?	
Kentucky	YES
Georgia	NA
Arkansas	NO
South Carolina	NA
Mississippi	NO
Texas	YES
North Carolina	YES
Florida	YES
Virginia	YES
Tennessee	YES
Louisiana	NO

Table 4.4 Responses to Question 4 of the Pavement Marking Survey

Question 4. What instrument(s), if any, does your agency use in evaluating pavement marking properties (e.g. LTL 2000 retroreflectometer, etc.)?			
State	**Instruments Used**		
	1	2	3
Kentucky	LTL 2000	Mobile Laserlux	
Georgia	LTL 2000	Mirolux 12	Mirolux 30
Arkansas	NONE	NONE	NONE
South Carolina	LTL 2000	Mirolux 12	Mirolux 30
Mississippi	NONE	NONE	NONE
Texas	LTL 2000	Mirolux 30	
North Carolina	LTL 2000	Mirolux 12	
Florida	LTL 2000	Mirolux 12	
Virginia	LTL 2000		
Tennessee	LTL 2000		
Louisiana	ART 940	Mirolux 30	

4.3 PAVEMENT MARKING SURVEY FINDINGS

4.3.1 Types of pavement markings

The survey showed that all eleven southern states surveyed use water-based paints, Alkyd thermoplastics and permanent tapes, two-thirds or more of the states use hydrocarbon thermoplastics and temporary tapes, less than a quarter of the states use, epoxy, polyester, and solvent-borne paints, and none of them use methacrylate paints on their roads as shown in Table 4.1. Table 4.2 shows that seven of the eleven states base their pavement marking acceptance on minimum retroreflectivity criteria, although specific values were not always available.

4.3.2 Minimum acceptable retroreflectivity values

Initial retroreflectivity values

Acceptable initial retroreflectivity values for white paints were reported as 250 and 375 mcd/m^2/lx in Florida and North Carolina, respectively. North Carolina bases the initial approval on the results of the NTPEP tests. For yellow paints, the initial acceptable values were reported as 175 and 250 in Florida and North Carolina, respectively. In Louisiana, acceptable initial retroreflectivity values of high performance tape were reported as 700 and 500 mcd/m^2/lx for white and yellow tapes, respectively. Other states , such as Kentucky and Georgia are either working on establishing minimum retroreflectivity criteria or awaiting the publishing of the MUTCD 2000 edition, which is expected to include minimum retroreflectivity criteria for pavement markings.

Table 4.5 Comments on Questions 1-4 of the Pavement Marking Survey

State	Question 1 Comments	Question 2 Comments	Question 4 Comments
Kentucky		Working to establish criteria for retroreflectivity	LTL handheld
Georgia		Waiting on the 2000 edition MUTCD requirements	LTL 2000 most consistent
Arkansas	Maintenance uses WP and AT	Material requirements only	NONE
South Carolina			
Mississippi		Attached info	NONE
Texas		On RPM and permanent tapes minimum values are used on test decks in a prequalification process	Evaluation Only
North Carolina	Heated-in-place Thermoplastic	Base initial approval on participation in NTPEP test deck then product demonstration in NC. Initial values in demo project are 375 mcd/m^2/lux for white and 250 mcd/m^2/lux for yellow markings. Color and bond are also observed for 180 days	Will be rewriting specs based on LTL 2000 and 30-meter geometry measurements
Florida		30-m white 250 initial/125 end of life;30-m yellow 175 initial/125 end of life;15-m white 300/150; 15-m yellow 250/150; Color requirements for yellow	BYK Color Guide
Virginia	Use of PP is minimal	Criteria for paint and tape; Have color requirements for markings and nighttime color requirements for thermoplastic	Hunterlab MiniScan daytime color, PR 650 / Illuminant A for nighttime color
Tennessee		Attached info	
Louisiana		15 m white 450 initial/130 end of life;15-m yellow 350 initial/130 end of life inverted profiled markings;15-m white 700/100; 15-m yellow 500/100 high performance tape	Use ART in lab and Mirolux in field

End of service life retroreflectivity values

The value of retroreflectivity corresponding to the end of the service life of both white and yellow markings was reported by Florida as 125 and 150 mcd/m^2/lx when measured using 30-m and 15-m geometry, respectively. Louisiana uses 100 mcd/m^2/lx as the threshold representing the end of service life of while and yellow tapes.

Testing geometry and retroreflectometers

Most of the states use retroreflectometers to read retroreflectivity measurements. Only Arkansas and Mississippi do not have such a program. Four states use both 15-m and 30-m testing geometry, and five states use 30-m geometry exclusively. All of retroreflectometers used are of the handheld type, except for one Mobile Laserlux used by Kentucky. The most commonly used retroreflectometer is the LTL 2000, which is used by eight of the eleven states. Mirolux 12, the 15-m geometry retroreflectometer used in this study, is used by four states.

Above retroreflectivity minimums represent state of the art practice in the southern states of the U.S. and will be used for comparison with the retroreflectivity threshold established for striping on Alabama highways as part of this study.

5. VARIABLES AFFECTING RETROREFLECTIVITY

5.1 EVALUATION METHODOLOGY

In the literature review, several variables were identified as having significant effects on PM retroreflectivity. This chapter applies statistical methods to quantify the effects of these variables and determine their significance.

5.1.1 Evaluation variables

The variables identified in the literature review as having significant effects on retroreflectivity values include pavement type (asphalt versus concrete), PM type (traffic paints versus durable materials), PM color (white versus yellow), traffic volume (in wheel path versus center of lane), and measurement geometry (15-m versus 30-m). With the exception of measurement geometry, these variables are evaluated for their effects on PM performance, and thus represent real differences in retroreflectivity values. The measurement geometry variable, on the other hand, is evaluated for differences in retroreflectivity readings that result from using measurement instruments that are based on different testing geometries, and therefore, does not reflect actual differences in the PM retroreflectance of the pavement markings.

5.1.2 Evaluation data

In order to identify the variables that affect PM retroreflectivity values, the study takes advantage of the existing NTPEP data of Database 1. The NTPEP data were derived from the NASHTO and SASHTO field tests on Alabama, Kentucky and Pennsylvania test decks. The massive amounts of data documenting the retroreflectivity of various types of pavement markings makes them the best available resource for identifying the variables affecting retroreflectivity. The data were collected over a period of more than six years (1989-1995 for the SASHTO data and 1997 for the NASHTO data). The SASHTO retroreflectivity readings were taken using Mirolux 12 retroreflectometer on over 2000 PM samples at 15 time periods: at end of Month 1 through Month 12 in the first year after application and at end of Months 15, 18 and 24 in the second year. The initial retroreflectivity reading is taken at the end of Month 1 to give the mixed glass beads the necessary time to become exposed in order to achieve maximum retroreflectivity. The SASHTO data are included in Appendix B-1. The NASHTO readings were taken on 375 PM samples at three-month intervals between August 1996 and July 1997 using Erichson 710 (15-m geometry) and LTL 2000 (30-m geometry) retroreflectometers. The July 1997 readings were incomplete due to equipment failure and thus discarded. The NASHTO data are included in Appendix B-2.

Practical values of retroreflectivity

The NASHTO and SASHTO data are the result of a fairly controlled environment where uniformity of PM thickness, bead content, and mixture homogeneity are controlled under near-ideal conditions, thus achieving extremely high initial retroreflectivity. Practical field values of retroreflectivity, however, rarely reach 800 mcd/m^2/lx. The maximum field retroreflectivity value collected as part of this project is 401 mcd/m^2/lx, which was measured on a two-month old white painted edge line, and the lowest reading was 25 mcd/m^2/lx measured on a 745-day (two-year) old painted edge line. The maximum reading on yellow paint was 250 mcd/m^2/lx taken on a 67-day old paint, and the lowest was 25 mcd/m^2/lx measured on a 972-day old paint. For white thermoplastic, the maximum and minimum field readings are 398 and 67 mcd/m^2/lx taken on 121-day old and 775 day old white thermoplastic. The maximum reading on yellow thermoplastic was 380 mcd/m^2/lx taken on a 160-day old thermoplastic, and the lowest was 41 mcd/m^2/lx measured on a 880-day old thermoplastic. Also, retroreflectivity of newly applied markings are usually very low when mixed-in glass beads are used. This is because glass beads take some time to become exposed and be able to redirect incident light. Field data collected as part of this project showed retroreflectivity of two-week old paint to be as low as 27 mcd/m^2/lx. To conform to retroreflectivity field limits, a practical maximum retroreflectivity value of 800 mcd/m^2/lx is imposed on the NEPEP data used in this study, and values above this limit are not considered in the evaluation.

5.1.3 Evaluation method

To evaluate the effect of a variable, it is desirable to compare pairs of individual readings, with one reading resulting from the sample being subjected to the effect of the variable and the other reading not subjected to it. For example, comparing pairs of individual retroreflectivity readings is possible when evaluating the effects of traffic volume and measurement geometry. This is because the retroreflectivity data were generated by subjecting each sample to the two different treatments. The readings for each PM sample were taken in the wheel path and non-wheel path, and using a 15-m and a 30-m geometry retroreflectometers. Thus individual retroreflectivity data points could be paired and compared. When evaluating the effects of the other three variables, on the other hand, namely pavement type, PM type and PM color, no pairing of individual data is possible, since the retroreflectivity measurements were taken on different samples. Therefore, pairing of readings for the purpose of comparing them can not be done on the individual level, and retroreflectivity data points belonging to each of these three categories are grouped by their age, the only common connection between them. Comparing mean monthly values would still meet the objective of this evaluation, which is to determine if retroreflectivity values are, on average, affected by the variables in question. In this study, where individual data points can not be paired, readings of same-age samples in each category are averaged, and the sets of averages are compared. Since retroreflectivity readings of all samples were taken at 15 different time intervals (periods of Month 1 through 12, and Months 15, 18, and 24), 15 pairs of mean R_L values are compared.

5.1.4 Evaluation tool

Statistical analysis is used to evaluate the effects of each variable on retroreflectivity values. For each variable evaluated, two sets of R_L data, one with and one without the influence of the variable, are compared. The R_L values are individual values in the case of the traffic volume and testing geometry variables, and are periodic mean values in the case of pavement type, PM type and PM color variables. Since R_L values vary with time for the same marking, a paired t-test analysis was selected for determining the statistical significance of a variable's effect on R_L. Paired t-test compares the sample means of two sets of data by comparing the differences between pairs of data points. When mean R_L values are used, the paired t-test compares same-period pairs of data from the two sets of mean R_L values. This serves as a control on the variations of mean R_L values from month to month within the same data set. A two-tailed test is used to determine if the means are distinct (unequal), while a one-tailed test determines if one mean is larger (or smaller) than the other at a certain level of statistical significance. This analysis uses the null hypothesis (H_0) that no significant difference in mean R_L values exists between markings placed on asphalt and those placed on concrete pavements (i.e. H_0: $\mu_D = 0$, where μ_D is the difference in means of the pairs of data). The alternative hypothesis, H_a, is that a significant difference between markings on asphalt and concrete pavements does exist (i.e. H_a: $\mu_D \neq 0$). A significance level, α, of 0.05 is used for statistical significance. The significance level represents the probability of having a Type I error, which is the probability of rejecting a true hypothesis. The paired t-test does not assume the variances of both populations to be equal. The pooled variance used in this analysis is an accumulated measure of the spread of the data about the mean, and can be thought of as the weighted average of the variances of the two populations of interest. The pooled variance is derived from the following equation:

$$S_p^2 = \frac{n_1 S_1^2 + n_2 S_2^2}{n_1 + n_2 - 2} \tag{8}$$

where S_1^2 = Variance of first data set

n_1 = Number of samples in first data set

S_2^2 = Variance of second set of data

n_2 = Number of samples in second data set

S_p^2 = Pooled variance

The effects of the variables on the PM performance over time is modeled using logarithmic regression. Logarithmic regression is selected since it best describes the decay characteristics of pavement markings with age. Plots of the R_L-PM age relationships are generated showing the equations and coefficients of determination, R^2, of the regression models. The R^2 coefficient represents the proportion of the data variability explained by the model, and is a good indicator of the correlation between the dependent and independent variables.

5.2 EVALUATION OF VARIABLES

5.2.1 Effects of pavement type on retroreflectivity

To evaluate whether the PM performance varies, on average, between the PM samples placed on asphalt pavement and those placed on concrete pavement, the periodic mean R_L readings taken on asphalt surfaces were compared with those taken on concrete surfaces. Table 5-1 presents the mean R_L values for the 15 testing periods, and the total number of samples from which these mean values are derived.

Table 5-1 Mean R_L values on asphalt and concrete surfaces

Month	Count of all PM samples	Avg. of all PM samples	Count of all asphalt	Avg. of all asphalt	Count of all concrete	Avg. of all concrete	% diff in count	% diff in R_L
1	2001	287	1051	282	950	292	10%	3%
2	2002	230	1052	225	950	235	10%	4%
3	1994	212	1045	210	949	214	9%	2%
4	1994	198	1045	197	949	200	9%	1%
5	1937	184	990	184	947	184	4%	0%
6	1991	170	1045	171	946	169	9%	-1%
7	1989	164	1044	162	945	165	9%	2%
8	1989	156	1044	154	945	159	9%	4%
9	1989	151	1044	150	945	151	9%	1%
10	1987	147	1043	148	944	147	9%	-1%
11	1985	135	1043	135	942	136	10%	1%
12	1984	130	1043	132	941	128	10%	-3%
15	782	143	434	141	348	144	20%	2%
18	780	125	433	118	347	133	20%	11%
24	775	123	433	122	342	124	21%	2%

Per Table 5-1, the periodic mean R_L values are based on approximately 1,000 PM samples (∀5%) in the first year and on approximately 390 samples (∀10%) in the second year. Table 5-1 also shows the mean R_L readings on concrete to be slightly higher than the mean readings on asphalt.

Logarithmic regression is used to model the R_L-PM age relationships of the samples on asphalt and concrete surfaces, and a plot of the relationships is presented in Figure 5-1. This Figure shows that the logarithmic model provides a very good fit of the data as evident by the high R^2 values of 0.95 and 0.96, for concrete and asphalt surfaces, respectively. This means that the above logarithmic models explain at least 95% of the variability in the periodic mean R_L values.

These models, however, seem to slightly over-represent the mean R_L values in the first year and to slightly under-represent them in the second year. Figure 5-1 also shows the asphalt and concrete models to almost coincide, indicating that the PM performance on asphalt and concrete surfaces is practically identical. The overall mean R_L values for the entire two-year testing period were 169 and 172 mcd/m^2/lx on asphalt and concrete surfaces, respectively. The difference in PM performance is is statistically significant at the α=0.05 significance level, indicating that higher R_L values are expected on concrete surfaces than on asphalt surfaces. The difference, however, is minor averaging only 3 mcd/m^2/lx. Although statistically significant, such a difference is practically insignificant, especially that a reading variation of this magnitude is possible with repeated tests of the same sample. Results the paired t-test are summarized in Table 5-2.

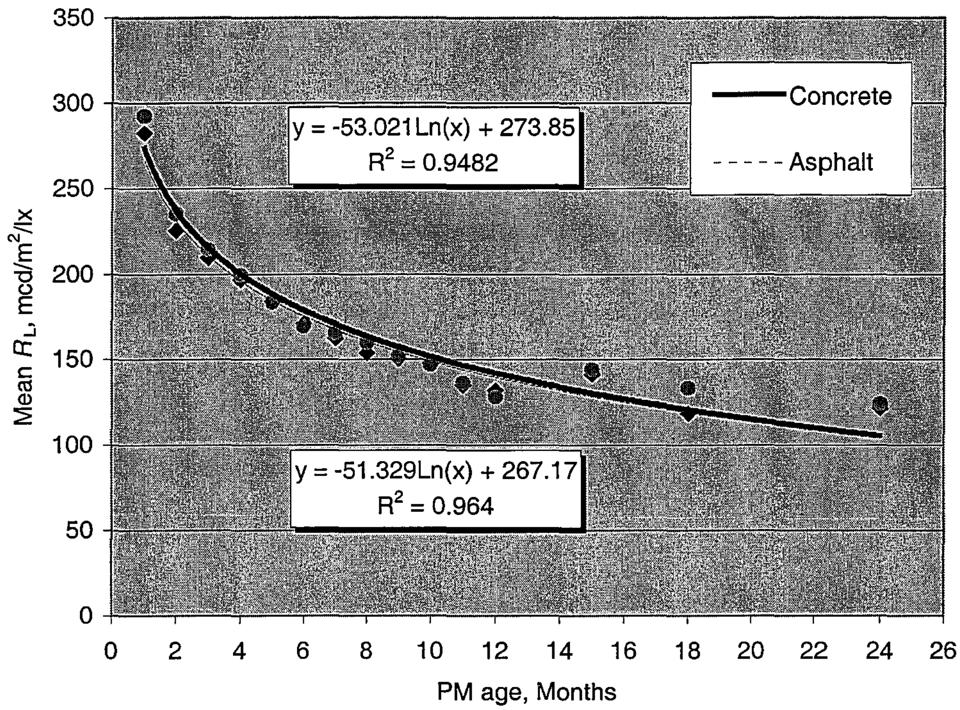


Figure 5-1 *R_L-PM age logarithmic model: Asphalt versus concrete surfaces*

Table 5-2 Statistical significance of the difference in mean R_L values on asphalt versus concrete surfaces

t-Test: Paired Two Sample for Means		
	Avg. of all Asphalt	Avg. of all Concrete
Mean	168.74	172.18
Variance	1992.5	2161.3
Observations	15	15
Hypothesized Mean Difference	0	
Degrees of freedom	14	
t Stat	-2.716	
P(T<=t) two-tail	0.0167	
t Critical two-tail	2.1448	

5.2.2 Effects of pavement marking type on retroreflectivity

To evaluate the effect of PM type on PM performance, mean R_L values of durable materials were compared to those of non-durable materials. The periodic mean R_L readings of durable material (alkyd and hydrocarbon thermoplastics, methacrylate and epoxy paints, and preformed tapes) are compared to those of traffic paints (water-based and solvent-borne paints) for the 15 testing periods. Table 5-3 presents the periodic mean R_L values for each of the two categories and the number of samples upon which the mean values are based. This table shows that approximately 1,000 samples (≅20%) of durable and non-durable material were tested in the first year. The number of traffic paint samples tested in the second year, however, is much smaller amounting to approximately 100 samples, while the number of durable material samples is slightly lower than the first year (approximately 667 samples). The reason for the small number of non-durable samples in the second year is most likely because of the expectation that service life of traffic paints is much shorter than durable material and that they are expected to fail in the second year. Table 5-3 shows this to be the case, with mean R_L values of traffic paints falling to a very low level (below 65 mcd/m^2/lx) in the second year. Despite the lack of national standards on R_L threshold, no research suggests that such a low level of retroreflectivity is acceptable. Table 5-3 shows mean R_L values of durable material to be approximately 30% and 60% higher than traffic paints in the first and second year, respectively, a statistically significant difference at the α=0.05 significance level, per the paired t-test results of Table 5-4.

