HIGH PERFORMANCE TRAFFIC MARKINGS IN WET WEATHER

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HIGH PERFORMANCE TRAFFIC MARKINGS IN WET WEATHER

Final Report

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16. Abstract

The purpose of this research is to perform a preliminary study which will establish a basis for future larger scale evaluation of traffic markings on wet pavement surfaces. The major objective is to set testing parameters and to develop a testing plan for the future larger scale test of wet-weather pavement markings. For this purpose, an extensive literature review has been undertaken to review testing procedures and evaluation guidelines used in past similar projects. The selected testing variables include detection distance, retroreflectivity, and service life of different traffic markings. A testing plan was developed to test the selected testing parameters of various pavement marking systems under different rainy conditions. In addition, several wet-weather pavement marking systems were also selected for the future larger scale test. These products were found by previous studies to have good visibility performance during wet-weather conditions.

The research team of this study summarized methodologies used by previous studies to simulate rainy conditions. There are basically two different methods for the simulation of rainy conditions, including the ASTM methods and the train tunnel methods. By following ASTM E 2176 and E 2177, it is possible to simulate rainy conditions. The rain tunnel method requires building an enclosed space to simulate wet weather environments. Twenty years of Florida rainfall data was acquired from the National Climatic Data Center. Statistical analysis was conducted based on the collected rainfall data. Based on the rainfall data analysis results, the research team determined three different rainfall rates that the rain tunnel should be able to simulate: 0.3 in./hr, 0.65 in./hr and 1.2 in./hr.

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ABSTRACT

Traffic markings are one of the most important traffic control and safety devices. The basic requirement for traffic marking is that it must be visible. During clear daylight hours, the visibility of traffic markings usually presents little problem. During night driving in rainy conditions, however, the accumulated water on the road surface will reduce the light reflected back to drivers' eyes. Thus, it will result in a greatly reduced visibility performance of traffic marking.

The purpose of this research project is to perform a preliminary study which will establish a basis for future larger scale evaluation of traffic markings on wet pavement surfaces. The major objective of this study is to set testing parameters and to develop a testing plan for the future larger scale test of wet-weather pavement markings. For this purpose, an extensive literature review has been undertaken to review testing procedures and evaluation guidelines used in past similar projects. The selected testing variables include detection distance, retroreflectivity, and service life of different traffic markings. A testing plan was developed to test the selected testing parameters of various pavement marking systems under different rainy conditions. In addition, several wet-weather pavement marking systems were also selected for the future larger scale test. These products were found by previous studies to have good visibility performance during wet-weather conditions.

The research team of this study also summarized methodologies used by previous studies to simulate rainy conditions. There are basically two different methods for the simulation of rainy conditions, including the ASTM methods and the train tunnel methods. By following ASTM E 2176 and E 2177, it is possible to simulate rainy conditions. The rain tunnel method requires building an enclosed space to simulate wet weather environments. The most crucial parameter is the maximum rate of rainfall that a material is able to overcome and maintain retroreflectance. This performance characteristic can be compared to real life Florida weather events. For this purpose, 20 years of Florida rainfall data was acquired from the National Climatic Data Center. Statistical analysis was conducted based on the collected rainfall data. Based on the rainfall data analysis results,

the research team determined three different rainfall rates that the rain tunnel should be able to simulate: 0.3 in./hr, 0.65 in./hr and 1.2 in./hr.

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1 INTRODUCTION

1.1 Background

Traffic markings are one of the most important traffic control and safety devices. There are several types of traffic markings, such as paint, thermoplastic, raised pavement marker, plastic tape, etc. Traffic markings must perform well under different weather conditions to communicate traffic regulations to roadway users. When markings are effective at this function, they provide a safety factor to the raveling public.

In order to provide drivers with adequate information about roadway delineation, traffic markings must be visible, audible or both. During clear daylight hours, the visibility of traffic markings presents little problem. Drivers can acquire visual information indirectly from roadway features and surrounding terrain. At night, when ambient and artificial illumination is not sufficient, the visibility of traffic markings becomes a concern. The visibility of traffic markings at night depends on a number of factors. However, the most important factor is the retroreflectivity. Retroreflectivity is the amount of light reflected directly back to the source. According to the Manual on Uniform Traffic Control Devices (MUTCD), traffic markings that must be visible at night should be retroreflective unless ambient illumination assures adequate visibility; and all markings on interstate highways shall be retroreflective *(1)*.

Retroreflectivity was found to be dependent on a number of factors such as the color and type of binding material, and pavement surface conditions. The most important component of a traffic marking that determines retroreflectivity are glass beads. Glass beads are small glass spheres used in highway signs and pavement markings to provide the necessary retroreflectivity *(2)*. When properly applied, glass beads can retroreflect light coming from vehicle headlamps directly back to drivers' eyes, as shown in Figure 1-1, and this is why we can see traffic markings at night when illuminated by a vehicle's headlight.

Traffic markings perform differently under different weather conditions. Practically, traffic markings provide better retroreflectivity and color performance on dry pavement

surfaces. Under wet-weather conditions, however, the accumulated water on the surface of traffic makings will reduce the light reflected back to drivers' eyes because the light is scattered through specular reflection. This phenomenon is depicted in Figure 1-2. During wet-night conditions, the degraded retroreflectivity coupled with the windshield wiper action, the slippery pavement surface, and the headlight glare from oncoming vehicles creates the most hazardous situation for roadway users *(2)*.

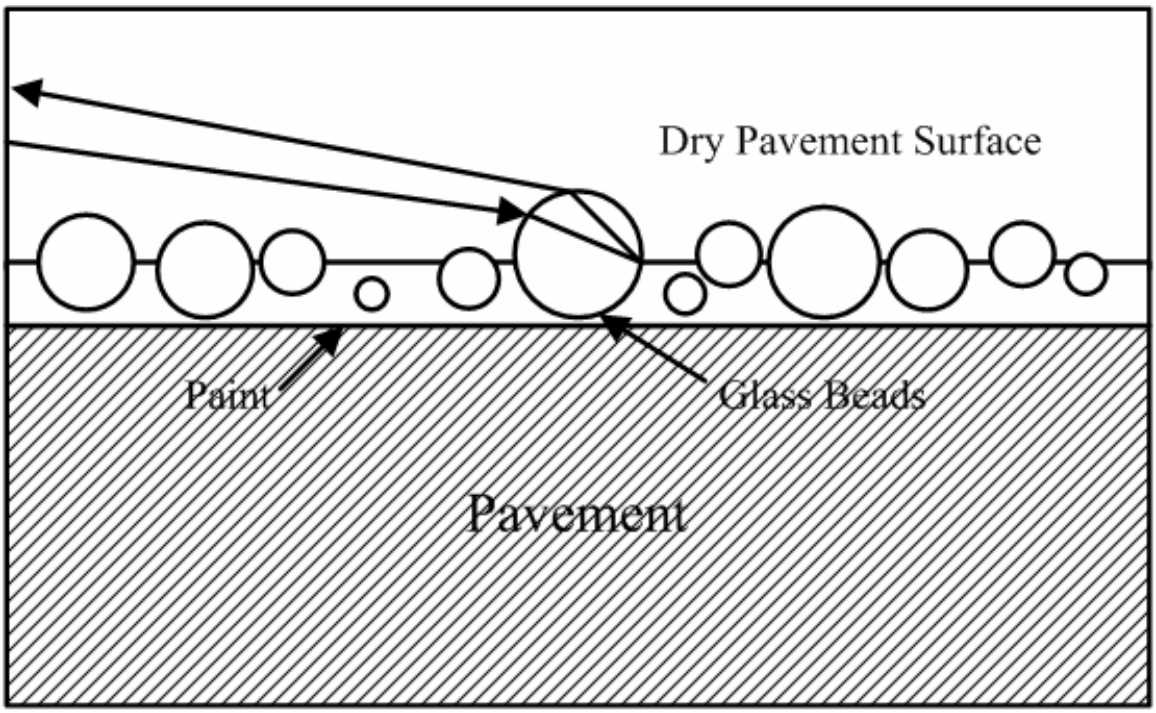

Figure 1-1. Glass Beads Retroreflect Light

During the past two decades, many techniques have been implemented to improve the visibility performance of traffic markings under wet-night conditions. These techniques include, but are not limited to: using raised pavement markers, using larger glass beads, using inverted profile or structured markings and using wet-weather traffic strips, etc. Several manufacturers claim that their products are "all-weather pavement markings" and have high levels of visibility under wet-night conditions. So far it is not clear whether these markings and techniques can provide adequate performance in Florida. In order to ensure markings can provide adequate safety to the traveling public in Florida, traffic

marking performance on wet pavement surfaces should be tested and evaluated under Florida environmental conditions.

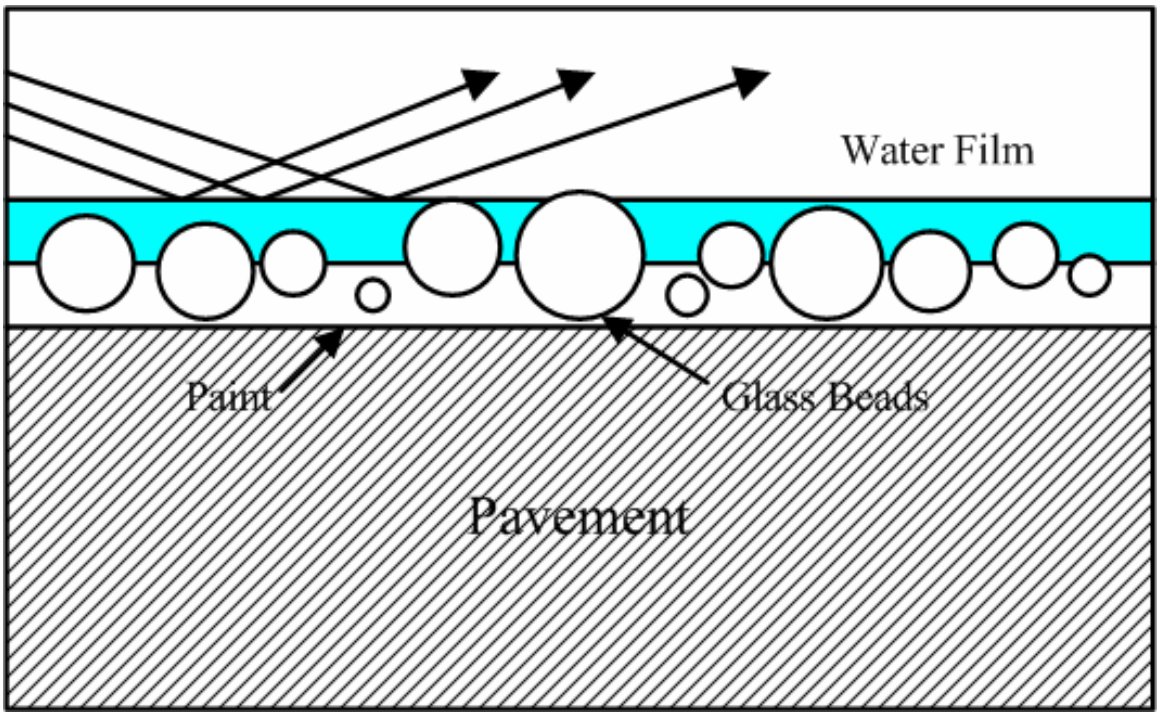

Figure 1-2.Specular Reflection Due to Water Film on Markings

The American Society for Testing and Materials (ASTM) has published two standards for measuring retroreflectivity of traffic markings in wet-weather conditions. These two standards are: (1) ASTM E 2176 (Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting *(3)*); and (2) ASTM E 2177 (Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness *(4)*). Several previous studies have been conducted to investigate the impacts of different factors on the visibility performance of traffic markings under wet-night conditions; and to evaluate the performance of different wet-weather traffic marking techniques (5, 6, 7, and 8). In those studies, rain tunnels were built to simulate different rainy conditions and participant evaluations were performed to measure the visibility distances of various traffic makings. Those studies also involve measuring the wet retroreflectivity of traffic markings using ASTM methods and correlated the

measured retroreflectance values with the visibility distance measured by participant evaluations. The purpose of doing so is to determine the suitability of using ASTM methods to predict the visibility performance of traffic markings under different weather conditions. Even though there are some inconsistencies among the results, previous studies generally show that there exists a positive relationship between the visibility distance measured by participant evaluations and the retroreflectance values measured using ASTM methods.

The previous studies were limited in the aspect that they focused on the visibility performance of new traffic markings under wet-night conditions. There is little in-use wet marking performance data for traffic markings. The retroreflectivity of traffic markings degrades over time. Several factors affect the service life of traffic markings, including environment, pavement surface type, and more importantly, the traffic load. Until now there are no widely accepted guidelines or criteria concerning the minimum retroreflectivity level of traffic markings that is essential for safety operation on the highway under wet-night conditions. In an unpublished report, the Federal Highway Administration (FHWA) recommended threshold retroreflectivity values for high-speed roadways. The threshold retroreflectivity for night time dry driving conditions are given in Table 1-1.

Table 1-1. Threshold Retroreflectivity Values Used in FHWA Research (mc/m^2/lux) (9)

Material	Roadway Type/Speed Classification		
	Non-Freeway (≤40 mph)	Non-Freeway (≥45 mph)	Freeway (≥55 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: Retroreflectivity values are measured at 30-m geometry.

However, one must ask whether these recommended retroreflectivity values can provide adequate visibility performance to drivers under wet-night conditions? Many manufacturers openly claim that their products have high levels of visibility under wet-night conditions. Even if their claims are true, it is still not clear whether these products

will perform well after being subjected to wear by motorists. A life cycle investigation is needed to ensure that traffic markings provide adequate safety performance to the traveling public. A study longevity of more than one year is needed. One possible solution to this problem is to use the Florida Department of Transportation (FDOT) Material Office's heavy vehicle simulator to accelerate the testing procedures for traffic markings. The FDOT Material Office's heavy vehicle simulator can be used to wear traffic panels with specific equivalent traffic loads. Subsequently the worn traffic markings could be tested under different rainy conditions. In this study, the research team will work with the FDOT project manager to study the feasibility of testing wet weather traffic markings utilizing the heavy vehicle simulator.

This project should be considered a preliminary review of past and current practices leading to a larger visibility performance evaluation of traffic markings in wet weather conditions. The literature review results will provide guidelines for further testing of traffic markings on wet pavement surfaces. The deliverables shall include determining testing parameters and procedures to quantify accurately the visibility performance of traffic markings under wet-weather conditions. In addition, this study will also develop testing procedures to test the visibility performance of traffic markings that have been worn by traffic passages. The FDOT Material Office's heavy vehicle simulator will be used for this purpose.

