AN INVESTIGATION INTO THE PREDICTIVE PERFORMANCE OF PAVEMENT MARKING RETROREFLECTIVITY MEASURED UNDER VARIOUS CONDITIONS OF CONTINUOUS WETTING

A Thesis

by

ADAM MATTHEW PIKE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Civil Engineering

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ABSTRACT

An Investigation into the Predictive Performance of Pavement Marking Retroreflectivity Measured Under Various Conditions of Continuous Wetting. (December 2005)

Adam Matthew Pike, B.S., Clarkson University

Chair of Advisory Committee: Dr. H. Gene Hawkins

This thesis research investigated the predictive performance of pavement marking retroreflectivity measured under various conditions of continuous wetting. The researcher compared nighttime detection distance of pavement markings in simulated rain conditions and the retroreflectivity of the same pavement markings in several continuous wetting conditions. Correlation analyses quantified the predictive performance of the resulting retroreflectivity values from the continuous wetting conditions.

The researcher measured the retroreflectivity of 18 pavement marking samples under 14 different conditions. The American Society for Testing and Materials (ASTM) has three standards for measuring the retroreflectivity of pavement markings under: dry (E-1710), recovery (E-2177), and continuous wetting conditions (E-2176). Using three ASTM standard conditions resulted in three sets of retroreflectivity data, and variations of the continuous wetting standard produced an additional 11 sets of continuous wetting condition data.

The researcher also incorporated detection distance values measured for the same 18 pavement marking samples under three different simulated rainfall conditions at

night. The three conditions included: high (0.87 in/hr), medium (0.52 in/hr), and low (0.28 in/hr) flow rates, these rates were to simulate typical rainfall rates in the state of Texas.

The correlation analyses measures the linear relationship as well as the logarithmic relationship between the detection distance and the retroreflectivity of the pavement markings. A pavement markings' retroreflectivity is typically used as a detection distance performance indicator, therefore a high degree of correlation between retroreflectivity and detection distance would be desired. A high degree of correlation would indicate that a measured retroreflectivity value of a pavement marking would provide a good indication of the expected detection distance.

The researcher conducted analyses for several subgroups of the pavement markings based on the markings type or characteristics. Dry, recovery, and all the continuous wetting retroreflectivity data were correlated to the detection distances. Correlation values found during this thesis research did not show a high degree of correlation for most of the subgroups analyzed. This indicates that measured retroreflectivity would not provide very good predictive performance of the pavement markings detection distance in rainy conditions.

DEDICATION

This thesis is dedicated to my parents and family, for their continued love and support.

ACKNOWLEDGMENTS

I would like to thank Dr. Paul Carlson for the opportunity to work as his Graduate Assistant Researcher. Under Dr. Carlson, my research focused on the evaluation of wet-weather pavement marking applications. The research project was conducted by the Texas Transportation Institute (TTI), and was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The research described in this thesis was conducted as an extension of the TTI research.

I would like to thank all of my thesis committee members who aided in the research and preparation of this thesis. My committee chair, Dr. H. Gene Hawkins, dedicated much time to the development of my thesis proposal and then to my final thesis. Dr. Hawkins spent many hours reviewing drafts and spent time with me helping me become a better researcher and writer. My committee members: Dr. Paul Carlson, Dr. Rodger Koppa, and Dr. Yunlong Zhang all aided in the development of my thesis proposal, and my final thesis. The final presentation of my research was impacted by comments from all members of my thesis committee. I thank them for all of their insight and professional assistance.

I would also like to thank all the members of the TTI project for any contributions they may have had to my thesis research. Specifically I would like to acknowledge and thank Jeff Miles and Ivan Lorenz. Jeff Miles spent many hours going over data with me and giving feedback on how my research was going. Ivan Lorenz constructed the wetting equipment setup that was used to collect the data for my thesis. To all other members of the research team I am very thankful for your hard work.

To those who made this research possible: Texas A&M University, TTI, TxDOT, and FHWA, I thank you. I would also like to thank the staff at the TTI facilities on Texas A&M University's Riverside Campus for allowing the use of their facilities to conduct the research.

Finally I would like to thank all my Professors, classmates, friends and family for their time and encouragement throughout my time as a college student. Without any of these people, I wouldn't be who I am today. Thank you.

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INTRODUCTION

The driving task is comprised of three broad tasks referred to as control, guidance, and navigation (*1*). The control task involves the drivers' interaction with the car itself. The guidance task involves maintaining a safe speed and proper path relative to the road and surrounding traffic. The navigation task involves pre-trip route planning and in-trip route following. Guidance information is gathered from the roadway, traffic, and the highway's information systems. Pavement markings are placed on the roadway to aid the driver in the vehicle guidance task.

At night, pavement markings illuminated by the vehicle headlights are typically the primary means of providing guidance information to the driver. Therefore, properly placed and properly maintained pavement markings are critical for safe driving (*1*, *2*). The Manual on Uniform Traffic Control Devices (MUTCD) requires pavement markings to be retroreflective if they are to be visible at night, unless sufficient ambient lighting is provided to make the markings visible. All markings on Interstate highways are required to be retroreflective (*3*).

As traffic control devices, pavement markings serve several purposes. To be effective and serve the intended purposes, the markings must be visible far enough in advance to provide adequate time for the driver to react to them and be visible in the periphery to aid in short range vehicle guidance (*1*, *4*). When properly implemented, these purposes can include the following (*3, 4, 5*):

This thesis follows the style of the *Transportation Research Record*.

- To regulate, guide, and warn traffic.
- To supplement other traffic control devices
- To provide proper positioning of vehicles.
- To separate opposing streams of traffic.
- To warn of restricted sight distances ahead.
- To improve traffic flow.

In wet-night conditions, many pavement markings retroreflectivity levels are lower than in dry conditions due to the accumulation of water on the marking surface. The accumulated water causes light from the headlight to be scattered before it reaches the retroreflective elements of the pavement marking, instead of being retroreflected back toward the driver. The reduced retroreflectivity of the markings in wet-night conditions results in shorter detection distance. The shorter detection distance that results creates a more demanding driving situation for the driver and potentially a less safe driving environment.

PROBLEM STATEMENT

The Texas Transportation Institute (TTI) conducted a study to evaluate the performance (as measured by detection distance) of pavement markings during wet-night conditions (*6*). The main objective of the study was to identify the relationship between detection distances and the retroreflectivity of the markings during the wet-night conditions. The detection distances were measured for individual subjects as they viewed the pavement markings in a simulated rain environment at night, under three rainfall intensities. The retroreflectivity data were measured using a handheld retroreflectometer.

The American Society for Testing and Materials (ASTM) has three standards for measuring retroreflectivity of pavement markings. ASTM E-1710 is for dry conditions, ASTM E-2177 is for recovery conditions, and ASTM E-2176 is for continuous wetting conditions (*7, 8, 9*). All three standards were used to measure the pavement markings' retroreflectivity, but ASTM E-2176 was explored in depth.

Currently ASTM E-2176 uses a wetting rate of approximately 9.3 inches per hour, which is much higher than any realistic expectation of rainfall on any highway. Since the test is intended to simulate the actual conditions that the pavement markings experience, this poses a concern and was investigated in this thesis. This thesis research explores the impacts of various wetting intensities (from less than 1 inch per hour to over 14 inches per hour) on retroreflectivity and compares the retroreflectivity at these wetting rates to the detection distances obtained from the TTI study (*6*). The researcher performed correlation analyses between the detection distance data and the varying sets of retroreflectivity data to determine the wetting intensity that provides the highest degree of correlation and thus the highest level of predictive performance.

OBJECTIVES

The researcher established three objectives for the thesis to evaluate the relationship between retroreflectivity and detection distance. The objectives of the thesis are:

- Evaluate the predictive performance of ASTM E-2176 by following the procedures outlined in the standard and correlating the measured retroreflectivity to the mean detection distance values for a range of pavement marking materials.
- Evaluate measured retroreflectivity as a function of different continuous wetting rates that are more consistent with typical rainfall intensities than those of ASTM E-2176. Find the rate that results in the retroreflectivity data that best correlate with the detection distances.
- If warranted, make recommendations for improvements to ASTM E-2176 to provide an accurate and simple testing procedure for measuring the retroreflectivity of pavement markings in rainy conditions.

SCOPE

This thesis was limited in several areas of data collection and analysis. There were 18 pavement marking samples studied, for retroreflectivity and detection distance. The retroreflectivity data were collected under 14 measurement conditions, including 12 different rates of continuous wetting. The detection distance data was gathered from 30 test subjects viewing the pavement markings while driving in a simulated rain environment. There were three levels of simulated rain in which the detection distance data were collected. Detection distance data was not collected for dry or recovery conditions.

The retroreflectivity data were collected with a single handheld retroreflectometer. The retroreflectometer used was an MX30, which was developed through a partnership between Potters Industries and Advanced Retro Technology. Other retroreflectometers that could have been used were the Delta LTL-X and the Mechatronic FRT01. These other instruments were not used due to the availability of the units.

An issue that was outside the scope of this thesis is the transmissivity of the atmosphere in conditions of continuous wetting. Transmissivity is the fraction of luminous flux which remains in a beam after traversing an optical path of a unit distance in the atmosphere. During normal dry conditions, transmissivity is close to 100%, but in rainy conditions transmissivity decreases. The light from headlights reaching a pavement marking is reduced due to the adverse atmospheric conditions. This would reduce the amount of illuminance reaching a pavement marking, and thus reduce the amount of luminance returned from the marking. Factors that can affect how much transmissivity is decreased are: rain droplet size, rain droplet distribution, rainfall intensity, and viewing distance.

No attempt was made to measure the atmospheric transmissivity during the detection distance data collection, or during the retroreflectivity data collection. The detection distance of the pavement markings is much greater than the distance at which retroreflectivity is measured and thus may factor into the appropriate continuous wetting rate. Transmissivity may be an issue that needs to be further explored, but there are also many other variables that affect the driver during rainy conditions, such as: rain on the windshield, windshield wiper activity, and glare on the roadway. Another issue that may need to be further explored is the difference in retroreflectivity measuring distance for the three retroreflectometers.

THESIS OVERVIEW

The following chapters in this thesis present the information used to achieve the stated objectives. The chapters are introduction, literature review, study design, results, and findings and recommendations. The literature review explores past studies related to pavement markings, with a focus on studies that looked at wet-night performance. The literature review also overviews pavement marking characteristics, how pavement markings are evaluated, and the visibility needs of drivers. The study design outlines the process by which data were collected, focusing on collection techniques and equipment used. The results of the data collection are summarized and analyzed. Analyses of the correlation between retroreflectivity and detection distance are found in the results chapter. The collected data and subsequent analyses led to recommendations based on the findings of the thesis.

LITERATURE REVIEW

Many studies have been conducted in regards to pavement markings, but few have focused on the wet-night visibility. Studies that have looked specifically at wet-night visibility are of utmost importance to this thesis. The researcher performed a review of the literature to determine the state-of-the-art in regards to pavement marking testing. This chapter addresses various aspects of pavement markings including 1) driver visibility needs, 2) pavement marking characteristics, 3) evaluating pavement markings, and 4) past pavement marking studies.

DRIVER VISIBILITY NEEDS

Many factors, such as driver age and visual acuity, affect the visual needs of a driver. As drivers age, visual capabilities decrease (i.e., decrease in visual acuity and contrast sensitivity), reducing their ability to detect and use pavement markings. It is not only vision that declines with age; motor skills also decline. Both vision impairment and the decrease in motor skills result in increased perception reaction time (PRT). Consequently, older drivers require greater detection distances than their younger counterparts. The older driver group is the critical population for pavement marking visual requirements (*2, 4, 5, 10, 11, 12*). It is important to improve pavement marking material visibility to provide the older drivers with the necessary roadway information with respect to roadway delineation. One manner of improving pavement marking visibility is by improving retroreflectivity.

Older drivers report an increasing inadequacy with respect to the nighttime visibility of pavement markings. In a statewide survey of 664 older drivers, Benekohal et al. found that as drivers age, the nighttime driving task becomes more difficult and worrisome (*13*). The activity of "following pavement markings" alone accounted for 17 percent of the concerns raised by the group. A comparison of the respondents ages 66 to 68 versus those 77 years and older indicated that the older group's level of difficulty in following pavement markings increased.

PAVEMENT MARKING CHARACTERISTICS

Pavement markings are typically made of materials such as thermoplastic, paint, epoxy, polyester, methyl methacrylate, polyurea, urethane (plural component), or tape (*14*). Glass beads are: mixed with the material, dropped on top when applying new material, or dropped on top when applying mixed material to help improve nighttime visibility (*4*). The glass beads should be imbedded enough so that they adhere to the material, but not over imbedded so they can provide additional retroreflectivity to the marking. Light enters the glass sphere and reflects off of the back of the sphere. The amount of light that is retroreflected depends on the following: 1) index of refraction of the glass bead, 2) shape of the bead, 3) size of the bead, 4) surface characteristics of the bead, 5) quantity of beads, 6) embedment depth of the beads, 7) the quality and quantity of pigment in the binder, 8) the quality of the binder, and 9) the weather conditions. Figure 1 shows a glass bead imbedded in a pavement marking retroreflecting light.

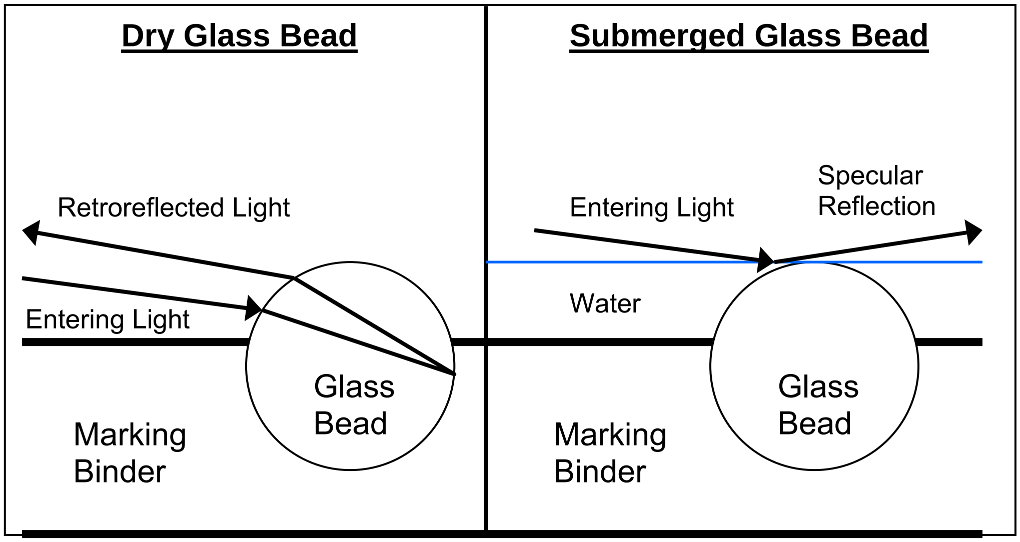

FIGURE 1 Glass Bead Retroreflection.

Over time, the markings' retroreflective ability decreases. Traffic and weather cause the levels of retroreflectivity to decrease by dislodging beads from the marking, and the buildup of non-retroreflective materials on the marking also keeps light from being retroreflected. Water on the marking also reduces retroreflectivity due to the increase in refraction and reflection of the incoming light to the glass beads embedded in the pavement markings.

There are a number of available technologies that may be used to improve the wet-night visibility of pavement markings. Some of these technologies are:

- Larger or high refractive index glass beads – large beads increase the height of the bead to keep it from being submerged under the water and beads with a refractive index greater than 1.89 can reduce the effects of refraction of light as it passes between the water and the bead.

- Structured pavement marking tapes – tape products with raised sections to keep portions of the retroreflective surface above the water.
- Enclosed lens tape – tape products which utilize a retroreflective surface that has the same refractive index of water to reduce the effects of the refraction of the light.
- Ceramic elements in polyurea – clusters of binder and beads dropped on top of the binder surface to raise the retroreflective beads above the water surface.
- Profiled thermoplastic, Dripline of cold spray plastic – markings have a profile and pattern to channel water away from the retroreflective beads and to keep portions of the retroreflective surface above the water.
- Rumble stripes – pavement marking is applied over a rumble strip providing a surface that does not get submerged in water.
- Rainline, Gulfline, Vibraline – patterned markings combining the effects of profile markings and rumble stripes.
- Retroreflective raised pavement markers (RRPMs) – a raised marker with a retroreflective face, used to supplement traditional pavement markings.

EVALUATING PAVEMENT MARKINGS

The two most important criteria for evaluating a pavement marking are nighttime visibility and proportion of missing or non-functional surface area (*5*). Wet-night conditions are affected by both of these criteria, with the non-functional area equating to the amount of pavement marking that does not properly retroreflect light to drivers due to the presence of water on the pavement marking.

The two forms of evaluating markings are subjective and objective (*2, 5*). Subjective analysis grades the marking on a scale based on the perceived adequacy of the marking. Objective analysis of the marking uses instruments to quantitatively measure characteristics of the pavement marking (i.e., retroreflectivity or luminance values).

It is important to note that the retroreflectivity of a marking changes during the first month, and thus a retroreflectivity value measured during the first month may not be a good representation of the long-term retroreflectivity levels of a marking (*2*). Recommendations indicate to measure the retroreflectivity of new pavement markings one month after striping.

Standard Geometry

Retroreflectivity is measured with either a handheld or mobile retroreflectometer. These units measure the retroreflectivity at a 30-meter viewing geometry. A 30-meter viewing geometry simulates the effectiveness of a marking that is located 30 meters in front of a vehicle. The entrance and observation angles that represent the 30-meter geometry are the standard values used by the American Society of Testing and Materials (ASTM) and the European Committee on Standardization (CEN). Figure 2 shows how the 30-meter geometry is represented (*15*).

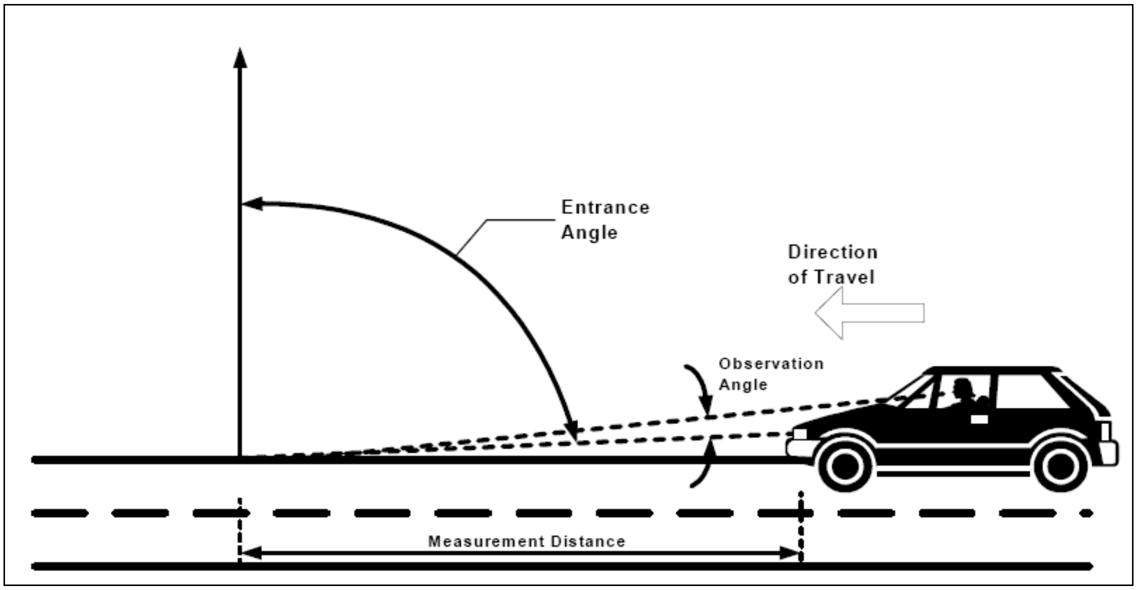

FIGURE 2 30-Meter Geometry (*15*).

A picture of one of the handheld units available for collecting retroreflectivity data at a 30-meter geometry is provided in Figure 3. This particular device is able to accurately measure retroreflectivity from 20 to 1200 mcd/m^2/lx, and it can measure accurately over a wide range of ambient conditions (*16, 17*). The open-ended design where the retroreflectivity is measured allows for continuous wetting measurements, as well as dry and wet measurements. Figure 3 is a depiction of how the device would be placed on a pavement marking while measuring the retroreflectivity (*18*).

FIGURE 3 Handheld Retroreflectometer (*18*).

Retroreflectivity

Retroreflectivity, measured in units of millicandelas per meter squared per lux (mcd/m^2/lx), is the measurement most often used to represent the nighttime visibility of a marking. Retroreflectivity of a pavement marking is the amount of light from the pavement marking that is reflected back toward the driver and is available for him to see. Retroreflectivity is the markings' ability to return the incoming light (illuminance) from the vehicles' headlights back to the driver. This retroreflected light is what makes the marking visible and seem bright. Luminance is measured in units of candelas per meter squared (cd/m^2) and measures the light intensity per unit area coming from the pavement marking. Luminance is the amount of light available for the driver to see.

Retroreflectivity is associated with visibility; the higher the retroreflective value then generally the more visible the marking is (*2, 4*). The more visible a marking is the further the detection distance will be and thus the driver will have a longer preview time. Earlier studies (*19, 20, 21*) clearly show a positive correlation between detection distance and level of retroreflectance.

In an unpublished report, the FHWA recommended dry retroreflectivity levels for high-speed roadways without RRPMs or continuous roadway lighting at 150 $mcd/m^2/lx$ for white and 100 $mcd/m^2/lx$ for yellow markings (*22, 23*). The summary of the unpublished FHWA recommended values for both white and yellow markings are provided in Table 1, which is separated by speed and roadway type (*23*). These values are based on the standard 30-meter geometry with a preview time of 3.65 seconds. Europe uses similar recommendations for in-service retroreflectivity requirements; their recommended value is 100 $mcd/m^2/lx$ for white pavement markings (*24*).

The ASTM has three standards for measuring retroreflectivity of pavement markings (*7, 8, 9*). The three standards cover the typical conditions that pavement markings typically face; dry, wet, and rainy. These procedures are designed for use with hand-held retroreflectometers:

- ASTM E-1710 for dry pavement markings,
- ASTM E-2177 for wet recovery pavement markings (see page 42), and
- ASTM E-2176 for continuously wetted pavement markings (see page 43).

TABLE 1 Unpublished FHWA Recommended Minimum Retroreflectivity Levels for Pavement Markings.

Material		Roadway Type / Speed Classification		
	Option 1	Non-freeway ≤ 40 mph	Non-freeway ≥ 45 mph	Freeway ≥ 45 mph
	Option 2	≤ 40 mph	≥ 45 mph	≥ 60 mph > 10,000 ADT
	Option 3	≤ 40 mph	45 - 55 mph	≥ 60 mph
White		85	100	150
White with RRPMs or Lighting		30	35	70
Yellow		55	65	100
Yellow with RRPMs or Lighting		30	35	70
Note: All values are based on the 30-meter ASTM geometry and are in units of mcd/m^2/lux, these values are based on a 3.65 second preview time.				

Durability

The durability of a marking is typically measured by the amount of material remaining on the roadway or the material's bond strength with the roadway (*4*). Durability can vary greatly depending on roadway characteristics. Traffic volume and surface type play a major role in the durability of a pavement marking. The environment also plays a role in the durability. Thermoplastic pavement markings can be expected to last two years on freeways and three years on non-freeways when the FHWA recommended threshold retroreflectivity levels were determined (*25*). The maximum service life for thermoplastic was found to be approximately four years (*25*).

PAST PAVEMENT MARKING STUDIES

Schnell and Zwahlen used the CARVE (Computer-Aided Road-Marking Visibility Estimator) computer model to determine minimum retroreflective requirements for pavement markings (*12*). This model uses geometric and photometric relationships to determine minimum retroreflectivity levels to provide the predetermined preview time. A preview time of 3.65 seconds was incorporated into the computer model for this study, which is considered to be a conservative value. The study also used a 62-year-old driver as the driver type.

The results of this study were based on various speeds with and without RRPMs: therefore, a range of retroreflectivity level is given based on the speed at which the vehicle is traveling. The results of this study showed that a minimum retroreflectivity level for pavement markings that are not aided by RRPMs ranged from 30 to 620 $mcd/m^2/lx$ at a 30-meter geometry for speeds ranging from 0 to 75 mph (0 to 120 kph). When RRPMs were used the minimum retroreflectivity levels were much lower and ranged from 30 to 70 $mcd/m^2/lx$ for the same speeds (*12*). The resulting values are provided in Table 2.

A major drawback of this computer method is that no field testing was done to compare with the results of the computer model. Other problems were that wet conditions were not studied, and the retroreflectivity of the RRPMs were not given. The authors recommended further study into the durability and photometric performance of the RRPMs.

TABLE 2 Zwahlen and Schnell's Minimum Retroreflectivity Requirements for White Markings for Fully Marked Roads.

Vehicle Speed (mph)	Vehicle Speed (kph)	Without RRPMs	With RRPMs
		Preview Time = 3.65s	Preview Time = 2.0s
0-25	0-40	30	30
26-35	41-56	50	30
36-45	57-72	85	30
46-55	73-88	170	35
56-65	89-104	340	50
66-75	105-120	620	70
Note: Minimum values for yellow dashed centerline are 76 percent of the values provided here. All values are measured in mcd/m^2/lux at the 30 m ASTM geometry.			

As part of a study conducted by Gates et al. bead size was evaluated as to its impact on dry retroreflectivity (*2*). Larger beads, referred to as TxDOT Type III beads were compared to smaller beads, referred to as TxDOT Type II beads. It was found that the Type III beads provided higher levels of retroreflectivity as compared to Type II beads. The average white edge line was found to be 20 mcd/m^2/lx higher with Type III beads than with Type II beads. The average yellow centerline was found to be 55 mcd/m^2/lx higher with Type III beads than with Type II beads. Retroreflectivity differences were found to be only statistically significant for yellow markings.

In a study conducted by Kalchbrenner, the effect of using larger glass beads versus standard glass beads in dry and wet-night conditions was determined to provide beneficial results in terms of retroreflectivity (*26*). The study was conducted in part at the Potters' "rain tunnel" facility and in part at field test sites across the country.

The study at the rain tunnel was to provide retroreflective values during controlled rain situations. Rainfall rates of 0.5 in/hr and 0.25 in/hr and a recovery period were studied.

The results of this controlled wet-night study clearly showed that larger beads provided beneficial increases to retroreflectivity over standard beads. The results are provided in Figure 4 and Figure 5 for epoxy and thermoplastic applications. The larger beads provided much higher levels of retroreflectivity for both rainfall rates and recovered much quicker than did the standard beads.

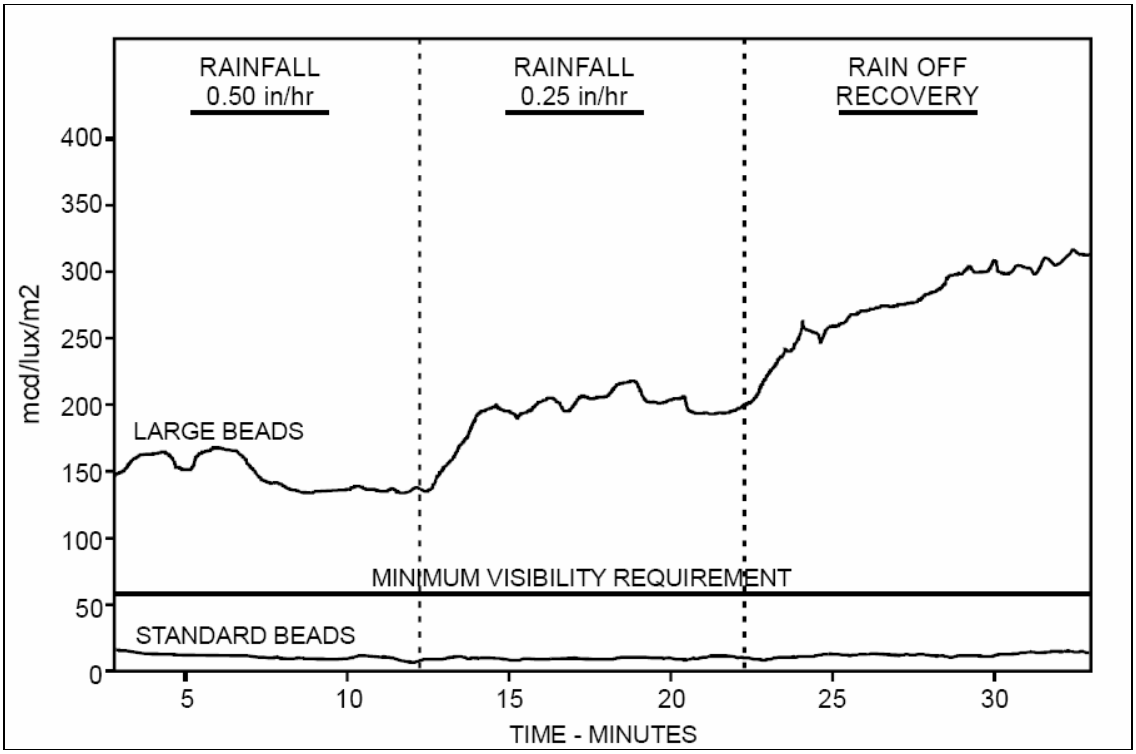

FIGURE 4 Large Beads Versus Standard Beads in Epoxy (*26*).

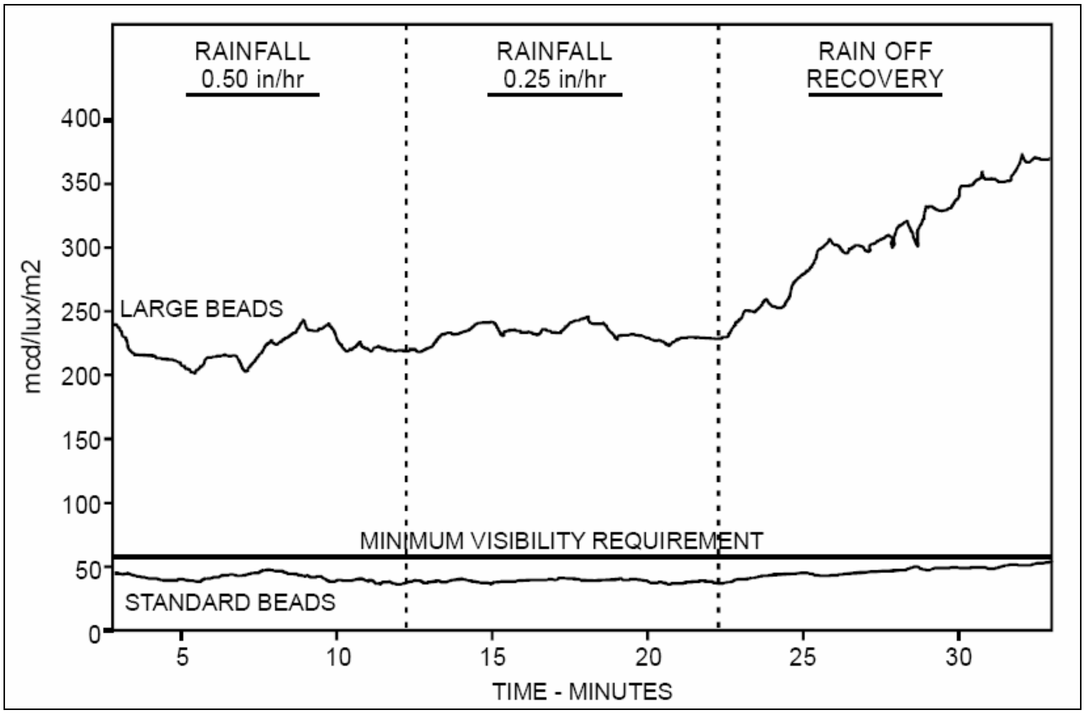

FIGURE 5 Large Beads Versus Standard Beads in Thermoplastic (*26*).

