THE IMPACT OF DIRECTIONALITY ON
PAINT PAVEMENT MARKING RETROREFLECTIVITY

William J. Rasdorf, Ph.D., P.E., F.ASCE

Professor

Department of Civil, Construction, and Environmental Engineering

North Carolina State University

Raleigh, NC 27606-7908

Telephone: (919) 515-7637 Fax:(919) 515-7908

Email: rasdorf@eos.ncsu.edu

Guanghua Zhang

Ph.D. Student

Department of Civil, Construction, and Environmental Engineering

North Carolina State University

Raleigh, NC 27606-7908

Telephone: (919) 515-6456 Fax:(919) 515-7908

Email: gzhang3@ncsu.edu

Joseph E. Hummer, Ph.D., P.E.

Professor

Department of Civil, Construction, and Environmental Engineering

North Carolina State University

Raleigh, NC 27606-7908

Telephone: (919) 515-7733 Fax:(919) 515-7908

Email: hummer@eos.ncsu.edu

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ABSTRACT

This paper addresses paint centerline pavement marking retroreflectivity. We collected yellow centerline retroreflectivity data on two-lane highways taking measurements in two directions. A paired t-test on the data showed that there were differences and they were statistically significant. A field study was initiated to investigate the relationship between the direction the marking was painted and the retroreflectivity direction. The key result of this study is that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than values measured in the opposite direction. Our findings indicate that it is the lower retroreflectivity values of yellow centerlines (measured in the opposite direction from paint striping) that should be used to compare with the newly proposed Federal Highway Administration (FHWA) minimum standard because the drivers in that direction experience lower marking retroreflectivity at night. The implications for safety, for policy making, and for transportation asset management are significant.

Keywords: Pavement Marking, Retroreflectivity, Directionality, Infrastructure Management, Asset Management

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PAINT PAVEMENT MARKING RETROREFLECTIVITY DIRECTIONALITY STUDY

INTRODUCTION

Traffic markings and markers, like traffic signs, are considered to be traffic control devices having the function of controlling traffic and encouraging safe and efficient vehicle operation according to the American Association of State Highway and Transportation Officials (AASHTO). For highways and streets three general types of markings are in use: pavement markings, object markers, and delineators [AASHTO 2004]. Pavement markings include centerline stripes, lane lines, and edge lines. These may be supplemented by other pavement markings such as approaches to obstructions, stop and crosswalk lines, and various word and symbol markings [AASHTO 2004]. The Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways specifies that pavement markings are commonly placed using paint or thermoplastic materials although other suitable marking materials can also be used [FHWA 2003].

Water-based paint is currently the most commonly used pavement marking material. Paint is used on almost 60% of the total pavement marking mileages [Migletz and Graham 2002]. In North Carolina, water-based paint markings are reported to make up more than 80% of the total marking mileages [NCDOT 2008]. As a result, the primary focus of this paper is on paint pavement markings.

Normally, paint markings are applied on secondary routes where traffic volumes are relative low [NCDOT 2008]. This is because paint materials often have lower initial retroreflectivity values and degrade at a faster rate than other pavement marking materials. They are usually classified as non-durable marking materials [TxDOT 2004]. Thus, they are more well positioned in areas of lower traffic volumes.

A congressional mandate (Section 406 of the 1993 Department of Transportation and Related Agencies Appropriations Act) directed the Secretary of Transportation to revise the MUTCD to include a standard for minimum levels of retroreflectivity that must be maintained for traffic signs and pavement markings [Vereen et. al. 2004]. The minimum retroreflectivity levels and maintenance methods for traffic signs were published in revision 2 of the 2003 version of the MUTCD. The final rule has been effective since January of 2008 [FHWA 2008]. The Federal Highway Administration (FHWA) is working with other research agencies to establish a similar minimum retroreflectivity standard for pavement markings. The minimum retroreflectivity requirement for pavement markings is expected to be included in a future version of the MUTCD.

Concern about meeting future MUTCD minimum retroreflectivity levels led the North Carolina Department of Transportation (NCDOT) to initiate a research project to evaluate pavement marking material performances and service lives. The retroreflectivity directionality study reported herein is part of the overall research effort to evaluate paint marking performance on roads with low traffic volumes.

