Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-06/0-5008-1		

4. Title and Subtitle	5. Report Date
EVALUATION OF WET-WEATHER PAVEMENT MARKINGS: FIRST YEAR REPORT	September 2005
	6. Performing Organization Code
7. Author(s) Paul J. Carlson, Jeffrey D. Miles, Michael P. Pratt, and Adam M. Pike	8. Performing Organization Report No. Report 0-5008-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-5008
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Technical Report: September 2004-August 2005 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Evaluation of Wet-Weather and Contrast Pavement Marking Applications

URL: http://tti.tamu.edu/documents/0-5008.pdf

16. Abstract

This report details the first year of a two-year project. During the first year the emphasis was on determining the wet-night visibility of various pavement marking systems under a variety of realistic rainfall levels. The researchers performed a literature review. They analyzed 20 years of Texas rainfall data to determine the most appropriate rainfall levels to use as design criteria for a rain tunnel. Using a low, medium, and high rainfall rate (0.28, 0.52, and 0.87 inches per hour, respectively), a 1600 ft long rain tunnel was designed and built at Texas A&M University's Riverside Campus.

Experimental subjects drove through the rain tunnel and looked for pavement markings simulating skip lines. The researchers rotated pavement marking samples at different locations before each trial. The detection distance was recorded when the subject located the pavement marking sample.

The data were analyzed in four main sections: waterborne paints, thermoplastics, tapes, and exotic materials. The analysis also included investigations into the wet-night visibility of rumble stripes, as well as wider lines. The measured dry and wet retroreflectivity measurements were analyzed, and the predictive capabilities of the wet retroreflectivity measurements were evaluated with respect to the wet-night detection distance of the markings.

During year two the researchers will supplement the detection distance data with additional data from a second round of wet-night visibility experiments. The researchers will also consider durability and cost information before finalizing the research. The researchers will also develop and implement research activities that can be used to develop application recommendations for contrast pavement marking materials based on visibility performance, durability, and cost.

17. Key Words	18. Distribution Statement
Pavement Marking, Visibility, Wet, Night, Contrast, Retroreflectivity, Rainfall Rates, Rumble Stripe	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	115	

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EVALUATION OF WET-WEATHER PAVEMENT MARKINGS: FIRST YEAR REPORT

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Report 0-5008-1
Project 0-5008
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Texas Department of Transportation
and the
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September 2005

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge of the project was Paul J. Carlson, P.E. (Texas # 85402).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The authors would like to thank the project director, Brian Stanford of the Traffic Operations Division, for providing guidance and expertise on this project. The authors would also like to thank other members of the TxDOT Advisory Panel for their assistance:

- Sally Wegmann, TxDOT Houston District
- Greg Brinkmeyer, TxDOT Traffic Operations Division
- Carlos Ibarra, TxDOT Atlanta District
- Carla Baze, TxDOT Maintenance Division
- Johnnie Miller, TxDOT Construction Division
- Wade Odell, TxDOT Research and Technology Implementation Office

Special thanks also go to Ivan Lorenz and Dick Zimmer of TTI for helping to design and build the rain tunnel and equipping the test vehicle with various electronics for this project, and to the industry professionals who provided all of the samples that were tested in this project.

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CHAPTER 1: INTRODUCTION

Pavement markings are considered by many to be the most valuable and important means of communicating roadway information to the driver. Longitudinal pavement markings provide a continuous stream of guidance for the driver that cannot be provided by signs or signals. Over the past decade, many pavement marking materials and/or applications have been developed that are marketed as providing improved visibility under conditions of wet weather or poor marking/pavement-surface contrast. Wet-weather marking materials include, but are not limited to:

- wet-weather tapes,
- profiled or structured markings,
- large glass beads, and
- other innovative technologies and applications.

TxDOT typically uses retroreflective raised pavement markings (RRPMs) to provide wet-weather visibility.

Contrast applications for light-colored pavement surfaces include, but are not limited to:

- leading black markings,
- trailing black markings,
- black borders around markings, and
- combinations of leading/trailing/bordered applications.

TxDOT and other agencies have experimented with many of these materials/applications, but there exists little formal documentation of quantifiable benefits or conditions; i.e., pavement, weather, etc., where these benefits are most likely to occur.

This research project is focused on the development of guidelines that can be used to select the most appropriate pavement markings application for wet-night conditions and light-colored pavement surfaces. The results will be based on the results of visibility studies, material durability, costs, and installation and maintenance ease.

This report includes a description of the research that was completed during year one, which focused on the wet-weather pavement markings aspect. During this first year, the researchers completed a literature review, analyzed 20 years of rainfall data, designed and built a

1600-ft-long rain tunnel, and conducted a visibility study of wet-weather pavement markings. This report includes detailed descriptions of each of these tasks, as well as preliminary results from the visibility study and a schedule of activities to be completed during the second year of the research.

CHAPTER 2: STATE-OF-THE-ART OF WET/NIGHT AND CONTRAST PAVEMENT MARKINGS

BACKGROUND

At night, pavement markings in conjunction with the vehicle headlights are typically the only means of providing guidance information to drivers. Therefore, properly placed and properly maintained pavement markings are critical for safe driving (*1*). The Texas Manual on Uniform Traffic Control Devices (TMUTCD) requires pavement markings to be retroreflective if they are to be visible at night, unless sufficient ambient lighting is provided to make the markings visible. Retroreflectivity is the measure of the ability of a pavement marking to return light in the direction from which it came. All markings on Interstate highways are required to be retroreflective (*2*).

Pavement markings serve several purposes as traffic control devices. To be effective in delineating the roadway, the markings must be presented far enough in advance to provide adequate perception reaction time (PRT), while also remaining visible in the periphery to aid in short-range lane navigation (*3*). When properly implemented, these purposes can include the following (*2*,*3*,*4*):

- regulate traffic flow,
- guide traffic flow (e.g., edgeline, lane line, and centerline for lateral position guidance),
- alert driver (e.g., no passing zones),
- separate opposing streams of traffic, and
- supplement other traffic control devices (e.g., stop bar).

Pavement markings must be visible in order for them to be effective. They must be visible 24 hours a day year round. During the day their presence is typically sufficient. At night, their retroreflectivity is key. However, at night and under rainy or wet conditions pavement markings have been reported to perform insufficiently (*5*,*6*).

The performance of pavement markings is reduced under wet-night conditions because water on the surface of pavement markings diminishes the amount of light retroreflected to drivers' eyes. The accumulated water scatters the incoming light through specular reflection and refraction, which reduces the amount of light retroreflected. Subsequently, the reduction in retroreflected light directly relates to a reduction in detection distance. The resulting shorter detection distance creates a more demanding driving situation for the driver and a potentially less safe driving environment.

DRIVER VISIBILITY NEEDS

Many factors, such as driver age and material conspicuity, affect the visual needs of a driver. As drivers age, their visual capabilities decrease (i.e., decrease in visual acuity and contrast sensitivity), so their ability to detect and use pavement markings decreases. It is not only vision that declines with age; motor skills also decline. Both vision impairment and the decrease in motor skills results in increased PRT. Consequently, older drivers require greater detection distances than their younger counterparts. The older driver population is the critical population for pavement marking visual requirements (*1*,*3*,*4*,*5*,*8*,*9*). It is important to improve pavement marking material conspicuity to provide the older drivers with the necessary roadway information with respect to roadway delineation. One manner of improving pavement marking conspicuity is by improving retroreflectivity.

To provide adequate detection distances under varying weather conditions, the pavement markings must retain adequate retroreflectance under these varying conditions. This is particularly true for older drivers. For instance, older drivers report an increasing inadequacy with respect to the nighttime visibility of pavement markings. In a statewide survey of 664 older drivers, Benekohal et al. found that as drivers age, the nighttime driving task becomes more difficult and worrisome (*10*). The activity of "following pavement markings" alone accounted for 17 percent of the concerns raised by the group. A comparison of the respondents ages 66 to 68 versus those 77 years and older indicated that the older group's level of difficulty in following pavement markings increased.

Preview Time

In COST 331, the absolute minimum preview time for safe driving was found to be 1.8 seconds. If drivers have less than 1.8 seconds, they will have difficulty keeping the vehicle within the lane. Also in COST 331, a preview time of 2.2 seconds was found to be too short for the driver to remain comfortable (*11*).

In a 1998 study conducted by the FHWA, two separate times were found to be necessary to provide adequate delineation: (1) long-range guidance PRT, and (2) short-range extreme driving conditions PRT (*12*). For long-range guidance, it was found to be 3 seconds. When 3 seconds or more of preview time are given to the driver, the task of guiding the vehicle is much easier. This longer preview time allows the driver to make adjustments sooner, instead of constantly having to adjust the guidance of the vehicle. Short-range extreme driving conditions PRT was found to be 2 seconds, which would be the safe minimum acceptable limit. The PRT of 2 seconds would allow just enough time for the driver to perceive the marking and react to it in hazardous conditions. Examples of extreme driving conditions would include heavy rain or fog.

According to another report, a pavement marking must provide between 3 and 3.65 seconds of preview time to complete the necessary related driving tasks (*9*). This time is much longer than the times suggested by COST 331. This longer time will provide a larger margin for driver error and provide higher levels of comfort to the driver.

PAVEMENT MARKING CHARACTERISTICS

Pavement markings are typically made of thermoplastic, paint, epoxy, polyester, methyl methacrylate, polyurea, urethane, or tape (*13*). Glass beads are mixed with the material, dropped on top when applying new material, or dropped on top when applying mixed material to help improve nighttime visibility (*3*). The glass beads should be imbedded enough so that they adhere to the material but not over-imbedded so they can provide additional retroreflectivity to the marking. Light enters the glass sphere and reflects off of the back of the sphere. The amount of light that is retroreflected depends on many factors such as the following:

- index of refraction of the glass bead,
- shape of the bead,
- size of the bead,
- surface characteristics of the bead,
- quantity of beads,
- embedment depth of the beads,
- quality and quantity of pigment in the binder,
- quality of the binder, and

- weather conditions.

Figure 1 shows a glass bead imbedded in a pavement marking retroreflecting light.

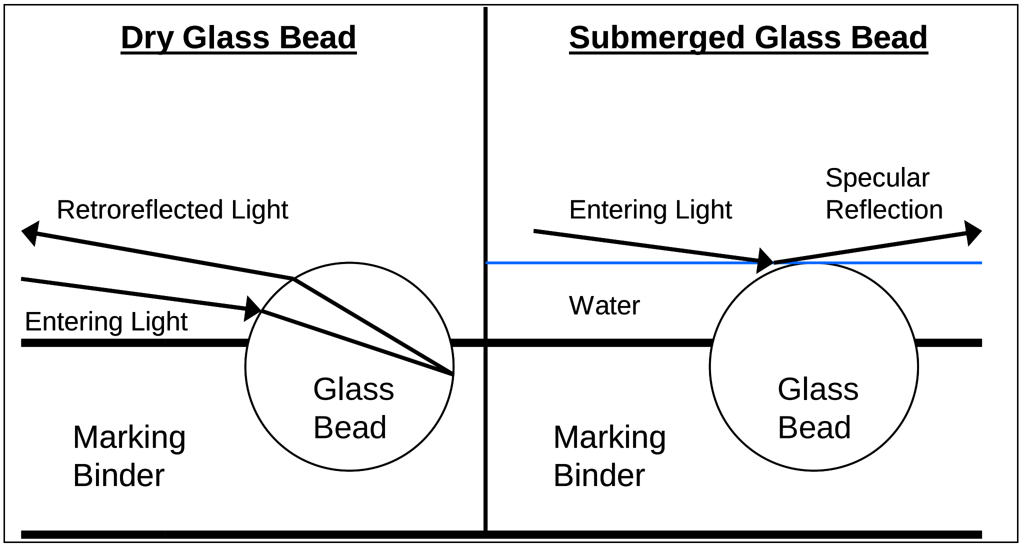

Figure 1. Glass Bead Retroreflection.

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

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

- larger glass beads,
- high refractive index glass beads,
- bead clusters,
- standard tapes,
- structured tapes,
- enclosed lens tape,
- profiled markings,
- RRPMs, and
- rumble stripes.

EVALUATING PAVEMENT MARKINGS

The two most important criteria for evaluating a pavement marking are nighttime visibility and proportion of missing or non-functional surface area (*4*). Wet-night conditions are affected by both of these criteria, with the non-functional area equating to the amount of pavement marking that does not properly retroreflect light to drivers due to the presence of water on the pavement marking.

The two forms of evaluating markings are subjective and objective (*1*,*4*). Subjective analysis grades the marking on a scale based on the perceived adequacy of the marking. Objective analysis of the marking uses instruments to quantitatively measure properties of the pavement marking (i.e., retroreflectivity or luminance values).

It is important to note that the retroreflectivity value of a marking will change during the first month, and thus a retroreflectivity value taken during the first month may not be a good representation of the long-term retroreflectivity levels of a marking. Gates et al. recommended taking the retroreflectivity readings one month after striping (*1*).

Standard Geometry

Retroreflectivity values are measured with either a handheld or mobile retroreflectometer. These units measure the retroreflectivity values at a 30 meter (98.5 ft) viewing geometry. A 30 meter viewing geometry simulates the effectiveness of a marking that is located 30 meters in front of a vehicle. The entrance and observation angles that represent the 30 meter geometry are the standard values used by the American Society of Testing and Materials (ASTM) and the European Committee on Standardization (CEN). Figure 2 shows how the 30 meter geometry is represented (*14*).

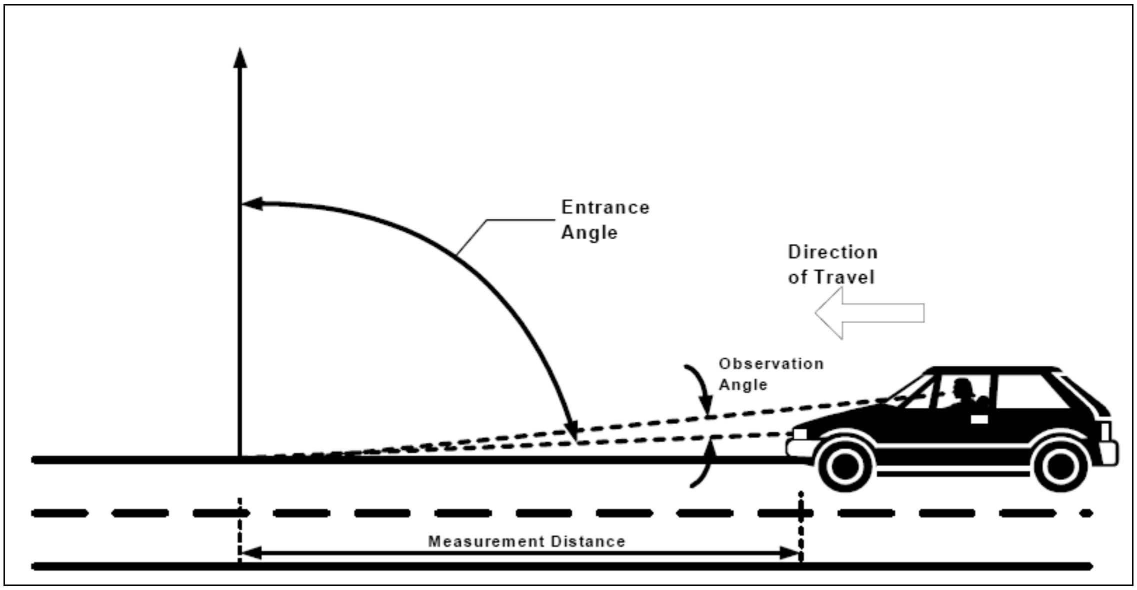

Figure 2. 30 Meter Geometry (*14*).

Figure 3 shows a picture of one of the hand-held units available for collecting retroreflectivity measurements for 30 meter geometry. This particular device is able to accurately measure retroreflectivity values from 20 to 1200 mcd/m^2/lux, and it can take accurate readings over a wide range of ambient conditions (*15*,*16*). The open-ended design where the measurements are taken allows for continuous wetting measurements, as well as dry and wet recovery measurements. Figure 3 shows how the device would be placed on a pavement marking while taking the retroreflectivity measurement (*17*).

Figure 3. Handheld Pavement Marking Retroreflectometer (*17*).

Visibility

Visibility can be represented by measures of retroreflectivity and luminance. Retroreflectivity measured in units of millicandelas per meter squared per lux (mcd/m^2/lux) is the measurement most often used to represent the nighttime visibility of a marking. Retroreflectivity of pavement markings is the amount of light from the pavement marking that is reflected back toward the driver and is available for him/her to see. Luminance is measured in units of candelas per meter squared (cd/m^2) and measures the light intensity per unit area coming from the pavement marking. Luminance is the amount of light available for the driver to see.

Retroreflectivity is associated with visibility; the higher the retroreflective value then generally the more visible the marking will be (*1*,*3*). The more visible a marking is, the further the detection distance will be, and thus the driver will have a longer preview time. Earlier studies (*18*,*19*,*20*) clearly show a positive correlation between detection distance and level of retroreflectance.

In an unpublished report, the FHWA has recommended dry retroreflectivity levels for high-speed roadways without RRPMs or continuous roadway lighting at 150 mcd/m^2/lux for white and 100 mcd/m^2/lux for yellow markings (*21*,*22*). The summary of the unpublished FHWA recommended values for both white and yellow markings can be found in Table 1 (*22*). Table 1 is also separated by speed and roadway type. As noted, these values are based on the standard 30 meter geometry with a preview time of 3.65 seconds. Europe uses similar recommendations for in-service retroreflectivity requirements; their recommended value is 100 mcd/m^2/lux (*11*).

Table 1. Unpublished FHWA Recommended Minimum Retroreflectivity Levels for Pavement Markings (*22*).

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

The ASTM has three standards for measuring retroreflectivity of pavement markings (23,24,25). The three standards cover the typical conditions that pavement markings will face: dry, wet, and rainy. These procedures are designed for use with hand-held retroreflectometers:

- ASTM E-1710 for dry pavement markings,
- ASTM E-2177 for wet recovery pavement markings, and
- ASTM E-2176 for continuously wetted pavement markings.

Durability

The durability of a marking is typically measured by the amount of material remaining on the roadway or the material's bond strength with the roadway (*3*). Durability can vary greatly depending on roadway characteristics. Traffic volume and surface type play a major role in the durability of a pavement marking. The environment also plays a role in the durability. It was found that thermoplastic pavement markings can be expected to last two years on freeways and three years on non-freeways when the FHWA-recommended threshold retroreflectivity levels were determined. The maximum service life for thermoplastic is approximately four years (*26*).

PAST STUDIES

As part of a research project conducted by Gates et al., bead size was evaluated as to its impact on dry retroreflectivity values (*1*). Larger beads, referred to as TxDOT Type III beads, were compared to smaller beads, referred to as TxDOT Type II beads. It was found that the Type III beads provided higher levels of retroreflectivity than Type II beads. The average white edgeline retroreflectivity was found to be 20 mcd/m^2/lux higher with Type III beads than with Type II beads. The average yellow centerline retroreflectivity was found to be 55 mcd/m^2/lux higher with Type III beads than with Type II beads. Retroreflectivity differences were found to be statistically significant only for yellow markings.

These values were for only dry conditions, but they show the increase in retroreflectivity based on bead size. It is believed that similar improvements based on increasing bead size would be seen under wet conditions (*1*).

In an attempt to determine minimum retroreflective requirements Schnell and Zwahlen used the CARVE (Computer-Aided Road-Marking Visibility Estimator) computer model (*9*). This model uses geometric and photometric relationships to determine minimum retroreflectivity values to provide the predetermined preview time. A preview time of 3.65 seconds was used in this study, which is a conservative value. The study also used a 62-year-old driver as the driver type.

The results of the CARVE model were based on various speeds with and without RRPMs; therefore, a range of retroreflectivity values is given based on the speed at which the vehicle is traveling. The results showed that a minimum retroreflectivity level for pavement markings that are not aided by RRPMs ranged from 30 to 620 mcd/m^2/lux at a 30 meter geometry for speeds ranging from 0 to 75 mph (0 to 120 kph). When RRPMs were used, the minimum retroreflectivity levels were much lower and ranged from 30 to 70 mcd/m^2/lux for the same speeds (9). Table 2 shows the resulting table of these values.

Table 2. Schnell and Zwahlen's Minimum Retroreflectivity Requirements for White Markings for Fully Marked Roads (9).

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

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

In a study conducted by Kalchbrenner, the effect of using larger glass beads versus standard glass beads in dry and wet-night conditions was determined to provide beneficial results in terms of retroreflectivity (*27*). The study was conducted in part at the Potters' "rain tunnel" facility and in part at field test sites across the country.

The study at the rain tunnel was to provide retroreflective values during controlled rain situations. Rainfall rates of 0.5 inch/hr and 0.25 inch/hr and a recovery period were studied. The results of this controlled wet-night experiment showed that larger beads provided beneficial increases to retroreflectivity values over standard beads. The results can be seen in Figure 4 and Figure 5 for epoxy and thermoplastic applications. The larger beads provided higher levels of retroreflectivity for both rainfall rates and recovered much quicker than did the standard beads.

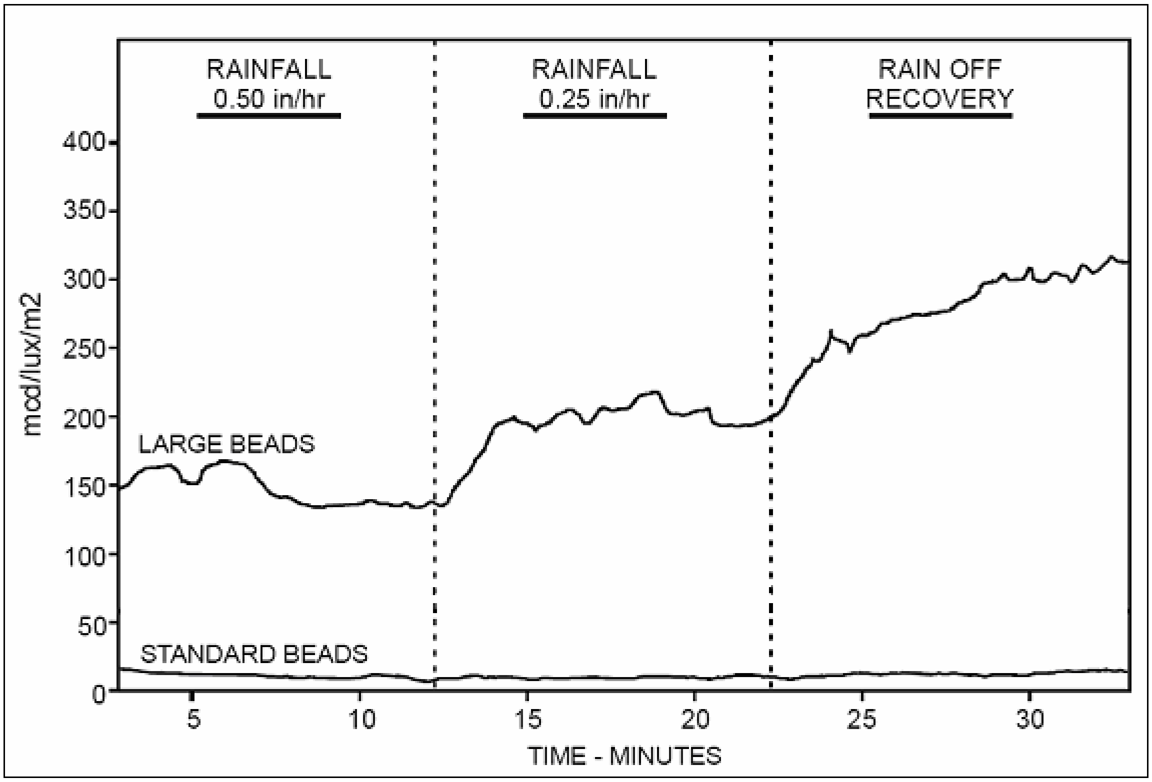

Figure 4. Large Beads Versus Standard Beads in Epoxy (*27*).

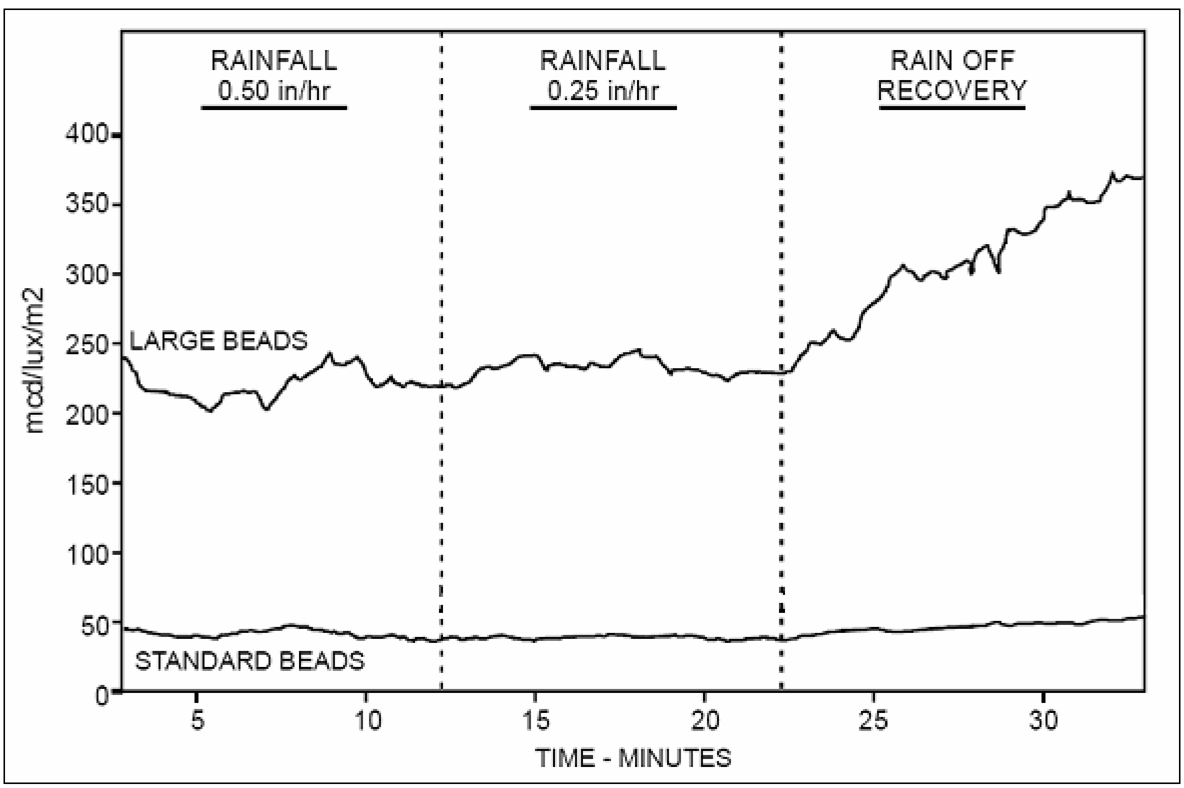

Figure 5. Large Beads Versus Standard Beads in Thermoplastic (*27*).

The field data for the experiment were collected at 32 sites around the country for several marking materials with the large and standard glass beads imbedded in them. These sites were used to observe the retroreflectivity of the markings over time in dry conditions. Not only is wet-night retroreflectivity important, but dry night retroreflectivity over the lifetime of the line is important as well. The results of the dry retroreflectivity experiment are provided in Figure 6 through Figure 8 (*27*). As shown, the large glass beads provide higher levels of retroreflectivity than the standard glass beads.

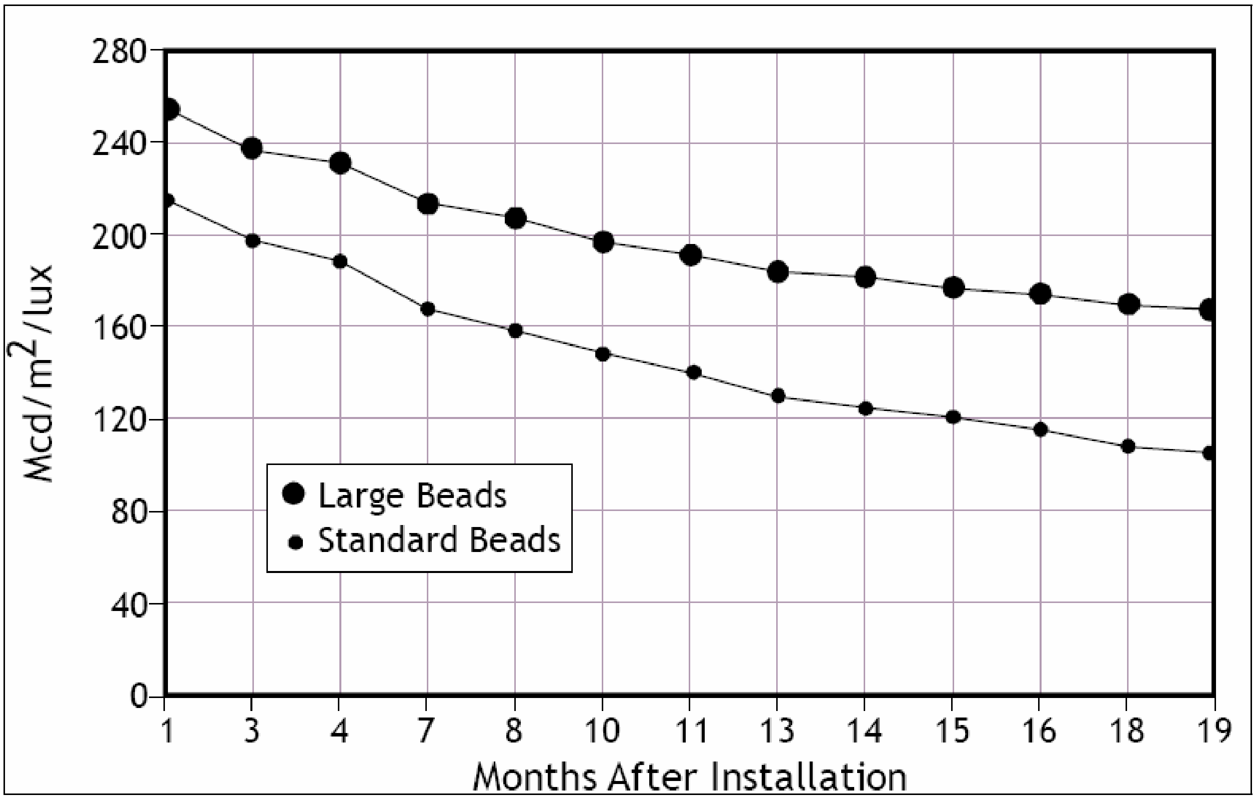

Figure 6. Retroreflectivity: Large Beads Versus Standard Beads in Epoxy (*27*).

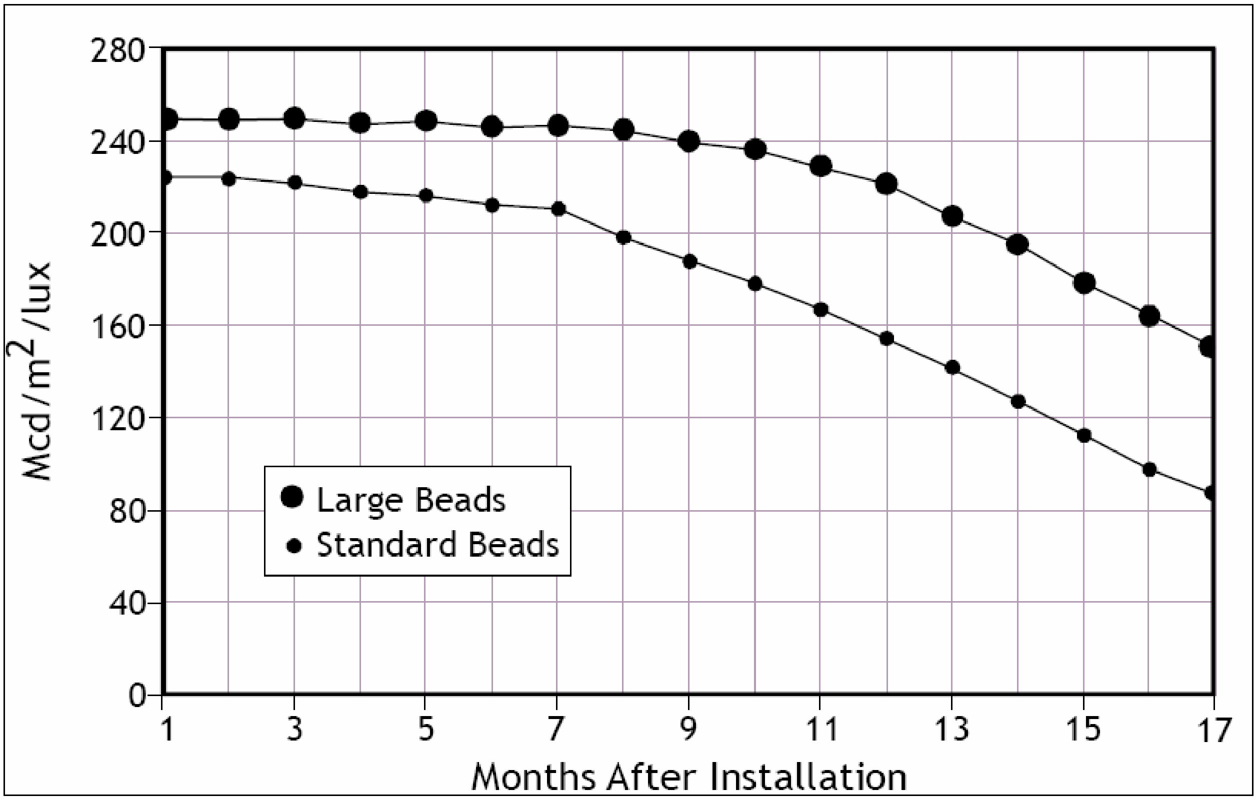

Figure 7. Retroreflectivity: Large Beads Versus Standard Beads in Thermoplastic (*27*).

