Standard Title Page - Report on Federally Funded Project

1. Report No. FHWA/VTRC 05-CR3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Wet Night Visibility of Pavement Markings		5. Report Date October 2004 6. Performing Organization Code
7. Author(s) Ronald B. Gibbons, Ph.D., Jonathan Hankey, Ph.D., and Irena Pashaj		8. Performing Organization Report No. VTRC 05-CR3
9. Performing Organization and Address Virginia Tech Transportation Institute 3500 Transportation Research Plaza Blacksburg, VA 24061		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 64135 and 60861
12. Sponsoring Agencies' Name and Address Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219	FHWA P.O. Box 10249 Richmond, VA 23240	13. Type of Report and Period Covered Final Contract 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report describes an investigation into the performance of pavement markings in wet night conditions. The performance of a typical pavement marking will degrade when it gets wet. This is a result of the flooding of the marking optics, thereby reducing retroreflectivity.

Several technologies are available to improve wet marking performance. In this project, six technologies were tested using both standard measurement methods and participant evaluations. The results show that two of the marking technologies, raised retroreflective markers and wet retroreflective tape, outperformed the group under all conditions. These markings were also highly accepted by the participants. The results also show that the standard paint and glass beads technology is the worst performing and the least desirable of those evaluated. A comparison of the ASTM retroreflectivity measurement methods and the measured luminance results also indicates that the methods are suitable for the conditions used in the evaluation; however, possible additions and corrections to the methods are outlined in this report. A follow-up study is underway to allow development of a performance-based specification for pavement markings for wet night visibility.

17 Key Words pavement markings, wet visibility, retroreflectometry, retroreflective materials, marking paint, thermoplastic, glass beads	18. Distribution Statement No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 108	22. Price

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FINAL CONTRACT REPORT

WET NIGHT VISIBILITY OF PAVEMENT MARKINGS

Ronald B. Gibbons, Ph.D.
Jonathan M. Hankey, Ph.D.
Irena Pashaj

Virginia Tech Transportation Institute
Virginia Polytechnic Institute & State University

Project Managers
Benjamin H. Cottrell, Jr., Virginia Transportation Research Council
Carl Andersen, Federal Highway Administration

Contract Research Sponsored by
the Virginia Transportation Research Council

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

October 2004
VTRC 05-CR3

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ABSTRACT

This project is an investigation into the performance of pavement markings in wet night conditions. A typical pavement marking's performance will degrade when it gets wet. This is a result of the flooding of the marking optics, thereby reducing retroreflectivity. As a result, the visibility distance of the marking is reduced. Several different technologies are available to improve pavement marking performance under wet conditions.

In this project, six pavement marking technologies were tested using standard measurement methods, in-situ photometric measurements, and participant evaluations. The standard measurement methods are the current ASTM methods for the measurement of the wet retroreflectivity of pavement markings, which consist of a test method for a standard condition of wetness (as the pavement marking dries following cessation of rain) and a test method for a standard condition of continuous wetting (for a pavement marking during rainfall). Two participant evaluations were performed. The first was a saturated evaluation, where participants were asked to evaluate marking visibility distance while simulated rain was flooding the marking. The second was a recovery evaluation, where participants were asked to evaluate the marking for a period of 10 min after the rain was turned off. During the participant evaluations, the retroreflectivity and the luminance of the marking were continuously measured. The results show that two of the marking technologies, raised retroreflective markers and wet retroreflective tape, outperformed the group in all conditions. These markings were also highly accepted by the participants. The results also show that the standard paint and glass beads technology is the worst performing and the least desirable of those evaluated. A comparison of the ASTM retroreflectivity measurement methods to the measured luminance results also indicates that the ASTM methods are suitable for the conditions used in this evaluation; however, some possible additions and corrections to the ASTM methods are outlined in this report.

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INTRODUCTION

Pavement markings convey regulations and warnings and provide vehicle tracking guidance to the driver. Much of the visual information needed by a driver to navigate safely in a variety of conditions, including daylight, darkness, and adverse weather, is provided by pavement markings. Visibility during wet night conditions is of particular concern to the Traffic Engineering and Materials Divisions of the Virginia Department of Transportation (VDOT) because the retroreflectivity of conventional pavement markings is degraded under these conditions. When headlight beams shine on dry pavement markings, the optical elements, typically glass beads, retroreflect; that is, the light is returned back toward the light source. When conventional markings, or more specifically, standard-sized glass beads, are covered with a film of water, the light is scattered, or reflected in all directions by the surface of the water and the efficiency of the retroreflective properties of the glass beads are reduced due to limitations in the index of refraction of the medium. This results in only a small portion of light when it is returned back to the light source. Therefore, the retroreflectivity of the markings is greatly reduced resulting in a reduction in visibility of the pavement markings. This reduced visibility renders the driving task more challenging because drivers have less tracking information.

Snow plowable raised pavement markers are the primary means currently used by VDOT to provide wet night retroreflectivity and may be viewed as a benchmark. Although these markers appear to be effective, they provide roadway delineation at points as opposed to the continuous delineation provided by effective pavement markings. A comparison of pavement markings and markers on the quality of their wet night retroreflectivity and cost-effectiveness was deemed to be useful to VDOT in determining a strategy for providing improved wet night visibility.

In 1997, VDOT conducted a customer service survey. In a telephone survey conducted by Coopers and Lybrand, more than 3,000 Virginians were asked to rate their satisfaction with seven aspects of Virginia's transportation system. "Nighttime visibility, especially in wet conditions" was identified as needing added attention. This issue has been discussed a number of times by the Traffic Research Advisory Committee of the Virginia Transportation Research Council. There are a number of pavement delineation products that are marketed as having high levels of visibility under wet night conditions. Pavement marking technologies include pavement markings and raised pavement markers. Pavement markings that are retroreflective under wet night conditions are designed either with components that sit above the pavement surface to avoid being covered by water or with material properties that permit retroreflection even under water.

The American Society for Testing and Materials (ASTM) has been investigating standards for measuring wet night retroreflectivity of pavement markings. One standard, a bucket or flooded method, is intended to simulate a standard condition of wetness that may be encountered just after a rainfall ends. The second, a spray or continuous wetting method, is intended to simulate a standard condition of continuous wetting that is encountered during rainfall. These measurement methods are being developed to enable field personnel to evaluate the retroreflective properties of wet in-service pavement marking materials. At this time, however, the applicability of these measurement methods to the actual performance of pavement marking materials is unknown.

PURPOSE AND SCOPE

The primary purpose of this project was to determine the visibility needs of motorists during wet night conditions. These findings should then be used to develop performance measures for evaluating wet night retroreflectivity of pavement delineation devices. These devices included conventional pavement markings (tapes, thermoplastics, and paints), profiled pavement markings, and raised pavement markers. In addition to information on the performance of various markers and marking materials, the ultimate product of this research would be to develop a performance-based specification that VDOT could use to evaluate alternate materials for inclusion in VDOT's *Road and Bridge Specifications.* The National Transportation Product Evaluation Program (NTPEP) should also be interested in the results of this experiment. It is hoped that NTPEP will consider adopting the performance measurement method selected.

The research sought to answer the following questions: 1) what level of retroreflectivity do drivers need under rain conditions; and 2) what levels of retroreflectivity are current pavement markings and markers capable of producing under various rain conditions? The rain conditions include 1) the period during rainfall of various intensities within a defined range, and 2) the recovery period (draining) after rain has stopped. The research also sought to evaluate the correlation of the ASTM measurement methods for wet pavement marking retroreflectivity and the human performance observation.

In order to answer the experimental questions, the initial project was broken into two phases. The first was the establishment of the standard rain event in the Commonwealth of Virginia. The second was a static participant evaluation that established the visibility of the pavement markings in the rain. A follow-on experiment based on the results of this work is currently being planned and will include a dynamic driving experiment. The results from the investigation reported here will be included as part of the experimental design for the next experiments.

PHASE 1 – RAINFALL CHARACTERIZATION

This phase of the project entailed reviewing rainfall data within the Commonwealth of Virginia and performing a data analysis to characterize the average rainfall event, which were then simulated on the Smart Road during the experimental sessions.

Methods and Materials

Data Sources

Two sets of rain data were purchased for this portion of the project from the National Climatic Data Center (NCDC) [1, 2]. The first set detailed hourly weather records from 424 weather stations across Virginia. The second set consisted of weather data that were recorded every 15 min from 54 weather stations across Virginia. The data covered the years of 1971 to 2001 for the 15 min data and 1948 to 1999 for the hourly data.

The datasets consisted of weather records that provided the rainfall over the specific 15 min or hourly timeframe of the data. Both sets of data were analyzed in terms of the reliability of the data for providing the most accurate representation of rain events in Virginia.

The data were broken into rain events, which were defined as continuous periods of rain accumulation that lasted for at least one measurement period. The rain events were then further refined into mid-rain events where the first measured and the last measured periods in the event were dropped from the event, leaving only a stable period of rain. The rain events were also coded for night or day occurrence.

An analysis of the data reliability indicated that the data from the 15 min mid-rain events, which were measured in hundredths of an inch of rain, provided the most accurate set of rain events. It was also found that there was a significant difference between day and night rain events. It was therefore decided to use the 15 min nighttime dataset that consisted of only stable mid-rain events.

These datasets were used to determine the typical rain event in Virginia through an analysis of the average rain event duration and rainfall rates.

Results

Mean and Quartile Analysis

Using the 15 min mid-rain event nighttime data as the selected dataset, the histograms for the average and maximum rainfall are shown in Figures 1 and 2. The summary statistics are shown in Table 1. It should be noted that “Maximum Event Data” are derived from the rain events, meaning that the average value in the Maximum Event Data column is the average of the maximum recorded values per rain event, which typically includes more than one 15 min measurement interval.

Table 1. Summary statistics for 15-min mid-event nighttime dataset.

	Average Data	Maximum Event Data
N	1912	1912
Mean	0.131	0.21
Median	0.088	0.12
Standard Deviation	0.146	0.287
Range (Maximum – Minimum)	2.4	3.48

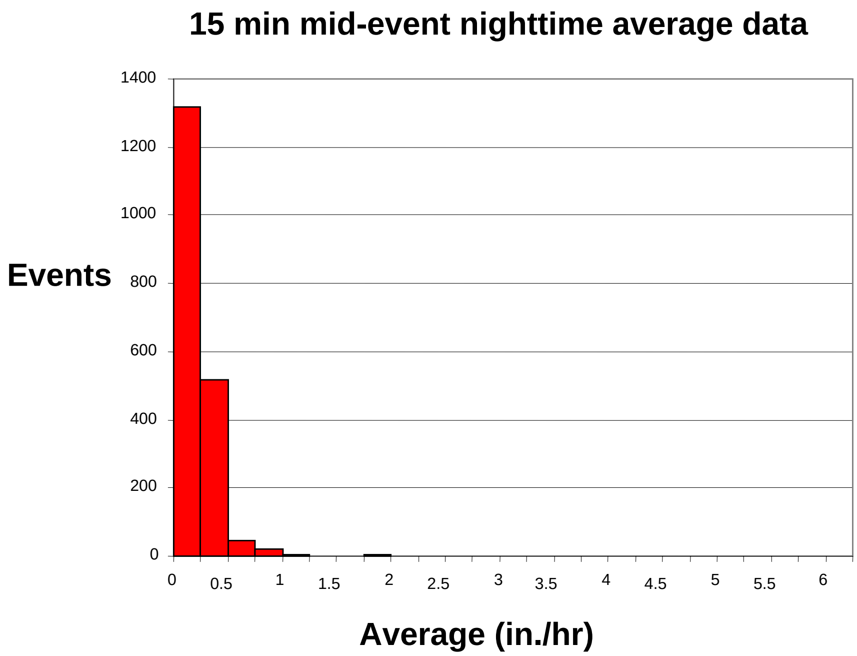


Figure 1. Histogram of average rainfall for nighttime 15 min mid-event data.

The other analysis performed on this dataset was a quartile analysis of the dataset. In order to more fully explore the rain event results, the maximum, minimum, duration, and average from each station was analyzed. The mean, maximum, minimum, and upper and lower quartiles were calculated for each of the data variables. The results are shown in Table 2. In Table 2, the numbers presented are related to each of the data variables. This means that for the minimum variable, the maximum of the minimums for each of the events was 0.04 in./hr and the minimum of the minimums for each event was also 0.04 in./hr.

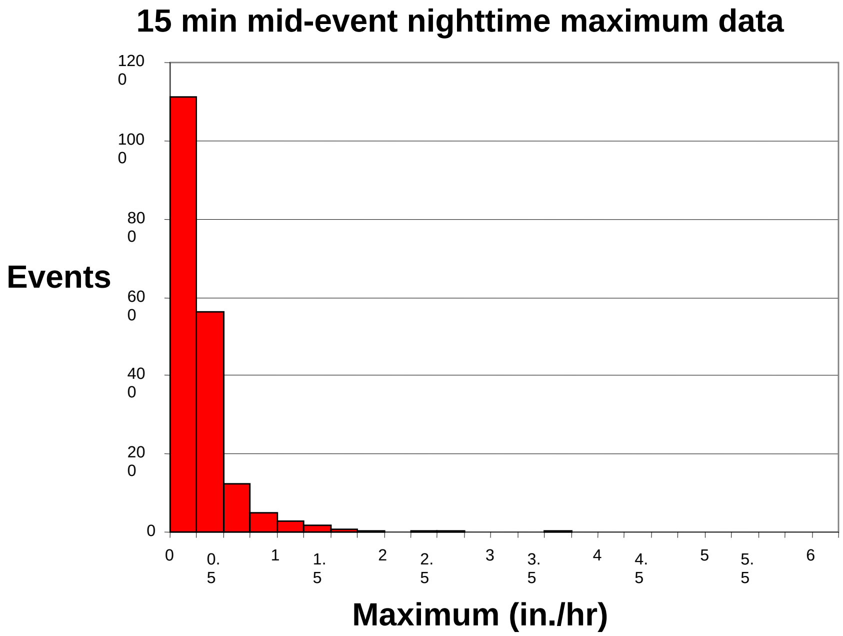


Figure 2. Histogram of maximum rainfall for nighttime 15 min mid-event data.

Table 2. Summary of the quartile analysis for the 15 min mid-rain event nighttime dataset.

Variable	Mean	Lower Quartile	Upper Quartile	Maximum	Minimum
Average (in./hr)	0.126	0.112	0.141	0.158	0.106
Minimum (in./hr)	0.04	0.04	0.04	0.04	0.04
Maximum (in./hr)	2.07	1.2	2.92	3.52	1.2
Duration (hr)	1.93	1.70	2.07	2.69	1.52

The rain events selected for this project were based on this dataset.

Duration Analysis

Previous research has shown that differences in rainfall behavior can be seen based on the duration of the rainfall [3, 4]. A plot of the average rainfall versus event duration for mid-events is shown in Figure 3.

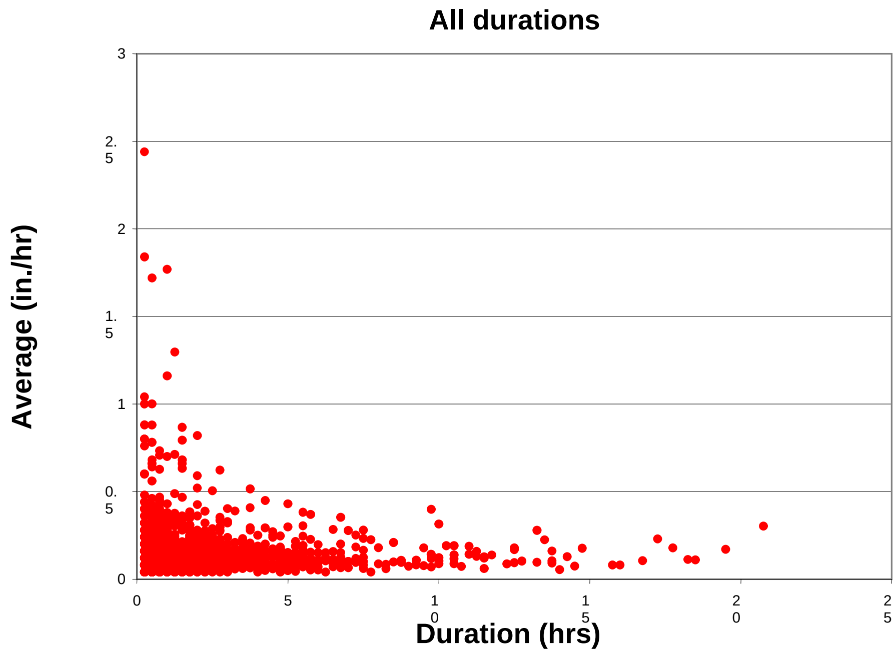


Figure 3. Relationship of duration and average rainfall.

Yu et al. [3] separated rain events by their duration using two different categories: Short (1 hr to 1.75 hr) and Long (greater than 2 hr). In that analysis, events shorter than 1 hr were considered showers and not included. For this analysis, the rain events were separated into three categories: Short (less than 1 hr), Medium (1 to 1.75 hr) and Long (greater than 2 hr). The dataset was partitioned by these categories and summary statistics were calculated, as shown in Table 3.

Table 3. Summary statistics for the various durations (all values are in in. per hr).

Variable	All Events	Short Events	Medium Events	Long Events
Average (in./hr)	0.126	0.121	0.128	0.134
Minimum (in./hr)	0.04	0.04	0.04	0.04
Maximum (in./hr)	2.07	1.18	1.58	1.58
Duration (hr)	1.93	0.452	1.347	4.60

There is an obvious trend in these data that the longer the event duration, the higher the average rainfall. This is not expected from the average and duration chart. That comparison shows a trend from higher to lower maximums. This relationship then implies that there is a much greater variability in the short duration data than in the longer duration data. This is also seen in the maximum data; the average maximums for all of the events are not the average of the duration averages. These averages were not weighted by the frequency of the data, and therefore the variability in the short duration data is again implied. For completeness, the duration versus maximum rainfall relationship is shown in Figure 4.

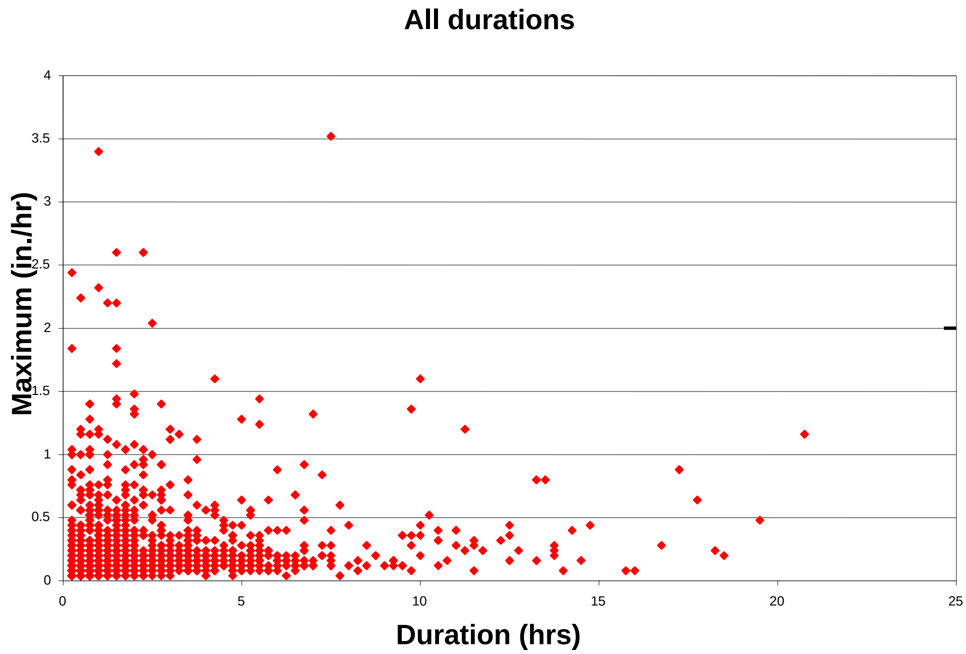


Figure 4. Relationship of duration and maximum rainfall.

This duration data are interesting for the assessment of the pavement markings. Flooding time on the pavement marking surface is a critical factor in how a marking behaves under wet conditions.

Discussion

The following rain event rates were chosen as possibilities for the simulated rain used for the other experiments:

1. 0.8 in. per hr (95^{th} percentile of all rain events)
2. 2.0 in. per hr (average of the maximum values of individual stations)
3. 2.9 in. per hr (upper quartile value for maximums of individual stations)

Within the datasets, event 2 and event 3 are greater than the 99^{th} percentile of the maximum rainfall recorded. Figure 5 shows the histogram of all of the average data points, and Figure 6 shows the maximum levels; both are marked with the selected rain event rates of 0.8, 2.0, and 2.9 in. per hr.