While collecting field data on paint markings, the research team found that painted centerline pavement markings have significant directionality, which means the retroreflectivity values measured in one traffic direction are significantly different from the values measured in the opposite direction on the same segment of roadway. Since this finding could affect how public agencies respond to the new standards and how they maintain their markings, public works managers need to be aware of this phenomenon, its significance and magnitude and its implications.

Sparrow pointed out that the new and recent legislation in the areas of transportation and environment has highlighted the need to incorporate a variety of previously extraneous factors into infrastructure decision making [Sparrow 2001]. Paint marking directionality is one of those factors which public works managers normally do not attend to. However, when the FHWA publishes a minimum retroreflectivity requirement, it must be met. Thus, pavement markings became an asset of greater significance, especially as they relate to maintenance and safety.

Public works managers are also well aware of the need to achieve increasing infrastructure performance and productivity [Price 2002]. Performance standards for infrastructure systems describe the qualities needed by the owner, users, and other stakeholders [Switzer and McNeil, 2004]. This paper provides some useful insight into this subject as well.

RESEARCH OBJECTIVE

Paint retroreflectivity directionality is important because we report herein that drivers experience different centerline levels of retroreflectivity in each travel direction. This also means it is possible that the paint pavement marking retroreflectivity in one direction meets the minimum requirement while in the other direction it does not. The objective of this study was to investigate the retroreflectivity directionality property of paint pavement markings to find the relationship between retroreflectivity values and the paint installation direction, to quantify these differences, and to determine whether retroreflectivity directionality could have an impact on paint markings meeting the pending FHWA minimum retroreflectivity levels.

RESEARCH SCOPE

The scope of this paper is on the retroreflectivity directionality of paint pavement markings on two-lane highway centerlines. The data collection efforts were made on two-lane highways because two-lane highways comprise the majority of the highway system. Furthermore, traffic control for data collection (for safety) was much easier on two-lane highways than on other types of highways. In North Carolina, 74,015 of the total 79,042 roadway miles (93.6%) are two-lane highways [NCDOT 2007]. Since most two-lane highways were marked with paint pavement markings, NCDOT estimated that more than 80% of its total marking mileages were paint [NCDOT 2008]. This paper does not address multi-lane roads or divided highways nor does it address any marking other than paint.

During our data collection effort the centerline pavement markings were measured in both directions of traffic flow. The retroreflectivity values in each direction were averaged separately for each stripe and for each direction. We found that the centerline pavement markings did not provide the same retroreflectivity levels for each travel direction. Instead, the average of all readings for each of the two directions (for each stripe) differs significantly.

The retroreflectivity values of edge pavement marking lines were measured in one direction because they are always painted in the direction of travel. Thus, drivers always see the same retroreflectivity no matter which edge line is being considered (or which direction traveled).

Other types of marking materials with glass beads dropped on during installation (such as thermoplastics and epoxy) are known to have the same retroreflectivity directionality property as paint, but they were not investigated in this study due to the time and budget constraints of the project.

BACKGROUND

Numerous papers and reports relevant to pavement marking research have been published in recent years. The congressional mandate to include the minimum levels of retroreflectivity in the MUTCD has given rise to a number of recent research efforts related to pavement markings. Various sources of information relevant to pavement marking studies were obtained and reviewed. A summary of the findings of these studies and sources is presented in the following paragraphs.

Paint Marking Material

Paint is the oldest and most widely used pavement marking material. Paint is mainly composed of finely ground pigments that are mixed into a resin or binder system. Various ingredients and additives are incorporated to obtain certain desired properties. A liquid (water or solvent) is added to the mixture to produce a material that is pliable by application equipment [VDOT 2008]. Paint can be classified into two broad categories, solvent-borne and water-based. Solvent-borne paint is also known as conventional paint. Both categories will be discussed below.

One NCHRP project reported that paint is associated with high Volatile Organic Compound (VOC) content [Andrady 1997]. A VOC is defined as any organic compound that participates in atmospheric photochemical reactions which have a negative impact on some aspect of the environment. The average VOC content of solvent-borne and water-based paints are 383 g/l and 84 g/l respectively [Andrady 1997]. The U. S. Environmental Protection Agency (EPA) published its initial standard with the goal of reducing VOCs in architectural coatings [USEPA 1998]. The standard also addressed paint pavement markings and specified that all types of pavement markings (including paints) are subject to a 150 g/l VOC content limit. The EPA did not completely prohibit the use of solvent-borne paint materials with high VOC content, but their uses are limited and are subject to container size restrictions. Most transportation agencies in the U.S. have eliminated their use and replaced solvent-borne paint with water-based paint because of the VOC content limit requirement. Thus, water-based paint is currently the most commonly used pavement marking material.