Table 5-3 Periodic Mean R_L values for traffic paints and durable materials

Month	Count of all PM samples	Avg. of all PM samples	Count of all paints	Avg. of all paints	Count of durable mat.	Avg. of durable mat.	% diff in count	% diff in R_L
1	2001	287	1202	247	799	347	34%	29%
2	2002	230	1202	191	800	288	33%	34%
3	1994	212	1202	178	792	263	34%	32%
4	1994	198	1202	167	792	246	34%	32%
5	1937	184	1169	158	768	224	34%	30%
6	1991	170	1202	148	789	204	34%	28%
7	1989	164	1202	144	787	194	35%	26%
8	1989	156	1202	138	787	185	35%	26%
9	1989	151	1202	132	787	180	35%	26%
10	1987	147	1202	129	785	176	35%	27%
11	1985	135	1201	118	784	163	35%	28%
12	1984	130	1201	110	783	161	35%	31%
15	782	143	113	64	669	156	-492%	59%
18	780	125	113	60	667	136	-490%	56%
24	775	123	109	55	666	134	-511%	59%

Table 5-4 Statistical significance of the difference in mean R_L values of traffic paints versus durable materials

t-Test: Paired Two Sample for Means		
	Avg. of all Paints	*Avg. of Durable Mat.*
Mean	135.77	203.73
Variance	2679.9	3615.2
Observations	15	15
Hypothesized Mean Difference	0	
Degrees of freedom	14	
t Stat	-13.13	
P(T<=t) two-tail	3E-09	
t Critical two-tail	2.1448	

The loss of retroreflectivity with age is modeled using logarithmic regression and a plot of the two models representing durable and non-durable materials is presented in

Figure 5-2. This figure and Table 5-4 show the difference in mean R_L values between the two models to be substantial, averaging 65 mcd/m^2/lx. The logarithmic models provide a very good fit of the mean R_L data as evident by the high R^2 coefficients of 0.94 and 0.98 for durable and non-durable materials, respectively. Note that the mean R_L values for thermoplastic show a slight increase at the end of the first year, especially for Month 15. This is inconsistent with the decay characteristics of pavement markings and the behavior assumed by logarithmic modeling.

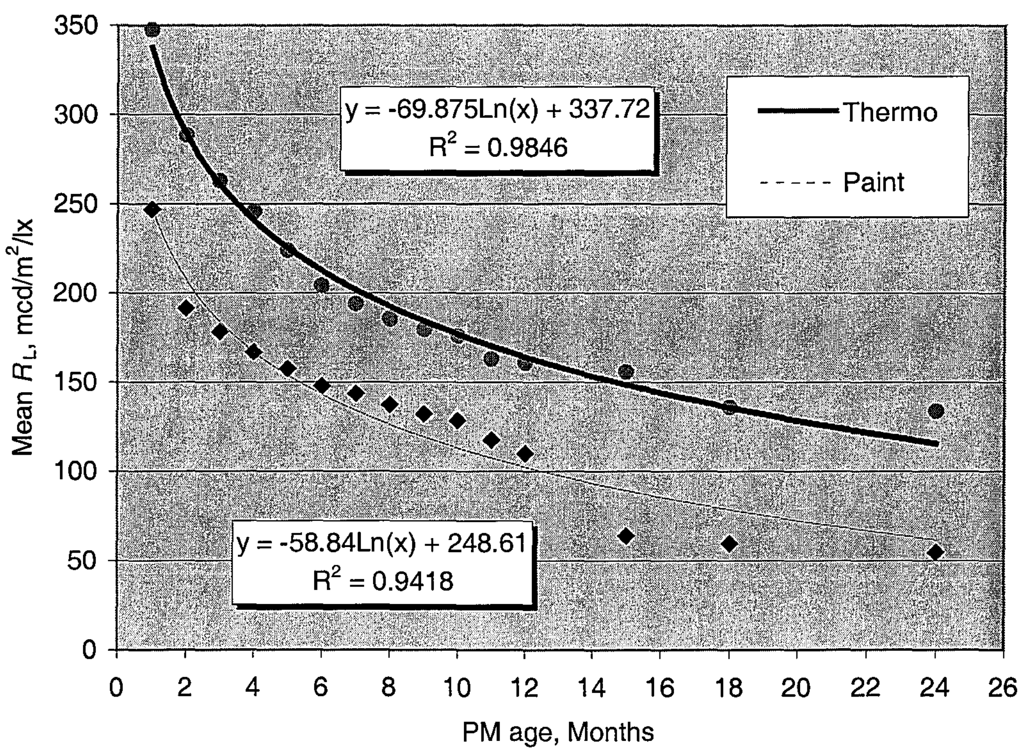


Figure 5-2 R_L-PM age logarithmic model: Traffic paints versus durable materials

5.2.3 Effect of pavement marking color on retroreflectivity

To evaluate the effect of PM color on PM performance, the periodic mean R_L values of all white markings were compared with those of yellow markings. The purpose of this evaluation is to provide statistical support to the general understanding that yellow markings perform less efficiently than white markings, and to quantify the difference in performance. The periodic mean R_L values are based on approximately 1,000 samples (∀6%) of each color in the first year and on approximately 400 samples of each color for the second year. Table 5-5 presents the mean R_L values and the number of samples upon which the mean values are based.

This table shows white markings to have approximately 20% to 30% higher R_L values than yellow markings. This difference is statistically significant at the α=0.05 significance level as shown in the paired t-test results of Table 5-6. The difference in the overall mean R_L values is more evident in the earlier months of PM age (approximately 90 mcd/m^2/lx in Month 1), but less pronounced in the long term (approximately 25 mcd/m^2/lx in Month 24). The performance of white and yellow markings over time is modeled using logarithmic regression, and a plot of the models representing white and yellow markings, with the equations and R^2 coefficient are presented in Figure 5-3. The good fit of the logarithmic models is indicated by the high R^2 values of 0.98 and 0.94 for white and yellow markings, respectively. As noted in the previous evaluations of pavement surfaces and PM types, the mean R_L values show a slight increase at the end of the first year, especially for Month 15. The reason for this increase is unknown, and may be attributed to seasonal characteristics or re-calibration of the retroreflectometer since readings were taken at same time of year.

Table 5-5 Periodic Mean R_L values for white and yellow pavement markings

Month	Count of all PM samples	Avg. of all PM samples	Count of all White	Avg. of all White	Count of all Yellow	Avg. of all Yellow	% diff in count	% diff in R_L
1	2001	287	935	334	1066	246	12%	27%
2	2002	230	935	275	1067	191	12%	30%
3	1994	212	930	248	1064	180	13%	27%
4	1994	198	930	233	1064	168	13%	28%
5	1937	184	901	215	1036	157	13%	27%
6	1991	170	928	199	1063	145	13%	28%
7	1989	164	926	191	1063	139	13%	27%
8	1989	156	926	182	1063	134	13%	26%
9	1989	151	926	175	1063	130	13%	26%
10	1987	147	926	170	1061	128	13%	25%
11	1985	135	924	156	1061	117	13%	25%
12	1984	130	923	150	1061	113	13%	24%
15	782	143	400	159	382	125	-5%	21%
18	780	125	400	140	380	109	-5%	22%
24	775	123	395	135	380	109	-4%	19%

Table 5-6 Statistical significance of the difference in mean RL values of white versus yellow pavement markings

t-Test: Paired Two Sample for Means		
	Avg. of ALL White	*Avg. of ALL Yellow*
Mean	197.51	146.09
Variance	3071.2	1395.9
Observations	15	15
Hypothesized Mean Difference	0	
Degrees of freedom	14	
t Stat	10.72	
P(T<=t) two-tail	4E-08	
t Critical two-tail	2.1448	

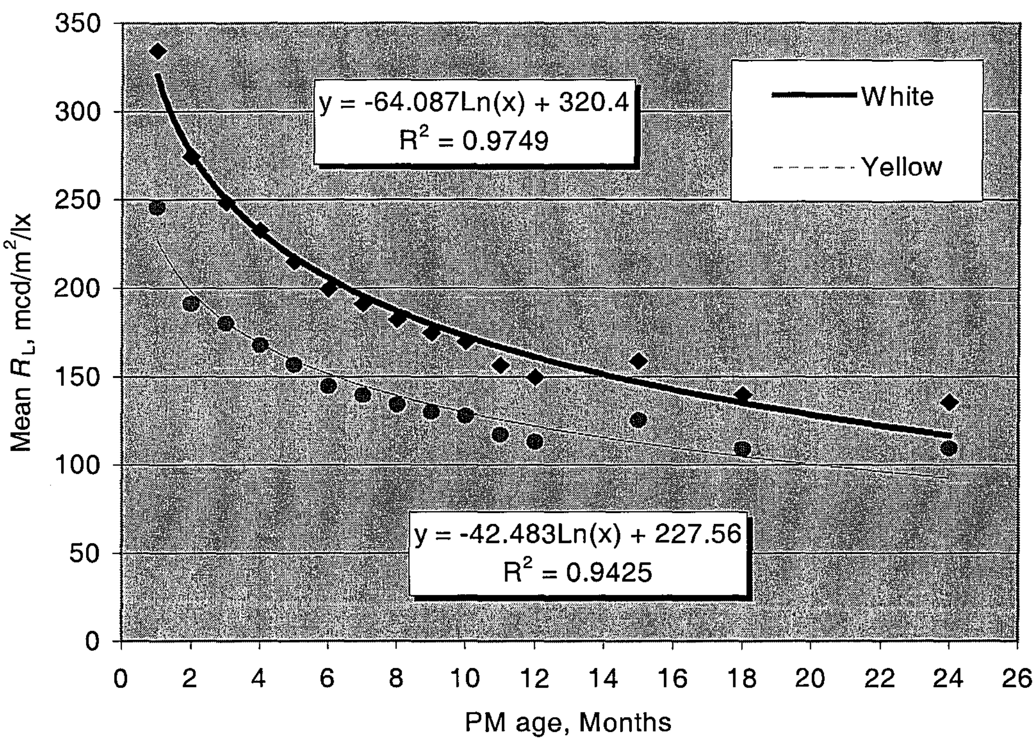


Figure 5-3 *R_L-PM age logarithmic model: White versus yellow markings*

5.2.4 Effects of traffic volume on retroreflectivity

To evaluate the effects of traffic volume of PM performance, individual traffic-exposed R_L readings taken in the wheel path of each PM sample were compared with the corresponding traffic-free readings taken in the center of lane (non-wheel path). The performance difference between the traffic-exposed and traffic-free marking categories represents the effect of 5,000 vpd/lane, which is the average test deck AADT. This evaluation quantifies the effect of traffic volume on PM performance (R_L values) and provides statistical support to the difference in performance. The total number of R_L

readings taken in the wheel path and non-wheel path amounted to 52,274 readings (26,137 pairs). The periodic mean R_L values are based on approximately 2,000 samples (±1%) in the first year and on approximately 775 samples in the second year. Table 5-7 presents the mean R_L values and the number of samples upon which the mean values are based. The difference in the overall mean R_L values is less pronounced in earlier months of PM age (approximately 15 mcd/m^2/lx in Month 1) and more pronounced in the long term (approximately 70 mcd/m^2/lx in Month 24), which indicates a compounded (cumulative) effect of traffic volume over time. Paired t-test analysis shows the difference in PM performance to be statistically significant at the α=0.05 significance level. The results of this paired t-test are shown in Table 5-8.

The performance of PM markings in the wheel path and center of lane is modeled using logarithmic regression, and a plot of these two models with the equations and R^2 coefficients are presented in Figure 5-4. The good fit of the logarithmic models is indicated by the high R^2 values of 0.96 and 0.93 for wheel path and center of lane readings, respectively. Note that the center of lane model is an indirect indicator of the weather effect, since weather is the other major factor affecting retroreflectivity besides traffic volume. The traffic volume effect is represented by the area on the graph enclosed by the two regression lines.

Table 5-7 Periodic Mean R_L values for traffic-exposed and traffic-free pavement markings

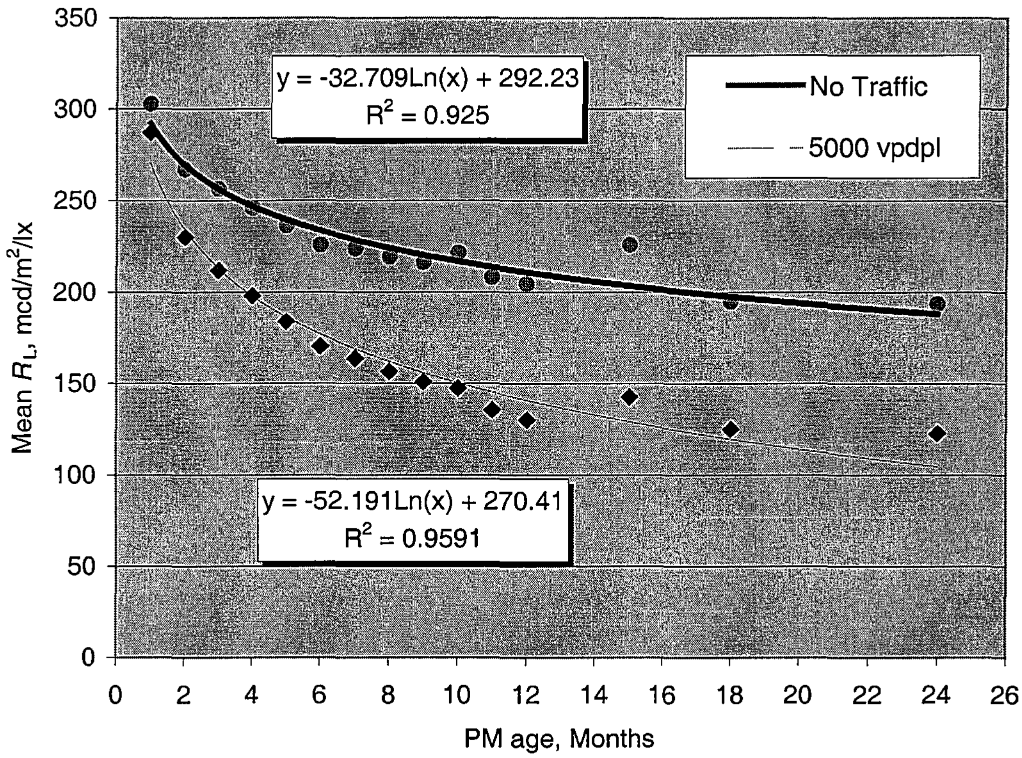
Month	Count of all PM samples	Avg. of all PM samples	Count of all Wheel	Avg. of all Wheel	Count of all non-wheel	Avg. of all non-wheel	% diff in count	% diff in R_L
1	2001	287	2001	287	2001	303	0%	5%
2	2002	230	2002	230	2002	267	0%	14%

3	1994	212	1994	212	1996	256	0%	17%
4	1994	198	1994	198	1996	246	0%	19%
5	1937	184	1937	184	1941	236	0%	22%
6	1991	170	1991	170	1996	226	0%	25%
7	1989	164	1989	164	1994	224	0%	27%
8	1989	156	1989	156	1993	219	0%	29%
9	1989	151	1989	151	1992	216	0%	30%
10	1987	147	1987	147	1991	221	0%	33%
11	1985	135	1985	135	1990	208	0%	35%
12	1984	130	1984	130	1990	205	0%	36%
15	782	143	782	143	770	226	-2%	37%
18	780	125	780	125	770	195	-1%	36%
24	775	123	775	123	770	194	-1%	37%

Table 5-8 Statistical significance of the difference in mean R_L values of traffic-exposed versus traffic-free pavement markings

t-Test: Paired Two Sample for Means		
	Traffic-exposed	*Traffic-free*
Mean	176.27	233.08
Variance	9507.2	13005
Observations	26137	26137
Hypothesized Mean Difference	0	
Degrees of freedom	26136	
t Stat	-159	
P(T<=t) two-tail	0	
t Critical two-tail	1.9601	

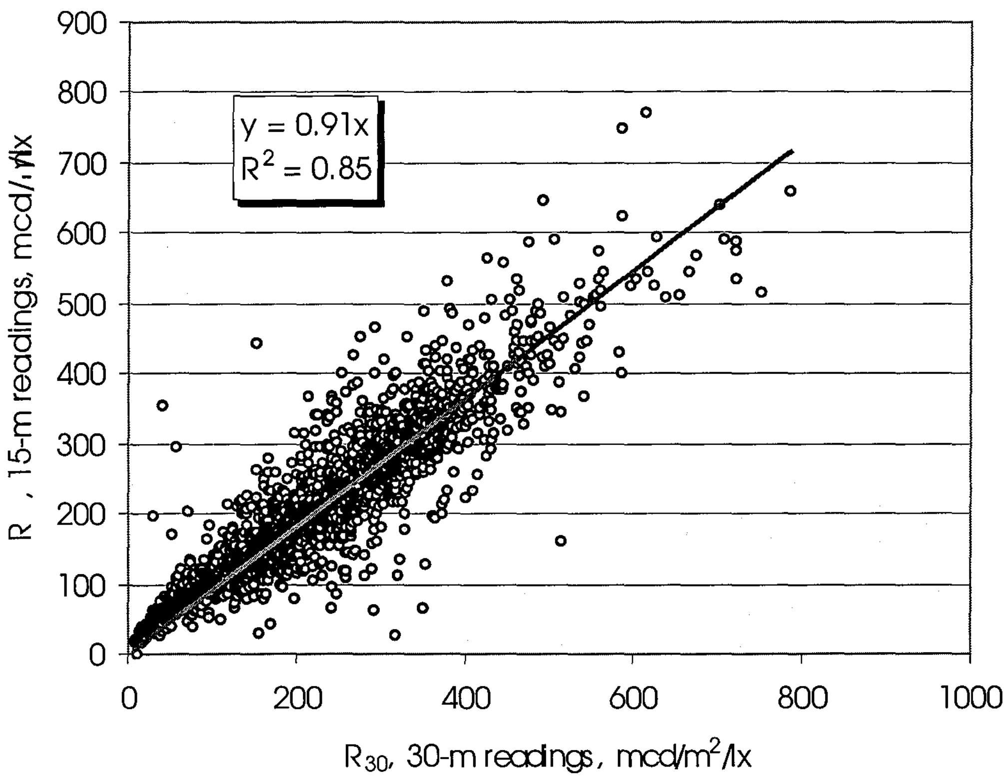
Figure 5-4 R_L-PM age logarithmic model: Traffic-exposed versus traffic free markings



5.2.5 Effects of testing geometry on retroreflectivity readings

To evaluate the effect retroreflectometers with different geometries have on R_L readings, the NASHTO test deck data of Appendix B-2 are used. The data include measurements of the same PM samples by both 15-m and a 30-m geometry retroreflectometers. The data include few points with extremely high R_L values. Retroreflectivity values higher than 800 mcd/m^2/lx are practically non-existent under in-situ operational conditions. This study sets a practical maximum R_L value of 800 mcd/m^2/lx. The number of data points above this value is very small constituting less than 1% of the data. Using the practical upper bound of 800 mcd/m^2/lx, the valid data amounted to a total of 4,468 readings out of a total of 4500 readings collected over a period of nine months. To correlate the readings taken by the two different geometry retroreflectometers, linear regression is performed. A plot of the regression model showing the equation and R^2 coefficient is presented in Figure 5-5.