The field data for the study were collected at 32 sites around the country for several marking materials with large and standard glass beads imbedded in them. These sites were used to study the retroreflectivity of the markings over time in dry conditions. Not only is wet-night retroreflectivity important, but dry-night retroreflectivity over the life time of the line is important as well. The results of the study are provided in Figure 6, Figure 7, and Figure 8 (*26*). Again, the large glass beads provide higher levels of retroreflectivity than the standard glass beads.

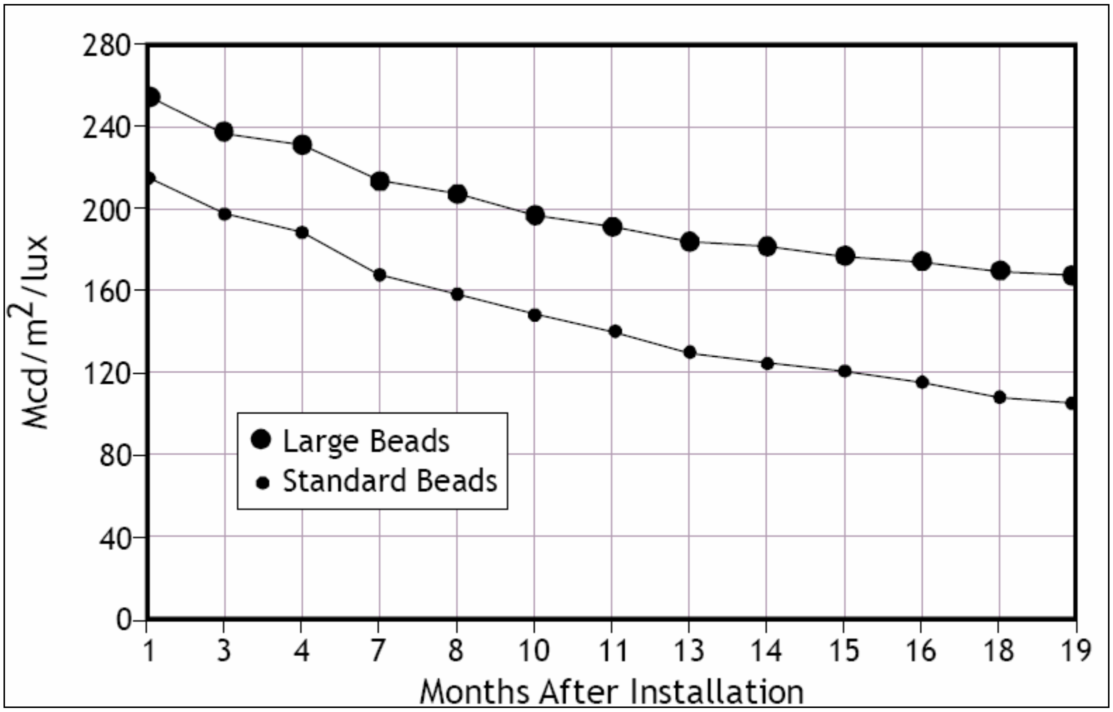

FIGURE 6 Retroreflectivity: Large Beads Versus Standard Beads in Epoxy (*26*).

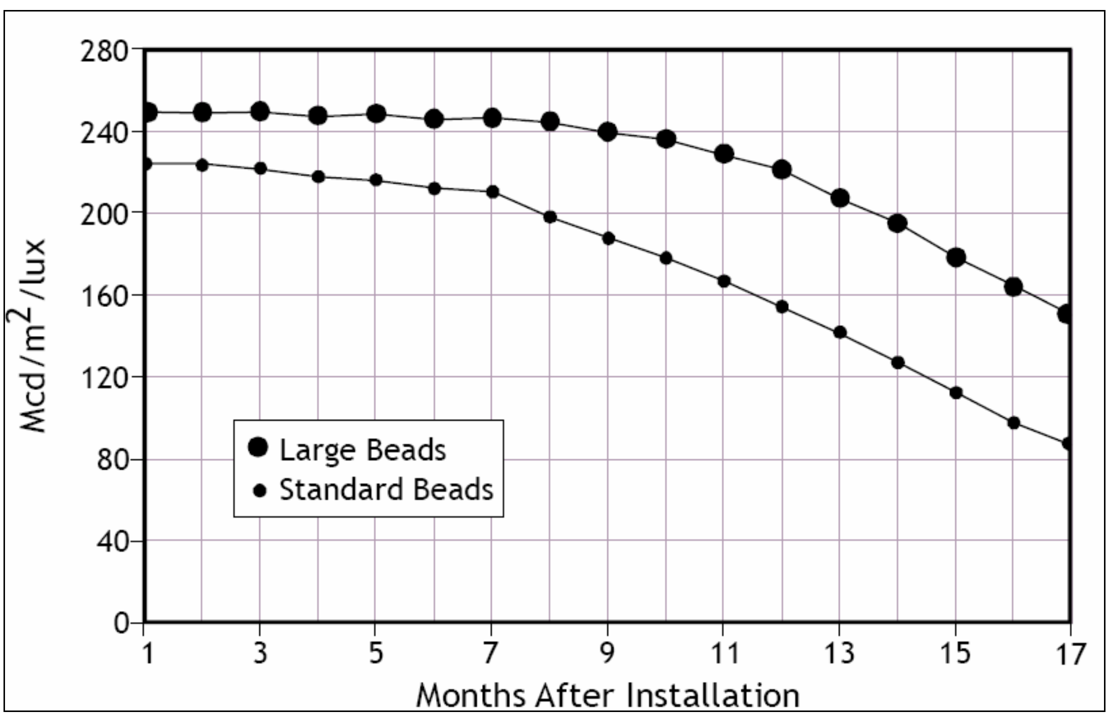

FIGURE 7 Retroreflectivity: Large Beads Versus Standard Beads in Thermo (*26*).

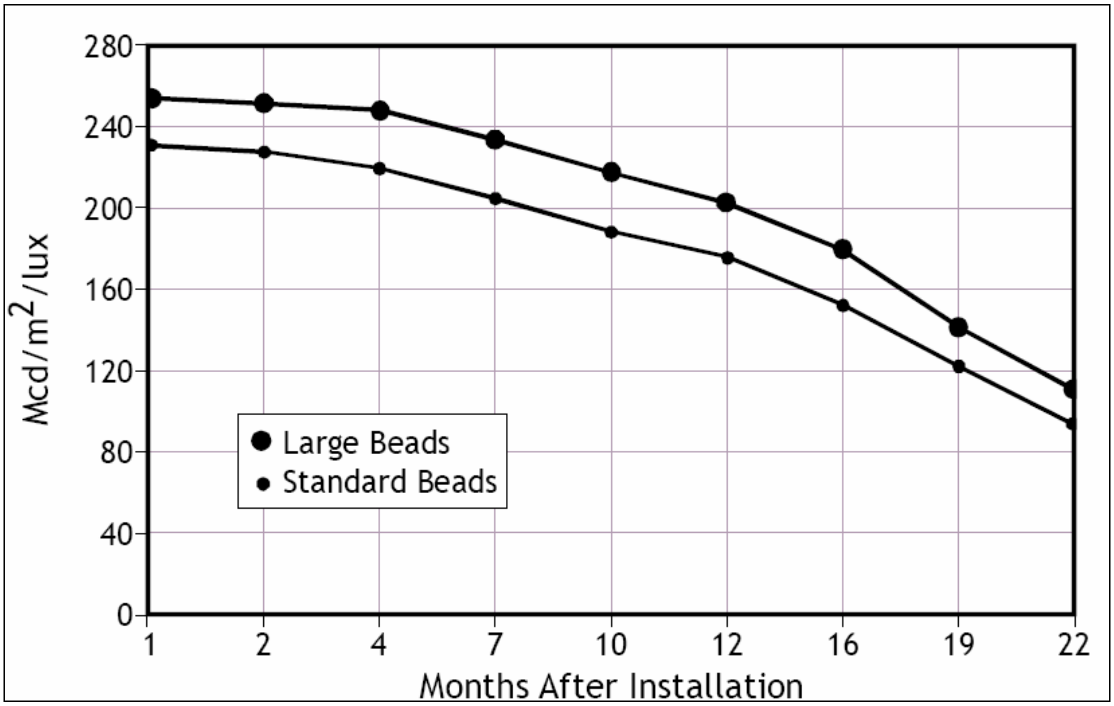

FIGURE 8 Retroreflectivity: Large Beads Versus Standard Beads in Polyester (*26*).

Many factors affect the performance of the beads placed on the marking. As evident in Kalchbrenners' study, bead size plays a major role in retroreflectivity levels, in wet conditions and over the life of the marking. Another major factor that applies to both the durability of the marking and the retroreflectivity levels was studied by O'Brien (*27*).

In O'Brien's study he looked mainly at embedment depth, but also looked at bead sizing and shape. He found that the optimal embedment depth in thermoplastic markings was 60 percent. This depth was achieved by using moisture proofed glass spheres, applied at a rate of 10lb/100ft^2. The findings included that the retroreflectivity of the standard gradation of glass spheres may be enhanced by increasing the percentage of spheres retained on U.S. sieves 30, 40, 50, and by increasing the roundness of the spheres from 70 to 80 percent (*27*). O'Brien also stated that controlled wear of the marking surface is important to maintain retroreflectivity levels. This can be achieved by using an intermix of glass spheres that are exposed as the marking wears; therefore maintaining retroreflectivity and nighttime visibility.

A European study was performed by Lundkvist and Astrom for the Swedish National Road Administration (*28*). This study sought to measure the performance of road markings in wet-night conditions. Minimum retroreflectivity requirements were found based on a set of predetermined preview distances. These distances were found by using a set preview time that was established in another European project COST 331 (*24*). In COST 331 the shortest possible preview time was found to be 1.8 seconds. For comfortable driving it was found that 2.2 seconds is too short of a preview time. Lundkvist used a value of 2 seconds to determine the required visibility distances. Table 3 shows the COST 331 model results for speeds with a 2-second preview time.

TABLE 3 Minimum Retroreflectivity Requirements for Wet Pavement Markings.

Type of Marking	Speed Limit	Visibility	Retroreflection (mcd/m^2/lux)
intermittent marking (1+2), 10 cm wide	70 km/h (44 mph)	39 m, 128 ft	40
	90 km/h (56 mph)	50 m, 164 ft	80
	110 km/h (68mph)	61 m, 200 ft	160
continuous edge marking, 10 cm wide	70 km/h (44 mph)	39 m, 128 ft	25
	90 km/h (56 mph)	50 m, 164 ft	45
	110 km/h (68mph)	61 m, 200 ft	80
continuous edge marking, 20 cm wide	70 km/h (44 mph)	39 m, 128 ft	20
	90 km/h (56 mph)	50 m, 164 ft	35
	110 km/h (68mph)	61 m, 200 ft	57
continuous edge marking, 30 cm wide	70 km/h (44 mph)	39 m, 128 ft	18
	90 km/h (56 mph)	50 m, 164 ft	30
	110 km/h (68mph)	61 m, 200 ft	50

Lundkvist's study was performed over a two-year period on two actual road sections that both had an annual average daily traffic (AADT) of approximately 2000. Ten companies applied pavement markings down on the test sections, totaling 39 different markings. These markings were extruded thermoplastic, spray on extruded thermoplastic, cold plastic, and waterborne paints. When tested, the markings were wetted by pouring a large amount of water over the marking and after a minute the retroreflectivity was measured. Retroreflectivity was measured with an LTL-2000 handheld retroreflectometer and the luminance coefficient was measured with the Qd30. The procedure for wet measurement is in accordance with the EN method and the dry procedure in accordance with SSEN 1436.

The study found that the typical Swedish intermittent edge line marking does not meet the wet retroreflection values found in Table 3 after two years of service. They also found that if the markings were continuous and 20 cm in width that all markings would meet the required value in the wet when new, and that many would also meet the value after two years of service. It was determined that it is possible to produce a road marking that provides 2 seconds of preview time over a two-year period, when applied as a 20 cm continuous edgeline (*28*).

In order to achieve a preview time of 2 seconds it was found that the lines need to have an increased surface area by making the lines continuous or wider. The wider lines are able to produce the same visibility with lower retroreflectivity as seen in Table 3**.** The problem is that most edge lines in the United States are not 20 cm (~8 inches) in width, which was stated as a good width for Swedish edgelines.

Jacobs et al. performed two separate tests to improve the understanding of the effects of pavement marking retroreflectivity on detection distance (*29*). These tests were a stationary test and a dynamic test. Figure 9 and Figure 10, give the results of these two tests. The dynamic test was conducted at a speed of 24 kph (15 mph). Even this low speed produced a significant reduction in visibility distances between the two tests for markings with the same retroreflectivity levels. This difference shows the need of a dynamic testing scheme to properly determine retroreflectivity standards for pavement markings.

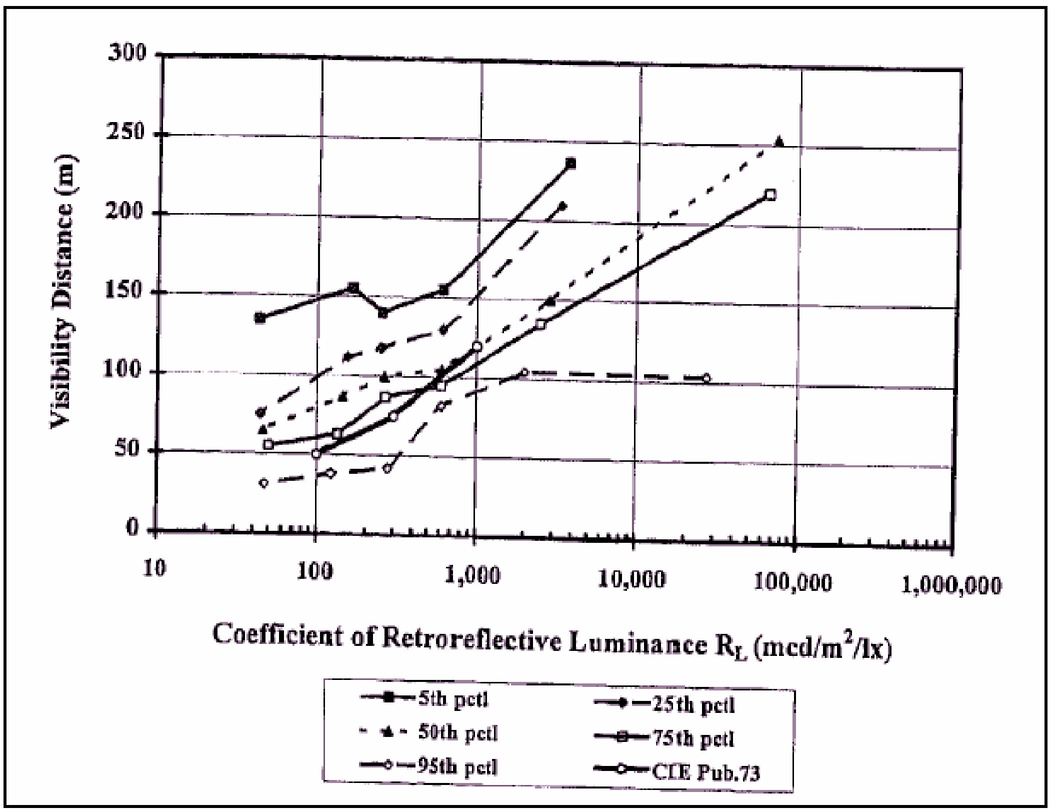

FIGURE 9 Static: Percentiles of Marking Visibility Distance Based on R_L (*29*).

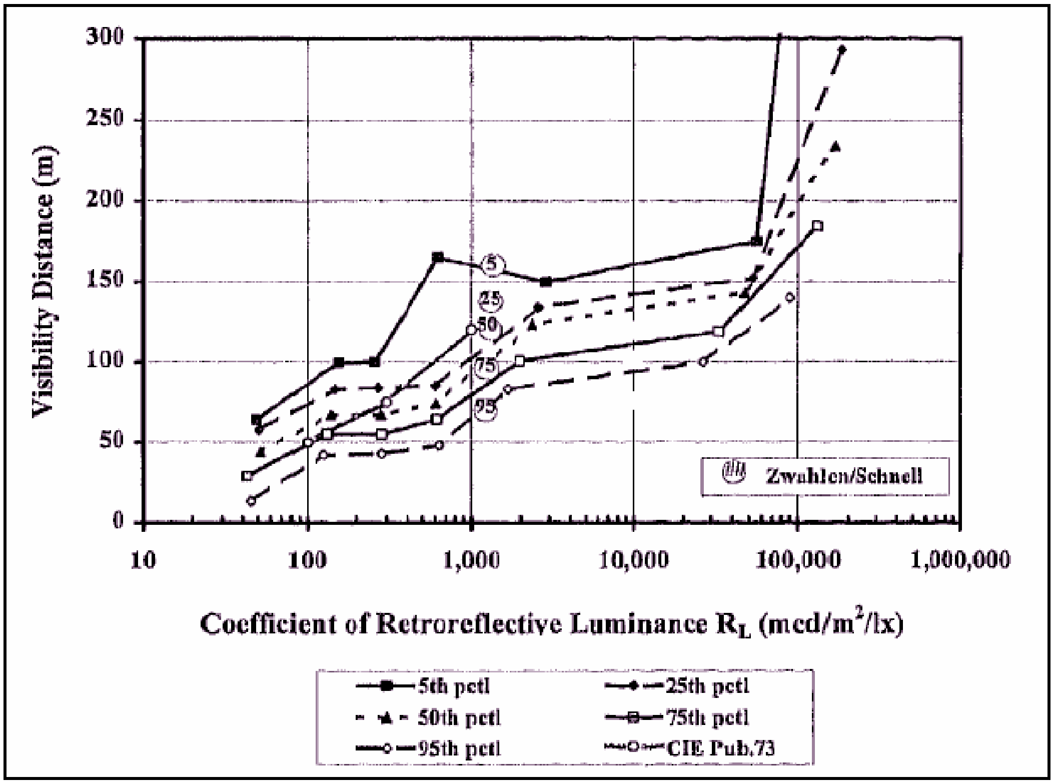

FIGURE 10 Dynamic: Percentiles of Marking Visibility Distance Based on R_L (*29*).

In a study conducted for the North Carolina Department of Transportation, King and Graham evaluated pavement marking materials for wet-night conditions (*5*). The study lasted 18 months and investigated the retroreflectivity and durability of eight pavement markings. Quantitative values of retroreflectivity (mcd/m^2/lx) and luminance (cd/m^2) were found, as were qualitative evaluations of the markings' adequacy. The study took place on actual roadways, in natural conditions.

The study found that there is a strong linear relationship between retroreflectivity and luminance. Figure 11 shows this relationship between luminance and retroreflectivity. Retroreflectivity levels were found during dry conditions only. Subjects viewed the pavement markings during dry day (daytime in a dry condition), dry night (nighttime in a dry condition), and wet-night (nighttime in a natural rain). Subjects were asked to rate the markings as less than adequate, adequate, or more than adequate. The retroreflectivity levels at which 100 percent of the participants found the marking to be adequate or more than adequate were 70 mcd/m^2/lx for dry day, 93 mcd/m^2/lx for dry night, and 180 mcd/m^2/lx for wet-night conditions (*5*). Figure 12 shows the regression analysis plots of subjective rating versus retroreflectivity levels. The dry conditions provide much better visual adequacy than the wet-nighttime condition. It was also found in the study that retroreflectivity levels for all markings decreased over time, with the largest decreases during the first six months.

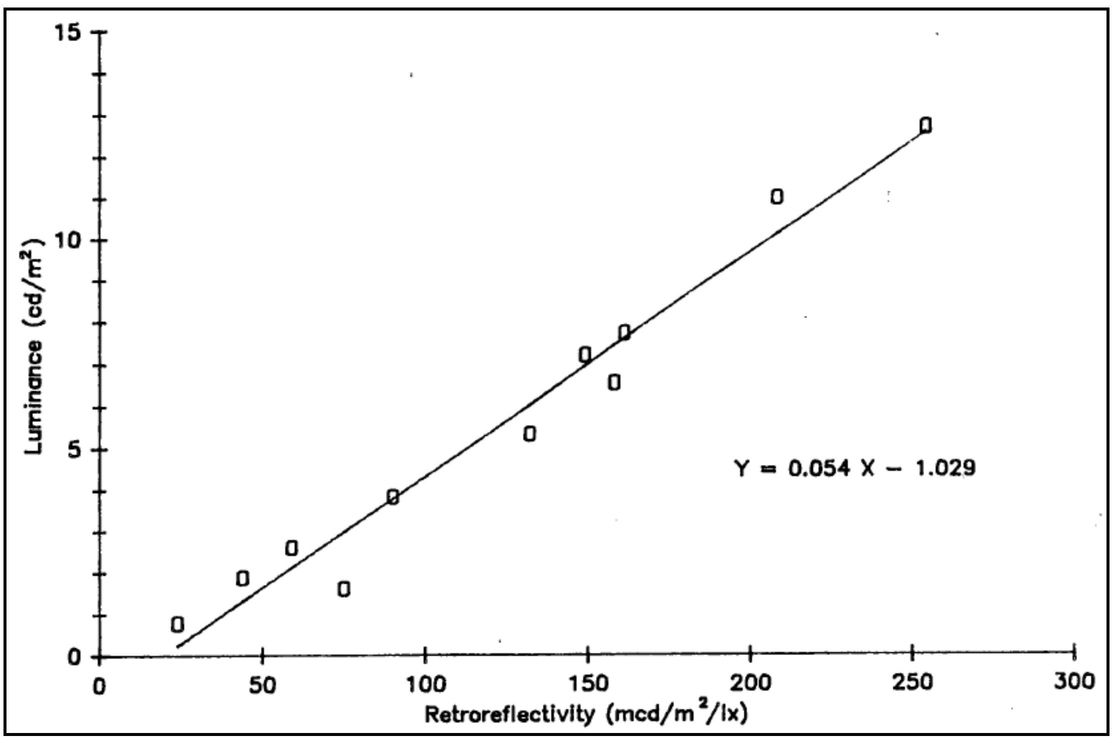

FIGURE 11 Luminance and Retroreflectivity Relationship (*5*).

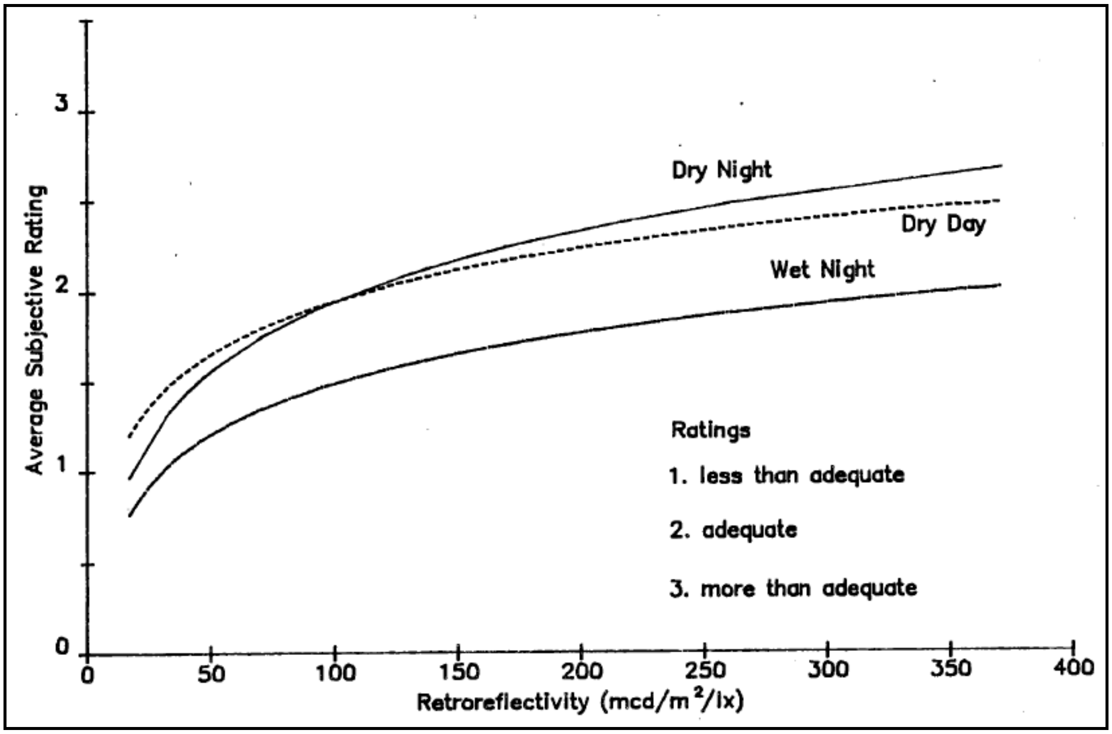

FIGURE 12 Subjective Rating and Retroreflective Values (*5*).

This study used test subjects that do not correlate well with actual driver age distribution. The age range was 19 to 47 with an average age of 24.5 years. Males also outnumbered the females in the test, 43 males to 16 females. If these two factors more accurately represented the typical driving population, the results of the study may have been different. It is likely that the retroreflective levels would need to be higher if an older population was used. Also the use of a qualitative adequacy evaluation, instead of quantitative detection distance evaluation, increases human errors and personal judgment on the test.

As previously mentioned pavement markings exhibit a positive correlation between detection distance and level of retroreflectivity. Studies conducted by Schnell et al. clearly show this positive correlation (*19, 20, 21*). Figure 13 shows the results of the studies conducted by Schnell et al.

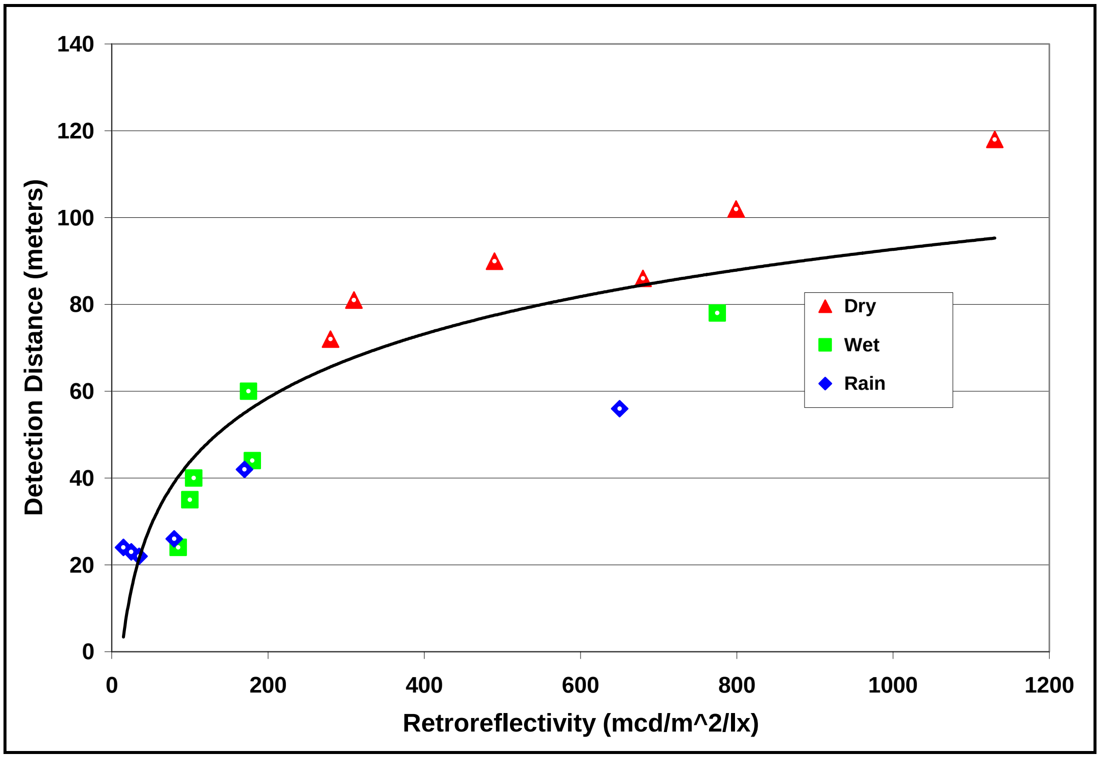

FIGURE 13 Relationship Between Retroreflectivity and Detection Distance.

Schnell et al. also conducted a study to quantify the performance of different types of pavement markings under dry, wet, and simulated rain conditions (*30*). The safety of the older driver population was of particular interest. An example of the detection distance results for the three marking types are provided in Figure 14. These findings show that the wet weather tape performed much better than flat or patterned tapes. The results of this study showed that the flat and patterned tapes would not provide an adequate preview time, even if 3.65 seconds was used as the required time. Even the wet weather tape only provides that amount of preview time up to 25 mph under rainy conditions. Due to the short detection distances drivers most likely overdrive their headlamps under rainy conditions. It should be noted that the rainfall rate used for this study was 1 inch per hour. This rainfall rate represents a worst case nighttime driving situation.

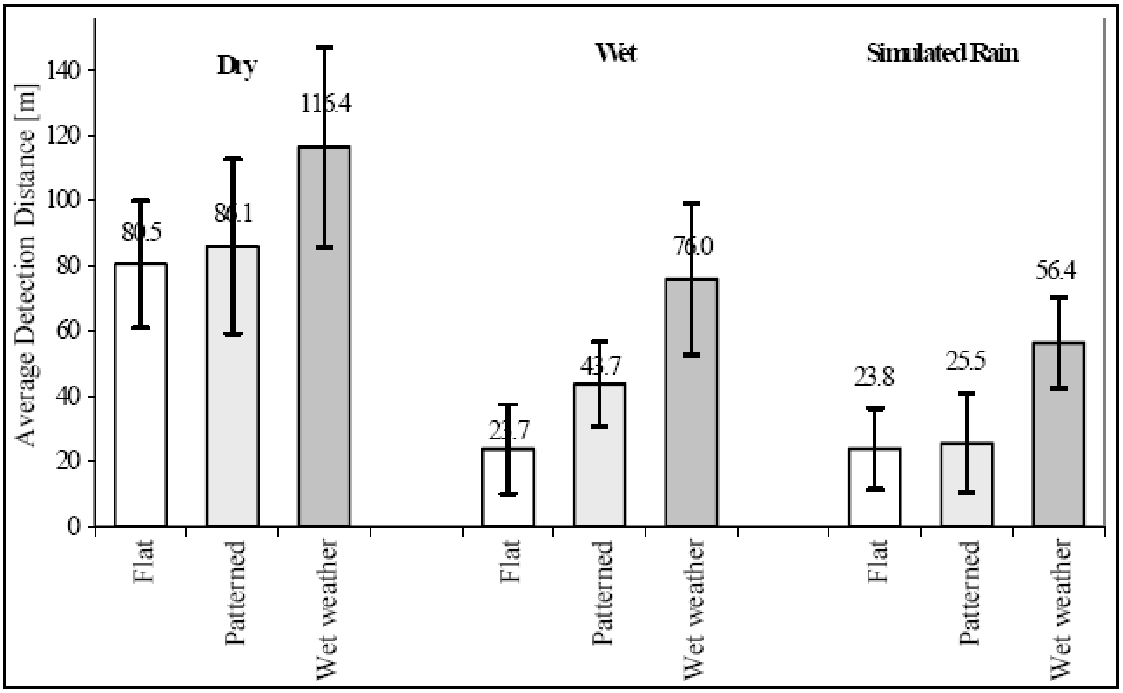

FIGURE 14 Example of Marking Detection Distances (*30*).