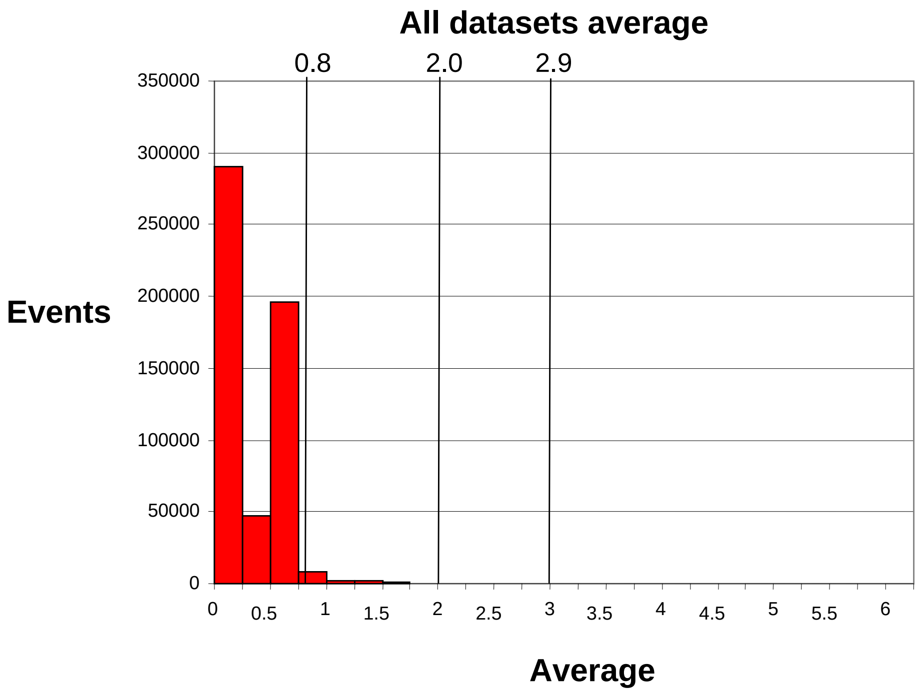


Figure 5. Histogram of all average data points with proposed rates marked (in in. per hr).

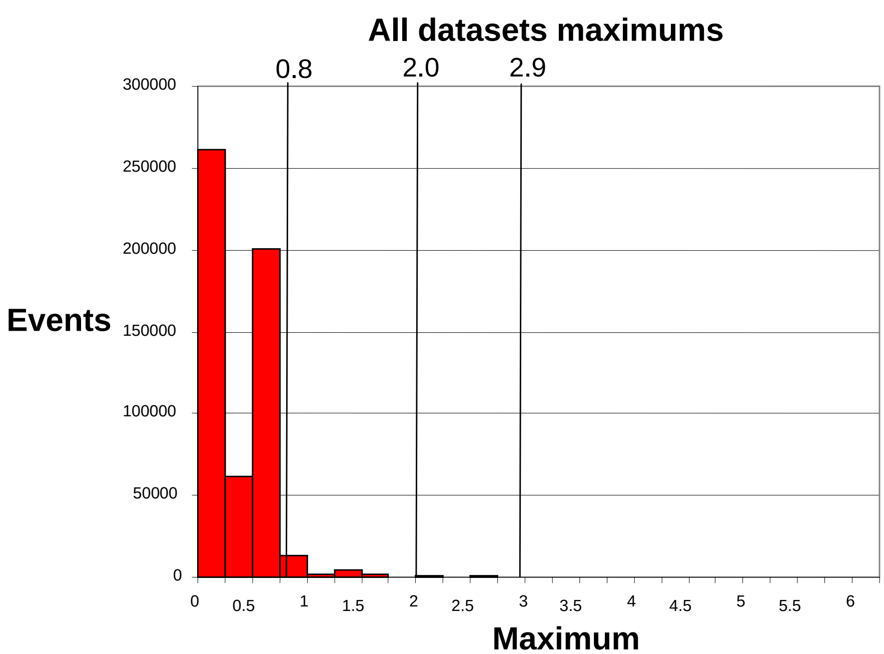


Figure 6. Histogram of all maximum data points with proposed rates marked (in in. per hr).

Because of the extreme rarity of rain events of 2.0 in./hr or greater, and to provide for a realistic evaluation of the ability of alternative pavement marking technologies to meet typical driver requirements, it was decided to minimize the simulated rain rate as much as possible.

The rain system on the Smart Road has been designed to provide the most even rainfall distribution possible on the road. This ability is accomplished by using bell-style nozzles mounted in a vertical, base-down position on the road's rain towers. Water is then dispersed from the towers evenly in a circular pattern. The overlap of the circles' edges provides a constant rainfall onto the road surface

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

Conclusions

In order to realistically evaluate all pavement marking technologies selected for this project, a minimum rain rate was established for the simulated rain on the road. This value was 0.8 in. per hr, which represents a 95^{th} percentile rain event in Virginia, which also coincides with the minimum capability of the Smart Road weather making system.

PHASE 2 – STATIC EXPERIMENTS

Methods and Materials

The experimental phase of the project required the completion of several different intermediate tasks. The first task evaluated the performance of the marking technologies in a saturated or a rainfall condition. The second task evaluated the pavement markings during a recovery or drying period. The third measured the performance of the evaluated pavement marking technologies during the wet conditions at non-standard geometries. This third task included measurement of the pavement markings using the ASTM test methods and measurement in the simulated rain.

Saturated Evaluation

Evaluation of the pavement markings in the saturated condition was conducted using both human observers and photometric measurements. The experimental design and the methods used are outlined below.

Experimental Design

The experimental design is a 6 by 2 by 2 partial factorial design. The conditions are shown in Table 4.

Table 4. Experimental design for saturated condition.

Pavement Marking	Standard Paint with Standard Beads Standard Paint with Large Beads Wet Retroreflective Tape Semi-Wet Retroreflective Tape Thermoplastic Profile-Type Markings Raised Retroreflective Pavement Markers
Marking Condition	Dry Wet (Saturated)
Vehicle Type	Sedan Truck

The design is a partial factorial in that the full blocks of marking condition and vehicle were not tested; only the conditions of dry sedan, wet sedan, and wet truck were used for the experiment. The impact of the vehicle type and the rain condition will be analyzed separately in the data analysis.

Independent Variables

The independent variables in this evaluation included the pavement marking types. These will be described in greater detail later, but the marking technologies were selected to provide the widest range of marking retroreflectivity possible. The markings were installed across the experimental area approximately 2 ft apart. All markings were installed as white, single-skip lines (10 ft lines, or skip marks, with 30 ft spacing).

The second variable, marking condition, was whether the simulated rain system was running and wetting the marking or if the marking was dry. For the wet or rain condition, the simulated rain was operated continuously during each evaluation session. The dry condition required that no rainfall had occurred within the 12 hr previous to any evaluation session. No natural rain was used in the experiment. The rain rate chosen for the wet portion of the experiment was the lowest value recommended in Phase 1: 0.8 in. per hr.

The final factor of vehicle type provided two different angular views of the roadway. The standard geometry (specified by ASTM as “30 m geometry”) used for the measurement of the retroreflectivity of pavement marking is for a sedan-style vehicle. It should be noted that the ASTM measurement methods use a single light source located in the same plane as the pavement marking and the observer. This is similar to having a motorcycle drive on the pavement marking, rather than the situation with two laterally separated headlamps, as on a sedan or truck, and with the vehicle offset from the line. The 30 m geometry specifies an observer height of 1.2 m looking at a point 30 m ahead of the vehicle with headlamps at 0.65 m high, which results in an entrance angle of 88.76° and an observation angle of 1.05°. Using a truck, the participant viewed the road at a much higher angle. Increasing the observation angle will change the observed retroreflectivity of the marking. The entrance and observation angles found for the vehicles used in this experiment are, respectively, 88.7° and 0.87° for the sedan and 88.2° and 2.44° for the truck. These dimensions are for a single headlamp. In the experiment, the passenger side headlamp was aligned with the pavement marking but the driver’s side headlamp was located at 1.3 m (51 in.) to the left for the sedan and 1.8 m (71 in.) to the left for the truck.

This offset results in changes to both the entrance and observation angles for the driver's side headlamps. The entrance and observation angles for the left headlight are respectively 88.5° and 2.63° for the sedan, and 86.1° and 4.22° for the truck. Thus, it is expected that the driver's side headlamp will contribute little to the luminance, and thus the calculated retroreflectivity, of the pavement marking.

Dependent Variables

During the saturated evaluations, the participants were asked to count the number of pavement marking skip lines visible from the passenger seat of the experimental vehicle. This count, representing the visibility distance, was measured for each marking in each of the experimental conditions.

As the participant was performing the count, the luminance of the pavement marking was measured from the experimental vehicle by a CCD photometer. The marking of interest was the third skip mark in the series, which was 30 m from the experimental vehicle. Similarly, the retroreflectivity of the pavement markings was measured using a standard 30 m geometry instrument placed in front of the vehicle. The instrument measured the first marking in the sequence.

The measured dependent variables are summarized in the Table 5. Other dependent variables were calculated from these measurements and are summarized later in this document.

Table 5. Measured dependent variable summary.

Visibility Distance	Collected from Participants as a Count of Skip Marks
Marking Luminance	Measured on the Third Skip Mark from the Vehicle
Retroreflectivity	Measured on the First Skip Mark in the Series

At the end of each evaluation for each pavement marking, participants filled out a rating sheet where they were asked to rank their comfort level while driving on a road in various conditions of rain.

At the end of the wet truck and the dry sedan experimental sessions, participants completed a ranking form where they ranked their preference for each marking type in a side by side comparison. All questionnaires and ranking forms are attached in Appendix A.

Participants

Thirty-three individuals participated in this evaluation. Sixteen males and 17 females, all 60 years old and over, were selected to participate. The average age of participants for both males and females was 70 years. Participants were chosen after successful completion of a screening questionnaire. During the initial screening, participants had to verify possession of a valid driver's license, lack of medical conditions that would present a risk if they partook in the evaluation, and appropriate age and gender demographics.

On the first day of the evaluation, participants were asked to fill out an informed consent form. They were informed about their right to freely withdraw from the experiment at any time without penalty and that they would be paid for the amount of actual participation time. Participants received $20 per hr for their participation.

A vision test was administered to ensure that all participants passed the visual acuity test. The average acuity for male participants was 20/26 and 20/25 for female participants. One male was colorblind, and five males and six females had mild color vision deficiencies. The posture of the participants' eye in the vertical and lateral plane was also tested. Only two females had non-normal posture of the eye in the vertical plane and one female had non-normal posture of the eye in the lateral plane.

After the vision test was administered, the participants were given a pre-evaluation questionnaire to complete. The questionnaires showed that 20 participants wore bifocal glasses while driving at night, eight participants wore trifocals, and one participant wore single-lens glasses. The rest of the participants did not use any corrective glasses while driving at night.

The frequency of the participants' nighttime driving was also gathered. The majority of the participants drove at night three times per week. Seven participants drove one time per week at night, four participants drove every night, and only two participants drove at night less often than one time per week. When asked if they had difficulty driving at night, the majority of participants said they experienced little difficulty. Forty-two percent of the participants said they experienced no difficulty at all while driving at night. Sixty-seven percent of participants said they were very comfortable driving at night in good weather. When asked how they feel about driving in typical rain conditions, 31 percent replied that they were somewhat comfortable whereas 30 percent said they were somewhat uncomfortable. Twenty-one percent of the participants felt very comfortable driving in typical rain conditions.

Each condition was viewed by a different number of participants. Twenty nine participants viewed the markings during the wet sedan condition, 28 participants viewed dry sedan and 31 participants viewed wet truck. Twenty-six participants viewed all three conditions, five participants viewed two conditions and two participants only viewed one condition.

Method

The saturated evaluations used a visibility panel method, where a large group of participants (approximately 15 at a time) viewed the pavement markings one person and one marking type at a time. The process was a static experiment, which meant that the experimental vehicles were not moving.

In order to accommodate all of the conditions, three evaluation sessions for each participant were required. When participants arrived at the building for the first night of evaluations and completed the required paperwork, they were briefed on the experimental procedure using a PowerPoint presentation, which is included in Appendix B. The purpose of the experiment, experimental instructions, and safety requirements were all presented. After the orientation, all participants were taken by bus to the experimental area. The bus was available to the participants as shelter as the evaluations were going on and refreshments were available.

The experimental area was laid out as in Figure 7. This area included space for the participants to fill out the questionnaires, the experimental vehicle, and the associated vehicle alignment grid.

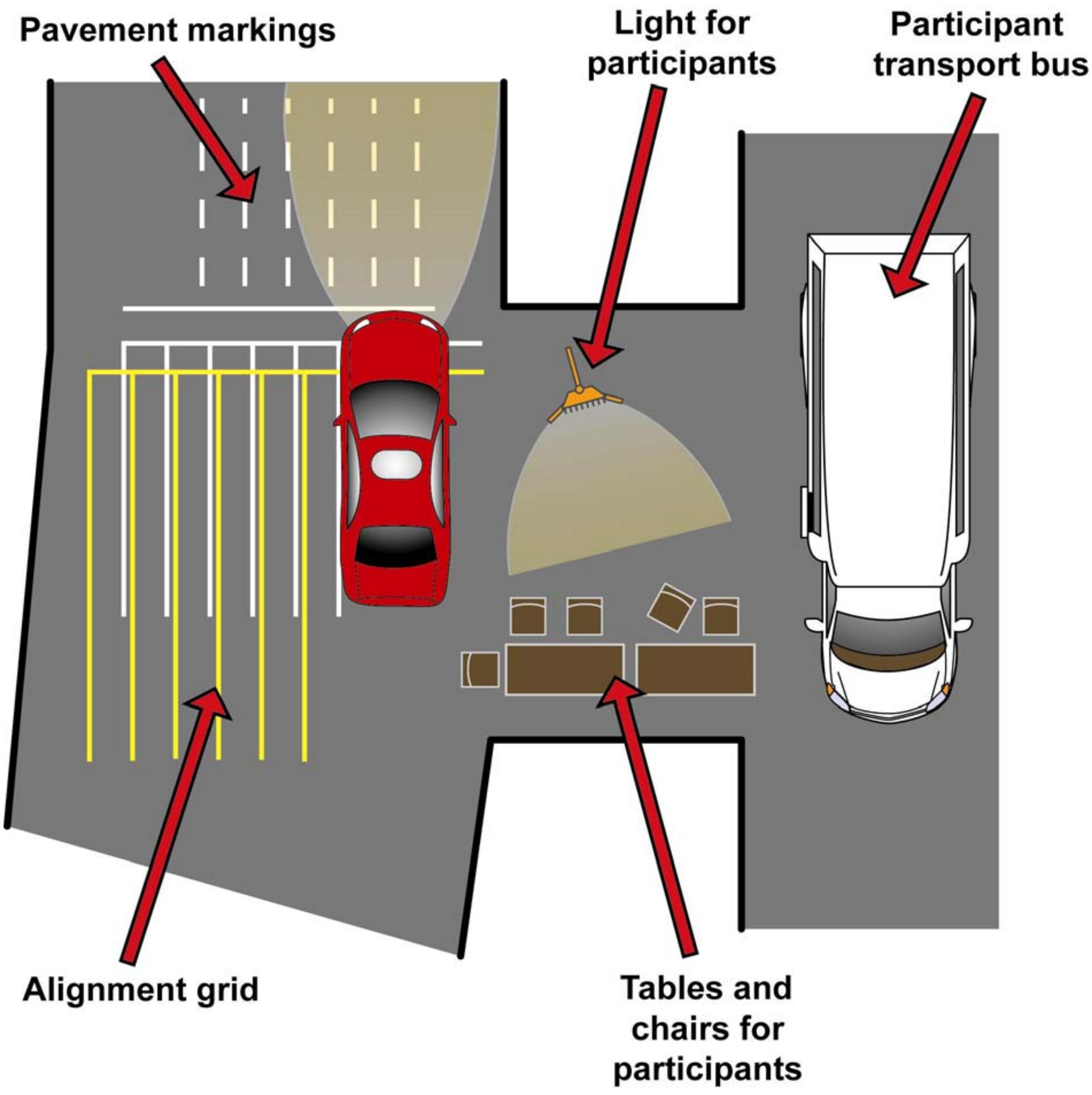


Figure 7. Experimental area.

Experimental staff were located at the vehicle assisting the participants in and out. Staff were also located at the table to assist in filling out the questionnaires, in the bus to maintain the sequence of the participants, and outside as escorts to help participants across to the experimental vehicle. A light facing away from the experimental area was used to illuminate the area where the participants were walking.

Each of the experimental vehicles was outfitted with a CCD photometer, a retroreflectometer, and a video camera to record the participant conversation. The equipment layout inside the vehicle is shown in Figure 8. A view of the retroreflectometer and the experimental vehicle on the alignment grid is shown in Figure 9.

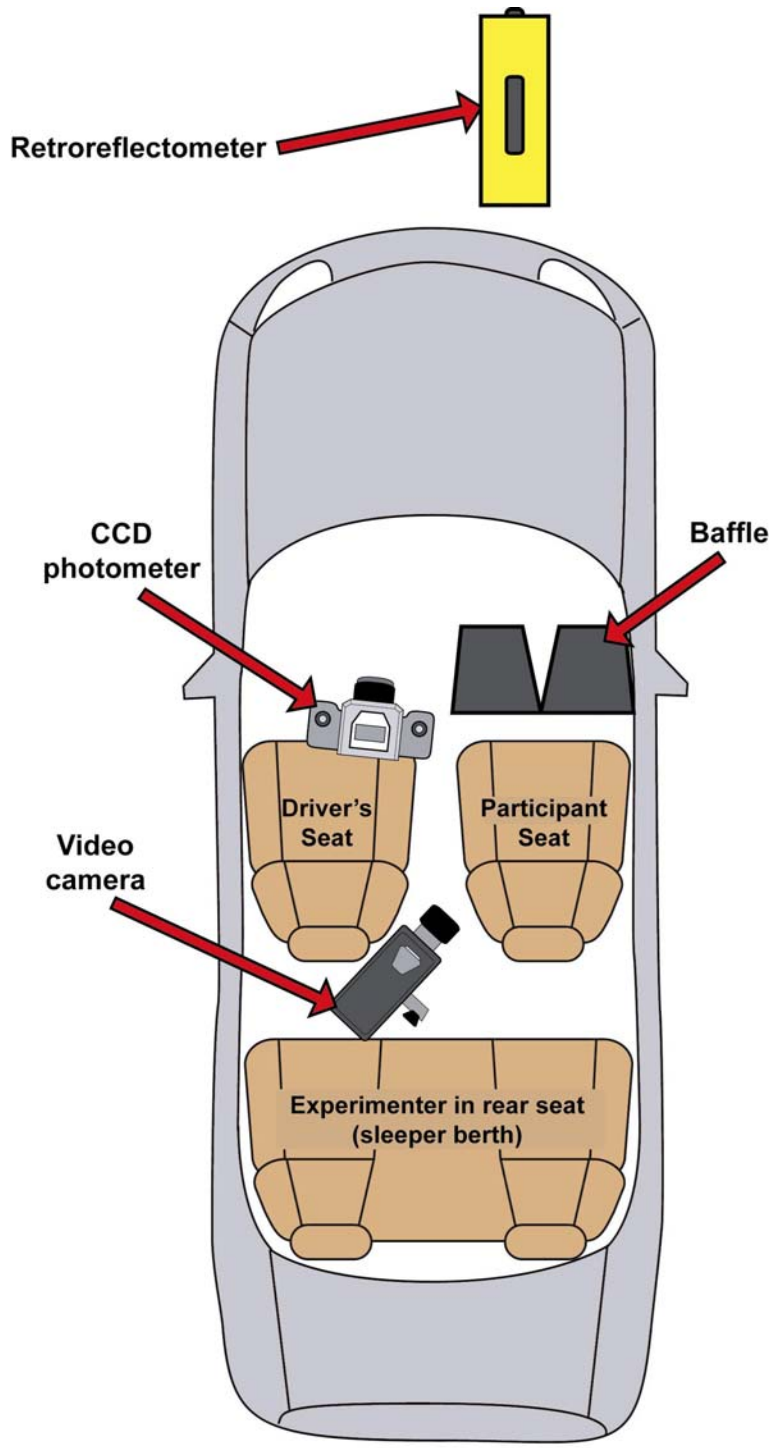


Figure 8. Vehicle equipment layout.

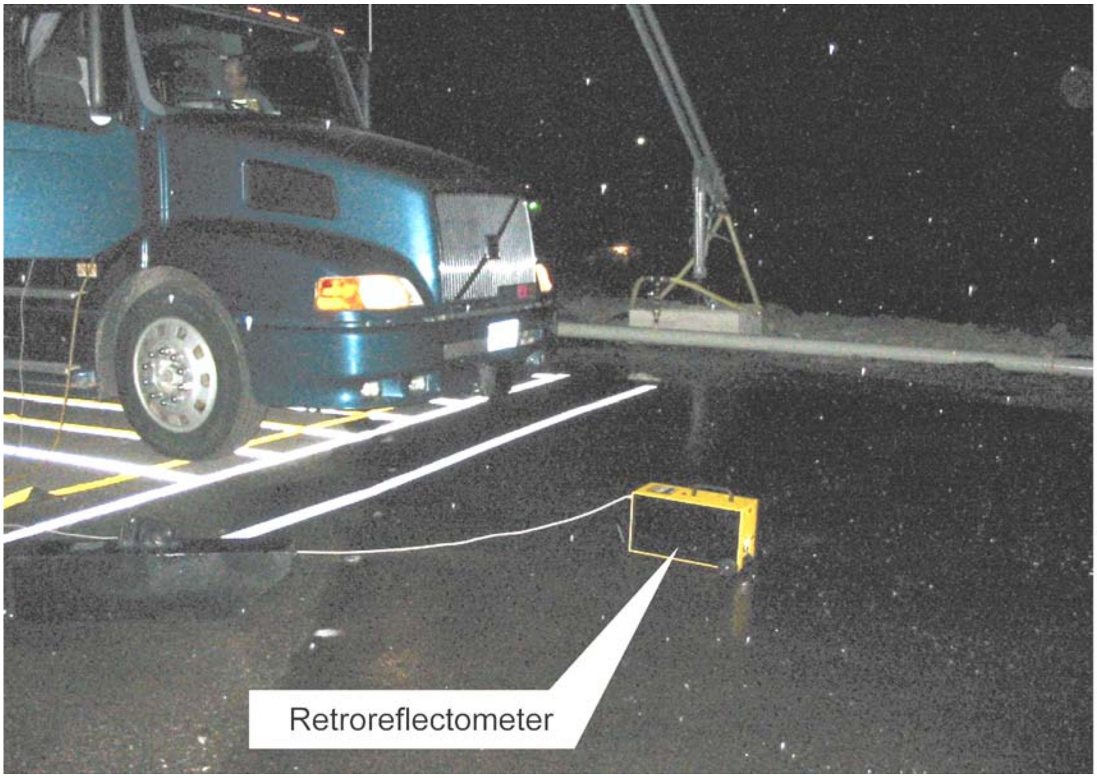


Figure 9. The alignment grid, the wet truck and the retroreflectometer in use at the experimental area.