Figure 5-5 R_L-PM age logarithmic model: 15-m versus 30-m geometry



The regression model shows the readings taken by the Erichson 710 (15-m geometry) retroreflectometer to be 91% those taken by the LTL 2000 (30-m geometry) retroreflectometer. This result is contrary to the general expectation that 30-m geometry readings should be lower than 15-m geometry readings because they represent the brightness of farther targets. The resulting relationship is described in the following linear model.

$$R_{15} = 0.91\ R_{30} \tag{9}$$

where

R_{15} = R_L reading using the 15-m geometry retroreflectometer.

R_{30} = R_L reading using the 30-m geometry retroreflectometer.

Figure 5-5 shows that a good correlation exists between the two retroreflectometers with an R^2 coefficient of 0.85. The overall difference in R_L readings between the above two retroreflectometers is approximately 16 mcd/m^2/lx. To determine if this difference is statistically significant, a paired t-test is performed. Since 2,250 readings were collected by each retroreflectometers on the same PM samples, the paired t-test has 2,249 degrees of freedom. The test results indicate that the difference in R_L readings between the above two retroreflectometers is statistically significant at the α=0.05 significance level. Table 5-9 presents the results of this paired t-test.

The relationship between the above two retroreflectometers as described in the linear regression model should be considered representative of the relationship between the LTL 2000 and the Erichson 710 retroreflectometers, and not necessarily representative of their respective testing geometries. This distinction is important since the literature review findings show that significant variability in R_L readings exists among retroreflectometers of the same geometry, and using 15-m and 30-m geometry retroreflectometers other than the above are expected to produce different relationships. Reading variability resulting from using different make and model retroreflectometers were shown to exceed the variability resulting from the above two different-geometry retroreflectometers. Thus, research studies requiring long term measurements and data compatibility, such as tracking R_L changes over time, should be based on same make and model retroreflectometers, and not merely same geometry.

Table 5-9 Statistical significance of the difference in mean R_L values of traffic-exposed versus traffic-free pavement markings

t-Test: Paired Two Sample for Means		
	30m Readings.	*15m Readings*
Mean	217.55	202.49
Variance	15093	12760
Observations	2234	2234
Hypothesized Mean Difference	0	
Degrees of freedom	2233	
t Stat	15.095	
P(T<=t) two-tail	4.24E-49	
t Critical two-tail	1.961	

5.3 CHAPTER SUMMARY

- All of the variables evaluated in this chapter have a statistically significant effect on the value of PM retroreflectivity. The extent of the effect, however, is different for each variable.
- Pavement type has a minor effect on the value of R_L values. The R_L readings of PM on concrete are approximately 3 mcd/m^2/lx higher than the mean R_L readings on asphalt pavements regardless of the age of the markings. Although this difference is statistically significant, its value is very small and may not warrant special consideration, especially that repeatability of R_L measurements in the field by the same instrument on the same marking can deviate by 3 mcd/m^2/lx or more.
- PM type has a substantial effect on R_L values. The mean retroreflectivity of durable markings is approximately 65 mcd/m^2/lx higher than that of traffic paints regardless

of the age of the markings. Therefore, when evaluating highways with various PM types, durable materials and traffic paints should be evaluated independently.

- PM color has a substantial effect on R_L values. The mean R_L reading of new white markings is approximately 90 mcd/m^2/lx higher than that of new yellow markings. The effect of PM color decreases, but remains substantial, with age, reaching approximately 25 mcd/m^2/lx at PM age of 24 months. Therefore, service life and retroreflectivity of edge lines are higher than those of centerlines, and drivers could use the edge line for guidance even after the centerline has faded.
- Traffic volume has a significant effect on R_L values. The R_L readings taken on traffic-free markings are higher than readings taken on traffic-exposed markings, ranging from approximately 15 mcd/m^2/lx when the markings are new to approximately 70 mcd/m^2/lx when the markings are 24 months old. This indicates a compounded effect of the cumulative traffic volume and PM age. Therefore, an evaluation of the effects of vehicular traffic on PM retroreflectivity should account for the PM age.
- Testing geometry has a significant effect on R_L readings, with 15-m geometry readings being approximately 10% lower than 30-m geometry readings. Variability in R_L readings, however, may be less than the variability in readings between different make and model retroreflectometers of the same geometry. An appropriate correlation between 15-m and 30-m geometry readings requires the correlation of readings by the different retroreflectometers on the market. This study shows R_L readings taken by an Erichson 710 (15-m) retroreflectometer to be approximately 90% of those taken by an LTL 2000 (30-m) retroreflectometer. Therefore, for

compatibility of R_L data, retroreflectivity studies should utilize one type of retroreflectometer for the whole study area and duration, and same retroreflectometer used in previous studies should be used in follow-up studies.

- The logarithmic model describing the deterioration of retroreflectivity with time on the test decks was found to under-predict or over-predict second year R_L values, especially for Month 15. The reason for a retroreflectivity increase instead of a decrease at Month 15 may be attributed to seasonal climatic effects or testing instrument calibration, among other reasons. An investigation of this phenomenon is warranted and future research to explain it is encouraged.

6. DETERMINATION OF RETROREFLECTIVITY THRESHOLD

This study is based on the premise that nighttime PM-related crashes increase as pavement markings age and their retroreflective properties deteriorate. To establish a crash-based threshold of PM retroreflectivity, the longitudinal PM field conditions and the highway crash experiences corresponding to the PM conditions are analyzed in this chapter. The variables affecting PM retroreflectivity identified in the previous section were based on test deck samples placed transversely across highway travel lanes to simulate accelerated wear. Most pavement markings, however, are applied longitudinally in the form of edge lines, lane lines, or centerlines for the purpose of guiding traffic. The variables identified in the previous chapter as having significant effects on PM retroreflectivity are used in this chapter for field R_L and crash data analyses. In the crash analysis, a critical point in a PM deteriorated state beyond which the crash rate exceeds the expected (mean) crash rate is identified. In the R_L data analysis, this critical point is related to a minimum acceptable level of retroreflectivity. The data necessary for these analyses included the field-collected R_L data (Database 2) and the crash data (Database 5). These two databases represent the in-situ PM conditions along Alabama State highways (Database 4) as subjected to the impact of daily traffic (Database 3). The evaluation of PM performance in this chapter focuses on the effects of prolonged vehicle exposure on the condition of the markings and the crashes associated with the marking conditions. Relationships are established between crash rate and vehicle exposure and also between PM retroreflectivity and vehicle exposure. These relationships are used for determining the minimum acceptable level of retroreflectivity needed to maintain a below-average crash rate.

6.1 ANALYSIS OF FIELD CRASH DATA

This section presents an evaluation of the crash experiences of Alabama State highways in relation to the longitudinal pavement marking line (long line) condition. Since long line retroreflectivity is the primary nighttime visual aid along rural highways, only nighttime crashes are considered in this analysis, of which only those crashes considered to be long line-related are expected to increase as retroreflectivity decreases.

6.1.1 Crash analysis variables

Relating the crashes of Database 5 of Appendix F to various highway-related variables is essential to analyzing crash experiences. New fields are added to the crash database to accommodate the following pertinent variables.

- *PM_Type*: represents the pavement marking type. The two types used in this analysis are paint and thermoplastic. *PM_Type* is obtained from Database 2 of Appendix C, and verified in the field.
- *Length*: represents the length of the highway segment, in miles. *Length* is obtained from Database 2 of Appendix C.
- *Striping_Date*: represents the start of the analysis period, and the basis for calculating the pavement marking age. *Striping_Date* is obtained from Database 2 of Appendix C.
- *num_Ln*: represents the highway number of lanes, obtained from Database 3 of Appendix D, and verified in the field.

Other variables were determined from other variables in the databases and added to the crash database. Such variables include:

- *ADT*: represents the average of the AADTs, in vehicles per day (vpd), at the crash location (log mile post) for the years from the *Striping_Date* to the present (July 1, 1999), calculated as:

$$ADT = \frac{\sum_{i=t_1}^{t_2} AADT_i}{t_2 - t_1} \tag{10}$$

where t_1 = Striping year

t_2 = Crash year (or 1999 for highways with no crashes)

$AADT_i$ = Annual Average Daily Traffic for Year i, obtained from Database 3 of Appendix D

- *ADT_Ln*: represents the average ADT per lane of a highway, calculated as:

$$ADT\_Ln = \frac{ADT}{num\_Ln} \tag{11}$$

- *Line_Type*: represents the long line type to which crashes are related: i.e. centerline (*CL*), edge line (*EL*) or lane line (*LL*). This variable is determined as follows:

CL: if *Crash_Type* is *HO* or *ODSS*

LL: if *Crash_Type* is *SS* and *num_Ln* equals 4 or more

EL: for all other types of crashes, namely *FO*, *ROR*, *OT/JK*.

- *PM_age@crash*: represents the age of the longitudinal pavement marking at time of crash, in months, calculated as follows:

$$PM\_age@crash = \frac{Crash\_Date - Striping\_Date}{30.4} \tag{12}$$

where 30.4 is the days-to-months conversion factor.

- *VE*: is the PM vehicle exposure, measured in thousands (or millions) of vehicles, and represents the total volume of traffic that traversed the crash site from the *Striping_Date* up to the crash date.

$$VE \quad = (ADT_{eff} * 30.4 * PM\_age@crash)/1000 \qquad (13)$$

where $ADT_{eff} = ADT\_Ln$ (for *EL*-related crashes), and

$= 2*ADT\_Ln$ (for *CL*- and *LL*-related crashes)

The effective average daily traffic, ADT_{eff}, is the daily traffic acting on the long line. As indicated in the above equation, its value is dependent on the *Line_Type* since the traffic of a single lane acts upon an edge line, while the traffic of two lanes acts upon a lane line or a centerline of a highway.

6.1.2 Pavement marking variables

According to the results of the previous chapter, the crash database is stratified according to the variables affecting the PM performance, namely PM type and PM color. This stratification converted the database into four groups: white paint, yellow paint, white thermoplastic and yellow thermoplastic, and thus the effect of each variable can be addressed independently. The effect of testing geometry and type of retroreflectometer was eliminated by using the Mirolux 12 for all measurements in this study. This is the same unit used in the SASHTO test deck measurements evaluated in the previous chapter, and using the same unit ensures compatibility among the readings.

The time used in the crash history analysis is the three-month period. That is the crash history of each highway segment is subtotaled for each three-month increment of PM age. The decision to use the three-month period as the unit time was made for the following two main reasons:

1) to allow a meaningful analysis of the data by reducing the number of zero crash entries. Analysis of exceptionally rare events, such as retroreflectivity-related crashes, results in having short-duration crash experiences equal to zero, since it discards all daytime and alcohol-related crashes. Therefore, aggregating the crash experience for a shorter time period, per month for example, and having most entries equal to zero is not of value in this analysis. Using shorter time period is possible if the scope of work is drastically increased so that a sufficiently large vehicle-mileage is accumulated in the shorter periods. Using regional or multi-state data can enable the use of shorter periods.
2) to have a meaningful time increment consistent with striping scheduling practices. Typically, practitioners schedule striping jobs in cyclical periods, which are multiples of three-month periods. Re-striping is scheduled every 6, 9 or 12 months for paints and every 12, 18 or 24 months, etc, for thermoplastics according to regional weather conditions, funding availability, and jurisdiction policies. Therefore, evaluating highway crash experiences in three-month increments is consistent with the need for such information.

The modified database that includes the stratified crash experiences of each PM type and PM color, which are aggregated in three-month time increments is presented as Appendix G.

6.1.3 Crash Analysis methodology

Standardizing the crash experiences of highway segments of different *Length*s, *ADT*, and *PM_age@crash* is necessary for evaluating the safety implications of long lines. One would expect, for example, a route that was last striped two years ago to have more crashes in its history than a route that was striped only six months ago, or a 10-mile long highway to experience more crashes than a two-mile long segment, and so on. To normalize the crash experience, unit distance, unit time, and unit traffic volume are applied to every highway segment. The unit time used in this study is a three-month increment, as discussed above. This study also uses a unit highway length of one mile, and a unit traffic exposure of one million vehicles. This makes a highway crash rate equivalent of the average crash experience of a one-mile segment of highway that is traveled by a total of a million vehicles over a period of three months.

A crash normalization value, *CNV*, is assigned to every highway segment. The *CNV* factor is used to convert highway crash experiences into crash rates. The *CNV* factor is calculated as follows.

$$CNV = \frac{(ADT_{eff} * 3 * 30.4) * Length}{10^6} \qquad (14)$$

Periodic CNV is calculated as the sum of the CNVs of all projects in each 3-month period.

Crash rate, *CR*, measured in crashes per million vehicle-miles of travel (crash/MVM), can then be obtained by normalizing the number of crashes, *num_crashes*, using the *CNV* factor, as follows.

$$CR = \frac{num\_crashes}{CNV} \qquad (15)$$

Crash rate calculation

The crash experience of each highway segment is aggregated for each three-month period. Whenever possible, the crash experience is evaluated for three years (12 periods) after the striping date. When three years post striping are not available, the crash experience is evaluated up to the date of re-striping or the present (July 1, 1999), whichever came sooner. The values of the *CNV*, *VE*, and *num_crashes* are subtotaled for each period, and the crash rate calculated for each period per the above equation. The overall crash rate for all projects is calculated from the overall sum of *num_crashes* and overall sum of *CNV* values for all projects as follows.

$$CR_{Avg} = \frac{\sum_{All\ periods} num\_crashes}{\sum_{All\ periods} CNV} \tag{16}$$

The value of CR_{Avg} is used as the critical crash rate that corresponds to the retroreflectivity threshold, $R_{\min}$, and is considered in this analysis as the maximum allowable crash rate before re-striping is warranted.

Crash-vehicle exposure relationship

The effect of traffic volume and PM age on the crash rate can be shown through the relationship between *CR* and *VE*. Using linear regression, the periodic *CR* for each PM type and color is related to the average *VE* for each period. Crash rates were modeled for white long lines (edge lines and lane lines) only. Yellow long lines were not modeled for the following reasons.

1. Yellow markings lose their retroreflectivity sooner than white pavement markings as was shown in Sections 2.4 and 4.2. Thus white edge lines could still provide guidance even after the yellow centerline has faded.
2. Driver eye scanning experiments cited in Section 2.4 indicate that drivers on fully-marked roads have the tendency to fixate almost exclusively on the right edge line when asked to detect the end of long lines (22).

3. The sample sizes of yellow paint and thermoplastic long lines are too small for a meaningful evaluation.

The *CR-VE* relationships for white paint and thermoplastic long lines are plotted, and the model equations and R^2 coefficients are generated.

6.1.4 Crash rate of painted long lines

The white paint category is the largest category analyzed in this study. It accounts for the crash experiences of a total of 123 striping projects on two and four-lane highways, with a total of over 900 highway miles (1,450 km). Most of the white paint crash data collected is associated with two-lane edge lines as shown in Table 6-1.

Table 6-1 Summary of crash history on projects with white paint striping

White Paint	Two-Lane Highways		Four-Lane Highways		Total
No. of projects	115	(93%)	8	(7%)	123
No. of crashes	146	(89%)	18	(11%)	164
Highway mileage	870	(96%)	32	(4%)	902

A summary of the variables used in evaluating the periodic crash rates is presented in Table 6-2. This table shows the number of projects per period to be smaller in the later periods since many of the highways are re-striped before they are three years old. The average number of striping projects per period is 65 projects.

The critical crash rate, CR_{Avg}, for white painted lines is calculated from Equation (16) above to be 0.2195 crash/MVM. This is the overall crash rate related to edge lines and lane lines of all two and four lane highways evaluated in this study. This rate means that, on average, a crash is expected every 4.5 MVM.

The relationship between *CR* and *VE* is modeled using linear regression. A plot of this relationship is presented in Figure 6-1. The equation and R^2 coefficient of this model is as follows.

$$CR = 0.0504\,(VE) + 0.1837 \qquad (17)$$

$$R^2 = 0.32$$

According to this model, the critical CR_{Avg} calculated above corresponds to *VE* value of 0.710 million vehicles. This is equivalent to the vehicle exposure of a one-mile section of highway with an AADT of 2,500 vpd for a period of nine months. Therefore, to maintain a below average crash rate, vehicle exposure of paint striping should not exceed 0.710 MV according to this model. This critical value of vehicle exposure is the maximum desirable value of vehicle exposure, VE_{max}.