Paint markings are typically 15 to 25 mils (1 mil = 0.001 inch) in thickness when applied. Paint drying time depends on the thickness and the formulation. As a rule of thumb, a paint truck speed of 10-12 mph will result in a paint thickness of 15-18 wet mils without beads. Paint markings can last 3 months to 4 years depending on the geographic region, traffic volume, snowplow frequency, application quality, and other factors that influence both performance and

durability. Paint markings last longer in the southern states where snowplowing does not impact marking performance. In northern states, paint markings deteriorate significantly faster over the winter due to a combination of severe weather conditions and snowplow activity. Some northern states report that they restripe paint markings more than once a year [Hawkins et. al. 2006].

Paint can be installed either using premixed paint or plain paint. Premixed paint has glass beads mixed into the paint during the manufacturing process. Plain paint, on the other hand, has no glass beads mixed in during manufacturing. Both premixed paint and plain paint have glass beads dropped on during application to provide immediate surface retroreflectivity in the finished product. Premixed traffic paint was once quite commonly used but due to equipment problems, crew downtime, special handling requirements, crew complaints, etc., most state highway departments have switched to plain traffic paints with drop-on glass beads [ITRE 1995]. For example, the NCDOT requires that glass beads be dropped (using a suitable pressurized means) into the wet paint as the paint is applied to roads [NCDOT 2006].

Pavement Marking Retroreflectivity

Pavement marking retroreflectivity is a term used to describe the amount of light returned back to a driver from a vehicle's headlight as it is reflected back from the markings. The reflected light provides the driver with information about the road (e.g. its center or its edge) and enables a safer drive at night. Thus, retroreflectivity is highly relevant to roadway safety. Retroreflectivity is represented by a measure referred to as the coefficient of retroreflected luminance (R_L), and is expressed in units of candelas per square meter per lux ($\text{cd}/\text{m}^2/\text{lux}$). The unit commonly used for pavement markings is millicandelas per square meter per lux ($\text{mcd}/\text{m}^2/\text{lux}$) because of the low values [ASTM 2001].

Pavement marking retroreflectivity is achieved through the use of glass beads embedded partially in the surface of the marking binder material (e.g. paint). Using glass beads to achieve nighttime marking retroreflectivity has a long history and is now an accepted practice worldwide. Pavement markings without glass beads are nowhere near as visible at night. (During daytime hours, a non-beaded pavement marking will also display richer and more uniform color [VDOT 2008].) Still, a much greater quantity of light will be reflected back at night if the marking is applied with glass beads embedded in its surface. Figure 1 shows how glass beads reflect back light from a headlight. There are actually thousands of beads in each segment of beaded pavement marking.

The glass bead refractive index, their embedment, and their density all have impacts on the retroreflectivity values of the pavement marking as a whole. The amount of retroreflected light depends on these parameters and on the type of the glass beads. The refractive index is determined by the chemical and physical makeup of the glass material [VDOT 2008]. AASHTO standard M247-07 requires glass beads to have a refractive index of 1.50-1.55 [AASHTO 2007]. Glass beads are recognized to provide their best retroreflection when about 40% of each bead is exposed above the marking and 60% is embedded in the marking. The Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-03) specifies the glass bead application rate to be 6 lb/gal or 12 lb/gal for waterborne paint depending on the type of glass bead used [FHWA 2003]. This application rate generally provides a density that results in an optimal number of beads to always be exposed at this 40/60 rate.

Paint Application

In this section we described the typical paint application practices in use by the NCDOT. Readers should note that while these are relatively standard practices, other transportation agencies may have minor differences in painting operation details. The NCDOT is divided into 14 divisions. Each division typically has one paint truck (one division has two). Each paint truck requires 4-5 crew members to operate. The paint truck can hold 210 gallons of paint materials in each of two tanks. One tank contains white paint and the other contains yellow paint.

Paint materials supplied by a manufacturer are usually made available in 30-gallon cans so a paint truck can hold 14 cans of paint in both tanks. Normally 210 gallons of yellow paint is enough for one day to apply but about 400 gallons of white paint are needed. Thus several extra cans of white paint are carried to the field in another truck and at some point during the day they need to be added to the white tank. It should be noted that the same paint (supplied by the N. C. Department of Correction) is used in all the divisions throughout the state. Thus, there should generally be excellent uniformity in paint materials used statewide by NCDOT personnel.