1.2 Research Objectives

Traffic markings are very important for safe operations of traffic. If traffic marking performance is reduced during the wet weather, it might cause safety problems to traveling public, and traffic operation efficiency may be reduced. This research will look at the performance of traffic markings on wet pavement surfaces and search for new products that may show better performance on wet pavement surfaces as compared to regular traffic markings. More importantly, this study will establish a testing plan for the future larger scale test and the testing of worn traffic markings. The research project will establish concluded results which may have potential for the development of guidelines to improve traffic marking performance under wet-weather conditions. The testing

parameters and plan to be established in the research will be used in future larger scale tests and experiments. More specifically, the research objectives of this study include the following:

1. to search and review existing practices for evaluating and testing service performances of traffic markings on wet pavement surfaces;
2. to set testing parameters for future larger-scale test of traffic markings on wet pavement surfaces;
3. to develop a testing plan for testing the visibility performance of worn traffic markings on wet pavement surfaces; and
4. to search for new marking materials that will provide better performance under wet weather condition as compared to regular marking materials.

1.3 Outline of the Report

This report consists of five chapters. Chapter 1 provides a brief introduction of the research, including the background of the research and the research objectives. Chapter 2 describes a summary of past studies conducted in this area. Chapter 3 will explain the methods used to simulate different wet-weather conditions that were found in Florida. Chapter 4 focuses on explaining the selected testing parameters for future larger scale test of wet-weather traffic markings. A procedure is developed for testing the visibility performance of new or worn traffic markings under wet night conditions. Several marking products were also selected and found by previous studies to perform well under wet-weather conditions. Hopefully these marking products can be considered in the future larger scale performance testing. Finally, Chapter 5 provides summary, conclusions and recommendations of this research.

2 LITERATURE REVIEW

2.1 Visibility Distance

Traffic marking/pavement marking is one of the most important traffic control and safety device types. The basic requirement for traffic marking is that it must be visible. The visibility of traffic marking is measured by its visibility/detection distance. Visibility/detection distance is the distance that the roadway delineation provides the driver to see upcoming changes in roadway alignment (2). Traffic markings should provide adequate detection distance so that drivers can detect roadway features and alignment ahead and have adequate perception-reaction time (PRT) in response to any change in roadway alignment.

In a FHWA study, Freedman et al. used computer simulations, observational field studies, and laboratory experiments to detect short- and long-range delineation requirements (10). For short-range delineation, roadway delineation should provide a preview time of 2 s. The 2-s preview time applies to the extreme conditions such as heavy rain, fog, and glare from opposing headlights. It is considered the minimum preview time for the safety operation of traffic. The preview time for long-range delineation was found to be 3 s. It was found that when drivers are provided with 3 s or more to view roadway delineation, the task of guiding the vehicle is substantially easier. The driver is no longer constantly making rapid compensations for guiding errors and can rely more on roadway information farther ahead.

A driver's perception-reaction time increase with age because of decreased cognitive abilities and psychomotor skills (11). It is commonly believed that the visibility distance required by older drivers to navigate safely on highways is greater than that required by young drivers.

There are two basic methods for the measurement of the visibility distance of traffic marking. These two methods are (1) subjective method and (2) objective method (7 and 8). The subjective method requires conducting a participant evaluation to rate traffic markings based on individuals' personal judgment. Participants may also help to measure

the visibility distance of markings under different conditions. The objective method usually uses instruments to measure properties of traffic markings such as retroreflectivity and luminance, etc.

2.2 Retroreflectivity

Many factors will influence the visibility distance of traffic markings, including the color of traffic marking, the width of traffic marking, the type of traffic marking, the ambient light and even the color of the pavement surface, etc. Retroreflectivity is the most critical factor for traffic marking to be visible at night. Retroreflectivity measures the ability that a pavement marking reflects light directly back to the source of the light. The most commonly used measure of retroreflectivity for markings is coefficient of retroreflected luminance, R_L. As defined by the ASTM, the coefficient of retroreflected luminance is the ratio of the luminance, L, of a projected surface to the normal illuminance, $E_\perp$, at the surface on a plane normal to the incident light. The coefficient of retroreflected luminance is expressed in candelas per square miter per lux ($cd.m^{-2}.lx^{-1}$) (12).

The retroreflectivity of a traffic marking is usually measured using retroreflectometers. There are basically two different types of retroreflectometers, including (1) mobile retroreflectometer, as shown in Figure 2-1 and (2) handheld retroreflectometer, as shown in Figure 2-2. Handheld/portable retroreflectometer is a retroreflectometer that can be used in the field or laboratory for measuring the coefficient of retroreflected luminance, while mobile retroreflectometer is a retroreflectometer that has been mounted to a vehicle for the purpose of taking measurements while the vehicle is moving.

The advantage of using a handheld retroreflectometer to measure traffic marking retroreflectivity is that it usually gives more accurate measurements. The disadvantage is that it requires the maintenances of traffic and can be quite tedious for examining large segments of roadway. Using mobile retroreflectometer to measure retroreflectivity has the benefits of reduced safety risks to road workers, faster data acquisition, as well as a reduction in traffic congestion as compared with handheld devices (13). The problem with mobile retroreflectometer is that it cannot be used effectively during rainfall, because such devices are not intended for marking readings in the presence of the splash

and spray generated by vehicles operating during a rain storm (14). Thus, the mobile retroreflectometer are currently considered a supplement to conventional handheld technology.

Figure 2-1. FDOT Van with Laserlux Attached (13)

The American Society for Testing and Materials has published three standards for measuring the retroreflectivity of traffic markings under different weather conditions. These standards are:

(1) ASTM E 1710 (Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer *(12)*)
(2) ASTM E 2176 (Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting *(3)*); and

(3) ASTM E 2177 (Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness *(4)*).

Figure 2-2. Handheld Retroreflectometer (13)

There are a number of factors that influence the retroreflectivity of traffic markings. According to the Texas Pavement Marking Handbook, the factors that influence traffic marking retroreflectivity include the following factors as given in Table 2-1.

2.3 Service Life

It is known that the retroreflectivity of traffic markings degrades over time for a variety of reasons such as the abrasion by traffic, sun and heat exposure, application methods, material type and chemical spilled on the road surface (13). Traffic markings can reach the end of service life either because bead loss resulting in poor retroreflectivity, loss of the base material because of chipping and abrasion, or color change or the loss of contrast of the base material of the marking (14).

There are two methods for deciding when to remove or replace traffic markings. The most commonly used method is to measure the percent of striping material completely removed from the pavement. For example, the FDOT requires that the striping material

line loss must not exceed 5.0%. The other method requires measuring retroreflectivity of traffic markings. Traffic markings should be replaced if the measured retroreflectivity values are found to be lower than a predetermined threshold value.

Table 2-1. Factors that Influence Pavement Marking Retroreflectivity (15)

Factor	Characteristic of Factor	Factor Effects
Glass Beads	amount and Dispersion	Amount: bead surface area for retroreflective
		Dispersion: scattering of reflection between beads
	Embedment Depth	Surface area available for retroreflectance, adhesion to binder material
	Refractive Index	Amount of light directed to reflecting binder surface
	Size	Surface area for retroreflection, wet weather performance
	Clarity	Diffusion of light within the bead
	Roundness	Direction of retroreflection
Binding Material	Color	White reflects more than yellow
	Type	Some materials are more durable than others
	Thickness	Marking longevity
Other Factors	Pavement Surface Roughness	Material adhesion
	Dirt or Other "Blinding" Material	Any object obscuring the view of the marking
	Type of Retroreflectometer Used for measurements	Ability to reproduce measurements varies between instruments

The problem of using threshold retroreflectivity values to determine the service life of traffic marking is that there are no widely accepted guidelines or criteria concerning the minimum retroreflectivity level of traffic markings that is essential for safety nighttime operation on the highway. In an unpublished report, the FHWA recommended some threshold retroreflectivity values of traffic marking on high-speed roadways. These threshold retroreflectivity values are determined based on a 3.65-s preview time. The threshold retroreflectivity values recommended by FHWA research are given in Table 2-2.

The threshold retroreflectivity values given in Table 2-2 are the desired retroreflectivity levels under night-time, dry pavement conditions. In 2000, the FHWA has sponsored a research to investigate the effects of rainfall on pavement-marking retroreflectivity (16). In the study, a technique was developed to simulate the wet pavement conditions. Retroreflectivity of traffic markings on dry and simulated wet pavements are measured with the Laserlux retroreflectometer parked on the roadway shoulder. The research team of that study went to 60 sites to measure retroreflectivity values of traffic markings under dry and wet conditions. The retroreflectivity values measured under wet pavement conditions were compared to the values measured under dry pavement conditions. The results are given in Table 2-3.

Table 2-2. Threshold Retroreflectivity Values Used in FHWA Research (mc/m^2/lux) (9)

Material	Roadway Type/Speed Classification		
	Non-Freeway (≤40 mph)	Non-Freeway (≥45 mph)	Freeway (≥55 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: Retroreflectivity values are measured at 30-m geometry.

The values in Table 2-3 show that the pavement marking retroreflectivity values measured under wet pavement conditions was generally much lower than those measured under dry pavement conditions. The pavement marking retroreflectivity under wet pavement conditions averaged only 42% of the retroreflectivity value under dry pavement conditions. Based on this finding, researchers of that study estimated the minimum retroreflectivity values under wet pavement conditions. These minimum retroreflectivity values are given in Table 2-4. In Table 2-4, the values in parentheses are the threshold values for dry pavement conditions. The values not in parentheses are equal to the values in parentheses divided by 0.42.

Table 2-3. Threshold Retroreflectivity Values Used in FHWA Research (mc/m^2/lux) (16)

Retroreflectivity Rage (mcd/m2/lux) Under Dry Conditions	Mean Retroreflectivity (mcd/m^2/lux) Under:		
	Dry Conditions	Wet Conditions	Ratio Dry/Wet
≥300	423	179	2.24
200-300	244	108	2.29
150-200	174	88	1.93
120-150	133	64	2.28
100-120	109	48	2.07
80-100	89	46	1.97
60-80	71	31	2.25
<60	45	20	2.36
			Average Ratio: 2.17

Note: Retroreflectivity values are measured at 30-m geometry.

Table 2-4. Estimated Minimum Wet Retroreflectivity Values Based on Threshold Values Used to Define Service Life for Dry Conditions (mc/m^2/lux) (16)

Pavement Marking Color and Environment	Roadway Type/Speed Classification		
	Non-Freeway (≤40 mph)	Non-Freeway (≥45 mph)	Freeway (≥55 mph)
White	185(85)	217(100)	326(150)
White with RRPMs or lighting	65(30)	76(35)	152(70)
Yellow	120(55)	141(65)	217(100)
Yellow with RRPMs or lighting	65(30)	76(35)	152(70)

Note: Retroreflectivity values are measured at 30-m geometry. The values in parentheses are the threshold values for dry pavement conditions.

2.4 Wet-Night Visibility of Traffic Markings

As mentioned before, traffic markings perform differently under different weather conditions. Practically, traffic markings provide better retroreflectivity and color performance on dry pavement surfaces. Under wet weather conditions, the accumulated water on the surface of traffic makings will reduce the light reflected back to drivers' eyes because the light is scattered through specular reflection. Thus, pavement markings under wet weather conditions will have a reduced retroreflectivity and visibility performance as compared with those on dry pavements.

In fact, performance of traffic markings in wet weather is not a new issue. Several studies have been conducted to investigate the impacts of different factors on the visibility performance of traffic markings under wet-night conditions and to evaluate the performance of different wet weather traffic marking techniques (5, 6, 7, 8, 17, and 18).

In 2004, FHWA sponsored a study to determine the nighttime visibility of flat pavement marking tape, patterned pavement marking tape, and wet weather pavement marking tape under dry, wet (just after rainfall), and simulated rain conditions(ongoing 1”/hr rainfall) (5, 17 and 18). The measures of effectiveness of that study were the detection distances, eye movements, and the pavement marking retroreflectance. The research team of that study conducted a experiment on a test track in Cottage Grove, Minnesota. The test track features a section where 1”/hr rainfall can be simulated. Participant evaluation was conducted in the study to determine the detection distances of various traffic markings under dry, wet and simulated rain conditions. The participants include eleven females and seven males. The task of the participants was to state the earliest point when they were able to see the end of the pavement markings when they were driving the experimental vehicles. It was found that the detection distances for traffic markings were longest in the dry condition, shorter in the wet condition, and shortest in the simulated rain condition; and the wet weather tape performed best in terms of the detection distances, followed by the patterned tape and the flat tape (5).

The retroreflectance of each pavement marking material was also measured with three handheld retroreflectometers under the three weather conditions according to ASTM E-1710 (dry), ASTM E-2177 (wet recovery), and ASTM E-2176 (continuous wetting). The retroreflectance values were correlated to the detection distances to determine the ability of each ASTM test method to predict visibility performance under the corresponding weather condition. The average detection distances and retroreflectivity values of three pavement marking types are given in Figure 2-3. Researchers of the study concluded that there is a positive correlation between the retroreflectance obtained with each ASTM test method and its corresponding detection distance performance.