6.1.5 Crash rate of thermoplastic long lines

The white thermoplastic is the second largest category evaluated. It includes a total of 48 striping projects on two and four-lane highways, with a total of 322 highway miles (520 km). Almost ¾ of the of the white thermoplastic crash data collected is associated with two-lane edge lines as shown in Table 6-3. A summary of the variables used in evaluating the periodic crash rates is presented in Table 6-4, which shows the number of projects per period to drop substantially in the third year to reach only two projects with a total combined mileage of less than six miles (9.6 km).

Table 6-2 Periodic summaries of variables used in crash evaluation of paint striped projects.

Periodic Values	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
Project count	122	121	111	92	75	63	57	41	32	24	15	10
ADT sum (vpd)	195,198	192,131	174,970	160,620	127,307	110,778	101,832	66,317	53,907	38,579	30,649	20,242
ADT Avg. (vpd)	1,600	1,588	1,576	1,746	1,697	1,758	1,787	1,617	1,685	1,607	2,043	2,024
Length sum (miles)	902	899	837	672	552	466	429	334	248	181	107	81
Length Avg. (miles)	7.33	7.37	7.48	7.23	7.26	7.28	7.39	7.95	7.51	7.24	6.71	7.40
num_crashes sum	15	20	16	19	21	21	10	12	10	6	6	4
num_crashes Avg.	0.122	0.164	0.143	0.204	0.276	0.328	0.172	0.286	0.303	0.240	0.375	0.364
CNV sum (MVM)	106.80	107.21	97.66	88.08	71.03	61.34	58.10	44.97	34.89	24.87	18.54	15.42
CNV Avg. (MVM)	0.868	0.879	0.872	0.937	0.935	0.958	1.002	1.046	1.057	0.995	1.091	1.402
VE sum (1000 veh)	18,280	36,230	49,635	60,678	62,425	64,027	74,024	52,179	47,284	39,927	35,880	27,844
VE Avg. (1000 veh)	149	297	443	652	821	1,000	1,276	1,242	1,433	1,597	2,242	2,531
VE Avg.(MV)	0.149	0.297	0.443	0.652	0.821	1.000	1.276	1.242	1.433	1.597	2.242	2.531
CR (crash/MVM)	0.1405	0.1866	0.1638	0.2157	0.2956	0.3424	0.1721	0.2669	0.2866	0.2412	0.3235	0.2593

Note: period = 3 months

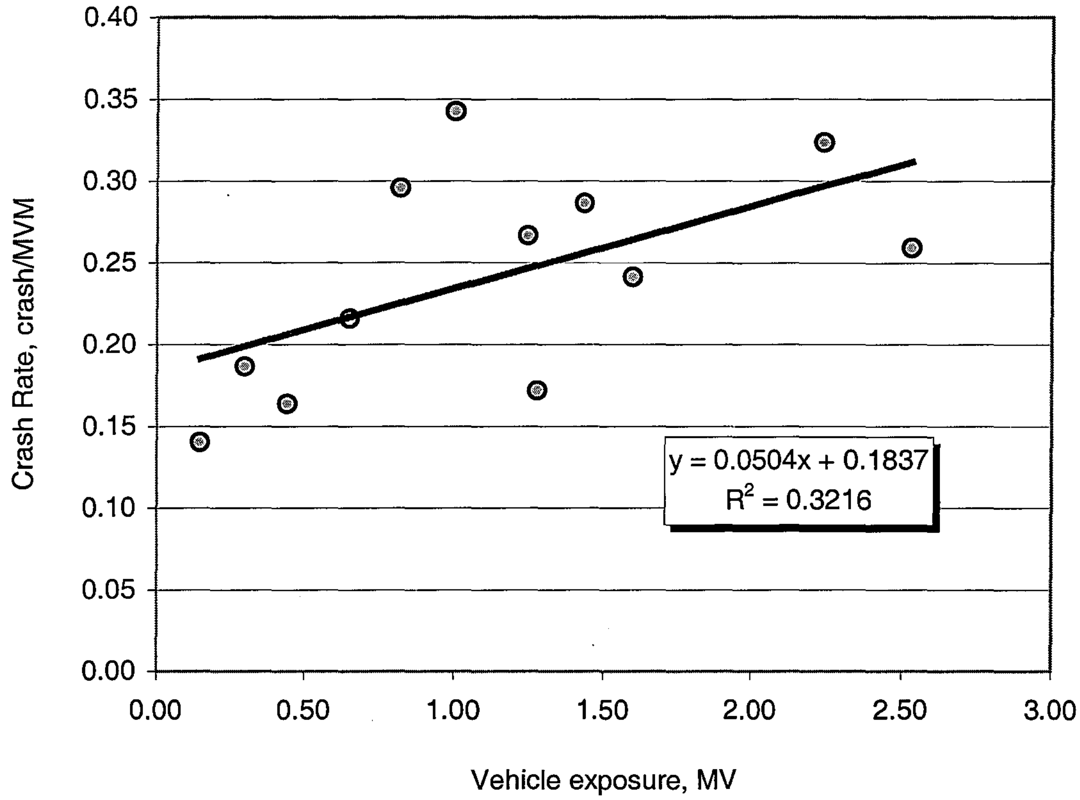


Figure 6-1 CR-VE relationship for white painted longitudinal lines

Table 6-3 Crash history summary of white thermoplastic striping projects

White Thermoplastic	Two-Lane Highways		Four-Lane Highways		Total
No. of projects	35	(73%)	13	(27%)	48
No. of crashes	33	(79%)	9	(21%)	42
Highway mileage	246	(76%)	76	(24%)	322

Having such a small number of projects per period warrants an evaluation of the validity of the crash data associated with it. On average, the number of striping projects per period for the first two years exceeds 30 projects, and the periodic crash rate is considered to represent the expected (mean) crash experience for that period. Since the third year crash experience is based on an extremely low vehicle-mileage, the probability of crashes in the periods 8 through 12 is very low. Thus Periods 8 through 12 are evaluated to determine if they should be discarded.

The overall average crash rate associated with white thermoplastic long lines over the two-year period is determined using Equation (16) as 0.1033 crash/MVM. This rate indicates that, on average, a crash would be expected every 9.7 MVM (1/0.1033). Therefore, periods with vehicle travel of less than 10 MVM are too lightly traveled to produce a crash, and therefore should not be considered in the crash analysis. This ensures that the crash rate per period is based on a sufficiently large sample of striping projects (or vehicle-miles) to be representative of the average crash experience. As can be seen from Table 6-4, all of the third year periods fall below the 10 MVM limit and, as a result, are eliminated from further evaluation.

The critical crash rate, CR_{Avg}, of 0.1033 crash/MVM is the overall crash rate related to thermoplastic edge lines and lane lines of all two and four lane highways evaluated in this study. Note that according to the data evaluated in this study, the average thermoplastic-related crash rate is less than half of the corresponding rate for paint, indicating that thermoplastic striping is a safer alternative than paint. These rates can be further refined by increasing the data size to include national or regional data. The relationship between CR and VE is modeled using linear regression, and a plot of this relationship is presented

Table 6-4 Periodic summaries of variables used in crash evaluation of thermoplastic striped project

Periodic Values	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6	Period 7	Period 8	Period 9	Period 10	Period 11	Period 12
Project count	48	48	44	29	25	24	19	12	6	4	2	2
ADT sum (vpd)	145,617	146,243	132,573	89,659	73,649	67,742	60,367	40,411	23,513	18,994	12,512	12,512
ADT Avg. (vpd)	3,034	3,047	3,013	3,092	2,946	2,823	3,177	3,368	3,919	4,749	6,256	6,256
Length sum (miles)	321.6	321.6	295.7	175.5	154.7	151.9	110.3	53.6	25.4	13.6	5.8	5.8
Length Avg. (miles)	6.7	6.7	6.7	6.1	6.2	6.3	5.8	4.5	4.2	3.4	2.9	2.9
Num_crashes sum	5	5	6	4	4	9	6	2	-	1	-	0
Num_crashes Avg.	0.10	0.10	0.14	0.14	0.16	0.38	0.32	0.17	-	0.25	-	-
CNV sum (MVM)	83.5	81.9	72.5	42.7	37.6	32.9	28.0	15.7	8.3	6.3	3.5	3.5
CNV Avg. (MVM)	1.7	1.7	1.6	1.5	1.5	1.4	1.5	1.3	1.4	1.6	1.7	1.7
VE sum (1000 veh)	13,280	26,675	36,272	32,707	33,584	37,068	41,680	29,484	19,299	17,323	12,552	13,693
VE Avg.(1000 veh)	277	556	824	1,128	1,343	1,545	2,194	2,457	3,217	4,331	6,276	6,846
VE Avg.(MV)	0.277	0.556	0.824	1.128	1.343	1.545	2.194	2.457	3.217	4.331	6.276	6.846
CR (crash/MVM)	0.05985	0.06106	0.08272	0.09367	0.10634	0.27347	0.21414	0.12773	0.00000	0.15787	0.00000	0.00000

Note: period = 3-month

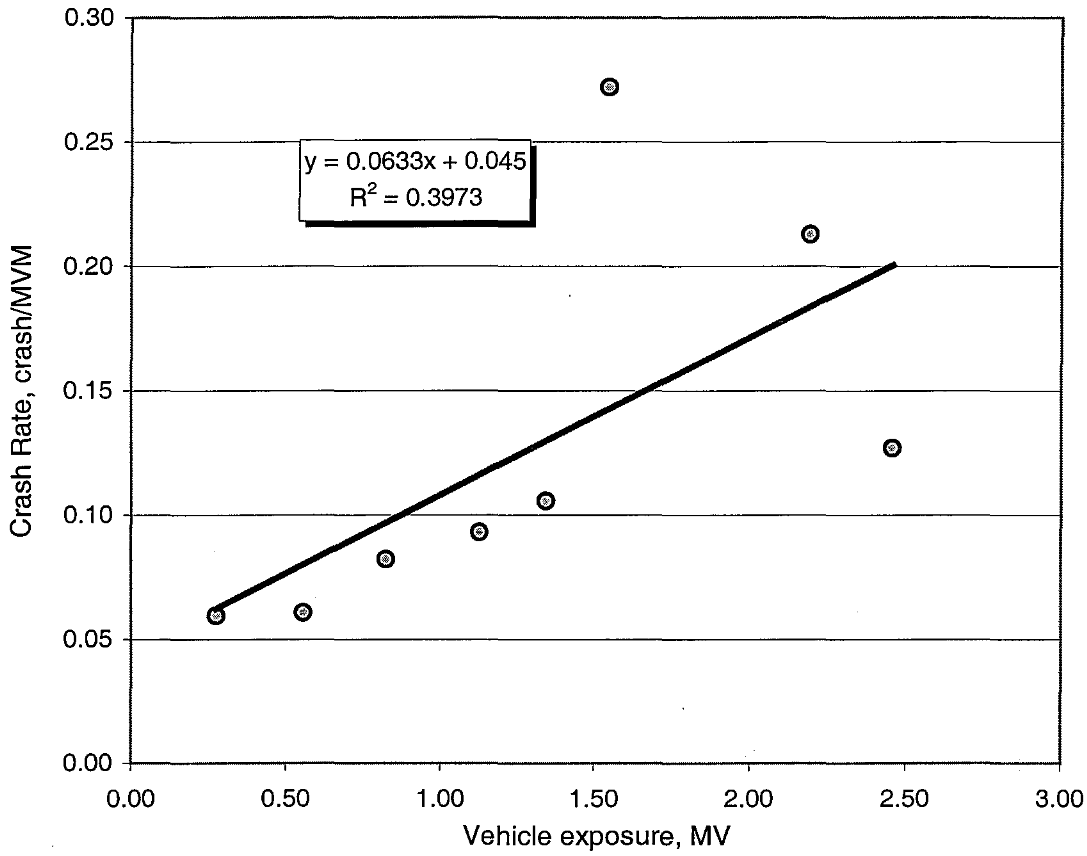


Figure 6-2 CR-VE relationship for white thermoplastic longitudinal lines

in Figure 6-2. The equation and R^2 coefficient of this model is as follows.

$$CR = 0.0633\ (VE) + 0.045 \qquad (18)$$

$$R^2 = 0.40$$

According to this model, the critical CR_{Avg} of 0.1033 crash/MVM corresponds to an average VE of 0.921 million vehicles. This is equivalent to the vehicle exposure of a one-mile section of highway with an AADT of 2,500 vpd for one year. Therefore, to maintain a below average crash rate, the value of VE on thermoplastic striping should not exceed the critical value of vehicle exposure, VE_{max}, of 0.921 MV.

A distinction between the crash experiences of paint and thermoplastic long lines can be made graphically by combining Figure 6-1 and Figure 6-2. Figure 6-3 shows that both models have fairly similar gradients, indicating that crash rates increase with the increase of *VE* at approximately the same rate for both paint and thermoplastic. The shift between the two models, however, indicates that highways with thermoplastic long lines provide a safer traffic operation than painted highways under equivalent vehicle exposure.

6.1.6 Evaluation of the models predictive power

The predictive power of a regression model is generally judged by the value of its coefficient of determination, R^2. The higher the R^2 value the better the correlation between the dependent and independent variables since a higher R^2 value explains more of the total variability in the model. Despite this fact, very high values of R^2 (perhaps exceeding 0.9) are almost exclusively possible in a highly controlled setting such as a laboratory or a computer-simulated environment. Observational experiments, upon which studies such as this are based, involve very limited control, and isolating the effects of each individual factor may not be practical. For example, one can not set up an observational experiment by which the weather effects are kept constant, or driver behavior is entirely predicted or dictated, and so on. To support the usefulness of the above models despite the relatively low R^2 values, the slope of the linear regression line is tested for significance, the standard error of the estimate is calculated, and confidence intervals of 90% and 95% about the slope of the linear model are determined. Summaries of the linear regression analysis for paint and thermoplastic long lines are provided as Tables 6-5 and 6-6, respectively.

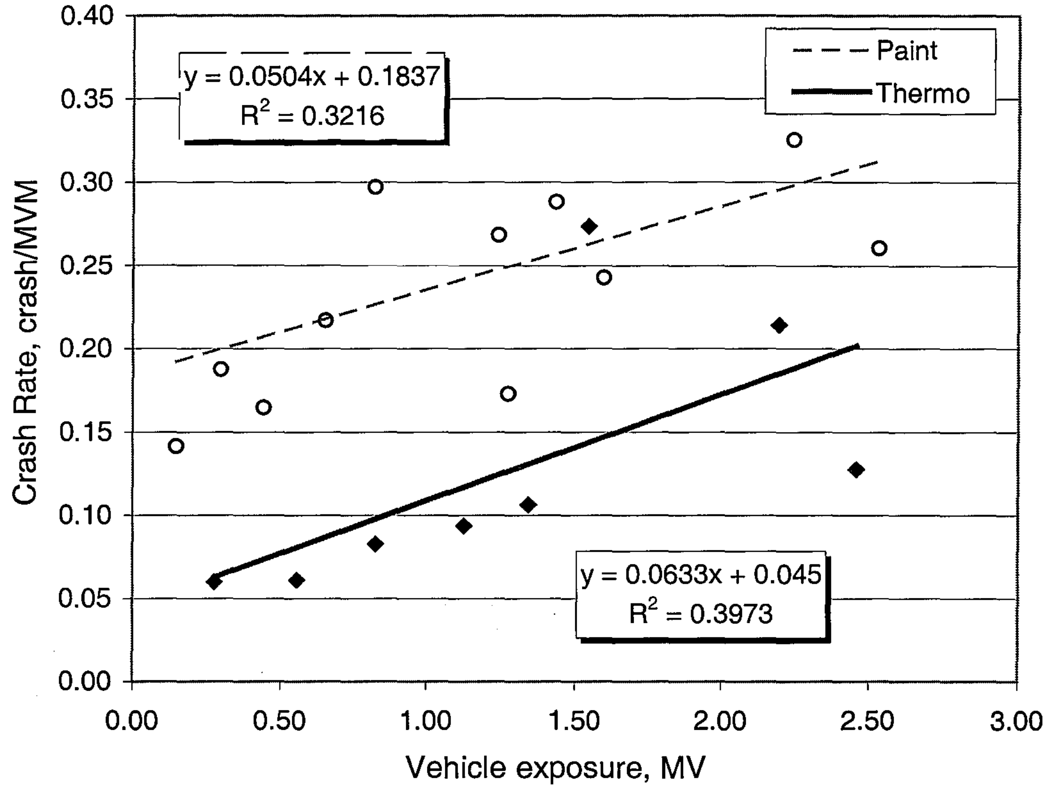


Figure 6-3 *CR-VE relationship for white paint and thermoplastic lines*

To verify that *VE* contributes information for the prediction of *CR* using the straight line model, the null hypothesis that the slope (β_1) is zero is tested (i.e. that there is no linear relationship between *VE* and *CR*.) against the alternate hypothesis that the slope is positive (i.e. that an increase in *VE* results in an increase in *CR*).

$$H_0 : \beta_1 = 0$$

$$H_a : \beta_1 > 0$$

Table 6-5 Summary of regression analysis output for paints

Regression Statistics (paint)	
R Square	0.32164
Standard Error	0.05681
Observations	12

ANOVA

	df	*SS*	*MS*	*F*	*p-value*
Regression	1	0.0153	0.0153	4.74134	0.05448
Residual	10	0.03227	0.00323		
Total	11	0.04757			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90%*	*Upper 90%*
Intercept	0.18365	0.0311	5.90571	0.00015	0.11436	0.2529	0.1273	0.2400
VE Avg. (10^6)	0.05045	0.02317	2.17746	0.05448	-0.0012	0.1021	0.0085	0.0924

Table 6-6 Regression analysis summary output for thermoplastics

Regression Statistics (thermoplastic)	
R Square	0.39726
Standard Error	0.06415
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*p-value*
Regression	1	0.01627	0.01627	3.95455	0.0939
Residual	6	0.02469	0.00412		
Total	7	0.04097			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90%*	*Upper 90%*
Intercept	0.04496	0.04695	0.95759	0.37525	-0.0699	0.15984	-0.0463	0.13619
VE Avg. (10^6)	0.06335	0.03186	1.9886	0.0939	-0.0146	0.1413	0.00145	0.12525

The observed significance level for testing H_a : $\beta_1 \neq 0$ (2-tailed test), shaded in Tables 6-5 and 6-6, are 0.05448 and 0.9390, for paint and thermoplastic, respectively. Thus, the *p-value* for the one-tailed test needed for this analysis is (0.05448 / 2) = 0.0271 and (0.9390 / 2) = 0.0469 for paint and thermoplastic, respectively. Since each of these *p-values* is less than the significance level of 0.05 used in this study, the *CR-VE* relationship is considered to be linear at the 95% confidence level. Additional information is gained by constructing a confidence interval for the slope. The 95% confidence interval is determined b the following term, with the positive sign (+) resulting in the upper bound of the interval and the negative (-) sign resulting in the lower bound.

$$\hat{\beta}_1 \pm t_{.025} S_{\hat{\beta}_1} \tag{19}$$

where

$\hat{\beta}_1$ = 0.0504 and its standard error, $S_{\hat{\beta}_1}$ = 0.023 for paint (Table 6-5), and

$\hat{\beta}_1$ = 0.0634 and its standard error, $S_{\hat{\beta}_1}$ = 0.032 for thermoplastic (Table 6-6)

Tables 6-5 and 6-6 also present the upper and lower limits of the 95% and 90% confidence intervals for the slope. The 95% intervals are (-0.001 to 0.102) for paints and (-0.01 to 0.14) for thermoplastic, indicating that the possible values of the slope are almost entirely above zero. The 90% confidence level shows all possible values of the slope to be above zero. The test results show that the slopes of the straight lines are greater than zero and thus the crash rate increases with increased vehicle exposure.