On two-lane highways, the centerlines are striped in one of three patterns (Figure 2) – two solid lines, one solid line and one skip line, or one skip line only. The striping work on a two-lane road consists of two runs of a paint truck. One run paints both of the yellow centerlines and one white edge line, which is illustrated by direction 3 in Figure 2 (a). The other run paints the last (other) white edge line, which is shown as direction 4 in Figure 2 (a). The key question is whether the paint striping direction is related to the retroreflectivity directionality. In other words, if the paint striping direction is same as that shown in Figure 2 (a), we want to know if the retroreflectivity values measured in directions 5 and 7 are higher than, the same as, or lower than in directions 6 and 8, and by how much.

Driver Line of Sight

Figure 3 shows the vehicle travel, paint application and driver line of sight directions. Figure 3 (a) illustrates the driver line of sight in one direction and Figure 3 (b) illustrates the other direction. In Figure 3 (a), the driver line of sight direction 9 is same as the paint striping direction 3. In Figure 3 (b), the driver line of sight direction 10 is opposite to the centerline paint striping direction 3. If the R_L values measured in the directions 9 and 10 are different for the centerlines, the drivers in the directions 1 and 2 would perceive different levels of retroreflectivity for the same centerline.

R_L Measurement Directions

R_L values were measured in both directions for each centerline. The directions 5 and 6 in Figure 2 (a) show the R_L measurement directions for one centerline. The directions 7 and 8 show the measurement directions for the other centerline.

Retroreflectivity Directionality Explanation

The hypothesis that explains the directionality phenomenon is that glass beads have a horizontal velocity when sprayed from a pressurized dispenser, which causes more paint resin to cover one side of their surface than the other side. Figures 4 (a) and (b) illustrate an idealized paint

application in which the glass beads are sprayed (or dropped) vertically into the paint resin. Alternatively, Figures 4 (c) and (d) show a more realistic painting scenario in which the glass beads have a horizontal speed when they are sprayed from a moving truck traveling at a speed of 10-12 mph. More headlight will enter and be retroreflected back from these glass beads in one direction than the other as is illustrated in Figure 4 (d). Thus, the retroreflectivity values measured in the paint truck striping direction are higher than in the other direction.

Data Collection Instrument

Two types of retroreflectometers can be used to measure pavement marking retroreflectivity values – a handheld unit (or portable unit) and a vehicle-mounted mobile unit. Handheld and mobile collection instruments each have advantages and disadvantages. Handheld units have a lower initial cost, but require a large crew (for safety reasons) to collect a small number of samples. Mobile devices are significantly more expensive initially, but provide a safer collection method and can collect continuous data throughout the highway system at highway speeds.

ASTM has published a series of standards related to retroreflectivity measurement. The measurement geometry of the handheld instrument is based on a viewing distance of 30 meters with a headlight at the height of 0.65 meter over the pavement marking and the driver's eye at a height of 1.2 meters above the pavement [ASTM 2005]. The entrance angle of the light into the glass beads is fixed at 88.76° and the observation angle is 1.05° . Figure 1 illustrates this retroreflectivity measurement geometry. The ASTM specification requires that a retroreflectometer uses a 30-meter viewing distance. Historically, 15-meter viewing distance instruments were developed and may still be used by some transportation agencies. Thus, when using retroreflectivity data made available by others, one must determine whether the instrument used to collect the data conforms to the current ASTM specification.

A mobile retroreflectometer is capable of measuring pavement marking retroreflectivity while driving at highway speeds. Currently there are no specifications on using a mobile retroreflectometer to measure marking retroreflectivity values. A South Carolina study compared field data collected under various conditions and via several types of retroreflectometers. The study found good correlation between handheld units but the linear fit between a mobile Laserlux device and a handheld unit (LTL 2000) was not found to be as good as the fit between handheld to handheld instruments. Still, the readings made by the Laserlux and LTL 2000 generally fell within the same ranges [Sarasua and Davis 2003].

Data Collection Method

ASTM Specification E 1710-05 specifies a method of measuring pavement marking retroreflectivity using a handheld retroreflectometer that can be placed on the road marking. The standard requires that readings shall be taken for each direction of traffic and averaged separately for each of the yellow centerlines. The standard also requires that the average of the readings shall be reported for each traffic direction for centerlines [ASTM 2005].