A baffle was placed across the vehicle windshield. The baffle had a slit through which to see one line of pavement markings. The participants were instructed on how to line up their view of the pavement marking with the baffle. Figure 10 was used to aid in the training.

One by one, the participants were called alphabetically by name from the bus during the evaluation session. An escort took them from the bus to the experimental vehicle. In order to allow for dark adaptation of the participants' vision, participants were typically held outside in the dark for at least one min. They were then seated in the experimental vehicle and asked to count the number of skip marks visible. They verbally told the count to the experimenter in the vehicle. At the same time, experimenters recorded the luminance and retroreflectivity of the pavement markings. Participants had a maximum of one min to make their count. In the case of the marking with the raised retroreflective pavement markers, the participants were instructed to count the markers and not the lines in between.

After completing the count, the participants were escorted to the table, where they filled out the rating sheets.

After all the participants were finished viewing a line, the vehicle was moved to align with the next pavement markings to be viewed, and the process would begin again. The presentation of the pavement markings was counterbalanced.

On wet truck or dry sedan nights, after all pavement markings were viewed, the vehicle was aligned with the middle of the experimental area. The participants were then allowed to walk in front of the experimental vehicle and rank their preference for each of the markings. Only these nights were used because the results for wet sedan and wet truck would be redundant.

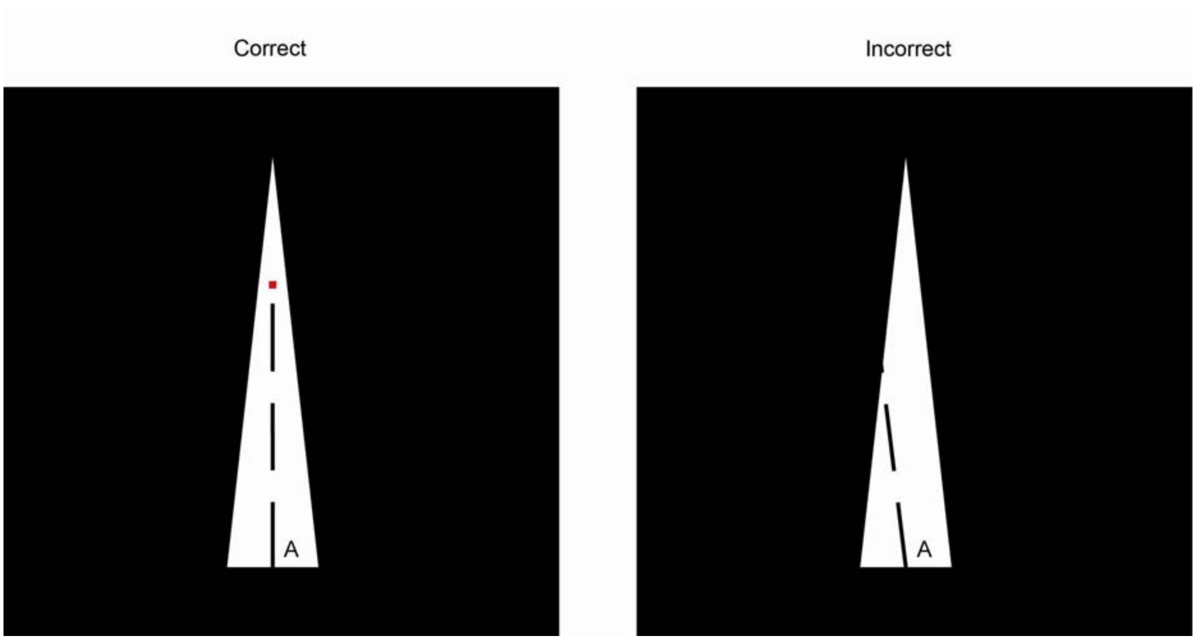


Figure 10. Pavement marking alignment method.

After the rankings were complete, the participants were then returned to the VTTI building and paid for their time.

Data Analysis

The analysis of the data for the saturated evaluations was conducted in two phases. The first was a correlation analysis that developed the relationship of the various measured and calculated values. The second analysis of the data was an ANOVA comparison that established the influence of the independent variables on the results.

Several pieces of data were calculated from measured values. These included the background luminance, contrast, and calculated retroreflectivity. Similarly, the participant count data were converted to a rank based on the participant performance (Max count = 1 and min count = 6; all others were ranked in order by the performance results). The measured and calculated variables used in the analysis are shown in Table 6.

For the ANOVA analysis, the independent variables used were participant number, condition, vehicle, and line. The condition was either wet or dry; vehicle was either truck or sedan; and line was the pavement marking technology being evaluated. The technologies were ordered by the letters A through F and are listed in Table 8. The correlations and the ANOVAs were performed with and without the inclusion of line A, the line with the raised retroreflective markers. The difference in the RRPM technology as compared to the other technologies forced the analyses on this line to be performed separately.

Table 6. Analysis variable summary.

On-Road Measurements	
Ranked Count	Calculated ranking based on the participant performance
Retroreflectivity	Measured on the first skip mark in the series
Photometric Measurements	
Center Luminance	Measured on the third skip mark from the vehicle with the CCD Photometer
Left, Right Luminance	Measured on the adjacent left and right of the third skip mark with the CCD photometer
Background Luminance	Average of the left and right luminances $Background = \frac{Left + Right}{2}$
Calculated Variables	
Visibility Distance	Number of Skip Marks Seen multiplied by 40 ft skip spacing
Contrast	Contrast of Marking and Background $Contrast = \frac{(Marking\ (Center)\ Luminance - Background)}{Background}$
Calculated Retroreflectivity R_L	Calculated from the luminance and illuminance measurements $R_L = \frac{Marking\ (Center)\ Luminance}{Illuminance} \bullet 1000$
Questionnaire Data	
Preference Rank	Participant post-evaluation ranking of pavement marking side by side
Rating in Dry Conditions No Wiper	The Rating is given after each evaluation with the participant rating comfort level in a dry road condition
Rating in Intermittent Wiper Conditions	The Rating is given after each evaluation with the participant rating comfort level in a road condition where wipers would be set on intermittent speed
Rating in Regular Wiper Conditions	The Rating is given after each evaluation with the participant rating comfort level in a road condition where wipers would be set on regular speed
Rating in High Wiper Conditions	The Rating is given after each evaluation with the participant rating comfort level in a road condition where wipers would be set on high speed

In the ANOVA, the dependent variables used were: the number of pavement marking skips identified by the participant ranked as described above, visibility distance, the measured retroreflectivity under standard 30 m geometry, contrast, pavement marking preference ranking, calculated retroreflectivity, and no wiper, medium wiper, regular wiper, and high wiper evaluations. The visibility distance, contrast and the calculated retroreflectivity are calculated (Table 6). The no wiper, medium wiper, regular wiper, and high wiper are the results from the participant rating provided after each marking evaluation.

Two two-factor ANOVAs were conducted with an $\alpha = 0.05$. One ANOVA assessed the impact of the dry versus wet condition and marking type for the sedan. The other ANOVA assessed the impact of the vehicle type and the marking type for the wet condition. Similarly, one way ANOVAs were used on the post evaluation participant ranking data for the wet and dry conditions, Line A was included for the participant rank counts and the participant post-evaluation ratings. Line A was not included in the analyses for the measured retroreflectivity, contrast, and calculated retroreflectivity because of the impact of the RRPMs.

Student-Newman-Keuls (SNK) *post-hoc* analysis was performed for any significant main effect ($p < 0.05$) found in the ANOVAs. For the significant interactions, the means and standard errors were graphed and discussed. Post-hoc analyses assisted in the identification of experimental levels that were responsible for the statistical significance of the main effect.

Recovery Evaluation

The recovery evaluation was made using a similar methodology as that of the saturated measurements. In order to simplify the experimental design, the sedan was the only experimental vehicle. All six pavement markings were used, and the same vehicle setup was used. The dependent variables for this evaluation remained the same.

Participants

Six individuals participated in this evaluation, three males and three females, who had participated in all three sessions of the saturated evaluations. The participants had successfully completed the requirements for the saturated evaluations and pre-experiment activities, which made them eligible to participate for the recovery evaluations.

On the day of the evaluation, participants were asked to reread and initial the informed consent form from the saturated evaluation. They were informed of their right to freely withdraw from the experiment at any time without penalty and that they would be paid for the actual amount of time of participation at a rate of $20 per hr.

Method

The recovery evaluations required only a single night of experimentation for each participant. Unlike the saturated evaluations, participants were run individually. Upon arrival at the building, the participant completed the paperwork and was instructed on the methods for the recovery evaluations. After completion, the participant was driven to the experimental area in an auxiliary vehicle.

After arrival at the experimental area, the participant sat in the passenger seat of the experimental vehicle. Experimental staff were located in the driver's seat and rear seat of the vehicle. As before, a black baffle with the viewing slot was set up on the windshield.

When the participant arrived at the experimental area, the simulated rain was already turned on. The participant was then asked to perform the first evaluation. This was a repeat of the saturated measurement in the previous evaluation. As in the saturated evaluation, the marking luminance and retroreflectivity were recorded.

After this saturated evaluation was complete, the rain was turned off. As soon as the rain stopped falling on the pavement markings, the participant performed an initial count of skip marks, and the experimenters measured the initial luminance and retroreflectivity measurements.

This time period represents the moment without falling rain while the marking is still saturated. After this evaluation was complete, the participant counted the number of visible skip marks every min for 10 min; luminance and retroreflectivity measurements were also made at these intervals.

After the 10 min count was finished, the vehicle was moved to align with the next pavement marking, and the process repeated until all lines had been viewed. The presentation of pavement markings was completely counterbalanced.

Data Analysis

The data from the six participants were merged with the results for the same participant in the saturated evaluation. The measurements of interest were as follows in Table 7:

Table 7. Recovery analysis variable summary.

On-Road Measurements	
Rank count	Calculated ranking based on the participant performance
Retroreflectivity	Measured on the first skip mark in the series
Photometric Measurements	
Center Luminance	Measured on the third skip mark from the vehicle with the CCD Photometer
Left, Right Luminance	Measured on the adjacent left and right of the third skip mark with the CCD photometer
Background Luminance	Average of the left and right luminances $\boldsymbol{Background} = \frac{\boldsymbol{Left} + \boldsymbol{Right}}{2}$
Calculated Variables	
Visibility Distance	Number of skip marks seen multiplied by 40 ft skip spacing
Contrast	Contrast of Marking and Background $\boldsymbol{Contrast} = \frac{(\boldsymbol{Marking}\ (\boldsymbol{Center})\ \boldsymbol{Luminance} - \boldsymbol{Background})}{\boldsymbol{Background}}$
R_L	Calculated from the luminance and illuminance measurements $\boldsymbol{R_L} = \frac{\boldsymbol{Marking}\ (\boldsymbol{Center})\ \boldsymbol{Luminance}}{\boldsymbol{Illuminance}} \bullet 1000$

Each of these variables was graphed versus time. The result was a time series during which the pavement marking was drying; the variable response rose from the saturated value to a stabilized value. The point where the data became stable was selected as the recovery time. Stable was defined as the time when two successive count measurements were equal; for the measured value, a change in 5 percent was used as the stable limit. The recovery time by line was then used as the metric for the comparison of the performance of the marking technologies.

Retroreflectivity Measurements

In this measurement portion of the experiment, the performance of the pavement markings in terms of retroreflectivity was evaluated using both the simulated rain and the ASTM measurement methods. This was performed in two steps: a retroreflectivity by distance measurement and the evaluation of the marking using the ASTM methods.

Retroreflectivity by Distance Measurements

During saturated and recovery evaluations, the luminance, measured retroreflectivity, and calculated retroreflectivity were evaluated, assuming a standard 30 m geometry. As mentioned, this is the geometry of the observer and the vehicle headlamps prescribed by ASTM for the measurement of retroreflectivity. In order to more fully understand the needs of the driver at night, the actual retroreflectivity at the visibility distance of the driver needed to be evaluated. This was performed by measuring the luminance of each pavement marking on the experimental area from the experimental vehicle, and the vertical illuminance provided by the vehicle headlamps at the center of the furthest skip-mark counted by the participants.

Using the results of the saturated evaluations, the maximum and minimum numbers of skip marks seen by all of the participants were established. Using these as the limits, the experimental vehicle was aligned to the pavement marking on the experimental area. The CCD photometer was mounted in the vehicle's passenger seat where the participant would have been seated. For each pavement marking type, an image of the roadway was then taken that showed all of the pavement markings of interest; pavement marking luminance was measured from this image. The illuminance at each location was also measured. This allowed for the calculation of the actual retroreflectivity at all markings, not just those at 30 m geometry.

This measurement was taken for all conditions used in the saturated evaluation: wet sedan, wet truck, and dry sedan.

ASTM Measurement Methods

The ASTM Measurement Methods for retroreflectivity consist of two types of measurements: the Flooded (Bucket) Method [5] and the Continuous (Sprayer) Method [6]. Both methods were performed on the road using a retroreflectometer to collect measurements.

The flooded method is intended to produce a condition of wetness like that found just after rainfall (Figure 11). In this test method, pavement markings are saturated with a large volume of water, and then allowed to drain for a specified period of time. Retroreflectivity measurements were taken 45 s after a gallon of water was poured on the pavement marking.

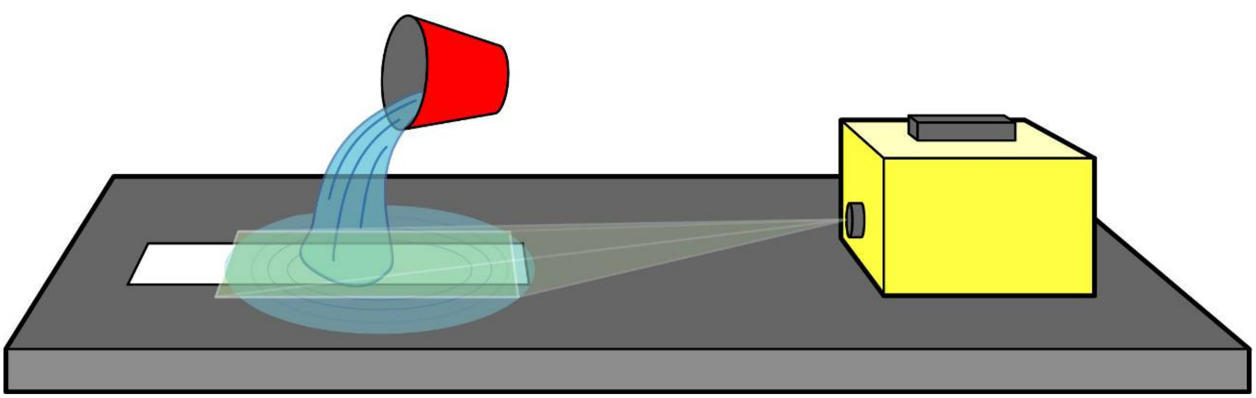


Figure 11. Flooded measurement method.

The continuous method is intended to produce a condition of wetness like that found during rainfall (Figure 12). To create this condition, a sprayer was held 18 in directly above the pavement marker. The sprayer was moved in a circular motion creating a 20-in-diameter wet patch. After 15 s of continuous wetting, three consecutive measurements were made during constant spraying of the pavement marking. The sprayer was set to spray 0.8 L of water per min.

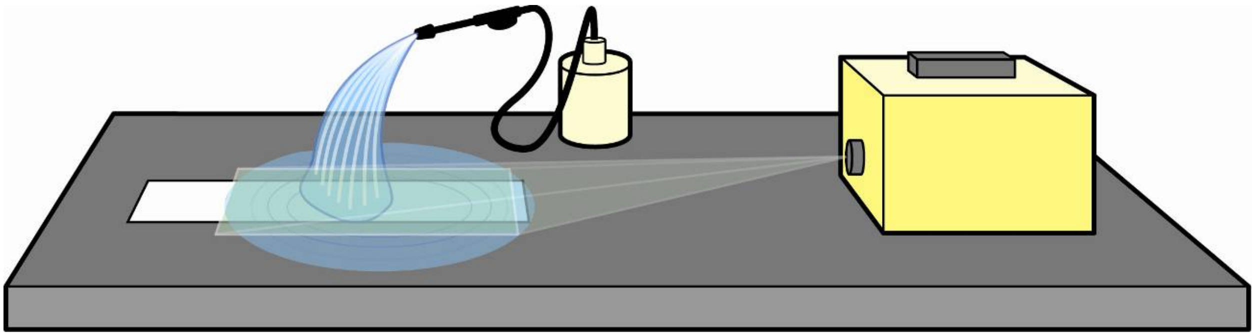


Figure 12. Continuous measurement method.

The results of these ASTM measurements can be compared to measurements in the recovery evaluations because the flooded and continuous methods represent conditions found in that process (Figure 13).

Figure 13. Measurement methods in practice.

Equipment

Experimental Area

The experiment was performed at the Smart Road facility. The Smart Road is a unique, state-of-the-art, full-scale research facility for pavement research and evaluation of vehicle and infrastructure technologies. The Smart Road is the first facility of its kind to be built from the ground up with its infrastructure incorporated into the roadway. It is currently a two-mile, two-lane road with a banked turnaround at one end and a slower-speed turnaround at the other end.

For this experiment, an auxiliary pavement section was paved to the side of the main Smart Road facility. This pavement section is 1,200 ft long with a constant grade of two percent. The experimental area was also paved flat, meaning it had no central crown or superelevation. The pavement type was bituminous asphalt. It should be noted that this asphalt surface did not have the final top coat of material installed, which left a relatively open surface, which might have impacted the drainage characteristics of the surface.

As the experiment was not to be on the main Smart Road, a new rain system was developed. This rain system used the existing water supply and pumping system from the main Smart Road, but it utilized a portable hose to direct the water to the auxiliary experimental area. The water was then directed through an above-ground steel pipe to which the rain towers were attached. Using the Smart Road pumping system, a constant water pressure was distributed to the towers. Each tower was equipped with a control valve to individually tune the tower's water pressure. Because the experimental area is sloped, individual tower control was required in order to provide an even rain distribution across the entire experimental area.

The rain towers were located every 30 ft, requiring that 40 towers be used for the system. The towers were mounted on portable, removable concrete bases. The tower heads were positioned over the centerline of the pavement marking area.

The experimental area with the rain system functioning is shown in Figure 14.

Figure 14. Experimental area during the daytime.

The rain system performance was characterized using standard rain measurement gauges. These measurements were made using nine gauges spread across the road. These were placed in a row starting underneath one rain tower. After measurement, the gauges were moved 10 ft. This was continued three times until the row of gauges was immediately underneath the next rain tower. This process, performed under Towers 4 and 5, allowed for evaluation of the consistency of the rain across the experimental area. The process of measuring the rain is shown in Figure 15. The results of the measurements are shown in Figure 16. In these figures, the first gauge (gauge 1) was located at the leftmost edge of the road, which is the rain tower side, and gauge 9 was located at the rightmost edge, the farthest edge from the towers.

Figure 15. Rain characterization in progress.

The rainfall deviation along the length of the roadway appears to be quite substantial. The important issue for this experiment, however, is to minimize the rainfall variance across the width of the roadway to ensure that all markings receive the same amount of rainfall. The mean of the rainfall at each location along the road was then compared to the mean for the entire area. This result is shown in Figure 17.

As shown, the deviation of the mean rainfall across the roadway from the overall mean is within +/- 6% across the road from one side to the other. The primary area for the pavement marking placement is between gauge locations 3 and 7, where the deviation from the mean is even less.