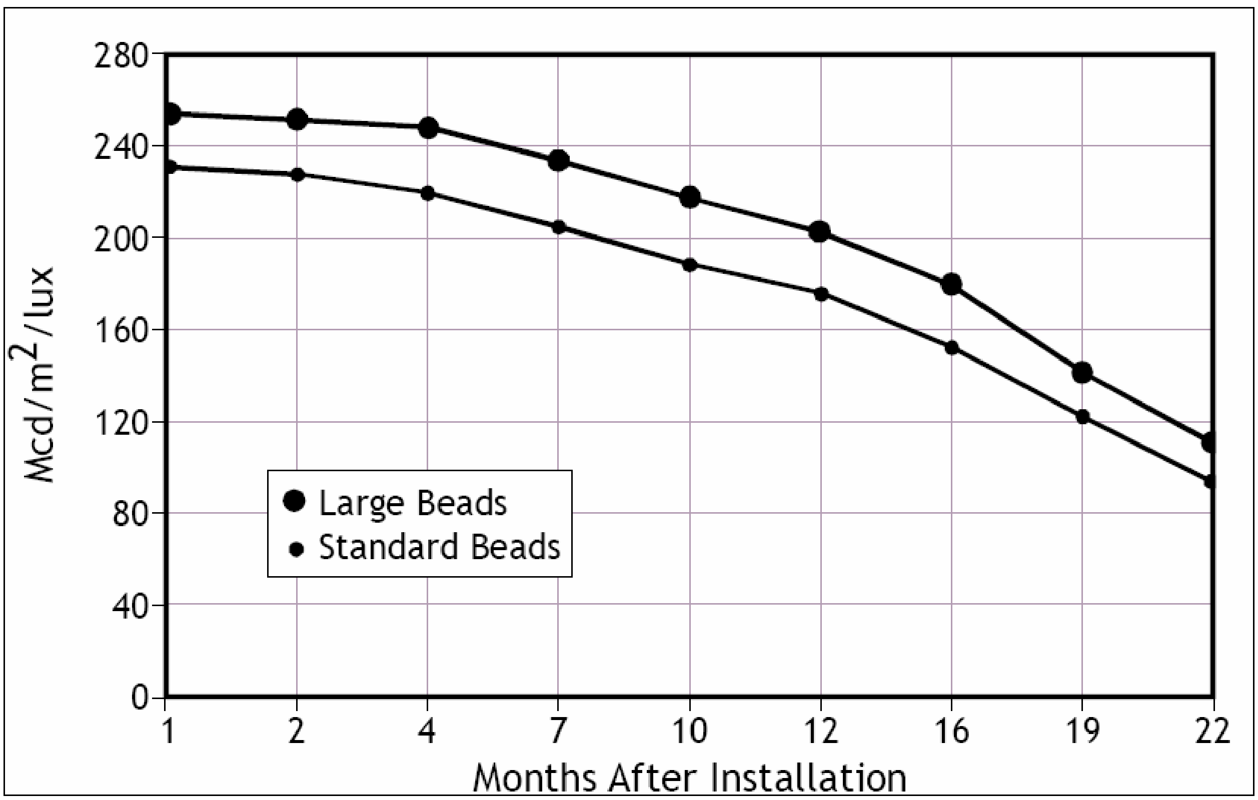

Figure 8. Retroreflectivity: Large Beads Versus Standard Beads in Polyester (*27*).

Many factors affect the performance of the beads placed on the marking. As shown in Kalchbrenners' study, bead size plays a major role in retroreflectivity levels, in wet conditions, and over the life of the marking. Another major factor that applies to both the durability of the marking and the retroreflectivity levels was studied by O'Brien *(28)*.

O'Brien looked mainly at embedment depth, but also looked at bead sizing and shape. He found that the optimal embedment depth in thermoplastic markings was 60 percent. This depth was achieved by using moisture proofed glass spheres, applied at a rate of 10 lb/100 ft^2. The retroreflectivity of the standard gradation of glass spheres may be enhanced by increasing the percentage of spheres retained on U.S. sieves 30, 40, 50 and by increasing the roundness of the spheres from 70 to 80 percent *(28)*. O'Brien also stated that controlled wear of the marking surface is important to maintain retroreflectivity values. This can be achieved by using an intermix of glass spheres that are exposed as the marking wears, therefore maintaining retroreflectivity and nighttime visibility.

A European study was performed by Lundkvist and Astrom for the Swedish National Road Administration *(29)*. This study sought to measure the performance of road markings in wet-night conditions. Minimum retroreflectivity requirements were found based on a set of predetermined preview distances. These distances were found by using a set preview time that was established in another European project, Cooperation in the Field of Scientific and Technical Research (COST) 331 *(11)*. In COST 331 the shortest possible preview time was found to be 1.8 seconds. For comfortable driving it was found that 2.2 seconds is too short of a preview time. Lundkvist used a value of 2 seconds to determine the required visibility distances. Table 3 shows the corrected results of the COST 331 model for various speeds with a 2-second preview time.

Lundkvist's research project was performed over a two-year period on two actual road sections that both had an annual average daily traffic (AADT) of approximately 2000. Ten companies applied pavement markings on the test sections, totaling 39 different markings. These markings were:

- extruded thermoplastic,
- spray on extruded thermoplastic,
- cold plastic, and

- waterborne paints.

Table 3. Minimum Retroreflectivity Requirements for Wet Pavement Markings *(29)*.

Type of Marking	Speed Limit	Visibility	Retroreflection (mcd/m²/lux)
intermittent marking (1+2), 10 cm wide	70 km/h (44 mph)	39 m (128 ft)	40
	90 km/h (56 mph)	50 m (164 ft)	80
	110 km/h (68 mph)	61 m (200 ft)	160
continuous edge marking, 10 cm wide	70 km/h (44 mph)	39 m (128 ft)	25
	90 km/h (56 mph)	50 m (164 ft)	45
	110 km/h (68 mph)	61 m (200 ft)	80
continuous edge marking, 20 cm wide	70 km/h (44 mph)	39 m (128 ft)	20
	90 km/h (56 mph)	50 m (164 ft)	35
	110 km/h (68 mph)	61 m (200 ft)	57
continuous edge marking, 30 cm wide	70 km/h (44 mph)	39 m (128 ft)	18
	90 km/h (56 mph)	50 m (164 ft)	30
	110 km/h (68 mph)	61 m (200 ft)	50

When tested, the markings were measured when dry and measured when wetted by pouring a large amount of water over the marking, and after a minute the retroreflectivity values were recorded. An LTL-2000 retroreflectometer and a QD30 were used to measure the retroreflectivity and luminance coefficient of the pavement markings. The procedure for the measurements is in accordance with the European Committee for Standardization method, CEN EN 1436.

The study found that the typical Swedish intermittent edgeline marking does not meet the wet retroreflectivity values found in Table 2 after two years of service. They also found that if the markings were continuous and 200 mm (7.9 inches) in width that all markings would meet the required value in the wet when new, and that many would also meet the value after two years of service. It was determined that it is possible to produce a road marking, that provides 2 seconds of preview time over a two-year period, when applied as a 200 mm continuous edgeline*(29)*.

In order to achieve a preview time of 2 seconds it was found that the lines need to have an increased surface area, by making the lines continuous or wider. The wider lines are able to produce the same visibility with lower retroreflectivity values as seen in Table 3. The problem is that most edgelines in the United States are not 200 mm in width, which was stated as a good width for Swedish edgelines.

In a research project performed to improve the understanding of the effects of pavement marking retroreflectivity on visibility distance, two separate tests were conducted (*30*). These tests were a stationary test and a dynamic test. Figure 9 and Figure 10 give the results of these two tests. The dynamic test was conducted at a speed of 24 km/h (15 mph). Even this low speed produced a significant reduction in visibility distances between the two tests, for markings with the same retroreflectivity levels. This difference shows the need of a dynamic testing scheme to properly determine retroreflectivity standards for pavement markings.

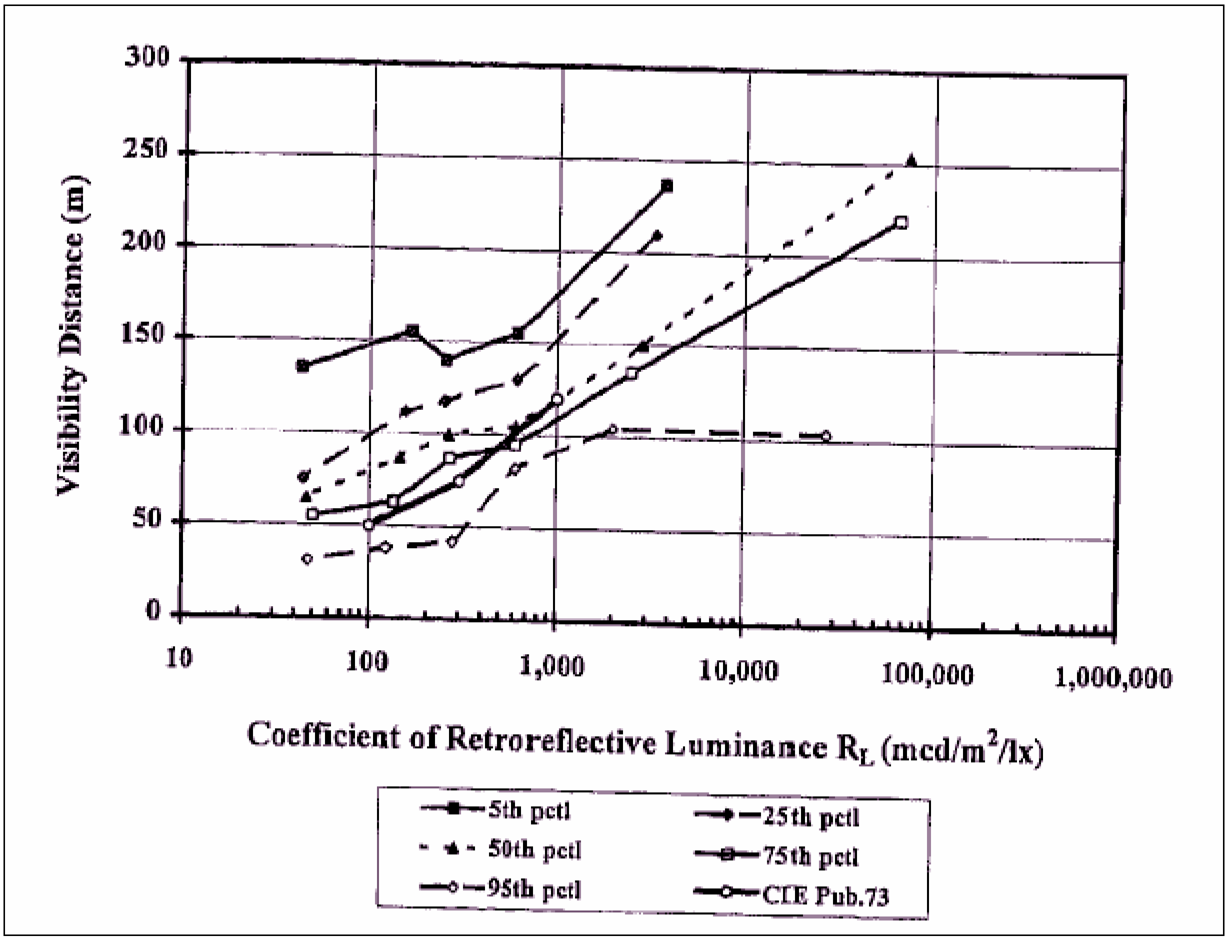

Figure 9. Stationary Test: Percentiles of Marking Visibility Distance Based on R_L Value (*30*).

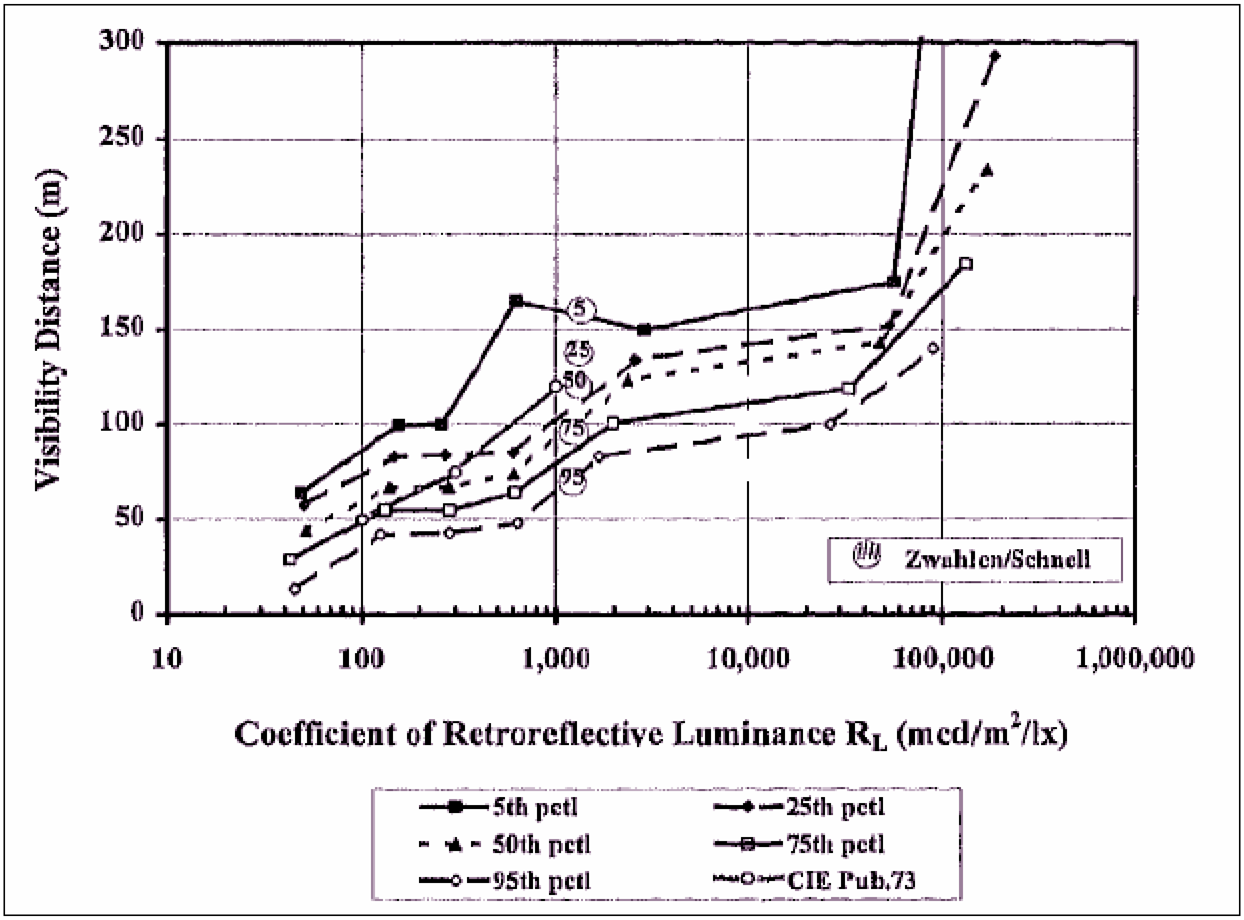

Figure 10. Dynamic Test: Percentiles of Marking Visibility Distance Based on R_L Value (30).

In a project conducted for the North Carolina Department of Transportation, King and Graham evaluated pavement marking materials for wet-night conditions (4). The project lasted 18 months and investigated the retroreflectivity and durability of eight pavement markings. Quantitative values of retroreflectivity (mcd/m^2/lux) and luminance (cd/m^2) were found, as were qualitative evaluations of the markings' adequacy.

In the study it was found that there is a strong linear relationship between retroreflectivity and luminance. Figure 11 shows the relationship that was found between luminance and retroreflectivity. Retroreflectivity levels were measured during dry conditions only. Subjects viewed the pavement markings during dry day (daytime in a dry condition), dry night (nighttime in a dry condition), and wet-night (nighttime in a natural rain). Subjects were asked to rate the markings as less than adequate, adequate, or more than adequate. The retroreflectivity levels at which 100 percent of the participants found the marking to be adequate or more than adequate were 70 mcd/m^2/lux for dry day, 93 mcd/m^2/lux for dry night and 180 mcd/m^2/lux for wet-night conditions (*4*). Figure 12 shows the regression analysis plots of subjective rating versus retroreflectivity levels. The figure shows that the dry conditions provide better visual adequacy than the wet-nighttime condition. It was also found that retroreflectivity levels for all markings decreased over time, with the largest decreases during the first six months.

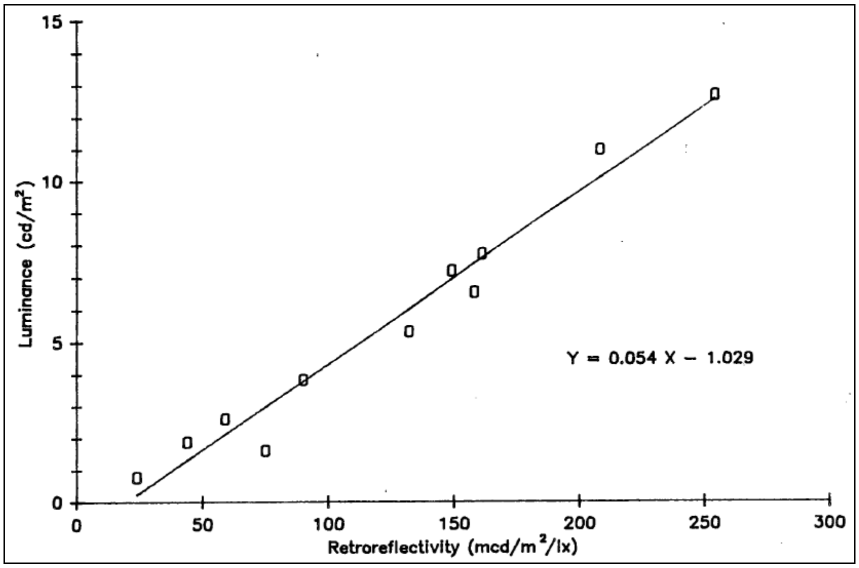

Figure 11. Luminance and Retroreflectivity Relationship (*4*).

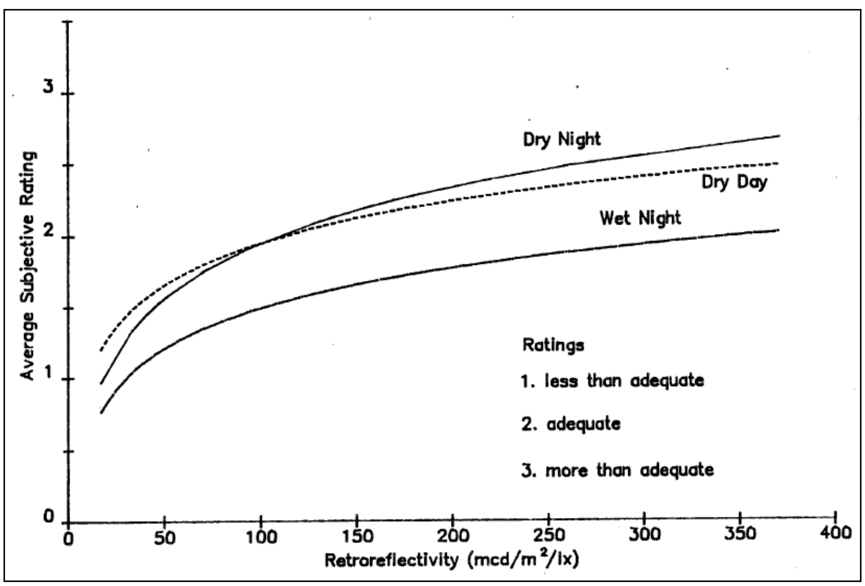

Figure 12. Subjective Rating and Retroreflective Values (*4*).

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

As previously mentioned, pavement markings exhibit a positive correlation between detection distance and level of retroreflectance. Studies conducted by Schnell et al. show this positive correlation (*18*,*19*,*20*). Figure 13 shows the results of the studies conducted by Schnell et al.

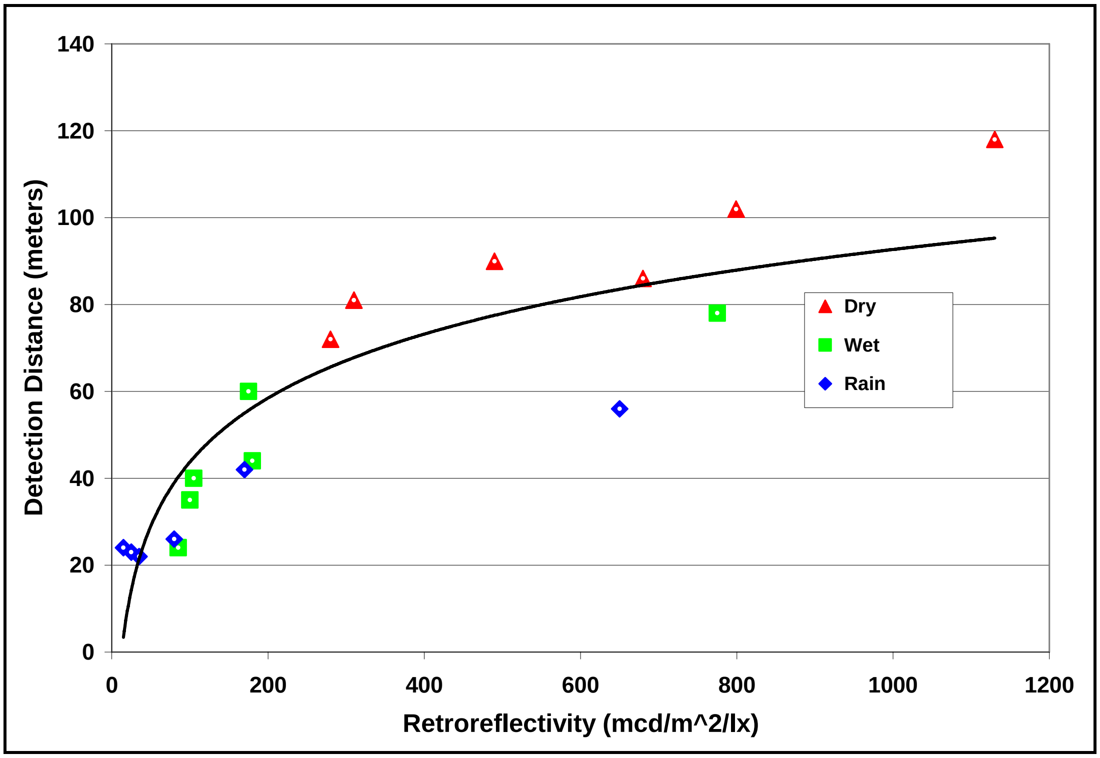

Figure 13. Relationship Between Retroreflectivity and Detection Distance.

Schnell et al. also conducted an experiment to quantify the performance of different types of pavement markings under dry, wet, and simulated rain conditions (*31*). The safety of the older driver population was of particular interest. An example of the detection distance results for the three marking types can be seen in Figure 14. These findings show that the wet weather tape performed much better than flat or patterned tapes. The results of this experiment showed that the flat and patterned tapes would not provide an adequate preview time, even if 3.65 seconds was used as the required time. Even the wet weather tape only provides that amount of preview time up to 25 mph under rainy conditions. Due to the short detection distances, drivers most likely overdrive their headlamps under rainy conditions. It should be noted that the rainfall rate used for this experiment was 1 inch per hour. This rainfall rate represents a worst case nighttime driving situation.

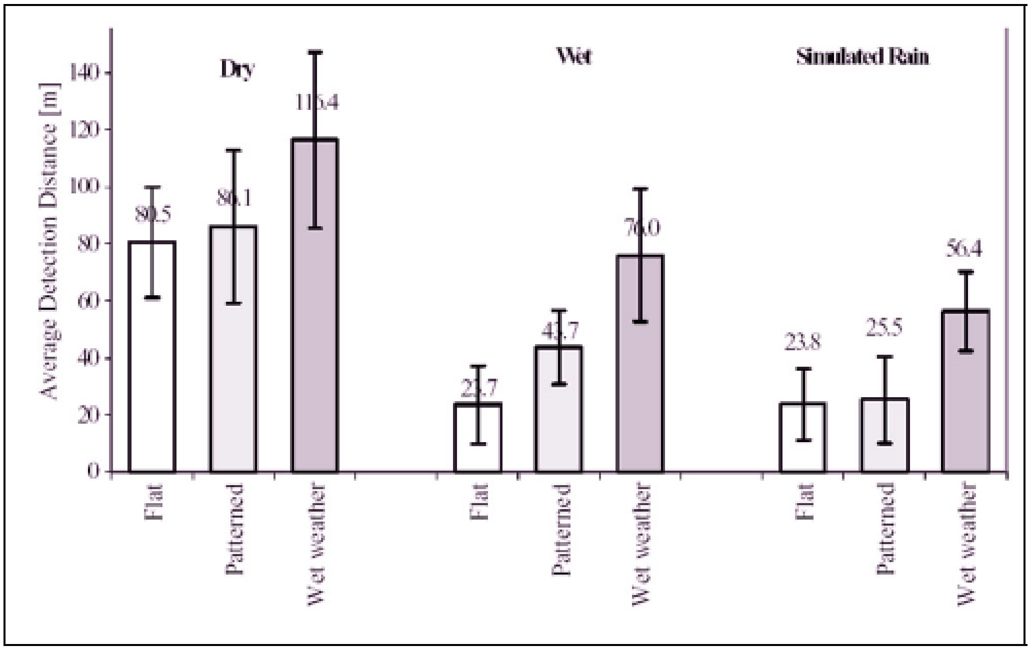

Figure 14. Example of Marking Detection Distances (*31*).

Atkan and Schnell conducted a second investigation to quantify the performance of different types of pavement markings under dry, wet, and simulated rain conditions (*32*). Under dry conditions, all materials provided adequate detection distances. Under the wet conditions, the patterned tape with mixed high index beads performed better than the other marking materials. The situation was the same for the continuous wetting condition, where the patterned tape with mixed high index beads performed better than the other marking materials. The results of the investigation can be seen in Figure 15.

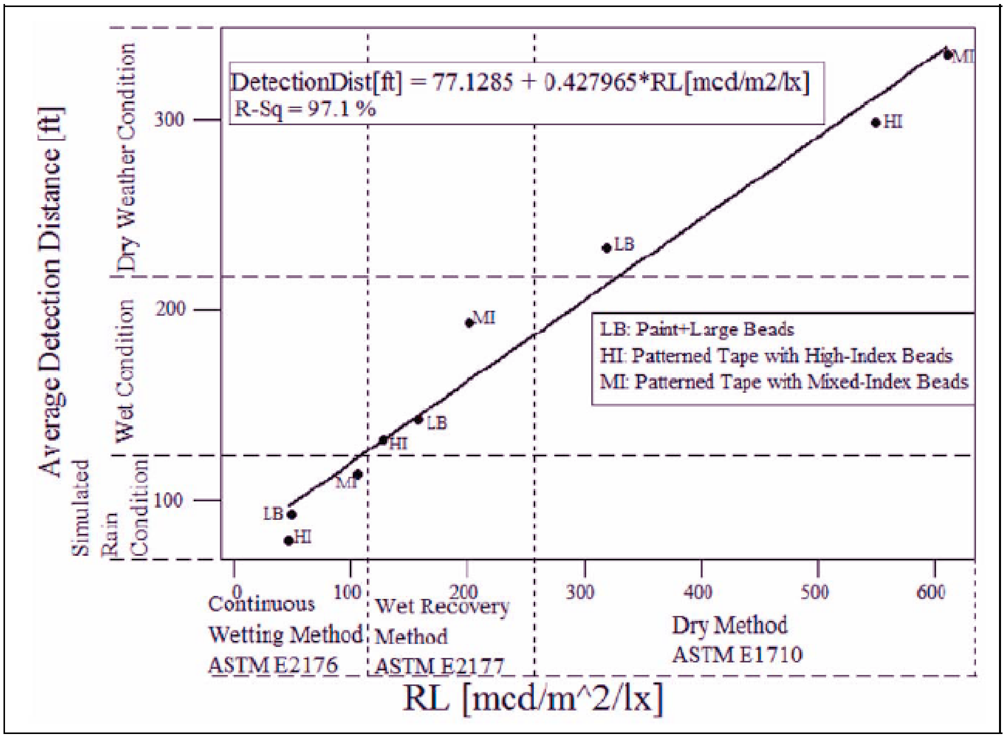

Figure 15. Examples of Pavement Marking Performance Under Different Conditions *(32)*.

The Virginia Tech Transportation Institute (VTTI) conducted a static wet-night study to evaluate the visibility of six pavement marking types (5). The markings were viewed by subjects over 60 years of age, under a simulated rainfall of 0.8 inch per hour of rainfall at night. Both a sedan and a truck tractor were used as the viewing vehicle in which the subjects sat while viewing the markings.

The results of the visibility study for the sedan under the continuous rain and dry conditions can be seen in Figure 16. From the figure a large decrease in visibility distance can be seen during the rainy condition versus the dry condition. The RRPM and the wet tape showed the least drop in visibility distance.

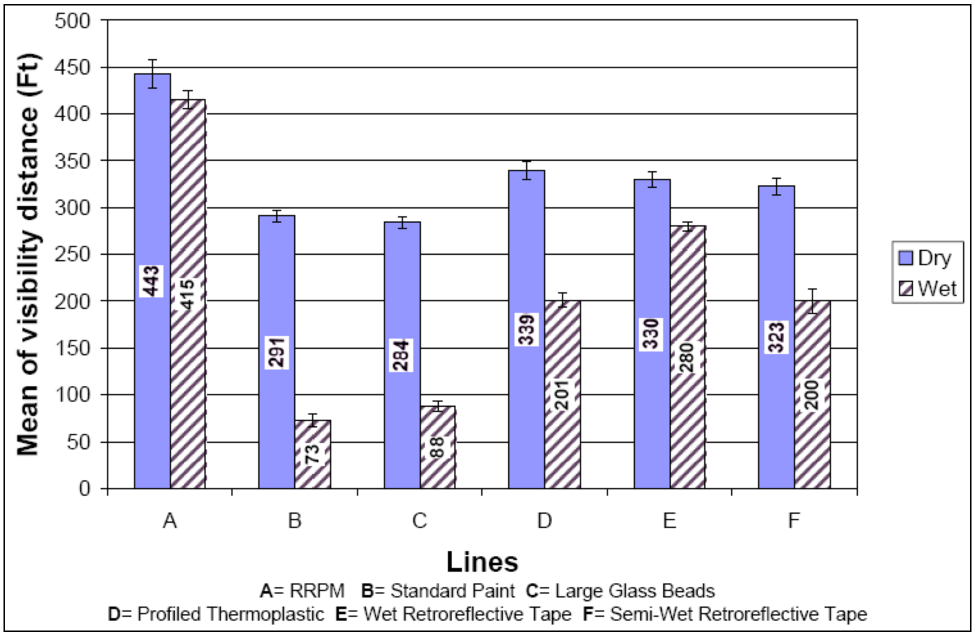

Figure 16. Sedan: Saturated Evaluation - Results of the Visibility Distance for the Condition X Line Interaction (5).

The results of the VTTI retroreflectivity tests are shown in Figure 17. In the VTTI study, the researchers analyzed the relationship of the retroreflectivity values measured using the continuous wetting standard (ASTM E 2176-01) to the number of skip lines counted by the test subjects under a simulated raining condition. The Pearson *r* correlation value was 0.932. This high correlation value should indicate a strong correlation between the ASTM test and the pavement marking performance; however, the high performing material, the wet retroreflective tape, skewed the data. No new correlation value was given after the high performing pavement marking materials were removed. The researchers concluded, "The ASTM methods seem to be highly correlated to the performance of the participants and to the calculated retroreflectivity from the pavement marking luminance. The results from the measurements have a wide range, and after removal of the high performing materials, the correlation is not as high." (5)

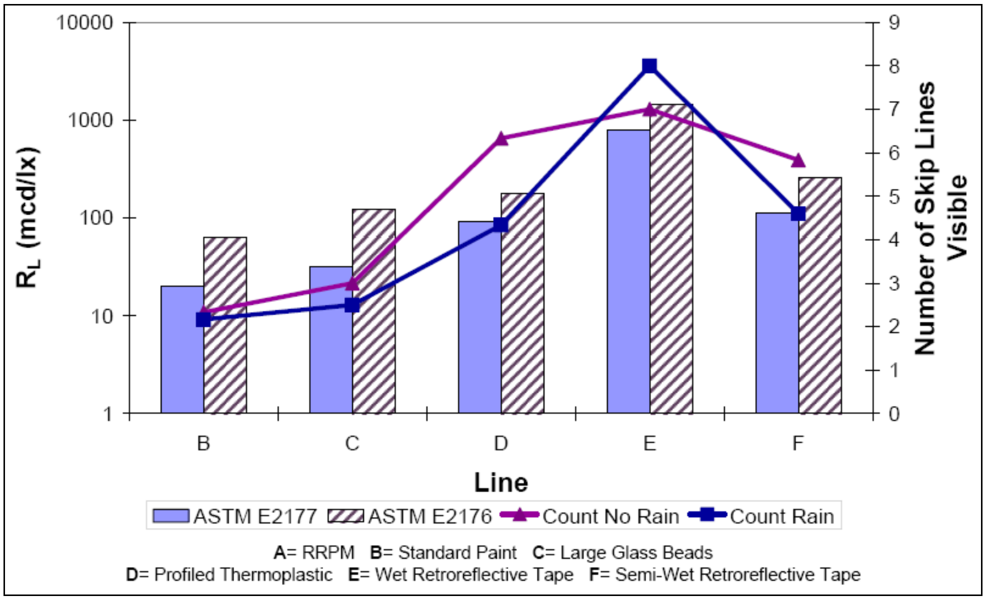

Figure 17. Relationship of Human Response to the ASTM Test Method Results (5).

CHAPTER 3:
RAIN ANALYSIS

This phase of the research project involved analyzing rainfall data for the state of Texas. The purpose of this analysis was to formulate a basic description of typical Texas rainfall events to be reproduced during the simulated experimental runs.

DATA SET CHARACTERISTICS AND ACQUISITION

Twenty years of rainfall data (October 1984 to September 2004) were acquired from the National Climatic Data Center (NCDC). The 15-minute data set was used. The analysis was broken down into the 10 climatic zones specified by the NCDC in Figure 18.

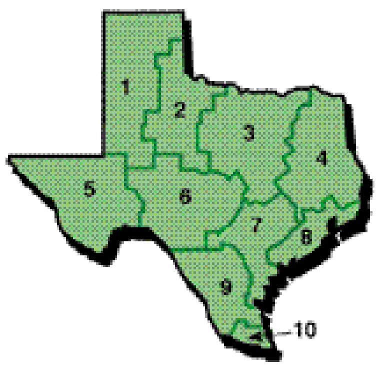

Figure 18. NCDC Climatic Zones (*33*).

In its raw form, the 15-minute data set contains identification numbers for the NCDC weather monitoring stations; the total amount of rain collected during a given 15-minute interval, measured in tenths or hundredths of an inch and reported in hundredths of an inch; and a time value corresponding to the end of the 15-minute interval, in 24-hour time format. Figure 19 shows the locations of weather stations throughout Texas where 15-minute rain data are recorded. Table 4 provides the number of recording stations in each climatic zone.

The NCDC also collects and maintains an hourly rain database, which would be roughly equivalent to a more aggregated formulation of the 15-minute database. In an analysis of NCDC rainfall data for the state of Virginia, Gibbons et al. acquired both the 15-minute and the hourly data sets, but analyzed only the 15-minute data set (*6*). Gibbons et al. observed that most rain events begin and end in the middle of a data collection interval, which means that the mid-event intervals would have consistent, stable rainfall values while the endpoints would have less stable values, as shown in Figure 20. The 15-minute data set can be considered more reliable than the hourly data set because it contains more mid-event data due to the shorter collection interval.

Since the scope of this project is nighttime wet pavement marking visibility, only night rain events were analyzed. Night was defined as beginning at 6 PM and ending at 6 AM. If a rain event occurred across this day/night cutoff point (for example, started at 5 AM and ended at 7 AM), only the night portion of the event was included in the nighttime data set.

Table 4. NCDC 15-Minute Data Recording Stations in Each Climatic Zone.