A critical shortcoming of the ASTM E 1710-05 standard is that it does not specify the sampling method to be employed when using a handheld unit to measure retroreflectivity values. Instead, the number of readings to be taken at each test location and the spacing between test locations shall be specified by the user. The ASTM E 1710 recommends readers to use the sampling

method in the ASTM Specification D 6359 [ASTM 2005]. However, the ASTM D 6359-99 specification was withdrawn in December 2006 because the sampling methods were not being used [ASTM 2008]. Thus, there is no current specified standard sampling method when using a handheld instrument to measure retroreflectivity values. An Iowa study reported that they collect samples once every 5 miles, unless conditions change. Each sample consists of an average of 5 readings over a minimum segment length of 160 feet [Hawkins et. al. 2006].

METHODOLOGY

The methodology of this study was to collect field retroreflectivity values using a handheld retroreflectometer and compare the retroreflectivity values of each traffic direction for two-lane road centerlines. First, we collected data at test locations on 40 roads. The markings on those 40 roads were installed at different times. The markings were measured at ages ranging from 1 to 23 months since initial installation. The paint striping direction on those roads were not observed. The results of the first study strongly pointed to directionality as a factor affecting retroreflectivity. Then, a controlled study was initiated to determine to what extent the paint striping direction influences the retroreflectivity. In this study we observed paint striping operations in the field and measured the centerline R_L values in each direction. The two studies are described below.

Unknown Striping Direction Study

The research team used a handheld LTL 2000 retroreflectometer for data collection. The LTL 2000 retroreflectometer uses 30-meter geometry, which is the geometry required by ASTM Specification E 1710-05. The standard operating procedure in the instrument manual was strictly followed during field data collection. Field calibration of the LTL 2000 was conducted before measurements were taken. The calibration was performed at each site prior to the start of data collection. A Global Position System (GPS) device was used to record the coordinates of starting and ending points on each test location and the field team used a digital camera to photograph the measured markings.

The paint data were collected on the secondary roads in four divisions in NC. Those roads have low traffic volumes, with annual average daily traffic (AADT) on most roads at less than 4000 vehicles per day. All measured roads were two-lane highways with asphalt pavement surfaces. Included in the study were 40 roads which were painted in 2006 and 2007. Paint installation data were provided by the NCDOT before the field data collection effort was undertaken. The installation data that was given to us included the road name, length, paint installation date, starting point, ending point, and other related information. The roads were measured twice by the research team. These measurements were taken in November, 2007 and May, 2008. Each round of data collection took about two weeks.

The purpose of the data collection activity was to evaluate paint marking performances. The research team selected a test location on each road to be measured. Test locations were not selected where there were sharp horizontal or vertical curves, but were otherwise randomly chosen. Test locations were about 200 feet long. Twenty measurements, approximately evenly distributed along the 200 feet segment, were taken for each pavement marking line. It is necessary to average numerous instrument readings in each direction on each line to account for variability in retroreflectivity along a line. The centerlines were measured in each direction of

travel. The average of the 20 readings was reported separately for each traffic direction for each centerline. It is this average that we present in our tables (1-4) of results.

Data Analysis

Tables 1-3 show the centerline data for the 40 roads that were measured but whose paint striping direction was unknown. The direction numbers in Tables 1-3 correspond to those presented in Figure 3 (a). The ages of the markings are listed in the first column. The R_L readings for each line in each direction are shown in columns 2, 3, 5, and 6. The differences between readings in each direction for each line are shown in columns 4 and 7. The data are sorted by the age of the markings, from youngest to oldest.

In Tables 1-3, the R_L values measured in the same direction for both centerlines (directions 5 and 7, directions 6 and 8) are close to each other. The R_L values measure in opposing directions for the same centerline (directions 5 and 6, directions 7 and 8) are different, which pinpoints the paint pavement marking retroreflectivity directionality property we sought to investigate in this paper. We used hypothesis tests to determine if the differences were statistically significant.

Paired t-tests were used to test if the retroreflectivity differences measured in two opposing directions are statistically significant. The null hypothesis is that H_0 : The R_L mean values in two directions are equal. The alternative hypothesis is that H_1 : the R_L mean value measured in one direction is larger than the value measured in the other direction. We used a one-tailed hypothesis test for this specific problem.