A research conducted by Virginia Tech Transportation Institute (VTTI) tested the performance of six different types of marking techniques under wet night conditions. These marking techniques include the following:

- Standard Latex Paint with Standard Glass Beads and Raised Retroreflective Markers;
- Standard Latex Paint with Standard Glass Beads;
- Standard Latex Paint with Large Glass Beads;
- Profiled Thermoplastic;
- Wet Retroreflective Tape; and
- Semi-Wet Retroreflective Tape

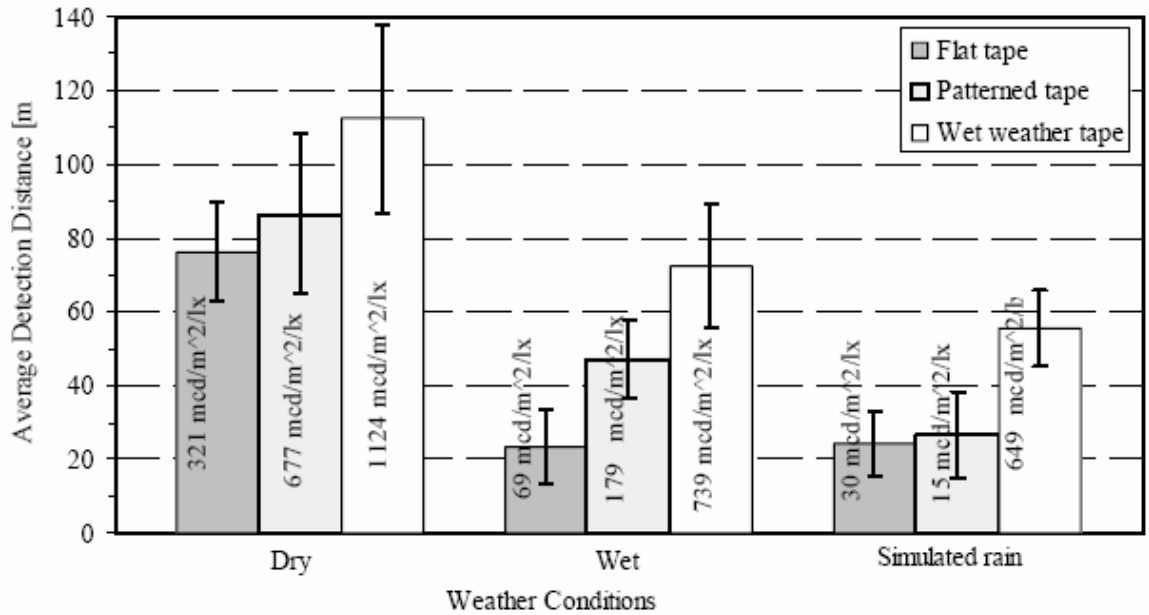

Figure 2-3. Mean Detection Distances and the Corresponding Mean Retroreflectance (mcd/m2/lux) Values in the VTTI Study (5)

The research team of the VTTI study built a rain tunnel to simulate the rainy condition in Virginia. The selected rainfall rate is 0.8 in. per hr, which is based on the analysis of rainfall data in Virginia. The selected marking techniques were tested using both standard ASTM measurement methods and participant evaluations. Thirty-three individuals participated in the evaluation including sixteen males and seventeen females. All

participants are 60 years old and over. The experimental vehicles used included a sedan and a truck tractor. Two different types of participant evaluations were performed. The first was a saturated evaluation, where participants were asked to evaluate marking visibility distance while simulated rain was flooding the marking. The second was a recovery evaluation, where participants were asked to evaluate the marking for a period of 10 min after the rain was turned off. During the participant evaluations, the retroreflectivity and the luminance of the marking were continuously measured. The mean detection distance for different marking techniques are shown in Figure 2-4. It was found that raised retroreflective markers and wet retroreflective tape, outperformed the group under all conditions. These two markings were also found to be highly accepted by the participants. The results of that study also show that the standard paint and glass beads technology is the worst performing and the least desirable of those evaluated.

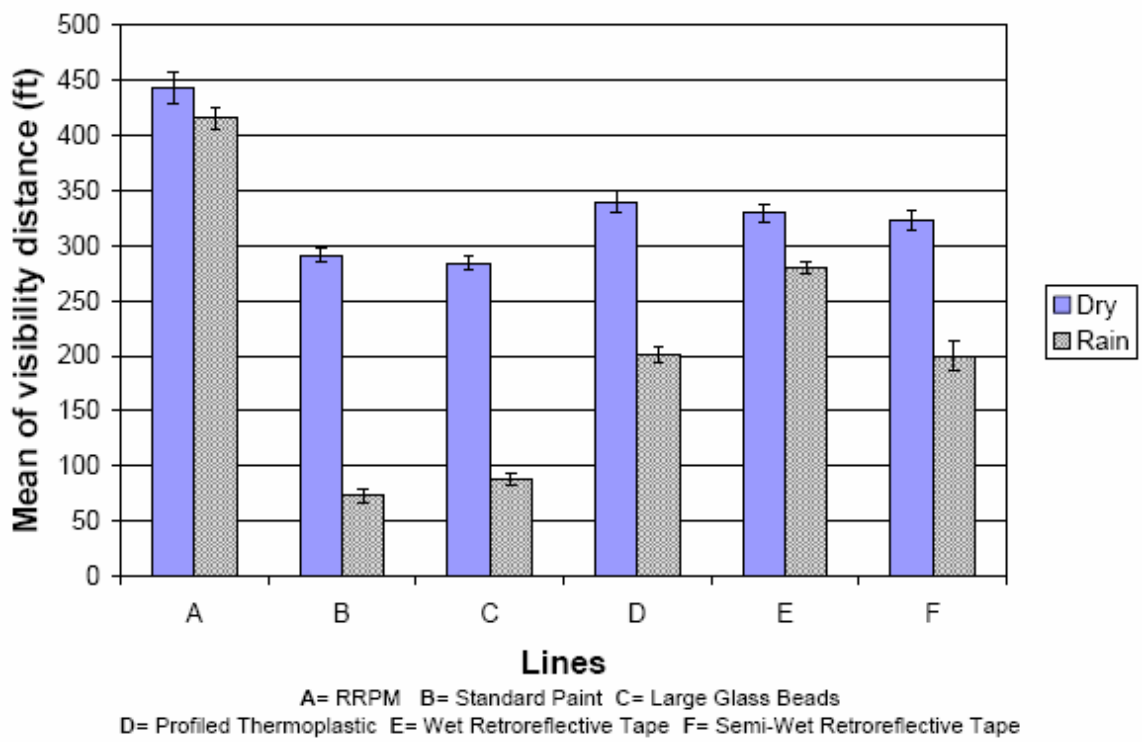

Figure 2-4. Results of the Visibility Distance for the Condition X line interaction (6)

In the VTTI study, correlation analysis was performed to identify the relationship of the ASTM measurement methods to the response of the participants. The purpose of doing so is to determine the suitability of using ASTM methods to predict the visibility performance of traffic markings under different weather conditions. The relationship of the ASTM measurement methods to the human response is shown in Figure 2-5. The correlation analysis showed a Person r value of 0.992, which seems to be very high. However, when wet retroreflective tape was removed from analysis, the recalculated Person r value was found to be 0.526. Thus, the authors of the study concluded that The ASTM methods seem to be highly correlated to the performance of the participants and to 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.

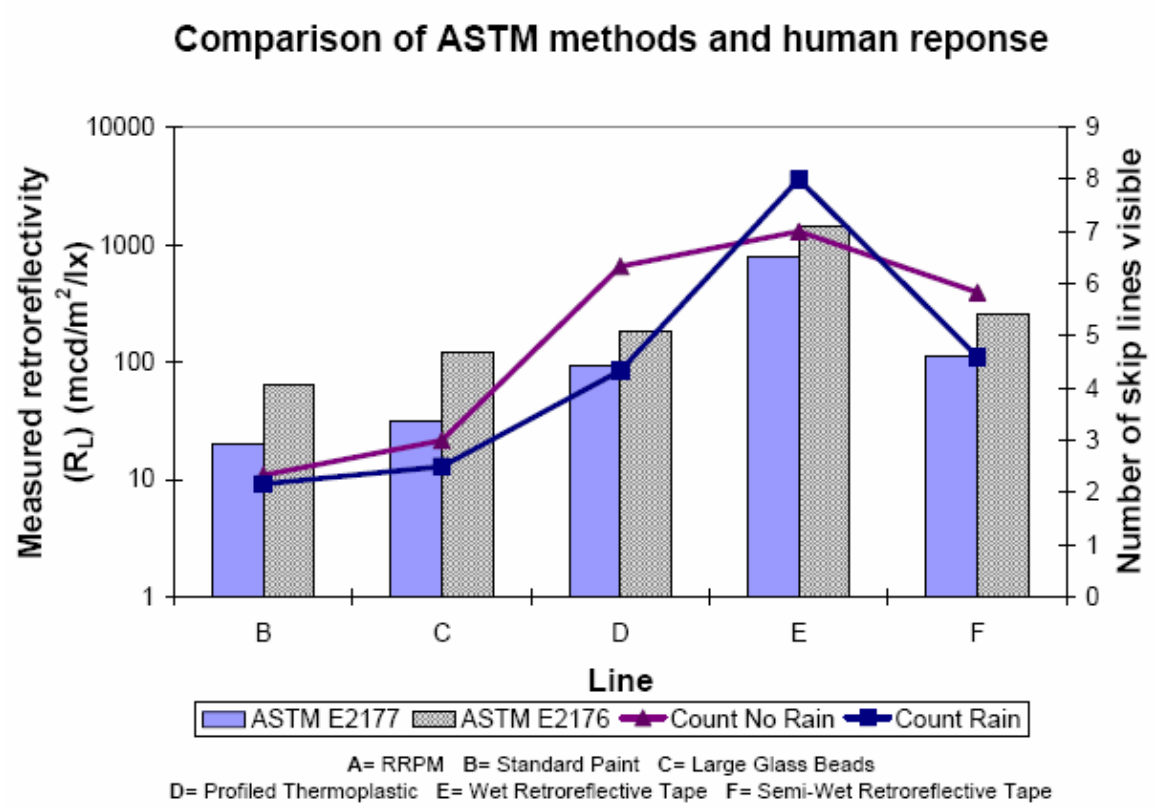

Figure 2-5. Relationship of Human Response to the ASTM Measurement Method Results (6)

The VTTI study is limited in the aspect that the participant evaluation conducted in that study is a static experiment. Participants were asked to sit in a static vehicle to evaluate the detection distance of traffic markings. This is quite inconsistent with the real situation where drivers are usually sitting in a moving vehicle. A recently completed research conducted by Texas Transportation Institute (TTI) evaluated the visibility distance of traffic markings in a dynamic way (8).

The major objective of the TTI research is to develop guidelines that can be used to select the most appropriate pavement markings application for wet-night conditions and light colored pavement surfaces. To achieve this research objective, a 1600 ft long rain tunnel was designed and built at Texas A&M University's Riverside Campus. The rain tunnel was built to simulate different levels of rainfall rate (0.28, 0.52, and 0.87 inches per hour, respectively). The rainfall rate was determined based on the analyses of 20 years rain data in Texas. The test vehicle used in the TTI study was a 2004 Ford Taurus sedan with HB4 halogen headlamps. The test vehicle was equipped with a distance measuring instrument for recording detection and recognition distances for the pavement marking samples. In the TTI study, participants were asked to drive the testing vehicle through the rain tunnel with a constant speed of 30 mph. The subject alerted the researcher when he/she could see a marking, and alert the researcher again when he/she could identify the type of marking. The researcher sitting in the test vehicle recorded the location values from the distance measuring instrument when the subject detected or identified the marking samples. In total, the TTI research team recorded 866 traffic marking detection distances. The detection distance by each pavement marking sample and rainfall rate are given in Figure 2-6.

The researchers of the TTI study investigated the relationship between dry retroreflectivity measurements using ASTM E 2170 and wet retroreflectivity measurements using ASTM E 2176 and ASTM E 2177. The purpose of doing so is to explore whether dry retroreflectivity measurements can be used to predict or estimate wet retroreflectivity performance of pavement markings. The results are given in Figure 2-7. The R^2 in Figure 2-7 are relatively low, indicating that there is essentially no relationship between dry and wet retroreflectivity measurements for most pavement marking

materials, and dry retroreflectivity measurements cannot be used to judge the performance of pavement markings when wet.

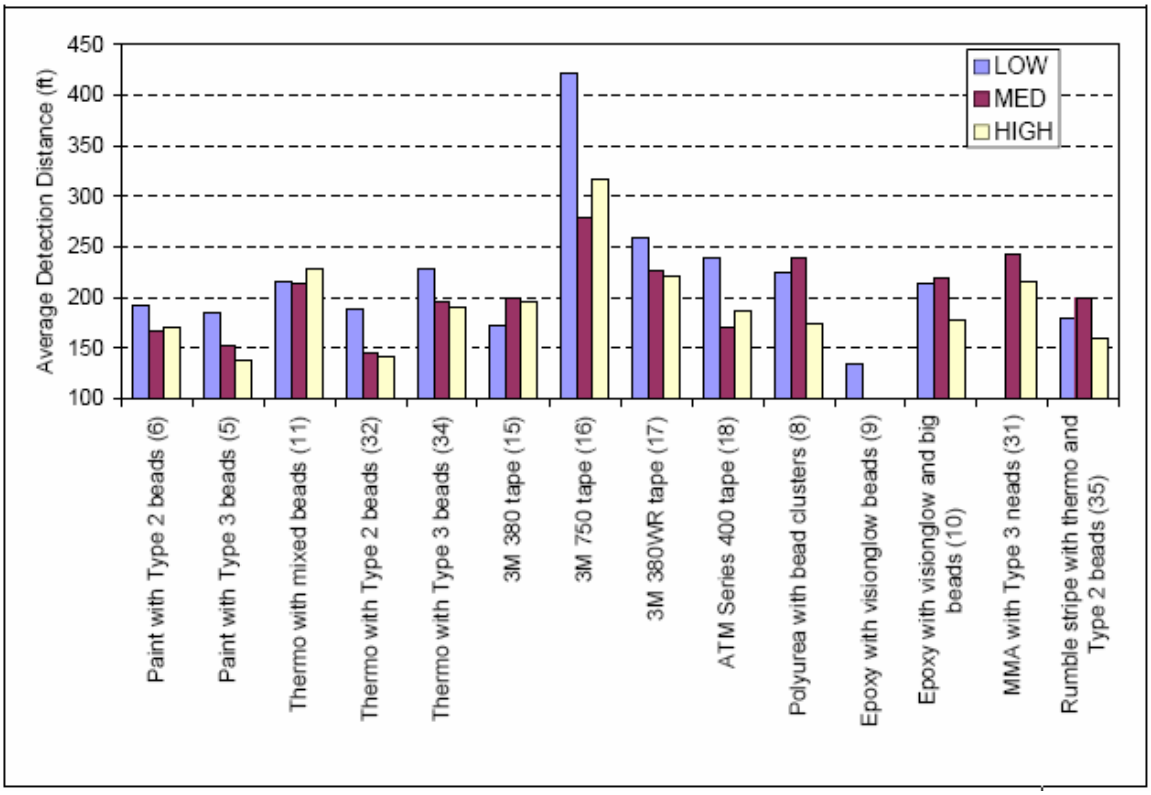

Figure 2-6. Detection Distances for all Marking Materials by Rainfall Rate (8)

Similar to other studies cited before, the TTI study also investigated the performance predictive power of the retroreflectivity measurement methods provided by ASTM. The detection distances and retroreflectivity measurements were analyzed to determine how well the results of the ASTM methods correlated to the detection distances obtained from the participant evaluations. Researchers of the study found that the Person r is very low (r=0.112) when three overly influential data points were removed from data analysis. Thus, the TTI study concluded that predictive power of the ASTM retroreflectivity measurements is only moderate in terms of providing an indication of how well the marking will be seen under wet-night conditions (8).