Zone	Name	Station Count	Percentage of State Stations
1	High Plains	17	7.6%
2	Low Rolling Plains	22	9.8%
3	North Central	67	29.9%
4	East Texas	22	9.8%
5	Trans Pecos	14	6.3%
6	Edwards Plateau	32	14.3%
7	South Central	27	12.1%
8	Upper Coast	10	4.5%
9	Southern	12	5.4%
10	Lower Valley	1	0.4%

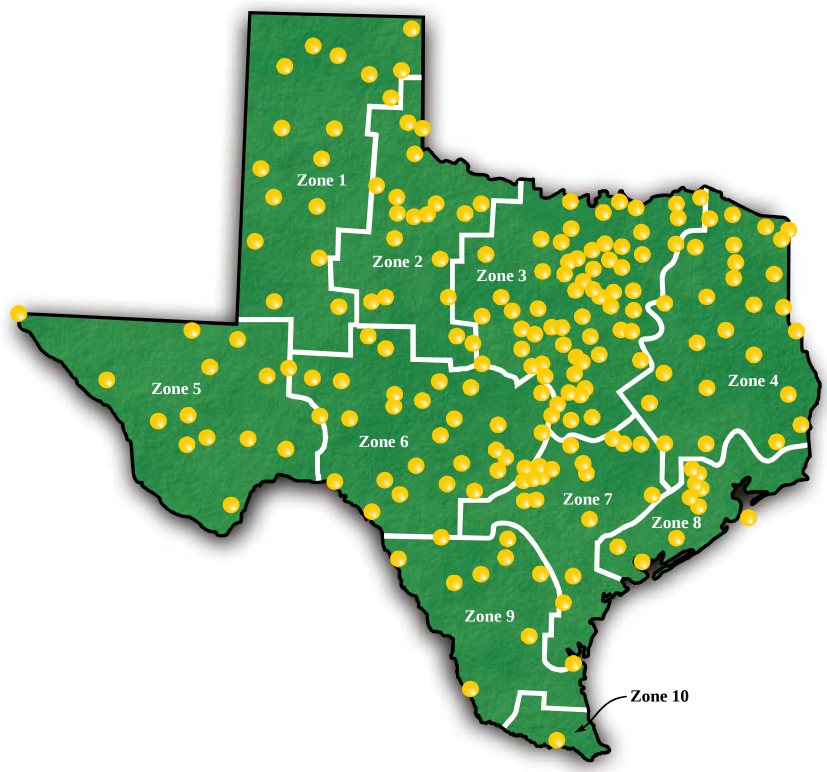

Figure 19. NCDC 15-Minute Data Recording Stations (33).

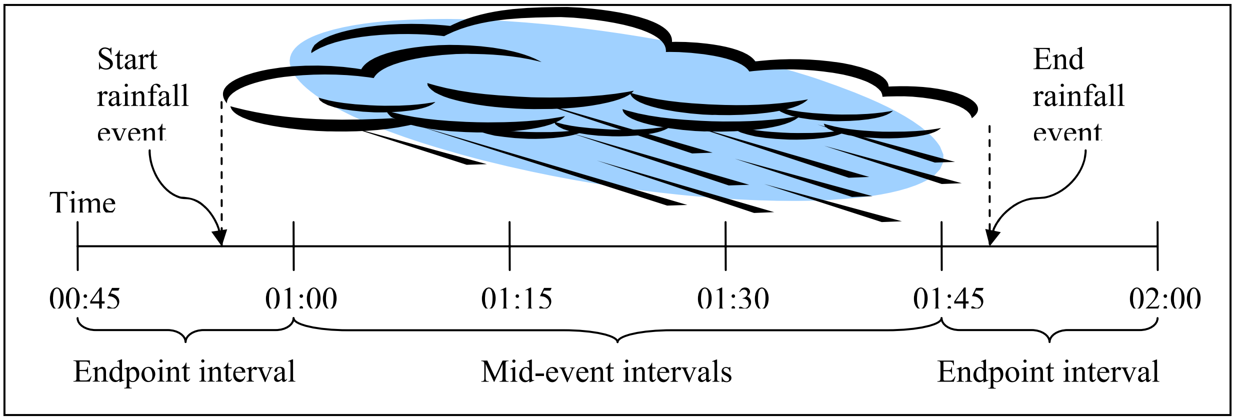

Figure 20. Mid-Event and Endpoint Data Intervals.

Rainfall events were divided into three duration categories: short (less than 1 hour), medium (1 to 1.75 hours), and long (greater than or equal to 2 hours). Some previous researchers have used these categories, while others have discarded the short events, considering them to be showers instead of consistent rain events (6). Furthermore, average and maximum rainfall rates (both measured in inch/hr) were determined. The average rate is the sum of rain accumulation (inch) observed during the event, divided by the length of the event (hr). The maximum rate is the rate corresponding to the heaviest 15-minute interval during the event. See Table 5 for an example rain event with calculated average and maximum rates.

Table 5. Example Rainfall Data.

Interval Ending Time	Rainfall Accumulation (in.)	Interval Duration (hr)
23:30	0.10	0.25
23:45	0.20	0.25
24:00	0.30	0.25
00:15	0.10	0.25
00:30	0.10	0.25
	$\sum$ = 0.80 in.	$\sum$ = 1.25 hr

- Total event rainfall accumulation = 0.80 in.
- Event length = 1.25 hr (medium event)
- Average rainfall rate = 0.80 in. ÷ 1.25 hr = 0.64 in./hr
- Maximum rainfall rate = 0.30 in. ÷ 0.25 hr = 1.20 in./hr

In addition to the known values for precisely defined 15-minute intervals, the data set also contains data for accumulation periods where the total amount of collected rainfall was known, but the exact beginning and ending times for the event or series of events were not known. These data were excluded from the analysis because the determination of accurate rainfall rates requires precise knowledge of event durations.

Microsoft Access was used to extract the data from the NCDC files. For each rain event, the duration, average rate, and maximum rate were calculated and exported into Microsoft Excel and Statistical Package for the Social Sciences (SPSS) for analysis.

DATA ANALYSIS

Sixty different subsets were created for the extracted data as follows:

- The state was divided into 10 different climatic zones (see Figure 18).
- Events in each zone were divided into short, medium, and long duration categories.
- Within each zone and duration category, average and maximum rates for the events were analyzed.

Descriptive statistics and histograms were generated in SPSS for all 60 subsets. Excel was then used to calculate the overall average and maximum rate means across zones and duration categories.

Event Duration

A grand total of 218,166 rain events were observed during the 20-year study period. Table 6 shows the distribution of events in terms of percentage of the grand total. Zone 3 had the largest number of events (37.3 percent of the grand total), which is expected because zone 3 (which includes the Dallas/Fort Worth area) has the largest concentration of recording stations, as shown in Figure 19.

Table 6. Observed Rain Events, Percentage of Grand Total.

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	7.1%	6.2%	34.0%	10.4%	3.6%	11.5%	10.8%	4.0%	3.1%	0.3%	91.1%
Medium	0.3%	0.4%	2.4%	0.6%	0.1%	0.8%	1.0%	0.5%	0.2%	0.0%	6.3%
Long	0.0%	0.2%	0.9%	0.2%	0.0%	0.3%	0.5%	0.3%	0.0%	0.0%	2.5%
Total	7.4%	6.8%	37.3%	11.2%	3.7%	12.6%	12.4%	4.9%	3.3%	0.3%	100.0%

It is also worth noting that the vast majority of rainfall events (91.1 percent) were categorized as short events. This is likely because storms often have short periods where no rainfall is actually occurring, though surface conditions would still be wet. For example, if a storm occurred between 7:10 PM and 9:15 PM, and the storm involved consistent rainfall except for a brief lapse from 8:10 PM to 8:35 PM, the storm would have been recorded as two events—7:15 PM to 8:15 PM, and then 8:35 PM to 9:00 PM (see Figure 21). These events would be categorized as medium and short events (1.25 hours, followed by 0.5 hour), though the overall storm is long enough (2 hours) to fall into the long event category.

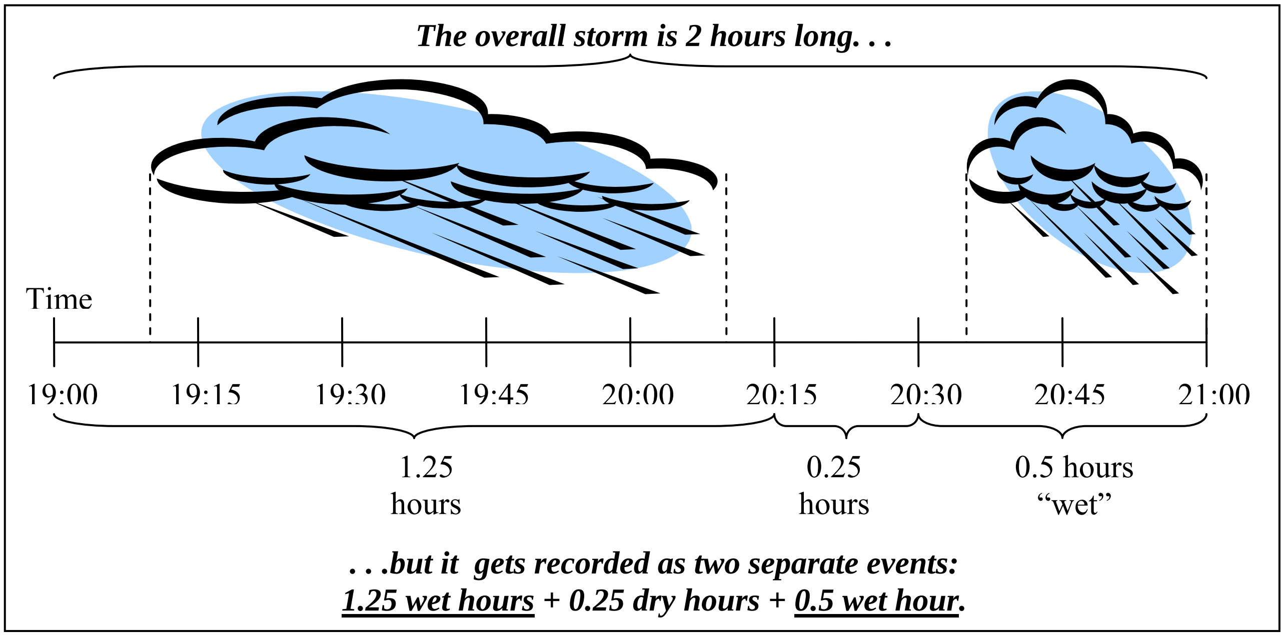

Figure 21. Event and Overall Storm Durations.

Table 7 provides the percentage of "wet" and "dry" hours observed in each zone and across the state. These numbers show that the vast majority of hours (99.51 percent across the state) are "dry" hours experiencing no rain. It should be noted that "dry" hours only refer to periods of time in which rain is not falling, and that immediately following a "wet" period, water will run off of the road for an unspecified amount of time. In actuality, this period is the recovery period that ASTM E2177-01 simulates; however, the true length of the recovery period is complicated by various factors including rainfall intensity, the geometry of the drainage area, and the ability of a drainage area to absorb the rainfall. Hence, the term "dry" will be used as a generic term to represent the periods of time when rain events are not occurring with the understanding that the periods immediately following a rain event will include wet recovery, which should not complicate the rain analysis when considering that 99.51 percent of the time was dry.

In the 20-year period used for this analysis, there were a total of 87,660 night hours. The number of total (dry and wet) hours for each zone was calculated by multiplying 87,660 by the number of recording stations in that zone, and then subtracting the number of hours within the discarded accumulation periods. This was done to correct for the fact that recording stations in close geographical proximity to each other will often provide data for the same rainfall event, thus creating the illusion that more rainfall is occurring, when in fact multiple samples are being taken of the same event. According to NCDC, all of the recording stations in Texas were in operation since before 1984 (*34*). Thus, there is no need to correct for time duration, as no new recording stations were brought online between October 1984 and September 2004.

Table 7. Wet and Dry Hour Percentages.

Zone	**1**	**2**	**3**	**4**	**5**	
Dry %	99.63%	99.66%	99.38%	99.49%	99.78%	
Wet %	0.37%	0.34%	0.62%	0.51%	0.22%	
Zone	**6**	**7**	**8**	**9**	**10**	**State**
Dry %	99.56%	99.41%	99.24%	99.75%	99.73%	99.51%
Wet %	0.44%	0.59%	0.76%	0.25%	0.27%	0.49%

Average Event Rates

The descriptive statistics for short, medium, and long rain events are provided in Appendix A in Table 22 through Table 24, respectively. These tables and their accompanying histograms are included in Appendix A (see Figure 57 through Figure 86).

Several noteworthy trends can be identified in the descriptive statistics. First, the means tend to be largest for medium events and smallest for short events. This trend is shown in Table 8. For all zones and the entire state, the overall mean is closest to the mean for short events. This is because short events comprise the vast majority of all rain events, as shown in the "State" column of Table 6.

Table 8. Average Rate Means (inch/hr).

Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**State**
Short	0.47	0.40	0.41	0.45	0.46	0.40	0.29	0.17	0.50	0.50	0.40
Medium	0.77	0.51	0.56	0.63	0.84	0.54	0.39	0.26	0.97	1.00	0.53
Long	0.74	0.31	0.34	0.46	0.54	0.34	0.28	0.25	1.07	1.36	0.33
All	0.48	0.41	0.42	0.46	0.47	0.41	0.30	0.18	0.53	0.53	0.40

Second, the standard deviations tend to be largest for medium events, as shown in Table 9. Across the state, the standard deviations for long events tend to fall between short and medium events.

Table 9. Average Rate Standard Deviations (inch/hr).

Zone	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**State**
Short	0.23	0.26	0.31	0.34	0.24	0.33	0.30	0.31	0.34	0.38	0.30
Medium	0.39	0.43	0.45	0.43	0.51	0.48	0.42	0.32	0.51	0.47	0.44
Long	0.27	0.29	0.33	0.42	0.43	0.38	0.29	0.23	0.50	0.79	0.32
All	0.24	0.27	0.32	0.35	0.25	0.34	0.31	0.31	0.35	0.39	0.31

Third, the skewnesses tend to decrease as event duration increases, as shown in Table 10. This can also be seen in the histograms in Appendix A (see Figure 57 through Figure 86). With the exception of long events in zone 10 (Figure 86), all of the histograms are skewed to the right, indicating that as duration increases, the event frequency decreases. The histogram for zone 10 is actually skewed to the left, but zone 10 has the least comprehensive data, as only one recording station is located in the zone.

Table 10. Average Rate Skewnesses.

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	5.2	3.5	5.6	7.0	6.4	6.3	4.6	7.4	7.6	8.5	5.7
Medium	2.1	1.3	1.2	1.1	2.6	1.4	1.7	3.0	1.4	0.5	1.5
Long	0.5	2.7	2.1	1.7	0.9	2.7	2.7	2.9	1.7	-1.7	2.4
All	5.1	3.3	5.2	6.6	6.3	5.9	4.3	6.6	7.2	8.0	5.4

Maximum Event Rates

The descriptive statistics for short, medium, and long rain events are provided in Table 25 through Table 27 in Appendix A. Note that the maximum event rate mean data subsets are comprised of the averages of the maximum rates observed during each event in the subsets. These tables and their accompanying histograms are included in Appendix A (Figure 87 through Figure 116).

Several noteworthy trends can be identified in the descriptive statistics. First, the means tend to be larger for medium and long events than for short events. This trend is shown in Table 11. For all zones and the entire state, the overall mean is closest to the mean for short events. This is because short events comprise the vast majority of all rain events, as shown in Table 6. The percent differences between the maximum and average event rate means for each zone are shown in Table 12. The differences are small for short events, but larger for medium and long events.

Table 11. Maximum Rate Means (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	0.51	0.43	0.44	0.48	0.49	0.43	0.31	0.20	0.54	0.56	0.43
Medium	1.39	0.97	1.05	1.14	1.54	1.02	0.76	0.52	1.85	1.99	1.00
Long	1.59	0.89	0.89	1.11	1.15	0.87	0.83	0.70	2.47	2.80	0.88
All	0.54	0.48	0.49	0.52	0.52	0.48	0.37	0.27	0.62	0.65	0.48

Table 12. Percent Differences Between Maximum and Average Rate Means.

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	9%	7%	7%	7%	7%	7%	7%	18%	8%	12%	8%
Medium	81%	90%	88%	81%	83%	89%	95%	100%	91%	99%	88%
Long	115%	187%	162%	141%	113%	156%	196%	180%	131%	106%	167%
All	13%	18%	17%	14%	11%	18%	24%	45%	17%	22%	18%

Second, unlike the average event rate data, the standard deviations in the maximum event rate data tend to increase with event duration, as shown in Table 13. The percent differences between the maximum and average event rate standard deviations are shown in

Table 14. The trends in Table 12 and

Table 14 suggest that longer-duration rain events are more prone to intensity spikes that appear as large standard deviations and large mean values in the maximum rate data.

Table 13. Maximum Rate Standard Deviations (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	0.35	0.36	0.41	0.42	0.34	0.42	0.38	0.37	0.47	0.58	0.40
Medium	0.96	0.96	0.97	0.97	1.16	1.02	0.91	0.71	1.19	1.28	0.95
Long	0.95	0.93	0.89	1.08	1.13	1.00	0.98	0.79	1.28	1.74	0.93
All	0.37	0.41	0.46	0.46	0.37	0.47	0.45	0.43	0.51	0.62	0.45

Table 14. Percent Differences Between Maximum and Average Rate Standard Deviations.

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	52%	38%	32%	24%	42%	27%	27%	19%	38%	53%	31%
Medium	146%	123%	116%	126%	127%	113%	117%	122%	133%	172%	118%
Long	252%	221%	170%	157%	163%	163%	238%	243%	156%	120%	190%
All	58%	52%	43%	33%	47%	39%	45%	42%	46%	61%	43%

Cumulative histograms for the statewide trends in average and maximum rate means are provided in Figure 22 through Figure 25. The dotted vertical lines represent the rainfall rates that were simulated during the research project documented in this report, and they relate the fact that the simulated rainfall rates in this project cover the majority of rainfall events in the state of Texas as reported within the last 20 years. The higher frequency of intensity spikes in medium and long events can be seen in Figure 23 and Figure 24, as the lines for average and maximum rate means are significantly separated, unlike the lines for short events shown in Figure 22. The only noteworthy difference between average and maximum rate means on Figure 22 occurs above the 85th percentile; less than 15 percent of the short events experienced intensity spikes. The cumulative distribution for all events is shown in Figure 25. Averaging the long and medium events in with the short events results in some separation between the distributions for average and maximum rate means, but not as dramatic as those shown in Figure 23 and Figure 24.

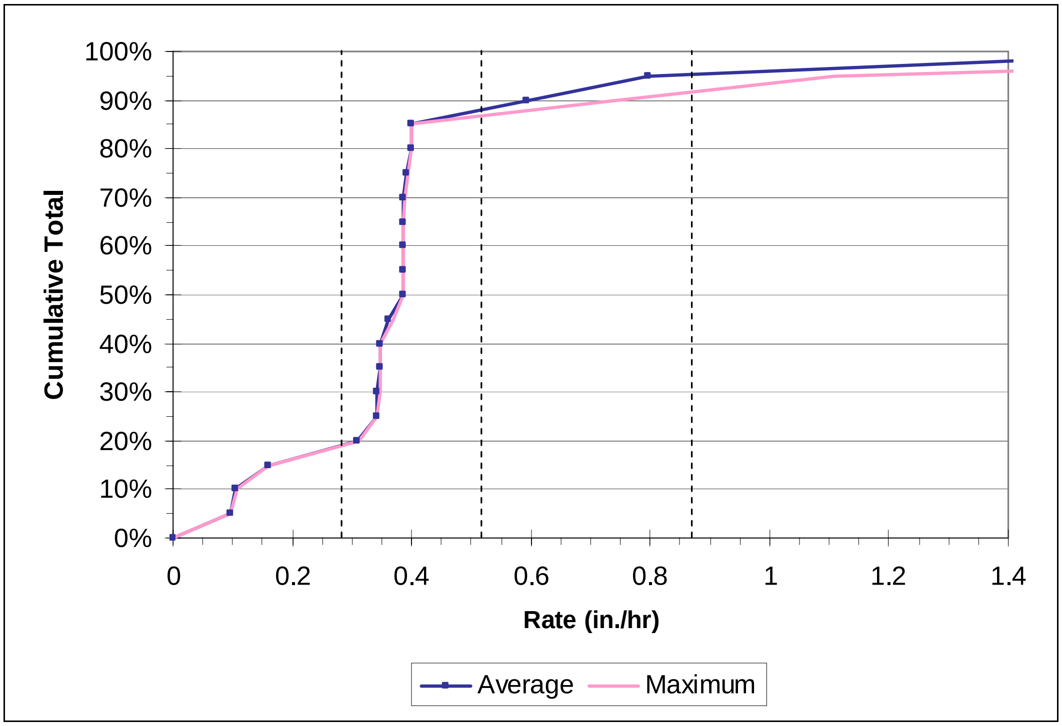

Figure 22. Cumulative Histogram for Short Events.

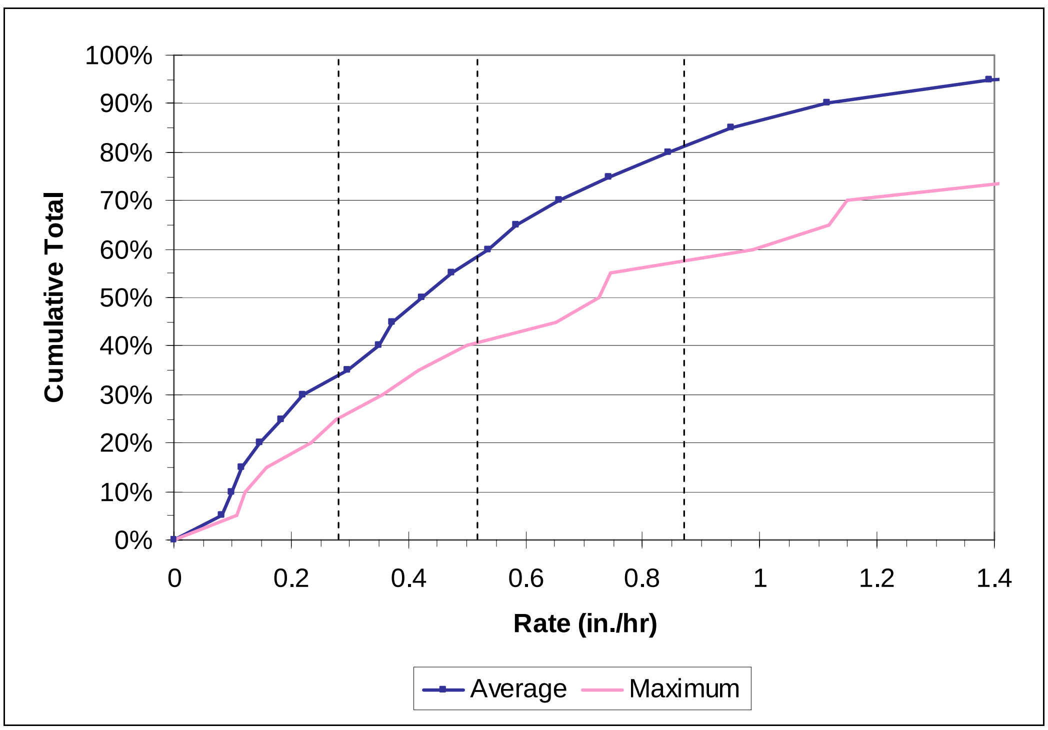

Figure 23. Cumulative Histogram for Medium Events.

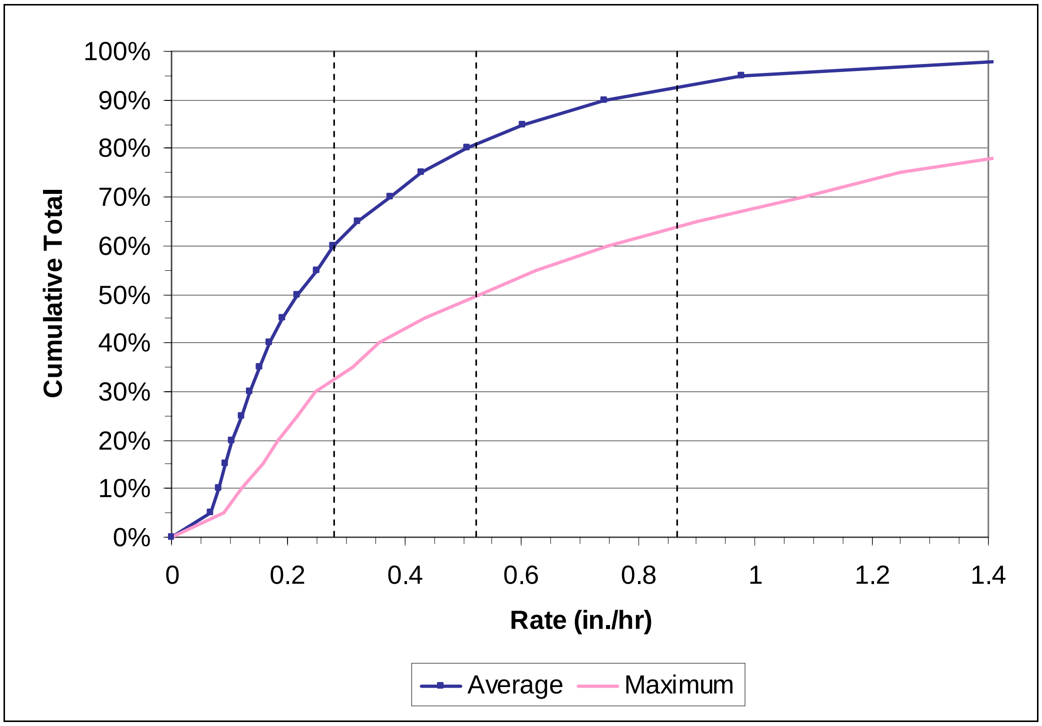

Figure 24. Cumulative Histogram for Long Events.

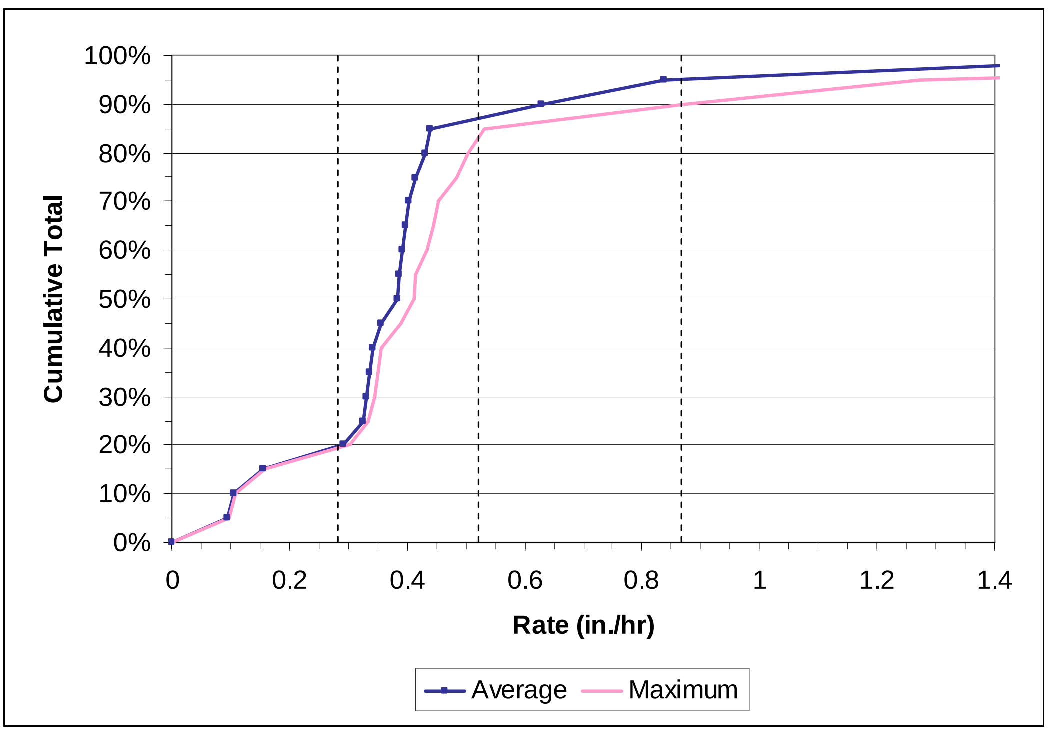

Figure 25. Cumulative Histogram for All Events.

Third, as was the case with the average rate data, the skewnesses tend to decrease as event duration increases, as shown in Table 15. This can also be seen in the histograms in

Appendix A (Figure 87 through Figure 116). With the exception of long events in zone 10 (Figure 116), all of the histograms are skewed to the right, indicating that as duration increases, the probability of occurrence of an event with a given duration decreases. The histogram for zone 10 is actually skewed to the left, but zone 10 has the least comprehensive data, as only one recording station is located in the zone.

Table 15. Maximum Rate Skewnesses.

Zone	1	2	3	4	5	6	7	8	9	10	State
Short	5.0	4.6	4.9	5.6	5.5	5.2	4.6	7.1	5.8	6.5	5.1
Medium	1.9	1.6	1.5	1.5	2.8	1.5	1.8	2.5	1.3	1.3	1.7
Long	1.2	2.1	1.6	1.6	1.8	2.2	2.0	2.1	1.3	-1.6	1.9
All	4.9	4.3	4.6	5.3	5.4	4.9	4.3	6.3	5.5	6.2	4.8

Regional Trends

The average and maximum event rate means are shown in Figure 26 and Figure 27, respectively. Interestingly, the zones in the eastern part of the state experienced lower rate means, despite the fact that more total rainfall occurs in eastern Texas *(35)*. Figure 28 shows a map of average annual rainfall compiled by the Texas Parks and Wildlife Department. The map indicates that average annual rainfall decreases farther west in the state.

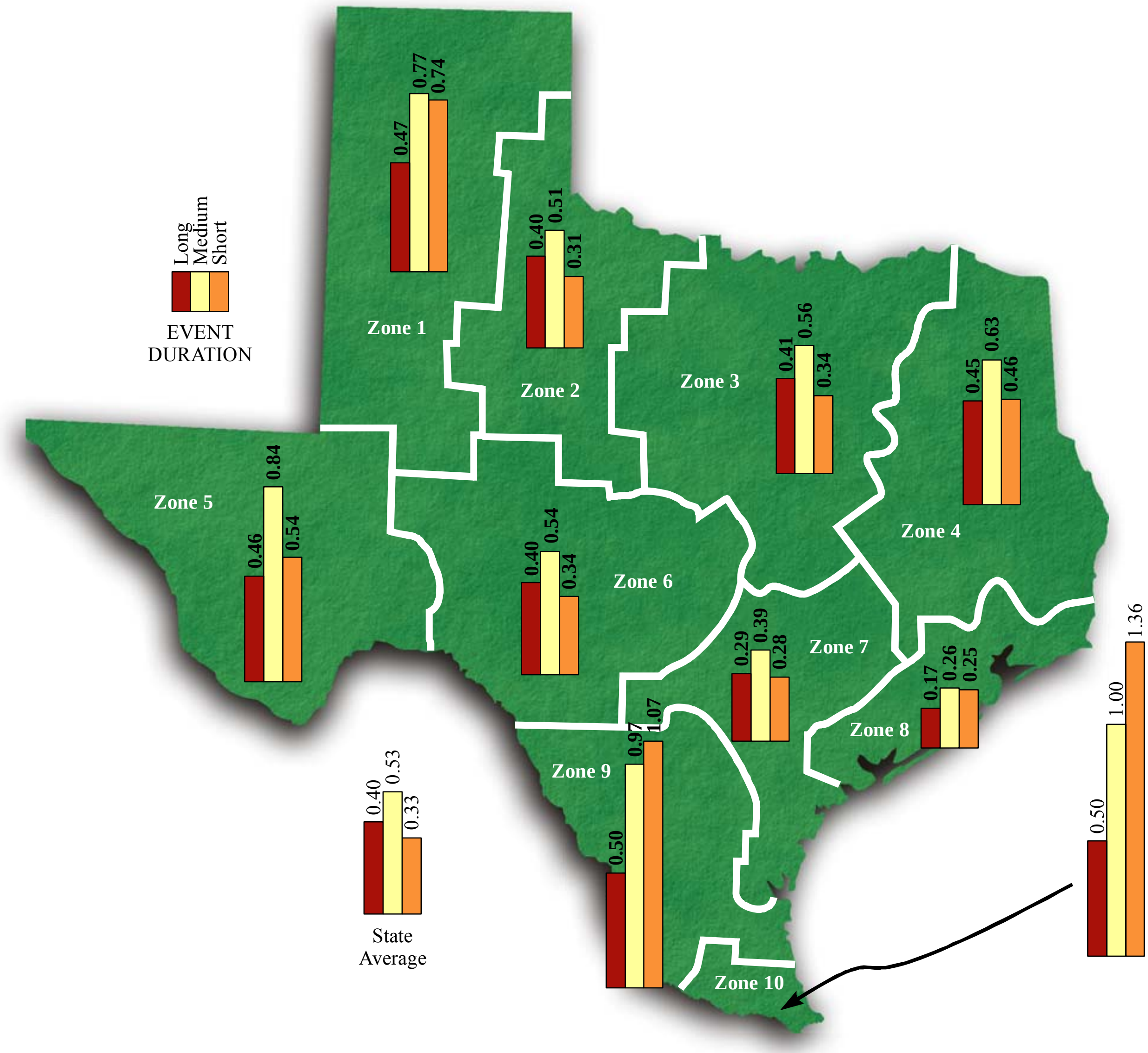

Figure 26. Average Rate Means by Zone.

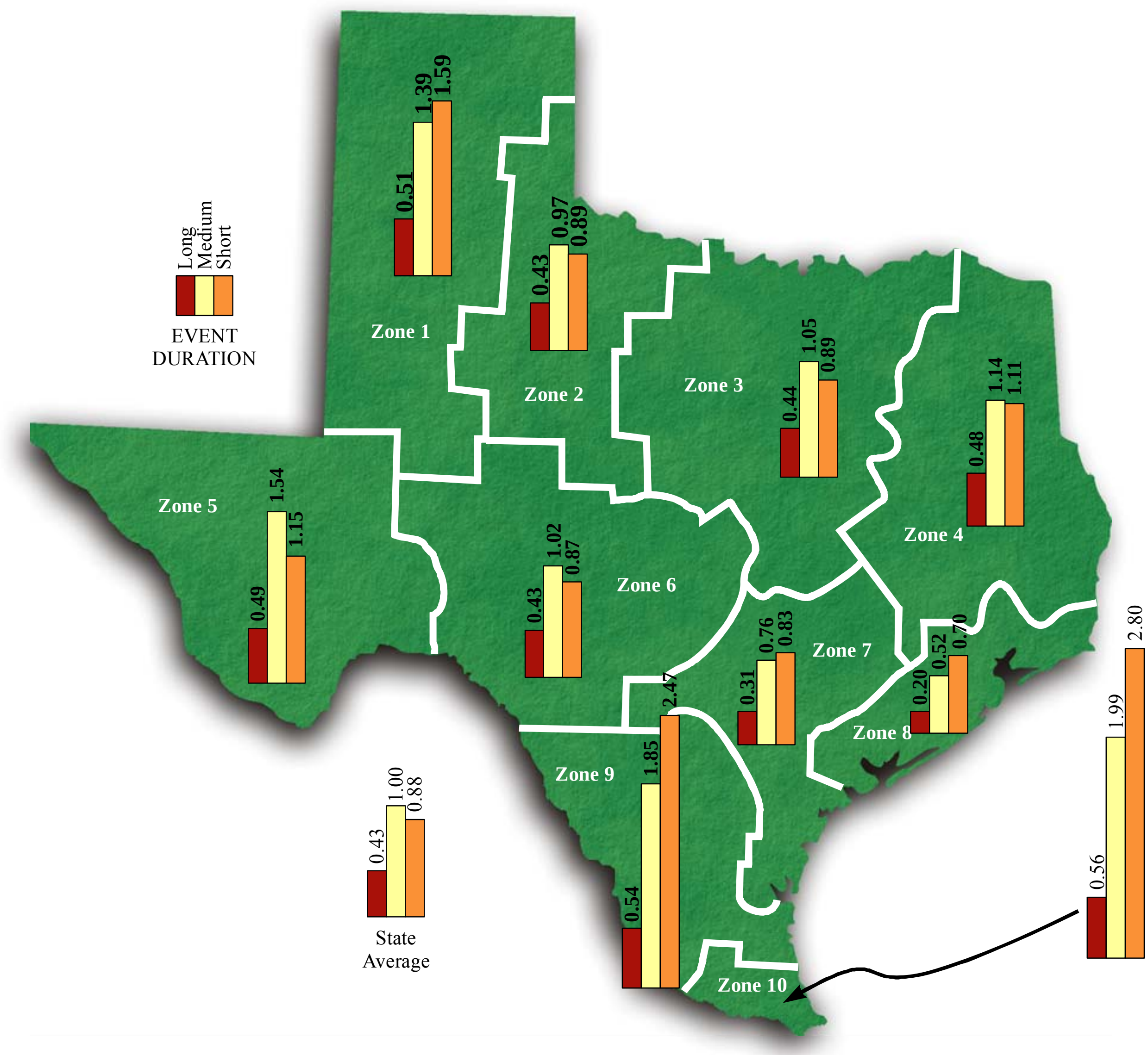

Figure 27. Maximum Rate Means by Zone.