Known Striping Direction Study

In addition to the unknown striping direction study, an additional field study was conducted to investigate the relationship between the paint striping direction and retroreflectivity. We worked directly with a NCDOT paint crew to identify the paint striping direction beforehand. First, the paint application and application direction were observed and recorded. Then, six routes were selected to measure retroreflectivity values just a few days after paint installation and the again 4 months later.

Figure 5 shows arterial roads (e.g. NC 905, US 701) and secondary roads (e.g. SR1147) in the field study area. Thinner lines represent the state routes. Darker lines indicate the observed and measured road segments. The arrows in Figure 5 show direction of striping. The arrows correspond to the paint striping direction 3 in Figures 2 and 3. The numbers correspond to the first column in Tables 4 and 5. These tables show the collected data for this known striping direction study. The ages of the markings, the R_L measurements, and the differences between readings in each direction are shown.

RESULTS

While the focus of this paper is on directionality there is a clear relationship that has emerged between age and retroreflectivity. Both of these subjects are discussed in the following two sections.

Retroreflectivity

Essentially Tables 1-5 present age related R_L data. Table 1 presents data for 1-2 month old markings. Table 2 presents data for 6-9 month old markings. Table 3 presents data for 17-23 month old markings. The trends in R_L values is evident and is as expected. For example, for the first yellow centerline measured in direction 5 we see average R_L values of 215, 170, 136, and 109 decreasing over time at a rate of approximately 55 mcd/m²/lux per year. The same analysis holds for the other direction (6) and for the second centerline in both directions. These results are close to the results reported by Sitzabee (Sitzabee 2008) that paint pavement marking retroreflectivity values degrade about 50 mcd/m²/lux per year on average.

Tables 1-3 also show that the differences between directions over time generally decrease as well. These values evolved from (25, 30) to (28, 30) to (25, 20). Although this is not a prominent decrease, it is nonetheless, a decrease over the long term.

Tables 4 and 5 illustrate similar results for the 6 sites of known paint direction. Table 4 represents paint of a ½ month average age and Table 5 represents paint of a 4½ month average age. We find that the retroreflectivity decreased from values of (215, 144, 190, 116) to values of (170, 114, 143, 89). Additionally, as time went by the difference between the R_L of the two directions decreased from (71, 74) to (56, 54). Thus, the results for the 6 sites and the 40 sites are consistent for both R_L over time and for the R_L difference over time. Finally, both data sets show a marked difference based on direction.

Directionality

We found that the centerline retroreflectivity values have obvious directionality, which means that the R_L values measured in one traffic direction were higher than the values measured in the opposite direction. The difference could be as large as 66 mcd/m²/lux.

Tables 1-3 show the yellow centerline retroreflectivity data for the unknown paint striping direction study. The data were sorted by the age of the paint markings (40 sites). The average directional differences are generally in the range of 20-30 mcd/m²/lux for the paints that are 35 to 696 days old. This represents between 15 and 30% more retroreflectivity in the painted direction than in the reverse.

Readers should recall that 20 readings were measured for each pavement marking line in each direction. Thus, at each testing site, 80 readings were taken for the two centerlines. The mean values of the 20 readings were reported in Tables 1-5. The standard deviation of the 20 readings was generally in the range of 10-25. The mean values for each direction are 141 and 114 mcd/m²/lux for the data collected in the four divisions. The t-test hypothesized mean difference is 0. The one tailed p-value is 6.09×10^{-28} . We specified the significance level $\alpha = 0.05$. We can reject the H_0 since the p-value is less than α , which means that the R_L mean value measured in one direction is larger than the other direction at a 0.05 significance level.

The retroreflectivity readings from the known striping direction study (6 sites) are shown in Table 4. The average R_L differences of the two yellow centerlines measured in two directions (directions 5 and 6, directions 7 and 8) are 71 and 74 mcd/m²/lux. The retroreflectivity differences are larger in this known striping direction study than the first study. Here one

direction is 50% higher than the other. One reason for this significant difference is that new paint markings have higher directionality differences than the older markings. In this study the newer measurements were made within days of the paint application. This is a point at which markings generally exhibit their highest R_L values. Furthermore, the 6 site study consisted of paint applied to a new asphalt surface whereas the 40 site study consisted of painting on older asphalt and even paint applied on top of older paint.