Aktan and Schnell conducted a second study to quantify the performance of different types of pavement markings under dry, wet, and simulated rain conditions (*31*). Under dry conditions all materials provided adequate detection distances. Under the wet conditions the patterned tape with mixed high index beads performed much better than the other marking materials. The situation was the same for the continuous wetting condition, where the patterned tape with mixed high index beads performed much better than the other marking materials. The results of the studies are provided in Figure 15.

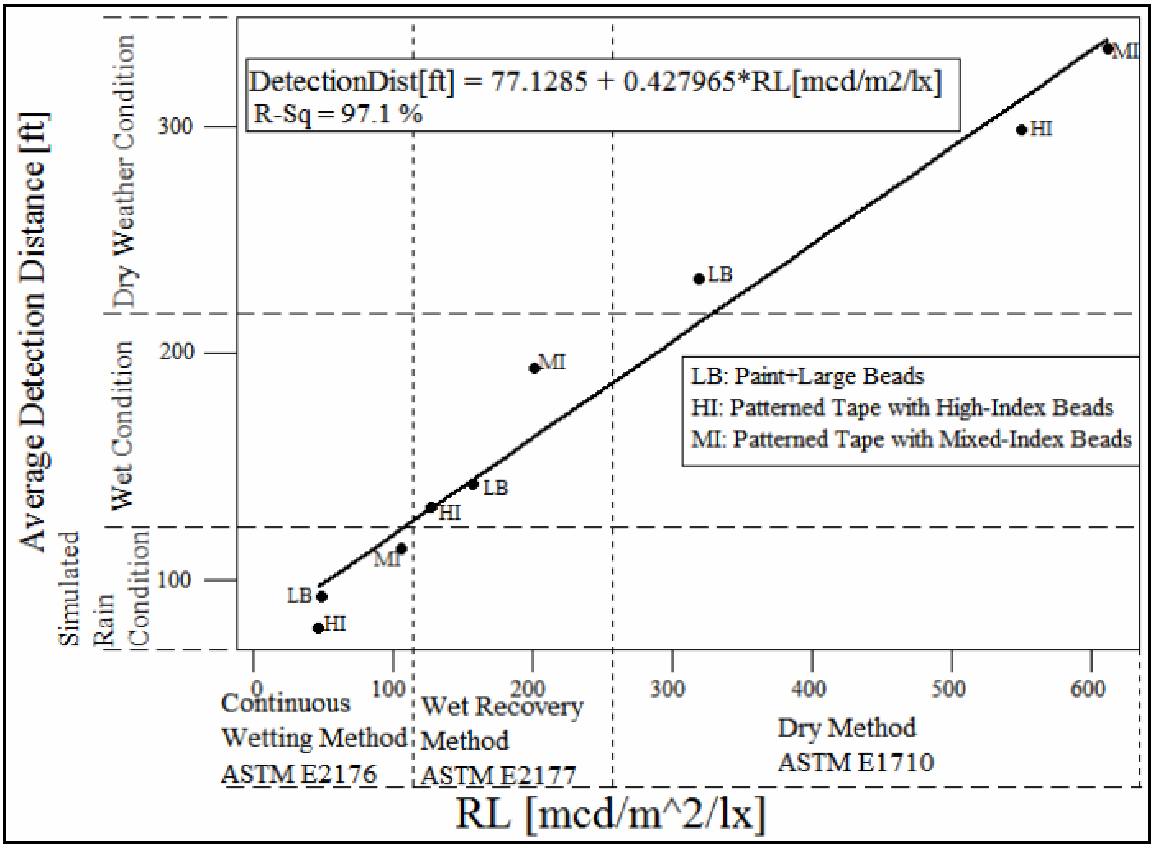

FIGURE 15 Examples of Pavement Marking Performance Under Different Conditions (*31*).

The Virginia Tech Transportation Institute (VTTI) conducted a static wet-night study to evaluate the visibility of six pavement marking types (*32*). The markings were viewed by subjects over 60 years of age, under a simulated rainfall of 0.8 in/hr at night. Both a sedan and a truck tractor were used as the viewing vehicle in which the subjects sat while viewing the markings.

The results of the visibility study for the sedan under the continuous rain and dry conditions are provided in Figure 16 (*32*). The figure shows a large decrease in visibility distance during the rainy condition versus the dry condition. The RRPM and the wet tape showed the least drop in visibility distance.

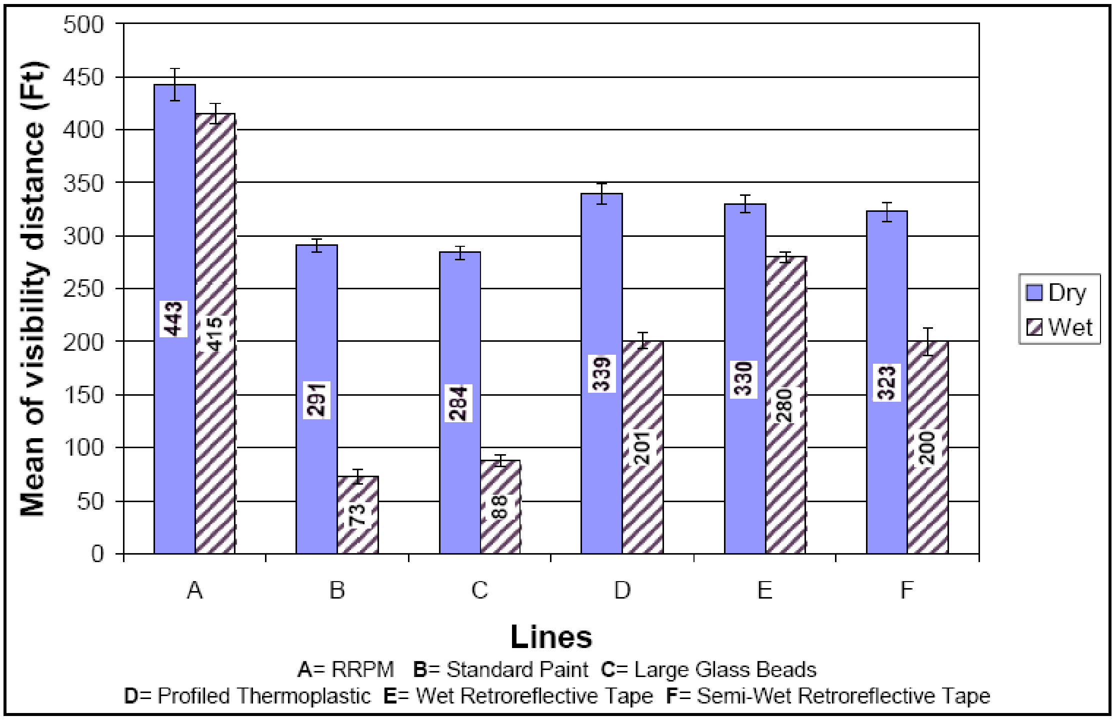

FIGURE 16 Sedan: Saturated Evaluation - Results of the Visibility Distance for the Condition X Line Interaction (*32*).

The results of the VTTI retroreflectivity tests are provided in Figure 17, with the line representing the number of visible skip lines and the columns representing the retroreflectivity (*32*). The results of the ASTM tests and the human responses to the markings were correlated using a Pearson *r* correlation for various conditions. Correlating measured retroreflectivity with visibility distance, for all conditions and vehicles yielded a Pearson *r* value of 0.796. When comparing measured retroreflectivity with visibility distance for the wet and dry sedan values the correlation value was 0.782. A correlation value of 0.752 resulted from correlating the measured retroreflectivity and visibility distance for the saturated sedan and truck conditions. These correlation values indicate a moderate correlation between the ASTM standards and the performance of the pavement markings.

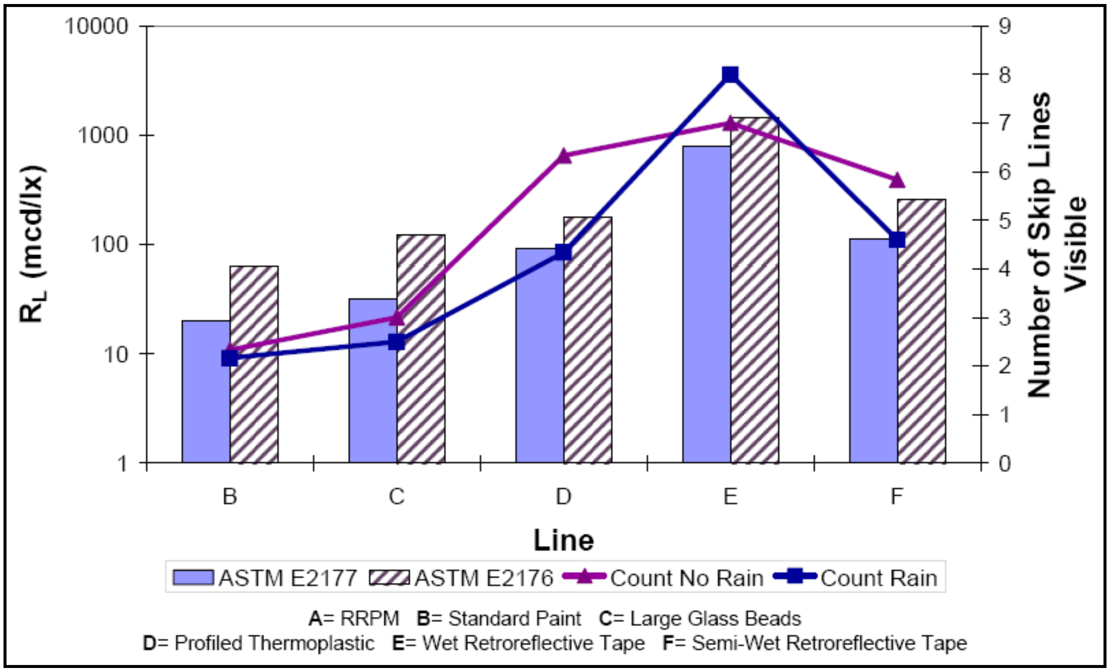

FIGURE 17 Relationship of Human Response to the ASTM Test Method Results (*32*).

The VTTI study then goes on to compare ASTM E 2176-01 directly to the skip line count, used in determining the visibility distance of the pavement markings. The Pearson *r* correlation value was 0.932 when comparing the ASTM continuous wetting standard and the skip line count under simulated rainy conditions. This high correlation value would indicate a strong correlation between the ASTM test and the pavement marking performance. The problem with this high correlation value is that after removing the high performing materials, the correlation value is not as good. A conclusion from the report states, "The ASTM methods seem to be highly correlated to the performance of the participants and to the calculated retroreflectivity from the pavement marking luminance. The results from the measurements have a wide range, and after removal of the high performing materials, the correlation is not as high." No new correlation value was given after the high performing pavement marking materials were removed. With a conclusion such as this, the predictive performance of the ASTM standards may not be as highly correlated as they may initially seem.

SUMMARY

During wet-night conditions, many pavement markings retroreflectivity levels are lower than in dry conditions due to the accumulation of water on the marking surface. The decrease in the retroreflectivity level due to the water accumulation on the markings results in shorter detection distances than for a dry marking. Several pavement marking technologies, including larger glass beads and higher refractive index beads, were studied and found to increase performance during rainy conditions. Several dry condition studies have resulted in a range of recommended retroreflectivity levels determined to provide adequate preview time to drivers. Recovery and continuous wetting studies should also be performed so that a range of retroreflectivity levels can also be determined for wet conditions as well as dry.

The process of measuring a pavement markings' retroreflectivity under a continuous wetting condition was used in only a few studies. In most of these studies, the ASTM standard to measure the continuous wetting retroreflectivity of a pavement marking was not correlated to the detection distance associated with the pavement markings. The VTTI study compared the ASTM continuous wetting retroreflectivity measurements to the detection distance data. The VTTI study found varying results when correlating the ASTM retroreflectivity to the detection distance data, depending on the selection of pavement markings. These varying results may indicate that the ASTM continuous wetting standard may not provide an adequate predictive performance for a range of pavement markings.

STUDY DESIGN

To achieve the objectives of this thesis research (evaluate the predictive performance of ASTM E-2176, and evaluate other rainfall rates correlation between retroreflectivity and detection distance), the researcher established a study design that addresses: 1) research variables, 2) equipment used during testing, 3) pavement marking materials studied, 4) study procedure, 5) data collection, and 6) data analysis techniques. The collection of the dependent variables of pavement marking retroreflectivity and detection distance of the pavement markings are each described separately in the study design.

The process of data collection and analysis is explained in this chapter to show how the study's results were developed. The researcher measured retroreflectivity of the pavement markings at various continuous wetting rainfall rates. The Texas Transportation Institute used the same pavement marking samples to collect and analyze all detection distance values in an effort that was separate from the thesis research (*6*). The detection distance values are imported into this research for correlation analyses purposes. The correlation of the retroreflectivity data and detection distance data were tested to determine the relationship between the two dependent variables.

RETROREFLECTIVITY MEASUREMENT

The retroreflectivity data is one half of the information needed to achieve the objectives of this thesis. The following sections describe the equipment used in collecting the retroreflectivity data and the process of collecting the retroreflectivity data. The pavement marking samples are also described.

Variables

The dependent variable for this section of the research is the pavement markings' retroreflectivity. Retroreflectivity is based on measurements taken with a handheld retroreflectometer.

The researcher determined the following independent variables for the retroreflectivity data, to achieve the objectives of the research.

- Pavement Marking Type: The researcher used the same samples in the retroreflectivity study as TTI used in their detection distance study. Descriptions of the pavement markings are provided in the pavement marking section on page 40.
- Continuous Wetting Rainfall Intensity: The researcher varied the intensity of the water falling on the pavement marking samples. The researcher measured the retroreflectivity of each sample under the different continuous wetting intensities.

Equipment

The researcher used two main pieces of equipment during the retroreflectivity data collection. These pieces of equipment are a handheld retroreflectometer used to measure the retroreflectivity and a specially designed continuous wetting spray unit used to produce a condition of continuous wetting.

Handheld Retroreflectometer

The researcher used an MX30 handheld retroreflectometer. Figure 3 is an image of the retroreflectometer and how it is aligned on a pavement marking. This device was used because it uses an external beam and can therefore measure continuous wetting conditions. Based on the literature review, the MX30 can accurately measure retroreflectivity from 20 to 1200 mcd/m^2/lx, and it can take accurate readings over a wide range of ambient conditions (*16, 17*).

Continuous Wetting Spray Unit

A spray unit was constructed to provide a consistent and uniform continuous wetting condition. The spray unit consisted of three parts: the spray shield, the spray nozzle and tripod, and the flow meter. The spray shield kept the water from getting onto the MX30 unit. The spray nozzle provided the cone of water that was sprayed onto the markings. The spray nozzle was extended on the end of a rod that was elevated by a tripod. This combination of spray nozzle and tripod allowed the researcher to provide the same pattern of water on every pavement marking. The spray nozzle was a FullJet, standard spray small capacity nozzle, with a capacity size of 1.5. The flow meter allowed small changes to the water flow. The researcher could make minor adjustments to the water flow to apply a specific amount of water to the marking. The spray setup can be seen in Figure 18 and Figure 19. In the figures, all parts of the spray unit can be seen as well as the placement of the MX30 retroreflectometer on a pavement marking.

It is worth noting that the source of water for the system was a standard garden hose attached to a water faucet. This source of water was preferred over a tank due to the large number of readings and thus the large amount of water necessary for the measurements. It should also be noted that the spray setup flow rates lower than 1.2 in/hr, the spray pattern from the nozzle became less uniform.

FIGURE 18 Tripod Setup with Retroreflectometer on Marking (Front View).

FIGURE 19 Retroreflectivity Data Collection Setup (Side View).

Pavement Marking Materials

A variety of typical pavement marking materials, pavement marking tapes, and pavement markings designed for improved wet performance are included in the set of study samples. Table 4 is a summary of the pavement markings used. Table A-1 in Appendix A includes pictures and further descriptions of the pavement marking samples. The sample code is used to identify the different pavement marking material types throughout this thesis.

All pavement markings are applied to two, four-foot long substrate panels. The two panels allowed for easy changing of the samples during data collection. Each panel was marked with an arrow to indicate the direction in which the material was applied and thus the direction that retroreflectivity should be measured. Bead types are based on the size of the bead; Type III beads are larger than Type II beads, Type II beads are larger than Type I beads, GloMarc 90 are clusters of beads, and high index beads have a larger refractive index than normal beads.

Newly-applied pavement markings are often covered with a thin film of residual oil that can repel water until worn off by traffic. Before the study began, the pavement marking samples were scrubbed with a solution of water and detergent to remove any film. This was done to provide retroreflectivity data more consistent with typical pavement markings placed in the field (*2*).

TABLE 4 Pavement Marking Material Summary.

Sample Code	Color	Material Type	Manufacturer	Glass Bead Type
5	White	Waterborne Paint	Ennis Paint	III
6	White	Waterborne Paint	All-American Coatings	II
8	White	LS90 Polyurea	EpoPlex	GloMarc 90, II
10	White	LS50 Epoxy	EpoPlex	III
11	White	Alkyd Thermoplastic	Ennis Paint	I, III, High Index
15	White	Tape A380I	3M	*
16	White	Tape A750ES	3M	*
17	White	Tape 380WR	3M	*
18	White	Tape ATM 400	Advanced Traffic Markings	*
21	Yellow	Tape A380I	3M	*
22	Yellow	Tape A750ES	3M	*
23	Yellow	LS90 Polyurea	EpoPlex	GloMarc 90, II
25	Yellow	Tape ATM 400	Advanced Traffic Markings	*
31	Yellow	Methyl Methacrylate	Dugussa	III
32	White	Thermoplastic	Dobco	III
33	White	Thermoplastic	Ennis Paint	E16, M247
34	White	Alkyd Thermoplastic	Ennis Paint	II
35	White	Alkyd Thermoplastic	Ennis Paint	II
Note: * indicates bead is not separate in tape products				

Pavement Marking Material Subgroups

The research evaluated a variety of pavement marking materials. Subgroups of the markings based on type were established to compare performance and for analyses purposes. The researcher decided to establish three different sets of groups. The first set is based on binder type, the second set is based on marking texture, and the third set is based on performance characteristics. In the performance subgroup, pavement marking materials with less than 300 mcd/m^2/lx in the continuous wetting condition were grouped together to remove the highest performers, also pavement markings specifically designed for wet conditions were grouped together as well. The subgroups are outlined in the following bulleted points. The pavement marking sample number associated with each group follows the group type.

- Performance
  - Less than 300 mcd/m^2/lx (continuous wetting) – 5, 6, 8, 10, 11, 15, 18, 21, 23, 25, 31, 32, 33, 34, 35.
  - Designed for wet conditions – 8, 11, 16, 17, 22, 23, 31, 35.
- Binder Type
  - Waterborne Paint – 5, 6.
  - Thermoplastic – 11, 32, 33, 34, 35.
  - Tapes – 15, 16, 17, 18, 21, 22, 25.
  - Others – 8, 10, 23, 31.
- Marking Texture
  - Flat – 5, 6, 10, 18, 25, 32, 33, 34.
  - Profiled – 8, 11, 15, 16, 17, 21, 22, 23, 31, 35.

Study Procedure

The researcher collected retroreflectivity data for all the pavement markings using an MX30 handheld retroreflectometer. The MX30 was properly calibrated before data collection began, and the accuracy of the readings was monitored throughout the data collection. The researcher measured dry, recovery, and continuous wetting retroreflectivity. The researcher measured the dry retroreflectivity when the markings were completely dry in accordance with ASTM E-1710 (*7*). Six dry retroreflectivity measurements were recorded for each pavement marking. The researcher measured recovery retroreflectivity after pouring five liters of water onto the marking, and waiting 45 seconds in accordance with ASTM E-2177 (*8*). Four recover retroreflectivity measurements were recorded for each pavement marking. An example of ASTM E-2177 is provided in Figure 20. The figure shows how the water is poured onto the marking and that the retroreflectivity is measured where the water was poured.

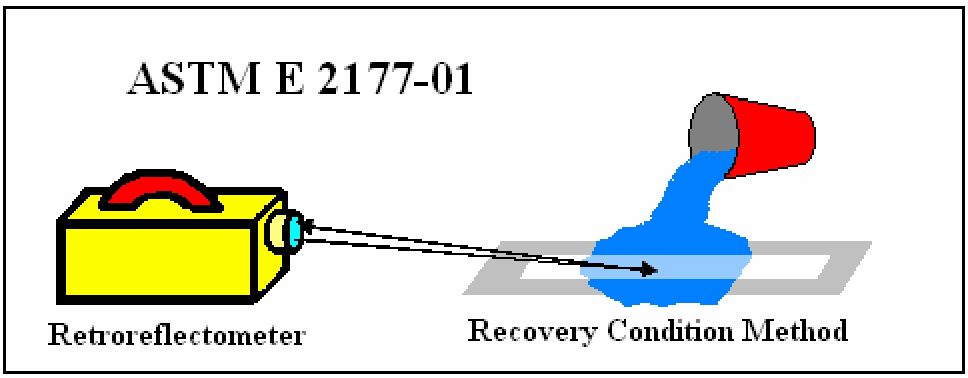

FIGURE 20 Example of Recovery Condition Setup.

The main objective of this research is to explore the predictive performance of ASTM E-2176, which measures retroreflectivity in a condition of continuous wetting. The researcher measured continuous wetting retroreflectivity in accordance with ASTM E-2176 (*9*). The basic setup of the ASTM standard can be seen in Figure 21. The ASTM standard calls for a continuous wetting rate of approximately 9.3 in/hr. The range of acceptable values according to the standard are displayed in Appendix A, Table A-2. The range is from approximately 5.75 in/hr to 14.5 in/hr, with 9.3 in/hr being the central value. This range of values result from the range of allowable values as stated in the standard. The standard states that a flow of 0.8 liters per minute ± 0.2 liters per minute should be sprayed in a circle that is 20 inches in diameter ± 2 inches.

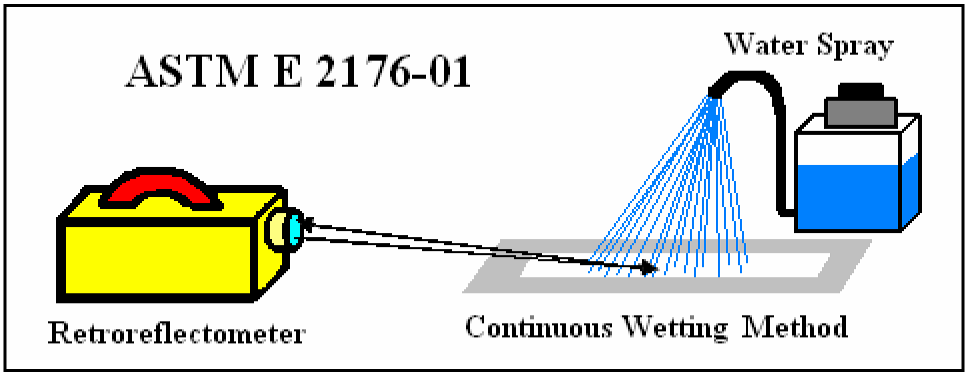

FIGURE 21 Example of Continuous Wetting Setup.

To achieve the objectives of the study, the researcher also measured continuous wetting retroreflectivity at wetting intensities within the ASTM range and below. The researcher followed the same method for each continuous wetting retroreflectivity measurement. Using the continuous wetting spray unit, the researcher would select a flow rate of water to apply to the marking. Once a consistent flow was achieved, a rain gauge was used to determine the rate of wetting. Two six-minute wetting rate measurements were made by placing the rain gauge under the spray unit at the location where the measurement was to be taken. Once an acceptable rate was achieved and two continuous readings produced a similar rate, the retroreflectivity measurements began.

The researcher would place a properly oriented pavement marking sample under the spray unit and allow the marking time to become wet. A properly oriented pavement marking means that the markings' retroreflectivity would be measured in the same direction that the marking was applied to the substrate material. The researcher would place the MX30 handheld retroreflectometer on the marking and take readings until six consecutive readings showed stabilization of the retroreflectivity level. A new marking would then be placed under the spray unit, and the process would be repeated. Once half of the pavement markings had been measured the researcher would check the wetting rate on the marking to make sure a consistent rate is falling on the markings. The researcher would again measure a six minute rate and compare to the previous readings. If the rate was the same, data collection would continue, if not data collection would restart, due to the variability of the wetting rate. Figure 18 and Figure 19 show the continuous wetting retroreflectivity data collection setup.

The researcher collected retroreflectivity data for all pavement marking samples at one continuous wetting rate. Once data collection was complete a new continuous wetting rate would be tested in the same manner. This was the process for collecting the continuous wetting retroreflectivity data using the spray setup. A second set of continuous wetting retroreflectivity data was also collected and is described below.

The second set of continuous wetting retroreflectivity data were collected at the rain simulator. A plastic shroud was put over the MX30 retroreflectometer so that the unit would remain dry. The researcher would place a properly oriented pavement marking under the simulated rain and measure the retroreflectivity until the value stabilized. The researcher would record six stabilized values. All three continuous wetting intensities were used as the continuous wetting rainfall rate at the rain simulator.

It is worth noting that for all sets, retroreflectivity data were not recorded until consistency was established between observations. This allowed the researcher to ensure that the surfaces of the pavement marking samples were wetted evenly. It is also worth noting that the retroreflectivity data for sample 35 (white thermoplastic rumble strip) were measured at the location of one of the oblique faces.

Data Collection

In total, 14 sets of retroreflectivity data were collected for all pavement marking samples. These sets were as follows;

- Dry (1 set – ASTM E-1710)
- Recovery (1 set – ASTM E-2177)
- Continuous Wetting (12 sets)
    - 1 set – ASTM E-2176
    - 3 sets – At Rain Simulator
    - 8 sets – Continuous wetting Rates to Compare to ASTM Rate

The three sets of data collected at the rain simulator were for the low, medium, and high intensity rainfall. The resulting continuous wetting rates at the rain simulator were determined to be 0.28, 0.52, and 0.87 in/hr. The continuous wetting rates collected using the spray setup were 1.2, 2, 4, 6, 8, 9.5 (ASTM), 11.5, 14 in/hr, and flooding. The researcher determined that the flooding rate was greater than 20 in/hr and was not reasonably recordable, thus deemed flooding. Using the spray setup, the minimum achievable continuous wetting rate was 1.2 in/hr. The continuous wetting condition became to variable at rates less than 1.2 in/hr with the spray setup.

DETECTION DISTANCE MEASUREMENT

The detection distance data is the second half of the information needed to achieve the objectives of this thesis. The Texas Transportation Institute collected and analyzed all detection distance values separate from the thesis research (*6*). The following sections describe the equipment used in collecting the detection distance data and the process of the detection distance data collection. The subject information from the drivers is also included in the data collection section.

Variables

The dependent variable for this section of the research is the detection distance. Detection distance is based on a single 8 foot skip line, being viewed by a subject driving in a controlled rain environment.

The independent variables associated with TTI's detection distance were:

- Pavement Marking Type: The study consisted of 18 pavement marking material samples. The pavement marking samples represent a variety of materials currently used on roadways, as well as many new and lesser used pavement marking materials. These are the same sample used in the retroreflectivity section of the thesis.
- Rain Simulator Rainfall Intensity: Three rainfall rates were used based on typical Texas rainfall rates. Low (0.28 in/hr), medium (0.52 in/hr), and high (0.87 in/hr) rainfall intensity were studied. It is worth noting that the high rainfall intensity of 0.87 in/hr is still less than the lowest of the acceptable ASTM E-2176 continuous wetting rates which is 5.78 in/hr.

- Driver Age: Drivers age was recorded when filling out the consent forms and taking the vision test. Each driver was required to hold a valid drivers license. The driver was classified as either young or old. Young was considered less than 55 years of age, and old was 55 years of age or greater.

The fixed components of the research are those that do not change during the study. The components of the TTI detection distance study that were unchanged are:

- Pavement marking size – Unless specifically noted, all pavement markings were approximately 4 inches wide and 8 ft long.
- Pavement marking position – All of the pavement markings used for the analyses were positioned in the center of the travel lane. Distracter pavement markings were offset outside of the travel lane, but they were not used for the analyses.
- Seat position – All the detection distances were recorded with the subjects driving the test vehicle and therefore seated in the driver's position.
- Vehicle speed – Each trial was performed with cruise control set at 30 mph.
- Ambient lighting - There is little lighting from buildings or nearby communities. No traffic was present beside that of the research vehicles. The only outside source of ambient lighting was the moon.

Equipment

There were two main pieces of equipment during the detection distance data collection. These pieces of equipment are a test vehicle driven by the subject and a rain simulator to provide the rainfall during the study.

Test Vehicle

The test vehicle is a state-owned 2004 Ford Taurus Sedan with HB4 halogen headlamps, this vehicle can be seen in Figure 22. The vehicle was driven by the test subjects when viewing the pavement marking samples. The car was equipped with a calibrated distance measuring instrument (DMI), cruise control, and researcher controlled windshield wipers.

FIGURE 22 Data Collection Vehicle.

Rain Simulator

A rainfall simulator controlled the rainfall rate on the pavement markings while the detection distance data were being collected. The simulator was 1600 feet long, and water was supplied by a fire hydrant located on an adjacent roadway. The rain simulator produced three rainfall intensities, these rainfall intensities are provided in Table 5. These rainfall intensities were controlled by three valves located along the rain simulator.

TABLE 5 Rain Simulator Rainfall Rates.

Flow Setting	Design Rate (in/hr)	Measured Rate (in/hr)
Low	0.25	0.28
Medium	0.50	0.52
High	0.75	0.87

The edges of a travel lane were marked along the roadway with blue raised pavement markings. The lane marked by the blue raised pavement markers was 9 feet wide. The rain simulator can be seen in Figure 23 and Figure 24. Figure 23 shows the rainmaker before the water is turned on. Figure 24 shows the rain simulator while the water is being sprayed on the road.

FIGURE 23 Midpoint of Rain Simulator (Dry).

FIGURE 24 Rain Simulator Wetting the Road.

Study Procedure

Each night of data collection followed the same procedure. Before detection distance data could be collected, the experimental subject had to sign consent forms and take an eye exam. Once the paperwork was signed and the subject had their visual acuity tested, the study could commence.

The researcher instructed the experimental subject as to how the data collection would be carried out. The experimental subject would drive the test vehicle with cruise control set at 30 miles per hour. The researcher would control the windshield wipers and record the detection distances of the markings. The researcher instructed the experimental subject to verbally indicate when they could first detect the pavement marking.

The researcher would instruct the experimental subject to make two test runs through the rain simulator while sample pavement markings were in place and the rain was falling. Once the test runs were complete the field crew would remove the test run markings and put down the first set for data collection. The field crew could place the pavement marking samples at any of nine locations. Five locations were along the centerline of the drive path. These five locations were the locations of interest, and where data would be recorded. The four locations at the edge of the travel lane served as distracter locations to keep the experimental subject from guessing the location of the pavement markings. These nine locations and their location in relation to the rainmaker can be seen in Figure 25.

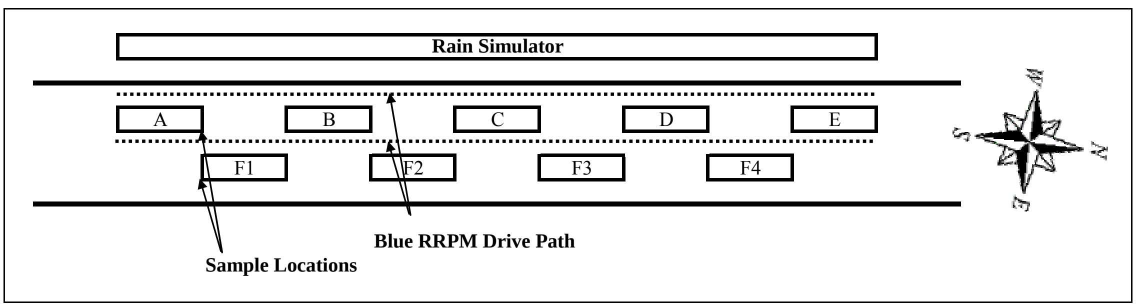

FIGURE 25 Pavement Marking Sample Locations.