For the purpose of data validation, the average annual rainfall amounts were extracted from the NCDC 15-minute data set and compared to the trends on Figure 28. These amounts and the wet-night hour percentages provided in Table 7 are superimposed onto the map, along with the climatic zone boundaries. As shown in Figure 28, the NCDC data set demonstrates good agreement with the Texas Parks and Wildlife Department map.

Figure 29 shows a second map of average annual rainfall rates, which was created by the Spatial Climate Analysis Service of Oregon State University *(36)*. Figure 29 was generated using 30 years of rainfall data that were collected by National Oceanic and Atmospheric

Administration (NOAA). The NCDC data set shows good agreement with the trends in Figure 29, though some of the NCDC numbers are slightly higher than the rates shown on the map, particularly in the western portion of the state. This discrepancy could be due to the fact that different time periods were used; the NCDC data were collected from 1984 to 2004, while the NOAA data were collected from 1961 to 1990.

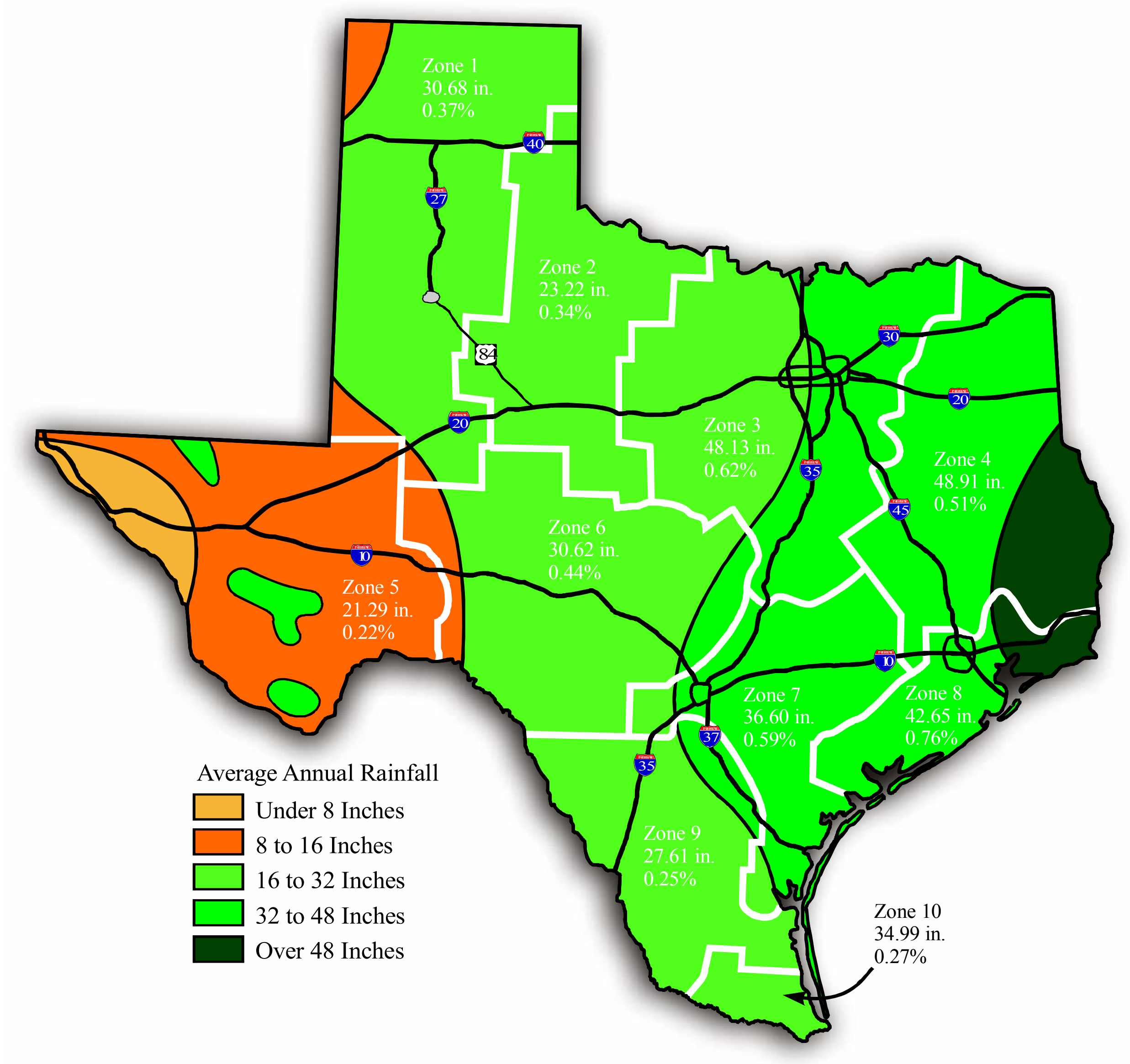

Figure 28. TPWD Average Annual Rainfall Map (35).

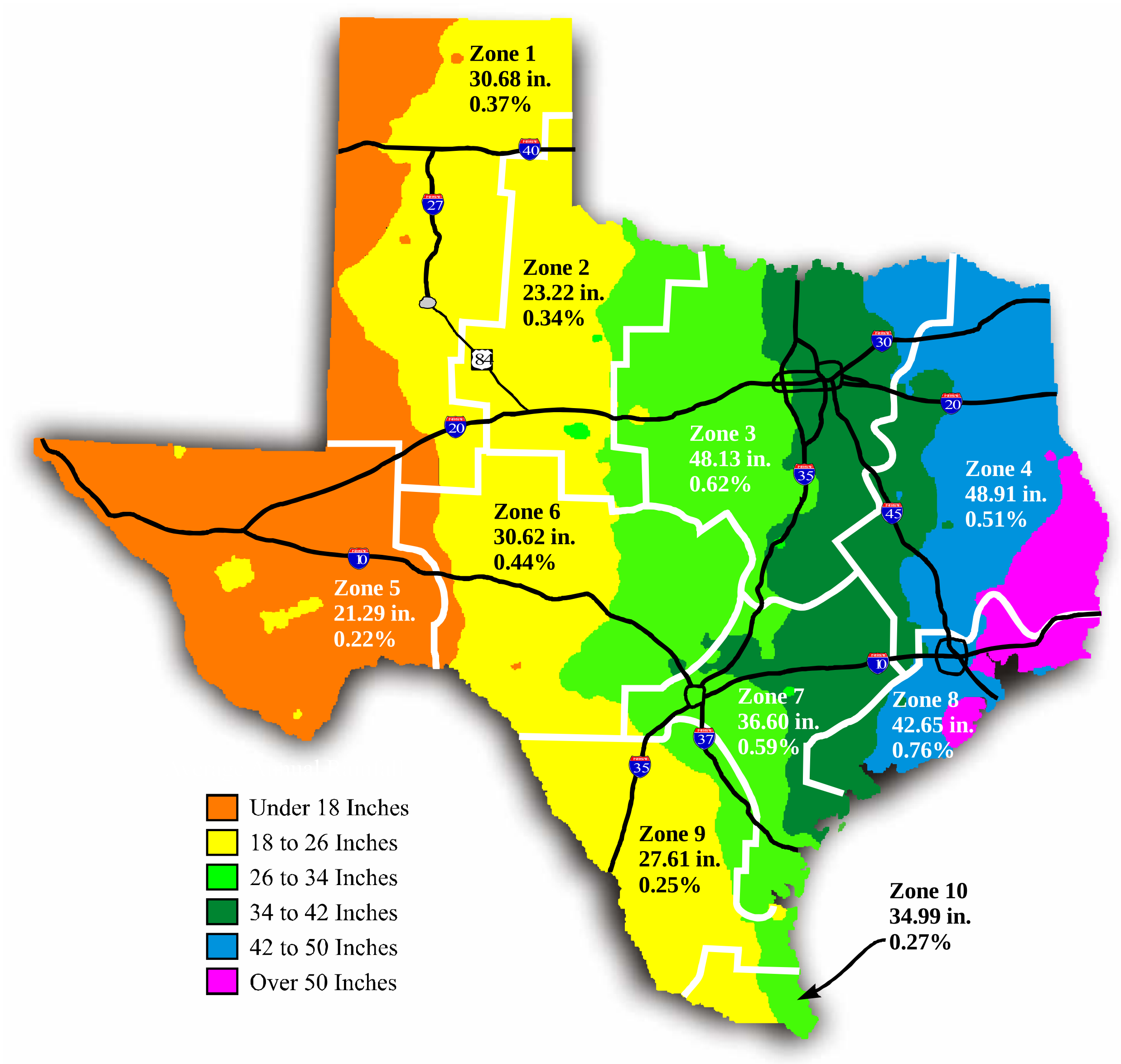

Figure 29. NOAA Average Annual Rainfall Map (*36*).

Table 16 provides the zone ranks for average rate means, maximum rate means, wet hour percentages, and average annual (day and night) rainfall. According to the zone ranks, zones 7 and 8 (which would be expected to experience more rainfall according to Table 7) did in fact rank high among the zones in wet hour percentage, though they ranked low in average and maximum rate means. Rain events in zones 7 and 8 were less severe but more frequent than in other zones. Zone 5 ranked in the middle of the zones for average and maximum rate means but last in wet hour percentage. Zones 9 and 10 ranked high in average rate means, but low in wet hour percentage, indicating that storms in these zones are rare but severe.

Table 16. Zone Ranks.

Zone	1	2	3	4	5	6	7	8	9	10
Average Rate	3	8	6	5	4	7	9	10	2	1
Maximum Rate	3	8	6	4	5	7	9	10	2	1
Wet Hour Percentage	6	7	2	4	10	5	3	1	9	8
Average Annual Rainfall	6	9	2	1	10	7	4	3	8	5

Implications for Rain Tunnel Design

The rain tunnel to be used in this project was designed to simulate three different rain rates: 0.25 inch, 0.5 inch, and 0.75 inch. These values are shown as dotted vertical lines on the cumulative histograms (Figure 22 to Figure 25). When the flow rates were measured on the completed tunnel, the actual values were observed to be 0.28 inch, 0.52 inch, and 0.87 inch. The percentile values for the design and measured flow rates are shown in Table 17.

Table 17. Percentile Values for Tunnel Flow Rates.

Design			Measured		
Flow Rate (in./hr)	**Average Rate Percentile**	**Maximum Rate Percentile**	**Flow Rate (in./hr)**	**Average Rate Percentile**	**Maximum Rate Percentile**
0.25	18%	18%	0.28	20%	19%
0.50	87%	79%	0.52	87%	83%
0.75	93%	88%	0.87	95%	90%

The numbers in Table 17 show that the tunnel design is adequate for simulating most rainfall events in Texas. More than 80 percent of rainfall events will produce maximum rates less than 0.52 inch, and 90 percent of events will produce maximum rates less than 0.87 inch. Almost all rain events occurring in Texas over the past 20 years produced rates within the limits of the tunnel's capacity of 0.87 inch, and those events with rates greater than 0.87 inch were medium or long events that are prone to short intensity spikes.

CHAPTER 4: WET-NIGHT PAVEMENT MARKING STUDY DESIGN

The objective of the field study was to determine the detection distances associated with various pavement marking systems under rainfall conditions that represented light to average to heavy rainfall, according to the information presented in the previous chapter. This chapter describes the variables that were considered in this effort, the test equipment and research stimuli, and the study procedures and data reduction activities.

SELECTION OF VARIABLES

Dependent Variable

The measure of effectiveness used in the project was the detection distance of one lane line placed along a stretch of roadway without any other markings. Previous research has used end detection of long continuous lines of pavement markings. However, because this project included many different types of markings and a controlled rain tunnel providing rain in an area about 1600 ft long by 12 ft wide, the end detection method was not feasible. In addition, other research has used the number of visible lane lines as the metric of visibility. This research has to be performed from a stationary vehicle and there is concern that the limit of counting skip or lane lines, regardless of their performance, is fixed because of the viewing geometries which make the appearance of skip or lane lines appear continuous at or about the sixth to eighth marking.

Independent Variable

To keep the scope of the study within the resources of the project, researchers identified and tested the following independent variables:

- Pavement marking groups – The researchers consulted with a TxDOT panel of pavement marking experts to determine the pavement marking materials that should be evaluated. Pavement marking vendors and contractors were contacted, and numerous samples were collected for testing. A detailed spreadsheet of all tested materials is in Table 28 in Appendix B. The markings can be grouped as follows.
    - Waterborne paint

        - Type II beads
        - Type III beads
    - Thermoplastic
        - Type I beads
        - Type II beads
        - Type III beads
    - Tapes
        - Profiled tape
        - Enclosed lens tape
        - Flat tape
        - Profiled tape with high refractive index beads
    - Exotics
        - Methyl methacrylate in a splattered pattern
        - Rumble stripes
        - Epoxy with big beads and Visionglow beads
        - Polyurea with bead clusters
    - Raised retroreflective pavement markings

- Rainfall rate – Using the results of the previous chapter, a rain tunnel was designed and built specifically for this project. The rain tunnel produced three levels of rain, which were varied so they could be used to enhance the analysis of the detection distances.
- Driver age – Two subject age categories were selected for this project: a younger group consisting of subjects under the age of 55 years, and an older group made up of subjects 55 years and older.

Fixed Factors

The factors that were held constant throughout the experiment include:

- Pavement marking size – Unless specifically noted, all pavement markings were 4 inches wide and 8 ft long. Some 6-inch-wide samples were used to investigate the potential detection distance gains by increasing the width of the marking.

- Pavement marking position – All of the pavement markings used for the analysis were positioned in the center of the travel lane. Distracter pavement markings were offset outside of the travel lane, but their detection distances were not used in the analysis.
- Seat position – All the detection distances were recorded with the subjects driving the test vehicle and therefore from the driver's seat position.
- Vehicle speed – Each trial was performed at 30 mph.
- Ambient lighting – The project was performed at Texas A&M University's Riverside Campus. This campus is an old Air Force Base that was donated to the University. It is approximately 12 miles from the main campus and is located in a dark, rural environment. There is little lighting from buildings or nearby communities.

Measured Factors

- Retroreflectivity – The dry, continuous wet, and recovery wet retroreflectivity measurements were recorded for each pavement marking before the study began. Each sample's retroreflectivity was measured using an MX30 handheld retroreflectometer. To obtain wet retroreflectivity observations, a nozzle was suspended over the samples and a metal screen was used to keep the retroreflectometer instrumentation dry, as shown in Figure 30.

Figure 30. Wet Retroreflectivity Observation Method.

- Visual acuity – Each of the test subjects was required to have a valid driver's license. The researchers measured the visual acuity of each subject using the Snellen visual acuity chart.
- Luminance – After the detection distance data were collected, the FHWA assisted with the measurement of the pavement marking luminance using their charged-coupled device (CCD) photometer. These data have been provided but are not included in this report as they were not in the scope of this project. These data will be used to support the ASTM work that is related to wet pavement marking specification development.

TEST EQUIPMENT

Test Vehicles

Two state-owned vehicles were used to conduct the test runs on the closed test course. One of the vehicles was a 2004 Ford Taurus sedan with HB4 halogen headlamps (see Figure 31). A researcher sat in the passenger seat during the test runs to collect data. The vehicle was equipped with (1) a special control switch on the passenger side that allowed the researcher to control the windshield wipers, and (2) a distance measuring instrument (DMI) for recording detection and recognition distances for the pavement marking samples. During the test runs, the low wiper setting was used for the low rainfall flow rate, and the high setting was used for the medium and high rainfall flow rates. The second vehicle was a pickup truck, which was used to deploy and retrieve the pavement marking samples between each test run. The box containing the various samples was kept in the bed of the truck, as shown in Figure 32.

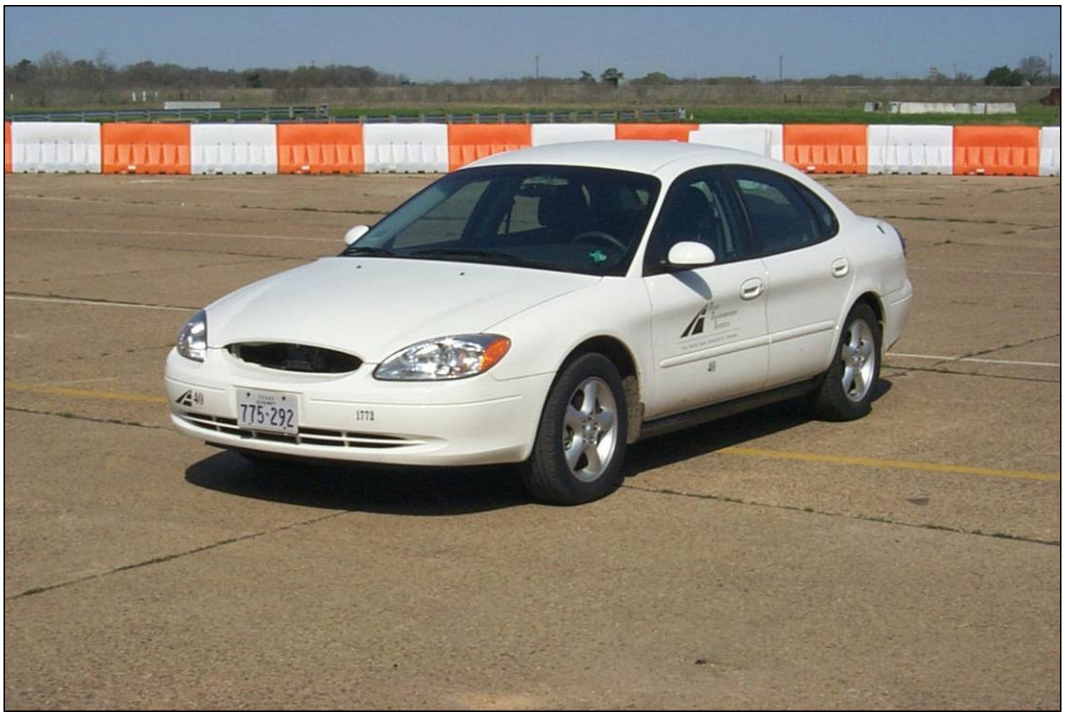

Figure 31. Data Collection Vehicle.

Figure 32. Pavement Marking Sample Storage Box.

Rain Tunnel

The rain tunnel or rain tunnel was supplied by a 4-inch trunk line that ran to a fire hydrant 800 ft away. The trunk line then split into three 3-inch lines that then fed into 3-inch gate valves. 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. There were a total of about 250 ¾-inch risers, each with a nozzle at the end. The nozzles were aimed upward. The risers were supported by cables that connected to posts spaced 50 ft apart.

Pressure gauges were used at several locations along both lines to verify that the water pressure was consistently adequate to provide the desired rainfall flow rates. Pressure gauges were also installed next to the gate valves to attain the desired rainfall flow rates for each line. These required pressures were determined by using a rain gauge and test cylinders (see Figure 33) to observe the rainfall rates at five sample locations. The rain gauge was placed at the center of each sample location, and test cylinders were placed at the ends and at several other points in the vicinity. The rain tunnel was then activated for a short period of time so readings could be taken from the rain gauge. The test cylinders allowed multiple rainfall flow rate readings to be taken simultaneously; water collected in each test cylinder was poured into the rain gauge to obtain additional observations after the water in the rain gauge was poured out. In addition to determining the required line pressures, this exercise was also used to verify that the tunnel was producing consistent rainfall flow rates at the sample locations.

Figure 33. Rain Gauge and Test Cylinders.

The rain tunnel was designed to provide the three rainfall flows specified in Table 18. The flow values measured after assembly were slightly higher than the intended design flow rates.

Table 18. Rain Tunnel Flow Rates.

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

The weather monitoring device shown in Figure 34 was installed next to the rain tunnel. The weather monitoring device had an accompanying portable liquid crystal display that provided the data measurements from the device. The field crew recorded the temperature, wind speed, and wind direction at the beginning and ending of each data collection session. The researchers determined that an easterly wind of greater than 6 mph would require data collection to cease because the simulated rain would not cover the test course's drive path consistently.

Figure 34. Weather Monitoring Device.

RESEARCH STIMULI

Each of the pavement marking materials to be tested was applied to two 4-ft substrate panels, which were then placed on the roadway at designated locations. The materials were applied such that there was at least 1 inch of substrate between the marking material and the edge of the panel, and there was no marking material on the leading front edge of the front panel. Any excess material applied by the marking manufacturers was chipped off. Arrows drawn on the panels indicated the direction of glass bead application during manufacturing, so that the panels could be oriented in the same direction every time they were deployed. Whenever a given material was sampled during the experiment, both substrate panels with the material were pulled out of the box simultaneously to minimize glass bead loss during handling.

Table 19 provides the specifications for each marking material that was tested, and the sample code numbers used to identify the samples in the field and in this report. Substrate panels of 6.1-inch width, 4-ft length, and 0.24-inch thickness were used for all but two of the material samples. The two exceptions were sample 24, which was applied to panels of 7.9-inch width and 0.35-inch thickness, and sample 35, which was applied to panels of 6.1-inch width and 0.5-inch thickness. Depressions cut into the panels for sample 35 approximated the shape of a road surface with milled rumble strips. The depressions were spaced 24 inches on-centers and cut to a depth of 0.25 inch. This application is sometimes referred to as a rumble stripe.

Table 19. Marking Sample Dimensions and Specifications.

Material Code	Color	Material Type	Manufacturer	Glass Bead Type
5	White	Waterborne Paint	Ennis Paint	III
6	White	Waterborne Paint	All-American Coatings	II
8	White	LS90 Polyurea	EpoPlex	GloMarc 90, II
9	White	LS50 Epoxy	EpoPlex	III
10	White	LS50 Epoxy	EpoPlex	III
11	White	Alkyd Thermoplastic	Ennis Paint	I, III, High Index
12	White	Alkyd Thermoplastic	Ennis Paint	I, III, High Index
15	White	Tape A380I	3M	
16	White	Tape A750ES	3M	
17	White	Tape 380WR	3M	
18	White	Tape ATM 400	Advanced Traffic Markings	
21	Yellow	Tape A380I	3M	
22	Yellow	Tape A750ES	3M	
23	Yellow	LS90 Polyurea	EpoPlex	GloMarc 90, II
24	White	Tape 380WR	3M	
25	Yellow	Tape ATM 400	Advanced Traffic Markings	
31	Yellow	Methacrylate	Degussa	III
32	White	Thermoplastic	Dobco	III
33	White	Thermoplastic	Ennis Paint	E16, M247
34	White	Alkyd Thermoplastic	Ennis Paint	II
35	White	Alkyd Thermoplastic	Ennis Paint	II
36	White	RRPM	Avery Dennison	None

Freshly applied pavement markings are often covered with a thin film of residual oil that can repel water until it is worn off by traffic. Since the goal of the research project was to observe the performance of the marking materials themselves, the marking samples were scrubbed with a solution of water and detergent before being used in the experiment, to remove any oil film.

STUDY PROCEDURE

The test course used a straight and flat 22-ft-wide road with a natural crown and cross slope but without existing markings. The simulated rain ran along the west side of the road for 1600 ft, but only wetted slightly over half of the roadway width. Figure 35 shows a typical section of the test course with the rain tunnel assembly. Two rows of blue RRPMs were installed to delineate a 9-ft drive path on the side of the road closest to the rain tunnel.

Figure 35. Test Course with Rain Tunnel.

During the subject test runs, pavement marking samples were placed at any of nine specified locations along the 1600-ft rain tunnel, as shown in Figure 36. Locations A, B, C, D, and E were used for actual data collection. Locations F1, F2, F3, and F4 were used as distracters, to minimize the possibility that the experimental subjects could begin to grow accustomed to the sample locations and thus guess at the presence of a sample before actually seeing it. Spray-painted black boxes on the pavement and thin red (non-retroreflective) tape strips on nearby risers indicated the marking sample locations so the field crew could identify them during the experiment.

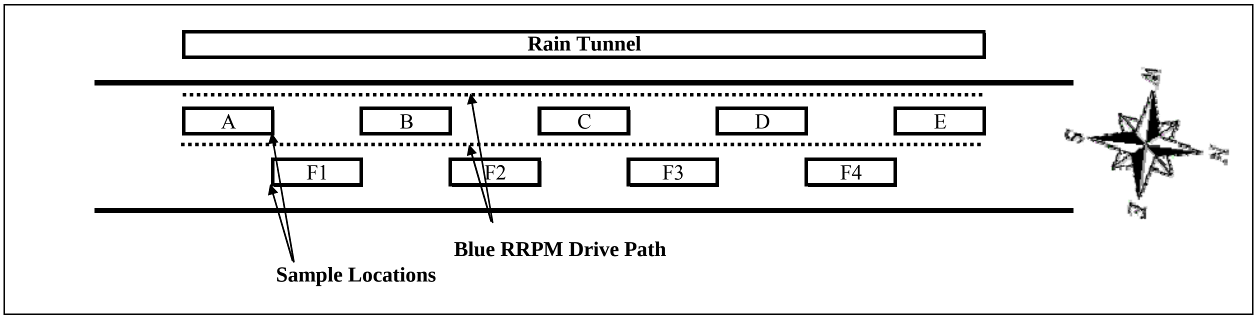

Figure 36. Pavement Marking Sample Locations.

During the test runs, the subjects specified when they could detect and recognize the deployed pavement marking samples. The following procedure was employed:

1. The experimental subject signed informed consent forms at the TTI office, and received a briefing of the tasks.
2. The subject drove the test vehicle to the test course; the researcher sat in the passenger seat. While the subject and the researcher were en route to the course, the subject activated the cruise control and set it to 30 mph.
3. The field crew in the pickup truck activated the rain tunnel and deployed an example marking setup. The example setup consisted of two markings in test locations (A, B, C, D, and E) and one marking in a distracter location (F1, F2, F3, and F4).
4. The subject drove the test vehicle to the southern end of the test course and stopped the vehicle between two cones. The cones were placed at a precisely measured distance from the southern end of the rain tunnel. The researcher zeroed the DMI at this location.
5. The subject drove through the test course twice, once in the northbound direction, and then once in the southbound direction, to get familiar with the course and the tasks.
6. As the test vehicle passed through the simulated rain, the subject drove between the two lines of blue RRPMs with the cruise control running, and scanned the entire road surface for pavement marking samples. The researcher activated the windshield wipers when the vehicle entered the simulated rain, and deactivated them when the vehicle exited the rain.

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. Markings were identified as white lines, yellow lines, or reflectors (RRPMs). The researcher recorded the location values from the DMI when the subject detected or identified the marking samples.

7. After the second test run was completed, the field crew removed the example markings and deployed the first experimental setup.
8. The subject drove through the course, and again stated when he or she could detect and identify each marking sample, and then stopped after exiting the simulated rain. The researcher recorded the detection and recognition locations from the DMI.
9. The field crew changed the sample deployment, removing old samples, deploying new ones, and changing the rainfall rate as specified by the experimental design. The crew then informed the researcher via radio when the new setup was ready.
10. The subject turned the vehicle around, stopped between another set of cones, and proceeded through the test course after the researcher zeroed the DMI. The researcher again recorded locations at which the subject detected or recognized marking samples.
11. Steps 8 through 10 were repeated until 12 test runs (six northbound and six southbound) were completed. The subject then drove back to the TTI office and was compensated for participating in the research project.

The researchers selected the marking setups for the test runs before the runs were conducted. The material codes and deployment locations were recorded into a spreadsheet, along with the detection and recognition locations from the DMI. The distances each subject required to detect and recognize each marking sample were then calculated based on the recorded DMI locations and the known distances to each deployment location.

DATA COLLECTION

The following three sets of data were collected for this project:

- pavement marking sample retroreflectivity values under dry, wet, and recovery conditions;

- experimental subject information, including age, sex, Snellen visual acuity, and color blindness testing; and
- detection and recognition distances for the marking samples.

Pavement Marking Retroreflectivity

The procedures used for the dry, wet, and recovery retroreflectivity measurements were consistent with ASTM test methods E1710-97, E2176-01, and E2177-01, respectively (*23*,*24*,*25*). Wet measurements were taken under a condition of continuous wetting, simulating rainfall. Recovery measurements were taken with a puddle of water on the marking samples, simulating the recovery period when rainfall has ceased but the roadway has not dried off. The MX30 retroreflectometer used an observation angle of 1.05 degrees and an entrance angle of 88.76 degrees (*15*,*17*). The simulated rainfall rate of the nozzle used for continuous wetting was measured to be 9.5 inches/hr; ASTM method E2176-01 allows for a range of flow rates and wetted area diameters, and the resulting rainfall rate at the middle of the allowed ranges is 9.32 inches/hr.

For all three sets of retroreflectivity measurements, observations were not recorded until consistency was established between observations. This allowed the researchers to ensure that the surfaces of the pavement marking samples were wetted evenly. The retroreflectivity measurements for sample 35 (white rumble stripe) were taken from one of the oblique faces. No retroreflectivity measurements were taken for sample 36 (white RRPM).

Experimental Subject Information

A total of 34 experimental subjects drove through the test course. The age and sex of each subject were recorded. The subjects were split up into two age groups: young (18 to 54) and old (≥55). Each subject's vision was also tested using the Snellen visual acuity chart and a color blindness test.

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

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

- 5 males 55 years of age and older.

Pavement Marking Detection and Recognition

Two sets of data were collected as described previously. However, after an initial review of the data, the research team determined that recognition data would not be useful. They were initially obtained to supplement the detection distances. Therefore, only the detection distances were analyzed.

CHAPTER 5:
WET/NIGHT PAVEMENT MARKING PRELIMINARY RESULTS

In all, 866 pavement marking detection distances were recorded during this study. This includes the low, medium, and high rainfall rates. Missing or suspicious data that were eliminated from further consideration dropped the total number of observations available for analysis to 707.

Besides the main analysis of detection distance by subclass of pavement marking type, several other smaller investigations were performed and are also included in this chapter. For instance, the study was designed to investigate the potential wet-night visibility gains of increasing pavement marking width from 4 inches to 6 inches. Another small investigation included an opportunity to test the potential wet-night visibility gains of rumble stripes (where traditional markings are laid on top of rumble strips). The data also allowed for a comparison of dry, to continuous wet, to recovery wet retroreflectivity measurements. The purpose of these comparisons was to determine if wet retroreflectivity levels could be predicted by dry levels, or if continuous wet levels were related to recovery wet levels.

SUBJECT DATA

A total of 34 subjects participated in this project. Four of the subjects' data were removed from consideration because of a variety of factors such as poor visual acuity (those worse than 20/40). Of the 30 subjects remaining, 13 had visual acuity scores better than 20/20, 14 had visual acuity scores of 20/20, and the others had visual acuity scores better than 20/40.

EXPERIMENTAL BIASES

One of the first important issues to evaluate after a designed experiment is whether any unexpected experimental biases developed despite the planning efforts that went into the design of the experiment. In order to investigate the potential impacts, the researchers examined the univariate relationship between:

- run number (did the subjects get better as they performed more trials?),
- direction (were the detection distances higher in one direction versus the other?), and

- location (were pavement markings at certain locations more visible than at other locations?).

The main effect plots for these considerations are shown in Figure 37. The differences in detection distance associated with the run number and direction were not significant, but the location of the marking sample was. Because this could undermine the remainder of the analyses, the relationship of the markings' locations and detection distances was further examined.

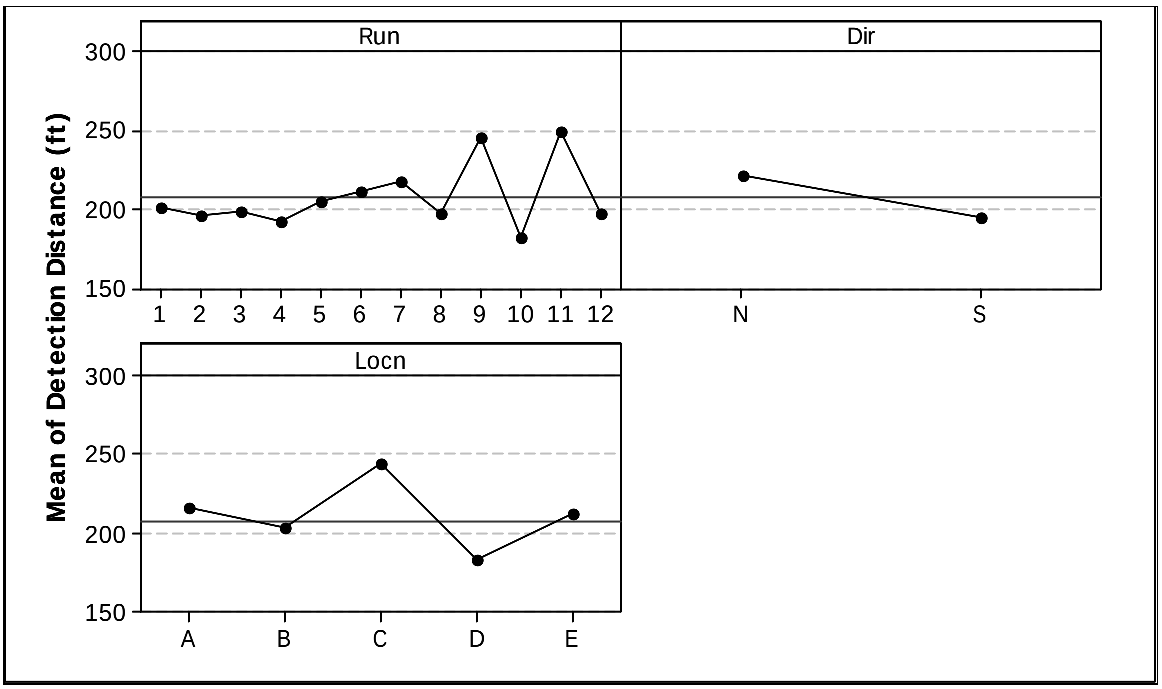

Figure 37. Main Effect Plots for Experimental Bias.

One of the reasons the location could have been found to be statistically significant is the way the pavement marking samples were assigned to each location. During the trial runs, the researchers realized that some markings were detectable at much longer distances than other markings. Therefore, these markings could not be placed at the first couple of designated locations (A and B for northbound runs, D and E for southbound runs, as shown in Figure 36) because they would be detectable before the vehicle entered the rain tunnel. Another limitation was that the first designated location (A for northbound runs, E for southbound runs) could not be used for that specific trial because it was only about 100 ft inside the rain tunnel. The 95 percent confidence interval detection distances for each of the five designated testing locations by direction of testing are shown in Figure 38. Some of these constraints are evident in the figure.