The practical significance of the models developed in this study is that despite the uncontrolled variability in driver, vehicle and highway conditions, a single factor, such as vehicle exposure, is shown to explain 35% to 40% of the total variability in the crash data. This finding is significant considering that the uncontrolled factors are numerous. For example, the models do not specifically address the effects of the following.

- driver mindset, aggressiveness, visual capacity and driving skills.
- traffic composition, vehicle type, size, and handling capabilities, condition of tires, eye height and glare from other vehicle headlights.
- highway terrain, pavement condition, surface temperature, and presence of debris on the road
- pavement marking application workmanship, glass bead quantity and distribution, and changes in material ingredients and industry standards over time.

The quality of the regression lines can be expected to improve by increasing the scope of work to incorporate a larger study area that includes a region of the U.S. or multiple states.

6.2 ANALYSIS OF FIELD RETROREFLECTIVITY DATA

This section relates the field-collected retroreflectivity data of Appendix C to the aging of long line striping. The two primary factors responsible for aging the pavement marking materials are the exposure to traffic and weather. The *VE* factor defined earlier accounts for the PM age and *AADT* effects. To account for the effects of weather on the pavement temperature, the Wisconsin study discussed in the literature review shows that a massive amount of data is needed, including solar radiation intensity, air temperatures and pavement temperatures [29]. An indirect means of accounting for the effects of weather was presented in Section 4.2, by comparing the rate of retroreflectivity deterioration of traffic-free (or low-ADT) routes with that of high-ADT routes. Since the

VE factor accounts for time and traffic volumes, high-ADT routes will accumulate larger *VE* values in a relatively short time compared to low-ADT routes. This means that long term effects of weather would be secondary along high-ADT routes as compared to low-ADT routes, which, in order to accumulate the same *VE* values, experience the weather elements for a much longer period of time. Thus the traffic volume effects are less pronounced on low-ADT routes, as are the weather effects on high-ADT routes. In the following analysis, retroreflectivity values are aggregated, whenever applicable, into three ranges of ADT (low, mid and high) to highlight the incremental effects of weather. The low-ADT range includes the R_L data for highways with *AADT*s of 2500 vpd or less; the intermediate (mid) ADT range includes the R_L data for highways with *AADT*s of greater than 2500 vpd and less than 5000 vpd; and the high-ADT range includes the R_L data for highways with *AADT*s of 5000 vpd or greater.

6.2.1 Field data reduction

Field-collected retroreflectivity data were entered into a Microsoft Excel worksheet for analysis. The total number of long line retroreflectivity readings amounted to 4,518 taken at 827 test locations on Alabama State highways. White long lines constituted 2,907 readings, of which 1,924 readings are for paint and 983 readings for thermoplastic markings. Yellow long lines totaled 1,611 readings, of which 1,112 readings are for paint and 499 readings for thermoplastic markings. In addition, a limited number of pavement retroreflectivity readings were taken for the purpose of calculating the contrast ratio. A total of 190 pavement surface readings were taken at 63 test locations. Some of the readings were discarded from further analysis because of inconsistency between striping records and field conditions, or because the striping was freshly applied. Newly striped highways have low retroreflectivity readings because the glass beads mixed in the marking take some time to get exposed and give the marking its maximum retroreflectivity. Recall that the NTPEP testing procedure required the first retroreflectivity measurement at the end of the first month. Field measurements of markings that are less than two weeks old were found to be as low as 30 mcd/m^2/lx, which supports the NTPTP procedure of starting measurement after one month of application. In this study, readings of striping one month old or less were discarded from further analysis. Other markings were clearly inconsistent with the striping records. Some highways reported as having two or three-year old striping were found to be newly resurfaced and/or re-striped when inspected in the field. Readings of such highways were also discarded if updated striping records were not available. The remaining valid retroreflectivity readings totaled approximately 3,730 readings in 746 test locations. The highest reading measured in the field belonged ot white thermoplastic edge line and amounted to 370 mcd/m^2/lx, and the lowest reading was 27 mcd/m^2/lx and belonged to white paint less than two weeks old. The number of retroreflectivity test sites aggregated for ranges of ADT for each PM type and color is presented in Table 6-7. The complete database of valid retroreflectivity readings is presented as Appendix C.

6.2.2 Retroreflectivity analysis variables

To calculate the *VE* factor, traffic volumes at the field test sites and striping dates of the long lines were used. Appendix C includes the following site-related variables.

- *Field_Date*, represents the date the field retroreflectivity readings were taken.
- R_L, represents the field retroreflectivity readings of the long lines.

Table 6-7 Number of valid retroreflectivity test sites on Alabama highways.

PM Type	ADT Range	PM Color		Total
		white	yellow	
Paint	Low-Range	254	161	415
	Mid-Range	80	52	132
	High-Range	13	9	22
	Sub-total	347	222	569
Thermoplastic	Low-Range	36	12	48
	Mid-Range	78	28	106
	High-Range	15	8	23
	Sub-total	129	48	177
Total	All Ranges	476	270	746

R_{Pvmt}, represents the retroreflectivity of the pavement surface. A limited number of pavement readings were collected.

In addition to Appendix C data, more variables needed for calculating the *VE* factor were added to the database. Such variables included the *PM_Type*, *Length*, *Striping_Date*, *ADT*, *num_Ln*, *ADT_Ln*, and *Line_Type*. These variables are as defined in Section 5-1 above. The following additional variables were calculated and added to the database.

- *LCR*, represents the luminance contrast ratio between the long lines and the adjacent pavement surface retroreflectivity, calculated per Equation (4).
- *PM-age*, represents the pavement marking age at the time of field measurements, calculated as the difference between *Field_Date* and *Striping_Date*, in days, and
- *VE*, the independent variable in this analysis, represents the long line vehicle exposure at the time of field measurement, measured in thousands (or millions) of vehicles.

The modified database that includes all of the variables needed for retroreflectivity analysis is presented as Appendix H.

6.2.3 R_L-VE relationship

Logarithmic regression analysis was performed on the retroreflectivity data of Appendix H to define the relationship between VE and R_L. This was done for white and yellow paint and thermoplastic long lines along two-lane and four-lane state highways. The logarithmic model was chosen because it best represents the decay properties of pavement marking retroreflectivity. The R_L-VE relationship is defined for all the R_L data within a specific PM type and color, and for three ranges of ADT.

R_L-VE relationship for white paints

White painted long lines of two-lane and four-lane highways constituted the largest set of retroreflectivity data (see Table 6-5). The logarithmic regression model describing the R_L-VE relationship is represented by the following equation and R^2 coefficient.

$$R_L = -19.457 * \text{Ln}(VE) + 267 \tag{20}$$

$$R^2 = 0.31$$

A plot of this relationship is presented as Figure 6-4, which shows the rate of retroreflectivity loss to be highest at early exposure to traffic and weather and becomes less significant with prolonged exposure. To isolate the effects of weather on the rate of retroreflectivity deterioration, the R_L data were stratified and plotted for the three ranges of ADT mentioned above. Aggregation of the data shows the bulk of the R_L data to be concentrated in the low-ADT range, indicating that low-ADT highways constitute the majority of the rural highways tested in this study.

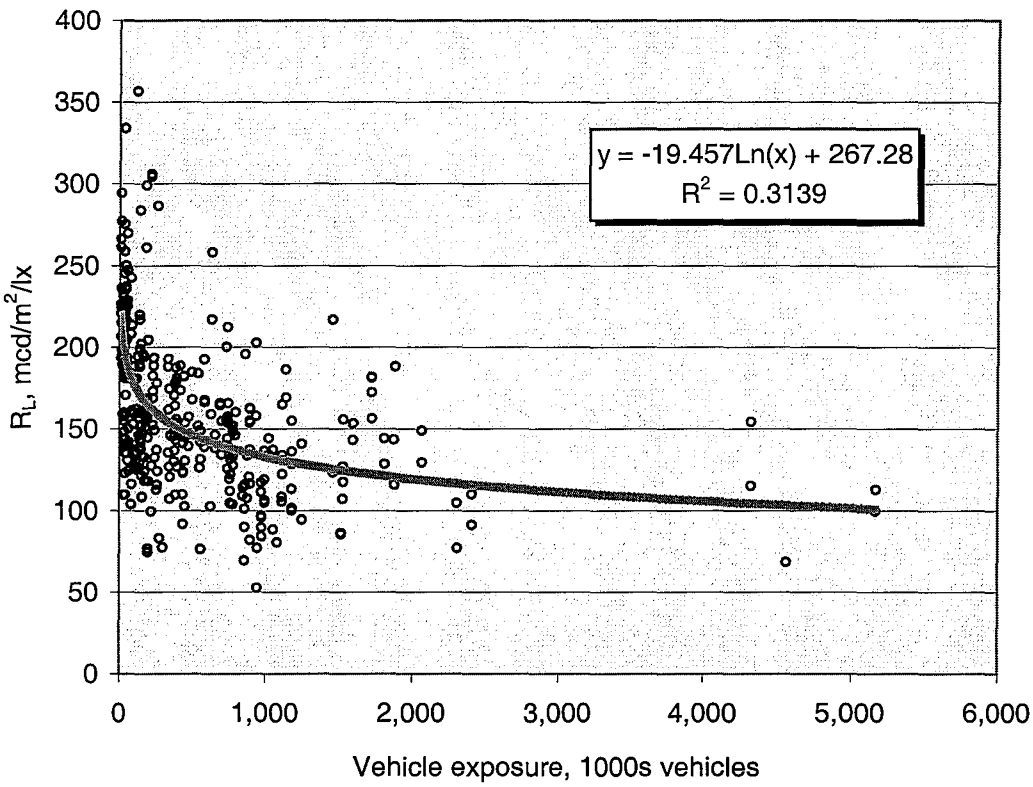


Figure 6-4 *R_L-VE relationship for white paints*

Figure 6-5 presents a plot of the R_L-VE models and the corresponding R^2 coefficients. This Figure shows no substantial shift in the R_L-VE models for low and mid-ADT ranges but a distinct shift in the high-range model. Thus for a specific *VE* value, the difference in R_L values between the low and high-ADT models is the result of the weather effect. This difference represents the additional loss in retroreflectivity experienced by low-ADT markings during the time needed to accumulate the same *VE* value as high-ADT markings. Thus the effect of weather can be indirectly accounted for by using the R_L-VE model specific to the ADT range.

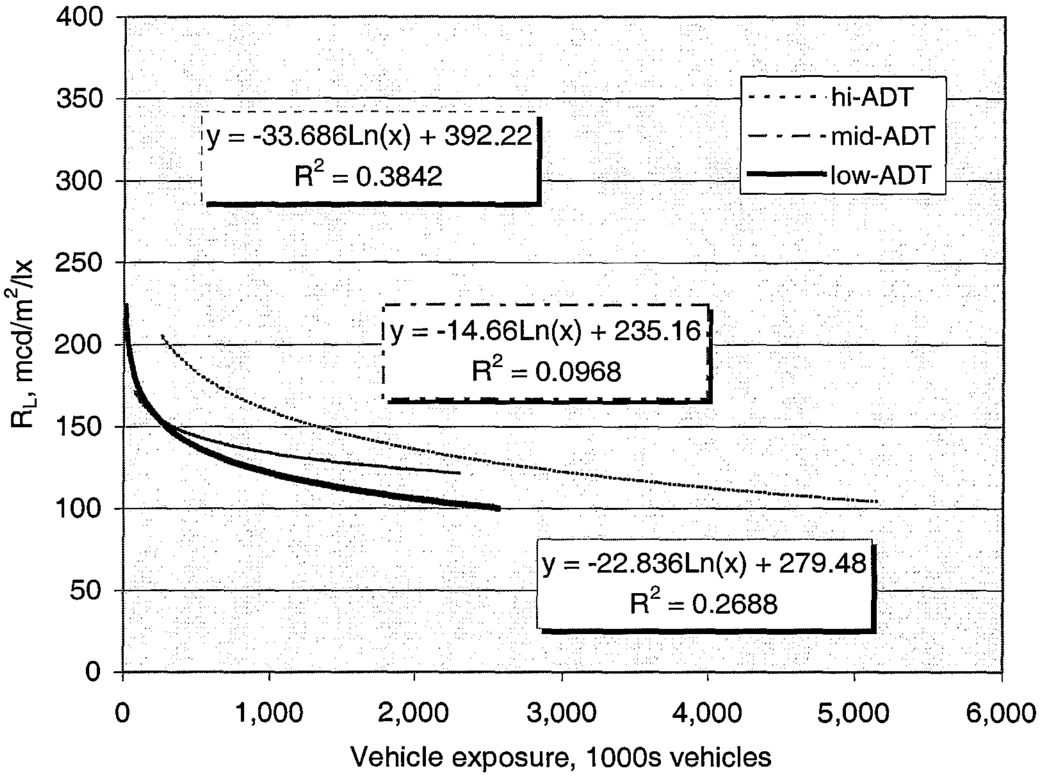


Figure 6-5 *R_L-VE relationship for white paints according to ADT*

The low and high-ADT models are almost parallel suggesting that the impact of weather on white paint occurs almost entirely in the earlier period of exposure, after which the weather effects diminish and only the effect of vehicle exposure on further R_L deterioration remains. Note that the high-ADT model is based on only 13 testing sites, and therefore, any inferences from this model should be made with caution.

R_L-VE relationship for yellow paints

Yellow painted long lines of two-lane and four-lane highways constituted the second largest set of retroreflectivity data. The logarithmic regression model describing the R_L-*VE* relationship for yellow painted long lines is represented by the following equation and R^2 coefficient, and plotted in Figure 6-6.

$$R_L = -13.086 * \mathrm{Ln}(VE) + 199 \quad (21)$$

$$R^2 = 0.30$$

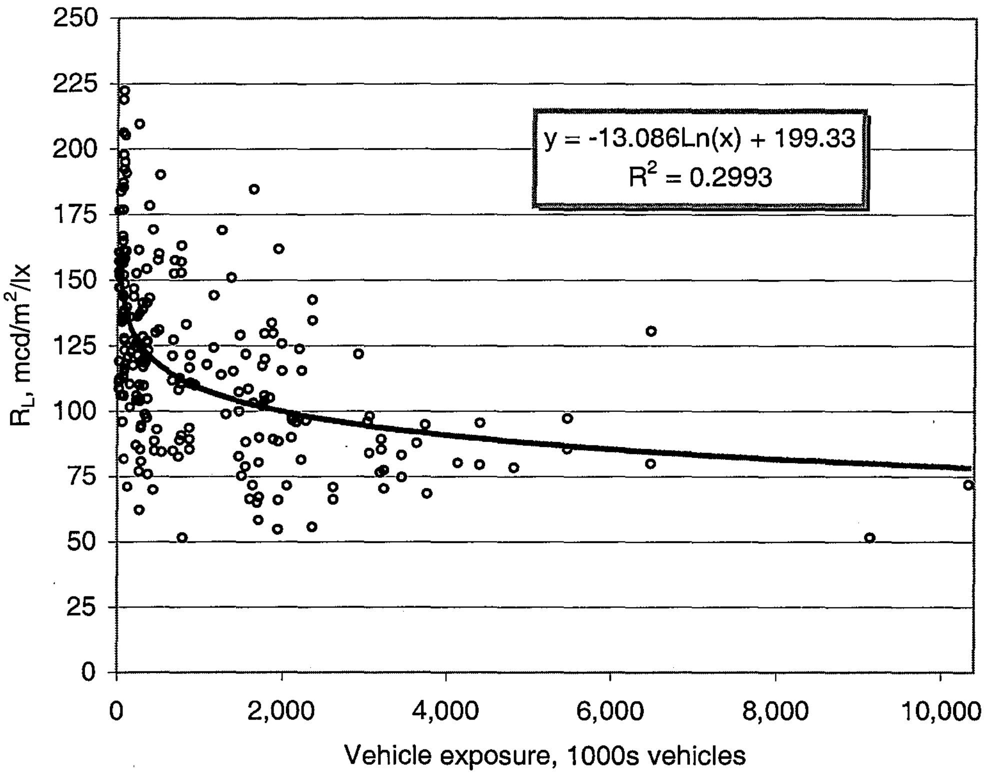


Figure 6-6 R_L-VE relationship for yellow paints

The R_L data were stratified and plotted for the three ADT ranges to isolate the effects of weather on the rate of retroreflectivity deterioration. A plot of the R_L-VE models shows a similar pattern as that of white paints, with the low and intermediate ADT ranges almost coinciding and the high-range ADT model to have a distinct shift. These yellow paint models, however, converge in the long run suggesting that vehicle exposure is eventually what determines the retroreflectivity loss. Since the high-ADT model is based on only nine testing sites, any inference from this model should be made with caution.

Plots of the R_L-*VE* models for the three ADT ranges with the corresponding R^2 coefficients are presented in Figure 6-7.