Pavement Markings

Six different types of pavement markings were viewed by the participants during the evaluations. These were installed on the experimental area from one end to the other in a standard single-skip line formation (10 ft lines with 30 ft spaces). Spacing of 40 ft was used

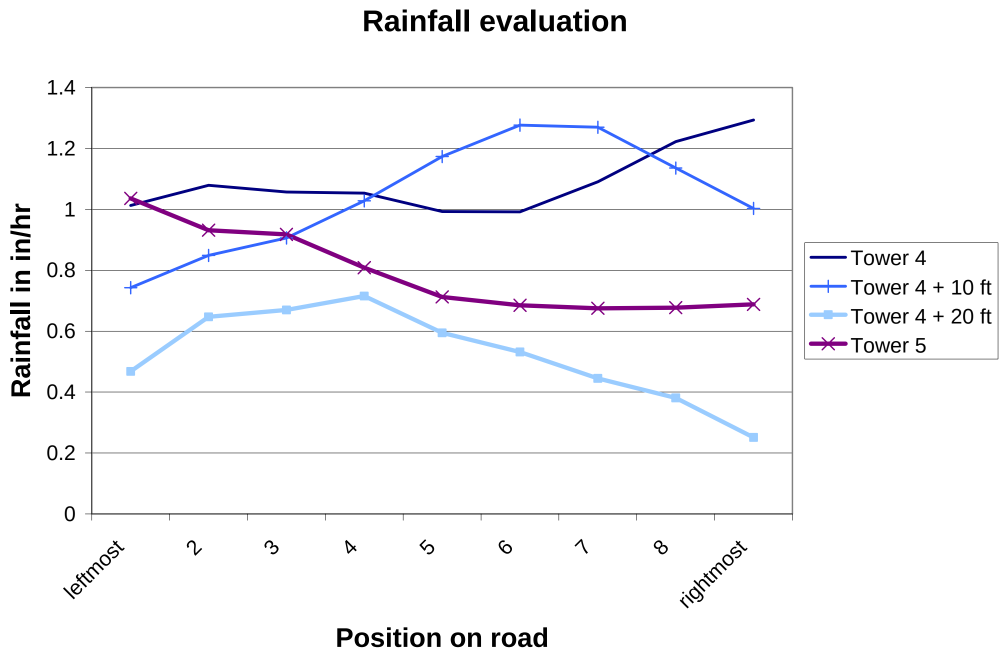


Figure 16. Rain characterization results.

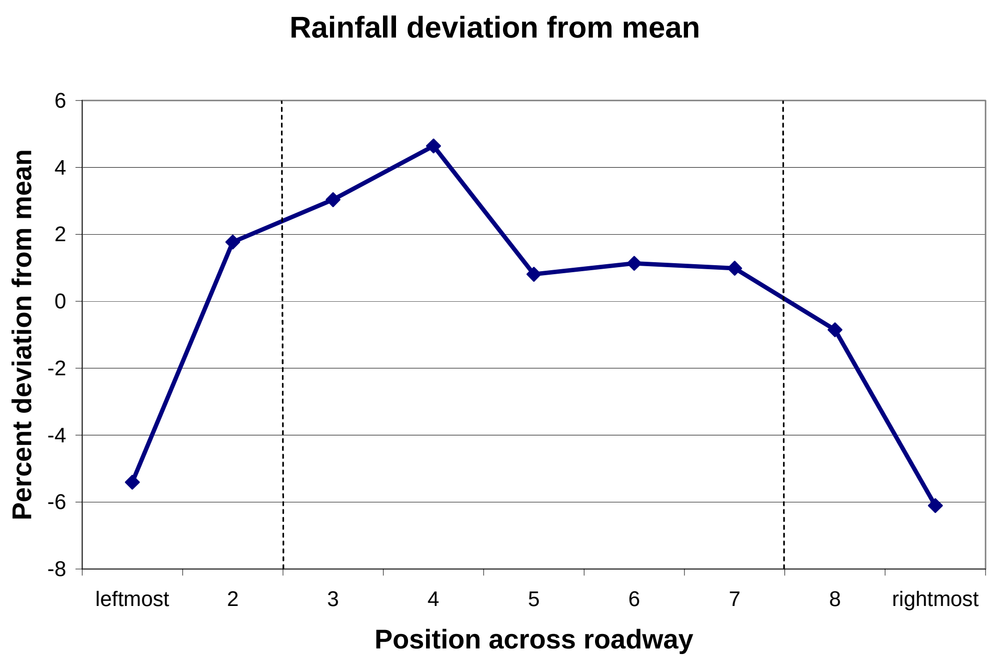
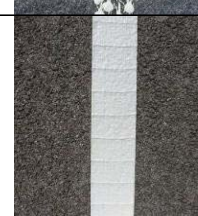


Figure 17. Rain characterization results.

between the RRPMs, which is different than the standard 80 ft spacing used by VDOT. The lateral spacing between the different types of markings was 2 ft. The technologies used are summarized in Table 8.

Table 8. Pavement marking technology summary.

Marking	Technology	Supplier/Trade Name	Image
A	Standard Latex Paint with Standard Glass Beads and Raised Retroreflective Markers	The Paint and Beads Conform with VDOT Road & Bridge Specification 2002 Section 246 RRPMs Are 3M PSA 290 Type Self Adhesive Markers with Red and White Lenses	
B	Standard Latex Paint with Standard Glass Beads	The Paint and Beads Conform with VDOT Road & Bridge Specification 2002 Section 246	
C	Standard Latex Paint with Large Glass Beads	Latex Paint and Visibeads Supplied by Potters Industries	
D	Profiled Thermoplastic	Drop on Line by Brite Line Technologies	
E	Wet Retroreflective Tape	3M 750 Tape	
F	Semi-Wet Retroreflective Tape	3M 860 Tape	

Experimental Vehicles

The two experimental vehicles used were a sedan and a truck tractor, both with standard halogen headlamps. The sedan was a 1998 Ford Crown Victoria, and the truck was a 1997 Volvo VN series class 8 tractor. In order to aid the participants in getting in and out of the experimental vehicles, a swiveling seat was installed in the sedan and a portable set of stairs was used with the truck.

The experimental vehicle headlights were the sole source of illumination during the experimental session. The headlamps were aligned using the standard Society of Automotive Engineer (SAE) alignment method. Note that using two headlamps for calculation of a single value of retroreflectivity is not typical as each light source results in a different value of retroreflectivity due to the different geometries presented by the headlamp, the measurement point on the road and the driver.

The actual viewing height and the headlamp height for each of the vehicles were measured. These are summarized in Table 9.

Table 9. Vehicle headlamp and viewing heights.

Vehicle	Headlamp Height	Entrance Angle	Viewing Height	Observation Angle
Sedan	27 in.	88.7°	45 in.	0.87°
Truck	37.5 in.	88.2°	88 in.	2.44°

An alignment grid installed at the experimental area allowed the experimental vehicles to be positioned such that the passenger seat was in line with the pavement marking to be evaluated. The vehicles were also positioned so that the headlamps were 30 m from the center of the third skip mark in the line. During the experiment, the vehicles were moved from one line to the next, aligning the driver's side tires to the grid shown in Figure 18.

Measurement Equipment

Three instruments were used in the experiment: an illuminance meter, a CCD photometer, and a retroreflectometer.

For the roadway illuminance measurement, a Minolta T-10 illuminance meter was used. A waterproof remote measurement head was used with the standard instrument body. A constructed fixture held the detector head in a vertical orientation. The instrument was laid flat and centered on the pavement marking and was aimed at the experimental vehicle during the measurement. When measuring in the rain, variation in the measurement required the experimental staff performing the measurement to manually average the reading over time. The illuminance reading was the vertical illuminance at the marking mid-point. As the calculation of retroreflectivity requires the illuminance normal to the incident angle of the light (1.3° or 1.7°) the illuminance values should be corrected for the slight difference between the vertical and the normal of the incident angle. As this would result in a correction factor less than 0.05 percent, and for consistency across all of the conditions, this correction was ignored.

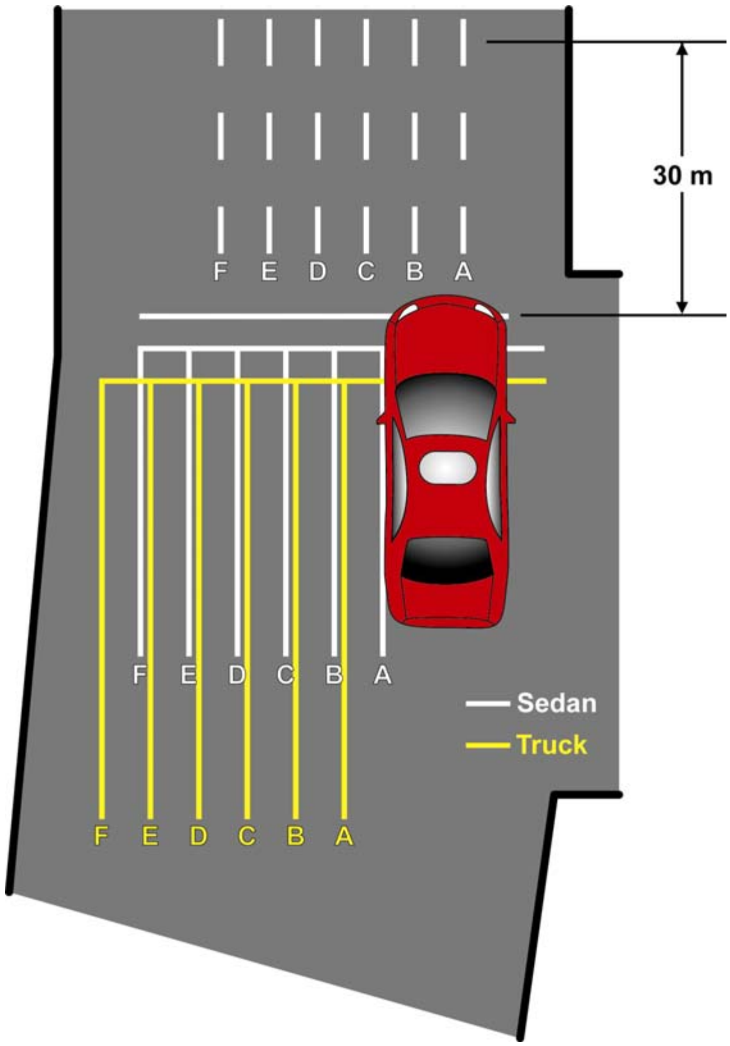


Figure 18. Alignment grid.

The luminance was measured with a Radiant Imaging CCD photometer with a 300 mm lens. The CCD photometer provided a method of capturing the luminance of an entire scene at one time. The object of interest in the scene can then be analyzed. Using the software provided with the system, the average luminance of the object and that of its background were measured as shown in Figure 19.

The final instrument was an external beam Mechatronic FRT 01 retroreflectometer. Using the measurement procedure developed by Mechatronic, the measurement was taken from a point 3 m from the center of the pavement marking line. Software was developed which allowed the measurement to be controlled by the experimenter in the vehicle. A waterproof cover was developed for the instrument that allowed for measurements to be made while the instrument was in the rain.

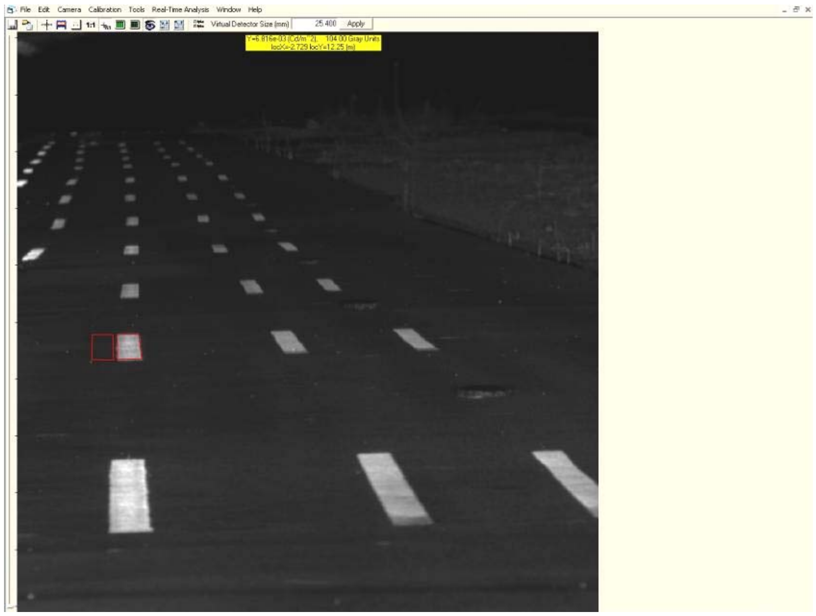


Figure 19. Measurement using the CCD photometer with the highlighted area of interest.

The Mechatronic FRT 01 was selected for this experiment because the instrument uses an external beam, which allows it to take retroreflectivity measurements at a distance. Since it projects the beam to a spot 3 m in front of the instrument, it also allows for measurement under the ASTM test method for continuous wetting, and under simulated rain. During the rain evaluations, the beam was attenuated by droplets falling through it. This may have caused the measured values to have higher levels of uncertainty.

Results

Saturated Evaluation

Correlation Analysis

Three Pearson *r* correlation matrices were generated to assess correlation between the following measurements: RANK COUNT (ranked number of pavement marking skip lines identified by the participant, Skip Line LUMINANCE, RETRO (the measured retroreflectivity under standard 30 m geometry), VISDISTANCE (visibility distance), CONTRAST, PREF RANKS (pavement marking preference ranking), and R_L (calculated retroreflectivity) across five pavement marking technologies: line B (standard paint and beads), line C (paint with large beads), line D (thermoplastic profile type markings), line E (wet retroreflective tape), and line F (semi-wet retroreflective tape). Data from the pavement marking technology, line A (RRPMs), were excluded from the correlation analyses due to the different technology that this pavement marking offers compared to the other pavement markings. In addition, as discussed earlier, there were no data for pavement marking preference ranking for the wet sedan condition.

A Pearson *r* correlation matrix was generated for both marking conditions, wet and dry, and both vehicle types, sedan and truck (Table 10). There were 15 observations for all the variables of interest except pavement marking ranking for which there were 10 observations.

Table 10. Pearson r correlation coefficients for all conditions and vehicles.

	Rank Count	Skip Marking Luminance	Retro	VisDistance	Contrast	Pref Ranks	R_L
Rank Count	1.000						
Skip Marking Luminance	0.481	1.000					
Retro	0.568	0.933	1.000				
VisDistance	0.695	0.857	0.796	1.000			
Contrast	0.838	0.711	0.821	0.765	1.000		
Pref Ranks	0.903	0.381	0.444	0.615	0.853	1.000	
R_L	0.491	1.000	0.937	0.861	0.722	0.393	1.000

The ranked count of pavement markings identified by the participant shows a very high correlation with the contrast (r = 0.84) and the participant preference ranking (r = 0.90). The rank also moderately correlates with the measured retroreflectivity (r = 0.57). The pavement marking luminance is highly correlated with the measured retroreflectivity (r = 0.93) and the visibility distance (r = 0.86). The measured retroreflectivity shows the highest correlation with the calculated retroreflectivity (r = 0.94). The measured retroreflectivity is also highly correlated with the visibility distance (r = 0.80) and the contrast (r = 0.82). The visibility distance shows a high correlation with the calculated retroreflectivity (r = 0.86) and the contrast (r = 0.77) and a moderate correlation with the pavement marking ranking (r = 0.62). Besides the correlation mentioned above with the number of skip marks identified by the participant, the measured retroreflectivity, and the visibility distance, the contrast also shows a high correlation with the pavement marking preference ranking (r = 0.85).

A Pearson *r* correlation matrix was generated for the sedan including both marking conditions (wet and dry) (Table 11). There were 10 observations for all the dependent variables except pavement marking ranking for which there were five observations only in the dry condition.

When looking at the sedan data only, the relationship of marking luminance and the participant preference rankings is strengthened as compared to the analysis for all data (r = 0.95). Similarly, the calculated retroreflectivity, and the participant preference ranks relationship is also strengthened (r = 0.95). All of the other relationships are similar to those listed above.

A Pearson *r* correlation matrix was generated to look at the wet data only. Both vehicles were included in the data (sedan and truck) (Table 12). There were 10 observations for all the dependent variables except pavement marking preference ranking for which there were five observations.

Table 11. Pearson r correlation coefficients for wet and dry sedan.

	Rank Count	Skip Marking Luminance	Retro	VisDistance	Contrast	Pref Ranks	R_L
Rank Count	1.000						
Skip Marking Luminance	0.491	1.000					
Retro	0.568	0.926	1.000				
VisDistance	0.593	0.881	0.782	1.000			
Contrast	0.804	0.744	0.832	0.702	1.000		
Pref Ranks	0.661	0.953	0.670	0.692	0.944	1.000	
R_L	0.498	1.000	0.928	0.882	0.751	0.953	1.000

Table 12. Pearson r correlation coefficients for saturated sedan and saturated truck.

	Rank Count	Skip Marking Luminance	Retro	VisDistance	Contrast	Pref Ranks	R_L
Rank Count	1.000						
Skip Marking Luminance	0.842	1.000					
Retro	0.757	0.988	1.000				
VisDistance	0.976	0.825	0.752	1.000			
Contrast	0.874	0.991	0.976	0.873	1.000		
Pref Ranks	0.988	0.867	0.772	0.988	0.894	1.000	
R_L	0.843	1.000	0.989	0.828	0.993	0.867	1.000

This matrix generated very high correlations, ranging from the lowest (r = 0.75), for the correlation of the measured retroreflectivity with the visibility distance, to the highest (r = 0.99), for the correlation of the measured retroreflectivity with the calculated retroreflectivity. In the previous two correlation matrices, the number of pavement skip marks identified by the participant show low correlations with the center luminance and the calculated retroreflectivity, and showed only moderate correlation with the measured retroreflectivity. In this matrix, the rank count variable (rank of number of identified skip marks) shows high correlations with the center luminance (r = 0.84), the measured retroreflectivity (r = 0.76), and the calculated retroreflectivity (r = 0.84). The rank count has the highest correlation with the pavement marking preference ranking (r = 0.99) and the contrast (r = 0.87). Beside the high correlations with the calculated retroreflectivity and the number of pavement skip marks identified by the participant, the contrast shows very high correlations with the measured retroreflectivity (r =

0.98), the visibility distance (r = 0.87) and the pavement marking preference ranking (r = 0.89). The pavement marking preference ranking is also highly correlated with the skip marking luminance (r = 0.87), the measured retroreflectivity (r = 0.77), the visibility distance (r = 0.99) and the calculated retroreflectivity (r = 0.87). Furthermore, the calculated retroreflectivity is highly correlated with the measured retroreflectivity (r = 0.99) and the visibility distance (r = 0.83). Lastly, the skip marking luminance, which shows a high correlation with the pavement marking preference ranking, shows high correlations with the measured retroreflectivity (r = 0.99) and the visibility distance (r = 0.83).

Historically, the human psychophysical response to a stimulus follows a relationship that can be approximated by a logarithmic relationship (Gescheider, 1997). As the pavement marking luminance, and in turn the contrast, measured retroreflectivity, and calculated retroreflectivity, represent measurements which humans respond to psychophysically, the response to this stimulus is typically related to the logarithm of the intensity of the source. This means that the visibility distance should be compared to the logarithm of the measured values. A correlation analysis that related these values is shown in Table 13 for all vehicles and all conditions.

Table 13. Correlation Coefficients for the Visibility Distance and the Log of the measured and calculated values.

	Log (Marking Luminance)	Log (Measured Retroreflectivity)	Visibility Distance	Log (Contrast)	Log (Calculated Retroreflectivity)
Log (Marking Luminance)	1.000				
Log (Measured Retroreflectivity)	0.955	1.000			
Visibility Distance	0.977	0.935	1.000		
Log (Contrast)	0.935	0.887	0.942	1.000	
Log (Calculated Retroreflectivity)	1.000	0.956	0.978	0.938	1.000

It can be seen that there is a substantial improvement of the Pearson Correlation Coefficients in this analysis over those calculated in the linear analysis. All of these correlations show a very high relationship between the metrics. The best of these correlations being that for the visibility distance with the pavement marking luminance and with the calculated retroreflectivity.

Analysis of Variance: Rain and Dry Condition

The ANOVA analysis to assess the change from dry to rain conditions was investigated by performing the analysis on the participant results for the sedan only. An ANOVA was performed on the objective measurements taken on the road, the calculated values, and the post-evaluation questionnaire. The model for this analysis was a 2 (condition) x 6 (lines) repeated measure design. ANOVA summary tables for the following dependent measurements are presented as part of Appendix C. All of the measured and calculated retroreflectivity values listed previously were included in the analysis.

In the analysis, the condition main effect shows a significant difference ($p < 0.05$) in all dependent measurements. The line main effect shows a significant difference ($p < 0.05$) in all dependent measurements. The line x condition ($p < 0.05$) interaction is significant for all dependent measurements as well. The results for the significant main effects and interactions are graphed (Figures 20-29) with standard error bars for the means.

The first analysis is for the visibility distance variable. As the visibility distance is dependent on the count of the number of pavement markings seen by the participants, the number of skip lines visible was not considered. The ANOVA was performed with all of the marking technologies (A-F) included.

In this comparison, the rain condition shows significantly worse performance than the dry condition with the same technologies. The interaction of the line type and the condition is shown in Figure 20.