Each night of study the field crew and the researchers had a predetermined setup of marking type, marking locations, and rainfall rate. After each run through the rain simulator the field crew would place a new set of samples on the roadway and subsequent runs would be made. An example of the panel layout for a night of study is provided in Appendix A, Table A-3.

Data Collection

The data collection consisted of two sets of data. The first sent of data was subject information and the second set of data was the pavement marking detection distances.

Experimental Subject Information

A total of 30 experimental subjects were used in detection distance data collection. The age and sex of each subject were recorded. The subjects were split up into two age groups: young (18-54) and old (≥ 55). Each subject's vision was also tested using the Snellen visual acuity chart and a color blindness test.

The distribution of the subjects were weighted equally by gender, but weighted towards younger drivers. The breakdown of subjects by age and gender was:

- 10 females under 55 years of age,
- 10 males under 55 years of age,
- 5 females 55 years of age and older, and
- 5 males 55 years of age and older.

Pavement Marking Detection Distance

Each experimental subject drove 12 runs of data collection through the rain simulator. Typically two pavement markings were viewed on each run in which data was recorded. All analyses are based on initial detection distances.

EXPERIMENTAL METHODOLOGY

The detection distance data collected during the TTI study are imported into this thesis research. The retroreflectivity data collected during this research are compared to the detection distance values from the TTI study (*6*). Descriptive statistics and correlation analyses are the means of analyzing the two sets of data, as described below.

Descriptive Statistics

The detection distance values are described by the following: number of observations, minimum, maximum, range, mean, 25th and 75th percentiles, and standard deviation. The retroreflectivity data are described by the following: mean and standard deviation. Based on the number of detection distance observations, the detection distance data was reduced. A minimum of five detection distance observation are needed for the pavement marking to be considered in the analysis. The researcher suggests' this value as a minimum to ensure enough observations to reduce variability of detection distance readings.

Correlation Analyses

Correlations measure how variables are related. The Pearson's correlation coefficient *r* is a measure of linear relationship. The Pearson *r* value ranges' from -1 to 1 depending on the relationship type. Values close to -1 or 1 indicate a strong relationship, whereas values close to 0 indicate a poor relationship between the sets of data. Squaring the Pearson *r* correlation coefficient results in the coefficient of determination (R^2). The coefficient of determination can only range between 0 and 1, and groups the poor relationship sets closer to zero than does the Pearson *r* value.

The Pearson's correlation coefficient *r* is given by the following equation. The x_i and y_i values are the retroreflectivity and detection distance values associated with each different pavement marking sample. The $\bar{x}$ and $\bar{y}$ values indicate the mean values of the retroreflectivity and detection distance values. The equation for Pearson's correlation coefficient is provided below in Equation 1.

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

EQUATION 1 Pearson's Correlation Coefficient *r*.

The researcher conducted a series of Pearson *r* correlation analyses to achieve the objectives of this study. The detection distances from the TTI study are correlated with the retroreflectivity data found during this thesis research (*6*). The researcher conducted correlation analyses for many combinations of pavement markings and continuous wetting rates. Each pavement marking subgroup for each continuous wetting rate were correlated.

Programs Used

Two programs were used for the analysis: Microsoft Excel and Statistical Package for the Sciences (SPSS). The researcher used Microsoft Excel to create data tables and calculate the mean and standard deviation values. Excel was also used to create the correlation analysis figures with the coefficient of determination values and linear trend line. The researcher used SPSS to conduct the Pearson *r* correlation coefficient calculations.

RESULTS

This thesis research effort evaluated the relationship between the nighttime detection distance of pavement markings in a simulated rain environment and the retroreflectivity of the same pavement markings measured under several different conditions. The pavement markings used in both the detection distance and retroreflectivity data collection efforts are listed in Table 4 and further described in Appendix A, Table A-1.

During the data collection effort (see Study Design), the researcher made 1476 retroreflectivity measurements on 18 pavement marking samples subjected to 14 different measurement conditions. These 14 conditions included dry, recovery, and 12 different continuous wetting measurements. The wetting intensity for the continuous wetting measurements ranged from 0.28 in/hr up to 14 in/hr, as well as a flooding condition. The researcher also incorporated 658 detection distance values from the study conducted by TTI (*6*). The detection distance values were the result of 30 experimental subjects viewing the 18 pavement markings under simulated rain conditions. The detection distances used were the first quartile, mean, and third quartile values.

The researcher conducted correlation analyses of the detection distances and retroreflectivity of the pavement markings. The pavement markings were divided into subgroups, based on pavement marking type, for further correlation analysis. Twelve sets of correlation values were determined. The researcher also created graphs of each correlation analysis to give an indication of the relationship of the values; the graphs also show the coefficient of determination value (R^2).

RETROREFLECTIVITY DATA

The researcher collected retroreflectivity data for all 18 samples following the methodology described in the Study Design. Table 6 summarizes the mean values of the collected retroreflectivity data. Measurement condition is listed in the first row; the first column lists the sample numbers.

Table 6 lists 14 conditions under which the researcher collected the retroreflectivity data. The general conditions were dry, recovery, and continuous wetting. The continuous wetting conditions were denoted as 0.28 r, 0.52 r, 0.87 r, 1.2 s, 2.0 s, 4.0 s, 6.0 s, 8.0 s, 9.5 s, 11.5 s, 14.0 s, and flood. Each of these conditions was for a single continuous wetting rate equal to the indicated value. The 0.28 r, 0.52 r, and 0.87 r were measured at the rain simulator as indicated by the r following the wetting rate. These wetting rates were the rates produced by the rainmaker under the low (0.28 in/hr), medium (0.52 in/hr), and high (0.87 in/hr) flow conditions (see Table 5). The numbered conditions were numbered according to their approximate respective rate of rainfall in inches per hour. The s following the wetting rate indicates that the spray setup was used to produce the continuous wetting condition. The flooding condition rate was not measurable due to the large amount of water, and thus noted as flood.

Table B-1 through Table B-14 in Appendix B show each retroreflectivity value recorded for all 14 conditions. The mean value, which is provided in Table 6, and the standard deviation are also given for each sample for each measurement condition.

TABLE 6 Summary of Mean Retroreflectivity Values.

Sample	Material, Bead, Color	Measured Retroreflectivity (mcd/m^2/lx) for Indicated Continuous Wetting Rate (in/hr)													
		Dry	Recovery	0.28 r	0.52 r	0.87 r	1.2 s	2.0 s	4.0 s	6.0 s	8.0 s	9.5 s	11.5 s	14.0 s	Flood
5	Paint, Type III, W	364	150	157	105	101	192	148	145	89	84	72	42	46	32
6	Paint, Type II, W	288	35	48	40	47	20	22	19	13	12	13	16	18	21
8	Polyurea, Cluster Bead, W	1232	243	250	225	182	184	176	162	159	155	128	127	116	75
10	Epoxy, Type III, W	524	253	72	43	40	55	49	19	16	18	16	17	20	24
11	Thermo, Mixed, W	787	134	203	146	129	87	76	67	67	69	65	60	52	50
15	3M 380 Tape, N/A, W	746	232	67	44	50	296	190	169	125	96	75	72	49	48
16	3M 750 Tape, N/A, W	1220	1240	1205	1284	1161	1302	1247	1291	1251	1263	1250	1235	1173	760
17	3M 380WR Tape, N/A W	1234	975	887	737	631	776	716	710	634	606	564	532	359	278
18	ATM 400 Tape, N/A, W	937	509	178	131	118	128	154	148	130	158	150	92	88	85
21	3M 380 Tape, N/A, Y	401	71	73	52	47	171	127	111	47	53	34	42	20	25
22	3M 750 Tape, N/A, Y	844	737	874	809	588	696	644	638	660	662	666	634	416	302
23	Polyurea, Cluster Bead, Y	1229	150	143	101	101	114	88	97	92	91	84	93	59	46
25	ATM 400 Tape, N/A, Y	596	243	147	136	112	158	165	124	123	133	120	122	121	71
31	Methacrylate, Type III, Y	334	113	149	117	114	129	110	99	90	64	62	60	59	47
32	Thermo, Type III, W	972	282	252	212	168	128	102	50	51	43	46	43	40	36
33	Thermo, Mixed, W	510	283	130	152	122	159	135	36	30	26	25	28	26	26
34	Thermo, Type II, W	524	96	71	47	39	31	25	19	22	23	22	22	27	21
35	Thermo Rumble, Type II, W	503	185	144	152	129	99	101	70	64	64	57	61	58	49

Note: Wetting rates are indicated by the rate followed by either an r or an s; r indicates measured at the rainmaker and s indicates measured with the spray setup. W indicates White and Y indicates Yellow.
Table B-1 through Table B-14 contain all individual sample readings and standard deviation values.

Plotting the retroreflectivity data with respect to the continuous wetting rate during measurement condition shows a trend of decreasing retroreflectivity level with an increase in wetting rate. Figure 26 shows the trend of the 15 (of 18 total) pavement marking samples that had retroreflectivity levels less than 300 mcd/m^2/lx. The decrease in retroreflectivity level for the pavement markings as the continuous wetting rate increases is displayed in the figure. Due to the large number of pavement markings in Figure 26, additional figures were created to show the decreasing trend based on the pavement marking subgroups. Figure B-1 through Figure B-4 in Appendix B indicates how the wetting rate affected the retroreflectivity level for each different type of pavement marking.

It should be noted that the continuous wetting rates less than 1.0 in/hr were measured at the rainmaker; whereas the continuous wetting rates greater than 1.0 in/hr were measured using the spray setup. The two different measuring setups are what create the initial decrease, and then the increase as the new measuring technique is started. The general trend for each separate setup (rainmaker or spray setup) is a decrease in retroreflectivity as continuous wetting rate increases, but comparing the two separate setups a general trend is not easily seen. This difference indicates that the two measuring techniques are not equivalent.

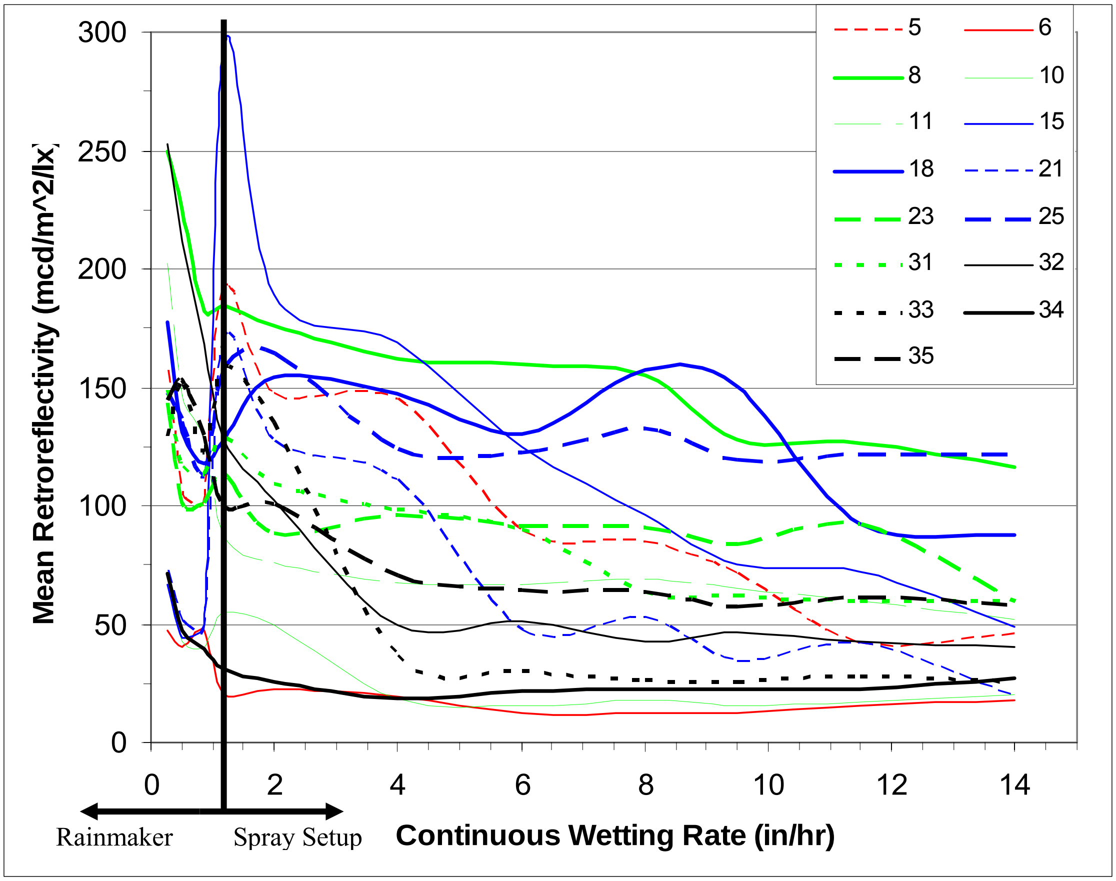

FIGURE 26 Continuous Wetting Rate Effect on Retroreflectivity Level.

DETECTION DISTANCE

Only pavement marking samples that had 5 or more detection distance values were analyzed. The TTI study resulted in a total of 658 detection distance values for the 18 pavement marking samples. Three different rainfall rates were used at the rainmaker when collecting detection distance data. The high rainfall rate (0.87 in/hr) had 15 samples that totaled 224 detection distance values; the medium rainfall rate (0.52 in/hr) had 18 samples that totaled 246 detection distance values and the low rainfall rate (0.28 in/hr) had 15 samples that totaled 188 detection distance values.

Summaries of the detection values for the high, medium, and low rainfall conditions are in Table 7, Table 8, and Table 9 respectively. For each pavement marking sample the number of times it was observed is given in the count column. The values used to describe the detection distance are the minimum (min), first quartile (Q1), mean, third quartile (Q3), maximum (Max), median value, and the standard deviation (StDev).

The detection distance values were analyzed in the TTI report for biases (*6*). The only significant impacts were from the pavement marking type, rainfall intensity and driver visual acuity. Data from drivers with poor visual acuity (20/50 or worse) was removed by TTI before conducting further analysis. The researcher conducted further analyses for all pavement marking types and for all three rain conditions, to consider all effects that had a significant effect on the detection distance data.

TABLE 7 Detection Distance Under High Rainfall Rate.

Sample	Count	Min	Q1	Mean	Q3	Max	Median	StDev
5	23	104	133	171.83	209	276	162	47.8
6	11	36	123	138.5	165	202	142	42.7
8	18	113	142	174.2	194	294	178	43
11	27	159	205	228.56	263	310	226	41.11
16	32	177	240.3	316.4	378.8	469	318	76.3
17	19	154	195	222.47	238	295	231	38.28
18	7	163	172	187	209	223	183	21.58
21	8	54	117.3	151.6	197.5	213	157.5	51.8
22	14	141	221.3	256.6	303	354	262.5	57.5
23	11	31	171	190.3	229	259	205	60.7
25	5	130	146	171.6	200.5	218	165	32.2
32	16	116	156.5	191.06	217.5	266	194.5	37.9
33	14	95	164.5	176.71	194.75	229	182	34.15
34	13	99	122	142.23	168	181	138	25.14
35	6	82	125.5	160	200.8	215	163.5	47.3

TABLE 8 Detection Distance Under Medium Rainfall Rate.

Sample	Count	Min	Q1	Mean	Q3	Max	Median	StDev
5	17	68	147.5	166.1	190	238	162	47.2
6	20	63	138.3	152.4	172.25	214	145.5	34.02
8	16	132	169.8	204.2	230.5	328	188	51.2
10	7	153	173	213	249	259	233	42.7
11	12	144	188.8	212.9	253.3	276	210	40.7
15	9	132	150.5	199.1	238	264	207	47.9
16	16	191	234.3	278.7	348.5	376	275.5	61.9
17	13	163	201.5	227.15	257.5	275	230	35.86
18	14	94	150.5	171.1	204.3	237	156.5	40
21	8	122	142	178	225.3	242	170.5	43.6
22	14	225	269	314.1	388.5	403	289.5	62.2
23	12	137	152	177.33	191	230	181	26.54
25	11	110	154	181.8	213	245	188	40.5
31	12	155	178	217.7	245	296	220.5	41.2
32	19	139	172	196	223	252	190	33.74
33	11	124	165	202.7	248	306	195	54.6
34	20	101	126.5	144.8	166.25	199	140.5	25.92
35	15	137	179	199.53	214	268	196	36.36

TABLE 9 Detection Distance Under Low Rainfall Rate.

Sample	Count	Min	Q1	Mean	Q3	Max	Median	StDev
5	22	93	167.5	191.64	218.5	257	196.5	41.93
6	16	112	140.8	185.3	228	287	177	55.5
8	18	142	189.8	223.5	268.3	292	203.5	45.1
11	6	76	169	215	264.5	305	229	76.7
15	5	143	149.3	171.8	193.5	199	172.5	23.2
16	9	298	329	421.6	506	543	411	93.6
17	14	181	216.5	259.4	300	312	275.5	44.5
18	16	117	200.5	240.6	276.8	357	242	56.8
22	6	237	245.3	286.2	338	344	276	45.9
23	7	179	183	233	257	292	239	40.1
25	6	220	235.8	261	282.8	318	258	33
32	20	123	199.8	229.1	265.5	298	239	46.9
33	15	116	133	178.4	209	256	183	44.8
34	19	96	168	188.68	211	230	196	33.31
35	9	139	151	178.8	220	237	165	37.4

A summary of the mean detection distance values for all the pavement markings is provided in Figure 27. Each pavement marking sample is noted by its sample number as well as the binder, bead type, and color. Generally the high flow condition results in the shortest detection distance and the low flow condition results in the longest detection distance. For some pavement marking samples, the flow condition did not result in a significant difference in detection distances. In some cases detection distance was greater for the higher flow than for the lower flow.

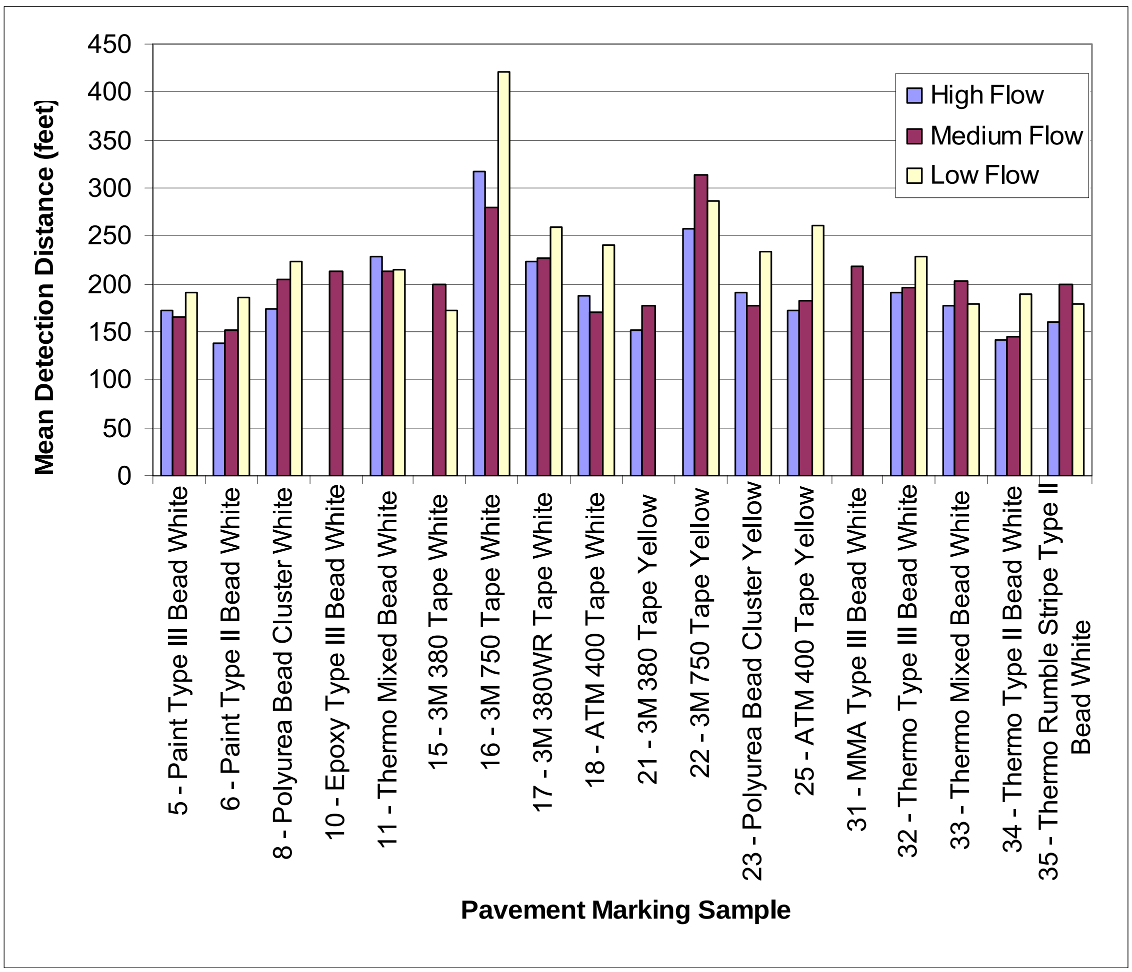

FIGURE 27 Mean Detection Distance for All Samples and Conditions.

CORRELATION

The researcher conducted correlation analysis for all pavement marking samples for all detection distance collection conditions. The Pearson correlation coefficient *r* was used to determine how well the detection distances and retroreflectivity relate. The Pearson *r* equation is provided in Equation 1. The researcher chose this correlation as it is a measure of linear relationship, and thus would be a good indicator of the predictive performance of retroreflectivity in regards to detection distance. Pearson *r* correlation values less than 0.5 are considered a weak correlation, values between 0.5 and 0.8 are considered a moderate correlation, and values greater than 0.8 are considered a strong correlation.

Prior to the correlation analyses, the general trends of the data were analyzed. The columns in Figure 28 show the mean detection distance for all pavement marking samples under the high flow (0.87 in/hr) condition. The vertical lines represent the range of retroreflectivity for each pavement marking sample for all 12 continuous wetting conditions; the scale is on the right axis. The black dash on the right side of the vertical line represents the mean retroreflectivity for the ASTM continuous wetting rate of 9.5 in/ for each pavement marking sample.

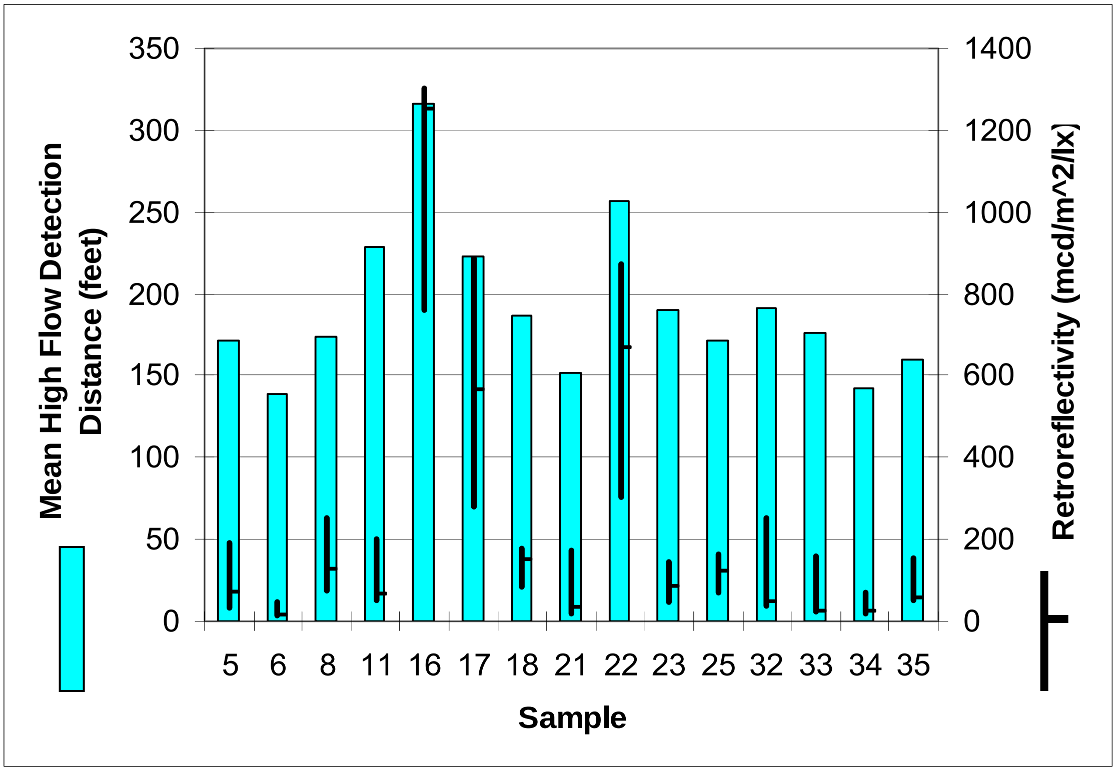

FIGURE 28 Detection Distance and Retroreflectivity for All Samples.

Pavement marking samples 16, 17, and 22 have retroreflectivity levels greater than any other markings' maximum continuous wetting retroreflectivity level. Figure 29 is the same as Figure 28 except the data for samples 16, 17 and 22 have been removed to change the scales to better show the differences between the remaining pavement markings. Figure 30 is the same as Figure 29 except that the pavement markings have been put into rank order, by mean detection distance.

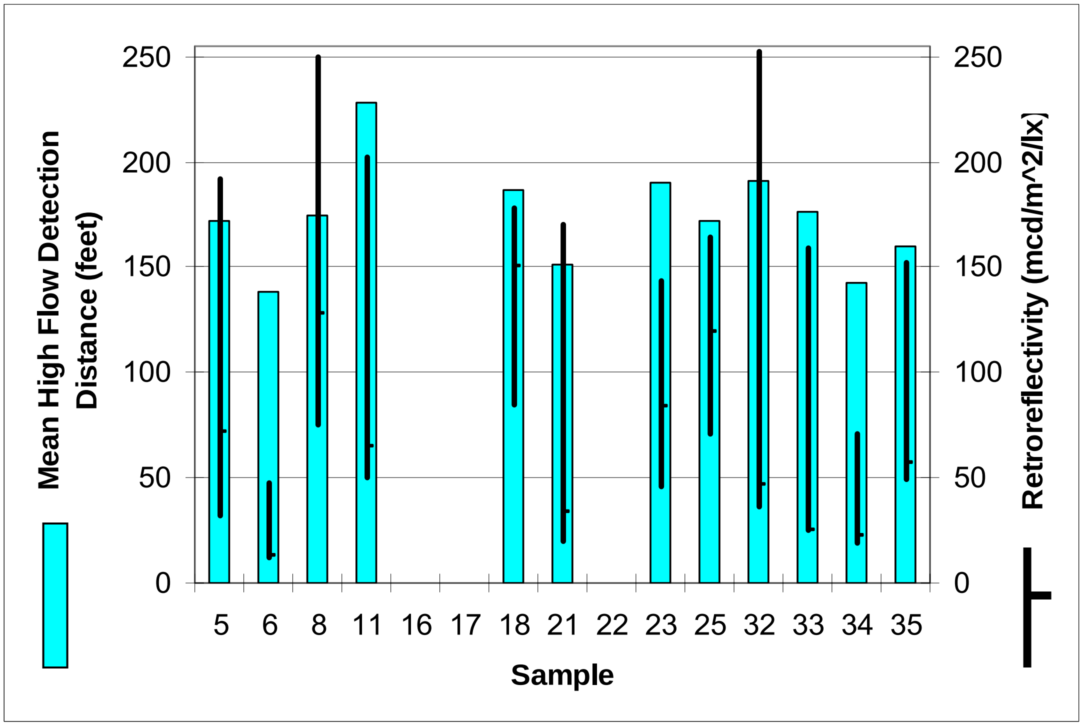

FIGURE 29 Detection Distance and Retroreflectivity for Reduced Sample Set.

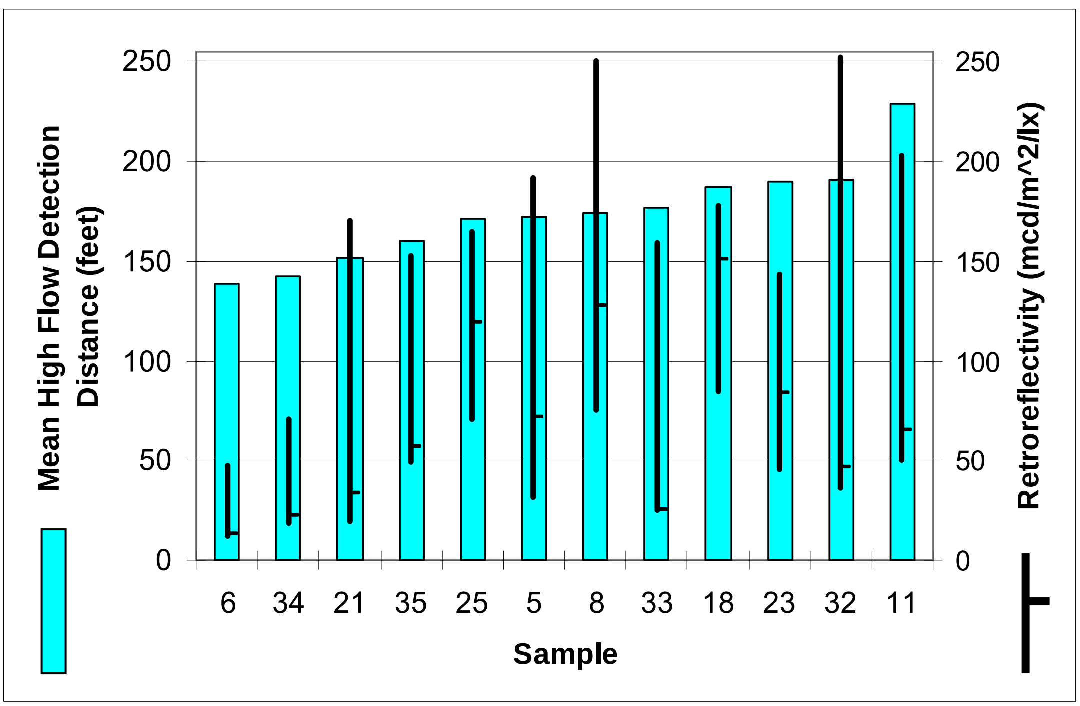

FIGURE 30 Rank Order by Mean Detection Distance for Reduced Sample Set.

There is no obvious relationship between retroreflectivity and detection distance based on Figure 28, Figure 29, and Figure 30. The pavement markings with higher levels of retroreflectivity have greater detection distances in some cases, but in others the detection distance is shorter. The expected outcome would be that pavement markings with higher retroreflectivity would have higher detections and those with lower retroreflectivity would have shorter detection distances. Conducting the correlation analyses of the data will show how well the pavement markings follow the expected outcome.

The correlation of the detection distance values with the retroreflectivity range for the 12 continuous wetting conditions is the primary purpose of this research. The following sections contain correlation analyses based on pavement marking groups, detection distance measurement conditions, and retroreflectivity measurement conditions. Figures are provided for each set of analysis; the figures are for the mean detection distance for the highest flow at which detection distance was measured for that set of analysis. The retroreflectivity data used in the figures are from the continuous wetting rate that provided the highest degree of correlation. The R^2 value is also indicated on all the figures as well. Logarithmic correlations were also evaluated to compare the detection distance with the retroreflectivity. The results from the logarithmic analysis can be found in Appendix C.