The overall result of this study is that paint centerline retroreflectivity values measured in the direction of paint striping are significantly higher than the values measured in the opposite direction. If the paint is striped in the pattern as shown in Figure 2 (a), the R_L values measured in directions 5 and 7 will be significantly higher than the values measured in directions 6 and 8. The differences are in the range of 20-30 $\text{mcd/m}^2/\text{lux}$ for older paints. For newer paint markings, the differences average 54-74 based on our field data.

CONCLUSIONS

Tables 1-5 consistently affirm that retroreflectivity values on painted centerlines measured in the direction of the striping (painting) are significantly higher than the values measured in the opposite direction on two-lane highways. In reality we did not watch the painting process for the unknown striping direction study (40 sites), but the research results are so strong that we can identify the striping direction from the analysis. For example, the R_L values measured in directions 5 and 7 in Figure 2 (a) are obviously higher than the values measured in directions 6 and 8, leading to the conclusion that the paint striping direction is same as direction 3. The results from the known striping direction study (6 sites) enabled us to verify this conclusion.

A previous study by Sitzabee (2008) showed that paint pavement marking retroreflectivity values should degrade about 50 $\text{mcd/m}^2/\text{lux}$ per year. This translates to an equivalent directional difference of 25 $\text{mcd/m}^2/\text{lux}$ for 6 months and 75 $\text{mcd/m}^2/\text{lux}$ for 18 months. Thus, the retroreflectivity directional differences [(71, 74), (56, 54), (25, 30), (28, 30), (25, 20)] noted herein are quite comparable to previous findings. Over time these lines clearly deteriorate.

An existing study by Lee et. al. did not find that frequency of nighttime accidents was sensitive to levels of marking retroreflectivity (Lee et. al. 1999). Thus, the only true correlation that can be made between safety and crashes on one hand and R_L on the other is that between measured data and published minimum values.

The research result we found indicates that drivers are faced with different levels of retroreflectivity, for the same pair of yellow centerlines, while driving in different directions on two-lane highways at night. In the paint striping direction, the retroreflectivity values are higher than in the other direction. This research result is consistent with the measuring requirement in the ASTM E 1710-05 that the average readings shall be reported for each traffic direction for centerlines. ASTM data collection procedures should be followed when collecting retroreflectivity data on two-lane highway centerlines with a handheld retroreflectometer. What this paper demonstrates is how to interpret and use that data.

Paint pavement marking directionality also has a significant impact on determining whether or not a centerline meets the pending FHWA minimum retroreflectivity standard. On two-lane

highways with two yellow centerlines, it is possible that one centerline meets the standard while the other does not. The lower average retroreflectivity value for a yellow centerline, measured in the opposite direction from the direction of paint striping (measurements 6 and 8 in Figure 2 (a)), should be used to compare with the future FHWA minimum standard to determine whether or not the centerline meets the standard. Both lines must be above the minimum. This is because drivers in that direction experience lower marking retroreflectivity at night, but they do see both lines. One should not use the average value of the two directions to compare with the minimum standard because no drivers observe the centerline with an average retroreflectivity from both directions simultaneously.

Readers should note that the proposed FHWA standard does not specify a measurement protocol for determining whether or not a line meets the new standard. The proposed standard merely specifies a minimum retroreflectivity value. This paper provides both measurement and analysis protocols to determine how to meet the standard. It provides an important addition to the standard in that it demonstrates the significant impact of directionality on retroreflectivity and it explains how to account for this in meeting the requirement.

Transportation officials and policy makers must be aware of the issues noted herein in order to effectively manage their pavement marking assets. It is important to measure and collect data according to ASTM standards. It is then essential to meet the minimum requirement established by FHWA. This paper shows how to determine the correct values to compare to the minimum. It also firmly quantifies retroreflectivity differences as a function of both paint application direction and travel direction for two-lane roads with painted pavement markings. It is highly recommended that a similar study be conducted for thermoplastics as well. This study focused on paints because they comprise the majority of markings on secondary roads.

One further question of interest that could not be definitively determined at the present time is the persistence of the retroreflectivity difference over time. In the unknown striping direction study the range at which we collected data was generally between 1 and 23 months old. In the controlled study we collected data on essentially new markings between $\frac{1}{2}$ and $4\frac{1}{2}$ months old. In a previous study we determined that paint markings should provide adequate performance for 2 years. In this study we focused that, to some extent, the difference decreases over time. Our future plans are to measure the controlled sites at a 2 year age. Doing so would bring closure to the work and would indicate what happens to retroreflectivity over the lifetime of a marking with respect to directionality.