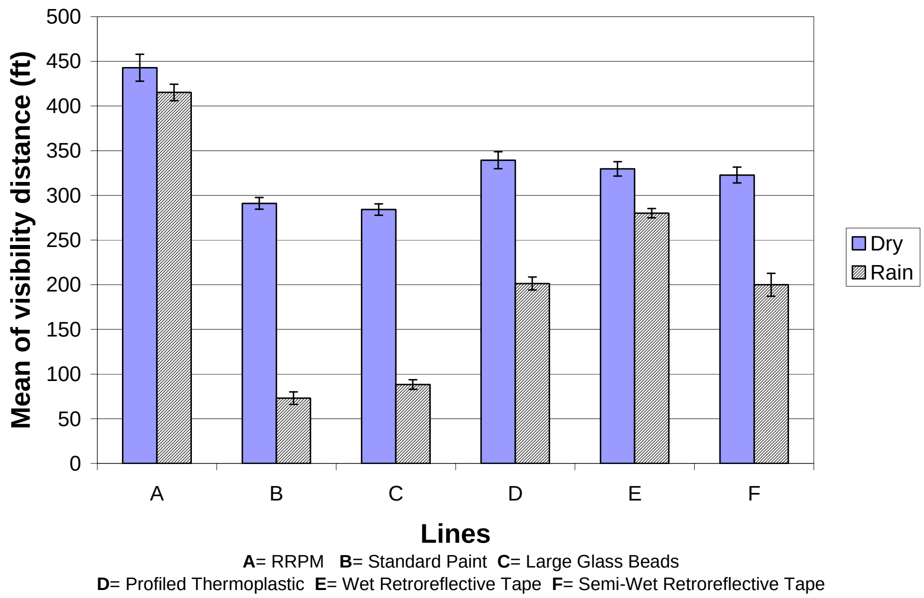


Figure 20. Sedan: Results of the visibility distance for the condition x line interaction.

The interaction of the pavement marking technology and the rain/dry conditions shows that the RRPM technology is impacted very little by rain. The wet retroreflective tape, profiled thermoplastic, and semi-wet retroreflective tape show similar performance in the dry condition, but in the rain condition the wet retroreflective tape shows the least impact from the rain, and the semi-wet tape and the thermoplastic show similar rain performance. Finally, the standard paint and beads shows the worst rain performance, with only a slight improvement by adding the large bead technology.

Table 14 shows the mean visibility distances measured in the evaluation.

Table 14. Visibility distance summary (ft).

Technology	Dry Condition	Rain Condition
A – RRPM	442	415
B – Standard Paint and Beads	291	73
C – Paint and Large Glass Beads	284	88
D – Profiled Thermoplastic	339	201
E – Wet Retroreflective Tape	329	280
F – Semi-Wet Retroreflective Tape	322	200

Like the visibility distance, the measured retroreflectivity shows a significant difference between the rain and dry conditions. The ANOVA for the measured retroreflectivity excluded the RRPMs. These markers were not able to be measured during the participant evaluations. Figure 21 shows the variation in the measurement by line. In this figure, lines B, C, and F all show similar performance (though statistically different), while Lines D and E show better individual performances.

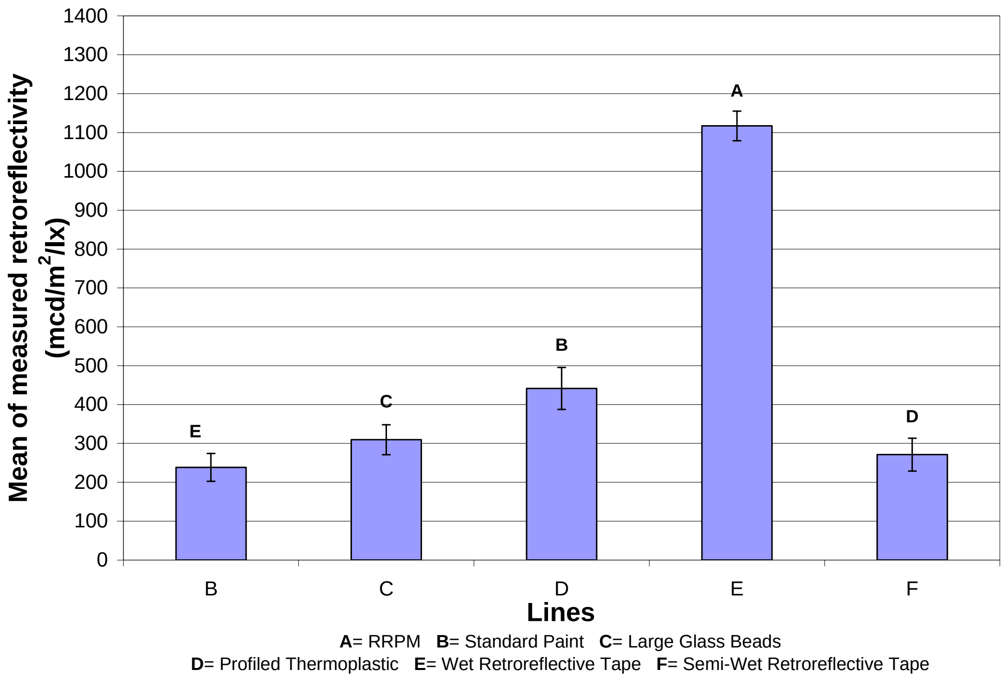


Figure 21. Condition without line A: SNK post-hoc results of measured retroreflectivity for the line main effect (means with the same letter are not significantly different).

The interaction of the line and conditions is shown in Figure 22. This interaction is similar to that of the marking count; however, the degradation of the measured retroreflectivity is much more significant than was found in the participant count measurement. This is particularly noticeable in the cases of the Lines B, C, and F.

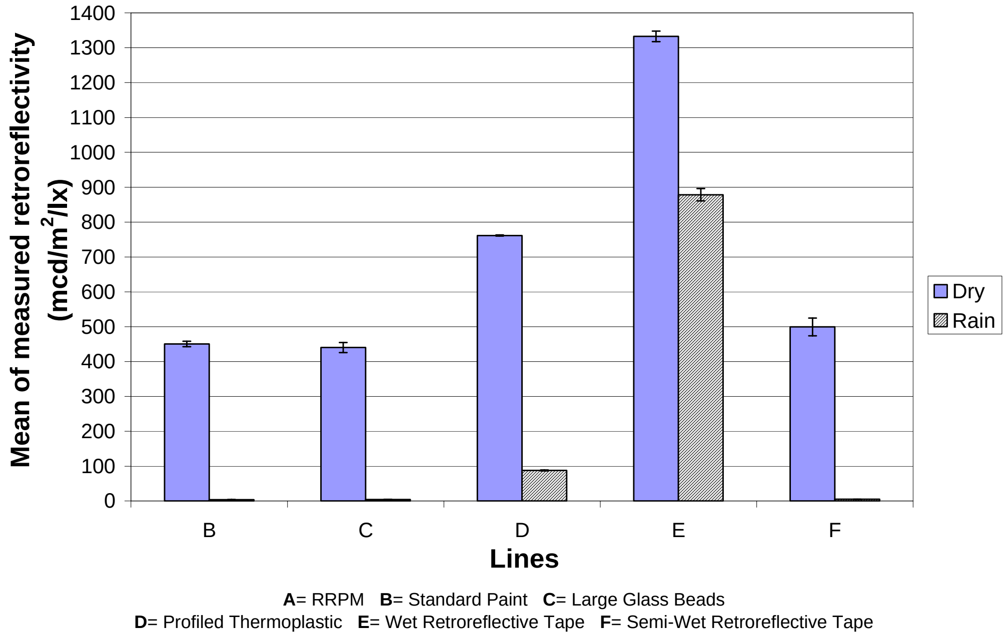


Figure 22. Condition without line A: Results of measured retroreflectivity for the condition X line interaction.

For the contrast variable, the calculations were made without the inclusion of the RRPM (line A) data. The luminance of the pavement markers is much higher than that of the regular lines and cannot be included in the analysis.

The results showed that the contrast drops in the rain condition as compared to the dry condition. This drop in the contrast because of the rain is typical with all of the dependent variables in the evaluation.

Figure 23 shows the impact of the line on the measured contrast. This pattern also shows a similar behavior as that of the other variables. It should be noted that line F (semi-wet retroreflective tape) is in a separate group, but in the participant count, it is grouped with the profiled thermoplastic.

Finally, Figure 24 shows the interaction of line and condition. The reduction in the contrast in the rain for lines F and D are not as significant as those in the measured retroreflectivity. Another interesting result is the increase in contrast in the rain for line E. This is likely because of the reduction in the pavement (background) luminance as it gets wet while the marking luminance does not drop as much.

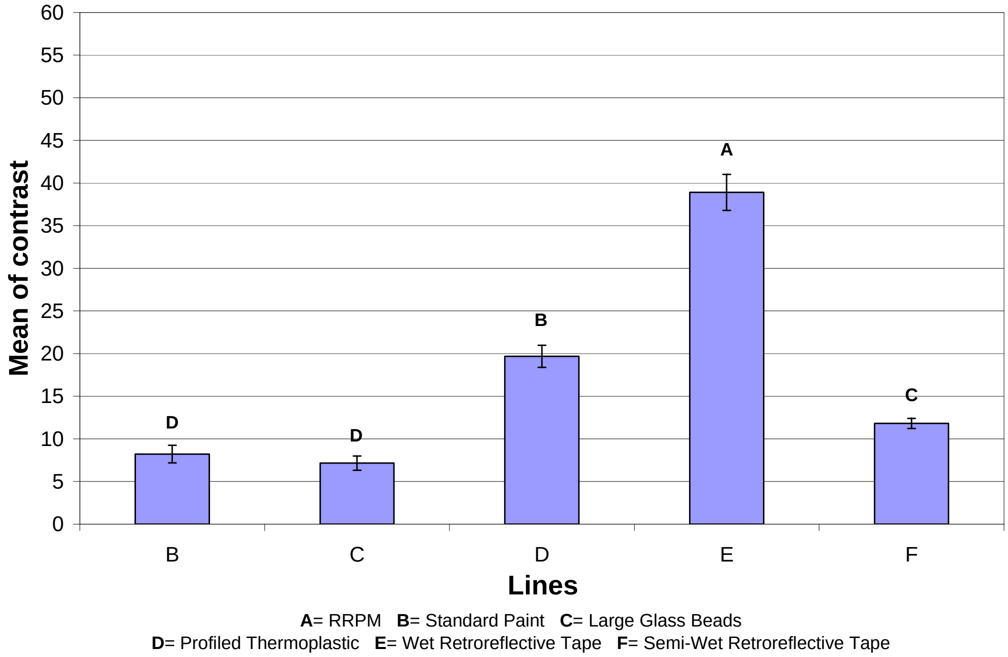


Figure 23. Condition without line A: SNK post-hoc results of contrast for the line main effect (means with the same letter are not significantly different).

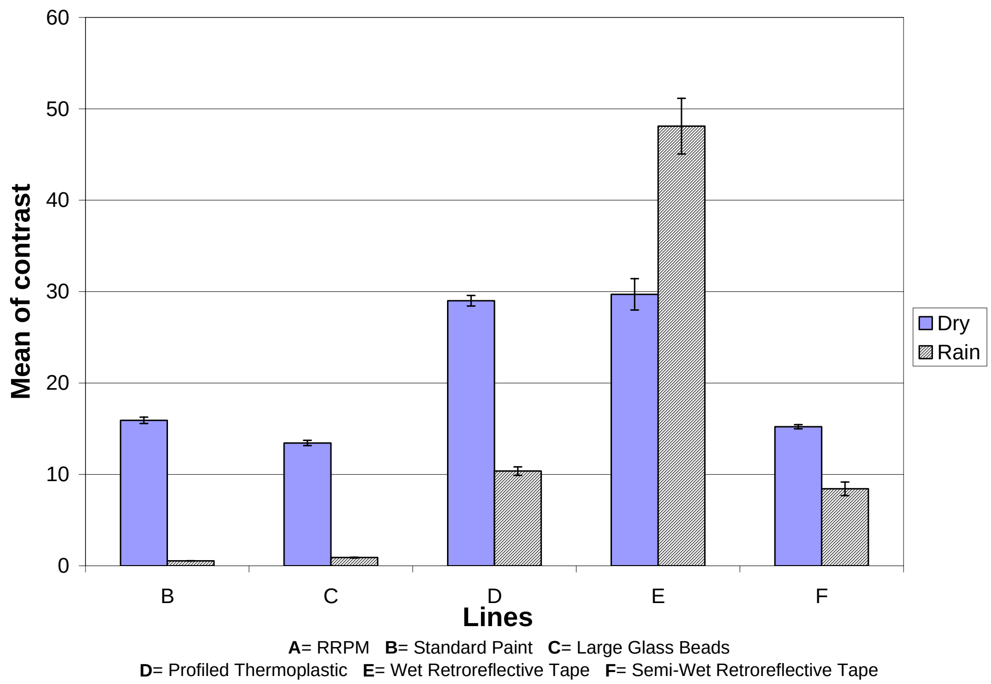


Figure 24. Condition without line A: Results of contrast for the condition X line interaction.

As with the measured retroreflectivity, the calculated retroreflectivity analysis does not include line A. The comparison of these measurements to those of the measured retroreflectivity shows that the calculated retroreflectivity is much lower than the measured retroreflectivity. Table 15 shows the mean values of the measured and calculated retroreflectivity.

Table 15. Measured and calculated retroreflectivity summary.

	Rain		Dry	
Technology	Measured	Calculated	Measured	Calculated
B – Standard Paint and Beads	3.91	4.41	450	128
C – Paint and Large Glass Beads	4.44	5.316	440	123
D – Profiled Thermoplastic	87.8	30.4	761	238
E – Wet Retroreflective Tape	878.6	142.7	1332	241
F – Semi-Wet Retroreflective Tape	5.06	21.98	499	124

Despite the difference between measured and calculated retroreflectivity, the correlation analysis shows that the measured and calculated retroreflectivity is r = 0.93. This means that the difference is likely a scaling factor between two variables with some variability due to measurement noise. The impact of the skip marking type and the interaction of the line and rain condition are shown in Figures 25 and 26.

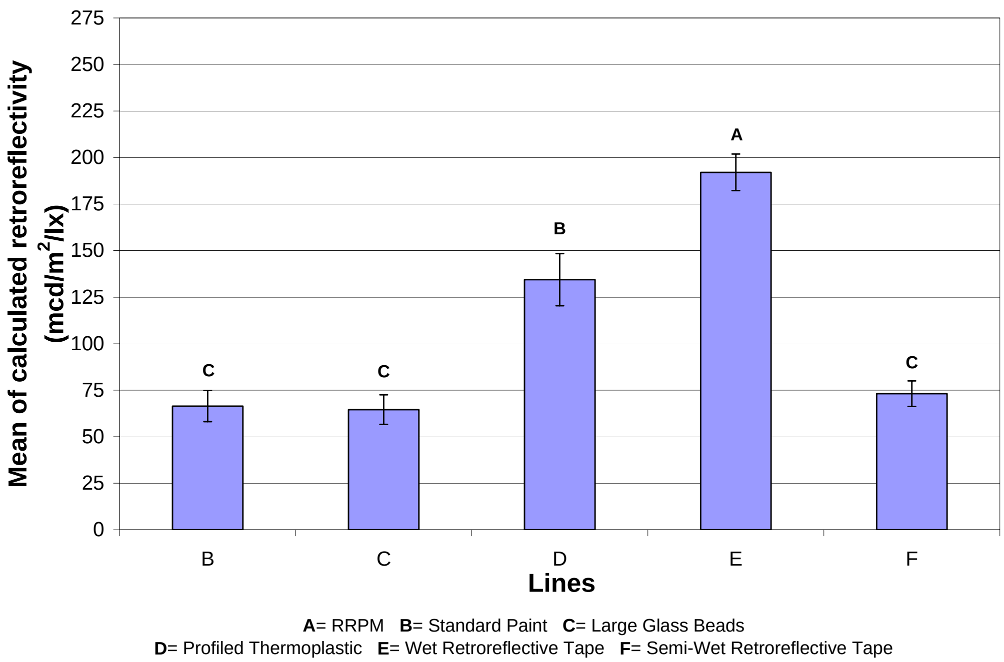


Figure 25. Condition without line A: SNK post-hoc results of calculated retroreflectivity for the line main effect (means with the same letter are not significantly different).

The post-evaluation ratings were performed by every participant; they assessed their comfort level with each of the pavement marking technologies. These questionnaires were completed immediately after the participant had seen the condition on the road. The same questionnaire was used for both the rain and dry conditions. The results were investigated using the speed of the wipers as an indication of the amount of rain on the road. The participant was asked to scale their driving comfort level from 1 (uncomfortable) to 5 (comfortable) for the conditions of dry road, intermittent (low) wipers, regular (medium) wiper speed, and high wiper speed. The main effect of condition is shown in Figure 27. All of the wiper speeds are shown in this figure.

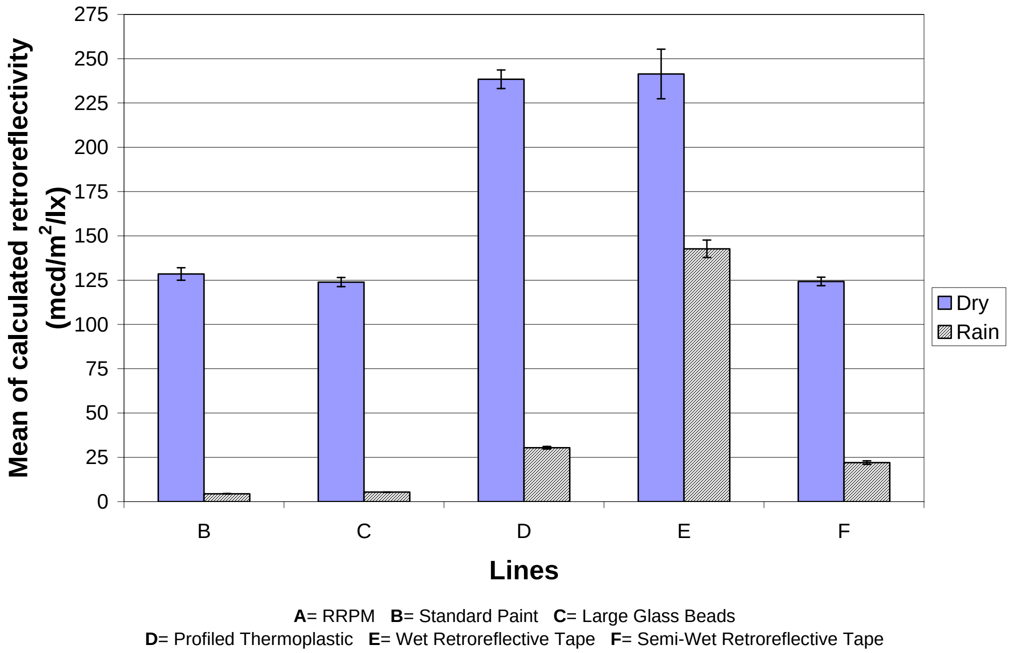


Figure 26. Condition without line A: Results of calculated retroreflectivity for the condition X line interaction.

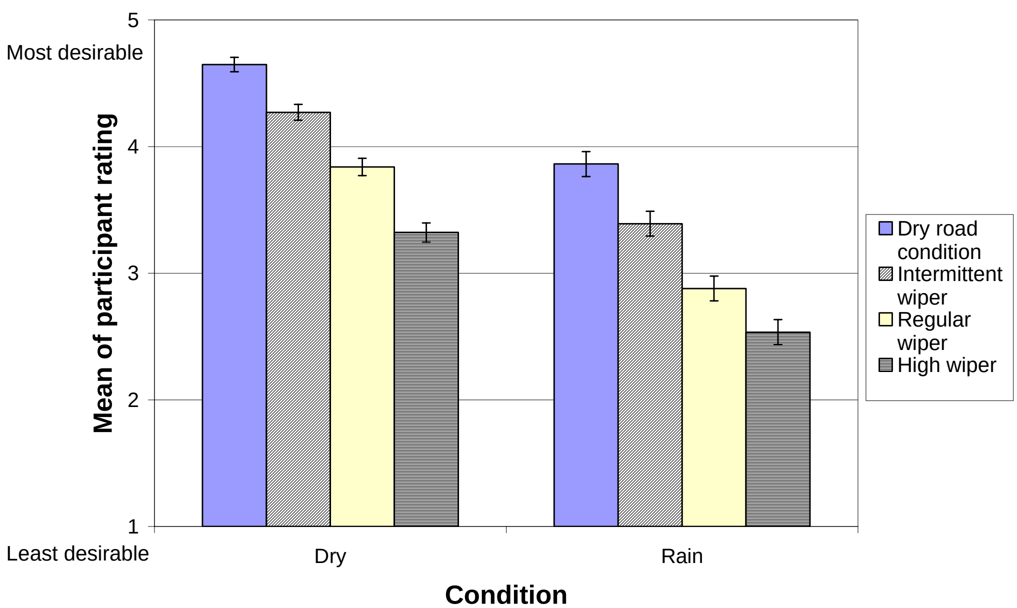


Figure 27. Impact of rain condition on participant rating for the sedan.

The participants show a reduction in their comfort level in the rain condition versus the dry. The participants also show a reduced comfort level with increasing wiper speed and rain rate.