High Flow Analysis

The Pearson *r* correlation values between detection distances under the high flow (0.87 in/hr) condition, and the 14 retroreflectivity measurement conditions are provided in Table 10. With a sample size of 15, and a correlation coefficient range of 0.874 to 0.906 for all the continuous wetting conditions (at mean detection distance), it would seem that any amount of water sprayed on the marking provides a strong correlation between retroreflectivity and detection distance. Figure 31 shows the retroreflectivity under the 0.52 in/hr continuous wetting condition and mean detection distances under high flow. This specific continuous wetting rate was chosen as it provided the strongest degree of correlation of all the values. From the figure it is evident that three points influence the trend of all the data. In the performance based analysis later in the results, the data is truncate to remove these three influential points to see how well the majority of the data correlates.

TABLE 10 High Flow Detection Distance and Retroreflectivity Correlation Values.

R_L Measurement Condition	Detection Distance High Flow (0.87 in/hr)		
	Q1	Mean	Q3
Dry	0.642	0.622	0.536
Recovery	0.803	0.853	0.799
0.28 r	0.824	0.897	0.867
0.52 r	0.814	0.906	0.889
0.87 r	0.799	0.902	0.889
1.2 s	0.768	0.875	0.867
2.0 s	0.773	0.878	0.868
4.0 s	0.767	0.877	0.873
6.0 s	0.788	0.892	0.887
8.0 s	0.789	0.893	0.891
9.5 s	0.795	0.898	0.898
11.5 s	0.786	0.894	0.898
14.0 s	0.743	0.874	0.888
Flood	0.767	0.887	0.894

Note: Q1 is the first quartile, and Q3 is the third quartile.
N = 15. r indicates rainmaker, s indicates spray setup

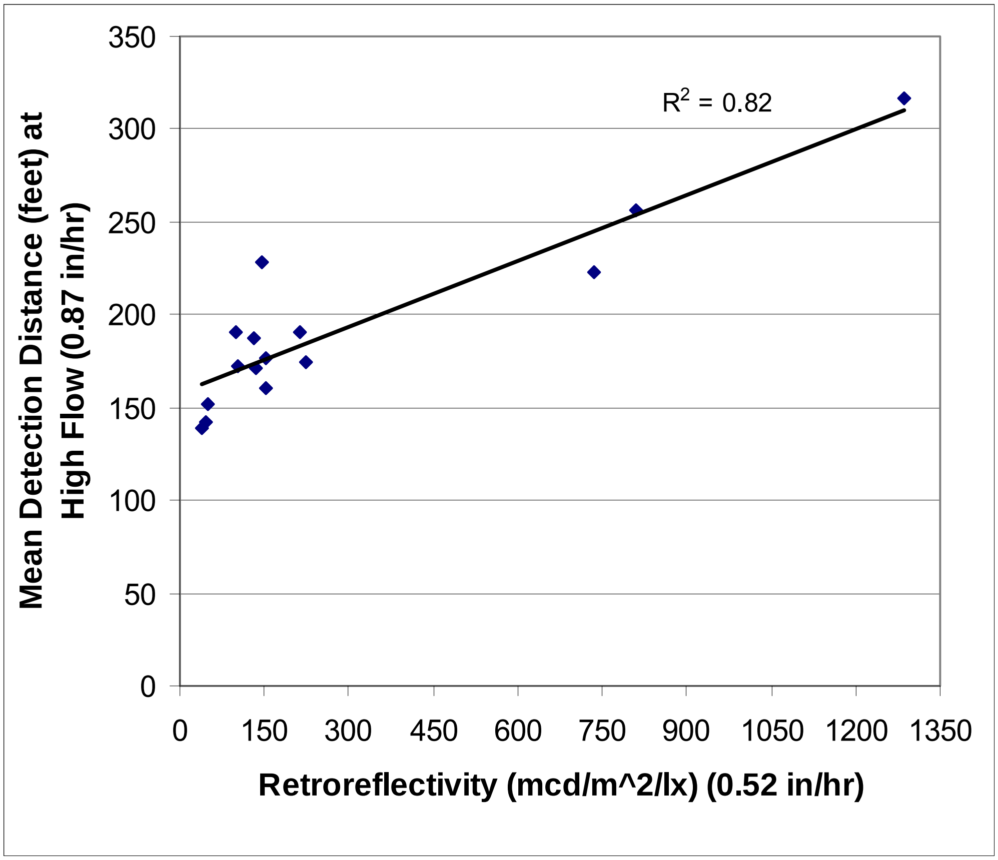

FIGURE 31 High Flow Detection, 0.52 in/hr Rate Correlation Graph.

Medium Flow Analysis

The Pearson *r* correlation values between detection distances under the medium flow (0.52 in/hr) condition, and the 14 retroreflectivity measurement conditions are provided in Table 11. With a sample size of 18, and a correlation coefficient range of 0.693 to 0.802 for all continuous wetting conditions (at mean detection distance), it would seem that any amount of water sprayed on the marking provides a moderate to strong correlation between retroreflectivity and detection distance. Figure 32 shows the retroreflectivity under the 0.52 in/hr continuous wetting and mean detection distances under medium flow rate. This specific continuous wetting rate was chosen as it provided the strongest degree of correlation of all the values. From the figure it is evident that three points influence the trend of all the data. In the performance based analysis later in the results, the data is be truncate to remove these three influential points to see how well the majority of the data correlates.

TABLE 11 Medium Flow Detection Distance and Retroreflectivity Correlation Values.

R_L Measurement Condition	Detection Distance Medium Flow (0.52 in/hr)		
	Q1	Mean	Q3
Dry	0.423	0.398	0.352
Recovery	0.741	0.719	0.724
0.28 r	0.842	0.802	0.795
0.52 r	0.832	0.802	0.804
0.87 r	0.788	0.760	0.763
1.2 s	0.749	0.754	0.771
2.0 s	0.756	0.750	0.766
4.0 s	0.743	0.733	0.747
6.0 s	0.772	0.759	0.771
8.0 s	0.768	0.753	0.768
9.5 s	0.776	0.760	0.775
11.5 s	0.773	0.761	0.776
14.0 s	0.699	0.693	0.714
Flood	0.723	0.713	0.733

Note: Q1 is the first quartile, and Q3 is the third quartile.
N = 18

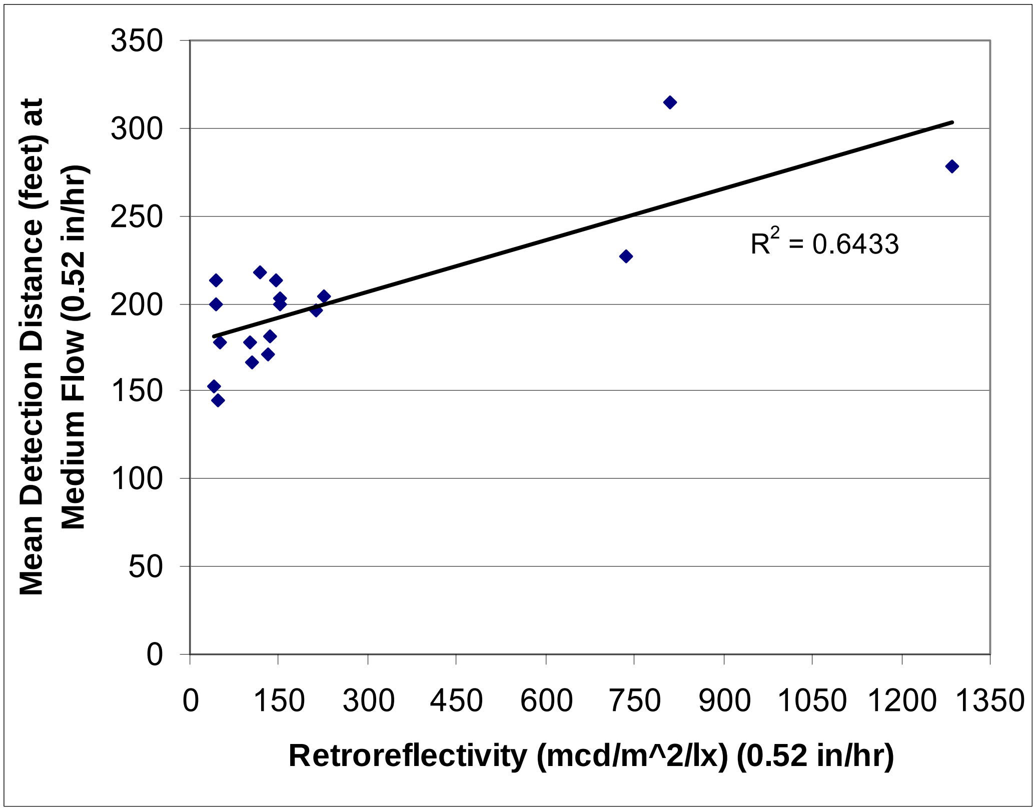

FIGURE 32 Medium Flow Detection, 0.52 in/hr Rate Correlation Graph.

Low Flow Analysis

The Pearson *r* correlation values between detection distances under the low flow (0.28 in/hr) condition, and the 14 retroreflectivity measurement conditions are provided in Table 12. With a sample size of 15, and a correlation coefficient range of 0.863 to 0.935 for all the continuous wetting conditions (at mean detection distance), it would seem that any amount of water sprayed on the marking provides a strong correlation between retroreflectivity and detection distance. Figure 33 shows the retroreflectivity under the 14.0 in/hr continuous wetting condition and mean detection distances at low flow rate. This specific continuous wetting rate was chosen as it provided the strongest degree of correlation of all the values. From the figure it is evident that three points influence the trend of all the data. In the performance based analysis in the next section, the data is truncate to remove these three influential points to see how well the majority of the data correlates.

TABLE 12 Low Flow Detection Distance and Retroreflectivity Correlation Values.

R_L Measurement Condition	Detection Distance Low Flow (0.28 in/hr)		
	Q1	Mean	Q3
Dry	0.576	0.594	0.575
Recovery	0.824	0.849	0.852
0.28 r	0.838	0.863	0.879
0.52 r	0.857	0.892	0.913
0.87 r	0.860	0.905	0.926
1.2 s	0.825	0.859	0.869
2.0 s	0.850	0.886	0.897
4.0 s	0.857	0.893	0.904
6.0 s	0.872	0.908	0.920
8.0 s	0.882	0.919	0.931
9.5 s	0.884	0.922	0.935
11.5 s	0.882	0.923	0.937
14.0 s	0.884	0.935	0.952
Flood	0.880	0.931	0.949

Note: Q1 is the first quartile, and Q3 is the third quartile.
N = 15

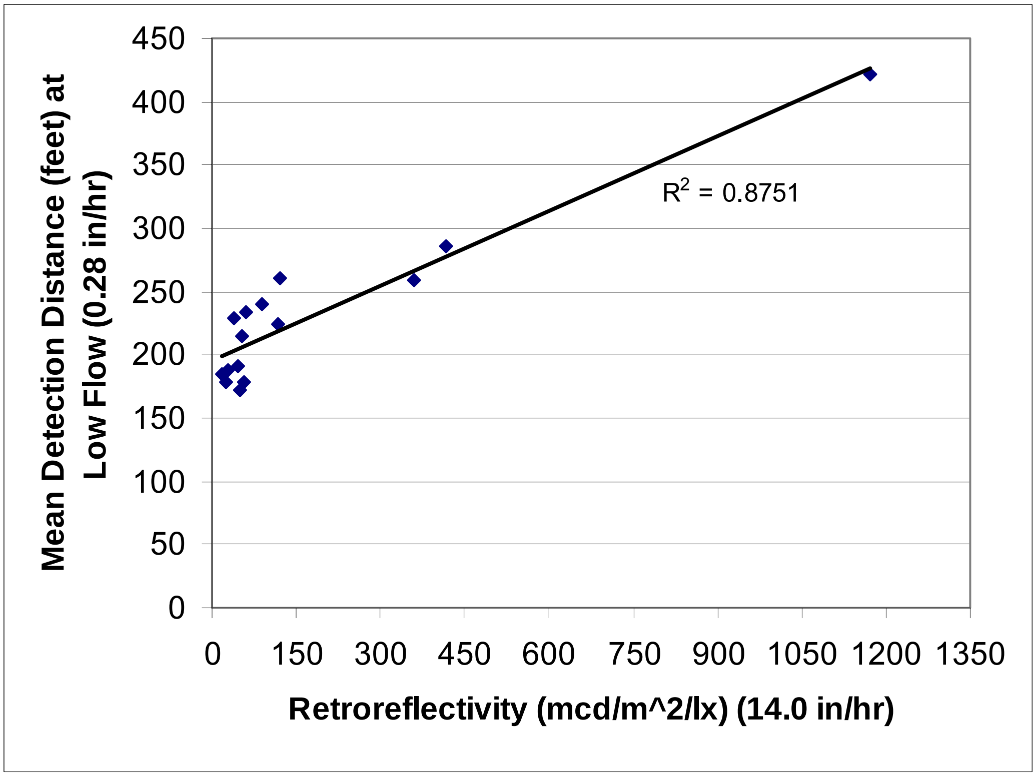

FIGURE 33 Low Flow Detection, 14.0 in/hr Rate Correlation Graph.

Performance Based Analysis

The three previous correlation analysis sections indicate that three data points from the high performing materials seemed to influence the correlation value. To further explore this, the three high performing materials (16, 17, 22) were removed from the analyzed set of data. The resulting correlation data are provided in Table 13 for all three detection distance conditions.

Based on the correlation results in Table 13 it is evident that the three high performing materials influenced the correlation value to seem like a stronger correlation than what the majority of the pavement markings actually would show. The correlation values now show poor to moderate correlation for the different measurement conditions as compared to all the pavement markings showing moderate to strong correlation. Figure 34 shows the distribution of the values that were correlated for mean detection distance under high flow (0.87 in/hr) condition, and retroreflectivity collected under 0.28 in/hr continuous wetting condition. This retroreflectivity condition was chosen as it provided the highest correlation value, for the high flow detection distance values. The correlation values tend to be higher for the high and low flow detection distance data than for the medium flow detection distance data.

TABLE 13 Performance Based Detection Distance and Retroreflectivity Correlation Values.

R_L Measurement Condition	Detect. Dist. High Flow			Detect. Dist. Medium Flow			Detect. Dist. Low Flow		
	Q1	Mean	Q3	Q1	Mean	Q3	Q1	Mean	Q3
Dry	0.549	0.575	0.462	0.199	0.171	0.080	0.467	0.570	0.578
Recovery	0.436	0.392	0.193	0.199	0.210	0.251	0.411	0.422	0.394
0.28 r	0.548	0.719	0.590	0.574	0.380	0.263	0.527	0.572	0.690
0.52 r	0.428	0.567	0.408	0.595	0.420	0.302	0.408	0.450	0.580
0.87 r	0.481	0.621	0.476	0.615	0.430	0.291	0.405	0.470	0.607
1.2 s	0.062	0.244	0.254	0.024	0.284	0.370	0.075	-0.046	-0.156
2.0 s	0.134	0.267	0.213	0.109	0.287	0.354	0.322	0.228	0.148
4.0 s	0.076	0.230	0.259	-0.041	0.092	0.113	0.387	0.296	0.222
6.0 s	0.264	0.366	0.299	0.125	0.192	0.137	0.553	0.495	0.444
8.0 s	0.278	0.348	0.282	0.064	0.074	0.046	0.646	0.620	0.582
9.5 s	0.355	0.403	0.316	0.099	0.068	0.024	0.697	0.690	0.653
11.5 s	0.291	0.356	0.303	0.169	0.184	0.101	0.694	0.692	0.646
14.0 s	0.233	0.295	0.193	0.207	0.161	0.065	0.765	0.722	0.693
Flood	0.406	0.435	0.326	0.273	0.220	0.155	0.659	0.670	0.690

Note: Q1 is the first quartile, and Q3 is the third quartile. High, Low N = 12 Medium N = 15

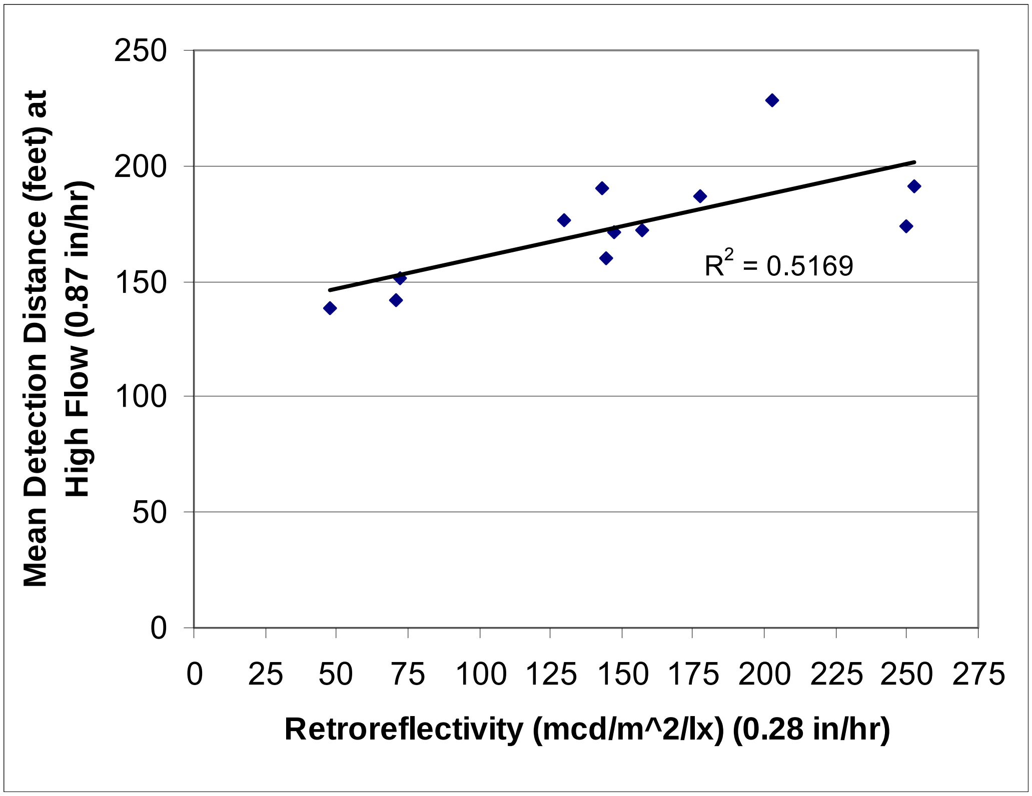

FIGURE 34 Truncated High Flow Detection, 0.28 in/hr Rate Correlation Graph.

Wet Product Analysis

The analysis of products designed to perform better in wet conditions was performed only for the high flow detection distance data. Correlation analysis for the wet pavement markings resulted in the correlation values provided in Table 14. For high flow (0.87 in/hr) mean detection distance the correlation values show a strong relationship for all continuous wetting conditions. The correlation values range from 0.861 to 0.905, the values resulting in r = 0.905 are displayed in Figure 35.

TABLE 14 Detection Distance and Retroreflectivity Correlation Values for Wet Products.

R_L Measurement Condition	Detect. Dist. High Flow (0.87 in/hr)		
	Q1	Mean	Q3
Dry	0.282	0.279	0.180
Recovery	0.714	0.810	0.751
0.28 r	0.784	0.861	0.806
0.52 r	0.771	0.884	0.852
0.87 r	0.756	0.886	0.856
1.2 s	0.754	0.870	0.832
2.0 s	0.747	0.870	0.835
4.0 s	0.755	0.878	0.844
6.0 s	0.768	0.891	0.864
8.0 s	0.770	0.897	0.874
9.5 s	0.779	0.905	0.887
11.5 s	0.773	0.904	0.890
14.0 s	0.725	0.890	0.891
Flood	0.745	0.899	0.893

Note: Q1 is the first quartile, and Q3 is the third quartile. N = 7

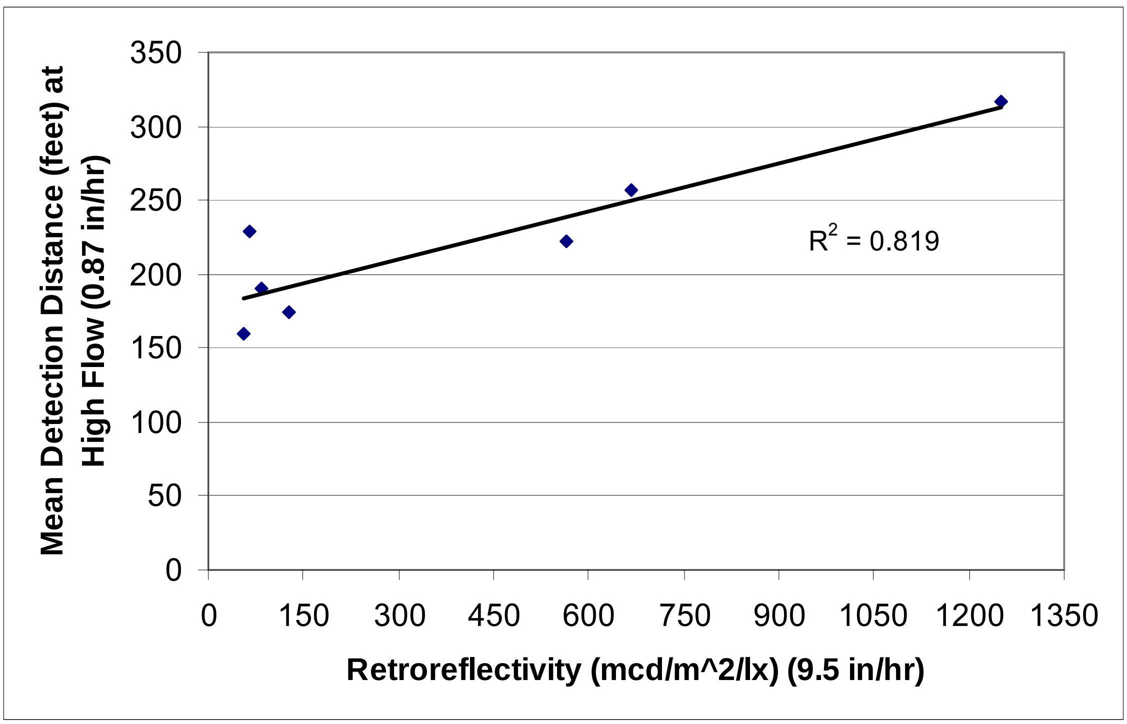

FIGURE 35 Wet Products High Flow Detection, 9.5 in/hr Rate Correlation Graph.

Waterborne Analysis

Correlation analysis cannot be performed for the waterborne paint pavement markings, due to the lack of sample size. With only two waterborne paint samples, the correlation regardless of the detection distance and retroreflectivity is always between -1 and 1. Figure 36 shows how the two pavement marking samples relate to each other.

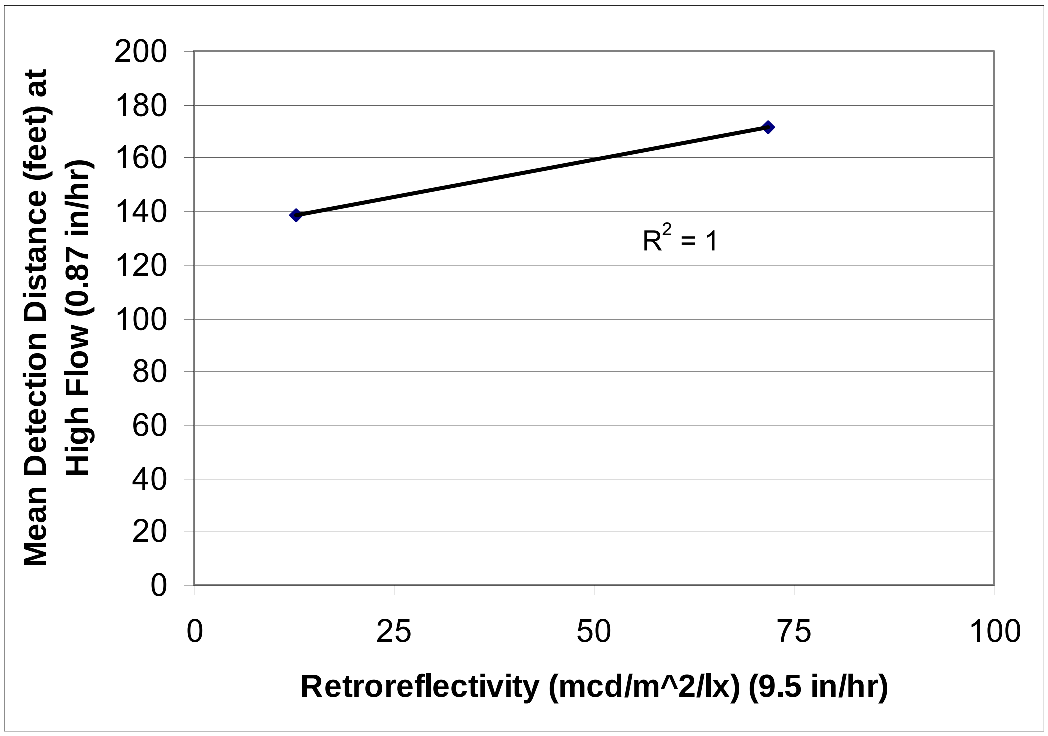

FIGURE 36 Waterborne High Flow Detection, 9.5 in/hr Rate Correlation Graph.

Thermoplastic Analysis

Correlation analysis for just the five thermoplastic pavement marking materials is provided in Table 15. Once again, the 0.28 in/hr continuous wetting condition produces the highest correlation with the mean detection distance data under high flow (0.87 in/hr) conditions. Figure 37 shows the relationship between mean detection distance under high flow condition and retroreflectivity measured under the 0.28 in/hr continuous wetting condition.

TABLE 15 Detection Distance and Retroreflectivity Correlation Values for Thermoplastic.

R_L Measurement Condition	Detect. Dist. High Flow			Detect. Dist. Medium Flow			Detect. Dist. Low Flow		
	Q1	Mean	Q3	Q1	Mean	Q3	Q1	Mean	Q3
Dry	0.508	0.661	0.622	0.408	0.333	0.314	0.857	0.985	0.941
Recovery	0.129	0.147	0.027	0.346	0.508	0.514	-0.024	0.134	0.111
0.28 r	0.573	0.750	0.745	0.730	0.674	0.592	0.624	0.834	0.907
0.52 r	0.405	0.554	0.537	0.773	0.794	0.688	0.288	0.503	0.606
0.87 r	0.455	0.611	0.612	0.838	0.844	0.728	0.268	0.501	0.637
1.2 s	0.345	0.330	0.223	0.549	0.727	0.751	-0.249	0.029	0.105
2.0 s	0.284	0.288	0.225	0.621	0.775	0.752	-0.350	-0.089	0.040
4.0 s	0.400	0.583	0.738	0.924	0.797	0.587	0.051	0.229	0.524
6.0 s	0.428	0.631	0.790	0.889	0.730	0.520	0.220	0.377	0.646
8.0 s	0.420	0.602	0.777	0.832	0.659	0.461	0.142	0.290	0.575
9.5 s	0.471	0.668	0.827	0.852	0.678	0.486	0.271	0.429	0.690
11.5 s	0.351	0.548	0.728	0.851	0.683	0.460	0.132	0.260	0.545
14.0 s	0.183	0.399	0.607	0.744	0.545	0.288	0.157	0.200	0.467
Flood	0.403	0.590	0.762	0.867	0.706	0.497	0.120	0.272	0.561

Note: Q1 is the first quartile, and Q3 is the third quartile. N = 5

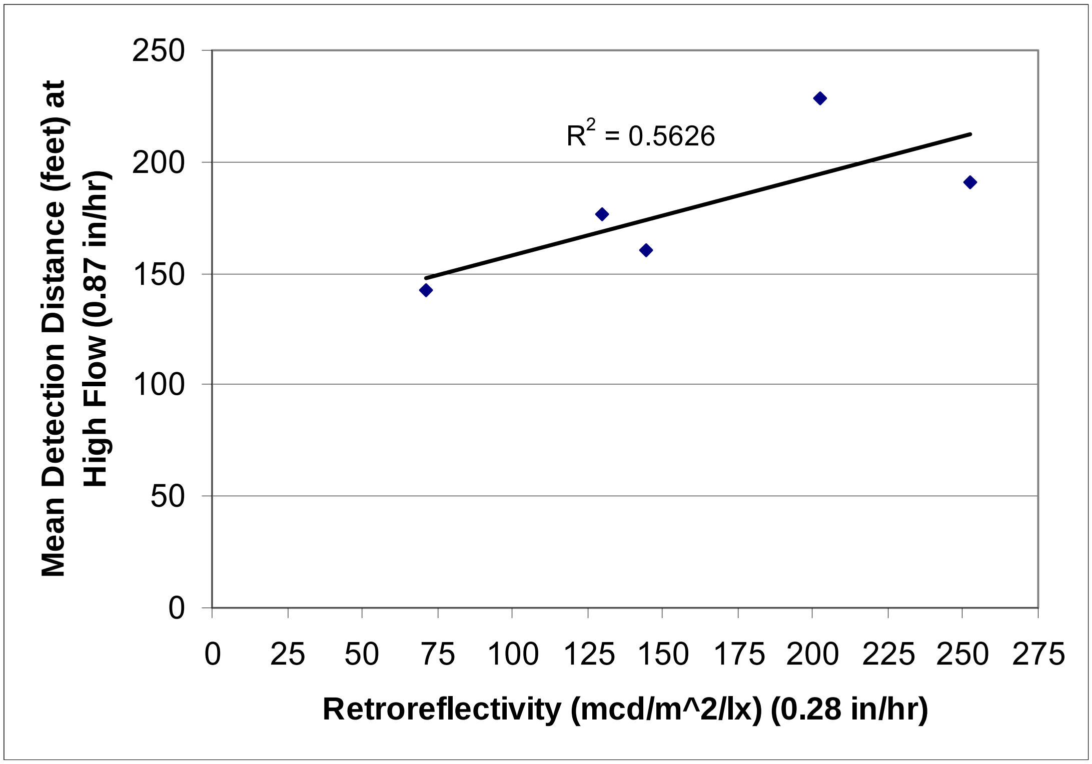

FIGURE 37 Thermoplastic High Flow Detection, 0.28 in/hr Rate Correlation Graph.

Only looking at the mean detection distance data collected under the high flow (0.87 in/hr) condition, a moderate correlation value occurs for most of the continuous wetting conditions. Unlike the performance analysis the medium flow (0.52 in/hr) mean detection distance data has a higher degree of correlation than does the high or low flow mean detection distance data. The high flow mean detection distance data provides a poor to moderate correlation for the various retroreflectivity conditions. The medium flow mean detection distance data provides a moderate correlation for all retroreflectivity conditions. The low flow (0.28 in/hr) mean detection distance data provides a poor correlation for most retroreflectivity conditions, except that of the dry condition which shows a high degree of correlation *r* = 0.985 and the low continuous wetting rate (0.28 in/hr) which also shows a high degree of correlation *r* = 0.834.

Tape Product Analysis

Correlation analysis for the tape pavement markings resulted in the correlation values provided in Table 16. For high flow (0.87 in/hr) mean detection distance the correlation values show a strong relationship for all continuous wetting conditions. The correlation values range from 0.947 to 0.988, the values resulting in r = 0.988 are displayed in Figure 38. The mean medium flow detection distance data resulted in moderate to strong correlation values, whereas the mean low flow detection distance data resulted in strong correlation values.

TABLE 16 Detection Distance and Retroreflectivity Correlation Values for Tape Products.