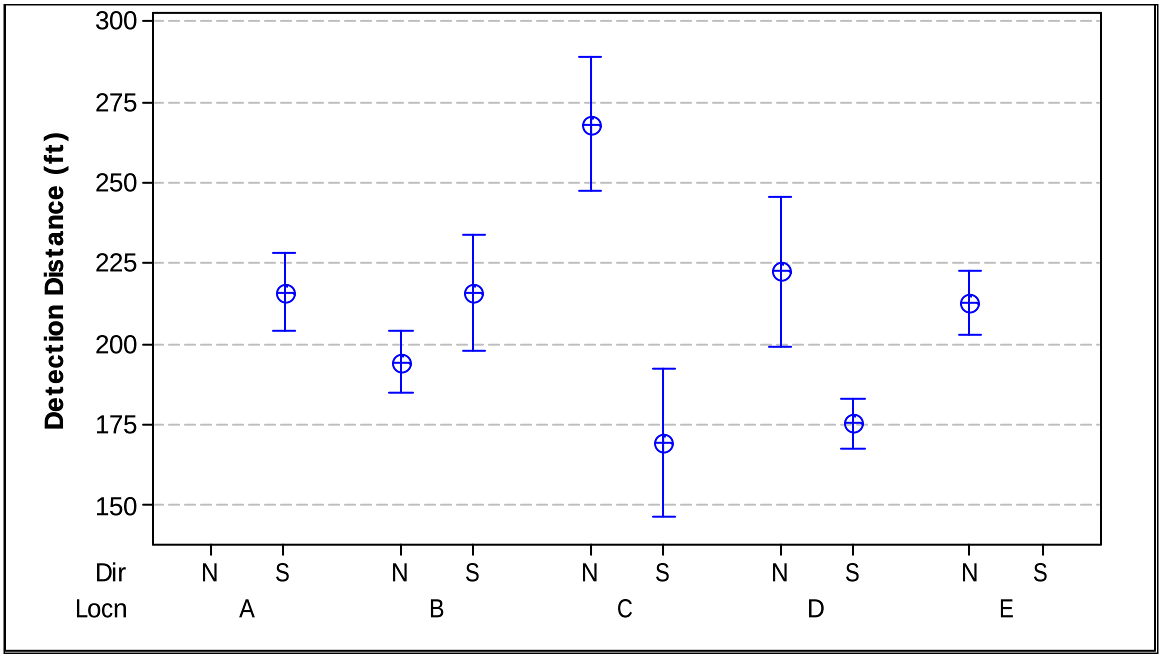

Figure 38. 95 Percent Confidence Intervals for Detection Distance by Location.

Figure 38 shows that trials proceeding in the southbound direction did not include testing at location E and trials proceeding in the northbound direction did not include testing at location A. As mentioned, another constraint was the detectability of some materials, such as the RRPMs (sample 36). Markings with relatively long visibility distances were always placed at location C (the midway point) or further. In addition, when the markings with longer visibility distances were used, there was little opportunity to include a second marking during the trial (in many trials, the researchers included two samples to increase the efficiency of data collection). These constraints mean that there was not necessarily a balance between the relative performance of the markings and their test locations. To further explore this possible imbalance, the continuous wet retroreflectivity measurements of the samples used at these locations were grouped by location and direction of flow and then averaged.

- Location B, North: 229
- Location B, South: 202
- Location C, North: 392
- Location C, South: 160
- Location D, North: 333

- Location D, South: 175

The detection distances at location B are statistically the same and the average retroreflectivity levels for the materials tested at location B are nearly the same, too. However, the detection distances by direction of testing at locations C and D are statistically different. The average retroreflectivity levels of the markings tested at those locations are substantially different, too. Therefore, it appears that the differences in detection distances by location appear to be a result of the constraints of the randomization of the study design and not because some locations provided better sight distances of the markings than others. In other words, there was a disproportionate number of marking samples at locations C and D with higher retroreflectivity values for northbound runs.

SUBJECT BIAS

The next issues to consider before the data can be analyzed without concerns over procedural issues are the subject-related information. The researchers examined the impacts of the age groups, gender, and visual acuity. The main effect plots of these three variables are shown in Figure 39.

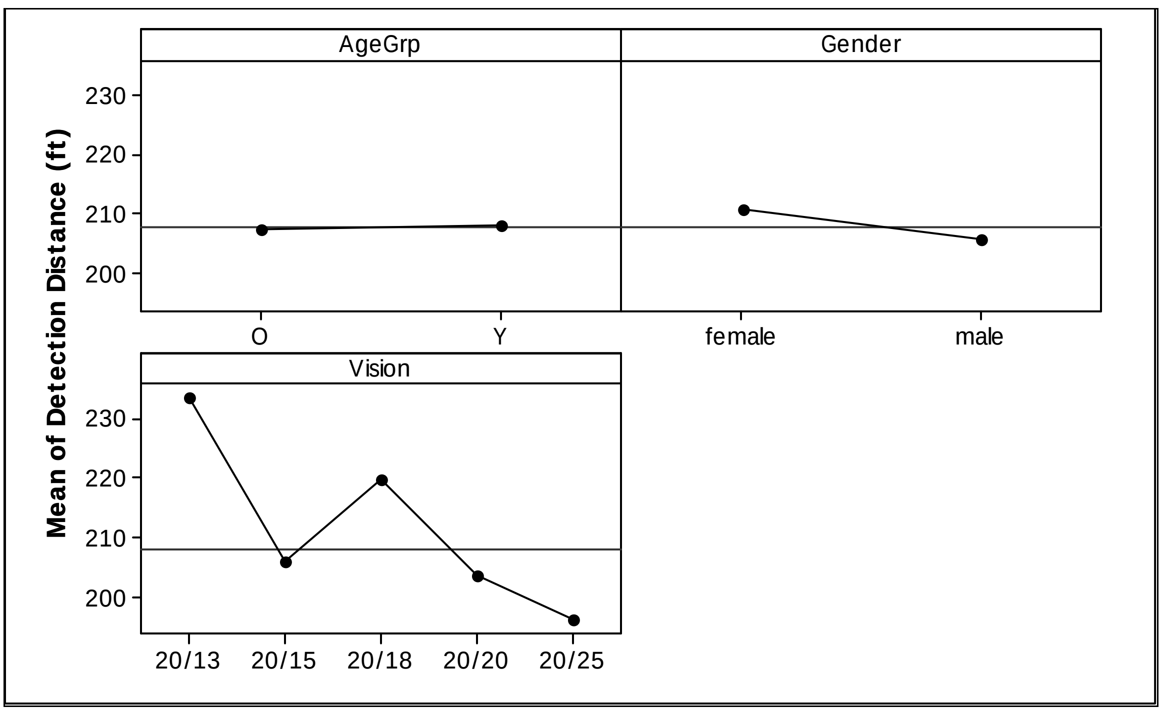

Figure 39. Main Effect Plots of Subject-Related Factors.

An analysis of the data confirms the observations apparent in Figure 39. For example, the age group ($p=0.253$) and gender ($p=0.175$) were not found to be statistically significant but the visual acuity was ($p=0.000$).[1] It was expected that the age group would produce more of a difference than it did in this project.

DESCRIPTIVE STATISTICS

The detection distances by each pavement marking sample and flow rate are shown in the boxplot in Figure 40. The median detection distances are shown by the black horizontal dash in the colored portion of each vertical bar. The ends of the bars represent the 25th and 75th percentile detection distances.

[1] The p-value is a reporting convention used to report the significance of a test. The p-value ranges from zero to one. A p-value close to one means that the data are the same with respect to the test. A p-value close to zero means that the data are not the same with respect to the test. For the 95th percentile confidence interval criteria, a p-value > 0.05 means the data are statistically similar and a p-value < 0.05 means the data are statistically different.

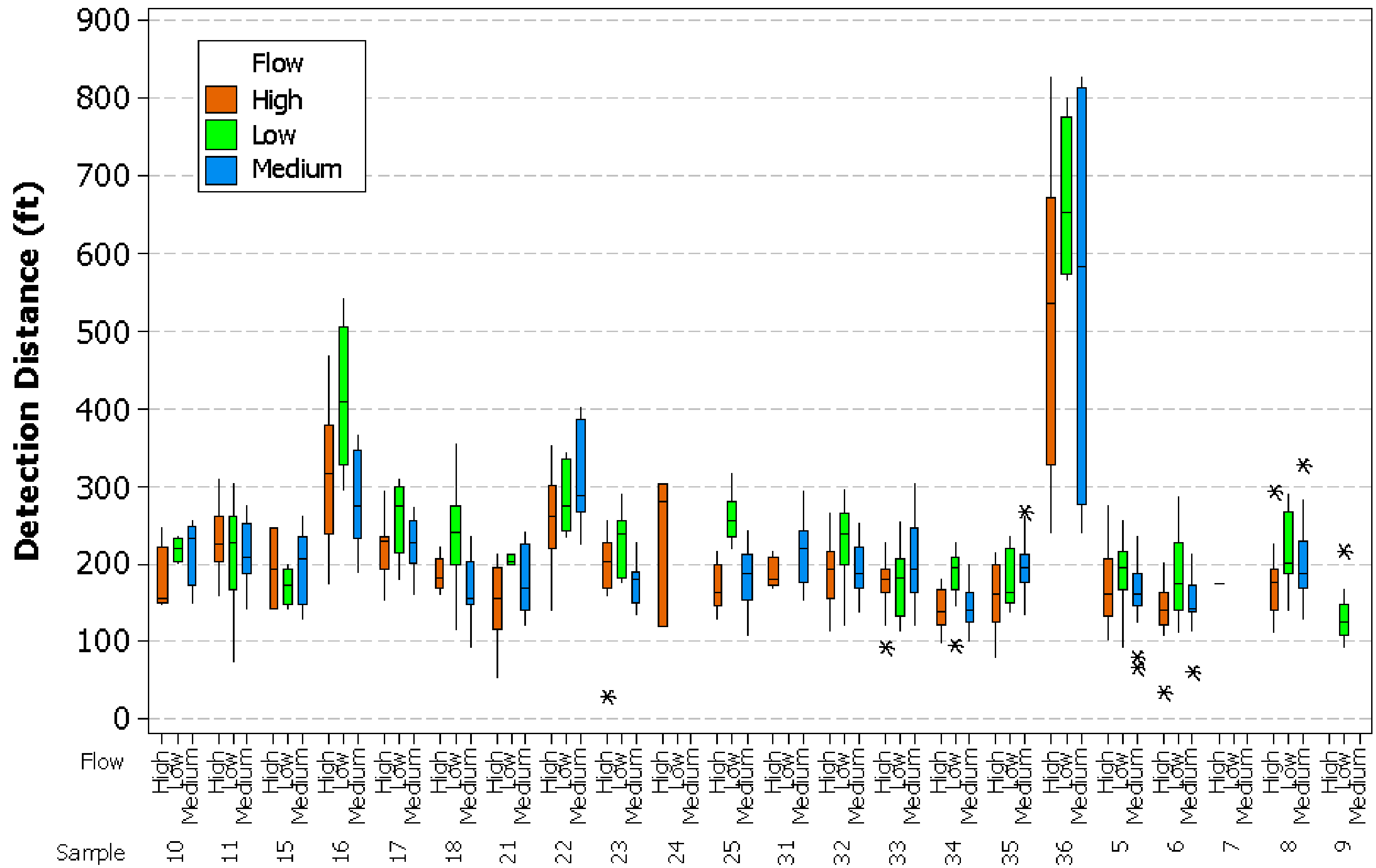

Figure 40. Detection Distances For All Conditions.

Sample 36 is an RRPM. RRPMs are meant to perform in the rain and at night. In fact, that is about their only usefulness. However, the basic analysis shows that there is not a pavement marking system that does nearly as good a job in terms of detection distances as the RRPMs. The RRPMs were excluded from subsequent analyses, but the measured detection distances are summarized below.

Table 20. RRPM Detection Distances (ft).

Statistic	Overall Performance	Rainfall Intensity		
		Low	Medium	High
5th percentile	828	787	821	798
25th percentile	749	729	794	595
50th percentile	567	654	586	539
75th percentile	388	594	351	332
95th percentile	241	572	263	275

After removing the RRPMs from the data to be analyzed, the researchers performed a statistical test called an analysis of variance (ANOVA) that showed that the sample and flow rate were both significantly related to the detection distances. Furthermore, the analysis showed that the interaction between the samples and flow rate was also significant. Figure 41 illustrates the interaction between average detection distances and each material tested by rainfall intensity. It should be noted that some samples were not tested often, and therefore there are no data available for all materials and all rainfall intensities. Detailed statistical testing and the appropriate results will be presented and discussed in the following sections.

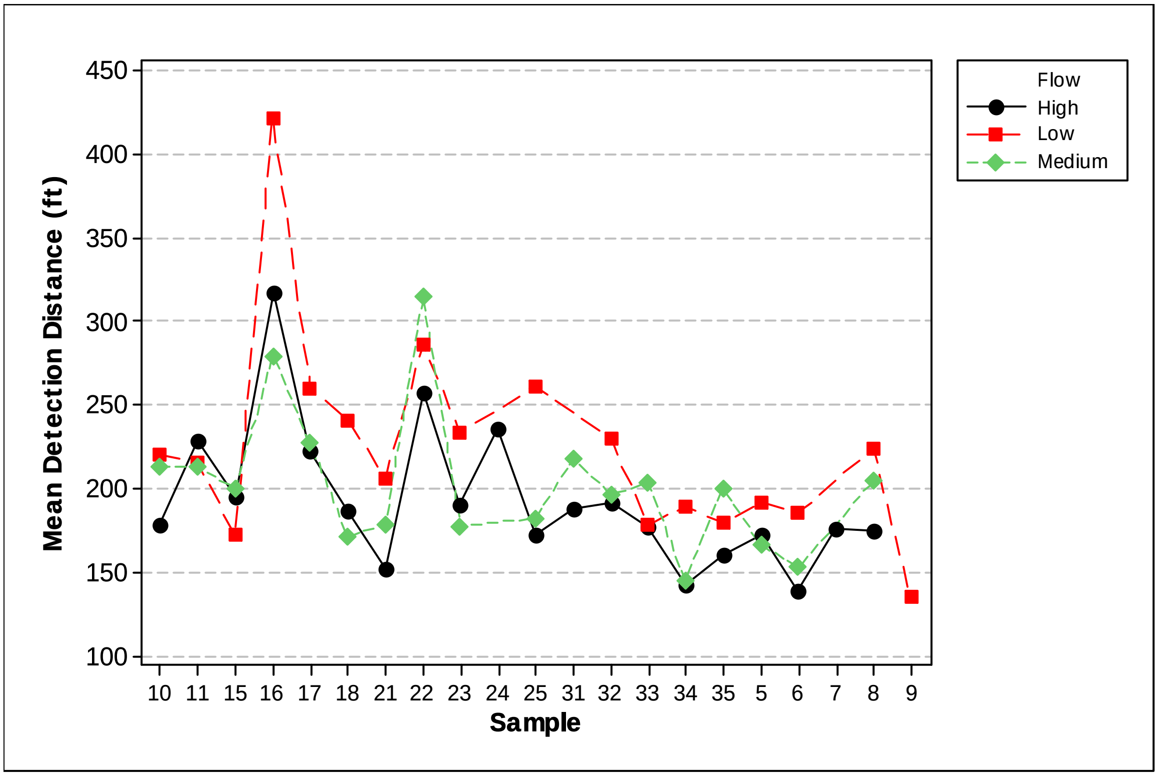

Figure 41. Detection Distances with the RRPMs Included.

One observation to be made from the data plotted in Figure 41 is that for some materials the rainfall rate appears to be very influential on detection distances, while other materials appear to maintain the same performance level, regardless of rainfall intensity. These observations are explored more thoroughly in subsequent analyses.

ANALYSIS OF BEAD TYPE IN WATERBORNE PAINT

Samples 5 and 6 were both waterborne paint samples with the only difference being the bead size. Sample 5 included Type III beads and sample 6 used Type II beads. A test between these samples was performed to determine if bead size added to the wet-night visibility of waterborne paints used by some of TxDOT's maintenance crews.

An ANOVA test showed that there was a statistically significant difference between each sample ($p=0.048$) and each flow rate ($p=0.005$), but not the interaction of the sample and flow rate ($p=0.468$). The paint with the Type III beads had average detection distances of 192, 166, and 170 ft for the low, medium, and high rainfall intensities, respectively. The paint with the Type II beads had average detection distances of 185, 152, and 138 ft for the low, medium, and high rainfall intensities, respectively. These results indicate that the large beads provide greater wet-night detection distances than standard beads, especially during the heavier rainfalls. Both bead types tend to lose performance when going from low to medium (or average) rainfall rates, but the bigger beads tend to maintain their performance at the average rainfall rate and higher while the Type II beads continue to lose their performance with rainfall rates greater than average. The main effect variables are illustrated in Figure 42.

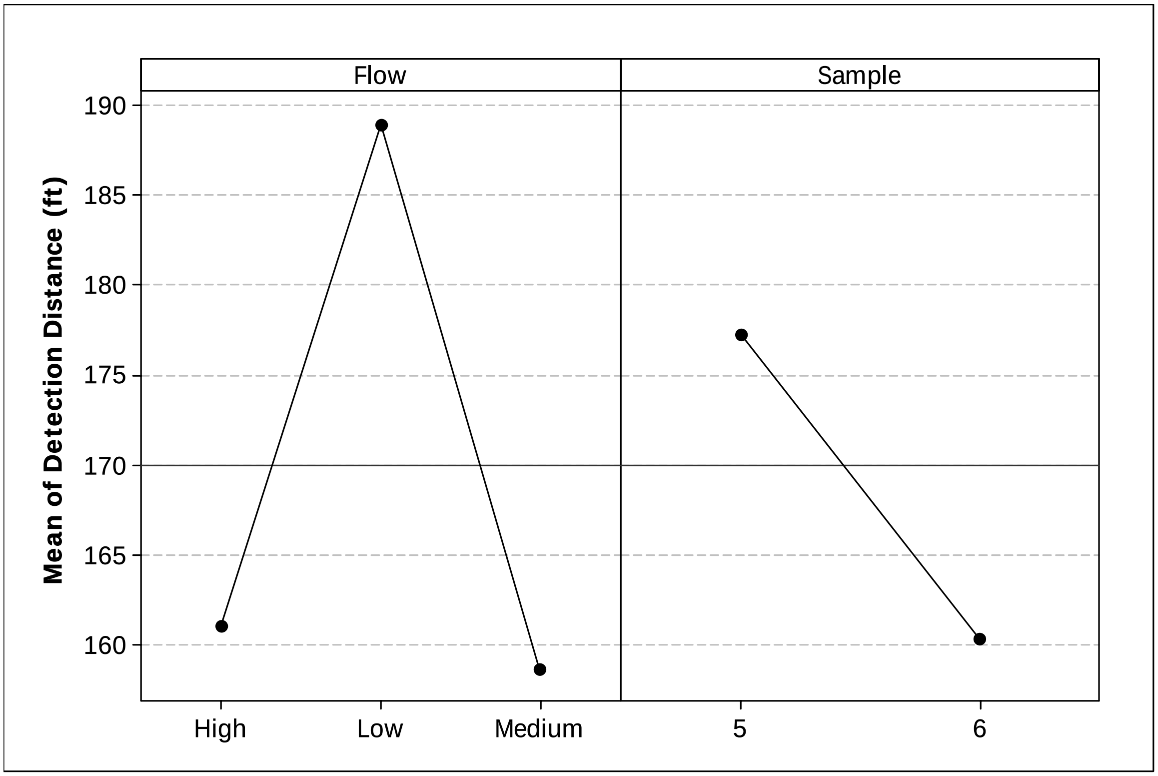

Figure 42. Main Effect Variables for Waterborne Paints.

ANALYSIS OF BEAD TYPE IN THERMOPLASTIC

Samples 11, 32, and 34 were used to compare how different bead sizes and mixtures impacted detection distances under wet-night conditions. Sample 11 included a mixture of beads using a double drop system. One part was Type III beads and the other part was Type I beads mixed with high refractive index beads. Sample 32 used Type III beads. Sample 34 used Type II beads. Sample 34 can be considered the default pavement marking system used in TxDOT. The majority of TxDOT's highways used this exact system—spray thermoplastic at 90 mil with Type II beads.

An analysis of variance test showed that there was a statistically significant difference between each sample (p=0.000) and each flow rate (p=0.006), but not the interaction between the sample and flow rate (p=0.089). The thermoplastic with the double drop beads had average detection distances of 215, 213, and 228 ft for the low, medium, and high rainfall intensities, respectively. The thermoplastic with the Type III beads had average detection distances of 229, 196, and 191 ft for the low, medium, and high rainfall intensities, respectively. The thermoplastic with the Type II beads had average detection distances of 189, 145, and 142 ft for the low, medium, and high rainfall intensities, respectively.

The main effect variables are illustrated in Figure 43, while the interactions are illustrated in Figure 44. Sample 34 was thermoplastic with Type II beads. It performed almost the same as sample 6, which was waterborne with Type II beads. Sample 32 was thermoplastic with Type III beads. While it had slightly longer detection distances at each rainfall rate, it performed the same as sample 5 which was waterborne with Type III beads. Just as before, these samples (34 and 32) lost considerable performance when the rainfall rate increased from a light rain to an average rain. However, they appeared to maintain their performance thereafter (see Figure 44). Even the thermoplastic sample with Type II beads followed this trend, which was not the case with the waterborne Type II sample. Perhaps the height of the thermoplastic helps with this aspect.

Sample 11 included the double drop beads. On average, it outperformed sample 32 (with just big beads) by 20 ft. It appears that the most significant benefit of using sample 11 over sample 32 is that its performance was consistent across the three rainfall rates. Up to this point, each material examined had a drop-off in performance when the rainfall was increased from a light rain to an average rain. Sample 11 maintained its initial performance all the way up through the heavy rainfall rate.

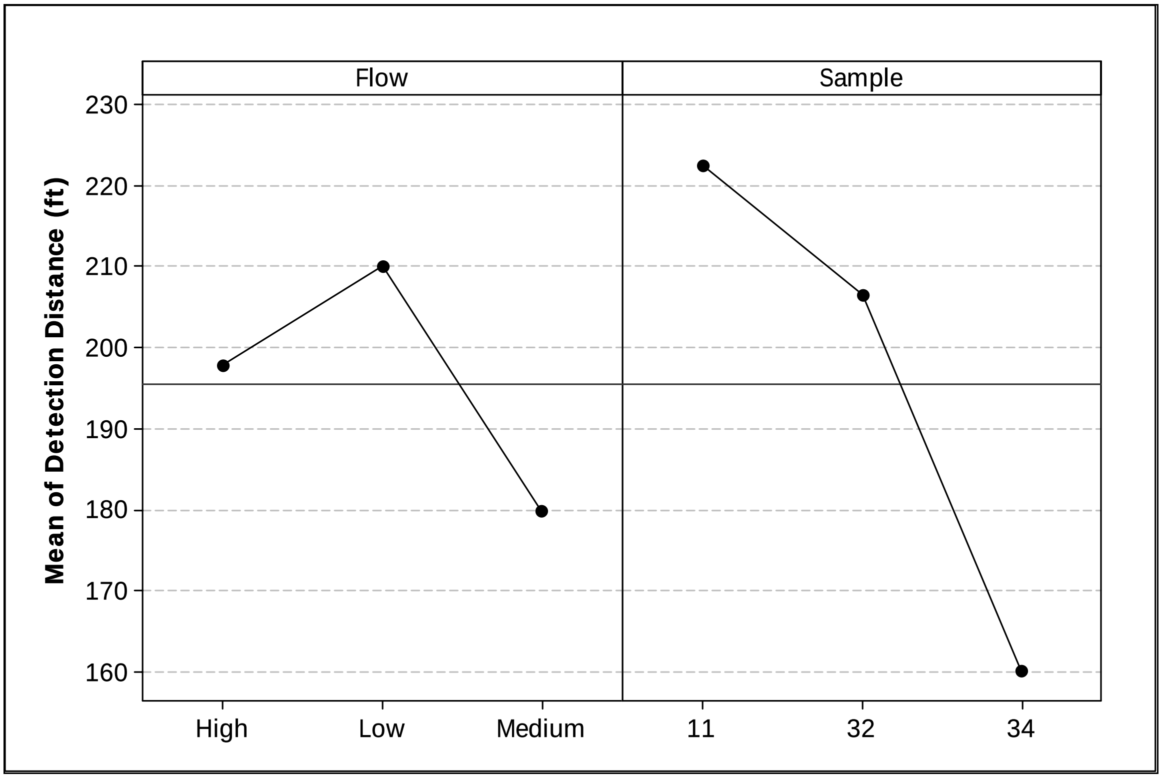

Figure 43. Main Effect Variables for Thermoplastic.

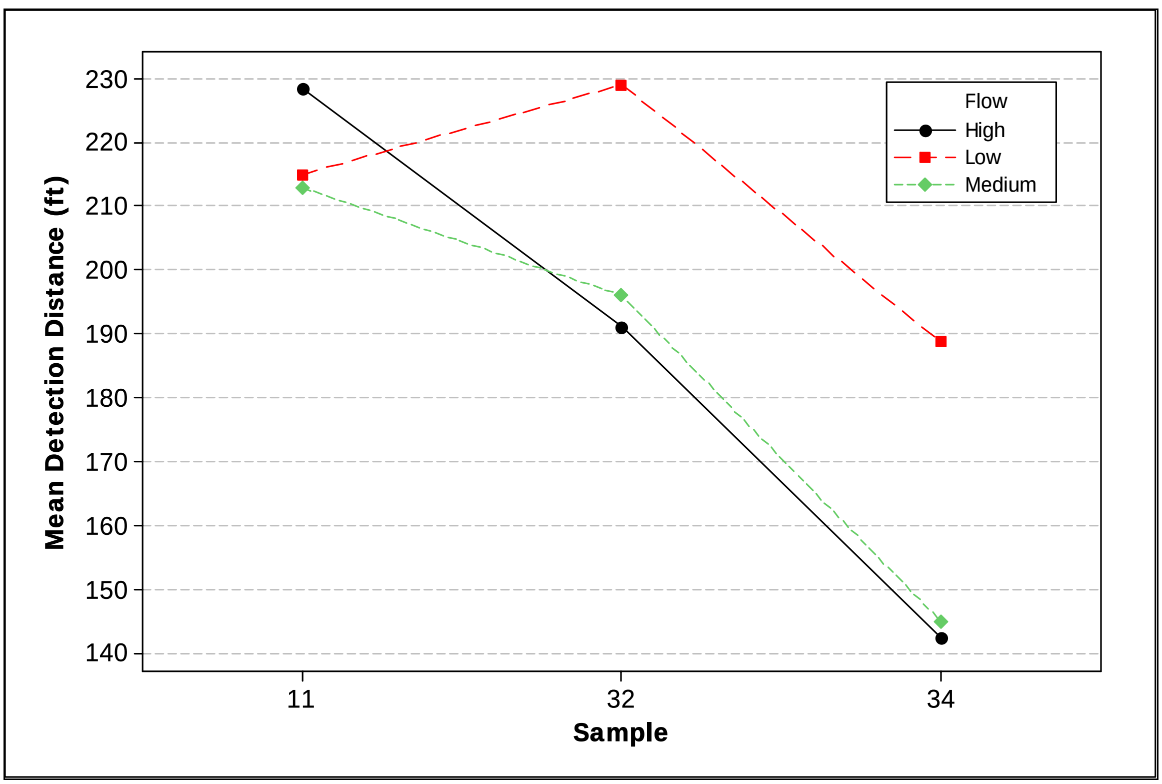

Figure 44. Interaction between Sample and Rainfall Rate for Thermoplastic.

ANALYSIS OF TAPE PRODUCTS

Four tape products were included in this project. Sample 15 was 3M's 380 series tape. Sample 16 was 3M's series 750 tape. Sample 17 was 3M's new 380WR (wet reflective) series tape. And finally, sample 18 was Advanced Traffic Marking's 400 series tape.

An analysis of variance test showed that there was a statistically significant difference between each sample (p=0.000) and each flow rate (p=0.000) and this time including the interaction between the sample and flow rate (p=0.004). The standard 3M 380 tape had average detection distances of 172, 199, and 195 ft for the low, medium, and high rainfall intensities, respectively. The 3M 750 tape (also called enclosed lens tape) had average detection distances of 421, 279, and 316 ft for the low, medium, and high rainfall intensities, respectively. The wet reflective 3M 380WR tape had average detection distances of 259, 227, and 222 ft for the low, medium, and high rainfall intensities, respectively. The ATM 400 tape had average detection distances of 240, 171, and 187 ft for the low, medium, and high rainfall intensities, respectively.

Figure 45 and Figure 46 show the main effect and interactions of this analysis. Besides the RRPMs, sample 16 provided the longest detection distances under all three rainfall levels. Much like many of the previously analyzed marking systems, most of the tapes lose a fair amount of performance when the rainfall rate is increased from low to medium. Interestingly, however, sample 15 did not.

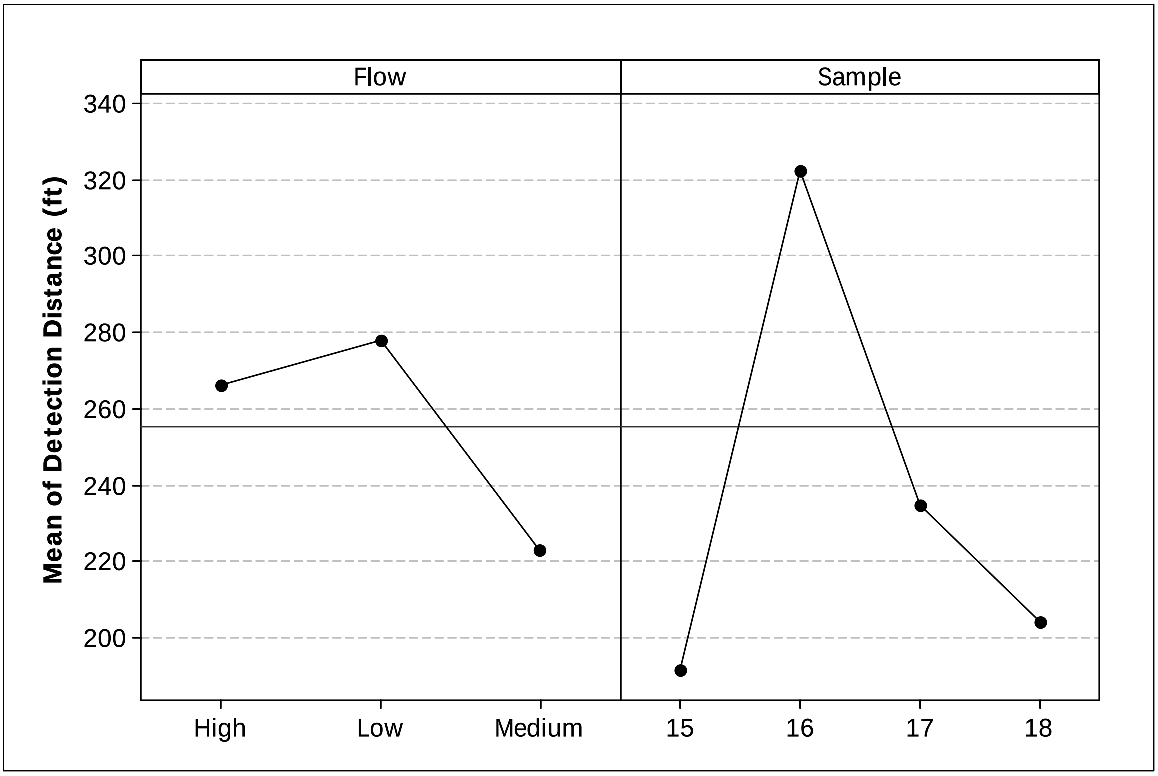

Figure 45. Main Effect Variables for Tapes.

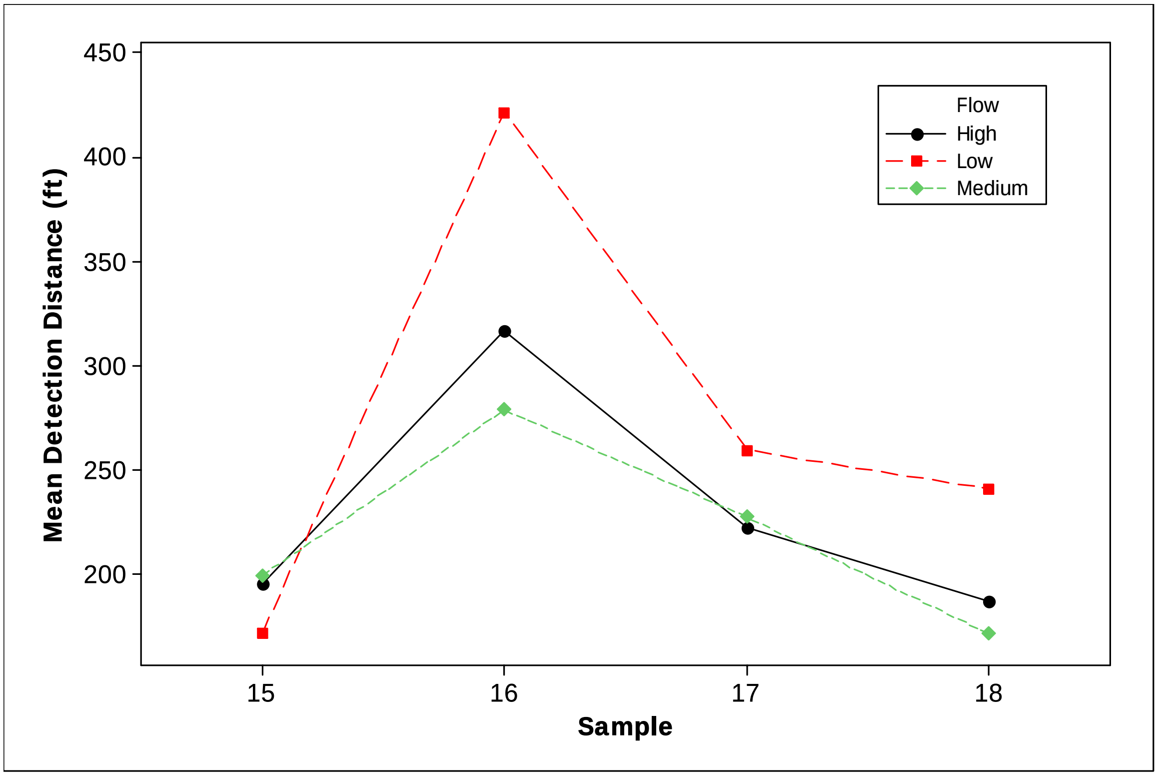

Figure 46. Interaction between Sample and Rainfall Rate for Tapes.

ANALYSIS OF EXOTIC PRODUCTS

TxDOT is primarily a thermoplastic state with some tape and some paint. However, many districts are experimenting with other pavement marking systems. The researchers wanted to include all of them, but the constraints of the project meant that there had to be a limit to what could be included. One possibility is that a second project be commissioned to follow this project. The next project could include more pavement marking systems.