The main effect of line type is shown in Figure 28, and the interaction of condition x line is shown in Figure 29. The main effect is primarily a result of the interaction between the line and condition. For the interaction, the SNK levels indicate that generally line types B and C are equally grouped for comfort. Lines D and F are equivalent in comfort, and lines E and A are not grouped. The interaction of the condition and the line shows that after viewing the pavement marking technologies under dry conditions the participants were equally comfortable will all the pavement marking technologies. However, after viewing the markings in the rain condition, comfort with lines B and C is significantly reduced. Comfort with Lines D and F is slightly reduced, while Lines E and A do not have a reduced comfort level in the rain versus the dry. This result shows that in general, the public is not able to assess their comfort level with the markings without seeing the actual condition on the roadway.

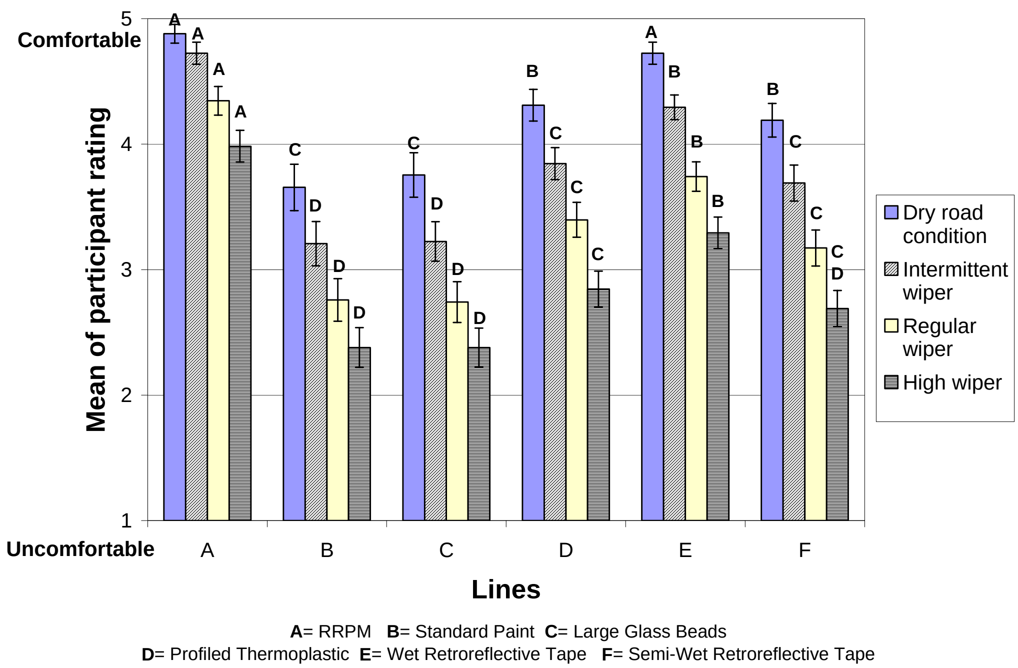
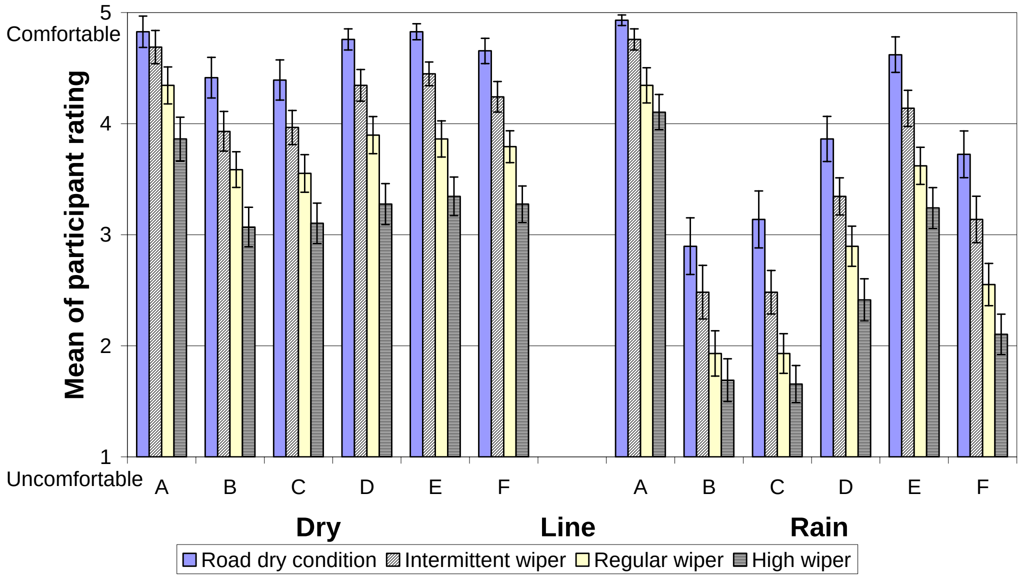


Figure 28. Impact of line type on participant rating for the sedan.

Analysis of Variance: Vehicle Impact

An ANOVA was performed to investigate the influence of the vehicle type on the measured and calculated retroreflectivity values. Like the analysis performed on the condition variable, ANOVAs were performed on all of the measured and calculated variables as well as those from the post-evaluation questionnaire. As before, Line A was included for the participant count and the visibility distance but was excluded from the contrast and measured and calculated retroreflectivity. Only the data from the rain condition were included in this analysis. The model for this analysis was a 2 (vehicle) x 6 (lines) repeated measure design. ANOVA summary tables created for the dependent measurements are presented in Appendix D.



A= Standard Latex Paint with Raised Retroreflective Markers **B**= Standard Latex Paint **C**= Latex Paint with Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retorereflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 29. Impact of line type and rain condition on participant rating for the sedan.

The vehicle main effect shows significant differences ($p < 0.05$) in the following measurements: number of pavement skip marks identified by participant, measured retroreflectivity, visibility distance, calculated retroreflectivity, and pavement marking preference rating with wipers on regular setting. The line main effect shows significant differences ($p < 0.05$) in all dependent measurements. The line x condition interaction shows significant differences ($p < 0.05$) in the following measurements: measured retroreflectivity, visibility distance, contrast, calculated retroreflectivity, pavement marking preference rating with wipers on regular setting, and pavement marking rating with wipers on high setting. The results for the significant main effects and interactions were graphed with standard error bars for the means. For the graphs of the line main effect, means with the same letter are not significantly different (based on the SNK *post-hoc* test).

The visibility distance results show that the truck provided greater distance than does the sedan. On average, this seems to show an improvement in the visibility distance of approximately one additional skip mark.

The influence of the line type is shown in Figure 30. Here the RRPM technology shows the best performance, followed by the wet tape. The profiled thermoplastic and the semi-wet tape show the same grouping. In this analysis, the paint with large glass beads shows a slight improvement in visibility distance over the standard paint and beads.

The interaction of the line and vehicle type is not significant and not presented here.

Table 16 is a summary of the calculated visibility distances.

Table 16. Visibility distance summary.

Technology	Truck	Sedan
A – RRPM	428	451
B – Standard Paint and Beads	182	94
C – Paint and Large Glass Beads	186	108
D – Profiled Thermoplastic	270	217
E – Wet Retroreflective Tape	304	299
F – Semi-Wet Retroreflective Tape	261	208

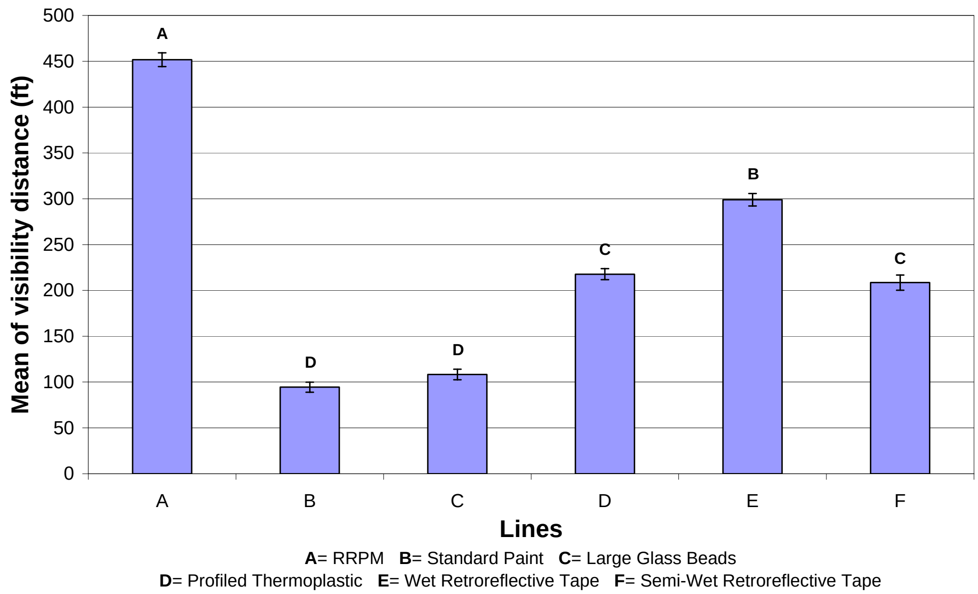
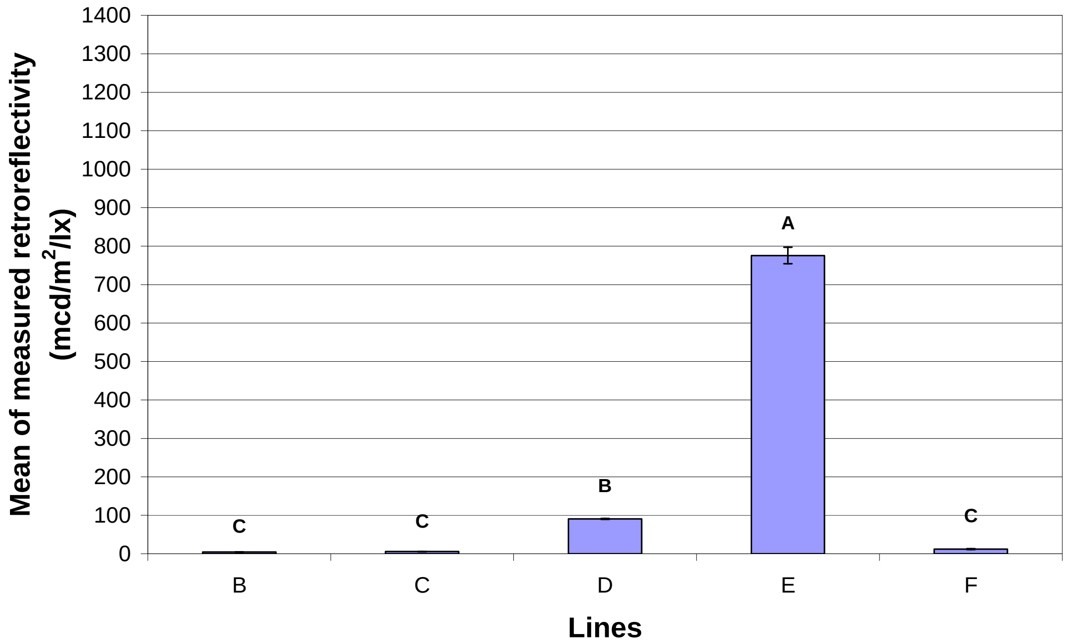


Figure 30. Rain: SNK post-hoc results of the visibility distance for the line main effect (means with the same letter are not significantly different).

The results of the measured retroreflectivity do not include Line A.

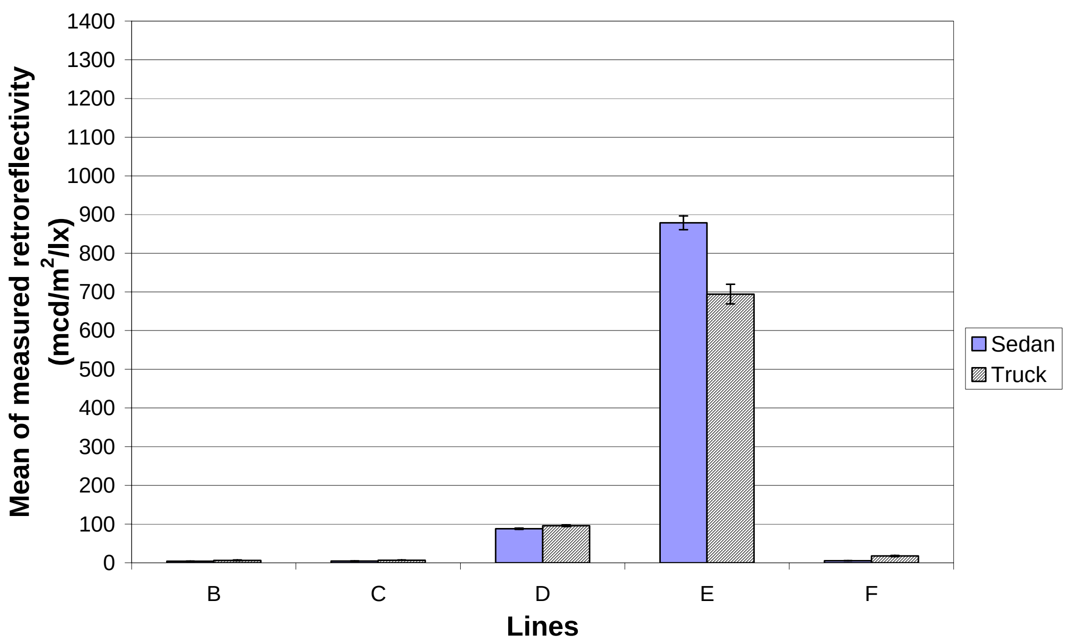
The mean of the measured retroreflectivity by line measurements are shown in Figure 31. Note that these measurements show that Lines B, C, and F all have the same grouping, which is different from that found by the visibility distance.

Figure 32 shows the interaction of line and vehicle. There is an unexpected relationship between vehicle type and measured retroreflectivity, since the measured values are performed with the same instrument in the same orientation and placement. However, measurements were made on multiple nights for each vehicle type, and on different nights between vehicles. Thus, slight differences in the instrument placement may have resulted in differences in the measured values. The difference in the measurements with the instrument, particularly seen with Line E, may be a result of measurement difficultly because of positioning of the instrument and the profiled nature of the measured material.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 31. Rain without line A: SNK post-hoc results of measured retroreflectivity for the line main effect (means with the same letter are not significantly different).



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 32. Rain without line A: Results of measured retroreflectivity for the vehicle X line interaction.

The contrast for each line is seen in Figure 33. As expected, the contrast by line is a significant measure. Here, all of the lines are statistically different except for lines B and C.

The interaction of line and vehicle for contrast is shown in Figure 34. Here the impact of the vehicle height influences the measurement. This is likely more significant for the lines with directional optical elements, which may show a lesser luminance performance as the observation angle is increased. An example of this would be with the wet retroreflective tape where optical elements may be oriented to optimize performance at the standard 30 m geometry. .When the observation angle is increased, the efficiency of the elements, and therefore the luminance, is reduced.

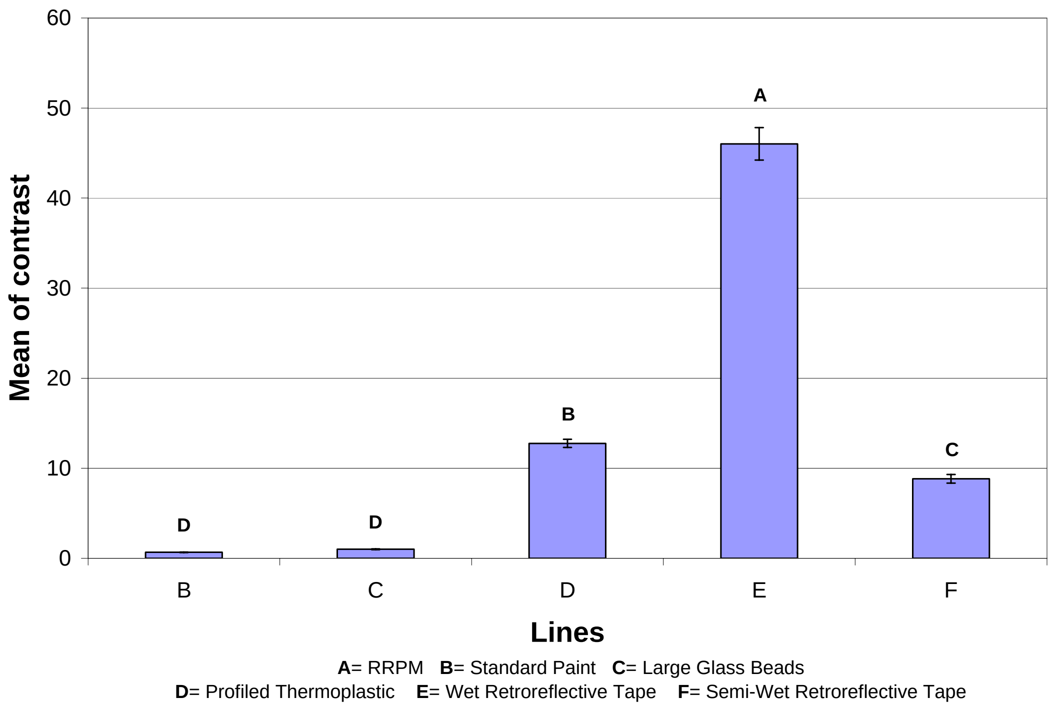
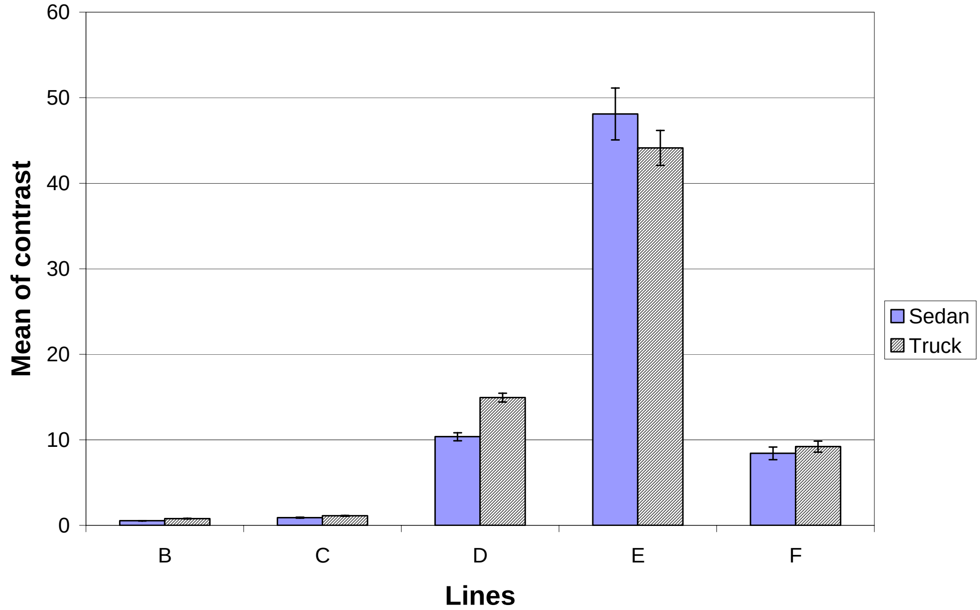


Figure 33. Rain without line A: SNK post-hoc results of contrast for the line main effect (means with the same letter are not significantly different).

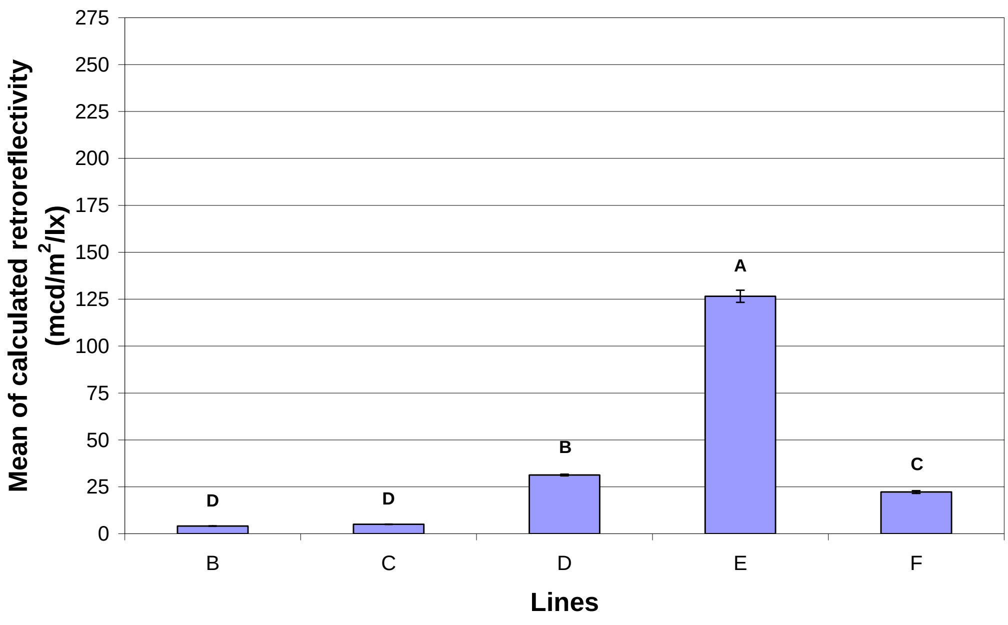
In the calculated retroreflectivity results, the influence of the vehicle height is seen again. The calculation of the pavement markings retroreflectivity is less for the truck than for the sedan. The luminance of the pavement markings would be reduced at the higher observation angles.