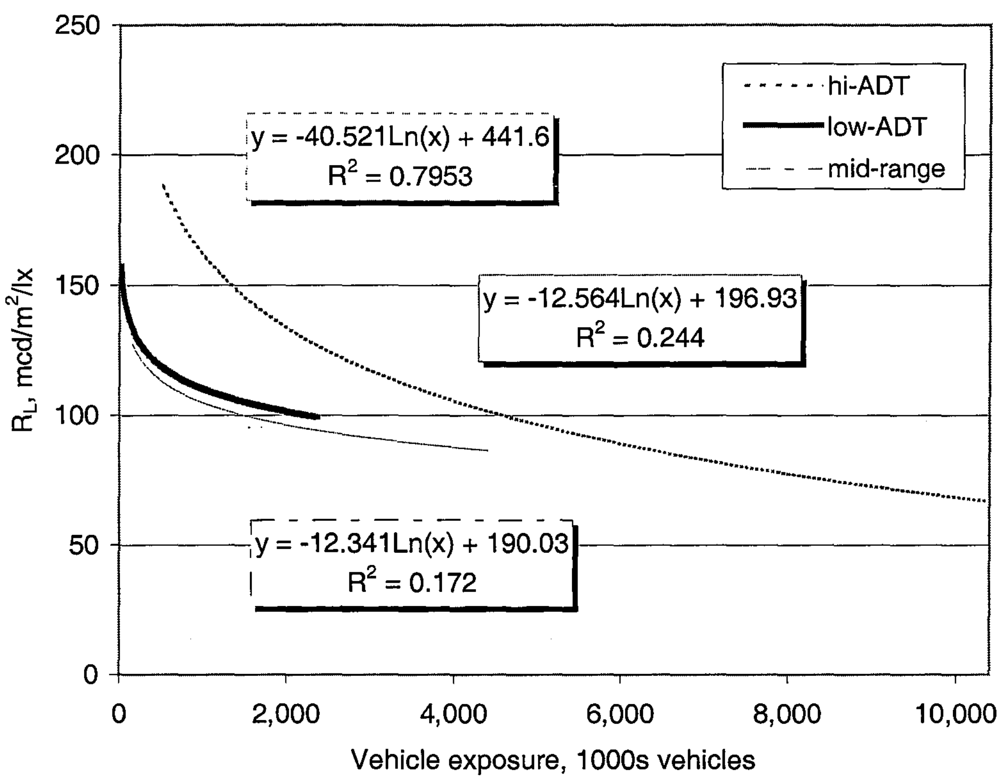


Figure 6-7 *R_L-VE relationship for yellow paints according to ADT*

Comparing the R_L-*VE* models for white and yellow painted long lines shows retroreflectivity of yellow painted lines to be 74% that of white painted lines, which is consistent with the literature review findings of 70 to 80%. The mean R_L values of all white and yellow paints tested in this study is 160 and 119 mcd/m^2/lx, respectively. Figure 6-8 presents a plot of both white and yellow paint models.

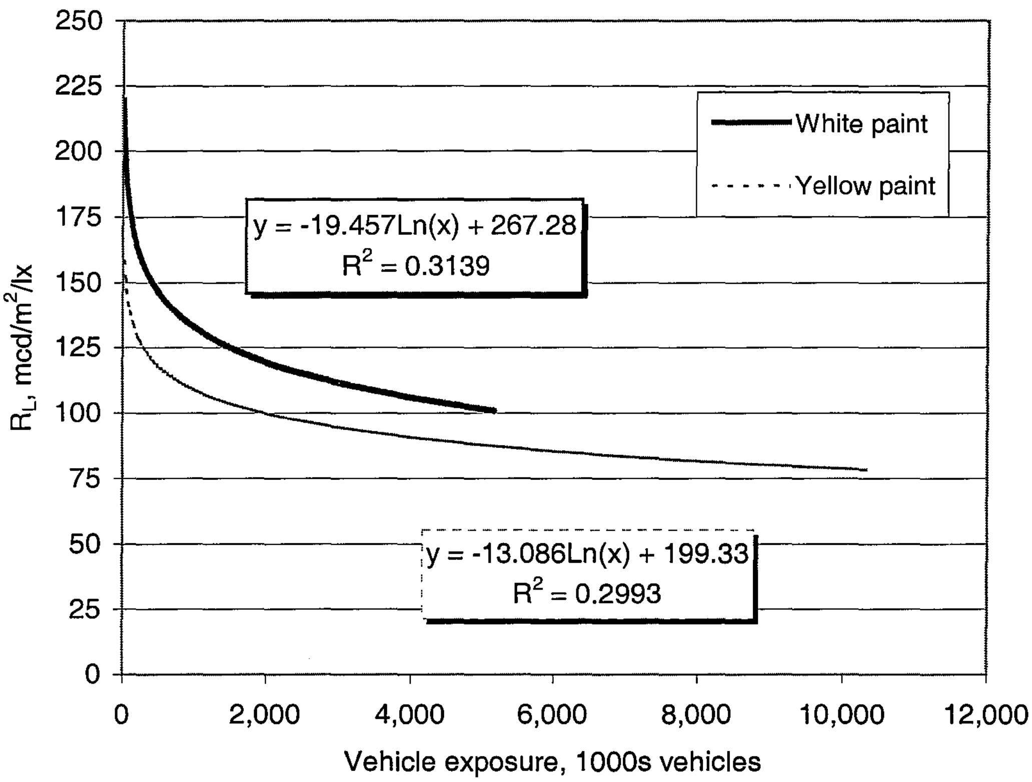


Figure 6-8 *R_L-VE relationship for white and yellow paint*

The logarithmic regression model describing the R_L-VE relationship for white thermoplastic long lines on Alabama State highways shows a greater scatter of the data than paint. The R_L-VE relationship is represented by the following equation and R^2 coefficient.

$$R_L = -70.806 * \mathrm{Ln}(VE) + 640 \qquad (22)$$

$$R^2 = 0.58$$

A plot of this relationship is presented as Figure 6-9, which shows relatively good correlation (R^2 =0.58), and a plot of the stratified data for the three ADT ranges shows the three models to be almost equally spaced, with the mid-range ADT model almost

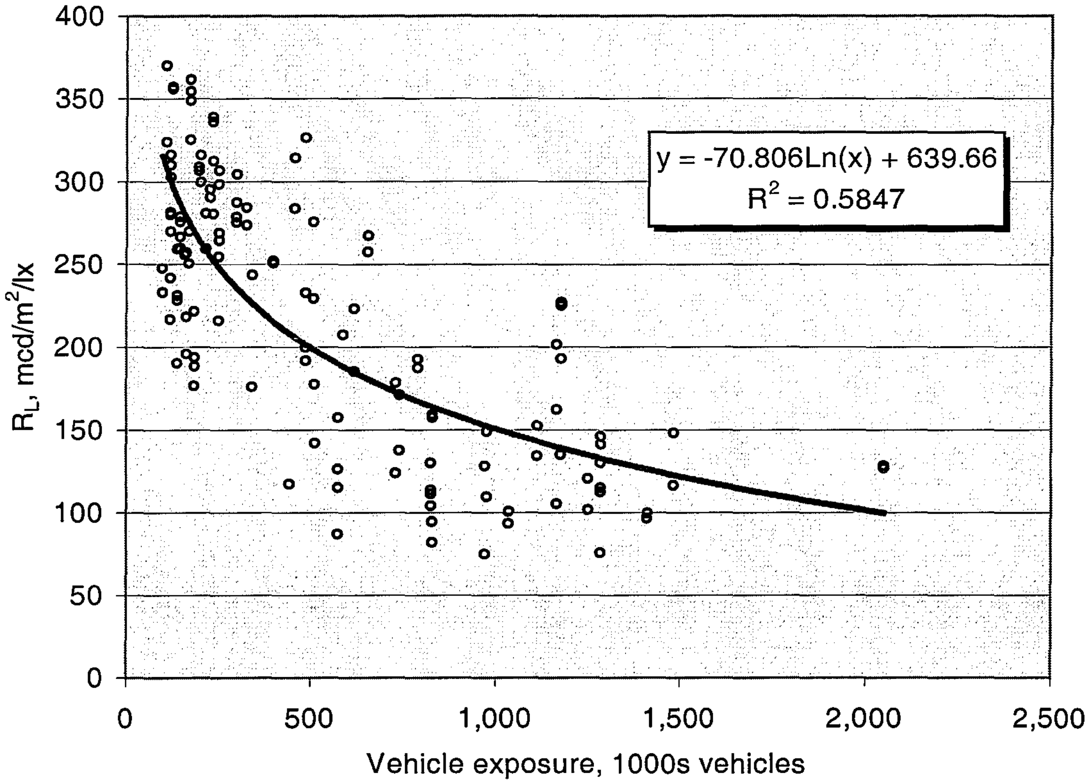


Figure 6-9 R_L-VE relationship for white thermoplastics

coincident to the overall (all-ADTs) model. All three models have moderate R^2 values ranging from 0.48 to 0.69. A plot of the R_L-*VE* relationship for the three ADT ranges of white thermoplastic is presented as Figure 6-10. Note that unlike the white paint models, the shift in the three models in Figure 6-10 is greater at higher vehicle exposure, which indicates that the weather impact on white thermoplastic is not limited to the short-term and that it increases with increased exposure time.

R_L-VE relationship for yellow thermoplastics

Yellow thermoplastic long lines constituted the smallest set of retroreflectivity data totaling only 48 R_L values, most of which (28 readings) are in the mid-ADT range. A

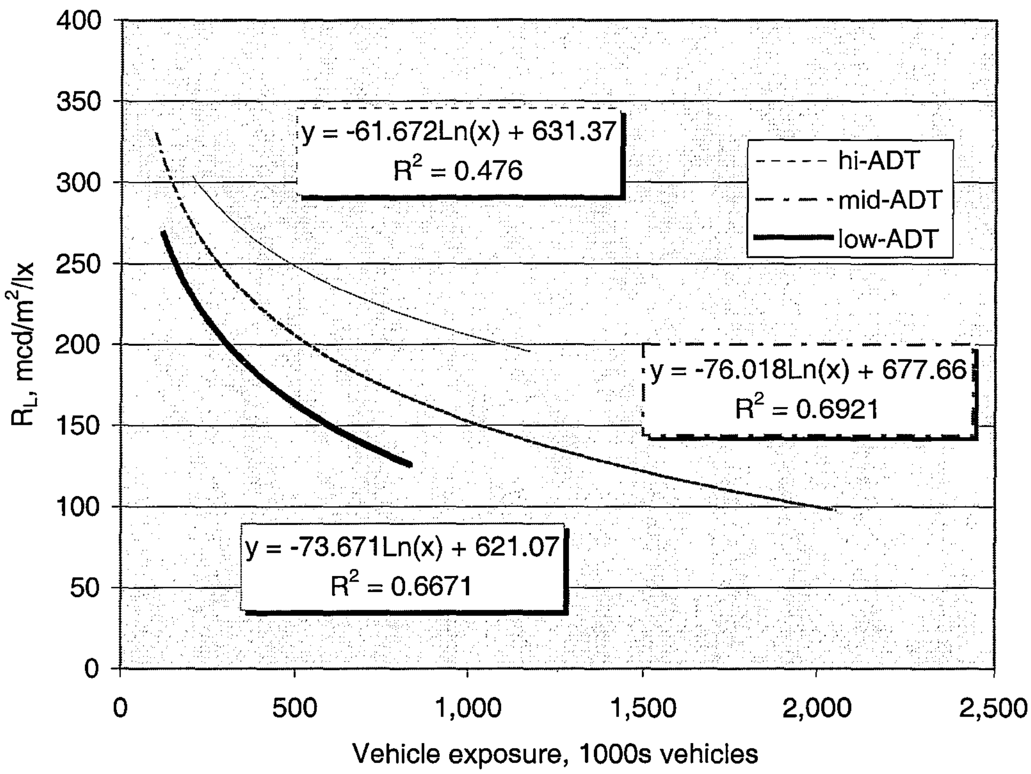


Figure 6-10 R_L-VE relationship for white thermoplastics according to ADT

plot of the R_L-*VE* relationship is presented as Figure 6-11, which shows a relatively good correlation represented by an R^2 coefficient of 0.54.

A plot of the stratified data, however, shows the high and low ADT ranges to be represented by flat models with very low R^2 coefficients. These two models are based on only 12 and 8 testing sites, respectively. The mid-ADT model, which constitutes the majority of the data, shows an improved fit with an R^2 coefficient of 0.66. The plot of the three ADT ranges is presented in Figure 6-12.

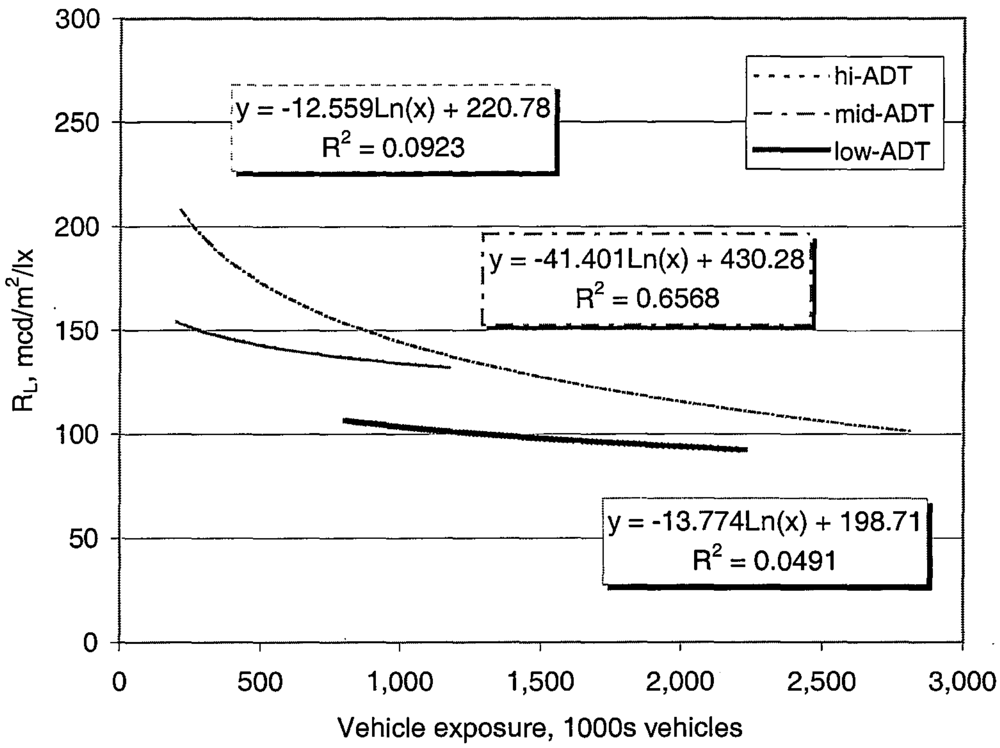


Figure 6-11 *R_L-VE relationship for yellow thermoplastics*

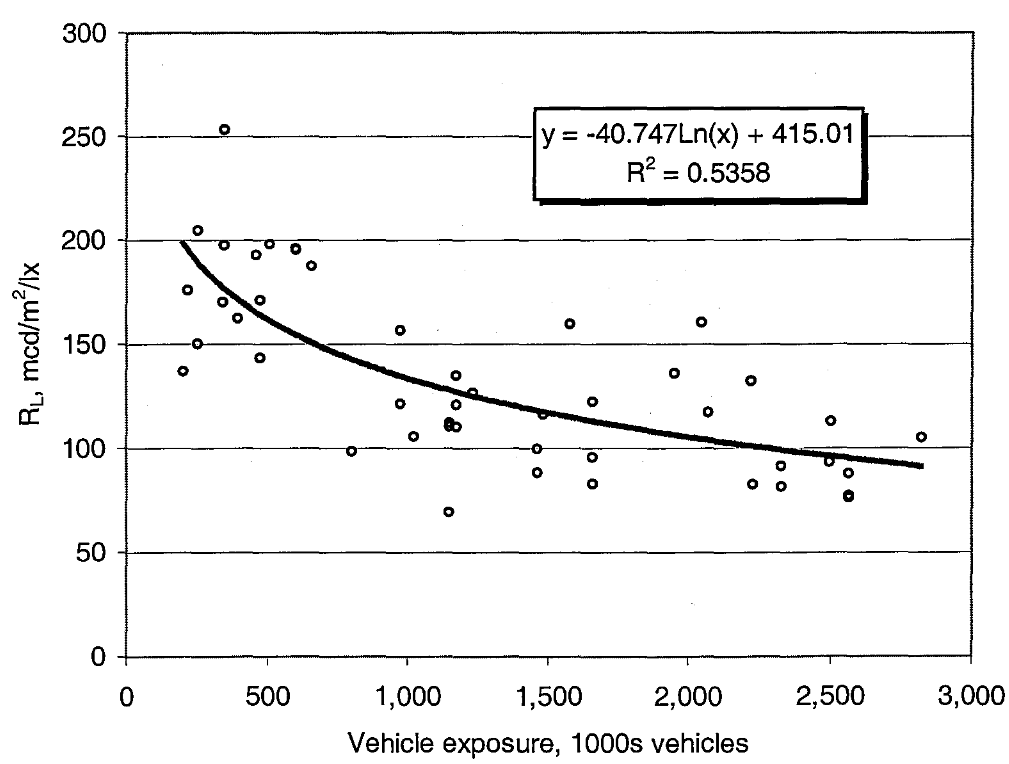


Figure 6-12 *R_L-VE relationship for yellow thermoplastics according to ADT*

6.3 RELATING CRASHES AND RETROREFLECTIVITY DATA

6.3.1 Linking *CR* and R_L

To determine a crash-based retroreflectivity threshold, the relationship between striping retroreflectivity and striping-related crashes is established. Since the values of both retroreflectivity and crash rate are *VE*-related, the *VE* factor is used as the common factor to relate them. In Section 5.1, critical values of vehicle exposure, VE_{max}, were determined for white paints and thermoplastics. The values of VE_{max} represent the maximum acceptable vehicle exposure before the crash rate reaches the expected (mean) value. In this section, the retroreflectivity models for white paints and thermoplastics established in Section 5.2 above are used to relate the retroreflectivity values to the VE_{max} values determined in Section 5.1.