Generally speaking, the three research studies cited in this research share some common features such as similar research objectives, similar measures of effectiveness, and even

similar statistical methods used for data analysis (5, 6, and 8). The differences among these studies lie in the methods used for conducting participant evaluations and the marking materials and techniques selected for test. The participant evaluations conducted in the VTTI research is a static experiment where participants were asked to sit in a static test vehicle to evaluate the detection distance of marking. The participant evaluations in TTI study is a dynamic experiment which requires participants to drive through the test area to evaluate the detection distances. It seems that the method used by TTI research to conduct participant evaluation is more reasonable because it is more consistent with the real situation. All of these studies involve building water tunnels to simulate rainy conditions. All of these studies tried to investigate the performance predictive power of the retroreflectivity measurement methods provided by ASTM by analyzing the relationship between the detection distances and the retroreflectivity values measured using ASTM methods. Even though there are some inconsistencies among the results, previous studies generally show that there exists a positive relationship between the visibility distance measured by participant evaluations and the retroreflectance values measured using ASTM methods.

One common limitation is shared by the studies cited above. The limitation is that these studies have only focused on the visibility performance of new traffic markings under wet-night conditions. There is no wet marking performance data for traffic markings that have been placed on the pavement surface for a certain time period. Previous studies concerning the wet-night visibility of traffic markings have only focused on answering the question about what is the detection distance of a particular marking material or technique under different wet-night conditions. These studies generally cannot answer the question such as what is the detection distance of this marking material or technique after it has been worn by a certain number of vehicles passing over them.

To measure the visibility performance of traffic markings that have been worn by traffic abrasion, the traditional method is to place the marking on the pavement, wait for several months, and then go to the field to measure the retroreflectivity values. For some durable marking materials such thermoplastic markings, it usually takes more than one year before the marking can be worn by traffic abrasion. For the future larger scale test of wet

weather pavement markings, this method is obviously not feasible. To overcome this problem, a possible solution is to use the Florida Department of Transportation (FDOT) Material Office's heavy vehicle simulator. The FDOT Material Office's heavy vehicle simulator can be used to wear traffic panels with given equivalent traffic repetitions. Then the worn traffic markings could be tested under different rain conditions. In this study, the research team will work with FDOT project manager to study the feasibility for testing wet weather traffic markings that will have been worn under different traffic repetitions. More details about the FDOT Material Office's heavy vehicle simulator will be explained later.

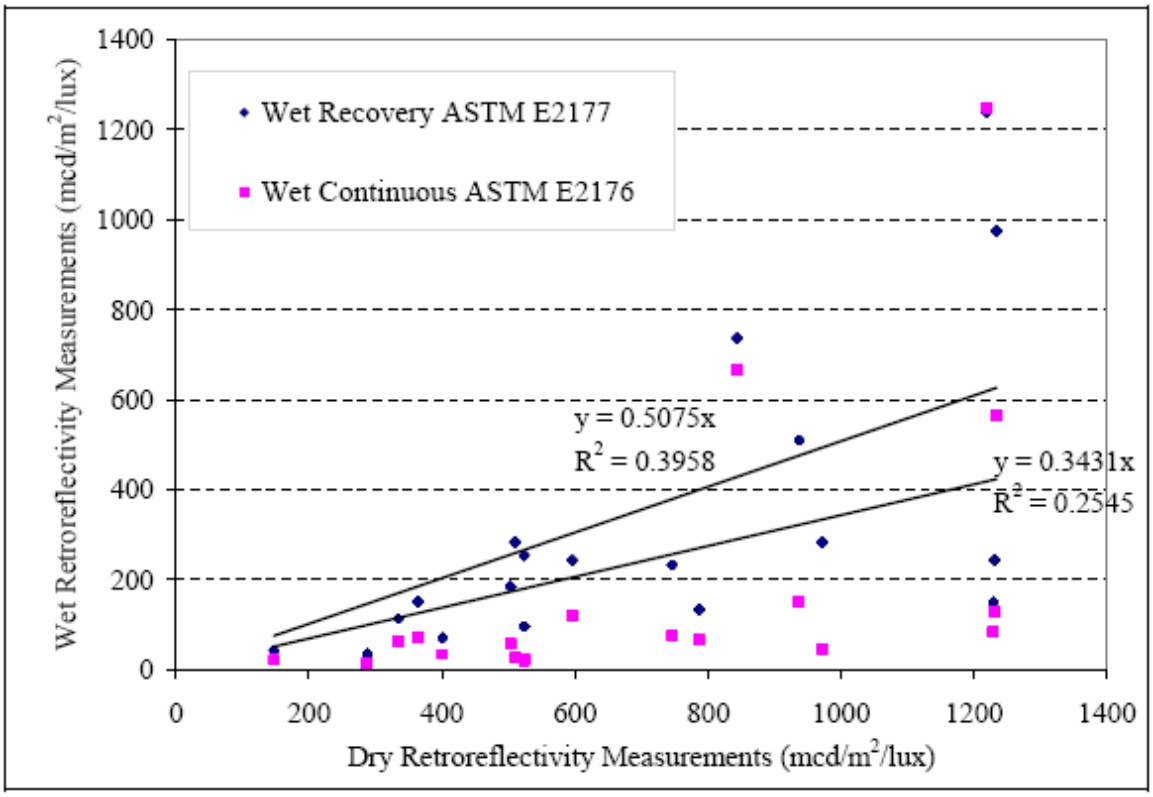

Figure 2-7. Comparison of Dry and Wet Retroreflectivity Measurements (8)

3 SIMULATION OF WET WEATHER CONDITIONS

To investigate the visibility performance of traffic markings under wet weather conditions, different wet weather conditions should be simulated so that the detection distance and retroreflectivity of traffic marking can be measured under the simulated wet-weather conditions. There are two different methods which have been used by previous studies to simulate wet weather conditions. There two methods are: (1) the ASTM methods, and (2) the water/rain tunnel method. ASTM methods include following the measurement procedures described in ASTM standards E 2176 and E 2177 to simulate different wet conditions while the rain tunnel method requires building rain/water tunnel to simulate rainy conditions.

In general, there are two different wet weather conditions to be simulated, including: (1) in rain condition and (2) after rain condition. In this chapter, we will discuss the methodologies used for the simulation of these two different wet weather conditions. Besides, we conducted a rainfall data analysis based on 20 years of precipitation data in Florida. The purpose of doing rainfall data analysis is to determine an average rainfall rate which is able to represent the characteristics of rainfall events in Florida. Such a rainfall rate could be simulated by a rain tunnel to provide a rainy condition which is in accordance with Florida rainfall characteristics.

3.1 ASTM Methods

The ASTM has published two standards for measuring the retroreflectivity of traffic markings under two different wet weather conditions. These two standards are: (1) ASTM E 2176 (Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting *(3)*); and (2) ASTM E 2177 (Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness *(4)*).

The ASTM E 2176 measurement method uses an 8 L (2 gal) minimum capacity, adjustable nozzle garden sprayer to simulate the rainy condition, as shown in Figure 3-1. The rate of water spray is set to be approximately 0.8 L/min.

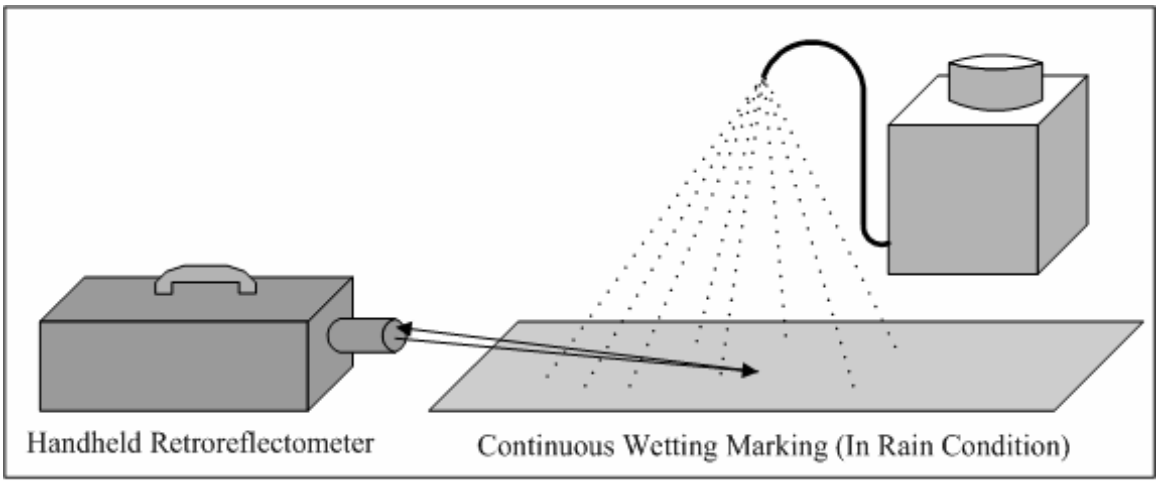

Figure 3-1. ASTM E 2176 Measurement Method

The ASTM E 2176 measurement method is intended to produce a condition of wetness like that found during rainfall. The specific procedure of ASTM E 2176 measurement method is given as follows *(3)*:

1. If necessary, use a shield to prevent water splatter onto the lens of the retroreflectometer;
2. Position and adjust the water spray with the nozzle such that it provides an even spray covering the whole area to be measured. Typically the spray area is approximately a 20±2 in. circle. Open the nozzle until the water rate is approximately 0.8±0.2 L/min. The pressure in the tank shall be maintained such that the flow does not noticeably diminish. Do not fill the sprayer too full of water so that one cannot keep a constant pressure. A range of 1⁄4 to 3⁄4 full works well. The spraying height shall be 0.45±0.15 m (18±6 in.) above the marking;
3. With the retroreflectometer in place, a reading shall be taken initially in the dry condition. (This is optional.);
4. With the retroreflectometer still in place, the water spray is turned on, and the area of the marking to be measured and adjacent area (road) is wetted for 10–15 s;

5. Hold the water spray over the area of the marking to be measured and take a measurement. Continue to take measurements approximately every 10 s thereafter until little change in the values or a steady state occurs. This usually takes about 30 s to obtain a steady state value; and
6. Record the measurements in millicandelas per square meter per lux, [(mcd·m-2)/lx]. Move to next measurement location which is separated sufficiently to provide meaningful data and repeat procedures step 2 and step 3.

The ASTM E 2177 measurement method is intended to produce a condition of wetness like that found just after rainfall, as shown in Figure 3-2. This test method includes pouring a bucket of clean water on pavement markings. Traffic markings are then allowed to drain for around 45 s before retroreflectivity measurements are conducted. The specific procedure of ASTM E 2177 measurement method is given as follows *(4)*:

1. Take a hand sprayer and wet the area of the marking to be measured and the adjacent surrounding area (road surface and marking) for 30 s. Verify that the marking and adjacent area are completely flooded. Or pour 2 to 5 liters of clean water from a bucket. Slowly pour the water over the area of the marking to be measured plus the immediate surrounding area. The water is poured evenly along the test surface so that the measuring field and its surrounding area is momentarily flooded by a crest of water;
2. Measure the coefficient of retroreflected luminance, R_L, of the wetted marking 45 ±5 s after completion of spraying or pouring the water on the marking as described in step 1; and
3. *Records*—Record the dry and wet measurements in millicandelas per square meter per lux, [(mcd·m-2)/lx]. Move to next measurement location which is separated sufficiently to provide meaningful data and repeat procedures in step 2 and step 3.

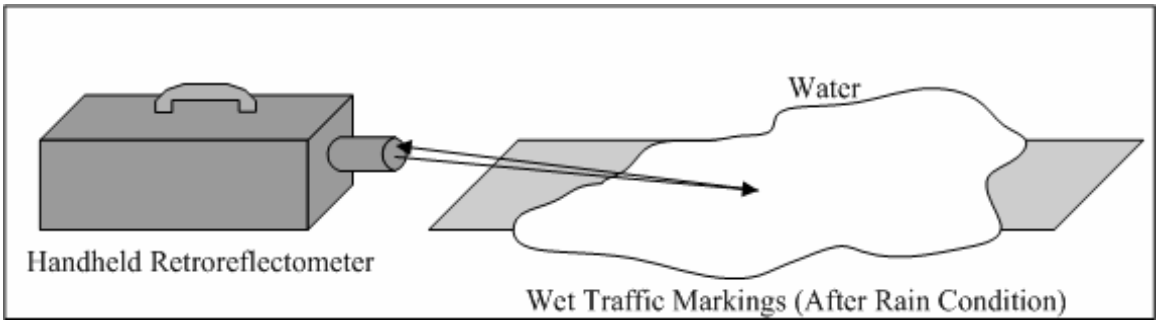

Figure 3-2. ASTM E 2177 Measurement Method

It is important to note that, both ASTM E 2176 and ASTM E 2177 suggests measuring the wet retroreflectivity of traffic markings after they have been installed on the pavement for one month. This is because newly installed pavement markings may have a natural surface tension or release agents that prevent wetting of the product by water. The water will tend to "bead up" on the marking. Attempts to measure markings with this surface "non-wetting" or "beading" of the water may give higher values *(3 and 4).* This phenomenon is usually short lived and will disappear after traffic markings have been installed on the pavement for one month.

3.2 Rain Tunnel

The most commonly used method for measuring the detection distance of pavement marking is to conduct participant evaluations. Participant evaluations include asking participants to evaluate the detection distance of traffic marking under a simulated rainy condition. The rainy conditions created by using ASTM methods are usually not adequate for such a purpose. Participant evaluations usually require building rain tunnels to simulate rainy conditions.

To design and build a rain tunnel is out of the scope of our research. However, two previous studies have built rain tunnels and used them to simulate different rainy conditions for the purpose of conducting participant evaluation (6 and 8). The way in which they build rain tunnels is described herein. We hope the information will help FDOT decide whether a rain tunnel should be built for the future larger scale test of wet weather traffic markings.