Figures 35 and 36 show the impact of line and the interaction of line type and vehicle type. These show the same behavior as those in the contrast comparison. Both of these measures are related to the marking luminance and are influenced in the same manner by the change in the vehicles.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 34. Rain without line A: Results of contrast for the vehicle X line interaction.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 35. Rain without line A: SNK post-hoc results of calculated retroreflectivity for the line main effect (means with the same letter are not significantly different).

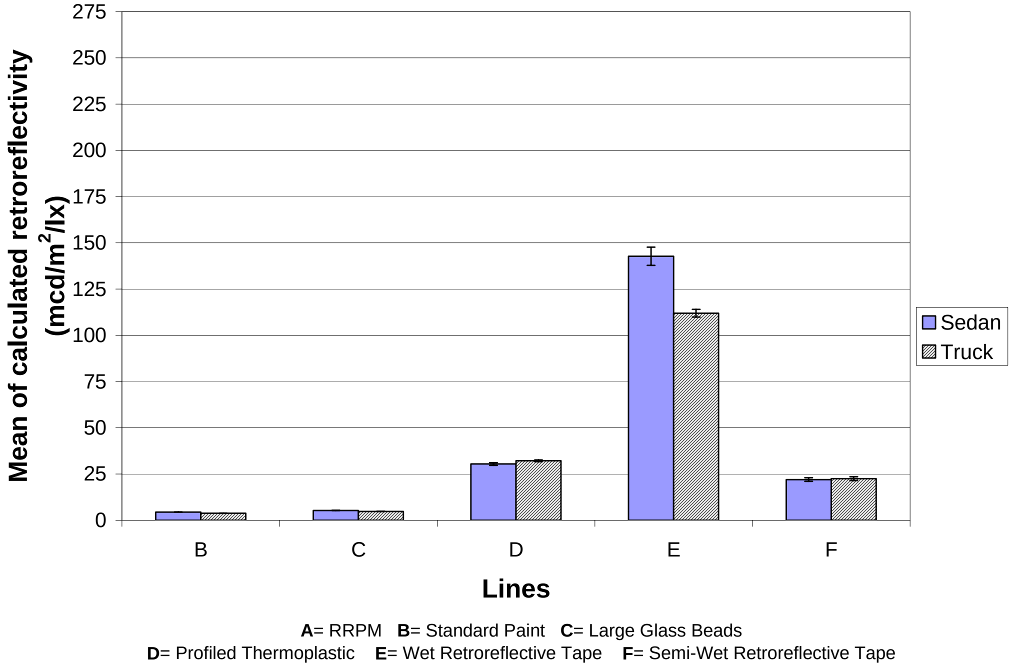


Figure 36. Rain without line A: Results of calculated retroreflectivity for the vehicle X line interaction.

The vehicle main effect on the post-evaluation rating is shown in Figure 37. All of the wiper speeds are shown in this figure.

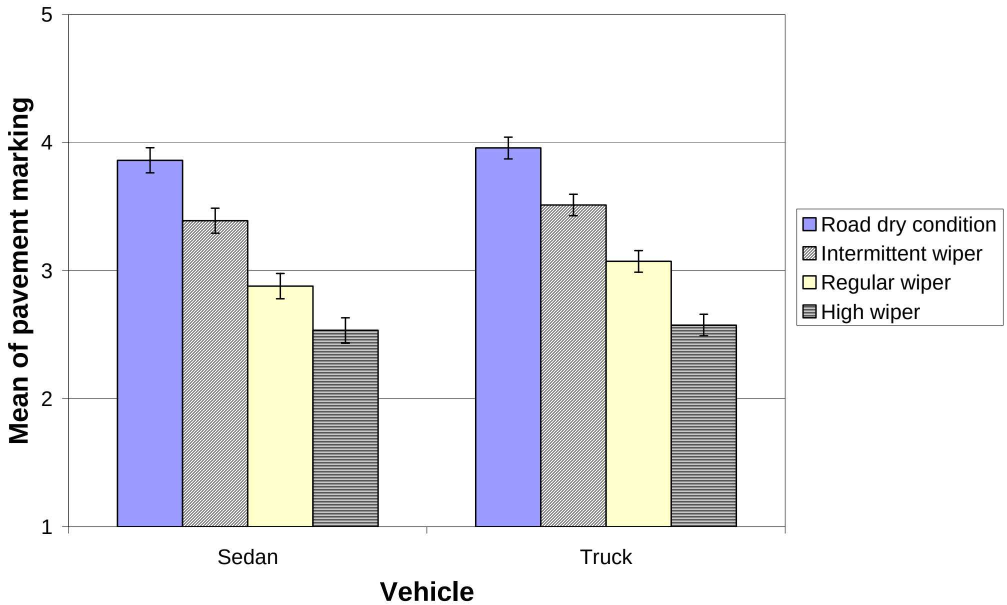


Figure 37. Impact of vehicle on participant rating for the rain condition.

The vehicle type does not appear to have an impact on the participant comfort level.

The line type main effect is shown in Figure 38, and the interaction of condition and line is shown in Figure 39. The SNK levels indicate that generally, line types B and C are equally grouped for comfort. Lines D and F are equivalent in comfort, and lines E and A are not grouped. These are very similar results as those of condition. The interaction of the condition and the line shows that in the wet conditions, comfort with lines B and C are reduced in the sedan more than the truck. Comfort with lines D and F are slightly reduced, while E and A do not have reduced comfort levels in the truck versus the sedan.

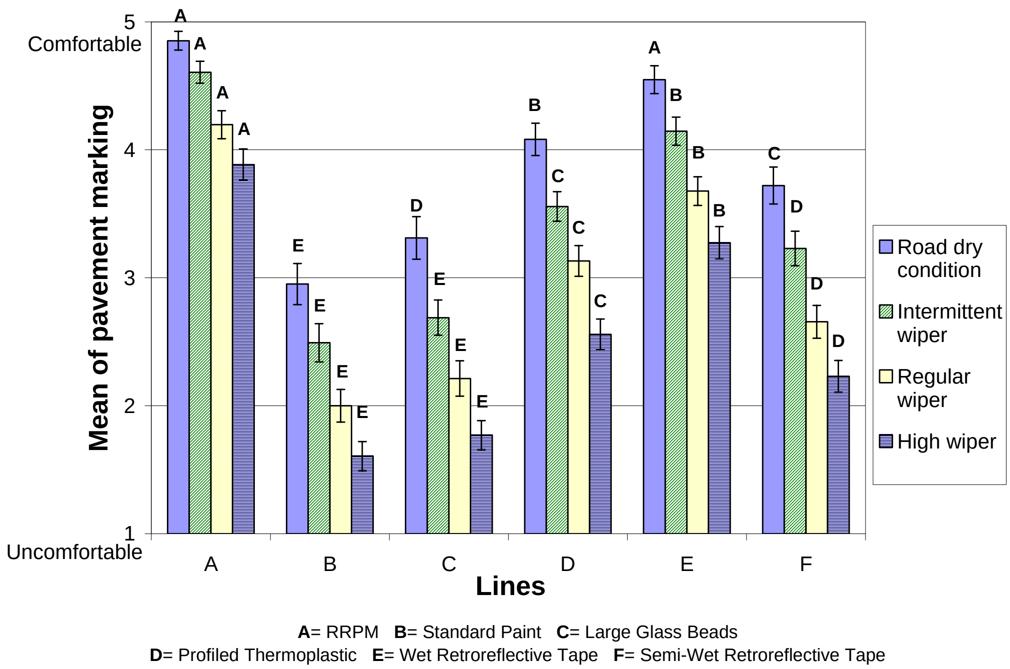


Figure 38. Impact of line type on participant rating for the rain condition.

ANOVA results for pavement marking preference ranking

There were two one-way ANOVAs performed on the pavement marking preference ranking by participant: an ANOVA for the sedan in the dry condition and ANOVA for the truck (this vehicle was run only in rain condition). These analyses evaluated whether there were significant differences among the different pavement markings in terms of participant preference. Student-Newman-Keuls (SNK) *post-hoc* analysis was performed for the significant line main effect ($p < 0.05$). ANOVA summary tables for the pavement marking ranking on both conditions are presented as part of Appendix D.

In the analysis, the line main effect shows a significant difference ($p < 0.05$) in both conditions: dry sedan and truck in the rain. The results for the significant line main effect were graphed, and standard error bars were provided with the means. Means with the same letter in their grouping are not significantly different (based on the SNK *post-hoc* test).

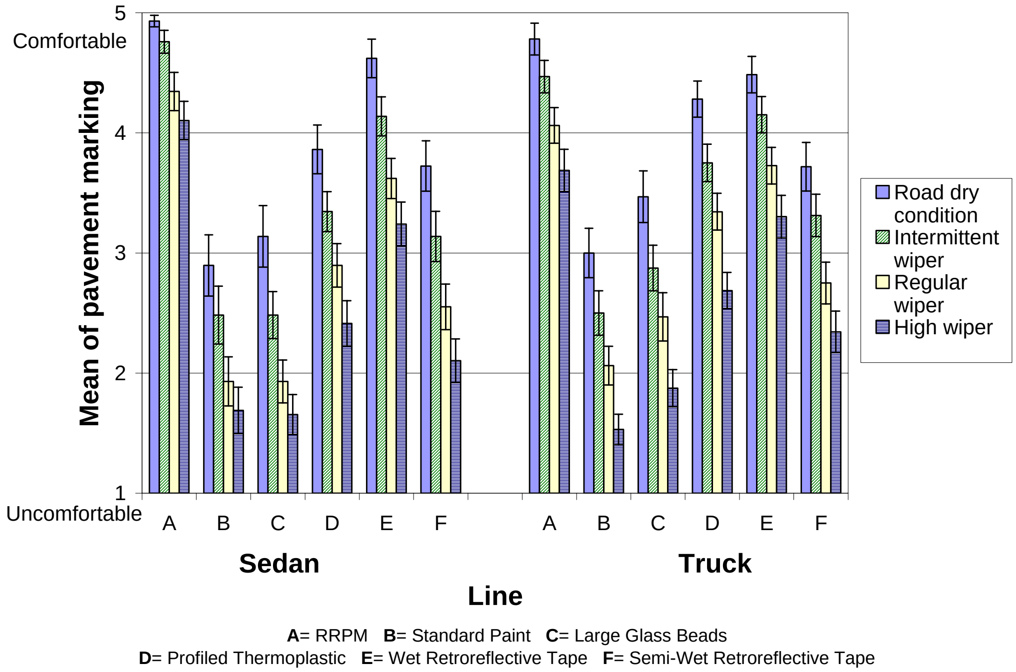


Figure 39. Impact of line type and vehicle on participant rating for the rain condition.

Figure 40 shows the results for the dry sedan. In the rankings, line A (RRPMs) showed the greatest preference by the participants. No other technologies stood out from the others in the dry condition. Lines E, B, and C are all grouped; lines D and E are grouped; and lines B, C, and F are grouped.

Figure 41 shows the results for the rain condition. In this case, lines E and A were equally preferred by the participants. Similarly, lines D and F were grouped, and lines C and B were individually the least preferred.

When comparing the grouping between in the lines from the rain truck and the dry sedan, it is somewhat interesting that lines E and F seemed to be preferred more in the rain truck than in the dry sedan. As both of these materials are tape products, this may be a result of the appearance of the materials in the rain condition. Both materials are structured such that water does not pool on the surface and they have a consistent luminous appearance in the rain.

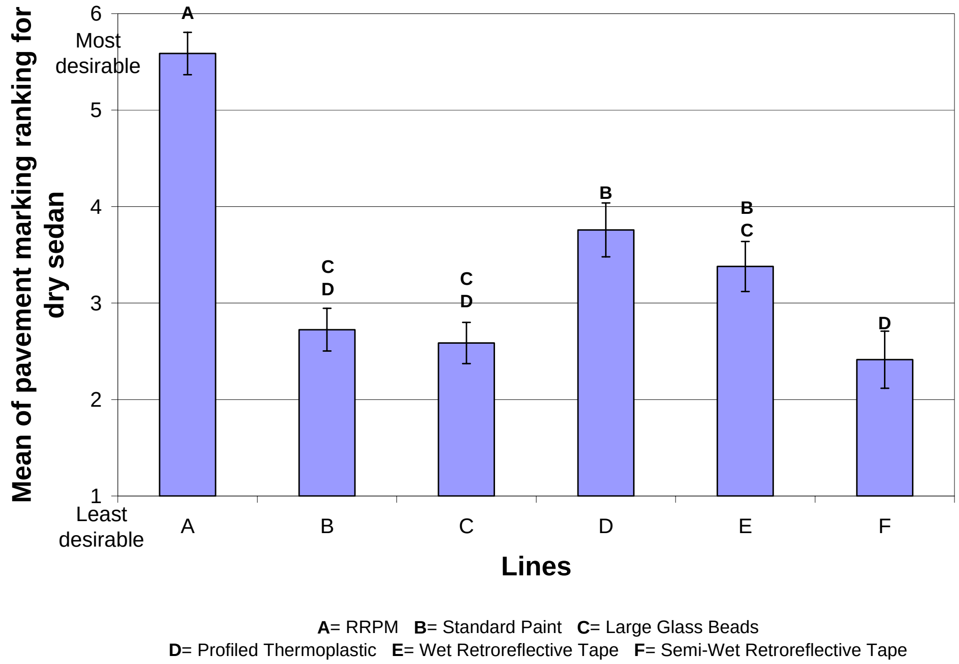


Figure 40. Dry sedan: Results of pavement marking ranking for the line main effect (means with the same letter are not significantly different).

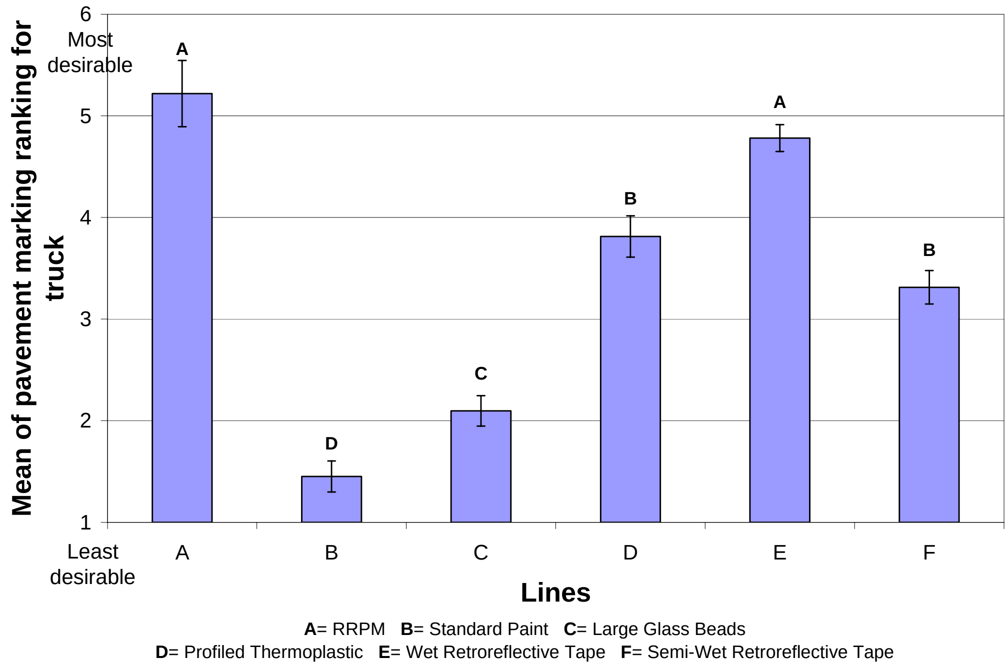


Figure 41. Truck: Results of pavement marking ranking for the line main effect (means with the same letter are not significantly different).

Recovery Evaluation

The analysis of the variables for the recovery portion of the experiment consisted of the plotting of the data from each of the measured variables and then assessing the point where the performance of the marking stabilized. This was performed for each of the dependent variables in the experiment. Again in this analysis, line A was left out from all of the measurements except for the participant counts.

Pavement Marking Counts

The mean of the participant results for the number of pavement skip marks identified is shown in Figure 42.

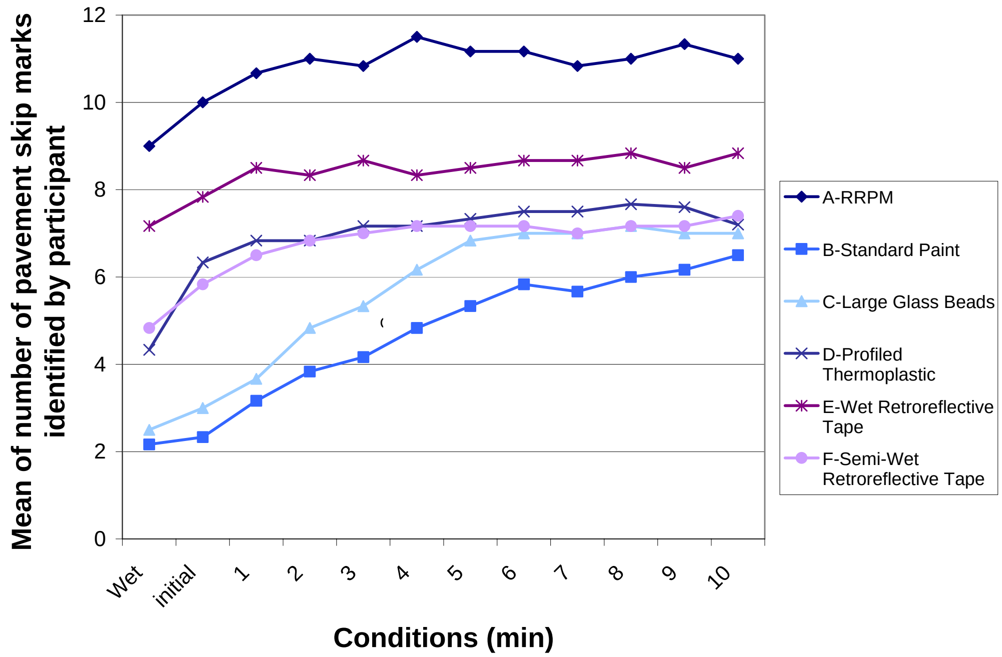


Figure 42. Recovery across participants: Results of number of pavement skip marks identified by participant.

Table 17 summarizes the mean recovery time for each of the marking technologies. In this table, the values are calculated from the mean recovery for each participant. For Line B, the standard paint and beads, the line in Figure 42 shows a continual rise to the 10 min point, but the value calculated from the individual participant results show a recovery at 5.3 min.

Table 17. Pavement marking count recovery time summary.

Technology	Recovery Time (in min)
A – RRPM	1.5
B – Standard Paint and Beads	5.3
C – Paint and Large Glass Beads	5.2
D – Profiled Thermoplastic	2.8
E – Wet Retroreflective Tape	1.8
F – Semi-Wet Retroreflective Tape	2.3

Since the visibility distance is dependent on the count, the recovery time results for visibility distance are the same as those shown above.

Measured Retroreflectivity Under Standard 30-meter Geometry

The results for the measured retroreflectivity are shown in Figure 43. For clarity, the results are shown in a log scale. In this case, they changed very slowly, leading to very long recovery times. The recovery times are shown in Table 18.

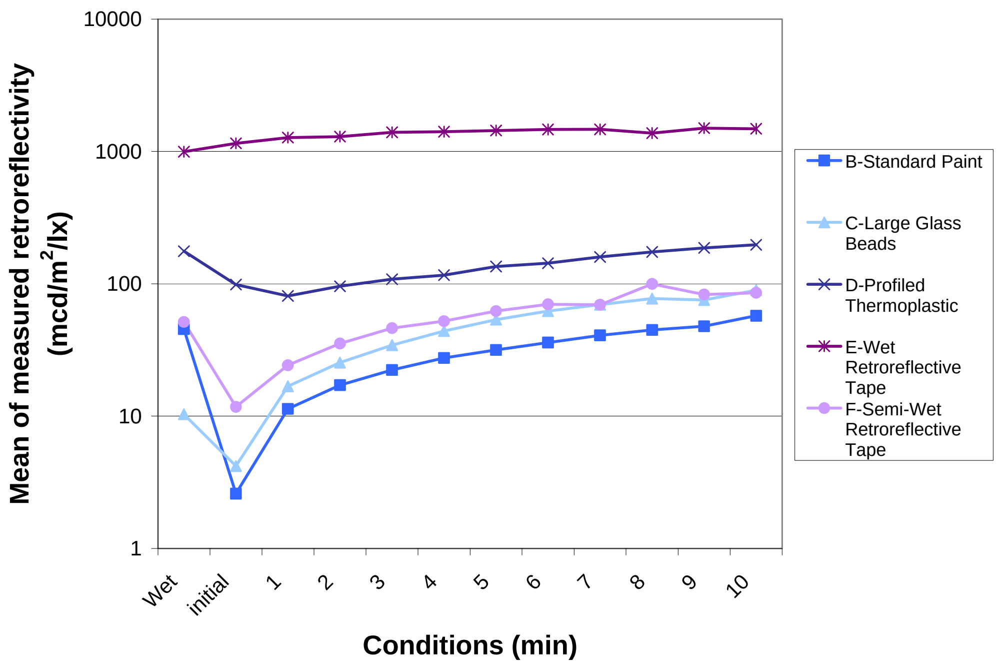


Figure 43. Recovery across participants: Results of measured retroreflectivity.