R_L Measurement Condition	Detect. Dist. High Flow			Detect. Dist. Medium Flow			Detect. Dist. Low Flow		
	Q1	Mean	Q3	Q1	Mean	Q3	Q1	Mean	Q3
Dry	0.826	0.754	0.618	0.562	0.493	0.421	0.472	0.570	0.610
Recovery	0.934	0.920	0.832	0.768	0.708	0.663	0.755	0.816	0.846
0.28 r	0.931	0.947	0.895	0.890	0.850	0.816	0.782	0.814	0.841
0.52 r	0.930	0.977	0.947	0.874	0.848	0.828	0.844	0.877	0.902
0.87 r	0.904	0.969	0.942	0.813	0.790	0.772	0.855	0.898	0.921
1.2 s	0.874	0.950	0.928	0.798	0.799	0.780	0.773	0.827	0.856
2.0 s	0.888	0.960	0.935	0.800	0.788	0.770	0.823	0.872	0.898
4.0 s	0.888	0.962	0.939	0.794	0.782	0.767	0.822	0.874	0.901
6.0 s	0.912	0.979	0.957	0.825	0.812	0.798	0.847	0.892	0.918
8.0 s	0.915	0.983	0.965	0.822	0.806	0.796	0.867	0.911	0.935
9.5 s	0.920	0.988	0.973	0.830	0.815	0.807	0.874	0.916	0.941
11.5 s	0.901	0.981	0.973	0.822	0.813	0.808	0.878	0.917	0.939
14.0 s	0.840	0.952	0.959	0.715	0.714	0.721	0.902	0.948	0.964
Flood	0.867	0.965	0.963	0.742	0.736	0.737	0.888	0.938	0.958

Note: Q1 is the first quartile, and Q3 is the third quartile. High, Low N = 6 Medium N = 7

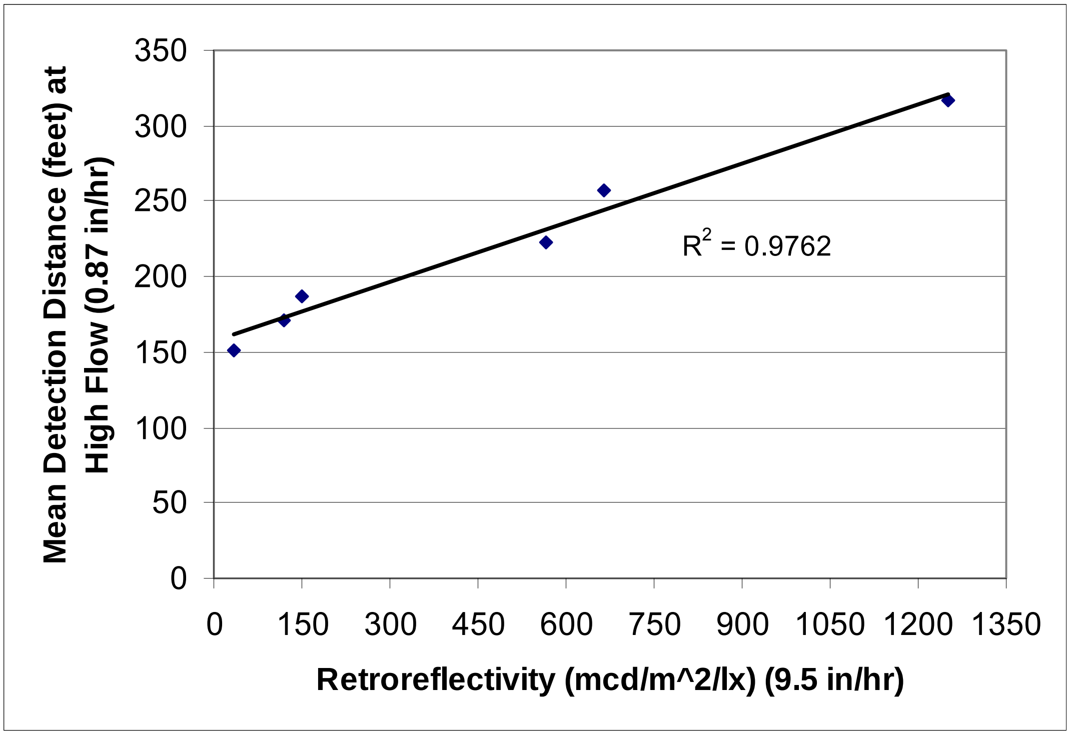

FIGURE 38 Tape Products High Flow Detection, 9.5 in/hr Rate Correlation Graph.

Other Product Analysis

The correlation analysis of the pavement marking materials grouped as "other" displayed very weak correlation, as shown in Table 17. Unlike the other correlation analyses conducted, the other product group provided a negative correlation between detection distance and retroreflectivity. The correlation values are also close to zero which indicates little or no correlation between the values. This would indicate that the pavement markings listed as "other" do not perform as one would expect. The weak correlation between the four products can be seen in Figure 39 which displays the mean detection distance values under the medium flow condition and the retroreflectivity measured at 2.0 in/hr.

TABLE 17 Detection Distance and Retroreflectivity Correlation Values for Other Products.

R_L Measurement Condition	Detect. Dist. Medium Flow (0.52 in/hr)		
	Q1	Mean	Q3
Dry	-0.763	-0.792	-0.768
Recovery	0.123	0.160	0.299
0.28 r	-0.047	-0.127	-0.202
0.52 r	0.031	-0.048	-0.117
0.87 r	-0.020	-0.104	-0.192
1.2 s	-0.010	-0.097	-0.193
2.0 s	0.093	0.012	-0.068
4.0 s	-0.125	-0.211	-0.307
6.0 s	-0.136	-0.220	-0.309
8.0 s	-0.264	-0.339	-0.396
9.5 s	-0.293	-0.371	-0.442
11.5 s	-0.395	-0.470	-0.536
14.0 s	-0.072	-0.151	-0.221
Flood	-0.064	-0.146	-0.226

Note: Q1 is the first quartile, and Q3 is the third quartile. N = 4

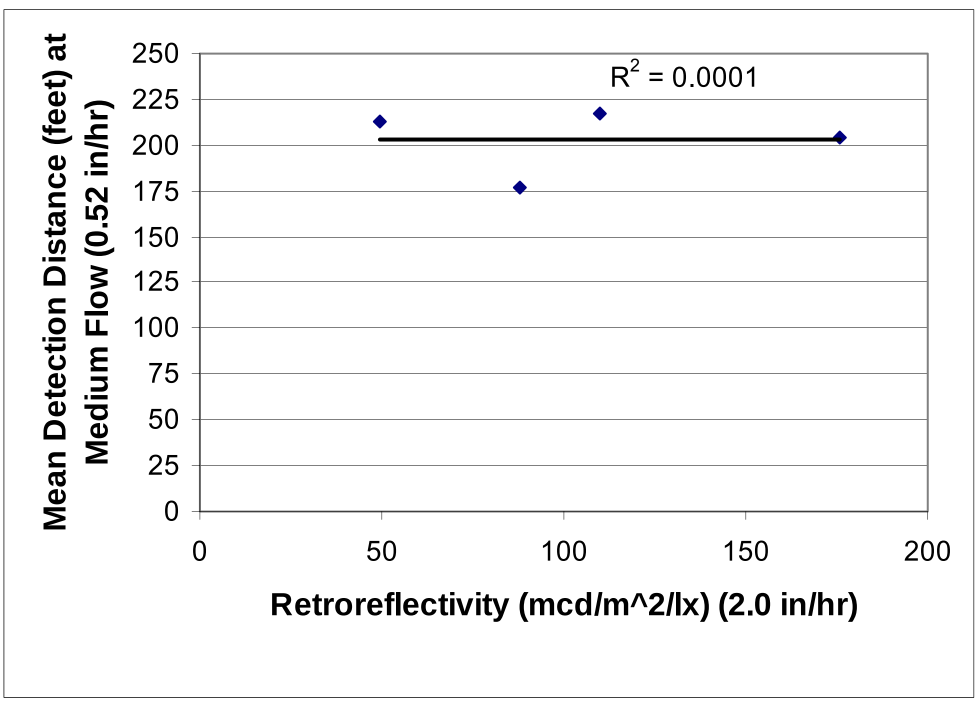

FIGURE 39 Other Products High Flow Detection, 2.0 in/hr Rate Correlation Graph.

Flat Pavement Marking Analysis

Correlation analysis for the flat pavement markings resulted in the correlation values provided in Table 18. For high flow (0.87 in/hr) mean detection distance the correlation values show a strong relationship for the continuous wetting conditions at the rainmaker (0.28, 0.52, 0.87 in/hr), but poor or moderate degrees of correlations for the other continuous wetting conditions. The correlation values range from 0.436 to 0.953, the values resulting in $r = 0.953$ are displayed in Figure 40. The mean medium flow (0.52 in/hr) detection distance data resulted in poor correlation values for all retroreflectivity conditions, whereas the mean low flow (0.28 in/hr) detection distance data resulted in poor to strong correlation values. The high flow mean detection distance values showed the highest correlation when the retroreflectivity was measured in the 0.28 in/hr continuous wetting condition, whereas the low flow mean detection distances showed the highest correlation when the retroreflectivity was measured at higher continuous wetting conditions.

TABLE 18 Detection Distance and Retroreflectivity Correlation Values for Flat Products.

R_L Measurement Condition	Detect. Dist. High Flow			Detect. Dist. Medium Flow			Detect. Dist. Low Flow		
	Q1	Mean	Q3	Q1	Mean	Q3	Q1	Mean	Q3
Dry	0.728	0.751	0.647	0.412	0.307	0.300	0.595	0.656	0.696
Recovery	0.936	0.829	0.698	0.501	0.471	0.532	0.446	0.582	0.612
0.28 r	0.678	0.932	0.946	0.476	0.316	0.287	0.547	0.562	0.579
0.52 r	0.779	0.924	0.865	0.538	0.421	0.422	0.426	0.488	0.504
0.87 r	0.789	0.953	0.915	0.512	0.376	0.377	0.423	0.496	0.528
1.2 s	0.565	0.778	0.842	0.378	0.328	0.364	0.321	0.323	0.248
2.0 s	0.701	0.807	0.828	0.329	0.287	0.344	0.501	0.556	0.493
4.0 s	0.372	0.548	0.670	-0.039	-0.122	-0.091	0.585	0.586	0.533
6.0 s	0.487	0.596	0.664	0.003	-0.070	-0.032	0.771	0.797	0.739
8.0 s	0.499	0.544	0.585	-0.029	-0.088	-0.041	0.749	0.795	0.748
9.5 s	0.540	0.571	0.596	-0.014	-0.080	-0.033	0.758	0.815	0.779
11.5 s	0.458	0.489	0.508	0.045	0.009	0.046	0.875	0.920	0.848
14.0 s	0.388	0.436	0.472	0.003	-0.027	0.007	0.879	0.905	0.820
Flood	0.613	0.563	0.533	0.064	0.008	0.059	0.772	0.868	0.855
Note: Q1 is the first quartile, and Q3 is the third quartile. High, Low N = 7 Medium N = 8									

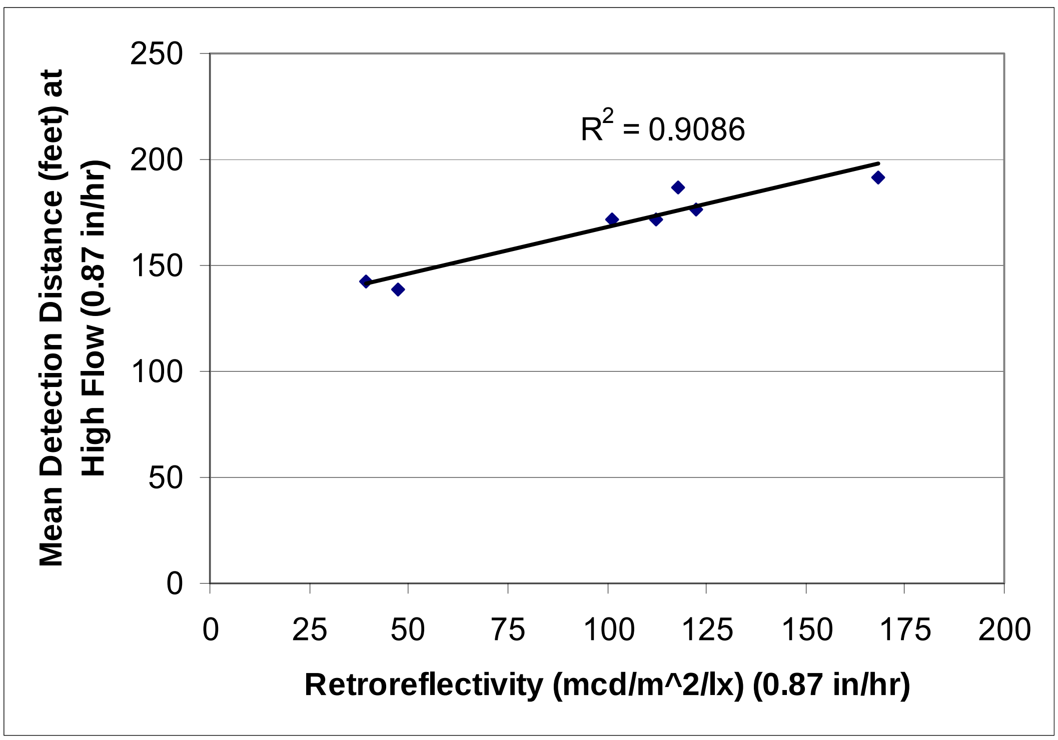

FIGURE 40 Flat Products High Flow Detection, 0.87 in/hr Rate Correlation Graph.

Profiled Pavement Marking Analysis

Correlation analysis for the profiled pavement markings resulted in the correlation values provided in Table 19. For high flow (0.87 in/hr) mean detection distance the correlation values show a strong relationship for all continuous wetting conditions. The correlation values range from 0.862 to 0.906, the values resulting in r = 0.906 are displayed in Figure 41. The mean medium flow (0.52 in/hr) detection distance data resulted in moderate to strong correlation values, whereas the mean low flow (0.27 in/hr) detection distance data resulted in strong correlation values. The results of this analysis are similar to those of the tape product analysis.

TABLE 19 Detection Distance and Retroreflectivity Correlation Values for Profiled Products.

R_L Measurement Condition	Detect. Dist. High Flow			Detect. Dist. Medium Flow			Detect. Dist. Low Flow		
	Q1	Mean	Q3	Q1	Mean	Q3	Q1	Mean	Q3
Dry	0.515	0.470	0.341	0.264	0.222	0.178	0.524	0.539	0.487
Recovery	0.754	0.836	0.781	0.749	0.747	0.731	0.896	0.864	0.853
0.28 r	0.812	0.880	0.829	0.843	0.830	0.812	0.928	0.893	0.889
0.52 r	0.797	0.897	0.869	0.832	0.829	0.819	0.961	0.933	0.933
0.87 r	0.782	0.897	0.872	0.776	0.775	0.769	0.965	0.949	0.949
1.2 s	0.745	0.862	0.840	0.717	0.751	0.768	0.928	0.901	0.890
2.0 s	0.747	0.867	0.846	0.736	0.759	0.769	0.945	0.921	0.913
4.0 s	0.755	0.874	0.855	0.730	0.753	0.764	0.952	0.931	0.923
6.0 s	0.780	0.895	0.877	0.768	0.789	0.793	0.966	0.944	0.938
8.0 s	0.780	0.898	0.885	0.770	0.788	0.796	0.972	0.952	0.947
9.5 s	0.788	0.906	0.897	0.782	0.801	0.808	0.975	0.956	0.952
11.5 s	0.781	0.904	0.900	0.771	0.790	0.799	0.977	0.961	0.957
14.0 s	0.735	0.888	0.899	0.691	0.717	0.733	0.968	0.968	0.970
Flood	0.754	0.897	0.902	0.715	0.737	0.751	0.970	0.965	0.966

Note: Q1 is the first quartile, and Q3 is the third quartile. High, Low N = 8 Medium N = 10

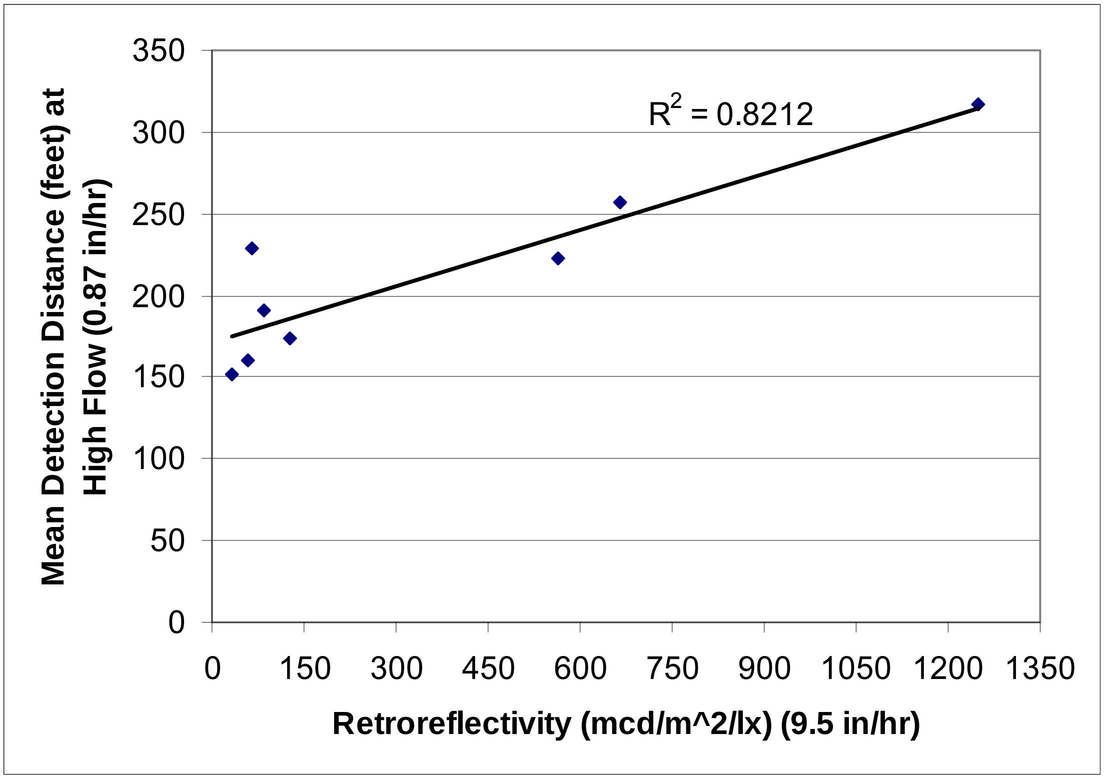

FIGURE 41 Profiled Products High Flow Detection. 9.5 in/hr Rate Correlation Graph.

ASTM Ratios Analysis

This analysis looks at retroreflectivity data that were measured using the ASTM standards and compares them to the mean detection distance under the high flow condition. New retroreflectivity data are also created by assigning a percentage value to the ASTM values and combining them. Table 20 provides the correlation values for the various retroreflectivity data sets. The assigned percentage is listed along side which measurement type is being used.

The pavement marking samples used in this analysis are the same that were used in the performance based analysis, which removed the high performing tape products.

The only difference is that the pair of tape samples 18 and 25 were removed due to their high recovery retroreflectivity. This left 10 samples to be analyzed.

TABLE 20 Detection Distance and Retroreflectivity Correlation Values for ASTM Ratio Analysis.

R_L Measurement Condition	Detect. Dist. High Flow (0.87 in/hr)		
	Q1 H	Mean H	Q3 H
Dry	0.519	0.560	0.460
Recovery	0.371	0.436	0.250
9.5 s	0.284	0.448	0.424
10% r + 90 % 9.5s	0.341	0.502	0.435
25% r + 75 % 9.5s	0.389	0.533	0.416
50% r + 50 % 9.5s	0.401	0.510	0.348
75% r + 25 % s	0.386	0.469	0.290
33.3% d + 33.3% r + 33.3% 9.5s	0.525	0.585	0.463
50% d + 50% r	0.534	0.584	0.457

Note: Q1 is the first quartile, and Q3 is the third quartile. N = 10
r = recovery, 9.5s = ASTM continuous wetting, d = dry

Like the performance based analysis and many of the other analysis groups, the dry retroreflectivity provides a poor to moderate degree of correlation, but it is better than the other ASTM standards in regards to predicting the wet performance of the pavement markings. The created retroreflectivity data slightly improved the correlation value when the dry and recovery values were factored together. Figure 42 is a plot of the mean detection distance values under high flow conditions and the retroreflectivity when 50% of the dry value is added to 50% of the recovery value. With $r = 0.584$ for this condition, the degree of correlation is only moderate.

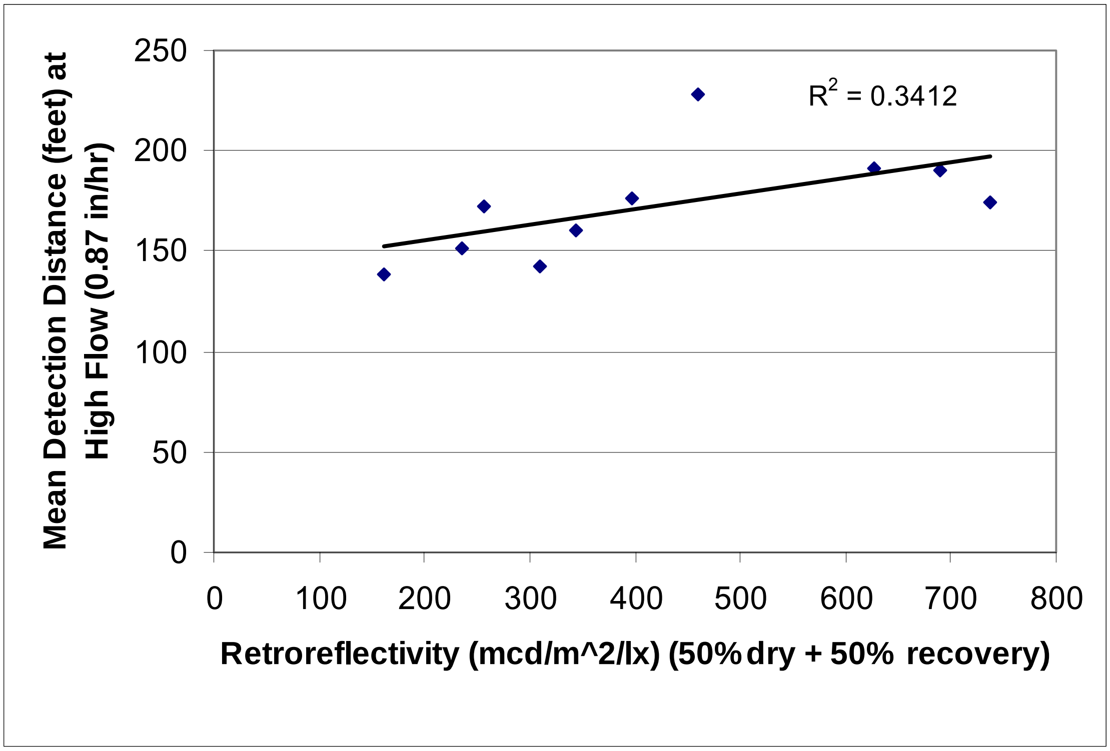

FIGURE 42 High Flow Detection, ASTM Ratio for 50% Dry + 50% Recovery Correlation Graph.

FINDINGS AND RECOMMENDATIONS

The objectives of this thesis research are to evaluate the predictive performance of ASTM R-2176, and possibly suggest any changes to the ASTM standard. Upon completion of the data collection and analyses, the results led to many findings and recommendations. Two key areas of the findings are: the problems with the continuous wetting data collection process, and the affect of various continuous wetting intensities on the pavement markings retroreflectivity. Findings based on the correlation analyses address continuous wetting intensity and the degree of correlation between the retroreflectivity and the detection distance.

GENERAL FINDINGS

The general findings of this thesis cover all aspects of the research with the exception of the correlation analyses. The focus of the general findings is on the data collection and the resulting values. Findings related to the correlation values are discussed in the next section.

Data Collection

The dry and recovery ASTM standards are simple tests to perform. This is not the same for the continuous wetting standard. There are many variables within the standard that make the test much more complicated. Water flow rate, elevation of the spray tip, diameter of the circle being sprayed, and uniformity of the water spray are all of concern and must be monitored while measuring the retroreflectivity. The researcher attempted to overcome these variables by using the spray setup that was previously described. The retroreflectivity data were collected in a laboratory environment; this setup would not be feasible for field data collection. The feasibility of this standard with off-the-shelf spraying devices is questionable, due to the number of variables present. Also of concern for field studies is water supply, as the standard can use large amounts of water if many retroreflectivity readings are being made.

Data Results

The low (0.28 in/hr), medium (0.52 in/hr), and high (0.87 in/hr) continuous wetting retroreflectivity data were measured at the rainmaker while it was in operation. The rest of the continuous wetting retroreflectivity data were measured in the controlled laboratory environment using the spray setup. The previous finding was that the continuous wetting test has many variables and the difference in the retroreflectivity between these two measurements shows that. Table 6 and Figure 26 indicate that there is a lack of consistency in retroreflectivity between the two measurement techniques. This is evident because the values in Table 6 and the curves in Figure 26 decrease initially and then increase once the new measurement technique is started before decreasing again. There are many factors that may cause this discrepancy, such as water droplet size, elevation from which the droplets fall, and direct sunlight on the pavement marking while measuring the retroreflectivity at the rainmaker.

Also looking at Table 6 and Figure 26 the relationship between the amount of water being sprayed on the pavement marking and the markings' retroreflectivity is evident. As the amount of water being sprayed onto the pavement marking increases, the retroreflectivity of that marking typically decreases. It can also be seen that some pavement marking materials suffer a greater loss in retroreflectivity when water is applied to the marking. Also some markings are able to maintain a constant level of retroreflectivity even when the amount of water applied is increased.

CORRELATION

The correlation figures consistently show that pavement markings exhibit a positive correlation between retroreflectivity and detection distance. This relationship would imply that the higher the retroreflectivity of a pavement marking, then the greater the detection distance.

The initial correlation analysis provides a strong correlation between the retroreflectivity and the detection distance $r = 0.898$ when correlating the mean high flow detection distances with the 9.5 in/hr (ASTM) continuous wetting rate. However, further investigation reveals that it is not as strong as initially thought. After removing the three high performing materials, the degree of correlation drops substantically to, $r = 0.403$. This would indicate a weak correlation between the two values.

Generally it was found that the detection distances collected in the high flow condition correlated better to the retroreflectivity than either the low or medium conditions. It was also found that there was no continuous wetting rate for the retroreflectivity data produced higher correlation values than any of the other rates. Actually it was found that when looking at all the markings together, excluding the high performers that the dry retroreflectivity measurement condition correlated as well as most of the continuous wetting retroreflectivity data.

Looking at the subgroups analysis, it was found that a strong correlation exists between retroreflectivity at all continuous wetting rates and high flow (0.87 in/hr) mean detection distance for pavement marking tapes, wet pavement marking products, and profiled pavement markings. It was also found that a moderate correlation exists between retroreflectivity all continuous wetting rates and high flow (0.87 in/hr) mean detection distance for flat pavement markings and thermoplastic pavement markings.

SUMMARY OF FINDINGS

The findings from all aspects of the study impact the recommendations made and possible further action in regards to investigating the current ASTM E-2176 continuous wetting retroreflectivity measurement standard.

- Overall, the research results indicate that ASTM E-2176 does not provide strong predictive performance for pavement marking visibility in wet weather conditions for all pavement marking materials. The standard has high correlation coefficient values for tape products (r = 0.988), but the correlation coefficient value is (r = 0.668) for thermoplastic products, and the correlation coefficient is (r = 0.403) for all of the pavement markings excluding the three highest performers.
- Currently, ASTM E-2176 is the only method to measure the retroreflectivity of a pavement marking in a state of continuous wetting. The ASTM standard should be considered a strong measure of predictive performance for all tape products and profiled markings, but only moderate at best for any other pavement marking types.
- ASTM E-2176 is not as simple a procedure as the other ASTM pavement marking retroreflectivity standards. The standard is not as feasible in the field

due to the additional necessary equipment and time it takes to conduct the measurements.

- ASTM E-2176 has many variables within the test such as the water flow rate, elevation of the spray tip, diameter of the circle being sprayed, and uniformity of the water spray.
- No single continuous wetting rate that was determined to produce higher levels of correlation as compared to the other rates. Actually the dry retroreflectivity data (r = 0.575), performed as well as most of the continuous wetting retroreflectivity data when looking at the truncated data for mean detection distances under the high flow (0.87 in/hr) condition. The correlation coefficient for the ASTM standard and mean detection distance under high flow rate for the truncated data is (r = 0.403).
- Tape products, wet products, and profiled pavement markings had a strong correlation between detection distance and retroreflectivity.
- Flat products and thermoplastic pavement markings had a moderate correlation between detection distance and retroreflectivity.
- High performing pavement markings can skew correlation values, thus indicating stronger correlation than what actually exists. This is evident from the three high performing materials greatly skewing the data. The correlation coefficient was r = 0.898 before removal of the high performing products and r = 0.403 after.
- Increasing the amount of water applied to a marking decreases the markings' retroreflectivity. This poses a major concern due to the large range of acceptable

continuous wetting conditions for the ASTM E-2176 standard. The range is from approximately 5.75 in/hr to 14.5 in/hr, with 9.3 in/hr being the central value. With a large range of acceptable continuous wetting intensities a large range of retroreflectivity data should be expected, but that should not be the case for a measurement standard.

- Not all pavement markings react in the same manner when water is applied to them. Some pavement markings lose most of their retroreflectivity when any amount of water is applied to the marking and as the continuous wetting rates are increased the marking remains at a low level of retroreflectivity. Other markings do not lose retroreflectivity as rapidly and thus display a gradual decrease in retroreflectivity as the continuous wetting rates are increased.

RECOMMENDATIONS

Based on the findings, the researcher recommends the following actions to further explore the retroreflectivity measurement of a pavement marking during a continuous wetting state.

- It is recommended that further studies should be conducted to expand on this thesis research for a variety of pavement marking materials, including more pavement markings that are typically used (i.e., more waterborne paint and thermoplastic pavement markings). Further research is necessary if the continuous wetting retroreflectivity standard is going to be considered a valid performance prediction technique.

- A research study is recommended that includes luminance data to allow for further comparisons of detection distances and retroreflectivity, as well as calculated retroreflectivity. This could possible yield a suggested minimum luminance value instead of a retroreflectivity value. The relationship between retroreflectivity, luminance, and sight distance could also be explored.
- The current ASTM standard for a retroreflectivity measurement in a condition of continuous wetting allows for a large range of continuous wetting rates. This seems appropriate as any amount of water applied to a marking tends to yield similar correlation results. However, the correlation that results for the retroreflectivity data is less than desirable. The problem with the large range of values is that retroreflectivity is affected by the amount of water placed on the marking, therefore higher retroreflectivity will be measured at the low end of the range and lower retroreflectivity will result from the higher continuous wetting rates. If a retroreflectivity requirement or recommendation was established for the continuous wetting standard, the range of continuous wetting rates would need to be narrowed to reduce variability of the measurement conditions.
- If a specific continuous wetting rate is deemed necessary, or if recommended levels of retroreflectivity under a continuous wetting condition are established, or a reduction in measurement variables is sought, then a specialized spraying setup should be created and made available to anyone performing these measurements. This spraying setup could address issues of practicality and variability of the measurement.

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APPENDIX A

STUDY DESIGN INFORMATION

TABLE A-1 Pavement Marking Material Descriptions and Images.