6.3.2 Retroreflectivity thresholds for paints and thermoplastics

The *CR-VE* relationship established in Section 5.1 for white painted edge lines resulted in VE_{max} value of 0.710 MV. Applying this value to the R_L-*VE* model of Figure 6-4 for white paints results in a corresponding $R_{L(min)}$ value of 140 mcd/m^2/lx. Similarly, using the R_L-*VE* model established for white thermoplastics, the VE_{max} value of 0.904 MV established in Section 5.1 for white thermoplastic edge lines corresponds to an $R_{L(min)}$ value of 156 mcd/m^2/lx according the model of Figure 6-9.

- This shows that a retroreflectivity threshold value in the range of 140-156 mcd/m^2/lx should be the minimum acceptable value if crash rate is to be maintained below the overall average. Practitioners can interpret the upper and lower bands of the range as the desired and absolute minimum retroreflectivity, respectively, or set the middle of the range, say150 $mcd/m^2/lx$, as a threshold for paints and thermoplastics. This range of retroreflectivity threshold can be further refined by increasing the scope of the research to incorporate retroreflectivity and crash data from a number of states or a region of the United States. The following chapter uses the 150 $mcd/m^2/lx$ value as the minimum acceptable retroreflectivity threshold.

7. STRIPING SCHEDULING

Effectiveness of pavement markings is dependent on their ability to maintain the minimum level of visibility necessary to delineate vehicle paths. When the visibility reaches this minimum level, the pavement marking primary function of providing positive guidance is gravely compromised and an increase in traffic crashes can result. Such an increase in user costs should be considered when developing a re-striping schedule based on an estimate of the effective service life of pavement markings. Previous efforts of this report concentrated on determining a quantifiable retroreflectivity threshold that identifies the effective service termination of pavement markings.

7.1 STRIPING USEFUL LIFETIME

The useful lifetime of striping material is defined in this study as the PM age at the time retroreflectivity reaches a minimum acceptable threshold of 150 mcd/m^2/lx. This value is the rounded off median value of the retroreflectivity threshold range of 140-156 mcd/m^2/lx established in Section 5.3.

7.1.1 White paint striping

To determine white paint striping useful lifetime along two-lane rural highways, Equation (20) is used to describe the R_L-VE relationships for painted edge lines.

$$R_L = -19.457 * \mathrm{Ln}(VE) + 267 \qquad (20)$$

or

$$VE = e^{\frac{(267-R_L)}{19.457}} \qquad (20\text{-a})$$

where VE = vehicle exposure, in thousands of vehicles, defined in Section 5.1.1 as:

$$VE = (ADT\_Ln * 30.4 * PM\_age)/1000 \qquad (13)$$

ADT_Ln = ADT per lane, in vehicles per day,

PM_age = Pavement marking age, in months, and

30.4 is the months-to-days conversion factor.

Equation (23), a variation of Equation (13), is used to describe the PM age-*VE* relationship

$$PM\_age = \frac{VE_{max}}{(ADT\_Ln)*30.4}*(1000) \qquad (23)$$

or

$$VE_{max} = ADT\_Ln * PM\_age * 30.4/(1000) \qquad (23\text{-a})$$

Where VE_{max} = Maximum vehicle exposure, in thousands of vehicles, is the *VE* value when retroreflectivity threshold is reached.

Substituting Equation (23-a) into Equation (20-a):

$$(ADT\_Ln * PM\_age * 30.4) / 1000) = e^{\frac{(267.27-R_L)}{19.457}}$$

Solving for PM_age for paint:

PM_age (paint)

$$= e^{\frac{(267.27-R_L)}{19.457}} * 1000 / (ADT\_Ln*30.4) \qquad (24)$$

7.1.2 White thermoplastic striping

To determine striping useful lifetime along two-lane rural highways, Equation (22) is used to describe the R_L-*VE* relationships for thermoplastic edge lines. All variables are as defined in the previous section.

$$R_L = -70.806 * Ln(VE) + 640 \qquad (22)$$

or

$$VE = e^{\frac{(639.66-R_L)}{70.806}} \text{, in 1000s of vehicles} \qquad (22\text{-a})$$

Equation (23) is used to describe the striping PM age-*VE* relationship.

$$PM\_age = \frac{VE_{\max}}{(ADT\_Ln) * 30.4} *(1000) \qquad (23)$$

or

$$VE_{\max} = ADT\_Ln * PM\_age * 30.4/(1000) \qquad (23\text{-a})$$

Substituting Equation (23-a) into Equation (22-a):

$$(ADT\_Ln * PM\_age * 30.4) / 1000) = e^{\frac{(639.66 - R_L)}{70.806}}$$

Solving for *PM_age* for thermoplastic:

$$PM\_age \text{ (thermoplastic)}$$

$$= e^{\frac{(639.66 - R_L)}{70.806}} * 1000 / (ADT\_Ln * 30.4) \qquad (25)$$

Equations (24) and (25) are plotted using the retroreflectivity threshold, $R_{L(min)}$, of 150 mcd/m^2/lx, and presented in Figure 7-1. This figure provides a graphical means for predicting paint and thermoplastic useful lifetime along two-lane highways for various *ADT*s. According to Figure 7-1 and Equations (24) and (25), the ratio of thermoplastic to paint useful life is 2.48. For example, the estimated useful lifetime of striping along a two-lane highway with an *ADT* of 3500 vpd according to Figure 7-1 is approximately 8 months if painted edge lines are used and approximately 19 months if thermoplastic edge lines are used.

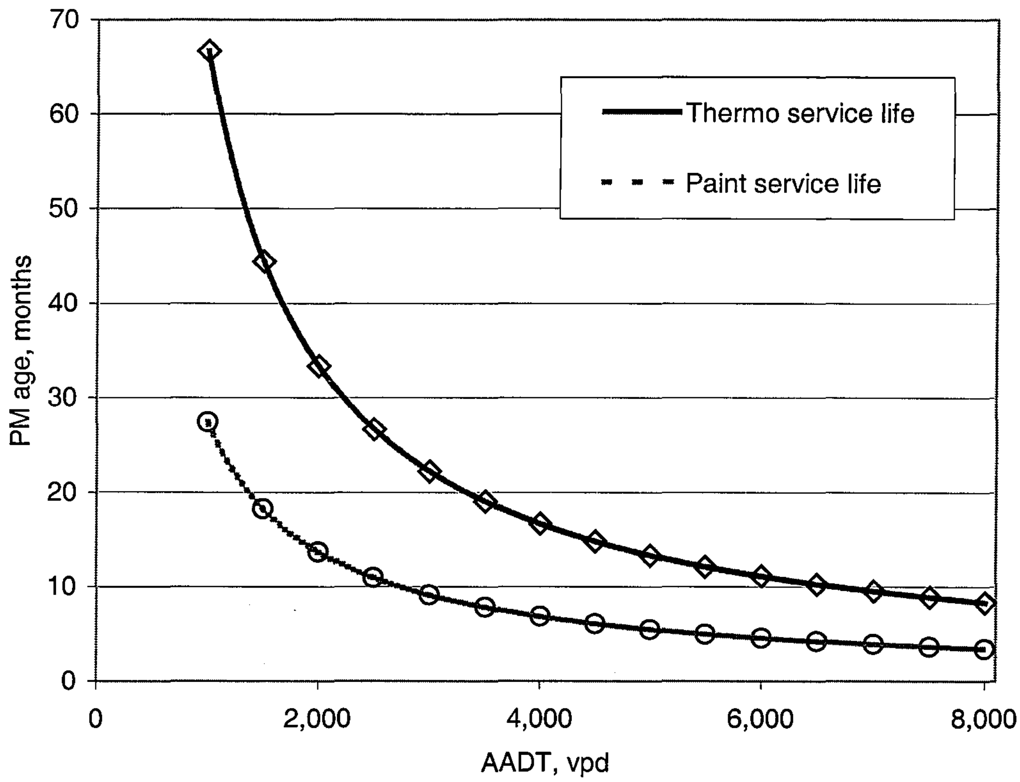


Figure 7-1 Useful life of striping on two-lane highways (based on 150 mcd/m²/lx)

To estimate the useful lifetime of striping along highways with unknown *ADT*s, three broad ranges of *ADT* are used: low, intermediate (mid) and high, and the expected useful lifetime for each range is calculated. The expected useful lifetime of striping is presented in Table 7-1 for highways in the three *ADT* categories. This table provides an alternate means for estimating striping lifetime along two-lane highways when specific *ADT* data is not available. Generally, two-lane rural highways fall in the low- to mid-*ADT* range.

Table 7-1 Expected useful lifetime* of paint and thermoplastic striping according to *ADT* levels

	Low-*ADT* (<2500 vpd)	Mid-*ADT* (2500 to 5000 vpd)	High-*ADT* (>5000 vpd)
Paint	22	7.5	4.5
Thermo	53	18	10.5

* PM age when R_L reaches 150 mcd/m^2/lx

7.2 STRIPING COST ANALYSIS

7.2.1 Application costs

Cost is an important consideration in the selection of marking material. Costs of longitudinal pavement markings vary according to their type, width and color. A breakdown of the costs of various longitudinal lines on Alabama State highways is presented in Table 7-2. According to this table, thermoplastic long line cost three to four times that of paint long lines for same width and color markings. As an example, striping a two-lane highway with two solid 4-inch white edge lines and a double-yellow line (one solid 4-inch line and one broken 4-inch line) costs $1,105/mile and $3,520/mile for paint or thermoplastic, respectively. This is a paint to thermoplastic (*p:t*) application cost ratio of 0.31. Thermoplastic, however, is expected to last longer than paint, thus a comparison of the equivalent annual cost of these two materials is prepared using the pavement marking useful lifetime of Table 7-1 and the application cost of Table 7-2. The resulting equivalent annual application cost of paint and thermoplastic striping is presented in Table 7-3. According to this table, the equivalent annual cost of paint edge lines is approximately ¾ that of thermoplastic for all ranges of ADT.

7.2.2 Safety costs

Although damage to public property can be substantial, such as when sign structures, guardrails, or crash attenuators are damaged, striping-related crash cost is still primarily a user cost with the main damages incurred by the vehicles and occupants involved. This study uses the safety costs associated with the retroreflectivity-related crash experience to predict safety costs of future crashes. Estimates of safety costs are determined using the

Table 7-2 Unit application cost of longitudinal stripes along Alabama State highways, per mile (unless stated otherwise)

Description of Longitudinal Stripes	Standard Paint Stripe, Class 1$^{(1)}$, Type A$^{(3)}$ (as of 8/2/99)	Standard Thermoplastic Stripe, Class 2$^{(2)}$, Type A$^{(3)}$ (as of 4/5/99)	Paint to Thermoplastic (*p:t*) Cost Ratio
Broken White, 4"	$175	$575 (0.09" thick)	0.30
Broken White, 6"	N/A	$875 (0.09" thick)	N/A
Solid White, 4"	$300	$900 (0.06" thick)	0.33
Solid White, 6"	$375	$1,410 (0.06" thick)	0.27
Broken Yellow, 4"	$180	$600 (0.09" thick)	0.30
Broken Yellow, 6"	$230	N/A	N/A
Solid Yellow, 4"	$325	$900 (0.06" thick)	0.36
Solid Yellow, 4"	$325	$1,120 (0.09" thick)	0.29
Solid Yellow, 6"	$405	$1,430 (0.06" thick)	0.28
Dotted, 4"	$0.35/LF*	$0.55/LF$^{(4)}$ (0.09" thick)	0.64
Dotted, 6"	N/A	$0.70/LF$^{(4)}$ (0.09" thick)	N/A
Dotted, 6"	N/A	$0.70/LF$^{(4)}$ (0.09" thick)	N/A

(1) Class 1 = Paint

(2) Class 2 = thermoplastic

(3) Type A = retroreflective

(4) LF = Linear Foot

National Safety Council (*NSC*) method, which convert losses incurred in crashes into an equivalent dollar value based on crash severity. The NSC estimates specify five levels of crash severity: (1) fatal injury (*Type K*), which applies to crashes with at least one fatality; (2) nonfatal disabling personal injury (*PI*), which includes incapacitating (*Type A*) injuries, non-incapacitating but visible (*Type B*) injuries and possible but not visible (*Type C*) injuries; and (3) property damage only (*PDO*) with no bodily injuries. The *NSC*

Table 7-3 Equivalent annual application cost of paint and thermoplastic striping

ADT Range	Variable	Paint	Thermoplastic	p:t cost ratio*
Low-ADT (<2500 vpd)	Useful lifetime, months	22	53	0.76
	Lifetime application cost, $/mile	1,105	3,520	
	Equiv. annual application cost, $/mile/year	603	797	
Mid-ADT (2500 to 5000 vpd)	Useful lifetime, months	7.5	18	0.76
	Lifetime application cost, $/mile	1,105	3,520	
	Equiv. annual application cost, $/mile/year	1,658	2,347	
Hi-ADT (>5000 vpd)	Useful lifetime, months	4.5	10.5	0.76
	Lifetime application cost, $/mile	1,105	3,520	
	Equiv. annual application cost, $/mile/year	2,947	3,840	

* *p:t* = paint to thermoplastic

Equivalent annual application cost of striping = (Lifetime cost *12) / (Useful lifetime), in $/mile/year.

dollar value estimates for each level of crash severity are based on the following five economic cost components:

- Wage and productivity losses, which include wages fringe benefits, household production, and travel delay.
- Medical expenses, which includes emergency service costs.
- Administrative expenses, which include the administrative cost of private and public insurance plus police and legal costs.
- Motor vehicle damage, which includes the value of damage to property.
- Employer costs resulting from injury to employees.

The 1998 estimates are used in this study to represent the majority of the striping-related crashes of the last three years. A listing of these estimated costs for all severity levels is presented in Table 7-4.

Table 7-4 *NSC* cost estimates of crash severity for 1998

Crash Severity Level	Crash Designation[1]	Estimated Economic Costs for 1998, $
Fatal Injury	K	$980,000
Incapacitating injury	A	$42,800
Non-incapacitating evident injury	B	$14,400
Possible injury	C	$8,200
Property Damage Only	PDO	$6,400

[1] Refer to text above for explanation of crash types.

The *NSC* estimates are based on a large nationwide database and provide the average costs associated with specific injuries. The estimates do not provide mean costs of crash types, such as the retroreflectivity-related crashes analyzed in this study. To estimate the safety cost of a crash with multiple-injuries, one sums up the cost estimates of each injury in that crash. Table 7-4 shows the *NSC* method to be sensitive to fatal crashes, with the estimated cost of a single fatality exceeding the cost of more than 100 *PDO*s or *Type C* injuries. In order to prevent over-representation of fatalities in safety studies, some states opted to use alternate methods, such as the Equivalent Property Damage Only (EPDO) method. The EPDO method converts crash severities into equivalent number of PDO crashes. For example, the following EPDO models have been used in Kentucky and Illinois:

KY Model: $\text{EPDO} = 9.5 * (K+A) + 3.5 * (B+C) + \text{PDO}$

IL Model: $\text{EPDO} = 12 * (K) + 3 * (A+B+C) + \text{PDO}$

According to these models, a fatality is approximately 3-4 times the value of a Type C injury. In this study, determining the expected cost estimate of a potential crash is based on the mean safety cost per crash. The main reasons for using a mean crash cost in lieu of injury-based crash cost for estimating future crash costs are:

1. Although the scope of this safety study covers a fairly large area (32 counties), the crash experience is aggregated in three-month increments of the useful life of pavement markings. The aggregation of data makes the number of retroreflectivity-related crashes in any 3-month period relatively small. The number of crashes in this study ranged from 2 to 21 crashes per period, and thus, a fatality will over-represent the safety risks associated with the PM retroreflectivity for that time period. For example, using the NSC estimates to compare the safety costs of two time periods, one period with the minimum crash experience of 2 crashes, one of which is fatal, and the other period with the worst crash experience of 21 crashes, all of which are of minor severities such as Type C or PDO, the estimates would show the period with 21 crashes to be approximately five times safer than the period with 2 crashes.
2. Since an average cost of a retroreflectivity-related crash is not available, a better estimate can be reached by using safety costs of all retroreflectivity-related crashes to generate a single average cost value of a typical crash, rather than having a different crash cost average per period varying with the severity of crashes in that period. This is equivalent to stating that the expected safety cost of a potential crash is estimated as the safety cost of an "average injury" crash, regardless of what time period it occurs. An estimate of crash cost based on a smaller sample size would also be more biased and less reliable than an estimate based on all crashes of this type.

3. The severity of a crash is not necessarily related to PM age or retroreflectivity. This study is based on the premise that the potential for nighttime run-off-the-road types of crashes is related to PM retroreflectivity. Once a crash occurs, however, its severity is dependent on vehicle and highway factors, such as travel speed, seat belt usage, air bag availability, presence and type of fixed objects, slope of embankment, etc., regardless of the PM age or retroreflectivity level. Correlating different values of average crash costs to a specific PM ages is not justified since it assumes crash severity to be PM age-related.

The overall mean crash cost is determined as follows:

- Convert each crash of Tables 6-2 and 6-4 into the injuries associated with the crash, so that each crash is represented by a number of K, A, B, C, and PDO types of severities.
- Tally each type of crash severity to get a total number of each type (K, A, B, C, and PDO).
- Multiply the total number of K, A, B, C, and PDO severities by their corresponding NSC cost estimates of Figure 7-4, and add the results to get the total of all crashes, in dollars.
- Divide the total cost of crashes by the total number of crashes to get the mean crash cost.

Table 7-5 presents the total number and cost of K, A, B, C, and PDO severities for paint and thermoplastic-related crashes. According to Table 7-5, the overall mean crash cost is calculated to be approximately \$58,000 and \$42,000 for paint and thermoplastic, respectively. Using these mean crash costs, the cost of paint and thermoplastic crash experiences are calculated for every three-month period, by multiplying the number of crashes in a period by the overall mean crash cost. Tables 7-6 and 7-7 present the crash costs of paint and thermoplastic-related crashes, respectively.

Table 7-5 Total number of injuries associated with paint and thermoplastic edge line retroreflectivity

Crash Severity	No. of injuries relating to paint striping	No. of injuries relating to thermoplastic striping	Paint crash cost[1], $*10^3$	Thermo crash cost[1], $*10^3$
Type K	6	1	5,880	980
Type A	60	14	2,568	599
Type B	18	1	259	14
Type C	9	1	74	8
PDO	86	26	550	166
# of crashes	160	42	9,331	1,768
		Overall average crash cost =	$58.3*10^3$	$42.1*10^3$

[1] Striping crash cost for each type of severity = No. of striping-related injuries * NSC severity cost.