In two previous studies, researchers built rain tunnels to simulate rainy conditions in Texas and Virginia (6 and 8). In the study conducted by Virginia Tech Transportation Institute, a 1200-ft long rain tunnel was built on a Smart Road facility. The Smart Road is a two-mile, two-lane road with a banked turnaround at one end and a slower-speed turnaround at the other end. The Smart Road was particularly designed for pavement research and evaluation of vehicle and infrastructure technologies. The rain tunnel is composed of 40 rain towers built on the Smart Road. The rain towers were located every 30 ft. The towers were mounted on portable, removable concrete bases. The tower heads were positioned over the centerline of the pavement marking area (6). A picture of the rain simulation system used by VTTI study is given in Figure 3-3.

Figure 3-3. Rain Simulation System Used in VTTI Study (6)

In order to provide the most even rainfall distribution on the road, researchers of VTTI study used bell-style nozzles mounted in a vertical, base-down position on the road's rain towers. Water is then dispersed from the towers evenly in a circular pattern. The overlap

of the circles' edges provides a constant rainfall onto the road surface. The selection of the nozzle used in the Smart Road rain system, combined with the system water pressure, controls the simulated rainfall rate. A theoretical rainfall rate was calculated based on the flow of water through an individual rain tower at the minimum sustainable pressure, measured at a rate of 36 gallons per min. This flow resulted in rainfall over an area measuring 50 ft in diameter, resulting in a theoretical rainfall rate of 0.88 in. per hr. It was found that the 0.88 in./hr. flow rate is the minimum amount that can be generated by the simulated rain system while still maintaining a diameter circle of 50 ft (6).

In a study conducted by Texas Transportation Institute, a rain tunnel was designed and built at Texas A&M University's Riverside Campus to simulate rainy conditions in Texas. A picture of the TTI rain tunnel is given in Figure 3-4. The rain tunnel built by the researchers of TTI study is 1600-ft long and 12-ft wide. The rain tunnel was designed to simulate three different rainfall rates, including the rainfall rate of 0.25 in./hr, 0.5 in./hr., and 0.75 in./hr.. These rainfall rates represent the rainfall level of low, median, and high respectively.

The researchers of TTI study used gate valves to control the rainfall rates created by the rain tunnel. A 4-inch trunk line connected the rain tunnel to a fire hydrant 800 ft away. The trunk line was split into three 3-inch lines. Each 3-inch line was then fed into a 3-inch gate valve. One of these lines was used for the low flow setting, and the other two were for the medium flow setting. The high flow setting was attained by opening all three valves at the same time. The low flow line supplied water to one set of risers spaced 12 ft apart, while the medium flow line supplied water to the second set of risers spaced 14 ft apart. In total, the rain tunnel in TTI study has 250 0.75-inch risers; and each riser has a nozzle mounted at the end. The nozzles were aimed upward. The risers were supported by cables that connected to posts spaced 50 ft apart (8).

Figure 3-4. Rain Tunnel Used in TTI Study (8)

3.3 Rainfall Data Analysis

Florida is one of the wettest states in the United States with most areas receiving at least 50 inches of rain annually (19). The main source of rain in Florida is found to be thunderstorms. Florida is also found to have the largest numbers of thunderstorms in U.S (19). The frequency and intensity of a thunderstorm usually peaks in July or August. Driving in Florida during the summer is sometimes dangerous because the regular summer rain storms often reduce the visibility performance of traffic markings and signs to a great extent. Figure 3-5 is a picture which was taken during a rain storm in the Tampa Bay area of Florida. The picture was taken at 5:00 in the afternoon. Event though it was not at night time, the markings on the pavement showed a poor visibility performance in the picture.

Figure 3-5. Driving During Rain Storm in Florida

In order to ensure that traffic markings can provide adequate performance services to traveling public in Florida, traffic marking performance on wet pavement surfaces should be tested and evaluated under Florida environmental conditions. This requires that the simulated rainy condition should be able to represent the rainfall events characteristics in Florida.

In this study, twenty years of Florida precipitation data (Jan 1986 to Jan 2006) were obtained from the National Climatic Data Center (NCDC) (20). The NCDC provides two different types of data set for the rainfall data, including: (1) the 15-minute data set and (2) the hourly timeframe data set. The 15-minute data set records the rainfall data at a 15-minute time interval while the hourly time frame data set records the rainfall data at a 1-hour time interval. The VTTI study compared the reliability of these two different data sets and concluded that the 15-minute data set provided the most accurate set of rain

events (6). The 15-minute data set was also used by our study to determine the rainfall rate used to simulate Florida rainy conditions.

The 15-minute precipitation data were recorded from 50 weather monitoring stations across Florida. The data was originally stored in a .TXT file. We used Microsoft Access to extract data from the original .TXT file. A picture of the rainfall database acquired from NCDC is given in Figure 3-6. In the database, the 4-digit variable “Time” indicates the end of a 15-minute time interval. For example, a time value of “1530” corresponds to a time interval between 3:15 PM to 3:30 PM. The rainfall data is recorded as a five-digit integer with the unit of inch/hr. The rainfall data were measured either with an accuracy of tenths of an inch or with an accuracy of hundredths of an inch. In fact, more than 85% of rainfall data in the NCDC database were found to be recorded at 0.1-in. accuracy. The Rainfall data at continuous time intervals were aggregated and defined as a single rain event. For each rain event, the duration and average rainfall rate were calculated. The aggregated database was exported into a Statistical Package for the Social Sciences (SPSS) file for data analysis.

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COOPID	CD	ELEM	UN	YEAR	MO	DA	TIME	VALUE	F
080616	00	QPCP	HI	1986	01	01	2500	00000	P
080616	00	QPCP	HI	1986	01	02	0800	99999	}
080616	00	QPCP	HI	1986	01	02	2500	00000	P
080616	00	QPCP	HI	1986	01	04	1545	00005	
080616	00	QPCP	HI	1986	01	04	1715	00001	
080616	00	QPCP	HI	1986	01	04	1800	00001	
080616	00	QPCP	HI	1986	01	04	1845	00001	
080616	00	QPCP	HI	1986	01	04	1930	00002	
080616	00	QPCP	HI	1986	01	04	2015	00001	
080616	00	QPCP	HI	1986	01	04	2100	00001	
080616	00	QPCP	HI	1986	01	04	2115	00003	
080616	00	QPCP	HI	1986	01	04	2500	00015	
080616	00	QPCP	HI	1986	01	06	0900	99999	a
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080616	00	QPCP	HI	1986	01	08	0800	00065	A
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080616	00	QPCP	HI	1986	01	08	0900	00002	
080616	00	QPCP	HI	1986	01	08	0930	00002	
080616	00	QPCP	HI	1986	01	08	1015	00001	
080616	00	QPCP	HI	1986	01	08	1045	00001	
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080616	00	QPCP	HI	1986	01	08	1745	00001	
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080616	00	QPCP	HI	1986	01	08	1900	00001	
080616	00	QPCP	HI	1986	01	08	2045	00001	
080616	00	QPCP	HI	1986	01	08	2230	00001	
080616	00	QPCP	HI	1986	01	08	2500	00083	P
080616	00	QPCP	HI	1986	01	09	0015	00001	
080616	00	QPCP	HI	1986	01	09	0045	00003	
080616	00	QPCP	HI	1986	01	09	0100	00005	
080616	00	QPCP	HI	1986	01	09	0115	00004	

Record: 1 of 284321

Figure 3-6. NCDC 15-minute Rainfall Database

The focus of this study is on the wet-night visibility of traffic markings. Thus, the interest lies in the rainfall data collected at night time. The night time is generally defined as the time beginning at 7:00 in the afternoon and ending at 7:00 in the morning. A total of 52553 night-time rain events were recorded during the past 20 years (1986 to 2006). A summary statistics of the rainfall data are given in Table 3-1. The range of the average rainfall rate is from 0.04 in./hr. to 11.6 in./hr with an average of 0.48 in./hr. The cumulative curve for the average rainfall rate is given in Figure 3-7. As shown in Figure 3-7, the 85th percentile value of rainfall rate is 0.6 in./hr, indicating the fact that 85% of rain events have a rainfall rate equal to or less than 0.6 in./hr.

Table 3-1. Summary Statistics for Rainfall Data

	N	Minimum	Maximum	Mean	Std. Deviation
Duration (hr.)	52553	0.25	8.75	0.38	0.341
Rainfall Rate (in./hr.)	52553	0.04	11.60	0.48	0.357

The range of the duration of each rain event is from 0.25 hr to 8.75 hr with an average of 0.38 hr. The rain events were then divided into three categories based on the duration of each rain event. A rain event with the duration less than 1 hr is defined as a short rain event. A rain event with the duration between 1 hr and 1.75 hr is defined as a medium rain event. A rain event with the duration being greater than or equal to 2 hr is defined as a long rain event. Several previous studies have used the same method to define the duration categories of rain event (6, and 8). The frequency histogram for the duration of all rain events were given in Figure 3-8. From Figure 3-8, it is clear that the vast majority of rain events (94.04%) in Florida are short rain events which have durations less than 1 hr. The medium rain events and long rain events account for around 5.13% and 0.83% of total rain events respectively. Among the short rain events, around 76.74% of rain events have durations of 15 minutes.

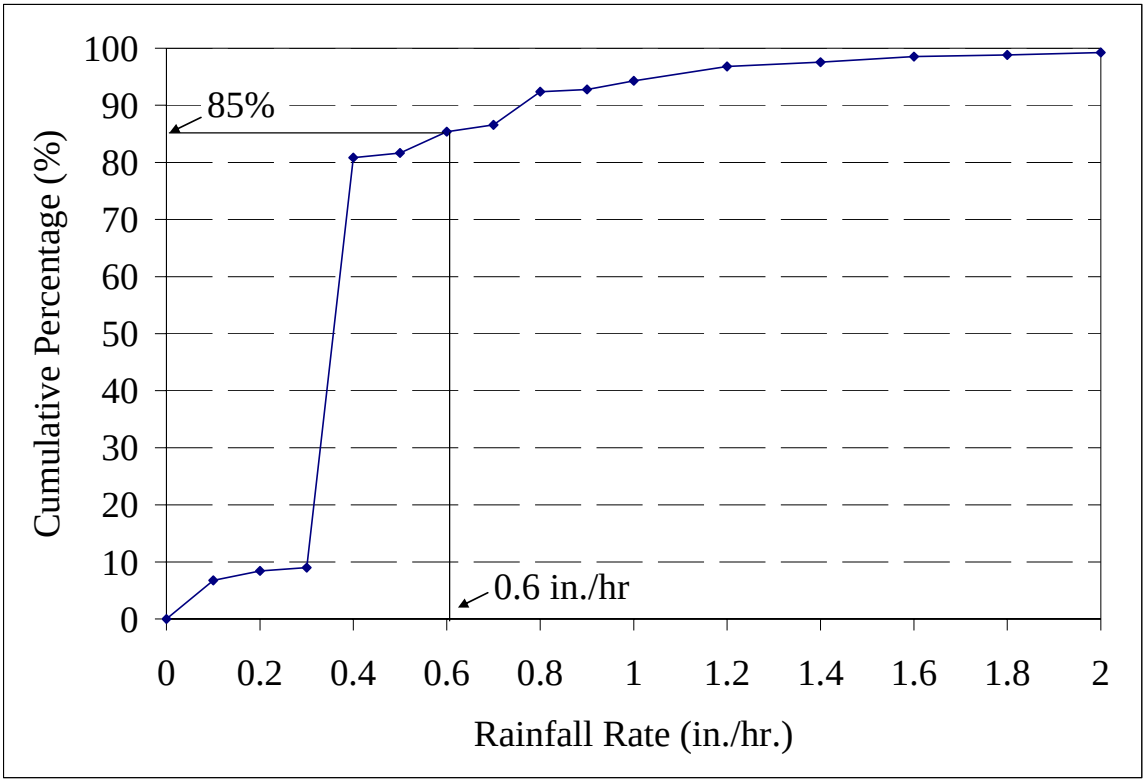

Figure 3-7. Cumulative Curve for the Rainfall Rate of all Rain Events

It is important to note that the duration of 15 minutes recorded in the rainfall database does not necessarily mean that the real duration of a rain event is 15 minutes. It only means that at a particular 15-min time interval a rain event occurs. For a particular rain event that was recorded in the NCDC database, the actual starting time and ending time of the rain event are actually unknown. What we know is in fact the starting time interval and ending time interval. Since 15 minutes is the minimum time interval used for recording rainfall data, any rain events with durations being less than or equal to 15 minutes will be recorded as 15-min rain events. For example, if a rain event starts a 3:14 PM and ends at 3:16 PM, it will be recorded to have a duration of 30 minutes, even though the actual duration of the rain event is only 2 minutes. Thus, using the duration data and rainfall data in the rainfall database to calculate the average rainfall rate will generally overestimate the rainfall duration and underestimate the actual rainfall rate. This problem is more severe for short rain events because the starting time interval and ending time interval accounted for relatively larger percent of the total duration of the short rain events as compared to medium rain events and long rain events.

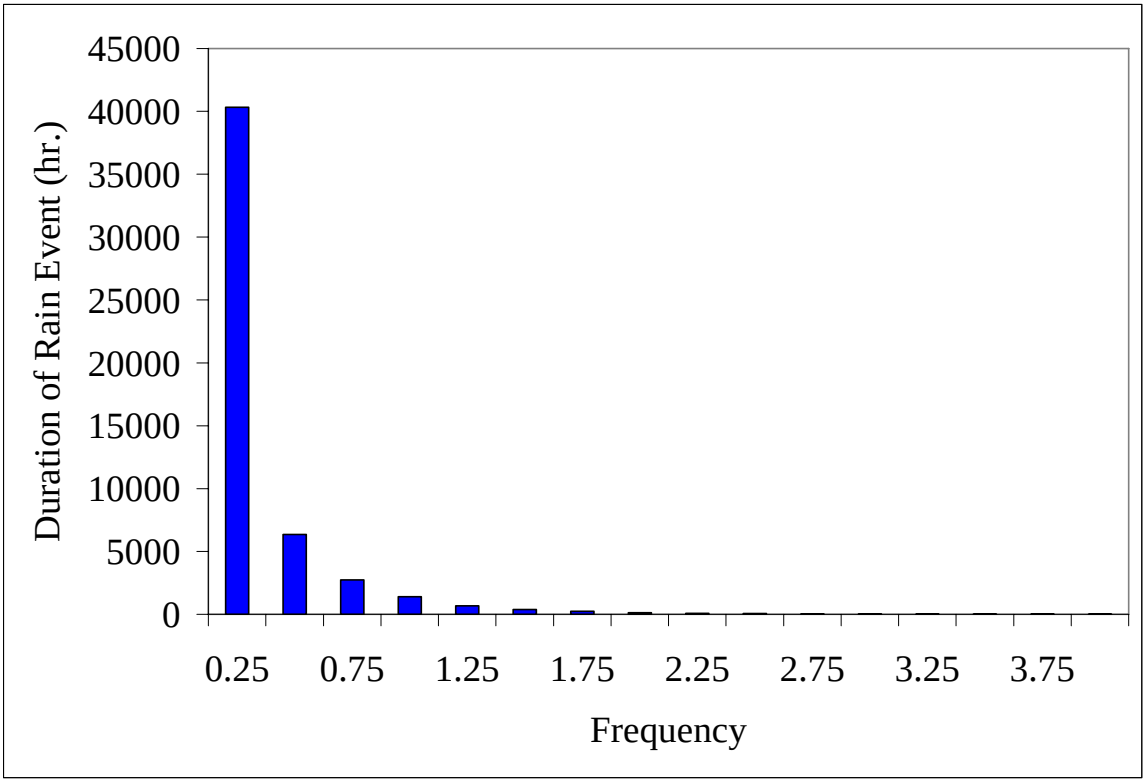

Figure 3-8. Frequency Histogram for the Duration of all Rain Events

To explain this problem more clearly, the research team analyzed the rainfall rate of short, medium and long rain events separately. The summary statistics of rainfall rate data for different duration categories are given in Table 3-2. Cumulative curves were also developed for short, medium and long rain events. These curves are given in Figure 3-9, Figure 3-10 and Figure 3-11 respectively.