In this research project, four samples were classified as exotic. Sample 8 was polyurea with bead clusters, sample 9 was epoxy with 100 percent Visionglow beads, sample 10 was epoxy with 25 percent Visionglow beads and 75 percent Type III beads (Visibead plus 2), and sample 31 was yellow splattered methyl methacrylate (MMA) with Type III beads. These four exotic products were not the primary focus of the project, so they could not be presented to the subjects as often as the paints, tapes, and thermoplastics. Therefore, the limited data in some circumstances prevent an ANOVA test. The detection distances for sample 8, which was the polyurea with bead clusters, were 224, 240, and 174 ft for the low, medium, and high rainfall rates, respectively. Sample 9, the epoxy with 100 percent Visionglow beads, proved to be ineffective during pilot testing, so it was only presented during the low rainfall rate and only 11 times during the entire experiment. On average, the detection was the lowest of all marking systems included in this project (135 ft). Sample 10, which also included the Visionglow beads but in a mix with 75 percent Type III beads, performed much better. During the low rainfall rates, the average detection distance was 213 ft, for the medium rainfall rate it was 220 ft, and for the high rainfall rate it was 178 ft. The detection distances for sample 31, which was the yellow splattered MMA with Type III beads, were 218 and 188 ft for the medium and high rainfall rates, respectively.

Unfortunately, the researchers were not able to obtain white splattered MMA for the evaluation. However, three combinations of white and yellow tape were used in the project. This was done in order to develop a white-to-yellow relationship that could be applied to the yellow MMA to predict the visibility distances if it had been white. The analyses between the yellow and white tapes included white samples 15, 16, and 18, and their yellow counterparts, samples 21, 22, and 25. The detection distances for the white samples were on the order of 21 (11 percent) to 30 ft (15 percent) farther than the yellow samples for the medium and high rainfall rates. Therefore, if sample 31 had been white MMA instead of yellow MMA, the detection distances would have been longer. It is reasonable to expect that the detection distances of white splattered MMA with Type III beads would have been about 242 and 216 ft for the medium and high rainfall rates, respectively.

ANALYSIS OF RUMBLE STRIPES

Rumble stripes are created when traditional pavement markings are applied over rumble strips. Research project 0-4472, which was completed last year, included the first testing of rumble stripes in the state. Several other states, Michigan, Mississippi, and Pennsylvania, have begun using more and more rumble stripes. They claim, among other advantages, that the wet-night visibility is increased. Even though retroreflectivity measurements can be made on rumble stripes, there is some disagreement among experts in the retroreflectivity arena as to whether the measurements made with handheld or mobile retroreflectivity devices give adequate or even reasonable results. To date, there has been no field evaluation of rumble stripes that could be used to fairly assess the claim that they provide enhanced wet-night visibility over traditional pavement markings. Therefore, the researchers tested the wet-night visibility of rumble stripes by modifying the substrate panels for sample 35.

Before the marking materials were applied to the substrate, the researchers cut lateral depressions into the substrate resembling rumble stripes at 24-inch centers. The rumble stripes were 0.25 inch deep. The researchers then placed sample 34 (which had no modifications) and sample 35 (which included the rumble strips) in front of a striping crew that sprayed the ubiquitous combination of thermoplastic and Type II beads on the panels. Each panel had the exact same material, beads, and bead rate. This eliminated many possible biases and allowed for a direct comparison between the samples.

An analysis of variance test showed that there was a statistically significant difference between each sample ($p=0.010$) and each flow rate ($p=0.010$) and the interaction between the sample and flow rate ($p=0.001$). The flat line thermoplastic with Type II beads had average detection distances of 189, 145, and 142 ft for the low, medium, and high rainfall intensities, respectively. Recalling from earlier, these detection distances are nearly identical to sample 6, which used a waterborne paint with Type II beads. Sample 35 was the rumble stripe made with thermoplastic and Type II beads. Sample 35 had average detection distances of 179, 200, and 160 ft for the low, medium, and high rainfall intensities, respectively.

Figure 47 and Figure 48 illustrate the relationships of the main effect variables and interaction of this analysis. The overall advantage of the rumble stripe versus the flat line is about 25 ft or 16 percent (Figure 47). The interaction between the samples and flow rates reveals more of the story. For the low rainfall rates, there is not a lot of difference between the flat line and the rumble stripe. However, when the rainfall reaches an average rate or greater, the impact of the rumble stripe becomes evident. For the medium or average rainfall rate, the impact of the rumble stripe increased the detection distance 55 ft, or 38 percent. For the heavy rainfall the impact was still impressive at 18 ft, or 13 percent. It is hard to predict what the results would have been for rumble stripes made with big beads, a bead mixture, or even some of the exotic materials that were tested in flat applications.

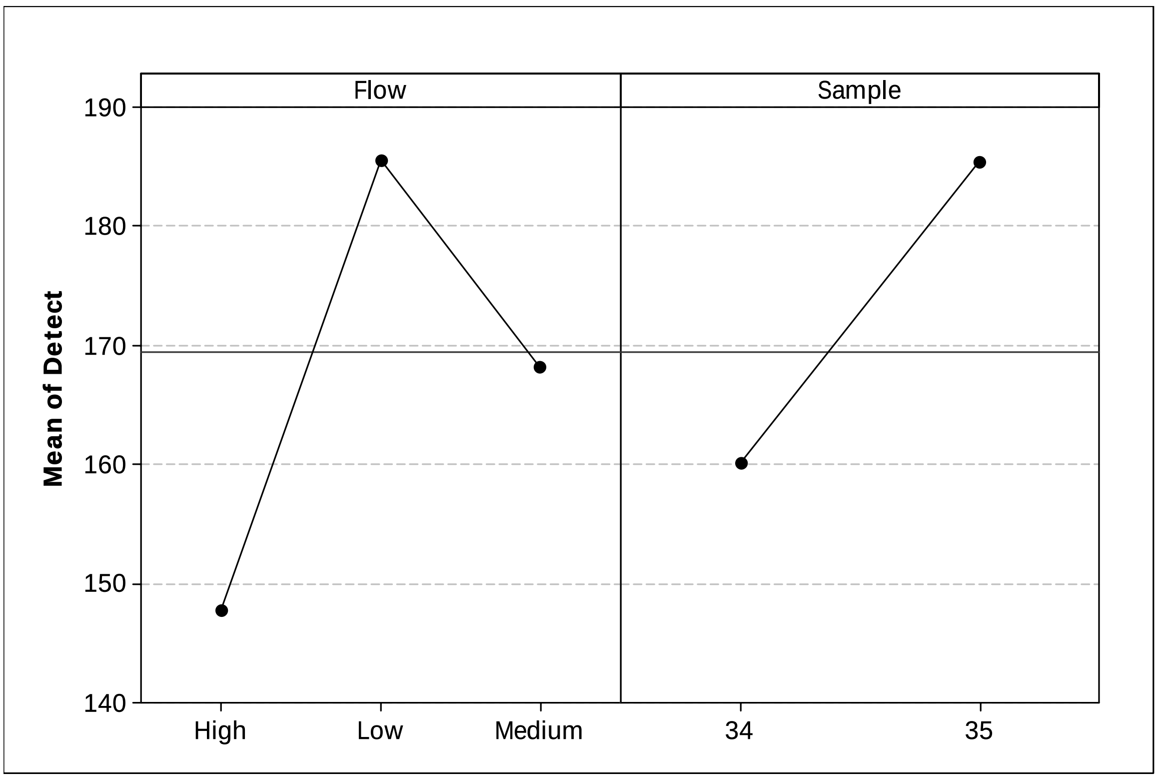

Figure 47. Main Effect Variables for Rumble Stripes.

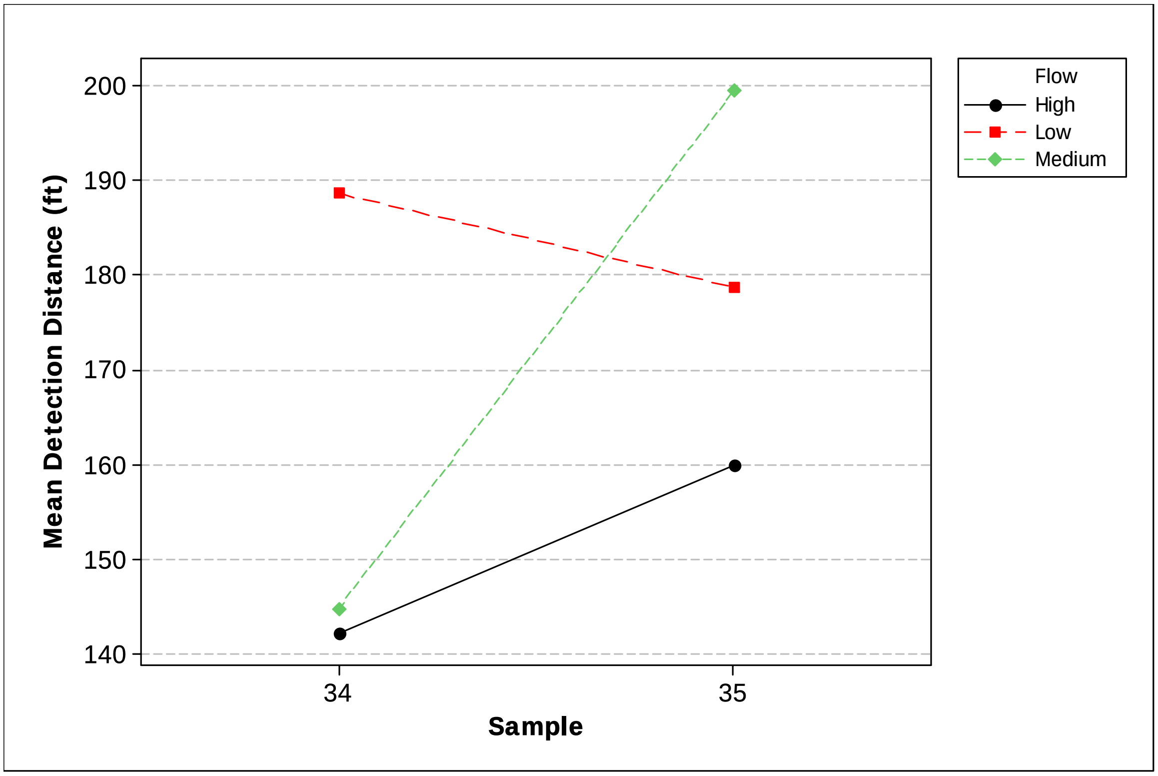

Figure 48. Interaction between Sample and Rainfall Rate for Rumble Stripes.

ANALYSIS OF WIDE LINES

Initially, the researchers had planned to comprehensively investigate the impacts of wide lines (6-inch widths) versus the standard width of 4 inches. However, adding the additional materials to the project scope meant that something had to be sacrificed. In this case, it was the investigation of wider lines. Only one sample with 6-inch markings was included in the analysis, sample 24. Sample 24 was 3M's new 380WR tape; sample 17 was the same product, but with 4-inch width, which allowed for a preliminary comparison of detection distance based on line width.

Because of the limited exposure of sample 24, the analysis is limited to a comparison of the mean detection distances when subjects were shown both samples 17 and 24. Using these controls for the analysis removes further analysis of the low rainfall condition. The remaining data were merged into one subset for subsequent analysis. Overall, the mean detection distances associated with the 6-inch-wide line were 294 ft versus 226 ft for the 4-inch-wide line. In other words, for the conditions examined herein, the additional 2 inches of pavement marking width provided about a 30 percent increase in mean detection distance during wet-night conditions.

There were not enough data to break down the analysis by driver age, although many claim that wider lines are particularly beneficial for older drivers. It should be noted that this analysis included a material that performed rather well in comparison to all the materials tested in this project. It would be useful and interesting to repeat this part of the analysis with materials that do not have such inherent wet-night performance characteristics.

ANALYSIS OF DRY AND WET RETROREFLECTIVITY MEASUREMENTS

Each test sample was measured five times using ASTM procedures for dry (E1710), wet recovery (E2177), and wet continuous (E2176) conditions. The average results of these measurements are shown in Table 21. These measurements were used to investigate the relationship between dry retroreflectivity measurements and both versions of wet retroreflectivity measurements. The intent of this investigation is to explore whether dry retroreflectivity measurements can be used to predict or estimate wet retroreflectivity performance of pavement markings. Figure 49 compares the dry measurements to both versions of the wet measurements and Figure 50 and Figure 51 were generated to compare the relationship between the wet measurements.

Table 21. Retroreflectivity Measurements (mcd/m^2/lux).

PANEL	DRY	RECOVERY	RAIN
5	364	150	72
6	288	35	13
8	1232	243	128
9	148	43	21
10	524	253	16
11	787	134	65
12	646	439	56
15	746	232	75
16	1220	1240	1250
17	1234	975	564
18	937	509	150
21	401	71	34
22	844	737	666
23	1229	150	84
25	596	243	120
31	334	113	62
32	972	282	46
33	510	283	25
34	524	96	22
35	503	185	57

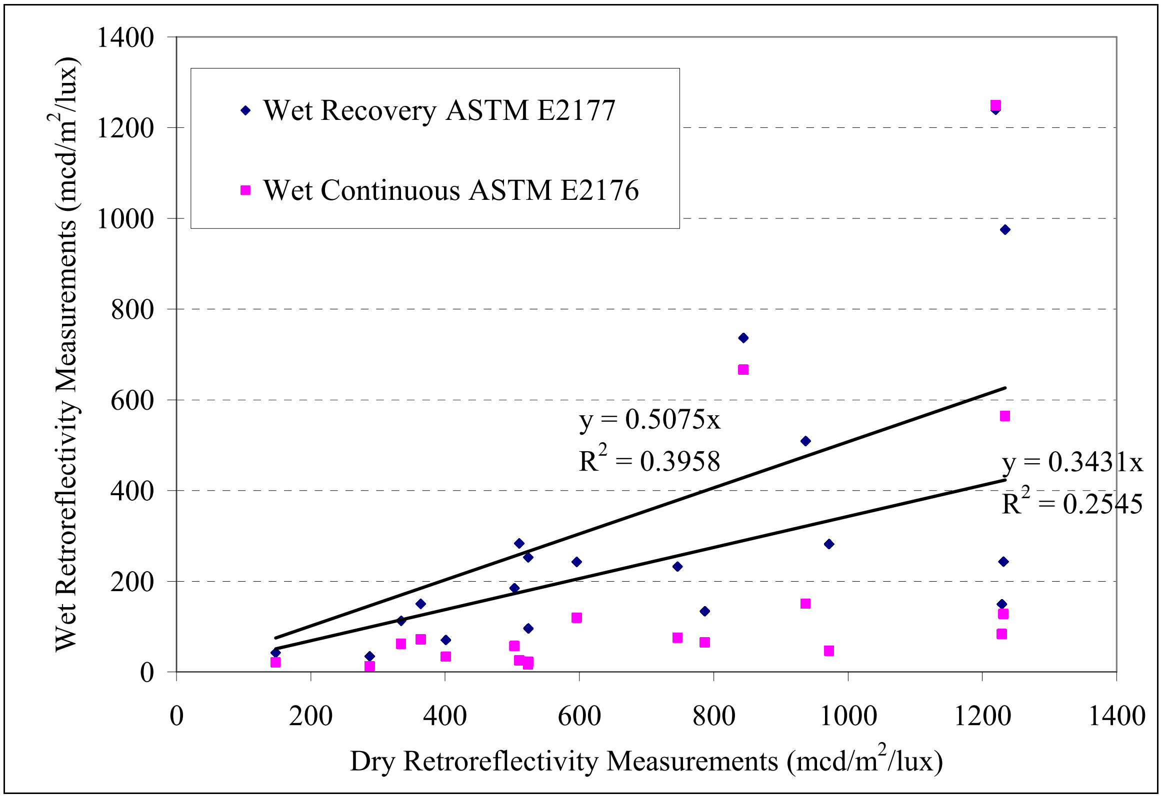

Figure 49. Comparison of Dry and Wet Retroreflectivity Measurements.

The data shown in Figure 49 support the general belief that dry retroreflectivity measurements cannot be used to judge the performance of pavement markings when wet, assuming that wet retroreflectivity measurements correlate to wet performance. These results illustrate that there is essentially no relationship between dry and wet retroreflectivity measurements for most pavement marking materials other than dry measurements are always higher than wet measurements.

There are two versions of wet retroreflectivity measurements—one that is based on continuous wetting and another that is based on the recovery of a marking after the wetting stops. Figure 50 and Figure 51 illustrate the relationship between these wet retroreflectivity measurements.

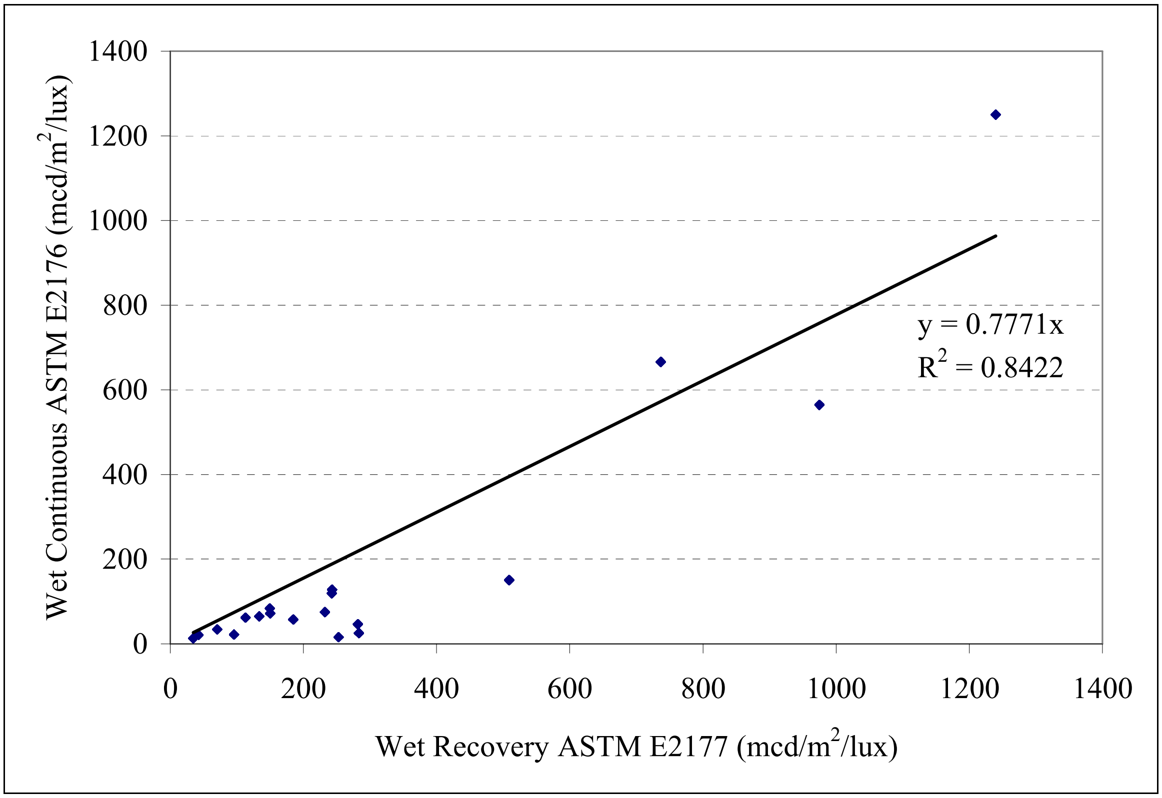

Figure 50. Comparison of Wet Retroreflectivity Measurements.

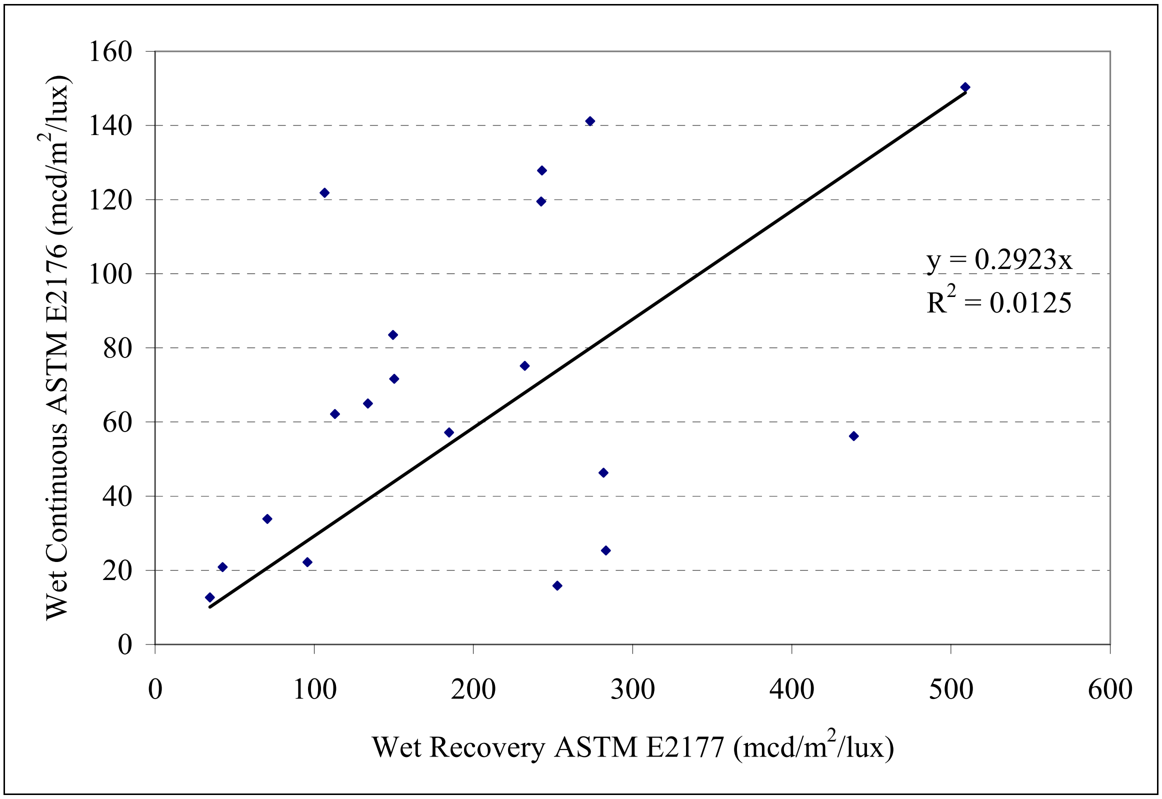

Figure 51. Comparison of Truncated Wet Retroreflectivity Measurements.

Figure 50 includes all the materials investigated in this project. However, the three data points with high retroreflectivity levels are over-representing in the relationship. Therefore, Figure 51 was generated without those three data points. These results illustrate that there is essentially no relationship between the two varieties of ASTM wet measurements.

ANALYSIS OF PERFORMANCE PREDICTIVE POWER OF DRY AND WET RETROREFLECTIVITY MEASUREMENTS

Although there are established ASTM procedures for measuring the retroreflectivity of pavement markings under dry and two wet conditions, it is fair to say that the retroreflectivity measurements resulting from carefully followed ASTM procedures, especially the wet methods, produce results that are not always in agreement with subjective evaluations of the markings' visibility. Therefore, the detection distances and retroreflectivity measurements were analyzed to determine how well the results of the ASTM methods correlated to the detection distances obtained during this project. The statistical test that was used for this analysis produced a number referred to as the Pearson correlation coefficient, or r. The Pearson correlation coefficient is always between 1 and -1. Positive r indicates positive association between the variables of interest, while a negative r indicates negative association. Values closer to the extremes (1 or -1), or farther from zero, imply strong linear relationships.

The Pearson correlation coefficients are shown below for the straight retroreflectivity measurement and the log retroreflectivity measurements. The log of the retroreflectivity measurements was used to transform the data because the human psychophysical response to light is approximated with a log-based relationship. Figure 52 through Figure 55 summarize the findings.

The Pearson coefficients for retroreflectivity measurements support the previous section with one possible exception, which can be explained. It would appear the retroreflectivity readings produced by following the ASTM rain and ASTM recovery show a high degree of association ($r = 0.945$). However, as shown in Figure 50, the relationship is influenced quite heavily by three data points. After removing the three overly influential data points, the associated drops to $r = 0.112$.

	Detect	ASTMdry	ASTMrec
ASTMdry	0.428		
ASTMrec	0.595	0.641	
ASTMrain	0.619	0.558	0.945
Log Retroreflectivity			
	Detect	LASTMdry	LASTMrec
LASTMdry	0.432		
LASTMrec	0.550	0.739	
LASTMrain	0.588	0.702	0.878

Figure 52. Retroreflectivity Correlations for All Flow Rates.

	Detect	ASTMdry	ASTMrec
ASTMdry	0.469		
ASTMrec	0.633	0.626	
ASTMrain	0.687	0.520	0.921
Log Retroreflectivity			
	Detect	LASTMdry	LASTMrec
LASTMdry	0.454		
LASTMrec	0.524	0.745	
LASTMrain	0.601	0.692	0.852

Figure 53. Retroreflectivity Correlations for Low Flow Rates.

	Detect	ASTMdry	ASTMrec
ASTMdry	0.366		
ASTMrec	0.558	0.630	
ASTMrain	0.572	0.540	0.942
Log Retroreflectivity			
	Detect	LASTMdry	LASTMrec
LASTMdry	0.389		
LASTMrec	0.555	0.750	
LASTMrain	0.570	0.707	0.876

Figure 54. Retroreflectivity Correlations for Medium Flow Rates.

	Detect	ASTMdry	ASTMrec
ASTMdry	0.471		
ASTMrec	0.643	0.660	
ASTMrain	0.679	0.596	0.958
Log Retroreflectivity			
	Detect	LASTMdry	LASTMrec
LASTMdry	0.479		
LASTMrec	0.595	0.720	
LASTMrain	0.644	0.703	0.897

Figure 55. Retroreflectivity Correlations for High Flow Rates.

SUMMARY OF DETECTION DISTANCES

This chapter has included a number of analyses classified into different groupings to help with the structure of the chapter and provide useful information in terms of wet-night visibility of products within certain groups. One final graphic was generated to illustrate the wet-night detection distances of the primary markings used in this project (see Figure 56).

Figure 56 does not include the detection distances for RRPMs. For the low, medium, and high rainfall rates, their detection distances were 508 ft, 560 ft, and 669 ft, respectively. Including these data would have decreased the resolution of the y-axis, making it difficult to observe small differences in some materials or by rainfall rates.

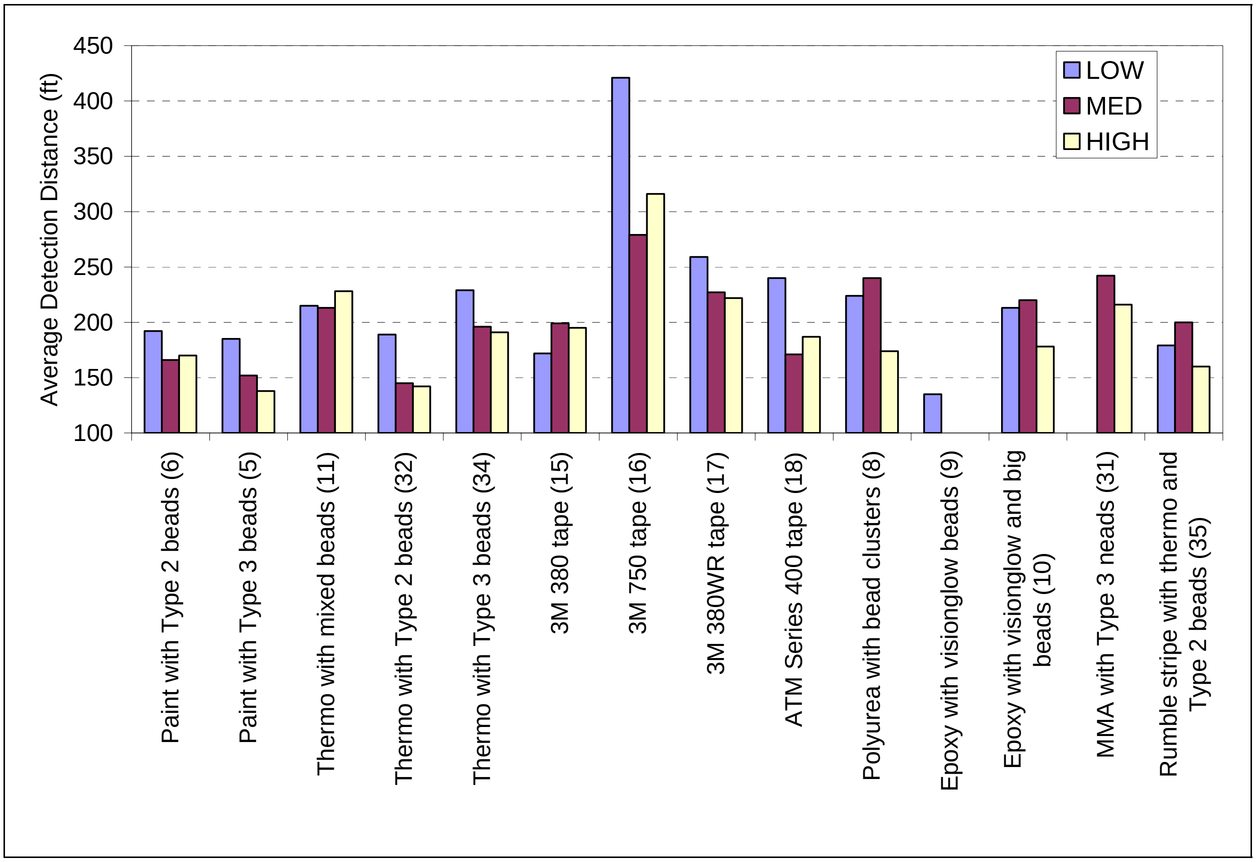

Figure 56. Detection Distances for all Marking Materials by Rainfall Rate.

CHAPTER 6:
FINDINGS AND PLANNED YEAR TWO ACTIVITIES

PRELIMINARY CONCLUSIONS

The objective of this research was to determine the wet-night visibility distance of various pavement markings under realistic rainfall intensities. This report documents the efforts undertaken to satisfy the objective. The previous chapter presented the analyses of the detection distance data that were obtained. From those data analyses, the following conclusions can be made.

- There were no statistical differences in detection distances among subject age or gender. However, the better a subject's visual acuity, the longer the detection distances were. This association was statistically significant.
- RRPMs have the longest wet-night detection distance of any other marking tested. The average detection distance of the RRPMs was over 550 ft, which was over 200 ft longer than the longest average detection distance for any of the other markings tested.
- 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.
- For thermoplastic markings, the 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.
- 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.
- 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.

- The potential of increasing the wet-night visibility of pavement marking by using rumble stripes was also tested. The test involved a direct comparison of a flat thermoplastic line with Type II beads and a rumble stripe line with Type II beads. For the low rainfall rates there was not much of a difference, but for the medium and high rainfall rates the mean detection distance of the rumble stripe was 38 to 13 percent greater than the conventional flat line.
- 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.
- An analysis of the retroreflectivity measurements shows that the wet retroreflectivity measurements cannot be predicted based on the dry retroreflectivity measurements. Further investigation into the two types of wet retroreflectivity measurements shows that they are not necessarily correlated, either.
- The predictive power of dry and wet retroreflectivity measurements was tested using the detection distances as the metric. Unfortunately, the predictive power of the retroreflectivity measurements is only moderate in terms of providing an indication of how well the marking will be seen under wet-night conditions. For all levels of rainfall, the retroreflectivity readings associated with the ASTM E2176 specification provided the strongest association with detection distances ($r = 0.619$). A log transformation of the retroreflectivity data did not improve the relationship. Further investigations by rainfall levels provided similar results.

PRELIMINARY RECOMMENDATIONS

Based on these preliminary conclusions, the researchers recommend the following actions.

- TxDOT should commission a follow-up project to further investigate the wet-night performance of pavement markings. One of two approaches is proposed. The first is more involved than the second but may provide even more realistic data than currently exists. This first recommendation for a continued effort includes adding rain to the east side of the road and modifying the experiment so that the subject drives down the middle of the road and identifies when a single long continuous line begins to curve left or right. The alternative recommendation for a continued effort would be to repeat the first project but with more emphasis on wide lines, big beads, and more exotic pavement marking systems. This alternative approach could be performed much quicker and without a large increase in funds.

- In their waterborne paint applications, TxDOT should consider using Type III beads for added wet-night detection distances.
- In their thermoplastic specification, TxDOT should begin to phase out Type II beads for mixed beads including high refractive index big beads. Alternatively, a switch to Type III beads would also be beneficial in terms of added wet-night visibility.
- For tape products, the wet-night performance was strong among many of the tested products. Warranty terms and costs need to be emphasized in future decisions.
- Some of the exotic materials demonstrated impressive wet-night detection distances. TxDOT should continue to experiment with new and innovative markings as they become available. There are a number of other markings that can be considered exotic that need to be tested, too. Profiled markings and inverted profile markings are two that should be included in future efforts.
- Where possible, TxDOT should be using rumble striping. Some benefits such as better driver discipline in terms of lane keeping have been shown in earlier research such as TxDOT research project 0-4472. With the findings of this research, it is now clear that the touted enhanced wet-night visibility claims are indeed achievable.
- More research is needed to fully understand the benefits, but it appears that the use of a 6-inch-wide line over a 4-inch-wide line provides about a 30 percent increase in wet-night detection distances. This is as much of a detection distance gain as some of the exotic products of tapes produced (over the TxDOT standard pavement marking). The cost may be much lower compared to these other alternatives.
- More research is needed to fully understand the cost and durability associated with all pavement marking products studied herein.

PLANNED SECOND-YEAR ACTIVITIES

During the second year of the project the researchers will supplement the wet-night detection distance data with cost and durability data. If approved, the researchers will also conduct a second round of wet-night visibility data collection, incorporating one of the main themes described in the first bullet of the recommendations but also including a factor for glare lighting.

The researchers will also develop and implement research activities that can be used to develop application recommendations for contrast pavement marking materials based on visibility performance, durability, and cost.

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APPENDIX A

Table 22. Average Rate Means for Short Events (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10
# of Events	15,597	13,498	74,245	22,717	7908	24,995	23,656	8811	6827	603
Mean	0.47	0.40	0.41	0.45	0.46	0.40	0.29	0.17	0.50	0.50
Std. Dev.	0.23	0.26	0.31	0.34	0.24	0.33	0.30	0.31	0.34	0.38
Skewness	5.18	3.53	5.62	6.96	6.36	6.29	4.63	7.39	7.64	8.55
Minimum	0.40	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.40	0.40
Maximum	4.80	4.40	10.00	10.40	6.00	11.60	8.80	7.20	8.80	6.53

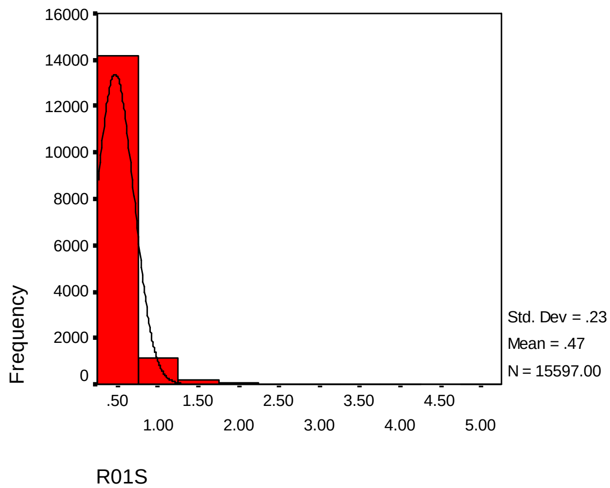


Figure 57. Average Rate Mean Histogram for Zone 1 Short Events.