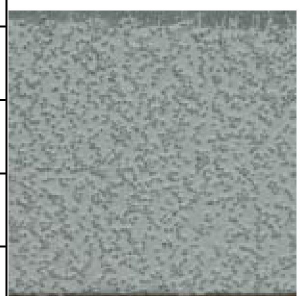
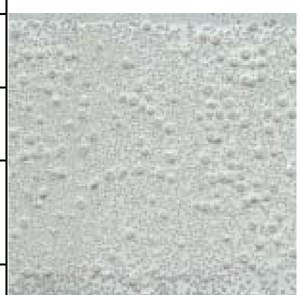
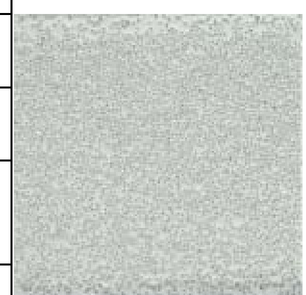
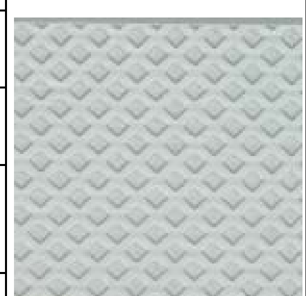
INFORMATION	IMAGE	INFORMATION	IMAGE
Marking Number: 5		**Marking Number:** 6	
Material Type: Waterborne Paint		**Binder Type:** Waterborne Paint	
Manufacturer: Ennis Paint		**Manufacturer:** All-American Coatings	
Bead: Type III Weissker		**Bead:** Type II Potters	
Marking: Width: 3.8 in. Thickness: .01 in.		**Marking:** Width: 4.0 in. Thickness: .02 in.	
Marking Number: 8		**Marking Number:** 10	
Binder Type: LS 90 Polyurea		**Binder Type:** LS 50 Epoxy	
Manufacturer: EpoPlex		**Manufacturer:** EpoPlex	
Bead: GloMarc 90, Type II Visibead		**Bead:** Type III (25% Visionglow, 75% Visibead)	
Marking: Width: 4.3 in. Thickness: .017 in.		**Marking:** Width: 4.1 in. Thickness: .02 in.	
Marking Number: 11		**Marking Number:** 15	
Binder Type: Thermoplastic		**Binder Type:** Tape A380I	
Manufacturer: Ennis Paint		**Manufacturer:** 3M	
Bead: Type I, III, High Index		**Marking:** Width: 4.0 in. Thickness: .02 in.	
Marking: Width: 4.3 in. Thickness: .11 in.			

Table A-1 Continued.

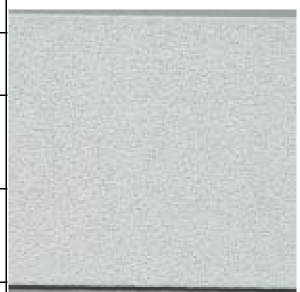
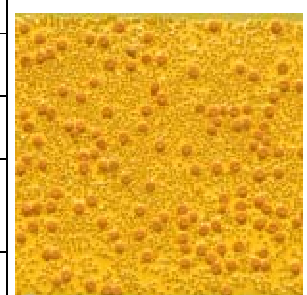
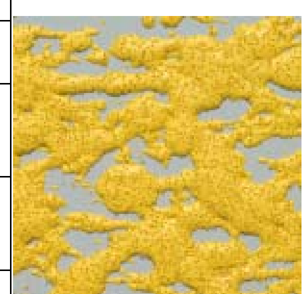
Marking Number: 16 **Binder Type:** Tape A750ES **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: .01 in.		**Marking Number:** 17 **Binder Type:** Tape 380WR **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: .02 in.	
Marking Number: 18 **Binder Type:** Tape ATM 400 **Manufacturer:** Advanced Traffic Markings **Marking:** Width: 4.0 in. Thickness: .06 in.		**Marking Number:** 21 **Binder Type:** Tape A380I **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: .02 in.	
Marking Number: 22 **Binder Type:** Tape A750ES **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: .01 in.		**Marking Number:** 23 **Binder Type:** LS90 Polyurea **Manufacturer:** EpoPlex **Bead:** GloMarc 90, Type II Visibead **Marking:** Width: 4.0 in. Thickness: .017 in.	
Marking Number: 25 **Binder Type:** Tape ATM 400 **Manufacturer:** Advanced Traffic Markings **Marking:** Width: 4.0 in. Thickness: .06 in.		**Marking Number:** 31 **Binder Type:** Methyl Methacrylate **Manufacturer:** Degussa **Bead:** Type III Virgin Swarco **Marking:** Width: 4.5 in. Thickness: .12 in.	

Table A-1 Continued.

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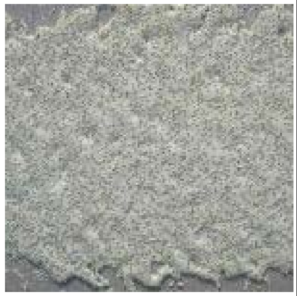
32</td><td rowspan="5"></td><td>Marking Number:
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Ennis Paint</td></tr>
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<tr><td>Marking:
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Thickness: .07 in.</td><td>Marking:
Width: 4.1 in.
Thickness: .09 in.</td></tr>
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35</td><td rowspan="5"></td></tr>
<tr><td>Binder Type:
Thermoplastic</td><td>Binder Type:
Rumble Stripe:
Thermoplastic</td></tr>
<tr><td>Manufacturer:
Ennis Paint</td><td>Manufacturer:
Ennis Paint</td></tr>
<tr><td>Bead: Type II</td><td>Bead: Type II</td></tr>
<tr><td>Marking:
Width: 3.9 in.
Thickness: .06 in.</td><td>Marking:
Width: 3.9 in.
Thickness: .06 in.</td></tr>
</table>

TABLE A-2 ASTM E-2176 Continuous Wetting Rate Chart.

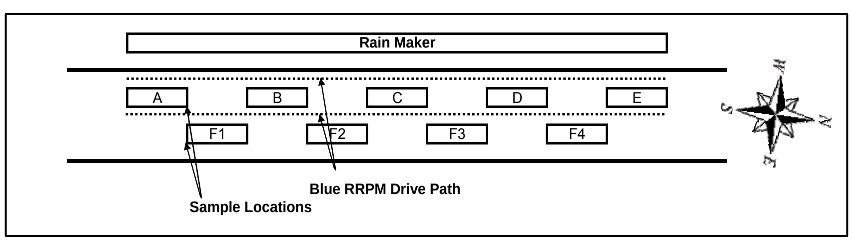
		Continuous Wetting Rate (inches/hour) for Indicated Circle Diameter (inches)															
Circle Diameter		12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Flow Rate (liters/minute)	1.000	32.37	27.59	23.79	20.72	18.21	16.13	**14.39**	**12.91**	**11.65**	**10.57**	**9.63**	8.81	8.09	7.46	6.90	6.39
	0.950	30.76	26.21	22.60	19.68	17.30	15.32	**13.67**	**12.27**	**11.07**	**10.04**	**9.15**	8.37	7.69	7.09	6.55	6.08
	0.900	29.14	24.83	21.41	18.65	16.39	14.52	**12.95**	**11.62**	**10.49**	**9.51**	**8.67**	7.93	7.28	6.71	6.21	5.76
	0.850	27.52	23.45	20.22	17.61	15.48	13.71	**12.23**	**10.98**	**9.91**	**8.99**	**8.19**	7.49	6.88	6.34	5.86	5.44
	0.800	25.90	22.07	19.03	16.58	14.57	12.90	**11.51**	**10.33**	**9.32**	**8.46**	**7.71**	7.05	6.47	5.97	5.52	5.12
	0.750	24.28	20.69	17.84	15.54	13.66	12.10	**10.79**	**9.69**	**8.74**	**7.93**	**7.22**	6.61	6.07	5.59	5.17	4.80
	0.700	22.66	19.31	16.65	14.50	12.75	11.29	**10.07**	**9.04**	**8.16**	**7.40**	**6.74**	6.17	5.67	5.22	4.83	4.48
	0.650	21.04	17.93	15.46	13.47	11.84	10.49	**9.35**	**8.39**	**7.58**	**6.87**	**6.26**	5.73	5.26	4.85	4.48	4.16
	0.600	19.42	16.55	14.27	12.43	10.93	9.68	**8.63**	**7.75**	**6.99**	**6.34**	**5.78**	5.29	4.86	4.48	4.14	3.84
	0.550	17.81	15.17	13.08	11.40	10.02	8.87	7.91	7.10	6.41	5.81	5.30	4.85	4.45	4.10	3.79	3.52
	0.500	16.19	13.79	11.89	10.36	9.11	8.07	7.19	6.46	5.83	5.29	4.82	4.41	4.05	3.73	3.45	3.20
	0.450	14.57	12.41	10.70	9.32	8.19	7.26	6.47	5.81	5.24	4.76	4.33	3.97	3.64	3.36	3.10	2.88
	0.400	12.95	11.03	9.51	8.29	7.28	6.45	5.76	5.17	4.66	4.23	3.85	3.53	3.24	2.98	2.76	2.56
	0.350	11.33	9.65	8.32	7.25	6.37	5.65	5.04	4.52	4.08	3.70	3.37	3.08	2.83	2.61	2.41	2.24
	0.300	9.71	8.28	7.14	6.22	5.46	4.84	4.32	3.87	3.50	3.17	2.89	2.64	2.43	2.24	2.07	1.92
	0.250	8.09	6.90	5.95	5.18	4.55	4.03	3.60	3.23	2.91	2.64	2.41	2.20	2.02	1.86	1.72	1.60
	0.200	6.47	5.52	4.76	4.14	3.64	3.23	2.88	2.58	2.33	2.11	1.93	1.76	1.62	1.49	1.38	1.28

Note: The bold values are within the acceptable range of the ASTM E-2176 continuous wetting standard. The bold value in the center of the bordered area is the center of the recommended value.

TABLE A-3 Panel Layout Setup.

Project	5008 - Wet/Night	Start Time		End Time	
Date		Temperature		Temperature	
Subject		Wind Speed		Wind Speed	
		Wind Direction		Wind Direction	

Run	Direction (N/S)	Flow (L/M/H)	Sample and Location									
			A	F1	B	F2	C	F3	D	F4	E	
1	N	H			6				16			
2	S	H	8				17					
3	N	H		X			21				22	
4	S	H			11				5			
5	N	H			31				32			
6	S	H	35				33					
7	N	H			32						31	
8	S	M	18			X			6			
9	N	M			34						16	
10	S	M	36									
11	N	M			15				17			
12	S	M	23						5			



APPENDIX B

RESULTS INFORMATION

TABLE B-1 Dry Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m^2/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	375	356	358	341	375	378	364	14.61
6	Paint, Type II, W	297	297	260	301	284	288	288	15.04
8	Polyurea, Cluster Bead, W	1254	1217	1239	1231	1217	1231	1232	14.02
10	Epoxy, Type III, W	557	514	482	493	580	517	524	37.68
11	Thermo, Mixed, W	756	752	797	847	807	761	787	37.31
15	3M 380 Tape, N/A, W	637	748	770	733	823	765	746	61.51
16	3M 750 Tape, N/A, W	1220	1232	1211	1222	1211	1223	1220	7.99
17	3M 380WR Tape, N/A W	1273	1241	1201	1242	1227	1220	1234	24.36
18	ATM 400 Tape, N/A, W	966	933	906	925	911	980	937	29.96
21	3M 380 Tape, N/A, Y	371	408	424	409	403	392	401	18.04
22	3M 750 Tape, N/A, Y	878	856	783	853	788	908	844	49.67
23	Polyurea, Cluster Bead, Y	1194	1225	1250	1234	1249	1222	1229	20.77
25	ATM 400 Tape, N/A, Y	549	547	626	617	590	647	596	41.44
31	Methacrylate, Type III, Y	318	307	342	354	351	334	334	18.64
32	Thermo, Type III, W	981	909	995	981	1028	937	972	42.48
33	Thermo, Mixed, W	501	519	528	505	497	512	510	11.69
34	Thermo, Type II, W	515	535	483	515	553	544	524	25.32
35	Thermo Rumble, Type II, W	492	520	479	538	511	480	503	23.68

TABLE B-2 Recovery Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	149	146	152	154			150	3.50
6	Paint, Type II, W	36	37	34	31			35	2.65
8	Polyurea, Cluster Bead, W	248	242	240	242			243	3.46
10	Epoxy, Type III, W	262	248	250	251			253	6.29
11	Thermo, Mixed, W	135	131	135	134			134	1.89
15	3M 380 Tape, N/A, W	240	225	242	222			232	10.21
16	3M 750 Tape, N/A, W	1220	1254	1240	1244			1240	14.27
17	3M 380WR Tape, N/A W	980	956	979	984			975	12.69
18	ATM 400 Tape, N/A, W	487	561	522	466			509	41.66
21	3M 380 Tape, N/A, Y	74	73	67	68			71	3.51
22	3M 750 Tape, N/A, Y	735	753	725	733			737	11.82
23	Polyurea, Cluster Bead, Y	150	143	153	152			150	4.51
25	ATM 400 Tape, N/A, Y	236	239	252	243			243	6.95
31	Methacrylate, Type III, Y	113	112	116	111			113	2.16
32	Thermo, Type III, W	301	282	274	270			282	13.77
33	Thermo, Mixed, W	275	288	286	284			283	5.74
34	Thermo, Type II, W	108	90	96	89			96	8.73
35	Thermo Rumble, Type II, W	197	202	165	175			185	17.63

TABLE B-3 Rainmaker Low Setting Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	161	158	154	156	155	158	157	2.53
6	Paint, Type II, W	47	46	46	45	45	56	48	4.23
8	Polyurea, Cluster Bead, W	257	255	250	244	245	249	250	5.22
10	Epoxy, Type III, W	75	69	75	66	69	75	72	3.99
11	Thermo, Mixed, W	205	212	214	193	194	198	203	9.07
15	3M 380 Tape, N/A, W	81	78	77	55	55	54	67	13.22
16	3M 750 Tape, N/A, W	1208	1211	1205	1184	1203	1218	1205	11.48
17	3M 380WR Tape, N/A W	887	884	887	889	887	889	887	1.83
18	ATM 400 Tape, N/A, W	179	177	177	176	179	178	178	1.21
21	3M 380 Tape, N/A, Y	70	70	73	73	73	76	73	2.26
22	3M 750 Tape, N/A, Y	870	869	870	879	869	884	874	6.41
23	Polyurea, Cluster Bead, Y	140	140	141	143	145	150	143	3.87
25	ATM 400 Tape, N/A, Y	140	145	145	156	150	148	147	5.43
31	Methacrylate, Type III, Y	147	148	148	149	151	151	149	1.67
32	Thermo, Type III, W	250	251	252	253	254	254	252	1.63
33	Thermo, Mixed, W	128	128	128	130	132	133	130	2.23
34	Thermo, Type II, W	67	69	72	74	75	70	71	3.06
35	Thermo Rumble, Type II, W	140	142	144	144	146	149	144	3.13

Note: Continuous wetting measurements conducted in the rain maker at low flow setting (0.28 in/hr).

TABLE B-4 Rainmaker Medium Setting Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	105	110	101	102	107	103	105	3.39
6	Paint, Type II, W	37	38	39	40	42	44	40	2.61
8	Polyurea, Cluster Bead, W	225	225	227	231	219	222	225	4.12
10	Epoxy, Type III, W	45	35	48	39	42	46	43	4.85
11	Thermo, Mixed, W	140	144	146	147	150	151	146	4.03
15	3M 380 Tape, N/A, W	41	43	45	51	38	47	44	4.58
16	3M 750 Tape, N/A, W	1276	1290	1295	1281	1279	1285	1284	7.15
17	3M 380WR Tape, N/A W	757	757	738	712	709	750	737	21.81
18	ATM 400 Tape, N/A, W	128	134	131	139	130	125	131	4.88
21	3M 380 Tape, N/A, Y	47	50	51	52	53	56	52	3.02
22	3M 750 Tape, N/A, Y	796	805	811	831	791	822	809	15.27
23	Polyurea, Cluster Bead, Y	101	99	97	105	99	102	101	2.81
25	ATM 400 Tape, N/A, Y	130	132	137	142	140	135	136	4.60
31	Methacrylate, Type III, Y	118	118	112	120	119	113	117	3.33
32	Thermo, Type III, W	203	212	217	214	218	207	212	5.85
33	Thermo, Mixed, W	150	150	151	151	154	157	152	2.79
34	Thermo, Type II, W	40	50	52	49	47	46	47	4.18
35	Thermo Rumble, Type II, W	152	144	160	162	147	149	152	7.23

Note: Continuous wetting measurements conducted in the rain maker at medium flow setting (0.52 in/hr).

TABLE B-5 Rainmaker High Setting Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	96	97	103	105	107	99	101	4.49
6	Paint, Type II, W	46	46	47	48	48	49	47	1.21
8	Polyurea, Cluster Bead, W	180	180	180	184	184	186	182	2.66
10	Epoxy, Type III, W	39	40	43	49	38	32	40	5.64
11	Thermo, Mixed, W	131	130	127	127	128	129	129	1.63
15	3M 380 Tape, N/A, W	45	48	50	50	51	54	50	3.01
16	3M 750 Tape, N/A, W	1168	1170	1165	1159	1154	1151	1161	7.73
17	3M 380WR Tape, N/A W	620	625	626	629	640	643	631	9.05
18	ATM 400 Tape, N/A, W	117	115	124	119	120	111	118	4.46
21	3M 380 Tape, N/A, Y	47	48	47	50	46	44	47	2.00
22	3M 750 Tape, N/A, Y	577	576	601	600	585	591	588	10.91
23	Polyurea, Cluster Bead, Y	96	96	92	108	104	110	101	7.35
25	ATM 400 Tape, N/A, Y	103	104	118	129	109	110	112	9.83
31	Methacrylate, Type III, Y	123	114	116	107	109	112	114	5.68
32	Thermo, Type III, W	163	166	167	169	175	170	168	4.08
33	Thermo, Mixed, W	126	127	120	119	120	122	122	3.39
34	Thermo, Type II, W	35	36	38	39	42	45	39	3.76
35	Thermo Rumble, Type II, W	129	131	133	127	126	130	129	2.58

Note: Continuous wetting measurements conducted in the rain maker at high flow setting (0.87 in/hr).

TABLE B-6 Continuous Wetting Rate of 1.2 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	192	190	191	191	194	195	192	1.94
6	Paint, Type II, W	22	19	19	20	21	21	20	1.21
8	Polyurea, Cluster Bead, W	187	186	185	185	183	179	184	2.86
10	Epoxy, Type III, W	54	56	56	55	55	55	55	0.75
11	Thermo, Mixed, W	85	85	86	86	90	88	87	1.97
15	3M 380 Tape, N/A, W	294	294	294	298	298	296	296	1.97
16	3M 750 Tape, N/A, W	1297	1301	1304	1311	1299	1300	1302	4.98
17	3M 380WR Tape, N/A W	772	773	774	778	779	779	776	3.19
18	ATM 400 Tape, N/A, W	120	126	126	130	132	132	128	4.63
21	3M 380 Tape, N/A, Y	166	169	169	172	173	175	171	3.27
22	3M 750 Tape, N/A, Y	682	691	704	706	694	700	696	9.00
23	Polyurea, Cluster Bead, Y	116	111	113	113	114	114	114	1.64
25	ATM 400 Tape, N/A, Y	154	157	159	160	161	158	158	2.48
31	Methacrylate, Type III, Y	127	127	128	131	130	129	129	1.63
32	Thermo, Type III, W	129	131	130	126	125	124	128	2.88
33	Thermo, Mixed, W	156	158	159	160	161	160	159	1.79
34	Thermo, Type II, W	30	30	31	32	32	32	31	0.98
35	Thermo Rumble, Type II, W	98	98	99	100	101	100	99	1.21

Note: Continuous wetting rate measured over six minute interval: 1.2, 1.3, 1.2 in/hr.

TABLE B-7 Continuous Wetting Rate of 2 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m^2/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	148	149	149	148	148	144	148	1.86
6	Paint, Type II, W	28	22	21	21	20	21	22	2.93
8	Polyurea, Cluster Bead, W	176	178	179	170	181	172	176	4.24
10	Epoxy, Type III, W	46	48	49	50	51	52	49	2.16
11	Thermo, Mixed, W	70	74	75	77	80	81	76	4.07
15	3M 380 Tape, N/A, W	183	185	188	190	190	201	190	6.28
16	3M 750 Tape, N/A, W	1251	1254	1257	1257	1261	1204	1247	21.49
17	3M 380WR Tape, N/A W	709	711	712	718	721	722	716	5.54
18	ATM 400 Tape, N/A, W	153	154	154	154	153	158	154	1.86
21	3M 380 Tape, N/A, Y	119	126	125	132	129	130	127	4.62
22	3M 750 Tape, N/A, Y	631	639	642	649	651	652	644	8.20
23	Polyurea, Cluster Bead, Y	85	86	88	89	89	91	88	2.19
25	ATM 400 Tape, N/A, Y	162	163	169	169	142	183	165	13.40
31	Methacrylate, Type III, Y	104	104	110	110	111	119	110	5.54
32	Thermo, Type III, W	97	97	99	103	107	111	102	5.75
33	Thermo, Mixed, W	131	133	133	135	137	138	135	2.66
34	Thermo, Type II, W	26	26	21	22	32	25	25	3.88
35	Thermo Rumble, Type II, W	98	98	102	102	103	103	101	2.37
Note: Continuous wetting rate measured over six minute interval: 1.8, 2.0, 2.0 in/hr.									

TABLE B-8 Continuous Wetting Rate of 4 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m^2/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	143	143	143	146	147	148	145	2.28
6	Paint, Type II, W	19	19	19	19	20	20	19	0.52
8	Polyurea, Cluster Bead, W	160	161	161	162	163	163	162	1.21
10	Epoxy, Type III, W	17	17	18	19	20	22	19	1.94
11	Thermo, Mixed, W	66	65	67	67	68	71	67	2.07
15	3M 380 Tape, N/A, W	162	166	167	170	172	175	169	4.63
16	3M 750 Tape, N/A, W	1282	1292	1294	1300	1288	1290	1291	6.03
17	3M 380WR Tape, N/A W	703	700	708	714	714	718	710	7.04
18	ATM 400 Tape, N/A, W	143	141	151	153	147	150	148	4.72
21	3M 380 Tape, N/A, Y	105	109	111	118	120	100	111	7.61
22	3M 750 Tape, N/A, Y	638	652	630	650	629	630	638	10.48
23	Polyurea, Cluster Bead, Y	97	95	96	96	97	98	97	1.05
25	ATM 400 Tape, N/A, Y	120	118	122	128	130	124	124	4.63
31	Methacrylate, Type III, Y	96	98	99	99	99	100	99	1.38
32	Thermo, Type III, W	47	47	50	50	52	52	50	2.25
33	Thermo, Mixed, W	35	35	36	37	37	38	36	1.21
34	Thermo, Type II, W	20	17	18	18	19	20	19	1.21
35	Thermo Rumble, Type II, W	71	68	70	70	72	71	70	1.37
Note: Continuous wetting rate measured over six minute interval: 4.0, 3.8, 3.9 in/hr.									

TABLE B-9 Continuous Wetting Rate of 6 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	85	89	90	90	90	91	89	2.14
6	Paint, Type II, W	12	12	12	13	13	14	13	0.82
8	Polyurea, Cluster Bead, W	153	157	159	162	164	161	159	3.93
10	Epoxy, Type III, W	13	15	15	16	16	18	16	1.64
11	Thermo, Mixed, W	66	66	66	67	68	68	67	0.98
15	3M 380 Tape, N/A, W	118	124	124	126	126	130	125	3.93
16	3M 750 Tape, N/A, W	1232	1250	1254	1254	1268	1247	1251	11.70
17	3M 380WR Tape, N/A W	621	628	641	648	648	618	634	13.43
18	ATM 400 Tape, N/A, W	127	128	128	132	132	135	130	3.14
21	3M 380 Tape, N/A, Y	45	46	46	48	49	49	47	1.72
22	3M 750 Tape, N/A, Y	676	648	652	660	653	671	660	11.26
23	Polyurea, Cluster Bead, Y	90	90	93	91	92	93	92	1.38
25	ATM 400 Tape, N/A, Y	110	119	121	124	129	132	123	7.82
31	Methacrylate, Type III, Y	87	89	90	91	91	92	90	1.79
32	Thermo, Type III, W	48	49	50	52	52	55	51	2.53
33	Thermo, Mixed, W	29	30	30	30	31	32	30	1.03
34	Thermo, Type II, W	21	21	22	22	23	23	22	0.89
35	Thermo Rumble, Type II, W	59	60	64	66	67	69	64	3.97
Note: Continuous wetting rate measured over six minute interval: 6.1, 5.9, 6.1 in/hr.									

TABLE B-10 Continuous Wetting Rate of 8 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	82	83	84	85	86	86	84	1.63
6	Paint, Type II, W	12	12	12	12	13	13	12	0.52
8	Polyurea, Cluster Bead, W	149	159	153	156	157	158	155	3.72
10	Epoxy, Type III, W	15	17	19	21	15	22	18	2.99
11	Thermo, Mixed, W	67	67	68	70	71	71	69	1.90
15	3M 380 Tape, N/A, W	94	94	95	96	97	100	96	2.28
16	3M 750 Tape, N/A, W	1256	1260	1262	1263	1266	1270	1263	4.83
17	3M 380WR Tape, N/A W	588	600	606	610	616	618	606	11.13
18	ATM 400 Tape, N/A, W	150	152	157	158	162	167	158	6.28
21	3M 380 Tape, N/A, Y	51	52	52	52	53	56	53	1.75
22	3M 750 Tape, N/A, Y	655	656	660	661	668	670	662	6.15
23	Polyurea, Cluster Bead, Y	87	91	91	91	92	94	91	2.28
25	ATM 400 Tape, N/A, Y	121	123	132	138	140	141	133	8.73
31	Methacrylate, Type III, Y	60	63	63	64	67	65	64	2.34
32	Thermo, Type III, W	40	40	43	43	45	47	43	2.76
33	Thermo, Mixed, W	22	23	25	27	32	28	26	3.66
34	Thermo, Type II, W	22	22	22	22	23	25	23	1.21
35	Thermo Rumble, Type II, W	63	67	70	60	62	61	64	3.87

Note: Continuous wetting rate measured over six minute interval: 7.9, 8.3, 7.8 in/hr.

TABLE B-11 Continuous Wetting Rate of 9.5 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m^2/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	68	68	71	74	74	75	72	3.14
6	Paint, Type II, W	12	12	12	12	13	15	13	1.21
8	Polyurea, Cluster Bead, W	123	125	126	131	131	131	128	3.60
10	Epoxy, Type III, W	14	15	16	16	17	17	16	1.17
11	Thermo, Mixed, W	64	65	65	65	65	66	65	0.63
15	3M 380 Tape, N/A, W	73	74	75	76	76	77	75	1.47
16	3M 750 Tape, N/A, W	1247	1257	1260	1254	1251	1230	1250	10.72
17	3M 380WR Tape, N/A W	572	573	561	567	558	555	564	7.47
18	ATM 400 Tape, N/A, W	141	142	150	155	157	157	150	7.31
21	3M 380 Tape, N/A, Y	32	33	34	34	35	35	34	1.17
22	3M 750 Tape, N/A, Y	652	660	667	678	672	668	666	9.13
23	Polyurea, Cluster Bead, Y	81	82	83	83	85	87	84	2.17
25	ATM 400 Tape, N/A, Y	107	115	119	121	124	131	120	8.14
31	Methacrylate, Type III, Y	57	60	61	63	67	65	62	3.60
32	Thermo, Type III, W	44	46	46	47	47	48	46	1.37
33	Thermo, Mixed, W	23	24	25	26	27	27	25	1.63
34	Thermo, Type II, W	21	22	22	22	23	23	22	0.75
35	Thermo Rumble, Type II, W	55	55	57	57	59	60	57	2.04

Note: Continuous wetting rate measured over six minute interval: 9.5, 9.1, 9.6 in/hr.

TABLE B-12 Continuous Wetting Rate of 11.5 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	39	41	40	43	37	51	42	4.92
6	Paint, Type II, W	17	19	11	16	17	15	16	2.71
8	Polyurea, Cluster Bead, W	127	132	122	129	124	126	127	3.56
10	Epoxy, Type III, W	15	19	17	18	14	20	17	2.32
11	Thermo, Mixed, W	54	56	67	61	60	59	60	4.51
15	3M 380 Tape, N/A, W	68	73	75	77	70	71	72	3.33
16	3M 750 Tape, N/A, W	1220	1249	1250	1217	1256	1219	1235	18.26
17	3M 380WR Tape, N/A W	515	528	532	543	513	559	532	17.41
18	ATM 400 Tape, N/A, W	100	89	103	104	78	79	92	11.86
21	3M 380 Tape, N/A, Y	47	41	43	42	40	38	42	3.06
22	3M 750 Tape, N/A, Y	609	651	597	691	621	634	634	33.77
23	Polyurea, Cluster Bead, Y	76	83	117	90	91	98	93	14.15
25	ATM 400 Tape, N/A, Y	119	123	125	126	120	117	122	3.56
31	Methacrylate, Type III, Y	60	58	61	63	57	60	60	2.14
32	Thermo, Type III, W	44	48	38	41	43	44	43	3.35
33	Thermo, Mixed, W	26	31	34	20	28	28	28	4.75
34	Thermo, Type II, W	16	23	25	21	26	23	22	3.56
35	Thermo Rumble, Type II, W	66	64	64	58	56	60	61	3.93
Note: Continuous wetting rate measured over six minute interval: 10.5, 11.5, 11.5 in/hr.									

TABLE B-13 Continuous Wetting Rate of 14 in/hr Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	42	45	45	47	48	49	46	2.53
6	Paint, Type II, W	17	17	18	18	18	19	18	0.75
8	Polyurea, Cluster Bead, W	110	120	122	113	114	118	116	4.58
10	Epoxy, Type III, W	16	18	21	22	23	22	20	2.73
11	Thermo, Mixed, W	46	47	52	53	55	59	52	4.90
15	3M 380 Tape, N/A, W	45	47	48	48	52	53	49	3.06
16	3M 750 Tape, N/A, W	1049	1170	1158	1232	1258	1171	1173	72.55
17	3M 380WR Tape, N/A W	345	369	377	352	360	351	359	12.12
18	ATM 400 Tape, N/A, W	73	84	84	84	97	103	88	10.75
21	3M 380 Tape, N/A, Y	23	26	28	2	3	35	20	13.75
22	3M 750 Tape, N/A, Y	397	401	409	422	439	425	416	16.00
23	Polyurea, Cluster Bead, Y	57	54	56	60	62	67	59	4.72
25	ATM 400 Tape, N/A, Y	101	119	130	127	121	130	121	10.97
31	Methacrylate, Type III, Y	55	57	65	62	58	59	59	3.61
32	Thermo, Type III, W	39	40	41	40	42	39	40	1.17
33	Thermo, Mixed, W	23	24	25	29	28	25	26	2.34
34	Thermo, Type II, W	29	28	27	26	26	27	27	1.17
35	Thermo Rumble, Type II, W	60	56	59	57	58	58	58	1.41
Note: Continuous wetting rate measured over six minute interval: 13.3, 15.0, 14.4 in/hr.									

TABLE B-14 Flooding Condition Retroreflectivity Readings.