Table 3-2. Summary Statistics for Rainfall Rate of Different Duration Categories

Duration Category	N	Minimum	Maximum	Mean	Std. Deviation
Short	49422	0.04	11.60	0.47	0.341
Medium	2695	0.04	3.54	0.76	0.492
Long	436	0.04	2.45	0.60	0.452

*Note: All the rainfall rates in this table have a unit of in./hr.

As shown in Table 3-2, the average rainfall rate for short rain events is 0.47 in./hr, which is generally smaller than the rainfall rates for medium rain events and long rain events.

The curves in Figure 3-9 to Figure 3-11 show that the cumulative distribution of the rainfall rate for short rain events is quite different from the distributions for the medium rain events and long rain events. By observing the cumulative curves, an unusual phenomenon was observed. As shown in Figure 3-9, around 75.3% of the short rain events have a rainfall rate of 0.4 in./hr. In addition, among these 75.3% short rain events, more than 90% of them have durations of 15 minutes.

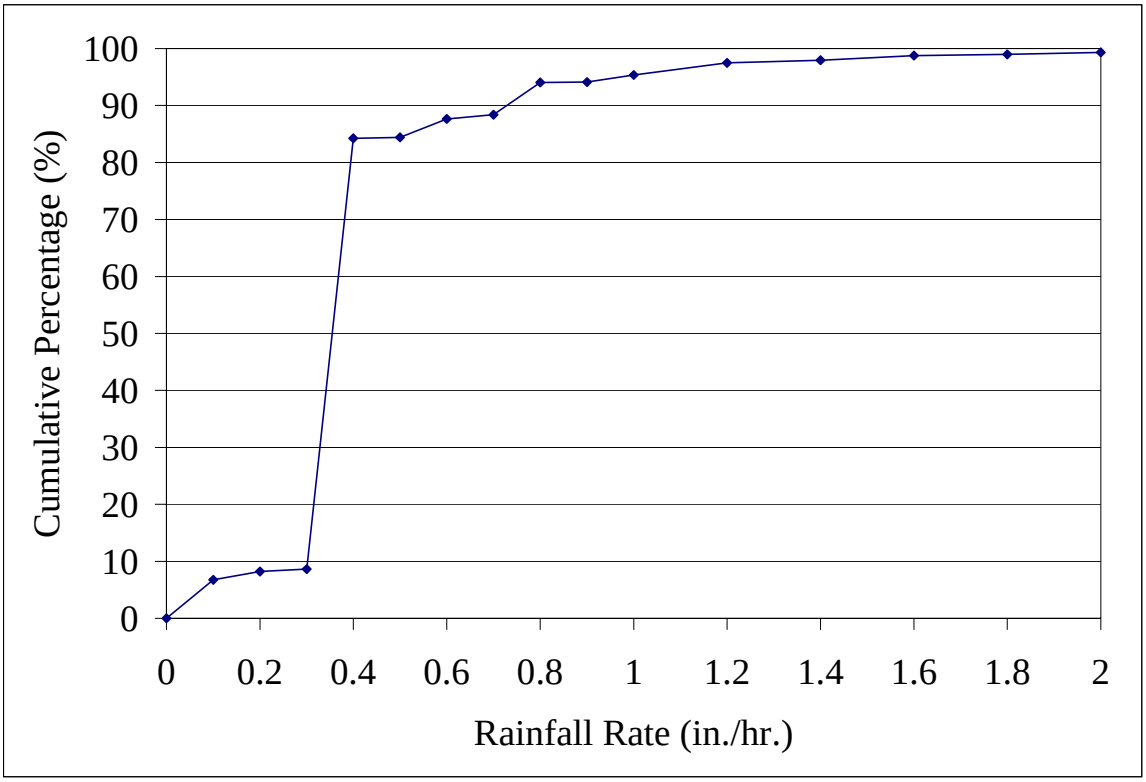

Figure 3-9. Cumulative Curve for the Rainfall Rate of Short Rain Events

A reasonable explanation to this phenomenon is that more than 85% of rainfall data in the NCDC database were measured with an accuracy of tenths of an inch. When the rainfall data is measured with an accuracy of tenths of an inch, any rainfall data that is less than 0.15 inch may be simply recorded as 0.1 inch.

The results of rainfall rate analysis and duration analysis generally show that the rainfall data for short rain events may not be as reliable as the rainfall data for medium rain events and long rain events. The research team of this study then decided to remove the

rainfall data for short rain events from analysis. The rainfall database for medium rain events and long rain events were combined into a single rainfall database. The cumulative distribution for the combined rainfall database is given in Figure 3-12.

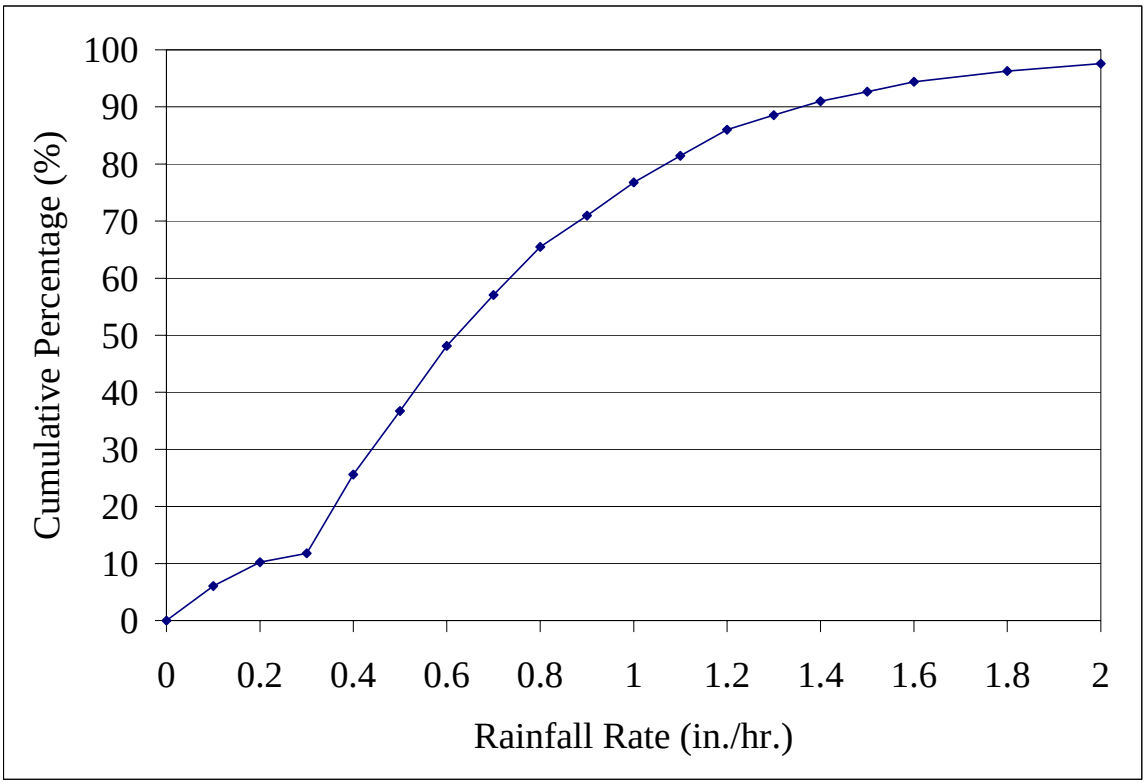

Figure 3-10. Cumulative Curve for the Rainfall Rate of Medium Rain Events

The 15th, 50th and the 85th percentile values were marked on the cumulative curve for rainfall rate, as shown in Figure 3-12. The 50th percentile value is simply the median rainfall rate. The 15th percentile value and the 85th percentile value represent the points where 15 percent and 85 percent of rain events have rainfall rates no larger than these points' X-coordinate values. These three percentiles are the most commonly used percentiles in engineering analysis. As shown in Figure 3-12, the 15th percentile value of rainfall rate is 0.32 in./hr. The 50th percentile value of rainfall rate is 0.63 in./hr and the 85th percentile value is 1.2 in./hr. Based on these data analysis results, recommendations are given about the rainfall rates that a rain tunnel should be able to simulate in the future larger scale test of wet weather pavement markings. The recommended rainfall rates are:

0.3 in./hr, 0.65 in./hr and 1.2 in./hr, which reflects a rainfall level of low, medium and high respectively.

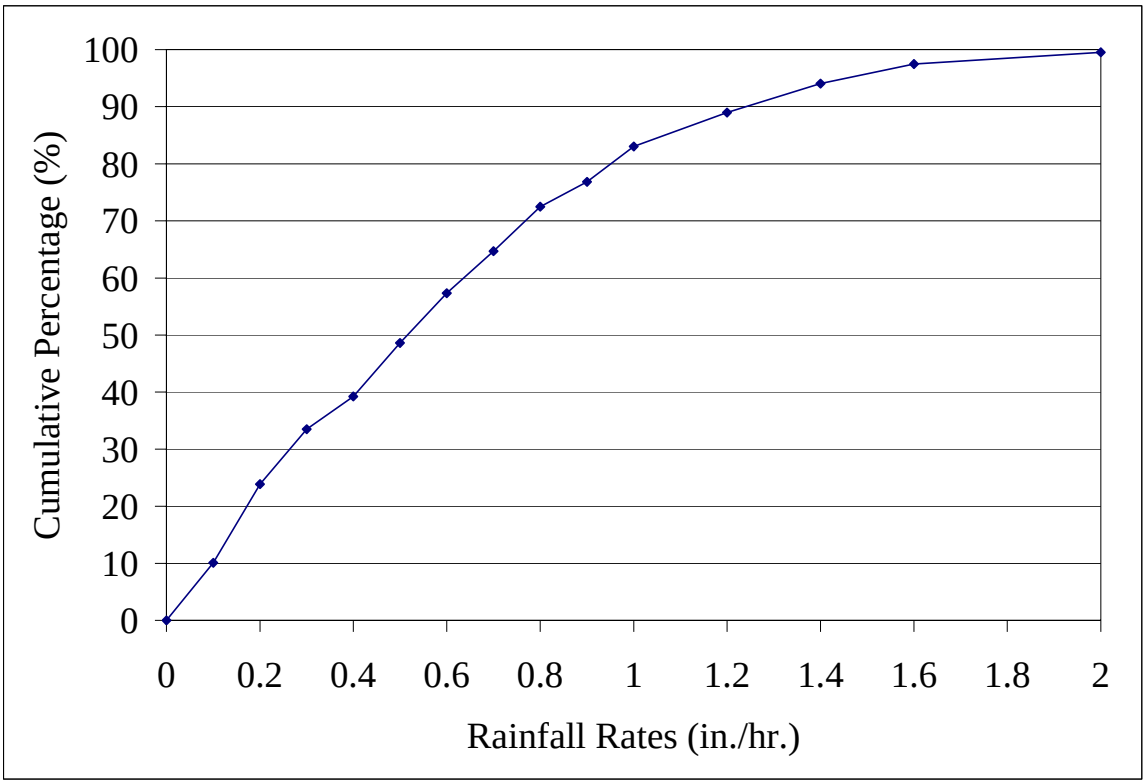

Figure 3-11. Cumulative Curve for the Rainfall Rate of Long Rain Events

3.4 Summary

This chapter explained the methodologies used to simulate the rainy conditions in Florida. There are basically two different methods for the simulation of rainy conditions, including ASTM methods and rain tunnel methods. The ASTM methods simulate the rainy conditions by following the procedures specified in ASTM standards E 2176 and E 2177. The rain tunnel method requires building rain tunnels to simulate rainy conditions. The key point for the rain tunnel method is how to determine a rainfall rate that is able to reflect the rainfall characteristics in Florida. Thus, the simulated rainy condition is in accordance with the Florida environmental conditions. In order to determine the rainfall rate, 20 years of rainfall data in Florida was acquired from NCDC. Based on the rainfall data analysis results, the research team determined three different rainfall rates that a rain

tunnel should be able to simulate. These rainfall rates are: 0.3 in./hr, 0.65 in./hr and 1.2 in./hr. These recommended rainfall rates reflect a rainfall level of low, medium and high respectively.