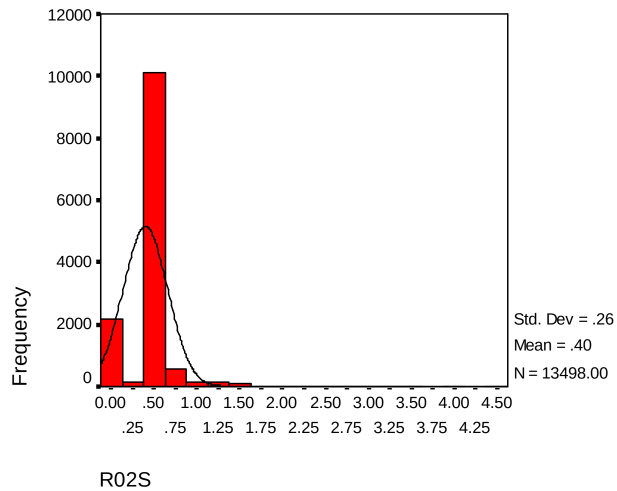


Figure 58. Average Rate Mean Histogram for Zone 2 Short Events.

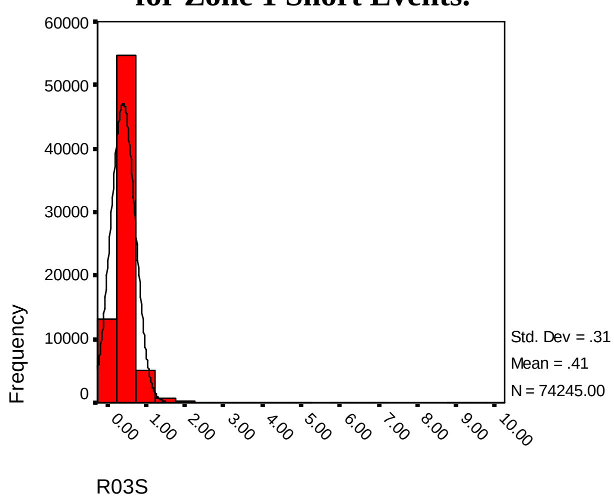


Figure 59. Average Rate Mean Histogram for Zone 3 Short Events.

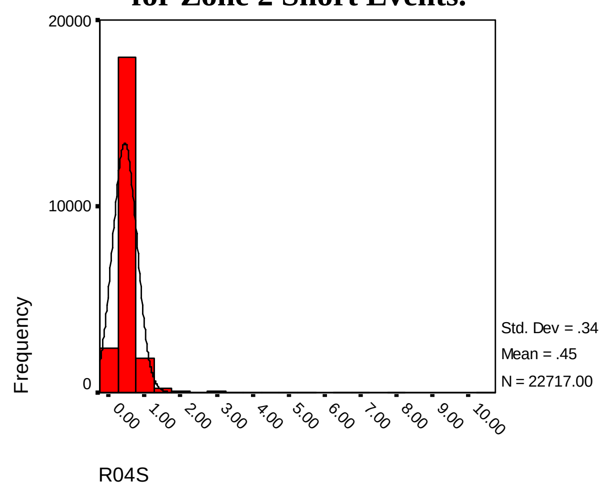


Figure 60. Average Rate Mean Histogram for Zone 4 Short Events.

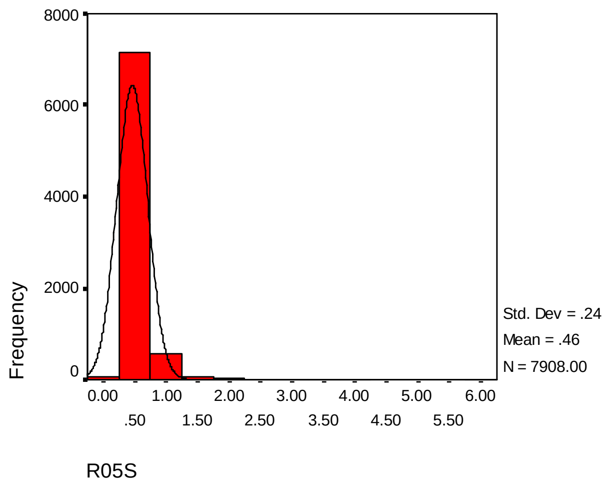


Figure 61. Average Rate Mean Histogram for Zone 5 Short Events.

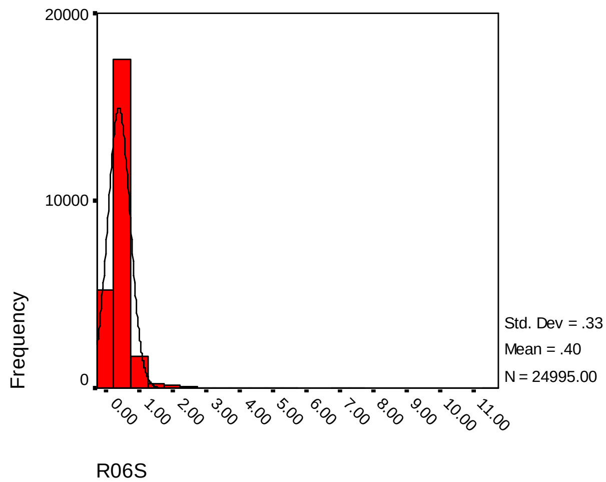


Figure 62. Average Rate Mean Histogram for Zone 6 Short Events.

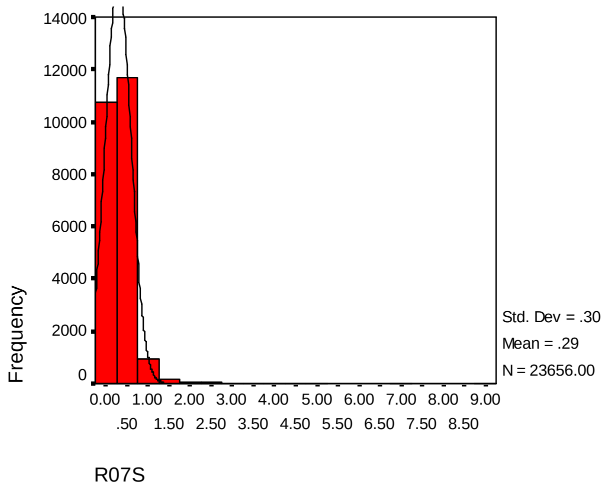


Figure 63. Average Rate Mean Histogram for Zone 7 Short Events.

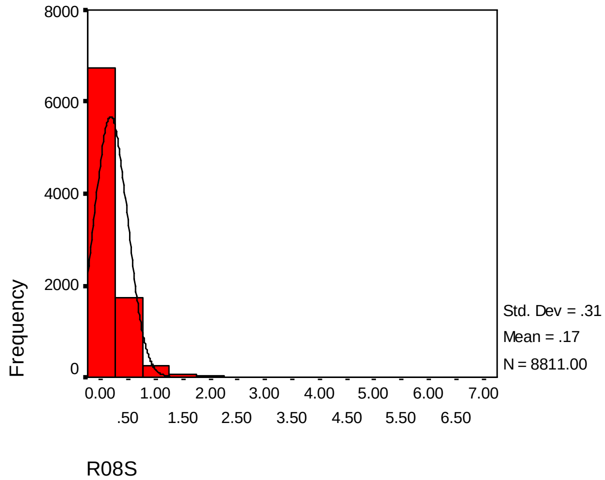


Figure 64. Average Rate Mean Histogram for Zone 8 Short Events.

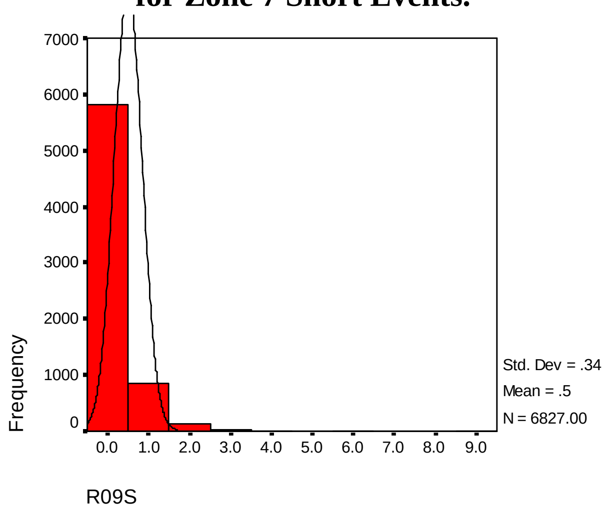


Figure 65. Average Rate Mean Histogram for Zone 9 Short Events.

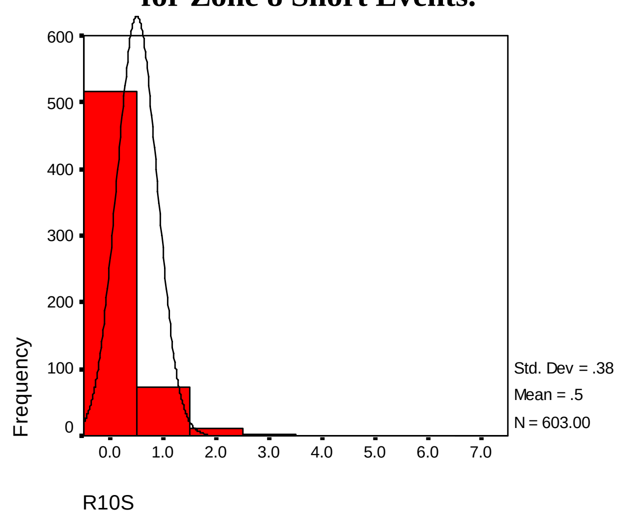


Figure 66. Average Rate Mean Histogram for Zone 10 Short Events.

Table 23. Average Rate Means for Medium Events (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10
# of Events	549	977	5215	1276	237	1788	2250	1141	379	36
Mean	0.77	0.51	0.56	0.63	0.84	0.54	0.39	0.26	0.97	1.00
Std. Dev.	0.39	0.43	0.45	0.43	0.51	0.48	0.42	0.32	0.51	0.47
Skewness	2.10	1.35	1.22	1.14	2.64	1.40	1.73	2.97	1.45	0.46
Minimum	0.40	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.40	0.40
Maximum	3.70	3.00	3.50	3.04	4.60	3.90	2.70	3.36	3.12	2.00

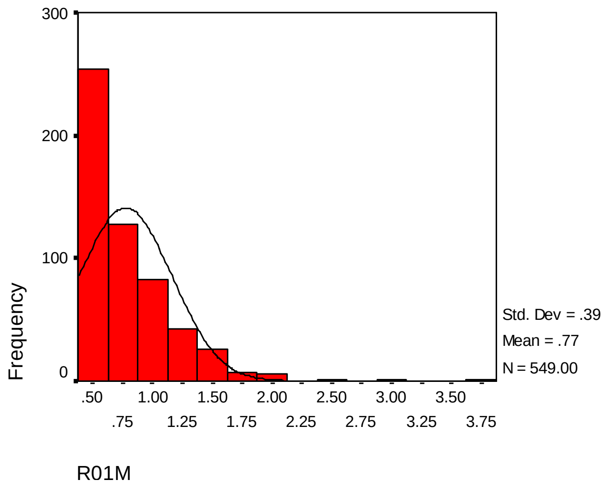


Figure 67. Average Rate Mean Histogram for Zone 1 Medium Events.

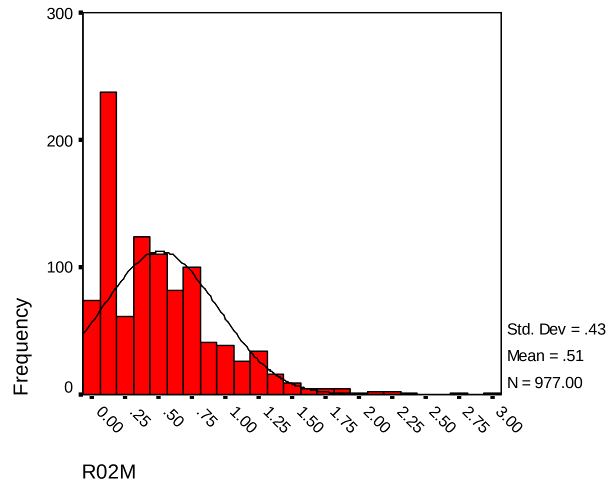


Figure 68. Average Rate Mean Histogram for Zone 2 Medium Events.

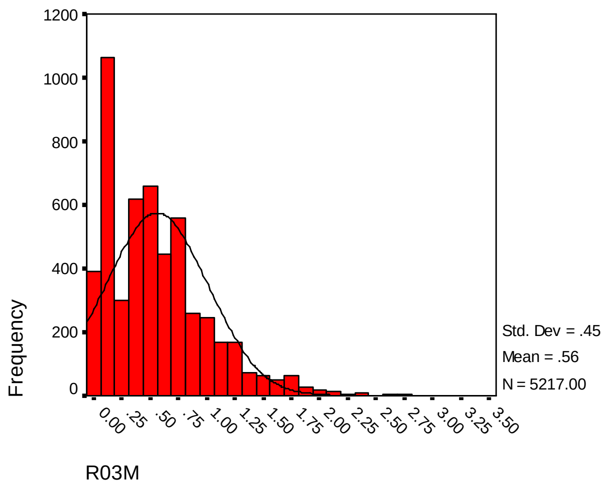


Figure 69. Average Rate Mean Histogram for Zone 3 Medium Events.

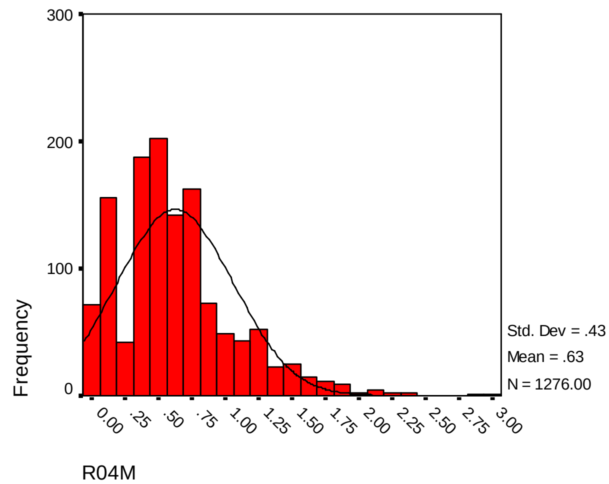


Figure 70. Average Rate Mean Histogram for Zone 4 Medium Events.

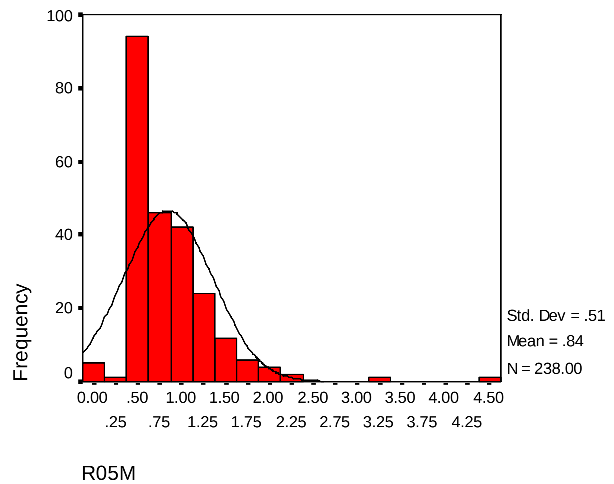


Figure 71. Average Rate Mean Histogram for Zone 5 Medium Events.

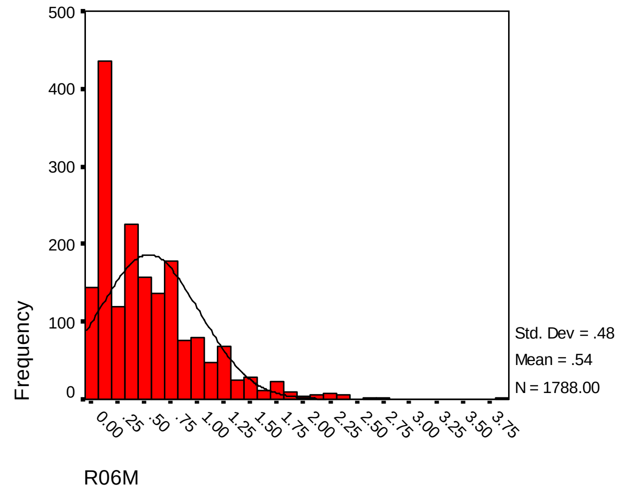


Figure 72. Average Rate Mean Histogram for Zone 6 Medium Events.

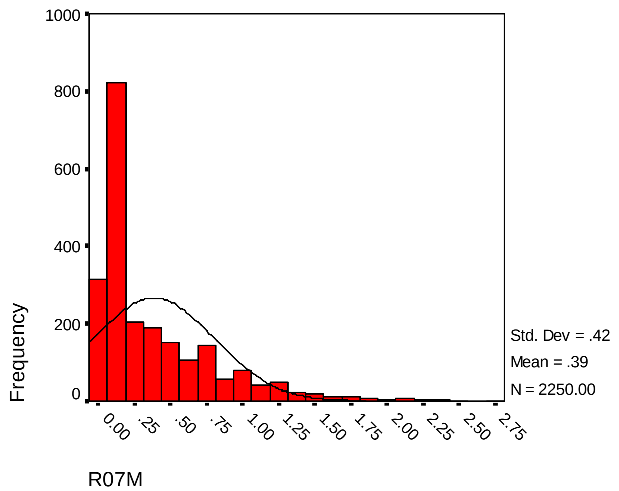


Figure 73. Average Rate Mean Histogram for Zone 7 Medium Events.

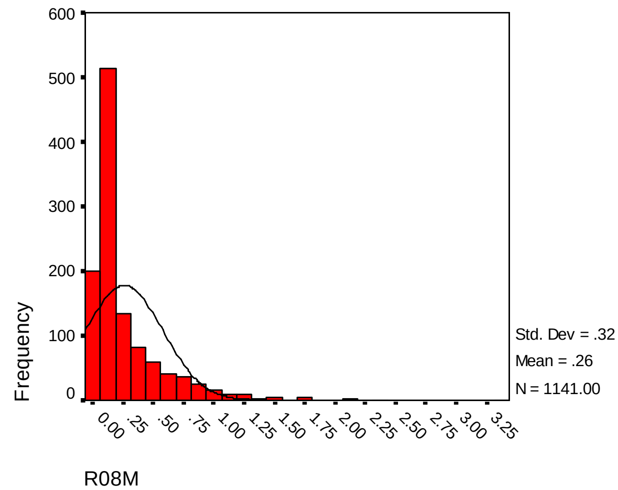


Figure 74. Average Rate Mean Histogram for Zone 8 Medium Events.

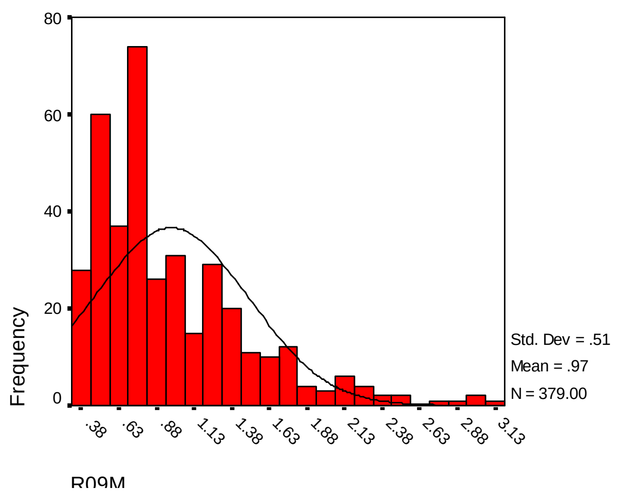


Figure 75. Average Rate Mean Histogram for Zone 9 Medium Events.

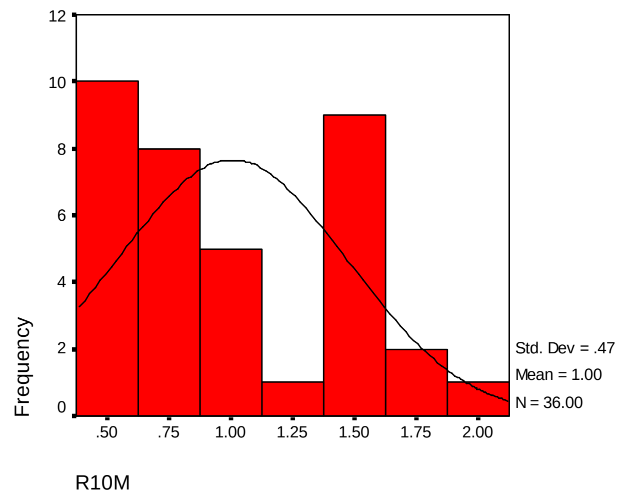


Figure 76. Average Rate Mean Histogram for Zone 10 Medium Events.

Table 24. Average Rate Means for Long Events (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10
# of Events	35	354	2024	391	16	722	1171	703	42	3
Mean	0.74	0.31	0.34	0.46	0.54	0.34	0.28	0.25	1.07	1.36
Std. Dev.	0.27	0.29	0.33	0.42	0.43	0.40	0.29	0.23	0.50	0.79
Skewness	0.48	2.71	2.12	1.68	0.86	2.68	2.73	2.94	1.74	-1.73
Minimum	0.40	0.04	0.04	0.04	0.08	0.04	0.04	0.04	0.43	0.44
Maximum	1.30	2.33	2.85	2.36	1.45	2.90	2.49	2.00	2.91	1.82

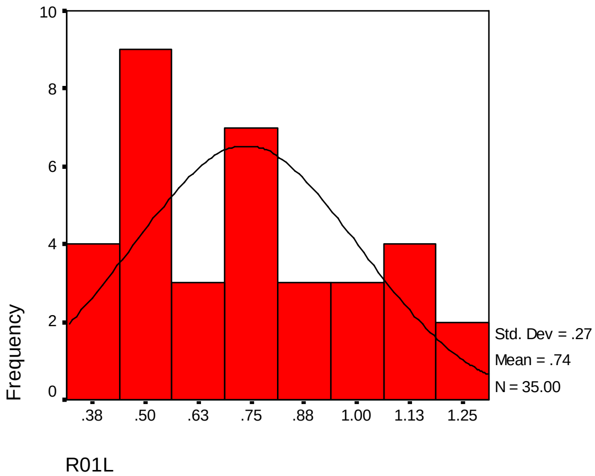


Figure 77. Average Rate Mean Histogram for Zone 1 Long Events.

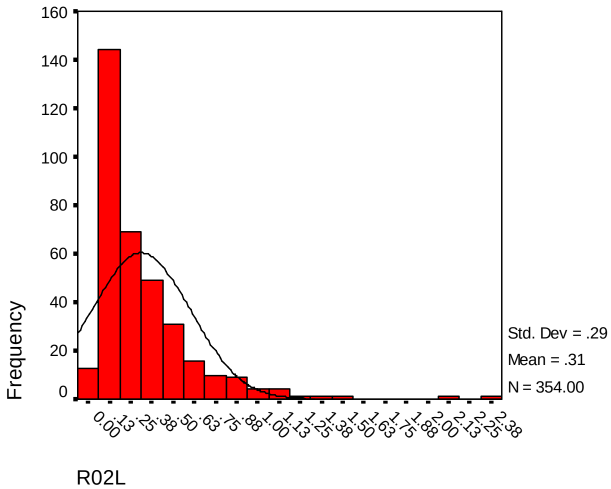


Figure 78. Average Rate Mean Histogram for Zone 2 Long Events.

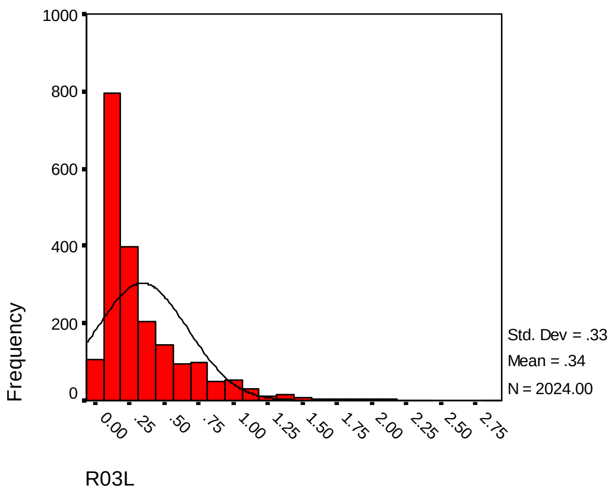


Figure 79. Average Rate Mean Histogram for Zone 3 Long Events.

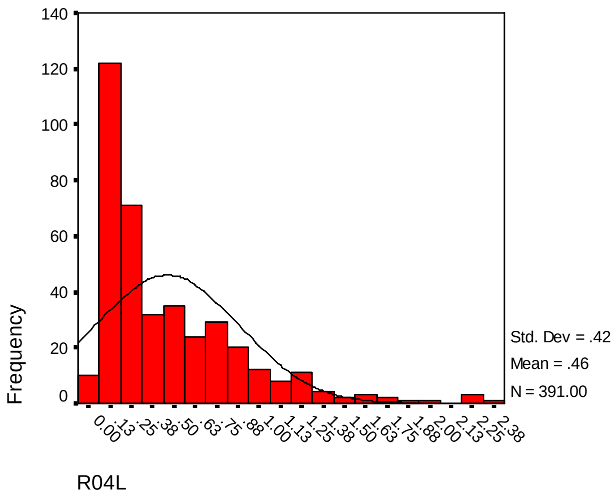
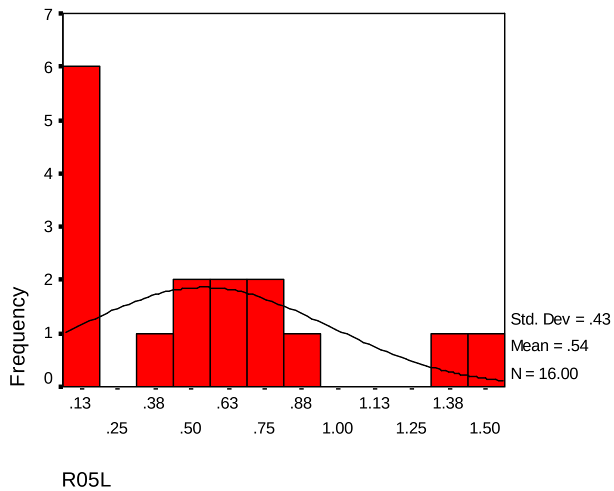


Figure 80. Average Rate Mean Histogram for Zone 4 Long Events.



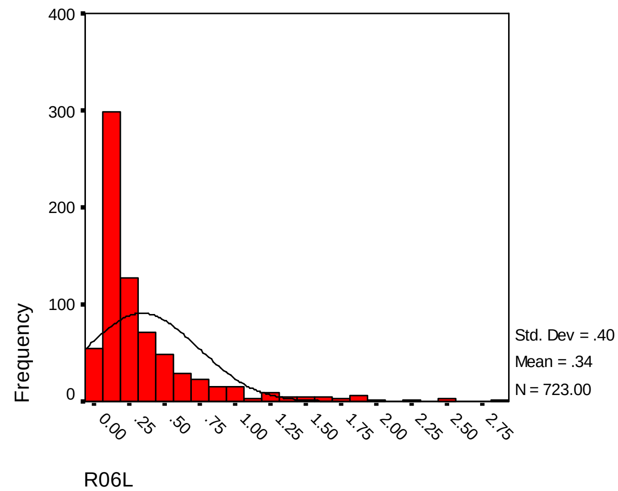
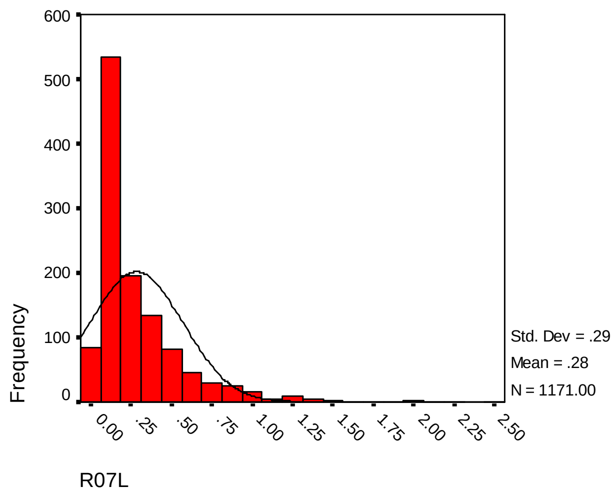


Figure 81. Average Rate Mean Histogram for Zone 5 Long Events.

Figure 82. Average Rate Mean Histogram for Zone 6 Long Events.



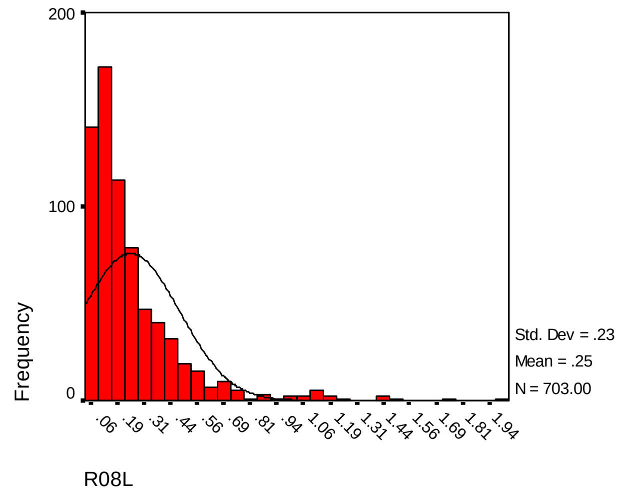
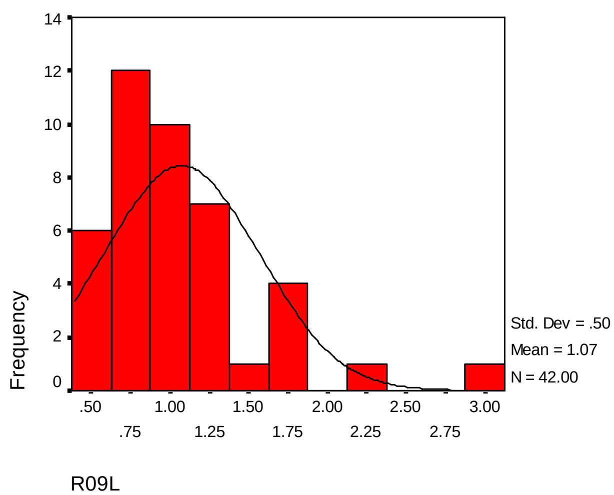


Figure 83. Average Rate Mean Histogram for Zone 7 Long Events.

Figure 84. Average Rate Mean Histogram for Zone 8 Long Events.



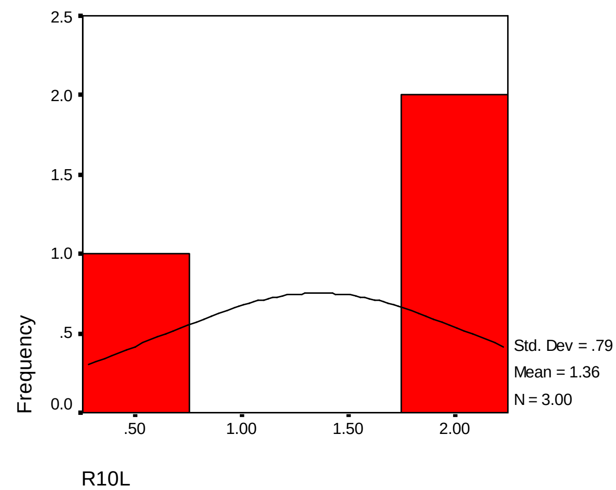


Figure 85. Average Rate Mean Histogram for Zone 9 Long Events.

Figure 86. Average Rate Mean Histogram for Zone 10 Long Events.

Table 25. Maximum Rate Means for Short Events (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10
# of Events	15,597	13,498	74,245	22,717	7908	24,995	23,656	8811	6827	603
Mean	0.51	0.43	0.44	0.48	0.49	0.43	0.31	0.20	0.54	0.56
Std. Dev.	0.35	0.36	0.41	0.42	0.34	0.42	0.38	0.37	0.47	0.58
Skewness	5.02	4.55	4.92	5.57	5.49	5.17	4.62	7.09	5.77	6.50
Minimum	0.40	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.40	0.40
Maximum	5.20	5.60	10.00	10.40	6.00	11.60	8.80	8.40	8.80	7.20

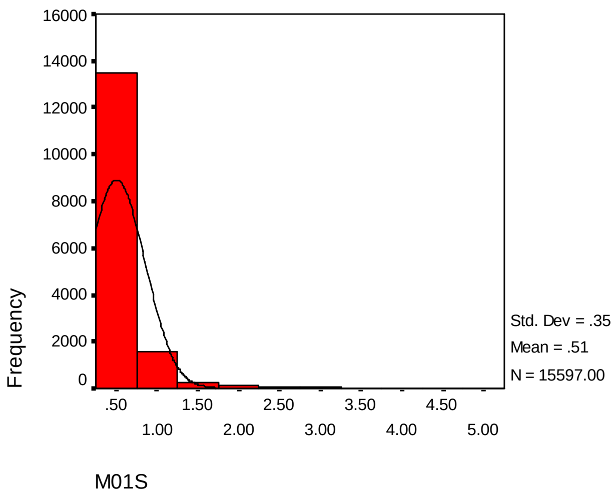


Figure 87. Maximum Rate Mean Histogram for Zone 1 Short Events.

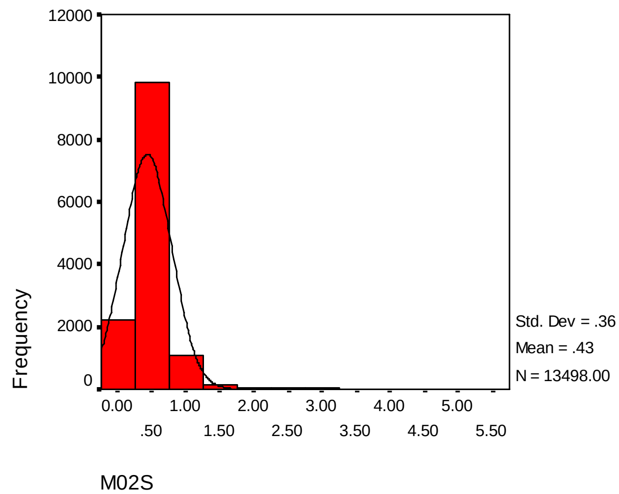


Figure 88. Maximum Rate Mean Histogram for Zone 2 Short Events.

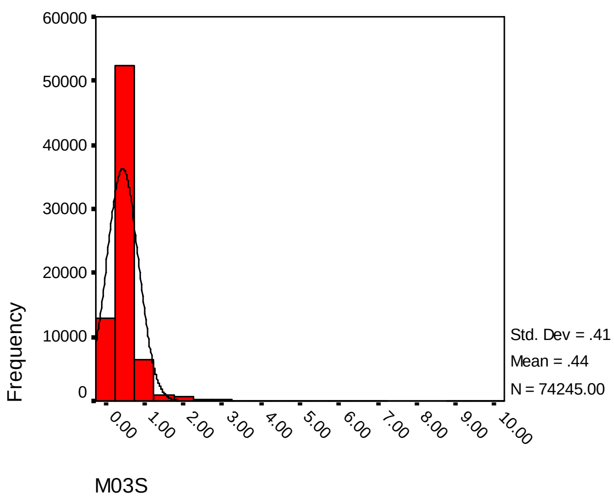


Figure 89. Maximum Rate Mean Histogram for Zone 3 Short Events.