The estimated crash costs of Tables 7-6 and 7-7 are normalized for highway length and ADT, consistent with Section 6.1 normalization of crash data. The unit assigned to the crash cost rate is $/MVM. A plot of the cumulative costs of retroreflectivity-related crashes of Tables 7-6 and 7-7 is presented in Figure 7-3 for paint and thermoplastic edge lines. This plot shows the cumulative cost rate of paint to be consistently higher than that of thermoplastic. The equivalent annual cost of crashes, in $/mile, is calculated using the cumulative crash cost of Figure 7-3, the striping useful lifetime of Figure 7-1, and the ADT ranges of Table 7-1. These equivalent annual crash costs are presented in Table 7-8 for paint and thermoplastic edge lines. This table shows the crash costs associated with paint to be substantially higher than that associated with thermoplastic, especially at lower *ADT*s. Combining the costs associated with pavement marking application (Table

7-3) and retroreflectivity-related crashes (Table 7-8), the total equivalent annual costs of paint and thermoplastic edge lines are compared. The combined costs are presented in Table 7-9 which shows the equivalent annual cost of paint to be higher than that of thermoplastic, especially at lower *ADT* levels, indicating that thermoplastic is a more economical striping alternative when equivalent crash costs are used.

Table 7-6 Cumulative cost of paint retroreflectivity-related crashes

Month	*VE,* MV	# of crashes	*period CC,* $\$*10^6$	*CC rate,* $/MVM	*Cum CC rate,* $/MVM	*CNV,* MVM
3	0.149	15	0.87	8,188	8,188	106.8
6	0.297	20	1.17	10,876	19,064	107.2
9	0.443	16	0.93	9,552	28,616	97.7
12	0.652	19	1.11	12,576	41,192	88.1
15	0.821	21	1.22	17,236	58,429	71.0
18	1.000	21	1.22	19,960	78,389	61.3
21	1.276	10	0.58	10,034	88,423	58.1
24	1.242	12	0.70	15,558	103,980	45.0
27	1.433	10	0.58	16,709	120,689	34.9
30	1.597	6	0.35	14,062	134,752	24.9
33	2.242	6	0.35	18,863	153,614	18.5
36	2.531	4	0.23	15,119	168,733	15.4

VE = vehicle exposure (cumulative), in million vehicles (MV)
Period CC = crash cost for the corresponding 3-month period = #crashes * 58,300 * 10^{-6}, in million dollars
CNV = Crash Normalization Value = sum (*Length* * *period traffic volumes* *10^6), in million vehicle miles (MVM)
Where *Length* = Highway length, miles
Period traffic volume = sum (ADT per lane * 3 * 30.4) for all projects in the period, in vehicles
CC rate = Crash cost rate = (*Period CC* * 10^6)/*CNV*, in $/MVM

This analysis has shown that despite the lower application cost of paint (approximately ¾ that of thermoplastic on an equivalent annual basis), the larger number of crashes experienced annually on painted highways makes thermoplastic a less expensive

Table 7-7 Cumulative cost of thermoplastic retroreflectivity-related crashes

Month	VE, MV	# of crashes	period CC, $\$*10^6$	CC rate, $/MVM	cum CC rate, $/MVM	CNV, MVM
3	0.277	5	0.21	2,506	2,506	84.0
6	0.556	5	0.21	2,557	5,064	82.3
9	0.824	6	0.25	3,464	8,528	72.9
12	1.128	4	0.17	3,923	12,451	42.9
15	1.343	4	0.17	4,453	16,904	37.8
18	1.545	9	0.38	11,452	28,356	33.1
21	2.194	6	0.25	8,968	37,324	28.2
24	2.457	2	0.08	5,349	42,673	15.7

VE = vehicle exposure (cumulative), in million vehicles (MV)
Period CC = crash cost for the corresponding 3-month period = #crashes * 42,100 * 10^{-6}, in million dollars
CNV = Crash Normalization Value = sum (*Length* * *period traffic volumes* *10^6), in million vehicle miles (MVM)
Where *Length* = Highway length, miles
Period traffic volume = sum (ADT per lane * 3 * 30.4) for all projects in a period, in vehicles
CC rate = Crash cost rate = (*Period CC* * 10^6)/*CNV*, in $/MVM

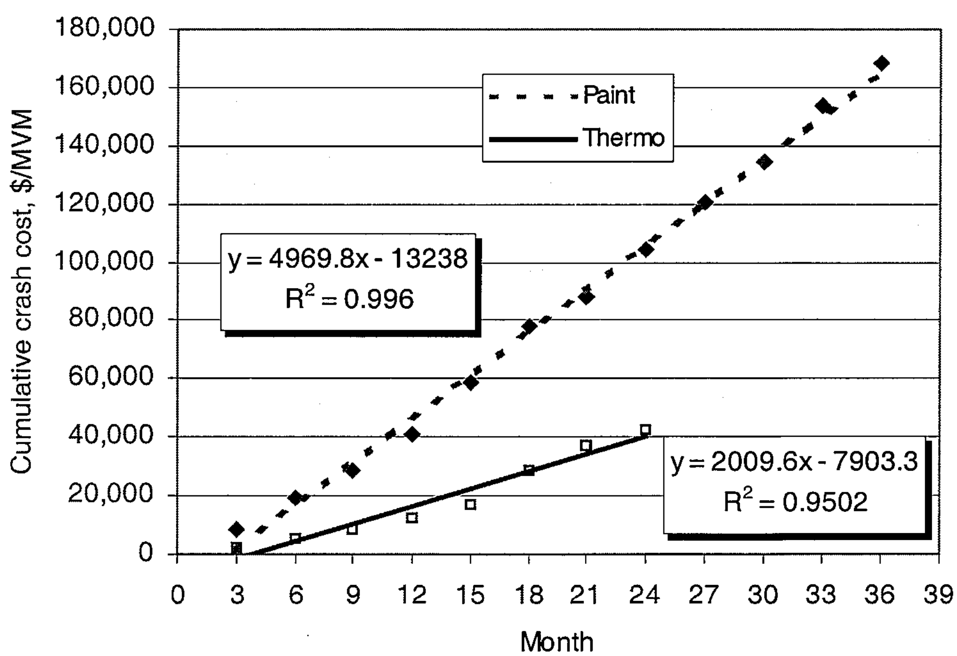


Figure 7-3 Cumulative costs of paint and thermoplastic retroreflectivity-related crashes

Table 7-8 Equivalent annual crash costs of paint and thermoplastic striping

Striping material	Low ADT (<2500 vpd)			Mid-ADT (2500 to 5000 vpd)			Hi-ADT (>5000 vpd)		
	Useful lifetime, months	Lifetime crash cost, $/mile	Equiv. annual crash cost, $/mile/Yr.	Useful lifetime, months	Lifetime crash cost, $/mile	Equiv. annual crash cost, $/mile/Yr.	Useful lifetime, months	Lifetime crash cost, $/mile	Equiv. annual crash cost, $/mile/Yr.
Paint	22	95,189	49,213	7.5	22,904	35,525	4.5	8,447	21,837
Thermo	53	98,689	26,554	18	27,628	22,301	10.5	13,415	18,048
p:t cost ratio	2.34			2.02			1.53		

Lifetime crash cost of paint, in $/mile = 4,969.8 * Useful lifetime – 13,238
Lifetime crash cost of paint, in $/mile = 2,009.6 * Useful lifetime – 7,903.3
p:t cost ratio = paint to thermoplastic cost ratio
= (Equiv. annual crash cost of paint) / (Equiv. annual crash cost of thermoplastic)

Table 7-9 Total equivalent annual costs (installation + equivalent crash cost) of paint and thermoplastic striping ($/mile/year)

Striping material	Low ADT (<2500 vpd)			Mid-ADT (2500 to 5000 vpd)			Hi-ADT (>5000 vpd)		
	Useful lifetime, months	Total lifetime cost, $/mile	Total equiv. annual cost, $/mile/Yr.	Useful lifetime, months	Total lifetime cost, $/mile	Total equiv. annual cost, $/mile/Yr.	Useful lifetime, months	Total lifetime cost, $/mile	Total equiv. annual cost, $/mile/Yr.
Paint	22	95,966	49,821	7.5	23,930	37,348	4.5	9,523	24,876
Thermo	53	102,209	27,350	18	31,148	24,690	10.5	16,935	22,029
p:t cost ratio*	2.28			1.87			1.37		

* *p:t = paint to thermoplastic*

alternative when considering the dollar-value of crashes. Therefore, when consideration is given to user costs in re-striping scheduling, thermoplastic becomes a more economical choice of highway striping material. This is particularly true for lower *ADT* highways where the equivalent safety and application costs of paint are more than double the costs of thermoplastic. Note, however, that the lifetime costs of thermoplastic (application and crash costs) are higher than the lifetime costs of paint. It is when these costs are spread over the useful lifetime of striping that thermoplastic becomes more economical. Thermoplastic will have an economic advantage over paint even when thermoplastic striping is not expected to be in place for its whole useful life, as in the case of planned highway resurfacing before the useful lifetime of thermoplastic is reached. Although the application cost of thermoplastic would be spread over the shorter period between re-striping and resurfacing, and not over the whole useful life, the difference in application costs is minor (see Table 7-3) when compared to the difference in cost of crashes (see Table 7-8). Therefore, based on the results of this chapter, practitioners who wish to consider user costs in their evaluation of striping material should use thermoplastic over paint for striping two-lane rural highways.

7.3 CHAPTER SUMMARY

- The application cost of thermoplastic is approximately three times that of paint with a paint-to-thermoplastic (*p:t*) cost ratio of 0.30 to 0.36.
- On an annual basis, the equivalent cost of paint is approximately ¾ that of thermoplastic with a *p:t* cost ratio of 0.76)
- Based on the crash data collected on Alabama roads, more retroreflectivity-related crashes occur on roads with painted longitudinal lines than on roads with thermoplastic lines.
- When considering the equivalent dollar value of crashes, thermoplastic becomes a more economical alternative than paint with a *p:t* cost ratio of 1.4 to 2.3.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 FINDINGS AND CONCLUSIONS

The findings of the study are presented herein with recommendations to traffic engineering practitioners on the application of the study results.

- Pavement marking retroreflectivity is the primary factor responsible for nighttime visibility. Retroreflection is mainly caused by the light bending characteristics of the glass beads embedded in the pavement and the light diffusing properties of the pavement marking pigments. The higher the refractive index of glass beads and marking pigments, the more scattered the light and therefore the more retroreflective the stripe.
- Retroreflection measurement is a surrogate method of quantifying PM visibility at night. It does not account for real-life driving conditions including veiling luminance (glare), dirty headlights and windshields, misaligned headlights, different driver eye height, age and condition, and contrast with the pavement/background.
- Factors affecting PM performance include PM type and color, traffic volume, and weather conditions. Pavement type has an insignificant effect on pavement marking retroreflectivity.
- Different PM types have different methods of application, useful lifetime, and unit cost.
- Retroreflectivity readings differ between portable retroreflectometers of different testing geometry (15-meter versus 30-meter), between portable retroreflectometers of

similar testing geometry, and between portable and mobile retroreflectometers of similar testing geometry.

- No national retroreflectivity standards exist for any type or color of pavement markings.
- Yellow pigments in pavement markings are less effective than white pigments in diffusing light. Organic lead-free yellow pigments are expensive and less effective than previously-used (currently-banned) lead chromate.
- Contrast ratio is a valid means of approximating pavement marking visibility since it accounts for the relative retroreflectivity of pavement markings against the background of the pavement surface. Minimum *LCR* safe values of 2-5 reported in the literature were found to be achievable on Alabama highways for the first two years of the pavement marking life. A minimum value of R_L needs to be established before a meaningful minimum contrast ratio can be determined.
- Evaluating the ambient temperature effects on pavement markings is feasible, but requires the collection of massive amounts of data that are not readily available. An alternate way to account for weather effects may be through comparing the rate of deterioration of low-ADT and high-ADT routes at equal vehicle exposure values.
- Standing water on the road creates a specular surface preventing the submerged pavement markings, and specifically the glass beads embedded in them, from receiving and retroreflecting the incident light regardless of the type of marking used. Only raised pavement markers, and to some extent profiled materials, are used to counteract this phenomenon.

- Snow removal operation is the primary factor responsible for pavement marking accelerated deterioration in colder climate states.
- The difference in PM performance on asphalt versus concrete pavement surfaces is too small to warrant any practical consideration.
- Retroreflectivity readings based on 15-meter geometry are not necessarily higher than readings based on 30-meter geometry. A correlation between the readings by an Erichson Model 710, a 15- meter retroreflectometer, and an LTL 2000, a 30-meter retroreflectometer, showed 15-meter geometry readings to be 91% those of 30-meter geometry. The regression model shows a good correlation between the 15-m and 30-m geometry readings, with a coefficient of determination, R^2, of 0.85.
- A survey of eleven southern states shows that most states have converted or in the process of converting to using 30-m geometry in measuring pavement marking retroreflectivity. Only four states still use 15-m geometry retroreflectometers and two states do not use any.
- A logarithmic regression model provides a good description of the decaying properties of pavement marking retroreflectivity with age. A retroreflectivity-age R^2 coefficient of up to 0.94 for paint and 0.98 for thermoplastic striping was found on test deck samples in Alabama and Kentucky.
- The variables necessary for the analysis of pavement marking crash experience include pavement marking types and colors, striping dates, crash dates, highway segment lengths and number of lanes, traffic volumes, and the crash types.
- The variables necessary for the analysis of longitudinal line retroreflectivity deterioration include pavement marking types and colors, striping dates, field

retroreflectivity measurement dates, highway segment lengths, number of lanes, traffic volumes, and type of longitudinal line.

- The types of pavement markings evaluated in this study were paint and thermoplastic. The survey of southern states shows that all states use water-based paints and alkyd thermoplastic for striping their roads.
- The vehicle exposure factor is a calculated measure of effectiveness that combines the effects of pavement marking age and traffic volume. The age of pavement markings is measured from the striping date to the crash date if used for crash analysis or from the striping date to the field measurement date if used for retroreflectivity deterioration analysis.
- Linear regression analysis shows a relatively low correlation between crash rate and vehicle exposure, with coefficients of determination of 0.32 and 0.40 for painted and thermoplastic longitudinal lines, respectively. An increase in *VE* was shown to produce an increase in crash rate by showing the slope of the linear regression line to be positive at a confidence level exceeding 90%.
- The overall average crash rate for thermoplastic long lines is 0.1033 crash/MVM is less than half the rate for painted long line (0.2195 crash/MVM), indicating that thermoplastic striped highways enjoy a safer crash record.
- A maximum vehicle exposure value of 710,000 and 921,000 vehicles was established for paints and thermoplastics, respectively. Exposing longitudinal stripes to values higher than these VE_{max} values corresponds to higher crash rates than the overall average rate.

- The R_L-*VE* relationship was modeled for paint and thermoplastic long lines using field collected retroreflectivity data, with a relatively low correlation. The R^2 coefficient for this relationship was 0.31 and 0.30 for white and yellow paints, respectively, and 0.58 and 0.54 for white and yellow thermoplastics, respectively.
- A minimum retroreflectivity value in the range of 140 to 156 mcd/m^2/lx was determined according to the maximum vehicle exposure associated with the overall average crash rate. A value of 150 mcd/m^2/lx was used in this study as the retroreflectivity threshold in lieu of the above retroreflectivity range.
- The survey of southern states shows that retroreflectivity values in the range of 100 to 150 mcd/m^2/lx are used to designate the end of service life of pavement markings.
- Based on a retroreflectivity threshold of 150 mcd/m^2/lx, a user-friendly chart was developed (Figure 7-1) to predict the service life of paints and thermoplastics along two-lane highways according to their *AADT*s.
- The useful lifetime of paint and thermoplastic striping was determined for three levels of *AADT* (Table 7-1).
- Cost of applying thermoplastic striping was found to be greater than three times that of paint on a per mile basis, but approximately 30% to 40% greater when calculated on an equivalent annual per mile basis.
- The equivalent cost of crashes associated with retroreflectivity was found to be approximately twice as high for paint striping than for thermoplastic striping (Figure 7-3).

8.2 RECOMMENDATIONS

Based on the above findings and conclusions, the following recommendations are offered to traffic engineering practitioners who are interested in using safety-based criteria for renewal of longitudinal pavement markings.

- Retroreflectivity readings should be taken using the same brand retroreflectometer, and whenever possible, the exact same unit should be used. This is especially critical if readings are needed over a long period of time, such as when tracking the rate of deterioration of pavement marking retroreflectivity over time. Simple usage of different retroreflectometers of the same geometry does not ensure compatibility of the readings.
- Figure 7-1 may be used for predicting the useful lifetime of longitudinal lines along two-lane highways based on the highway *AADT*. This crash-based age of pavement markings is an indicator of when the crash rate of a highway is likely to exceed the overall average crash rate, and thus can be used by practitioners to schedule highway re-striping based on safety considerations.
- A minimum acceptable retroreflectivity level of 150 mcd/m^2/lx should be used by practitioners for evaluating the need for striping especially at locations where heavy traffic volume, turning traffic, or roadway curvature exist. Locations with retroreflectivity levels below this threshold can be earmarked for spot striping, or special treatment (such as raised pavement markers, or flexible post delineators) even when the overall pavement marking age has not exceeded the overall service life as determined by Figure 7-1.

- Thermoplastic is a safer and a more economical alternative to paint when equivalent crash cost is considered. In general, practitioners should consider using thermoplastic for striping highways. When highways are planned for resurfacing prior to the end of thermoplastic useful life, Table 7-1 may be consulted to determine which of the useful lives of paint or thermoplastic is more in line with the restriping schedule, and to ensure that the useful life of the striping material selected does not extend beyond the resurfacing date.
- A larger scale research may help to refine the models developed in this research, especially if a larger set of crash data is included. A multi-state or national data may be necessary to accomplish that.
- Future research is needed to explain the increase in R_L values found in the second year of the NTPEP test data, and to determine the validity and repeatability of such an increase. This study noted but did not address this phenomenon.

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