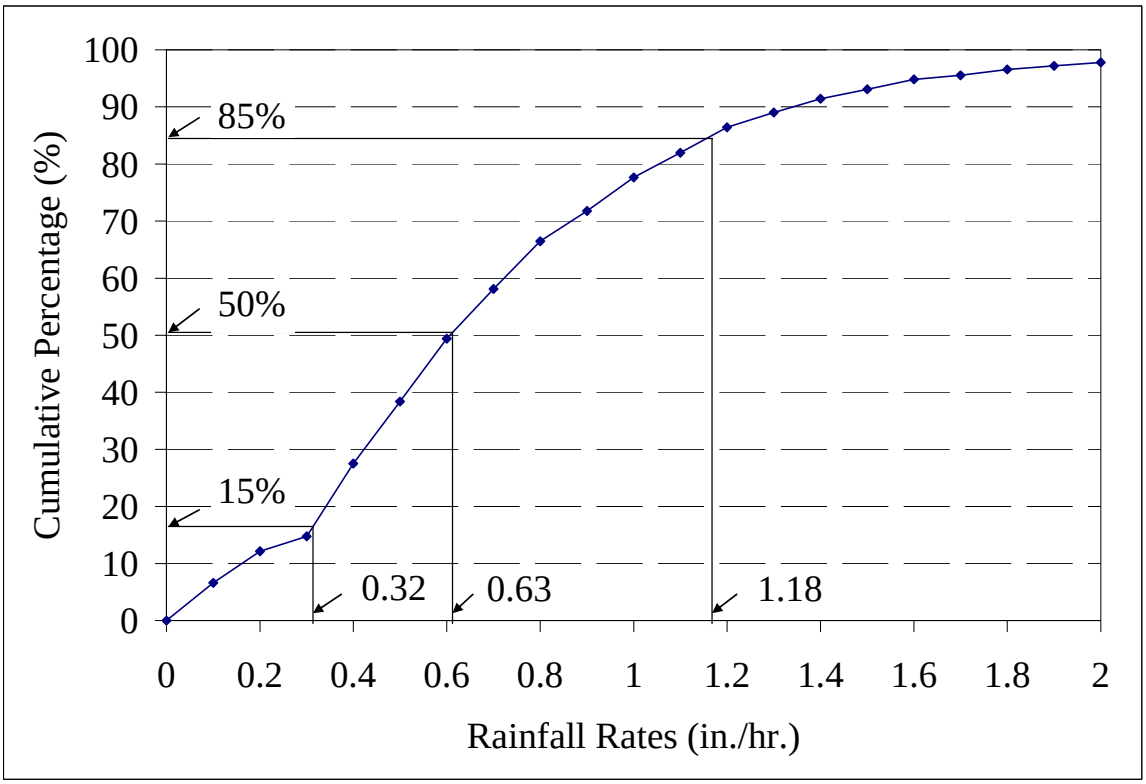

Figure 3-12. Cumulative Curve for the Rainfall Rate of Medium and Long Rain Events

4 EXPERIMENTAL DESIGN

The major objective of this study is to set testing parameters and to develop a testing plan for the future larger scale test of wet weather pavement markings. For this purpose, an extensive literature review has been undertaken to review testing procedures and evaluation guidelines used in past similar projects. Besides, the research team of this study also analyzed 20 years of rainfall data in Florida. Based on the rainfall data analysis results, recommendations were given about the rainfall rates that a rain tunnel should be able to produce. The recommended rainfall rates reflected three different rainfall levels that were found in Florida.

This chapter discussed the testing variables that were selected for the future larger scale test of wet weather traffic markings. The selected testing variables include detection distance, retroreflectivity, and service life of traffic markings. A testing plan was developed in this chapter to evaluate the visibility performance of various pavement marking systems under different simulated rainfall conditions. Besides, several pavement marking systems were also selected for the proposed future test. These products were found by several previous studies to have good visibility performance during wet weather conditions.

4.1 Selection of Testing Variables

Detection Distance

Detection distance is the distance that the roadway delineation provides the driver to see upcoming changes in roadway alignment. It directly measures the visibility performance of traffic marking. Traffic markings should provide adequate detection distance so that drivers can detect roadway features and alignment ahead and have adequate perception-reaction time to respond to any change in roadway alignment. For the future larger scale test of wet weather pavement markings, the detection distance of a longitudinal line should be selected as the measure of effectiveness.

Previous studies have measured the detection distance of traffic marking under wet-night conditions by conducting participant evaluations (5, 6 and 8). In those studies, participants were asked to evaluate the detection distance of traffic marking under various simulated rainy conditions. Usually, each individual participated in the participant evaluation must have a valid driver's license, and should be able to pass the visual acuity test before the evaluation starts. Since the wet-night visibility of traffic markings is of particular concern to aged drivers, the selected participant group should also contain a certain number of drivers under the ages of 60 years and older.

Previous studies have conducted two different types of participant evaluations, including a static participant evaluation and a dynamic participant evaluation. The static participant evaluation was conducted by the Virginia Tech Transportation Institute (6). In the VTTI study, participants were asked to sit in a static vehicle to count the number of pavement marking skip lines visible from the passenger seat of the experimental vehicle. This count, representing the visibility distance, was measured for each marking in each of the experimental conditions. The dynamic participant evaluation was conducted by the Texas Transportation Institute (8). In the TTI study, participants were asked to drive the testing vehicle through the rain tunnel with a constant speed of 30 mph. The subject alerted the researcher when he/she could see a marking, and alert the researcher again when he/she could identify the type of marking. The researcher sitting in the testing vehicle recorded the location values from a distance measuring instrument installed on the testing vehicle when the subject detected or identified the marking samples. The dynamic participant evaluation method is found to be superior to the static method simple because it is more in consistent with the real driving situation. If possible, the future larger scale test should use the dynamic participant evaluation method to determine the detection distances of wet weather traffic markings.

The participant evaluation method usually requires building a rain tunnel to simulate various rainy conditions. The way in which previous studies build rain tunnels have been described in chapter 3. It was recommended by the author that the FDOT should build a rain tunnel for the future larger scale test of wet weather traffic markings. The rain tunnel should be built in a place where there exits little ambient light from buildings or nearby

communities. The rain tunnel should be able to simulate three different rainfall rates. These rainfall rates are 0.3 in./hr, 0.65 in./hr, and 1.2 in./hr. As mentioned before, these recommended rainfall rates were determined based on the analysis of 20 years rainfall data in Florida. The recommended rainfall rates reflect different rainfall levels that were found in Florida.

Retroreflectivity

The participant evaluation method described in the previous section is a subjective method. The results of the participant evaluation method depend on participants' subjective judgment. As an alternative, the visibility performance of wet weather traffic markings can also be measured indirectly by measuring traffic marking retroreflectivity. Retroreflectivity measures the ability that a pavement marking reflects light directly back to the source of the light. It is considered the most critical factor for a traffic marking to be visible at night.

For the proposed larger scale test, the retroreflectivity of traffic markings should be measured under some simulated rainy conditions. The methods that can be used to simulate different rainy conditions have been explained in chapter 2. In general, rainy conditions can be simulated either by following the procedures specified in the ASTM standards E 2176 and E 2177, or by using a rain tunnel.

Both handheld retroreflectometer and mobile retroreflectometer can be used to measure traffic marking retroreflectivity. It was recommended by the author that a handheld retroreflectometer should be used in the future larger scale test of wet-weather traffic markings. As compared with a mobile retroreflectometer, the handheld retroreflectometer usually gives more accurate measurements of traffic marking retroreflectivity.

Traffic marking retroreflectivity should be measured at a 30 Meter CEN Geometry. The 30 Meter CEN Geometry is specified by the European Committee for Standardization (CEN). The 30 Meter CEN Geometry corresponds to a headlamp height of 0.65 meters and an observer height of 1.2 meters at a distance of 30 meters from the center of the reflective stripe. This results in the entrance and observation angles of 88.76° and 1.05°,

respectively. A figure depicting the 30 Meter CEN Geometry is given in Figure 4-1. The 30 Meter CEN Geometry is also used by ASTM standards E 1710, E 2176 and E 2177 to measure traffic marking retroreflectivity.

The method of using retroreflectivity values to evaluate the visibility performance of traffic markings suffers from a major disadvantage that there are no widely accepted guidelines or criteria concerning the minimum retroreflectivity level of traffic markings that is essential for safety operation on the highway during wet-night conditions. As mentioned before, the FHWA have sponsored a research in 2000 to investigate the effects of rainfall on pavement-marking retroreflectivity (16). It was found that the pavement marking retroreflectivity under wet pavement conditions averaged only 42% of the retroreflectivity value under dry pavement conditions. Thus, the minimum retroreflectivity under wet pavement conditions should, theoretically, be equal to the minimum retroreflectivity values under dry pavement conditions times 2.2, as shown in Table 4-1.

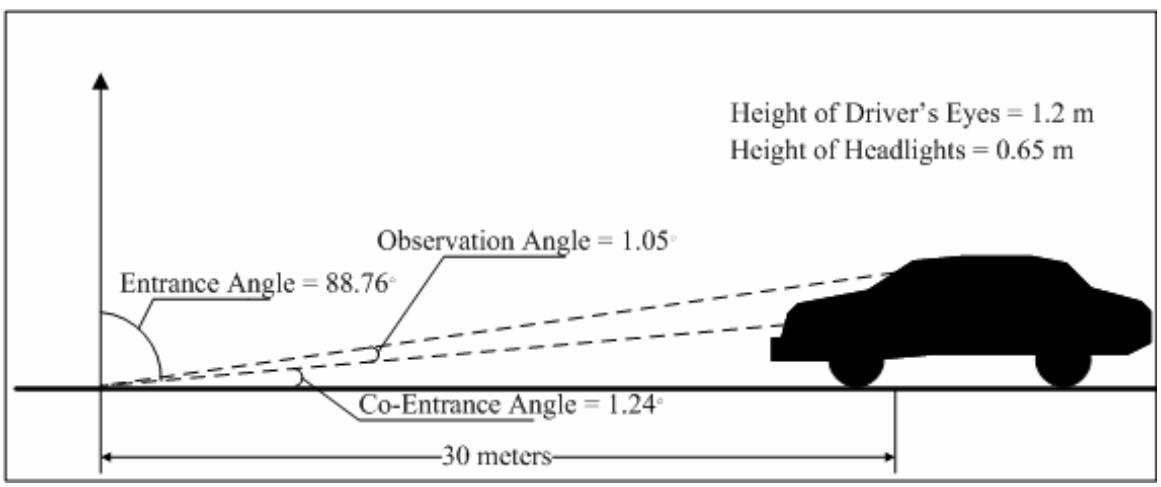

Figure 4-1. 30 Meter CEN Geometry

The FDOT has published some specifications for the performance of traffic markings. The FDOT has also specified the minimum retroreflectivity values for wet weather traffic stripes, as shown in Figure 3-2. However, the minimum retroreflectivity values specified by the FDOT are quite inconsistent with those recommended by the FHWA. On the contrary to the FHWA, the minimum retroreflectivity values specified by the FDOT for

wet weather traffic stripes under wet weather conditions are found to be the half of the minimum retroreflectivity values that was measured under dry weather conditions, as shown in Figure 4-2.

Table 4-1. Estimated Minimum Wet Retroreflectivity Values Based on Threshold Values Used to Define Service Life for Dry Conditions (mc/m^2/lux) (16)

Pavement Marking Color and Environment	Roadway Type/Speed Classification		
	Non-Freeway (≤40 mph)	Non-Freeway (≥45 mph)	Freeway (≥55 mph)
White	185(85)	217(100)	326(150)
White with RRPMs or lighting	65(30)	76(35)	152(70)
Yellow	120(55)	141(65)	217(100)
Yellow with RRPMs or lighting	65(30)	76(35)	152(70)

Note: Retroreflectivity values are measured at 30-m geometry. The values in parentheses are the threshold values for dry pavement conditions.

Table 4-2. Minimum Retroreflectivity for Wet Weather Traffic Stripes (21)

	White		Yellow	
Retroreflectance	Dry	Wet	Dry	Wet
Initial*	300 mcd/lx·m2	150 mcd/lx·m2	250 mcd/lx·m2	125 mcd/lx·m2
Intermittent and Final**	150 mcd/lx·m2	75 mcd/lx·m2	150 mcd/lx·m2	75 mcd/lx·m2
* Initial retroreflectance is measured within 14 days of exposure to traffic.				
** Intermittent retroreflectance is measured at the discretion of the Department and final retroreflectance is measured at 3 years ± 2 weeks after exposure to traffic.				

So far there are no widely accepted guidelines that have specified the minimum retroreflectivity level of traffic markings under wet weather conditions. No previous studies have verified if the minimum retroreflectivity values specified by FHWA or FDOT can provide adequate visibility performance to drivers under wet-night conditions. We recommend that the future project could focus on this issue. The proposed study should be able to answer the following two questions: (1) what is the minimum retroreflectivity value of traffic marking that is essential for safety operation on the

highway during wet-night conditions; and (2) is it suitable to use the ASTM standards E 2176 and E 2177 to evaluate the visibility performance of traffic markings under wet-weather conditions? To answer these two questions, it is essential to build a rain tunnel and to conduct participant evaluations. The relationship between the detection distances measured using the participant evaluation method and the retroreflectivity values measured by following the ASTM standards should be carefully studied.

Service Life of Wet Weather Traffic Markings

The retroreflectivity of traffic marking will degrade over time for a variety of reasons such as the abrasion by traffic, sun and heat exposure, application methods, material type and chemical spilled on the road surface (13). Among those factors, the most important factor is found to be the traffic abrasion. A previous study has tried to establish a relationship between the average daily traffic (ADT) and service life of traffic markings (22). It was found that ADT is loosely correlated with service life.

In a FHWA sponsored research, Migletz et al. evaluated the service life of durable pavement markings. The service life of traffic marking is defined as the time or number of traffic passages required for its retroreflectivity to decrease from its initial value to a minimum threshold value that indicates the marking needs to be refurbished or replaced (23). It was found that the service life of marking materials and roadway types can be modeled as a function of time and cumulative traffic passages. The model is in the following equation:

$$SL_{\text{Months}} = \frac{SL_{\text{CTP}}}{\left[\dfrac{\text{CTP}_{\text{Final}}}{\text{Date}_{\text{Final}} - \text{Date}_{\text{Install}}}\right]\left[\dfrac{365.25\,\text{days}}{12\,\text{months}}\right]} \tag{1}$$

where, SL_{Months} = service life in elapsed months,

SL_{CTP} = service life in cumulative traffic passages (millions of vehicles),

$\text{Date}_{\text{Final}}$ = date of final field measurement, and

$\text{Date}_{\text{Install}}$ = installation date of pavement marking.

There have been several studies conducted concerning the performance of traffic marking under wet weather conditions (5, 6, 7, 8, 17 and 18). The focuses of these studies are on the visibility performance of new traffic markings under wet night conditions. There is no wet marking performance data for traffic markings that have been placed on the pavement surface for a certain time period. These previous studies were intended to answer the question about what is the detection distance of a particular marking material or technique under different wet-night conditions. However, they are not able to answer the question about what is the detection distance of this marking material or technique after it has been worn by certain numbers of vehicles passing over them.