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Figure 1. Pavement Marking Retroreflectivity Using Glass Beads [Craig, 2007]

Figure 2. Vehicle Travel, Paint Application, and R_L Measurement Directions

Figure 3. Vehicle Travel, Paint Application, and Driver Line of Sight Directions

Figure 4. Bead Embedment Illustration

Figure 5. Directionality Data Collection Map (Columbus County, NC)

Table 1. Centerline RL Readings for 35-73 Day Old (2 Month Average Age) Paint Markings (Paint Striping Direction Unknown)

Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
	Measurement Direction		Difference	Measurement Direction		Difference
	↑5*	↓6*		↑7*	↓8*	
35	192	167	25	194	164	30
45	106	93	13	145	131	14
49	146	133	13	124	100	24
49	160	103	57	166	100	66
51	208	190	18	140	130	10
52	157	138	19	99	94	5
52	174	160	14	199	180	19
58	205	212	-7	212	198	14
70	162	127	35	205	170	35
72	147	109	38	172	118	54
72	238	213	25	195	159	36
73	148	103	45	190	136	54
Average	170	146	25	170	140	30

* Measurement directions are illustrated in Figure 3 (a).

Table 2. Centerline RL Readings for 190-273 Day Old (8 Month Average Age) Paint Markings (Paint Striping Direction Unknown)

Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
	Measurement Direction		Difference	Measurement Direction		Difference
	↑5*	↓6*		↑7*	↓8*	
190	141	128	13	158	135	23
204	150	105	45	152	98	54
217	149	127	22	107	86	21
217	148	149	-1	212	181	31
223	196	182	14	199	185	14
224	195	175	20	213	195	18
224	155	114	41	199	160	39
225	113	77	36	111	78	33
226	159	101	58	144	101	43
226	178	149	29	214	193	21
227	134	87	47	138	92	46
229	97	76	21	110	93	17
243	90	79	11	116	100	16
245	83	48	35	93	54	39
245	103	90	13	109	89	20
249	102	62	40	124	69	55
249	124	76	48	128	70	58
253	117	92	25	92	77	15
253	137	109	28	185	166	19
273	150	111	39	118	94	24
273	138	127	11	124	108	16
Average	136	108	28	145	115	30

* Measurement directions are illustrated in Figure 3 (a).

Table 3. Centerline RL Readings for 518-696 Day Old (20 Month Average Age) Paint Markings (Paint Striping Direction Unknown)

Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
	Measurement Direction		Difference	Measurement Direction		Difference
	↑5*	↓6*		↑7*	↓8*	
518	69	46	23	59	44	15
538	143	103	40	120	88	32
550	101	98	3	120	91	29
569	92	64	28	86	61	25
632	116	82	34	142	123	19
675	107	54	53	85	50	35
678	65	58	7	87	75	12
695	118	110	8	93	91	2
696	126	99	27	112	97	15
696	155	130	25	145	129	16
Average	109	84	25	105	85	20

* Measurement directions are illustrated in Figure 3 (a).

Table 4. Centerline RL Readings for 14-22 Day Old (1/2 Month Average Age) Paint Markings (Paint Striping Direction Known)

Loc. **	Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
		Measurement Direction		Difference	Measurement Direction		Difference
		↑5*	↓6*		↑7*	↓8*	
1	19	212	136	76	181	114	67
2	19	230	152	78	226	142	84
3	18	190	135	55	153	89	64
4	19	232	156	76	214	119	95
5	22	192	126	66	134	82	52
6	14	235	159	76	231	147	84
	Average	215	144	71	190	116	74

* Measurement directions are illustrated in Figure 3 (a).

** Locations are shown in Figure 7.

Table 5. Centerline RL Readings for 127-135 Day Old (4½ Month Average Age) Paint Markings (Paint Striping Direction Known)

Loc. **	Days Since Installation	First Yellow Center Line			Second Yellow Center Line		
		Measurement Direction		Difference	Measurement Direction		Difference
		↑5*	↓6*		↑7*	↓8*	
1	132	156	103	53	133	88	45
2	132	186	134	53	189	122	67
3	131	170	113	56	136	75	61
4	132	195	138	57	168	99	68
5	135	159	94	65	100	62	38
6	127	156	103	53	133	88	45
	Average	170	114	56	143	89	54

* Measurement directions are illustrated in Figure 3 (a).

** Locations are shown in Figure 7.