Sample	Material, Bead, Color	Retro Readings (mcd/m²/lux)						Mean	StDev
		1	2	3	4	5	6		
5	Paint, Type III, W	29	30	31	32	33	36	32	2.48
6	Paint, Type II, W	20	21	21	23	19	20	21	1.37
8	Polyurea, Cluster Bead, W	71	73	73	76	78	79	75	3.16
10	Epoxy, Type III, W	21	22	23	25	26	24	24	1.87
11	Thermo, Mixed, W	47	54	53	50	49	49	50	2.66
15	3M 380 Tape, N/A, W	43	46	49	48	48	51	48	2.74
16	3M 750 Tape, N/A, W	740	781	753	750	766	771	760	15.14
17	3M 380WR Tape, N/A W	277	284	306	261	272	269	278	15.66
18	ATM 400 Tape, N/A, W	82	80	84	90	89	85	85	3.90
21	3M 380 Tape, N/A, Y	22	23	24	27	28	25	25	2.32
22	3M 750 Tape, N/A, Y	290	299	318	307	301	295	302	9.83
23	Polyurea, Cluster Bead, Y	43	42	45	51	51	43	46	4.12
25	ATM 400 Tape, N/A, Y	78	68	68	68	69	73	71	4.08
31	Methacrylate, Type III, Y	42	45	46	51	50	50	47	3.56
32	Thermo, Type III, W	33	35	36	39	37	38	36	2.16
33	Thermo, Mixed, W	25	26	26	28	27	25	26	1.17
34	Thermo, Type II, W	20	21	21	22	23	21	21	1.03
35	Thermo Rumble, Type II, W	49	47	51	51	50	48	49	1.63

Note: Continuous wetting rate was not measured due to the high intensity of greater than 20 in/hr.

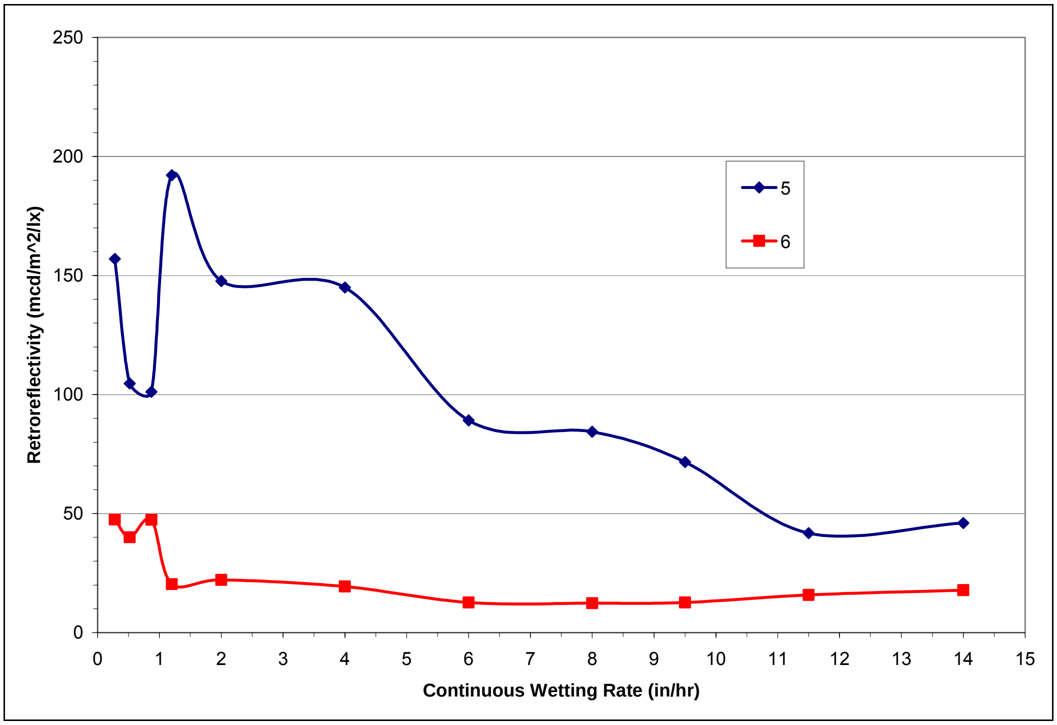


FIGURE B-1 Continuous Wetting Rate Effect on Waterborne Paint Retroreflectivity.

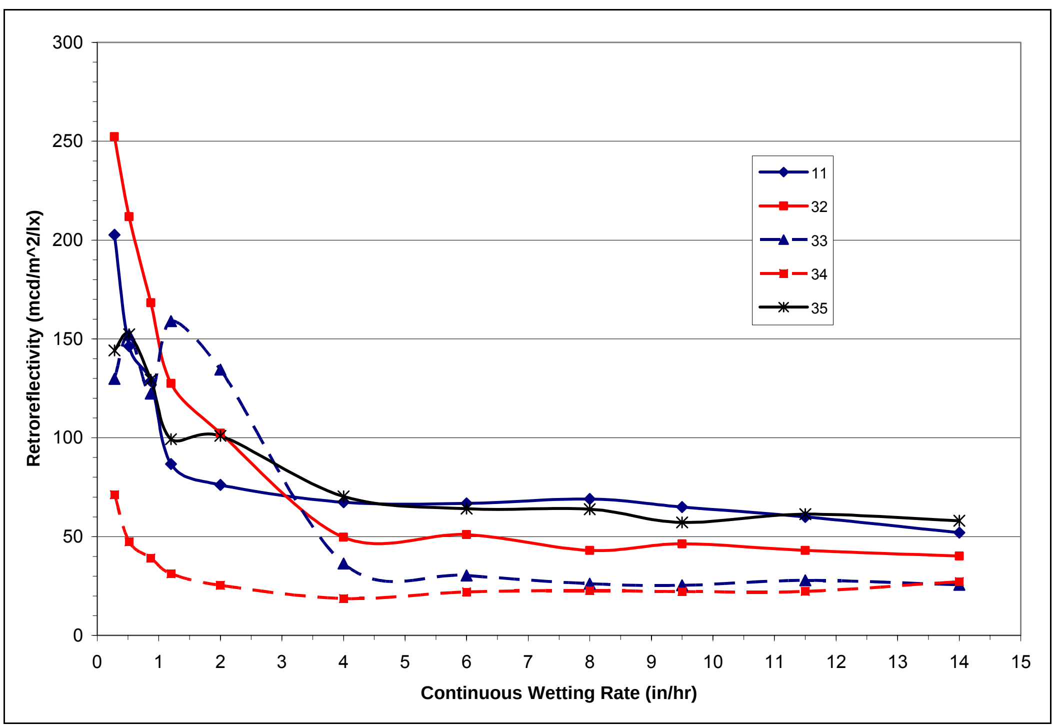


FIGURE B-2 Continuous Wetting Rate Effect on Thermoplastic Retroreflectivity.

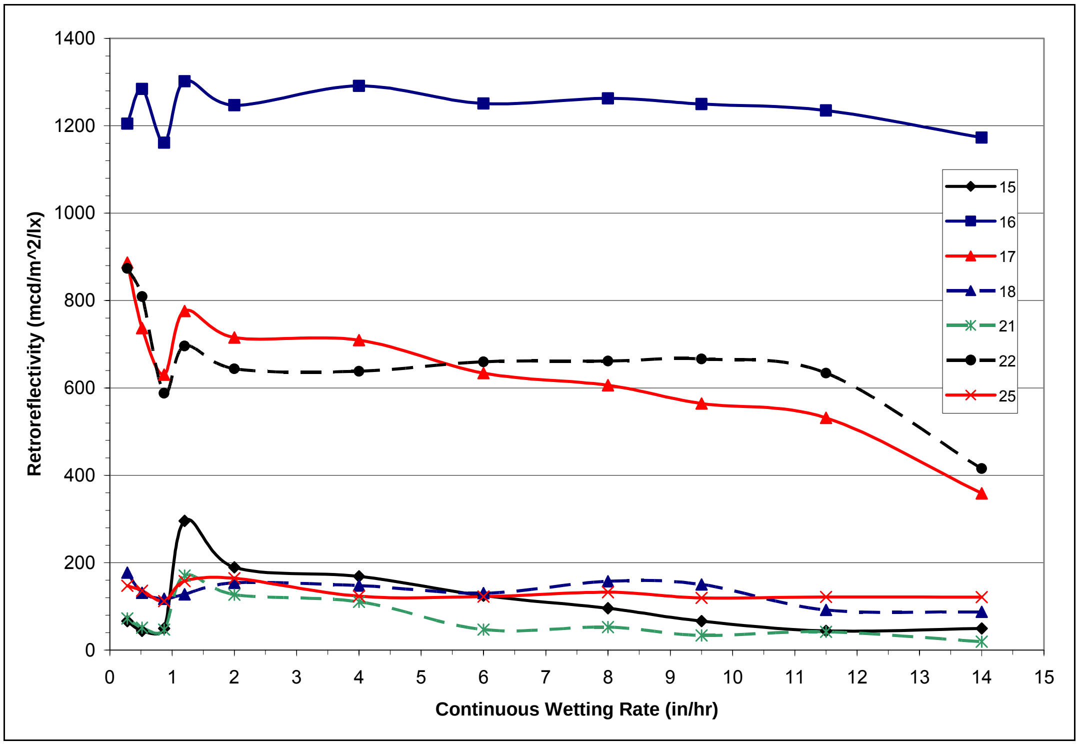


FIGURE B-3 Continuous Wetting Rate Effect on Tape Products Retroreflectivity.

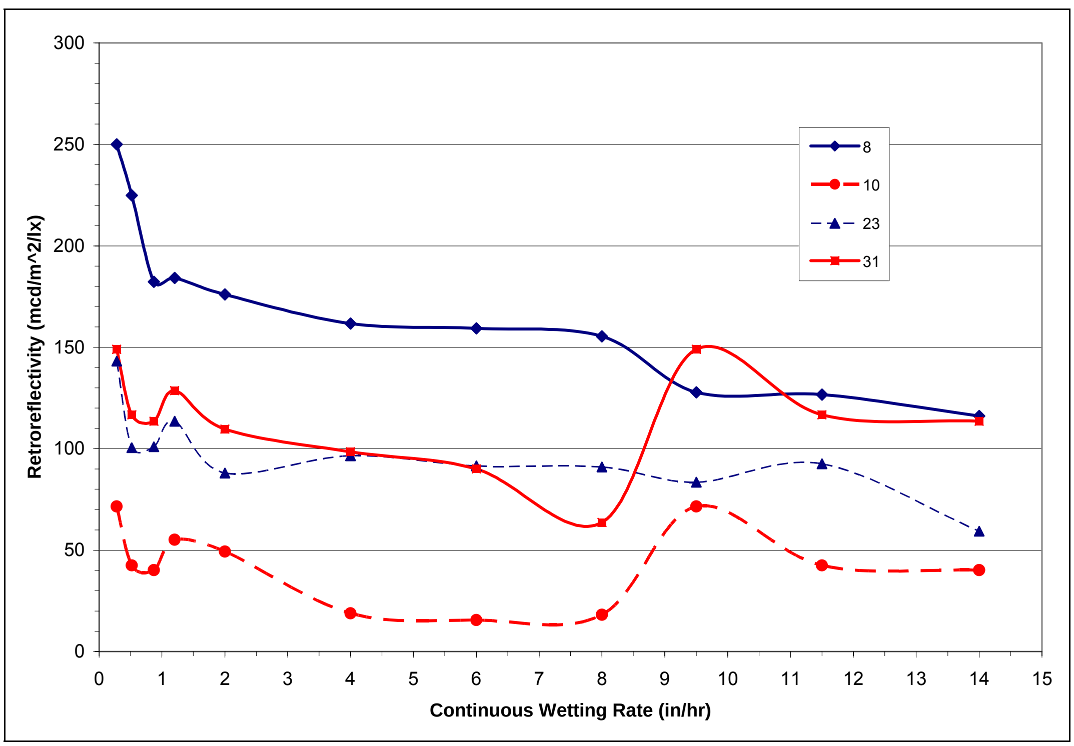


FIGURE B-4 Continuous Wetting Rate Effect on Other Products Retroreflectivity.

APPENDIX C

LOGARITHMIC ANALYSIS

The logarithmic analysis of the retroreflectivity data were conducted due to the human psychophysical response to light, which can be approximated with a logarithmic based relationship. The correlation method is the same as the analysis for the non-logarithmic retroreflectivity data. This analysis uses mean detection distances collected at the three rainfall rates, and the retroreflectivity data for each pavement marking. The retroreflectivity data used were the retroreflectivity data measured at the rainmaker for the same flow that the detection distance was collected in and the center of the ASTM suggested wetting rate (9.5 in/hr).

Tables of correlation values are provided in Table C-1 through Table C-3. Table C-1 is the original linear Pearson *r* correlation values for the data that is to be analyzed with logarithmic correlation. Table C-2 is the equivalent coefficient of determinations R^2 for the Pearson *r* values provided in Table C-1. Table C-3 is the resulting coefficient of determination R^2 values for the logarithmic analysis of the selected pavement marking groups and conditions.

Comparing Table C-2 and Table C-3 indicates the difference between the linear and logarithmic analysis. For all the pavement markings and for the tape products the log analysis did not show improvements to the correlations. For the pavement markings with $R_L < 300$ mcd/m^2/lx and for thermoplastic pavement markings the log analysis showed improvements in some cases and not in others. Figure C-1 through Figure C-8 are plots of the data with their R^2 values indicated.

TABLE C-1 Pearson *r* Values for Select Conditions and Marking Groups.

		Pavement Marking Material Group			
Mean Detection Distance Condition	Retroreflectivity Wetting Rate (in/hr)	All	R_L < 300 ($mcd/m^2/lx$)	Thermoplastic	Tape Products
High Flow (0.87 in/hr)	0.87	0.902	0.621	0.611	0.969
	9.5	0.898	0.403	0.668	0.988
Medium Flow (0.52 in/hr)	0.52	0.802	0.420	0.794	0.848
	9.5	0.760	0.068	0.678	0.815
Low Flow (0.28 in/hr)	0.28	0.863	0.572	0.834	0.814
	9.5	0.922	0.690	0.429	0.916

TABLE C-2 Linear Coefficient of Determination R^2 Values for Select Conditions and Marking Groups.

		Pavement Marking Material Group			
Mean Detection Distance Condition	Retroreflectivity Wetting Rate (in/hr)	All	R_L < 300 ($mcd/m^2/lx$)	Thermoplastic	Tape Products
High Flow (0.87 in/hr)	0.87	0.8136	0.3856	0.3733	0.9390
	9.5	0.8064	0.1624	0.4462	0.9761
Medium Flow (0.52 in/hr)	0.52	0.6432	0.1764	0.6304	0.7191
	9.5	0.5776	0.0046	0.4597	0.6642
Low Flow (0.28 in/hr)	0.28	0.7448	0.3272	0.6956	0.6626
	9.5	0.8501	0.4761	0.1840	0.8391

TABLE C-3 Logarithmic Coefficient of Determination R^2 Values for Select Conditions and Marking Groups.

		Pavement Marking Material Group			
Mean Detection Distance Condition	Retroreflectivity Wetting Rate (in/hr)	All	R_L < 300 ($mcd/m^2/lx$)	Thermoplastic	Tape Products
High Flow (0.87 in/hr)	0.87	0.8050	0.4730	0.4042	0.8705
	9.5	0.7294	0.2962	0.4308	0.8683
Medium Flow (0.52 in/hr)	0.52	0.6093	0.1659	0.8013	0.6596
	9.5	0.6132	0.0365	0.4929	0.6695
Low Flow (0.28 in/hr)	0.28	0.6477	0.3414	0.5159	0.6037
	9.5	0.6888	0.3898	0.2114	0.7028

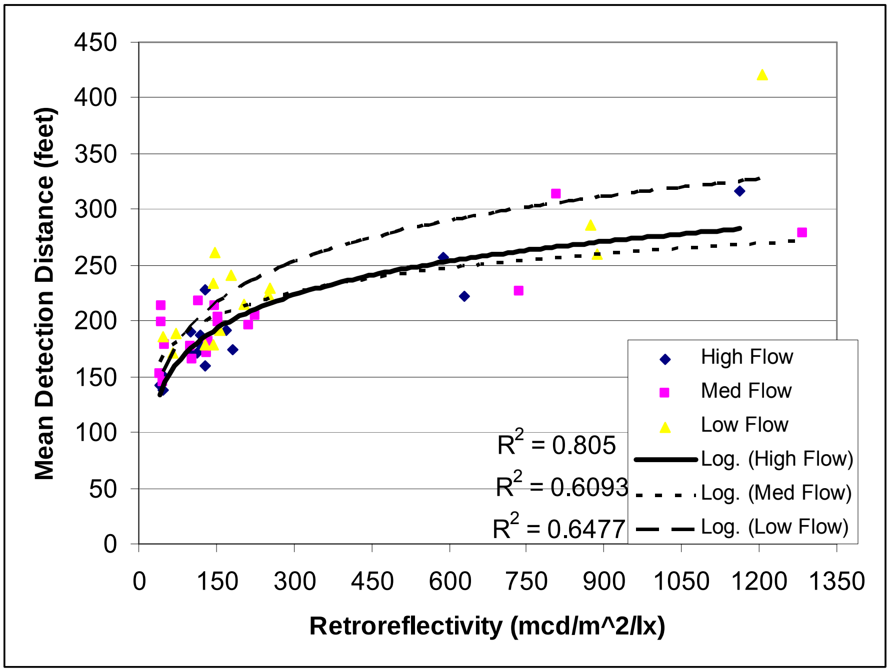


FIGURE C-1 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at Rainmaker (for Equivalent Flow) for All Pavement Markings.

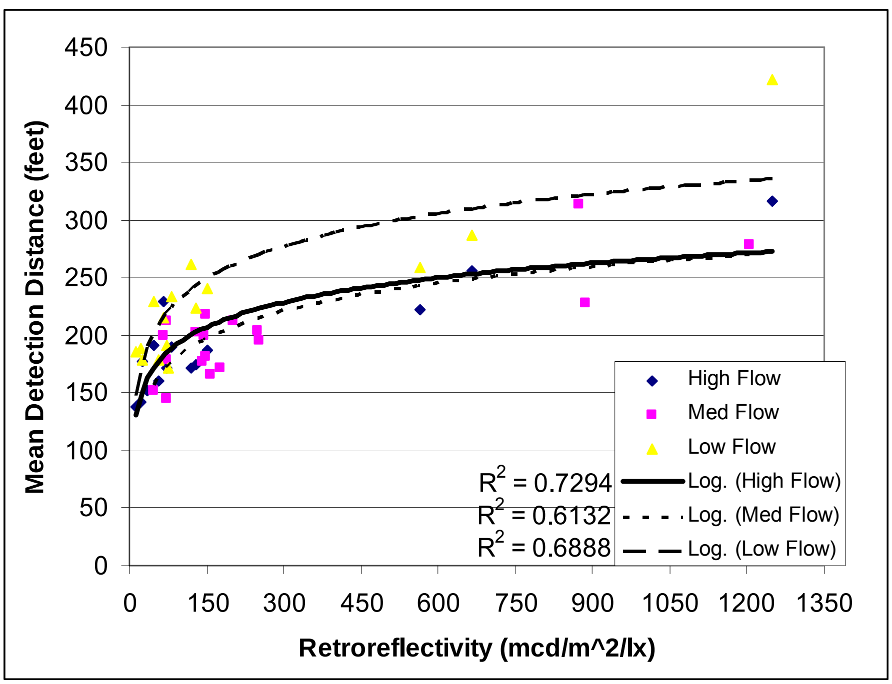


FIGURE C-2 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at 9.5 in/hr for All Pavement Markings.

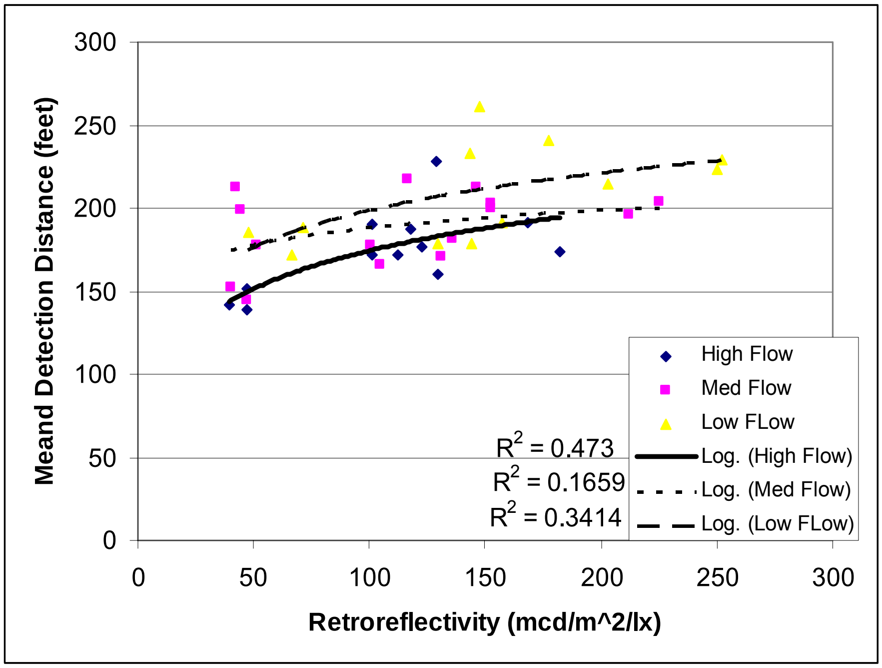


FIGURE C-3 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at Rainmaker (for Equivalent Flow) for Pavement Markings with R_L < 300.

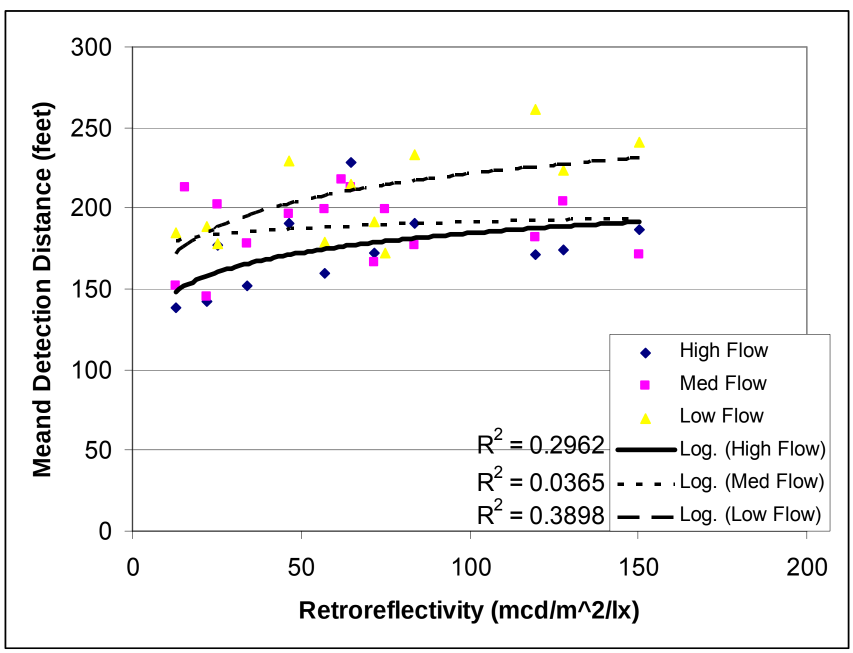


FIGURE C-4 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at 9.5 in/hr for All Pavement Markings with R_L < 300.

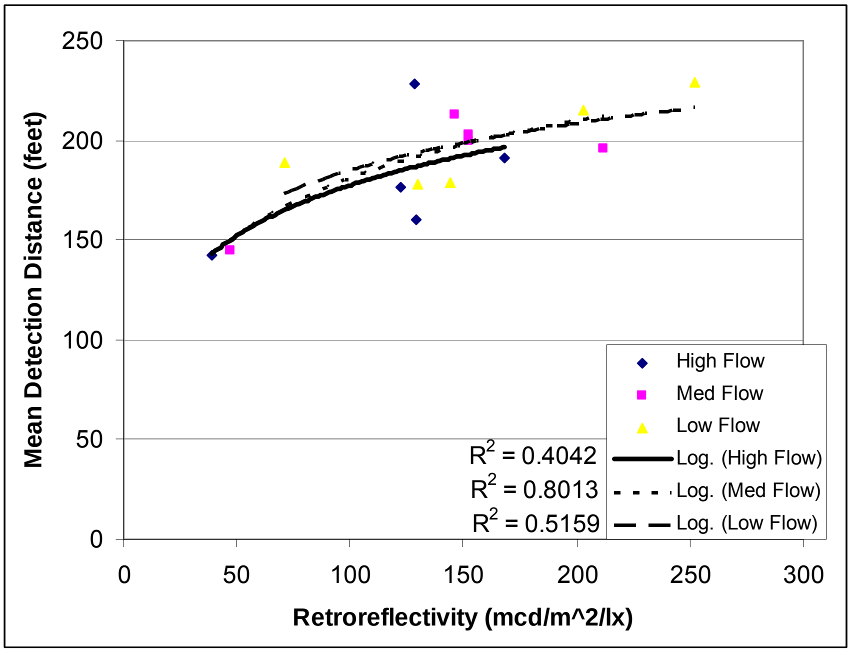


FIGURE C-5 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at Rainmaker (for Equivalent Flow) for Thermoplastic Pavement Markings.

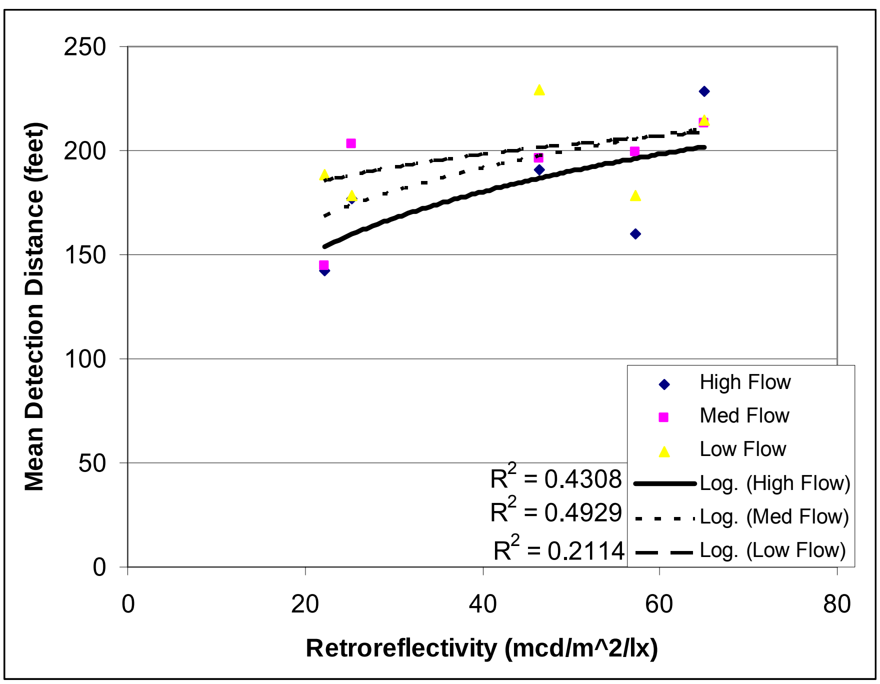


FIGURE C-6 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at 9.5 in/hr for Thermoplastic Pavement Markings.

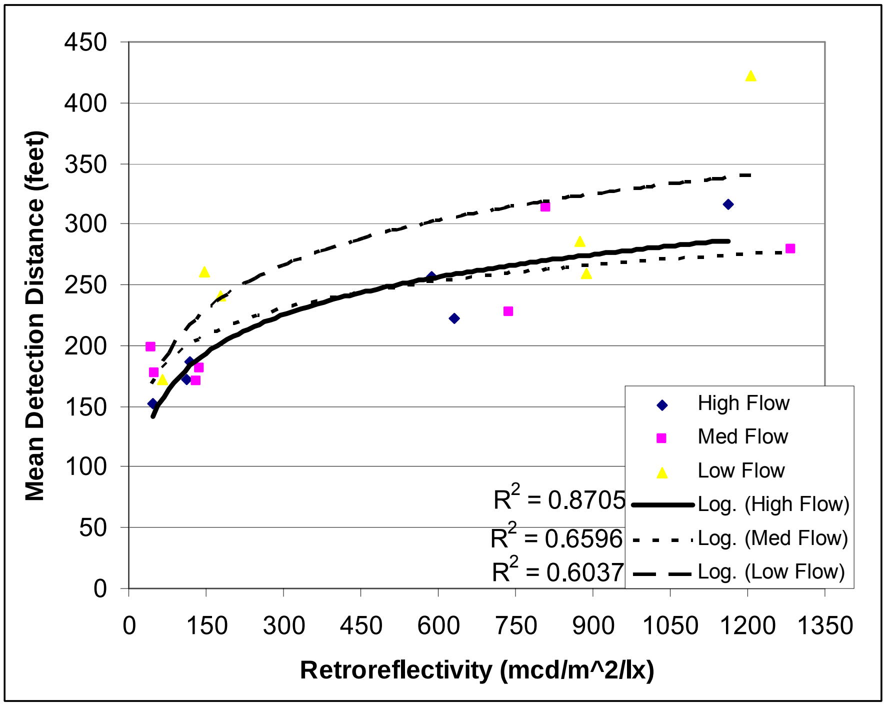


FIGURE C-7 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at Rainmaker (for Equivalent Flow) for Tape Pavement Markings.

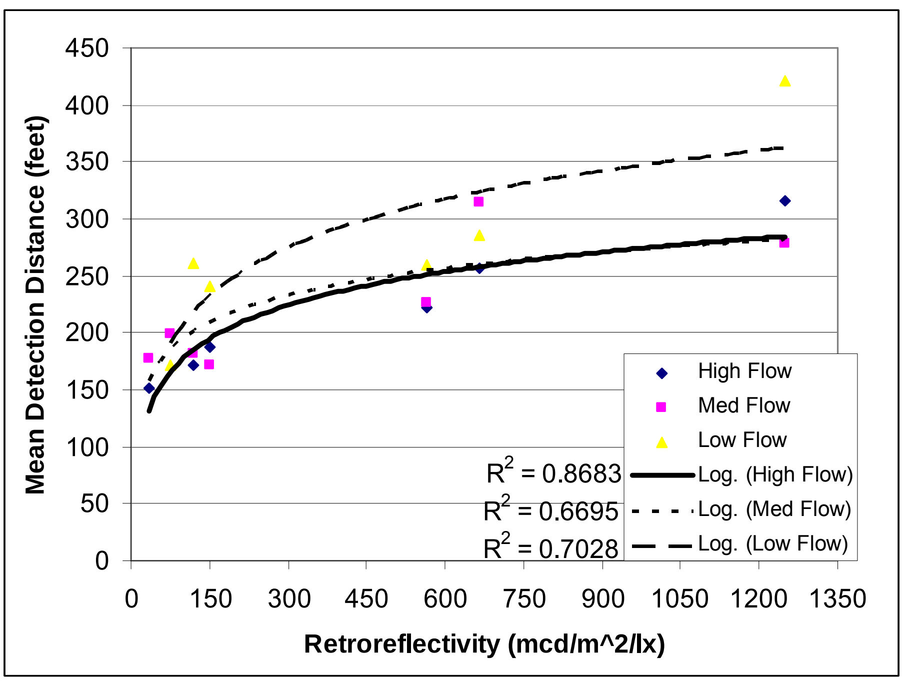


FIGURE C-8 Mean Detection Distance at the Given Flow Versus Retroreflectivity Measured at 9.5 in/hr for Tape Pavement Markings.

VITA

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Adam M. Pike was born in Glens Falls, New York, on December 12, 1981. He graduated from South Glens Falls High School with honors in June 2000. The following September he entered Adirondack Community College and in May 2002 completed his first two years of college. He entered Clarkson University in August 2002 and received a Bachelor of Science Degree in Civil Engineering in May 2004. In August 2004 he entered Texas A&M University and received a Master of Science Degree in Civil Engineering in December 2005.