To measure the visibility performance of traffic markings that have been worn by traffic abrasion, the traditional method is to place the marking on the pavement, wait for several months, and then go to the field to measure the retroreflectivity values. For some durable marking materials such thermoplastic markings, it usually takes more than one year before the marking can be worn by traffic abrasion. For the future larger scale test of wet weather pavement markings, this method is obviously not feasible. To overcome this problem, a possible solution is to use the FDOT Material Office's heavy vehicle simulator. The FDOT Material Office's heavy vehicle simulator is a mobile machine used to subject roads to accelerated trafficking. It can simulate 20 years of road deterioration within three months (24). A picture of the heavy vehicle simulator that is used by the FDOT is given in Figure 4-2. Since the service life of marking materials and roadway types can be modeled as a function of time and cumulative traffic passages, it is ideal to use the heavy vehicle simulator to wear traffic marking panels with given equivalent traffic repetitions. Then the worn traffic markings could be tested under different rainy conditions.

Figure 4-2. FDOT Material Office's Heavy Vehicle Simulator

4.2 Wet-Weather Pavement Markings

During the past two decade, many techniques have been implemented to improve the visibility performance of traffic markings under wet-night conditions. These techniques include but not limited to the following:

(1) raised pavement markers (RRPMs),

(2) wet-weather traffic stripes,

(3) large glass beads and bead clusters,

(4) high refractive index glass beads,

(5) inverted profiled or structured markings, and

(6) rumble stripes.

In a FHWA sponsored study, Schnell et al. evaluated the visibility performance of flat pavement marking tape, patterned pavement marking tape, and wet weather pavement marking tape under dry, wet (just after rainfall), and simulated rain conditions (ongoing 1”/hr rainfall). The measures of effectiveness of that study include the detection distances, eye movements, and the pavement marking retroreflectance. It was found that the wet weather tape performed best in terms of the detection distances, followed by the patterned tape and the flat tape. Under the dry condition, all three pavement markings provided long detection distances. Under the wet condition, the flat tape gave a very short detection distance of 24 meters (79ft) on average. The patterned tape gave a slightly longer detection distance of 44 meters (144ft) on average. The wet weather tape performed best with an average of 76 meters (249ft) of detection distance (5).

The study conducted by the Virginia Tech Transportation Institute tested the wet-night visibility of six different marking techniques. The selected marking techniques include:

(1) Standard Paint with Standard Beads

(2) Standard Paint with Large Beads

(3) Wet Retroreflective Tape

(4) Semi-Wet Retroreflective Tape

(5) Thermoplastic Profile-Type Markings

(6) Raised Retroreflective Pavement Markers

In the VTTI study, both ASTM methods and participant evaluation methods were used to evaluate the visibility performance of selected markings techniques. The mean detection distance for different marking techniques have been shown in Figure 2-4. The results show that two of the marking technologies, raised retroreflective markers and wet retroreflective tape, outperformed the group under all conditions. These markings were also found to be highly accepted by the participants. The results also show that the standard paint and glass beads technology is the worst performing and the least desirable of those evaluated (6).

The study conducted by the Texas Transportation Institute measured the visibility of twenty-one selected marking techniques under simulated wet-night conditions. The marking materials selected for test in the TTI study include thermoplastic, traffic paints, traffic tapes, exotics and raised retroreflective pavement markings. The research team of the TTI study also looked at the influence of marking width and bead size on the visibility performance of traffic markings. The measured visibility distances of the selected markings haven been shown in Figure 2-6. By comparing the detection distances shown in Figure 2-6, the following conclusions are made by the researchers of that study (8):

(1) Using Type III beads in waterborne paint provides significantly longer detection distances over the use of Type II beads in waterborne paint. The benefits of the bigger beads are particularly noticeable during heavier rainfall events.

(2) For thermoplastic markings, use of a double drop with large high refractive index beads provided wet-night detection distances that were impervious to rainfall rates. Type II and Type III beads, by themselves, had a substantial drop in performance when the rain rate was increased from the low to the medium level.

(3) As a group, the tapes performed better than any other class of material. With the exception of the RRPMs, the 3M 750 tape provided the longest detection distances for all three rainfall rates.

(4) The exotic materials produced some surprising results along with some disappointing results. The polyurea with bead clusters performed well during the low and medium rainfall rates but dropped off during the heavy rainfall rates. The splattered MMA with the big beads performed well, too. It had the second longest average detection distance for medium rainfall and the third longest detection distance for heavy rainfall.

(5) An investigation in the potential advantage of wider lines with respect to wet-night visibility demonstrated the promise of wider lines. Despite a limited data set,

a 6-inch-wide line showed 30 percent longer detection distances than a comparable 4-inch-wide line.

For the future larger scale test of wet weather traffic markings, we recommend that all the pavement marking materials that are widely used in Florida should be tested for their wet-weather performance. Besides, we also specifically selected several traffic markings. Most of these products were found by previous studies to perform well under wet-weather conditions. Two products are inverted profile traffic stripes that were listed in the FDOT qualified production list (25). These selected products are given in Table 4-3. We hope these marking materials can be considered in the future larger scale test of wet-weather traffic markings.

Table 4-3. Preliminarily Selected Marking Products for Future Test

Material	Manufacturer	Glass Bead Type
Tape A750ES	3M	
Tape 380WR	3M	
Alkyd Thermoplastic	Ennis Paint	Type I, III, High Index
Gulfline Inverted Wt.	Gulf Industries Inc	
Gulfline Inverted Yl.	Gulf Industries Inc	

4.3 Basic Testing Procedures

Based on the literature review results, it is recommend by the author that a follow-up project should be conducted to evaluate the wet-night visibility of traffic marking materials. The proposed project is intended to answer the following questions:

(1) what is the minimum retroreflectivity value of traffic marking that is essential for safety operation on the highway during wet-night conditions;

(2) what is the retroreflectivity value a particular traffic marking can produce under Florida environmental conditions;

(3) what is the retroreflectivity value a particular traffic marking can produce after it has been worn by certain numbers of traffic passages; and

(4) is it suitable to use the ASTM standards E 2176 and E 2177 to evaluate the visibility performance of traffic markings under wet-weather conditions?

A flow chart depicting the tasks of the proposed future larger scale test is given in Figure 4-3. More specifically, the proposed testing plan for the future larger scale test of wet weather traffic markings includes the following five tasks:

(1) To measure the detection distance of new traffic markings under different simulated rainy conditions. This task requires building rain tunnels to simulate different rainy conditions and conducting participant evaluations. There are two different rainy conditions to be simulated, including (1) in rain condition, and (2) after rain condition. The "in rain condition" represents a condition of wetness like that found during rainfall. Three different rainfall rates need to be simulated by the rain tunnel. These rainfall rates are: 0.3 in./hr, 0.65 in./hr and 1.2 in./hr. These recommended rainfall rates reflect a rainfall level of low, medium and high respectively. The "after rain condition" represents a condition of wetness like that found just after rainfall. This condition can be produced by turning off the water flow of the rain tunnel after an in rain test has been conducted.

(2) To measure the dry, wet and recovery retroreflectivity of new traffic markings by following the procedures specified by ASTM standards E 1710, E 2176 and E 2177, respectively.

(3) To measure the detection distance of traffic markings that has been worn by certain numbers of traffic repetitions under different simulated rainy conditions. The FDOT Material Office's Heavy Vehicle Simulator can be used to worn traffic markings.

(4) To measure the dry, wet and recovery retroreflectivity of worn traffic markings by following the procedures specified by ASTM standards E 1710, E 2176 and E 2177, respectively.

(5) To analyze the relationship between the detection distances measured using the participant evaluation method and the retroreflectivity values measured by following the procedures specified ASTM standards.

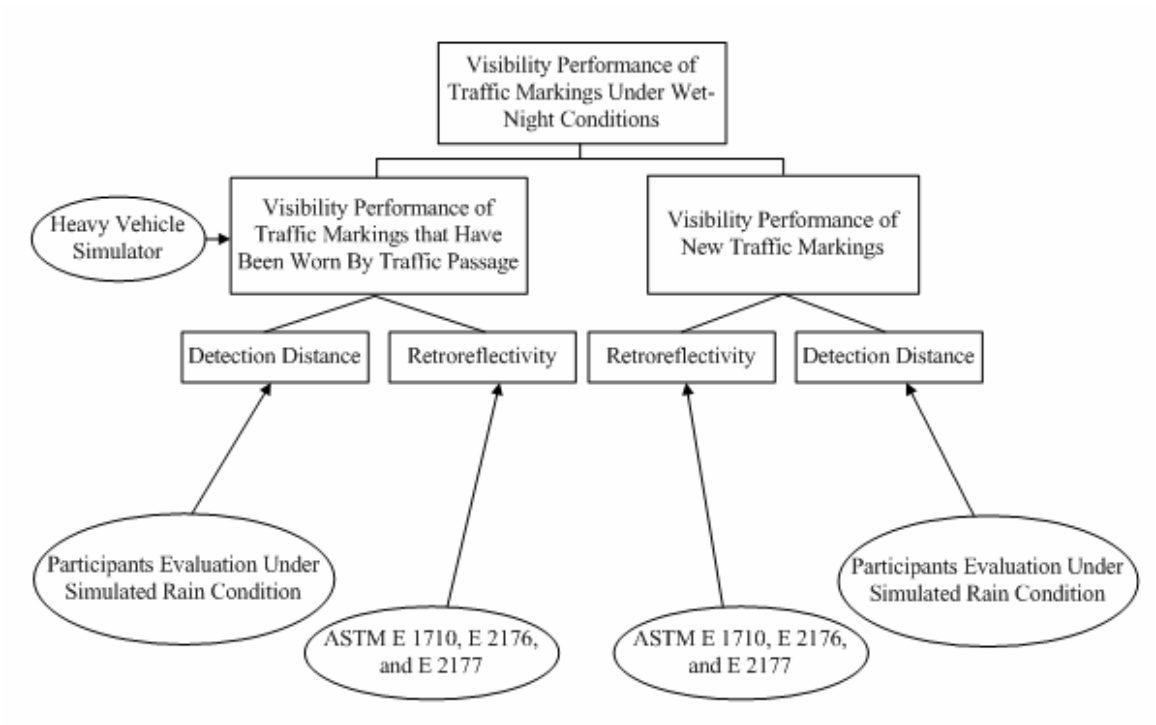

Figure 4-3. Major Tasks for Future Larger Scale Test of Wet-Weather Traffic Markings

To accomplish these tasks, the basic testing procedures should be followed:

(1) Researchers make different traffic marking panels using different marking materials;

(2) After the traffic marking panels have been made for one month, researchers measure the dry, wet and recovery retroreflectivity of new traffic markings by following the procedures specified by ASTM standards E 1710, E 2176 and E 2177, respectively.

(3) Researchers conduct a participant evaluation to measure the detection distance of new traffic markings under various simulated rainy conditions. These rainy conditions should be simulated by using a rain tunnel.

(4) After the participant evaluations are completed, researchers use the FDOT Material Office's heavy vehicle simulator to worn traffic markings until the loss of striping material line exceeds 5%. Researchers record the number of traffic repetition for each traffic marking panel.

(5) Researchers measure the dry, wet and recovery retroreflectivity of worn traffic markings by following the procedures specified by ASTM standards E 1710, E 2176 and E 2177, respectively.

(6) Researchers conduct another participant evaluation to measure the detection distance of worn traffic markings under various simulated rainy conditions.

(7) Researchers analyze the measured detection distances and retroreflectivity values to establish a relationship between the detection distances measured using the participant evaluation method and the retroreflectivity values measured by following the procedures specified ASTM standards.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Traffic markings are one of the most important traffic control and safety devices. The basic requirement for traffic marking is that it must be visible. During clear daylight hours, the visibility of traffic markings usually presents little problem. During night driving in rainy conditions, however, the accumulated water on the road surface will reduce the light reflected back to drivers' eyes. Thus, it will result in a greatly reduced visibility performance of traffic marking.

The purpose of this research project is to perform a preliminary study which will establish a basis for future larger scale evaluation of traffic markings on wet pavement surfaces. The specific objectives include setting testing parameters and developing a testing plan for the future larger scale test of wet-weather pavement markings. For this purpose, an extensive literature review has been undertaken to review testing procedures and evaluation guidelines used in past similar projects. The selected testing variables include detection distance, retroreflectivity, and service life of different traffic markings. A testing plan was developed to test the selected testing parameters of various pavement marking systems under different rainy conditions. In addition, several wet-weather pavement marking systems were also selected for the future larger scale test. These products were found by previous studies to have good visibility performance during wet-weather conditions.

The research team of this study also summarized methodologies used by previous studies to simulate rainy conditions. There are basically two different methods for the simulation of rainy conditions, including the ASTM methods and the train tunnel methods. By following ASTM E 2176 and E 2177, it is possible to simulate rainy conditions. The rain tunnel method requires building an enclosed space to simulate wet weather environments. The most crucial parameter is the maximum rate of rainfall that a material is able to overcome and maintain retroreflectance. This performance characteristic can be compared to real life Florida weather events. For this purpose, 20 years of Florida rainfall

data was acquired from the National Climatic Data Center. Statistical analysis was conducted based on the collected rainfall data. Based on the rainfall data analysis results, the research team determined three different rainfall rates that the rain tunnel should be able to simulate: 0.3 in./hr, 0.65 in./hr and 1.2 in./hr.

5.2 Conclusions and Recommendations

Based on the literature review results and rainfall data analysis results, the following conclusions are made:

(1) There are no widely accepted guidelines that have specified the minimum retroreflectivity level of traffic markings under wet weather conditions.

(2) Previous studies concerning the wet-night visibility of traffic markings have only focused on the visibility performance of new traffic markings under wet-night conditions. There is no wet marking performance data for traffic markings that have been placed on the pavement surface for a certain time period.

(3) For the future larger scale test of wet weather traffic markings, it is essential to build a rain tunnel to simulate different rainy conditions that were found in Florida. The rain tunnel should be able to produce the rainfall rates of 0.3 in./hr, 0.65 in./hr and 1.2 in./hr.

The authors of this report recommend that a follow-up project should be conducted to investigate the wet-night visibility of traffic marking materials in Florida. The research team have selected the testing parameters and developed a testing procedure for the proposed test. We recommend that participant evaluations should be conducted in the proposed test to measure the visibility distance of traffic marking. To conduct participant evaluations, a rain tunnel should be built to simulate different rainy conditions. The research team have analyzed 20 years of rainfall data in Florida and recommended three rainfall rates that the rain tunnel should be able to simulate. It is recommended that all the pavement marking materials that are widely used in Florida should be tested for their wet weather performance. Besides, we specifically selected several traffic marking products that were found by previous studies to perform well under wet-weather conditions. We

will also consult with the FDOT project manager to determine the pavement marking materials that should be evaluated in the proposed future test.

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