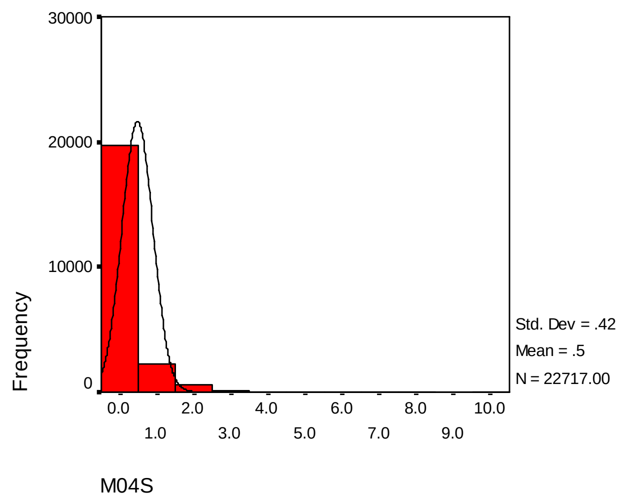


Figure 90. Maximum Rate Mean Histogram for Zone 4 Short Events.

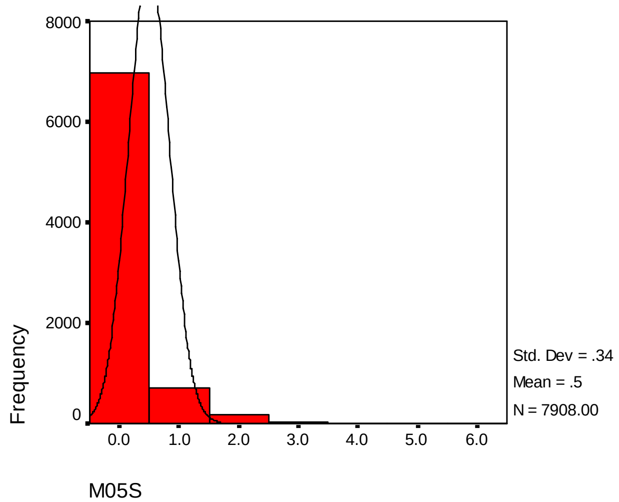


Figure 91. Maximum Rate Mean Histogram for Zone 5 Short Events.

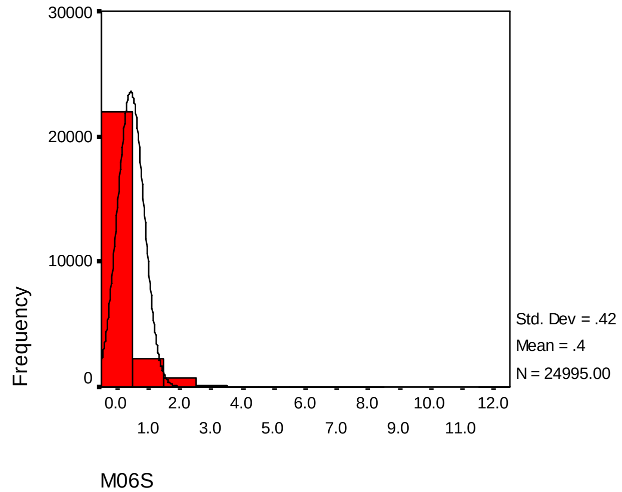


Figure 92. Maximum Rate Mean Histogram for Zone 6 Short Events.

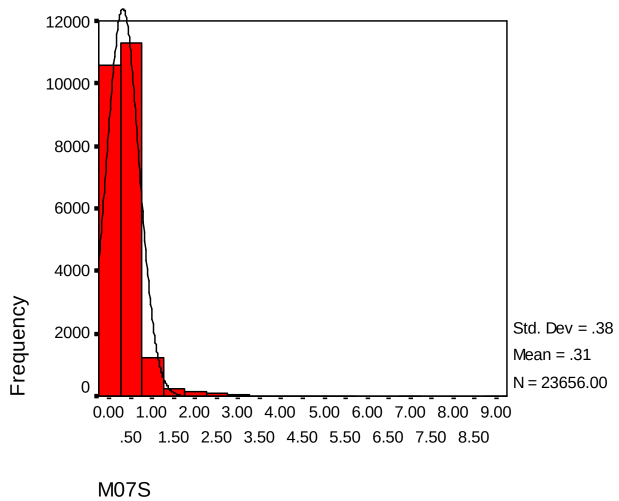


Figure 93. Maximum Rate Mean Histogram for Zone 7 Short Events.

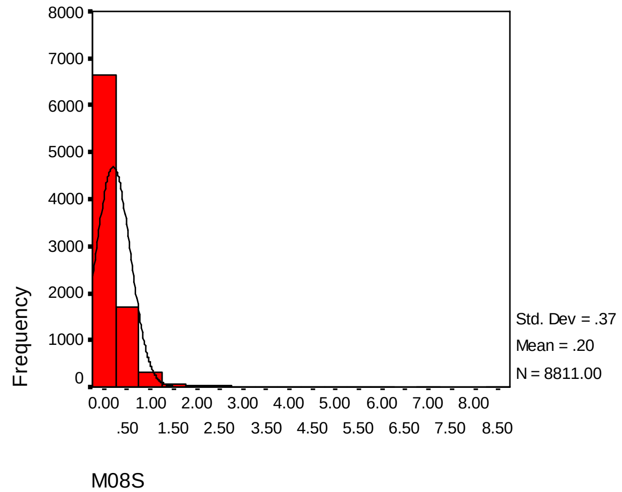


Figure 94. Maximum Rate Mean Histogram for Zone 8 Short Events.

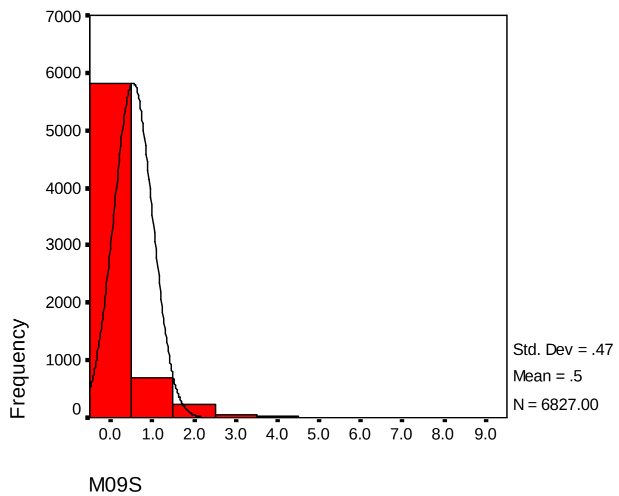


Figure 95. Maximum Rate Mean Histogram for Zone 9 Short Events.

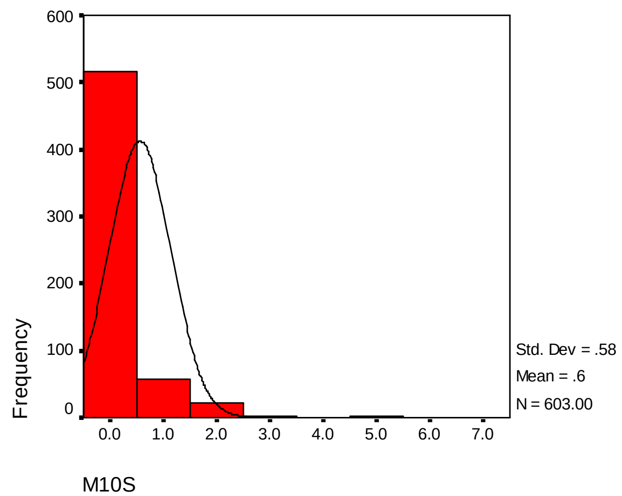


Figure 96. Maximum Rate Mean Histogram for Zone 10 Short Events.

Table 26. Maximum Rate Means for Medium Events (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10
# of Events	549	977	5215	1276	237	1788	2250	1141	379	36
Mean	1.39	0.97	1.05	1.14	1.54	1.02	0.76	0.52	1.85	1.99
Std. Dev.	0.96	0.96	0.97	0.97	1.16	1.02	0.91	0.71	1.19	1.28
Skewness	1.86	1.61	1.47	1.46	2.68	1.53	1.82	2.53	1.32	1.26
Minimum	0.40	0.04	0.04	0.04	0.08	0.04	0.04	0.04	0.40	0.40
Maximum	6.80	6.00	6.80	6.00	10.40	6.40	5.60	5.20	7.20	6.40

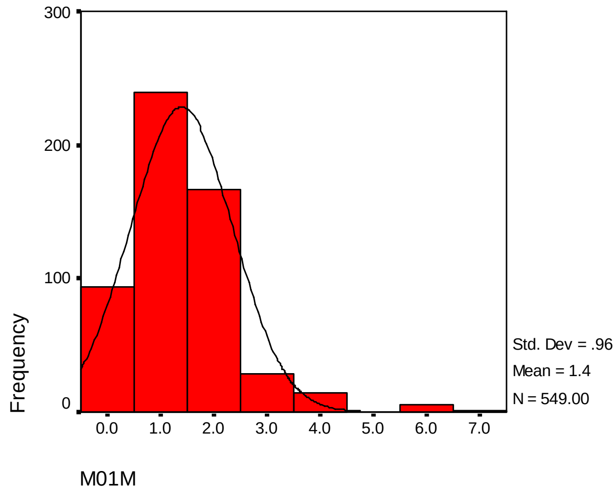


Figure 97. Maximum Rate Mean Histogram for Zone 1 Medium Events.

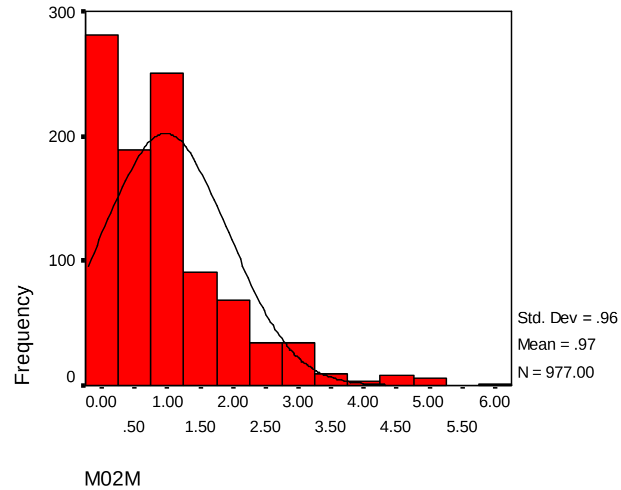


Figure 98. Maximum Rate Mean Histogram for Zone 2 Medium Events.

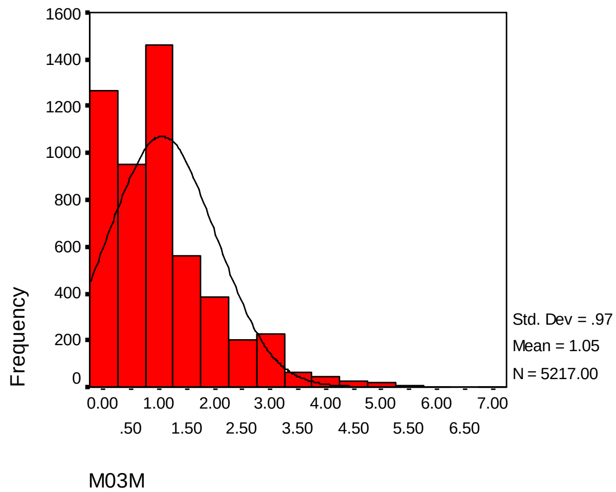


Figure 99. Maximum Rate Mean Histogram for Zone 3 Medium Events.

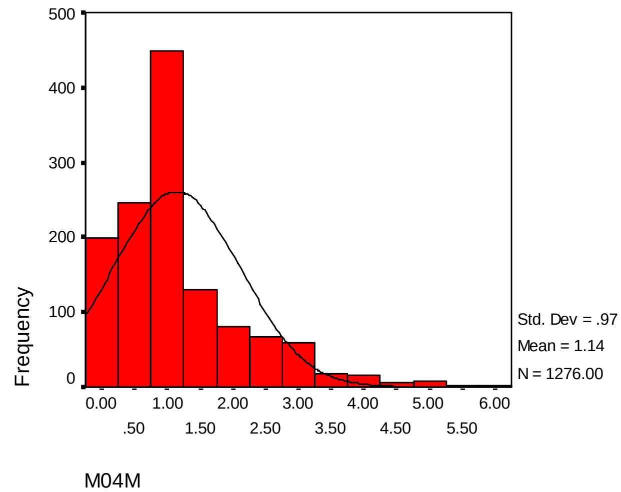


Figure 100. Maximum Rate Mean Histogram for Zone 4 Medium Events.

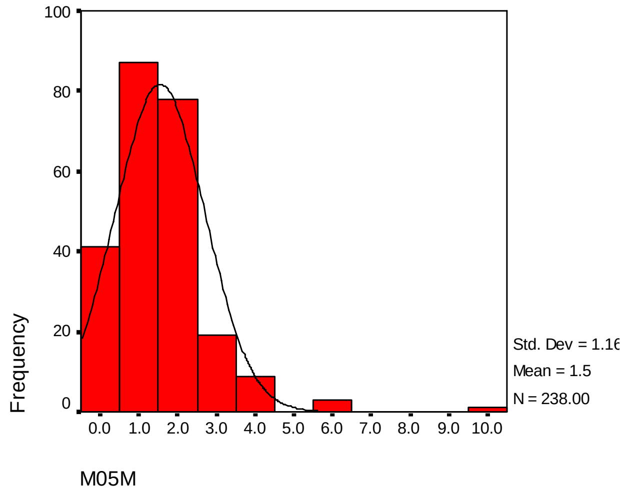


Figure 101. Maximum Rate Mean Histogram for Zone 5 Medium Events.

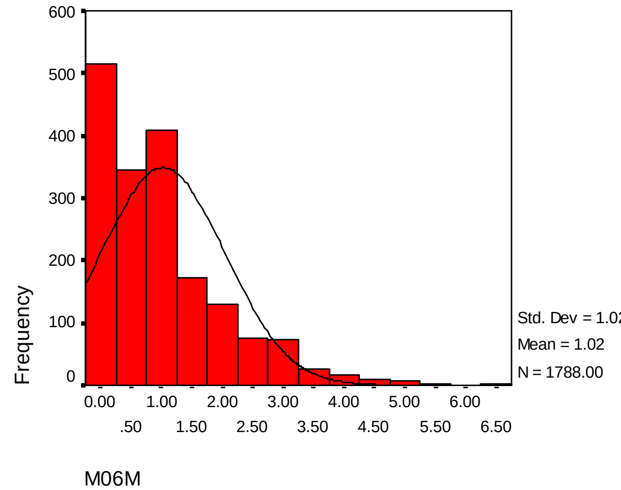


Figure 102. Maximum Rate Mean Histogram for Zone 6 Medium Events.

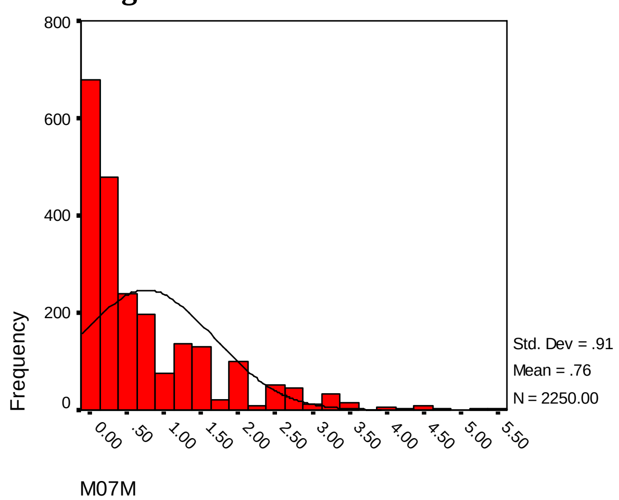


Figure 103. Maximum Rate Mean Histogram for Zone 7 Medium Events.

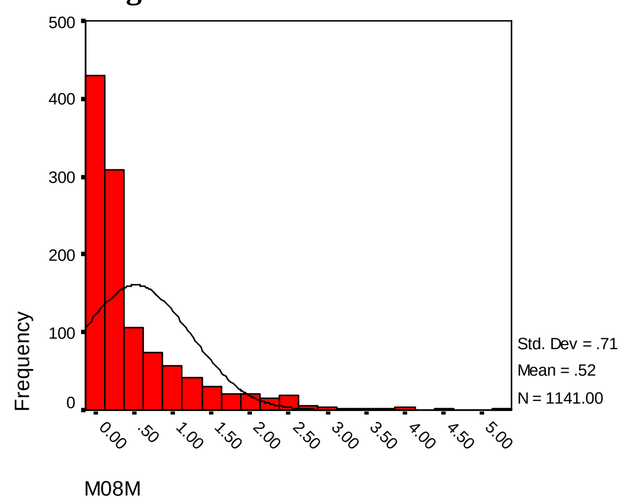


Figure 104. Maximum Rate Mean Histogram for Zone 8 Medium Events.

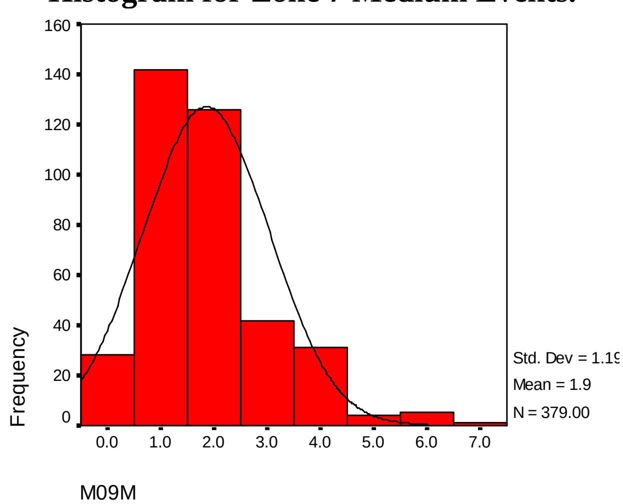


Figure 105. Maximum Rate Mean Histogram for Zone 9 Medium Events.

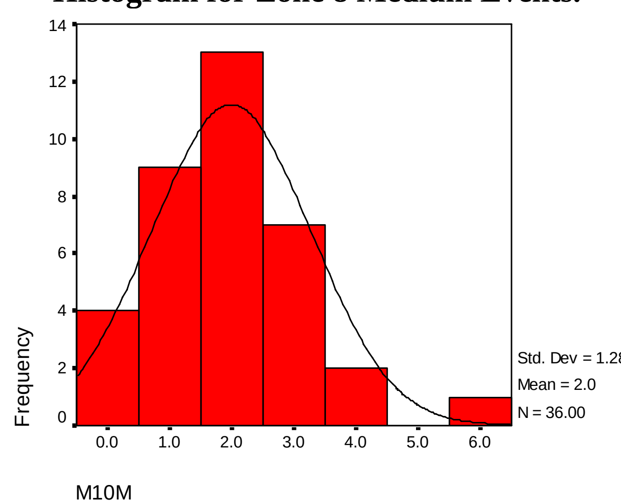


Figure 106. Maximum Rate Mean Histogram for Zone 10 Medium Events.

Table 27. Maximum Rate Means for Long Events (inch/hr).

Zone	1	2	3	4	5	6	7	8	9	10
# of Events	35	354	2024	391	16	722	1171	703	42	3
Mean	1.59	0.89	0.89	1.11	1.15	0.88	0.83	0.70	2.47	2.80
Std. Dev.	0.95	0.93	0.89	1.08	1.13	1.00	0.98	0.79	1.28	1.74
Skewness	1.17	2.10	1.64	1.56	1.83	2.16	2.04	2.12	1.31	-1.63
Minimum	0.40	0.08	0.04	0.04	0.12	0.04	0.04	0.04	0.80	0.80
Maximum	4.80	6.80	5.60	6.00	4.40	6.80	7.60	4.92	6.80	4.00

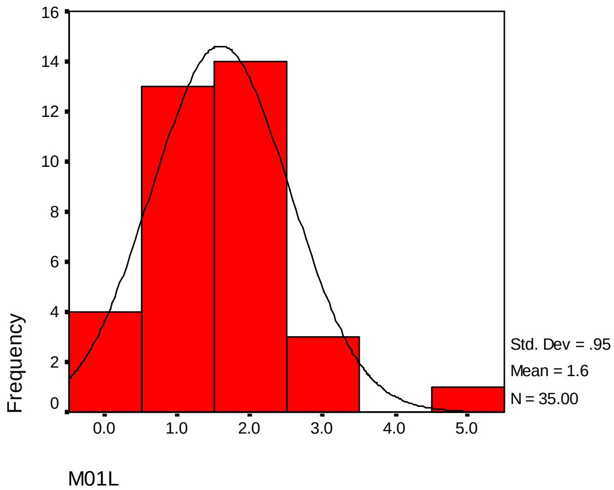


Figure 107. Maximum Rate Mean Histogram for Zone 1 Long Events.

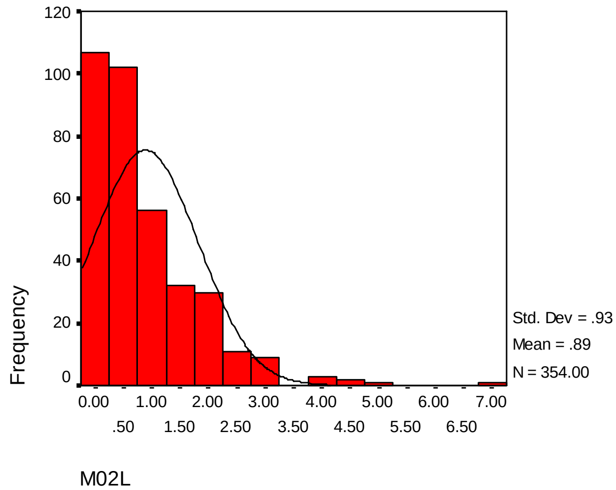


Figure 108. Maximum Rate Mean Histogram for Zone 2 Long Events.

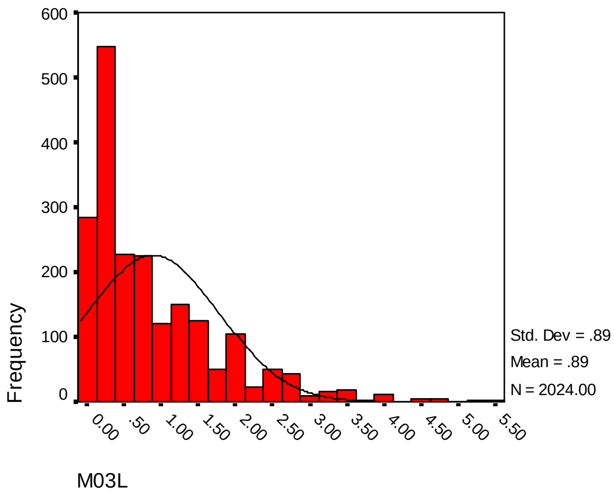


Figure 109. Maximum Rate Mean Histogram for Zone 3 Long Events.

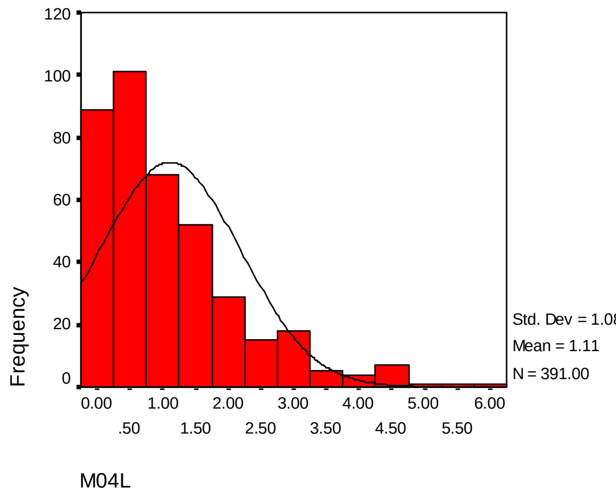


Figure 110. Maximum Rate Mean Histogram for Zone 4 Long Events.

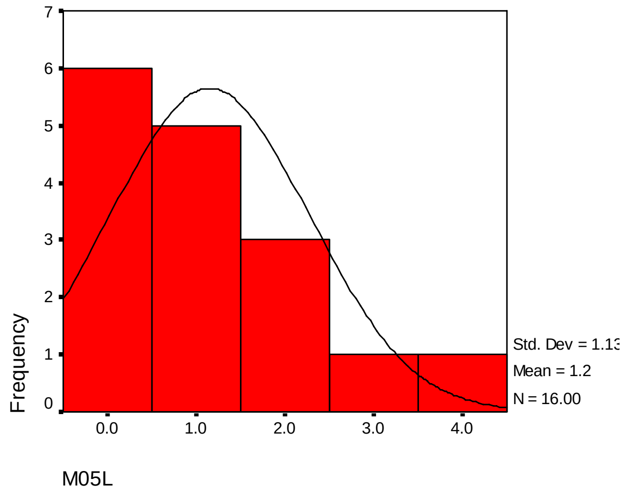


Figure 111. Maximum Rate Mean Histogram for Zone 5 Long Events.

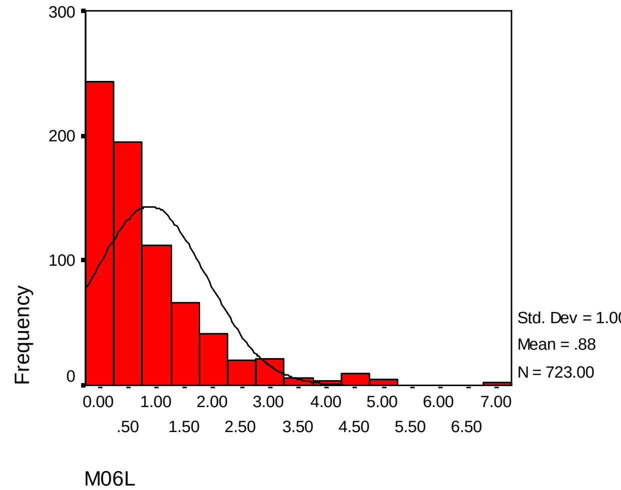


Figure 112. Maximum Rate Mean Histogram for Zone 6 Long Events.

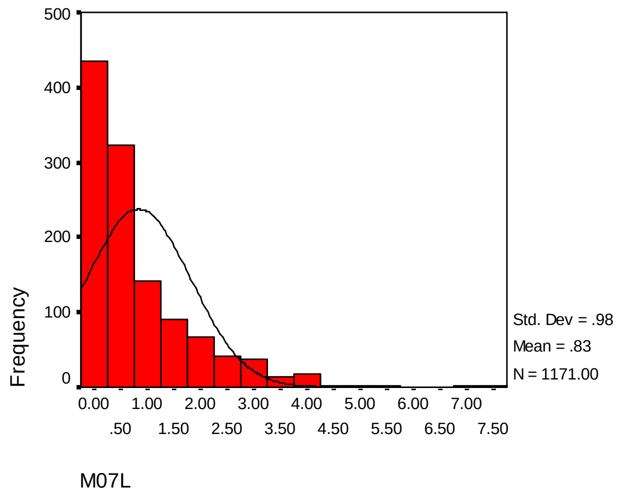


Figure 113. Maximum Rate Mean Histogram for Zone 7 Long Events.

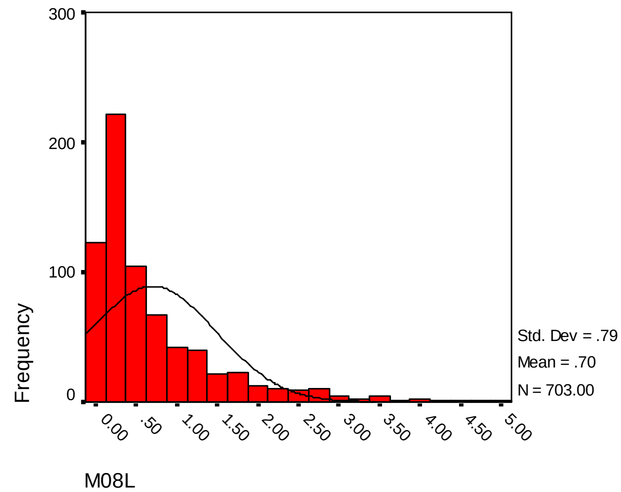


Figure 114. Maximum Rate Mean Histogram for Zone 8 Long Events.

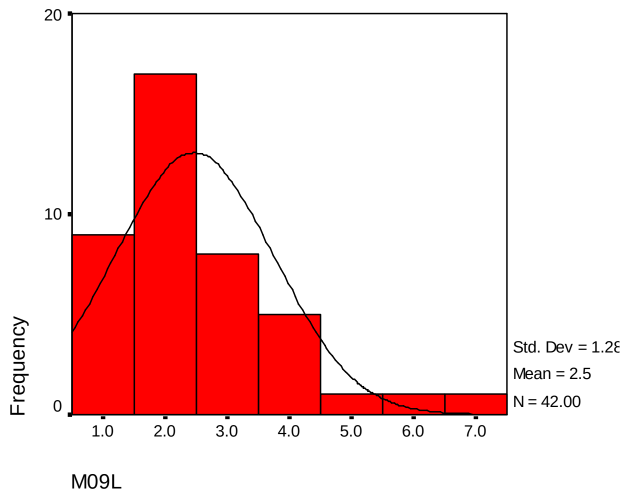


Figure 115. Maximum Rate Mean Histogram for Zone 9 Long Events.

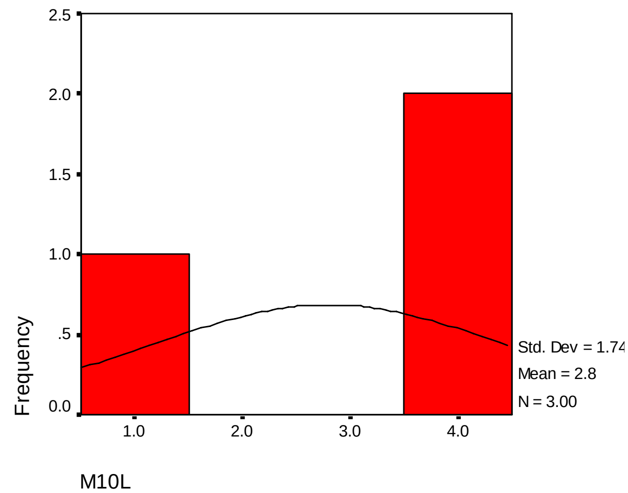


Figure 116. Maximum Rate Mean Histogram for Zone 10 Long Events.

APPENDIX B

Table 28. Pavement Marking Samples.

Marking Number: 5 **Binder Type:** Waterborne Paint **Manufacturer:** Ennis Paint **Bead:** Type 3 Weissker **Marking:** Width: 3.8 in. Thickness: 0.01 in.		**Marking Number:** 6 **Binder Type:** Waterborne Paint **Manufacturer:** All-American Coatings **Bead:** Type 2 Potters **Marking:** Width: 4.0 in. Thickness: 0.02 in.	
Marking Number: 8 **Binder Type:** LS90 Polyurea **Manufacturer:** EpoPlex **Bead:** GloMarc 90, Type 2 Visibead **Marking:** Width: 4.3 in. Thickness: 0.017 in.		**Marking Number:** 9 **Binder Type:** LS50 Epoxy **Manufacturer:** EpoPlex **Bead:** Type 3 (100% Visionglow) **Marking:** Width: 4.1 in. Thickness: 0.02 in.	
Marking Number: 10 **Binder Type:** LS50 Epoxy **Manufacturer:** EpoPlex **Bead:** Type 3 (25% Visionglow, 75% Visibead) **Marking:** Width: 4.1 in. Thickness: 0.02 in.		**Marking Number:** 11 **Binder Type:** Thermoplastic **Manufacturer:** Ennis Paint **Bead:** Type 1, 3, High Index **Marking:** Width: 4.3 in. Thickness: 0.11 in.	
Marking Number: 12 **Binder Type:** Thermoplastic **Manufacturer:** Ennis Paint **Bead:** Type 1, 3, High Index **Marking:** Width: 6.0 in. Thickness: 0.11 in.		**Marking Number:** 15 **Binder Type:** Tape A380I **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: 0.02 in.	

Table 28. Pavement Marking Samples (Continued).

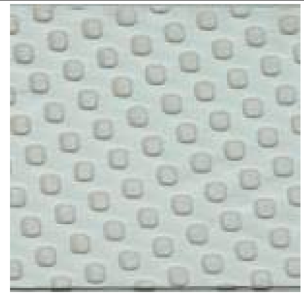
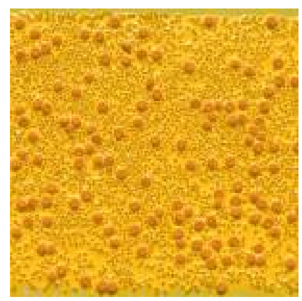
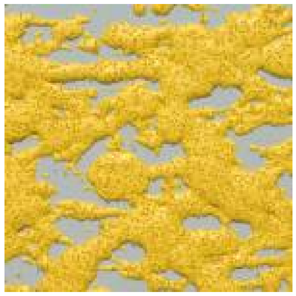
Marking Number: 16 **Binder Type:** Tape A750ES **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: 0.01 in.		**Marking Number:** 17 **Binder Type:** Tape 380WR **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: 0.02 in.	
Marking Number: 18 **Binder Type:** Tape ATM 400 **Manufacturer:** Advanced Traffic Markings **Marking:** Width: 4.0 in. Thickness: 0.06 in.		**Marking Number:** 21 **Binder Type:** Tape A380I **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: 0.02 in.	
Marking Number: 22 **Binder Type:** Tape A750ES **Manufacturer:** 3M **Marking:** Width: 4.0 in. Thickness: 0.01 in.		**Marking Number:** 23 **Binder Type:** LS90 Polyurea **Manufacturer:** EpoPlex **Bead:** GloMarc 90, Type 2 Visibead **Marking:** Width: 4.0 in. Thickness: 0.017 in.	
Marking Number: 24 **Binder Type:** Tape 380WR **Manufacturer:** 3M **Marking:** Width: 6.0 in. Thickness: 0.02 in.		**Marking Number:** 25 **Binder Type:** Tape ATM 400 **Manufacturer:** Advanced Traffic Markings **Marking:** Width: 4.0 in. Thickness: 0.06 in.	

Table 28. Pavement Marking Samples (Continued).

Marking Number: 31		**Marking Number:** 32	
Binder Type: Methyl Methacrylate		**Binder Type:** Thermoplastic	
Manufacturer: Degussa		**Manufacturer:** Dobco	
Bead: Type 3 Virgin Swarco		**Bead:** Type 3	
Marking: Width: 4.5 in. Thickness: 0.12 in.		**Marking:** Width: 4.6 in. Thickness: 0.07 in.	
Marking Number: 33		**Marking Number:** 34	
Binder Type: Thermoplastic		**Binder Type:** Thermoplastic	
Manufacturer: Ennis Paint		**Manufacturer:** Ennis Paint	
Bead: Flexolite M247, Visibead E16		**Bead:** Type 2	
Marking: Width: 4.1 in. Thickness: 0.09 in.		**Marking:** Width: 3.9 in. Thickness: 0.06 in.	
Marking Number: 35		**Marking Number:** 36	
Binder Type: Rumble Stripe: Thermoplastic		**Binder Type:** RRPM	
Manufacturer: Ennis Paint		**Manufacturer:** Avery Dennison	
Bead: Type 2		**Marking:** Width: 3.6 in. Thickness: 0.6 in.	
Marking: Width: 3.9 in. Thickness: 0.06 in.			