Table 18. Measured retroreflectivity recovery time summary.

Technology	Recovery Time in min
B – Standard Paint and Beads	9.4
C – Paint and Large Glass Beads	8.6
D – Profiled Thermoplastic	8.3
E – Wet Retroreflective Tape	7.2
F – Semi-Wet Retroreflective Tape	8.0

The contrast changes over time are shown in Figure 44. For clarity, the results are shown in a log scale. Here again, the changes are much slower than the changes in the participant count. The contrast actually rises to a high point and then slowly drops with time. This rise and then reduction is a result of the initial change in the pavement marking luminance followed by a gradual change in the background (pavement) luminance. As the pavement dries it gets lighter, which will slowly reduce the contrast. Recovery times were not calculated for the contrast variable due to the continual change of the measurement.

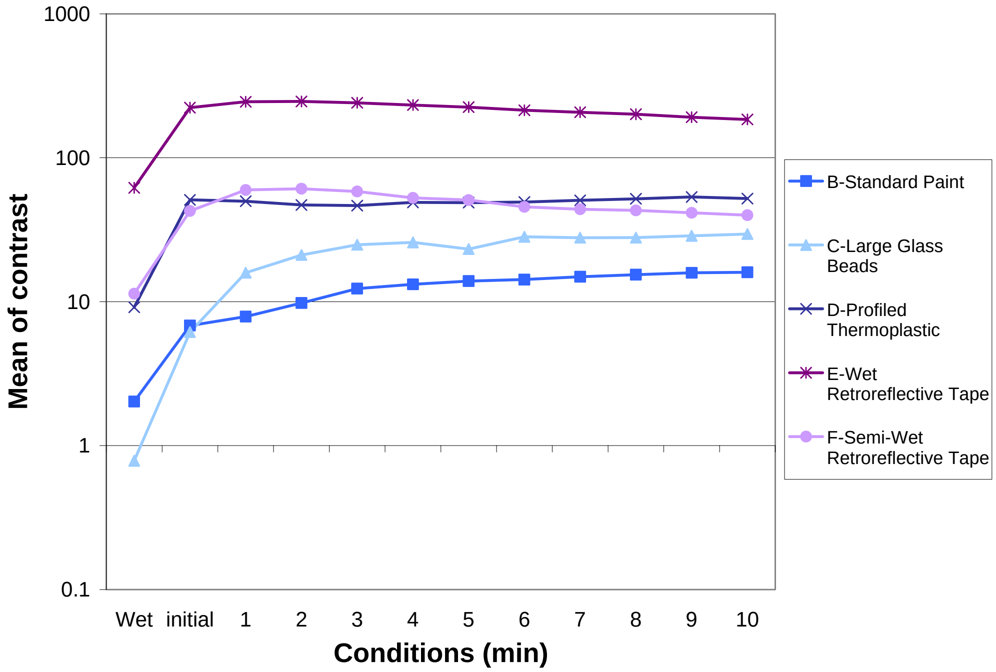


Figure 44. Recovery across participants: Results of contrast.

The calculated retroreflectivity most closely represents the luminance of the pavement marking. Again, Figure 45 shows the calculated retroreflectivity shows a slow rise over the measurement period. Like the previous figures, the results in Figure 45 are shown in a log scale for clarity. This is much slower than the change in the participant count.

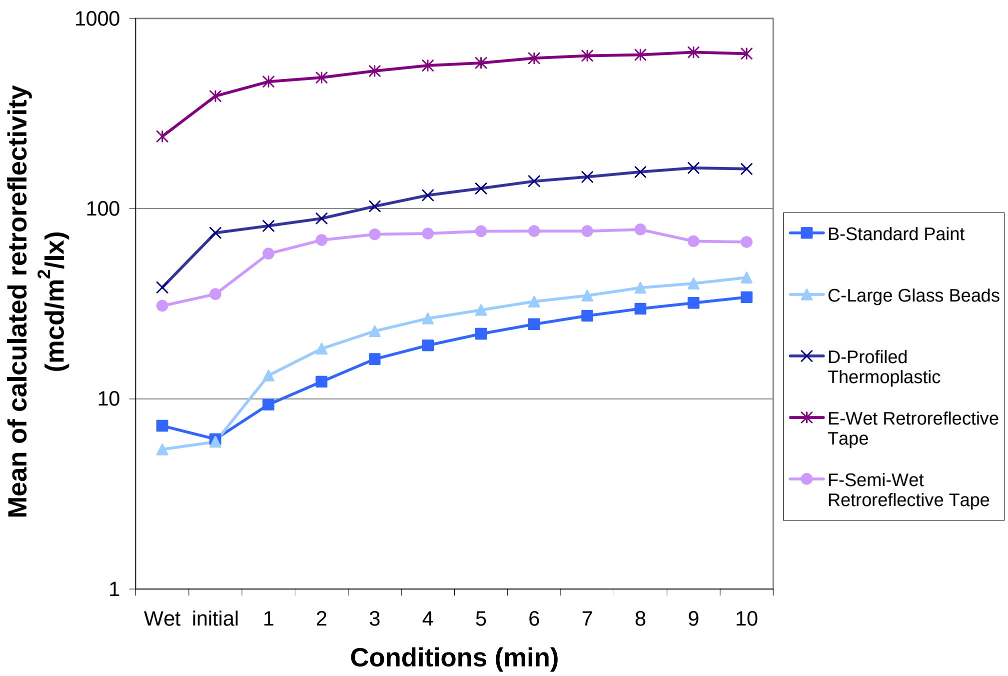


Figure 45. Recovery across participants: Results of calculated retroreflectivity.

The recovery times for the calculated retroreflectivity are shown in Table 19.

Table 19. Calculated retroreflectivity recovery time summary.

Technology	Recovery Time (in Min)
B – Standard Paint and Beads	9.0
C – Paint and Large Glass Beads	8.7
D – Profiled Thermoplastic	7.7
E – Wet Retroreflective Tape	6.2
F – Semi-Wet Retroreflective Tape	5.6

Using the recovery time data for each participant allowed for a further one-way ANOVA analysis to investigate the impact of line type on the recovery behavior. This analysis was performed for the variables of count, measured retroreflectivity, and calculated retroreflectivity. The one-way ANOVA tables are shown in Appendix E.

Figure 46 shows the line main effect on the recovery time for count. Lines A, D, E, and F are all grouped with the shortest recovery time, whereas Lines B and C are grouped as the longer recovery times.

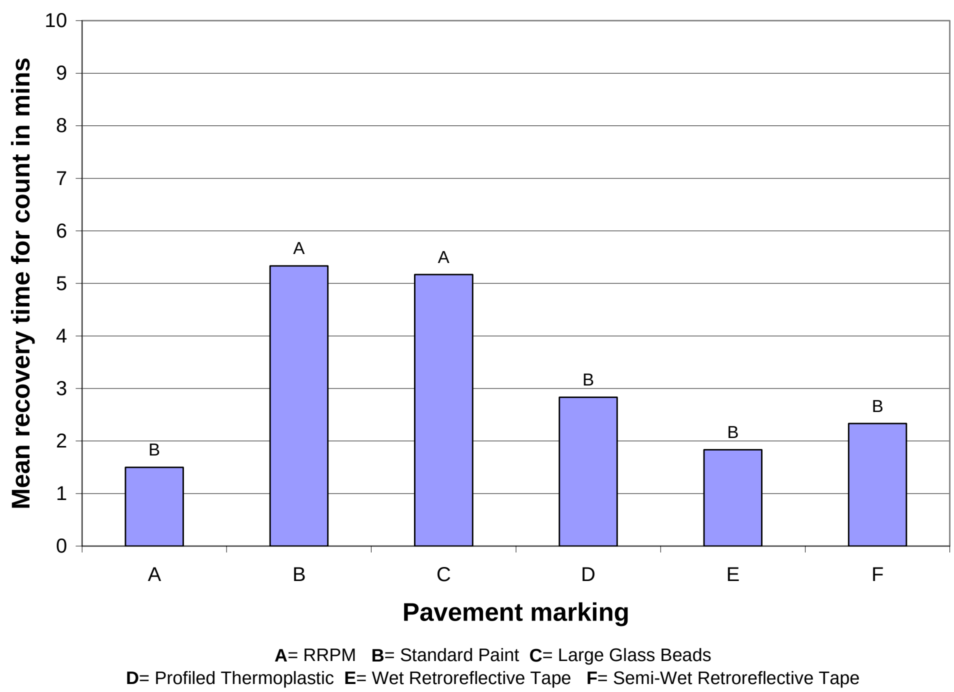


Figure 46. Main effects of line on the mean recovery time for count.

Figure 47 shows the means for the recovery time for the measured retroreflectivity. It is important to note that the times are much longer than those for the count. There is also much less separation between the line types. The paint and standard beads (B), paint and large beads (C), profiled thermoplastic (D) and semi-wet retroreflective tape (F) are not statistically different, and the paint and large beads (C), profiled thermoplastic (D), wet and semi wet retroreflective tape (E and F) are also not statistically different. Similarly, Figure 48 shows the means for the recovery time for the calculated retroreflectivity by line. In this analysis, recovery times again are much longer than those for the count. The non-statistically different groups are Lines B, C, and D, Lines D and E, and Lines E and F.

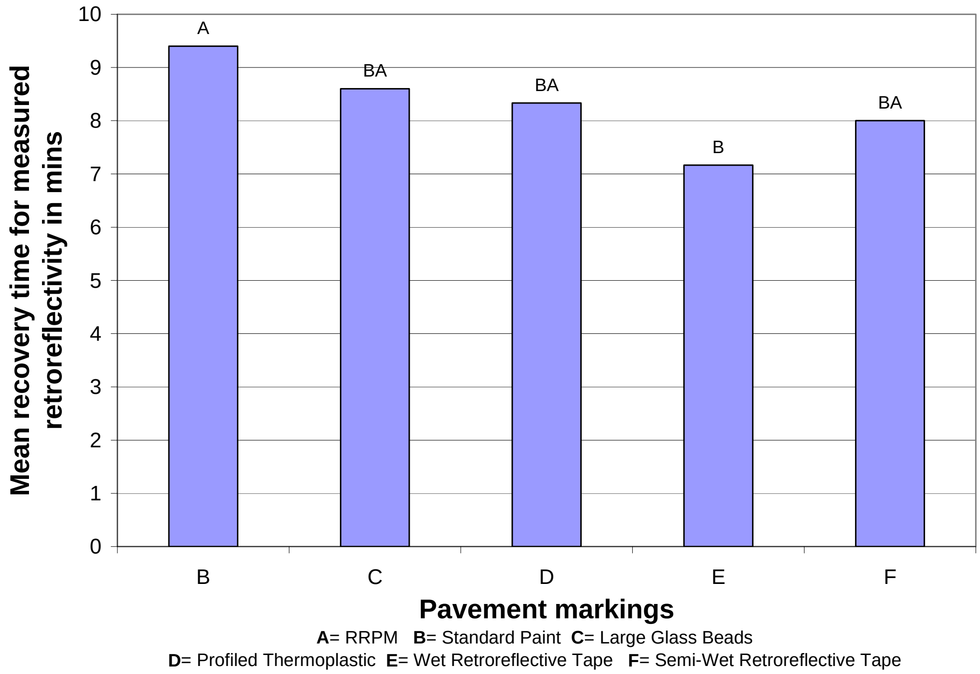


Figure 47. Main effects of line on the mean recovery time for measured retroreflectivity.

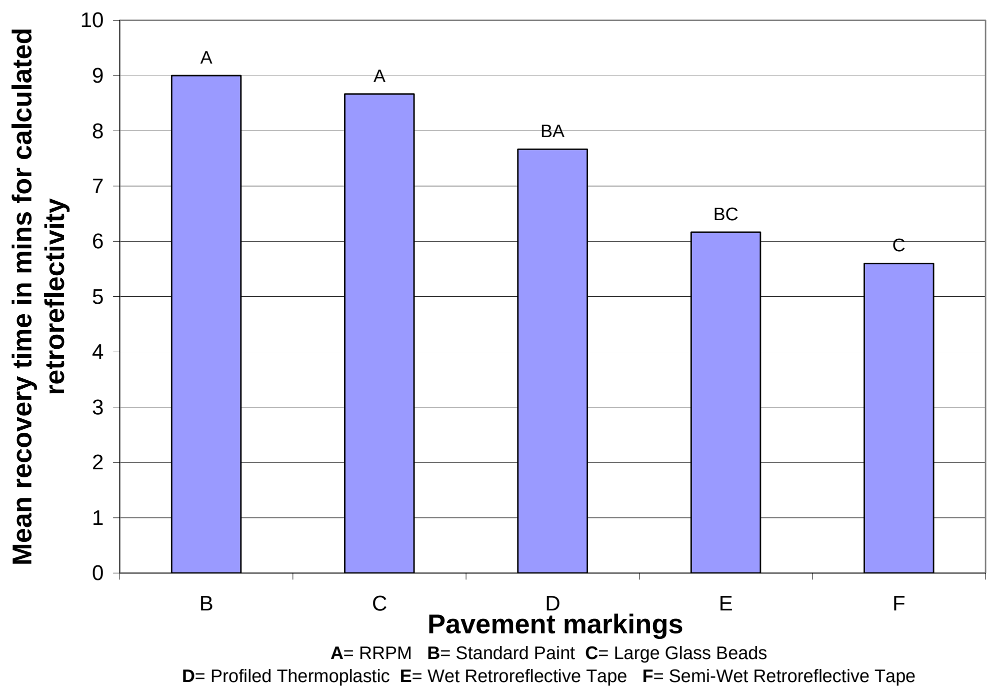


Figure 48. Main effects of line on the mean recovery time for calculated retroreflectivity.

It is noteworthy in this dataset that the recovery time for the count is significantly shorter than for the other characteristics of the markings. This implies that a very small change in the luminance and retroreflectivity of the markings will bring about full visibility after the end of a rain event. This may be related again to the log relationship of the luminance level and the human response. As the luminance level of the marking continues to increase, the change in the human response is smaller for the same incremental change in the luminance. This results in the visual recovery stabilizing earlier than photometric values.

Retroreflectivity Measurements

Two sets of retroreflectivity values were obtained for the pavement markings. The first set calculated from measurements of the marking luminance for each skip mark seen on the road, which provides a retroreflectivity by distance measurement. The second were the measurements made with existing ASTM standard measurement methodologies.

Retroreflectivity by Distance Measurements

The two variables that are available in this analysis are the measured marking luminance and the calculated retroreflectivity. The results for the luminance by skip mark and marking technology are shown in Figures 49 through 51 for the dry sedan, wet sedan, and wet truck conditions. Note that in these figures, the luminance axis has been converted to a log scale for clarity.

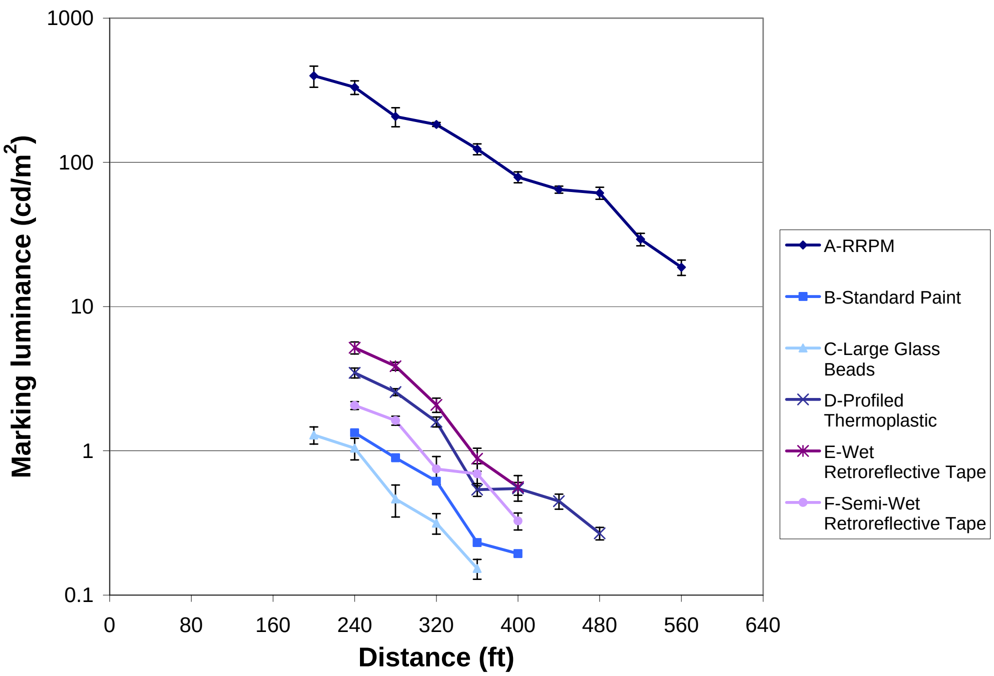


Figure 49. Pavement marking luminance for each line type by distance for the dry sedan condition.

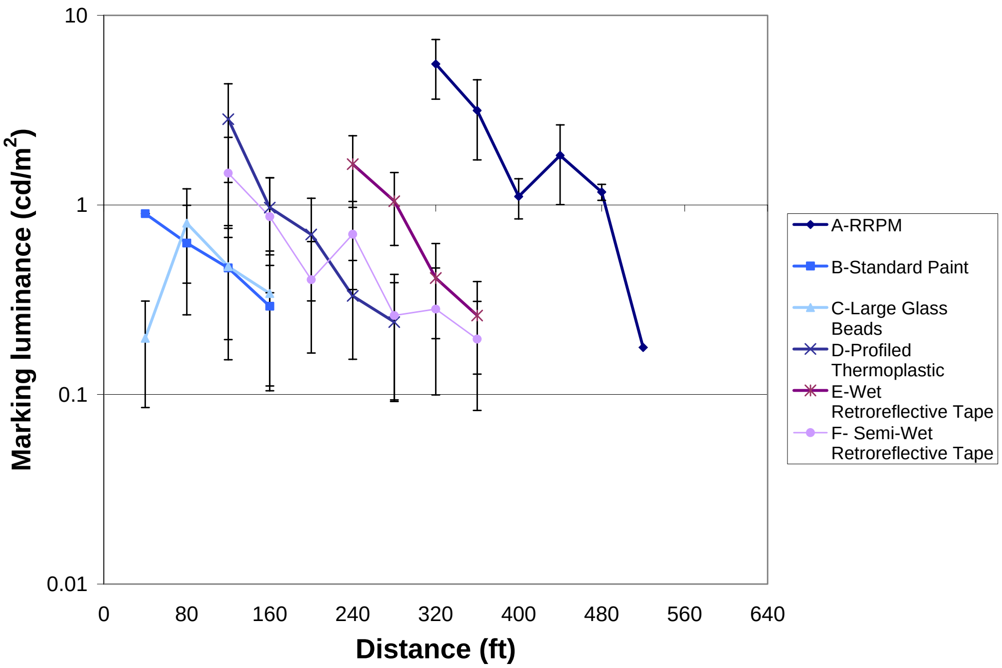


Figure 50. Pavement marking luminance for each line type by distance for the wet sedan condition.

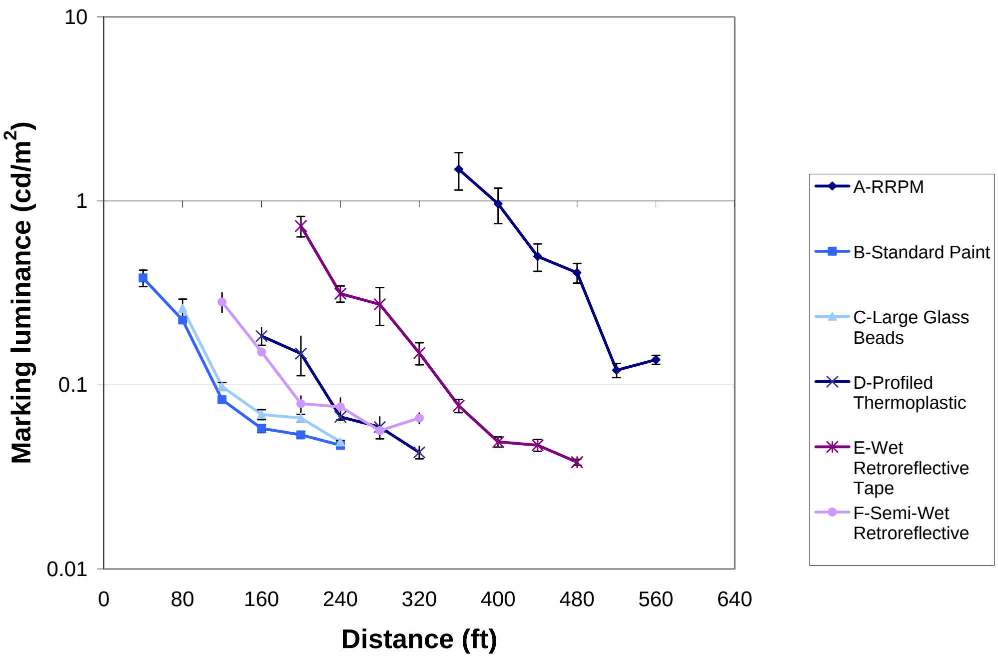


Figure 51. Pavement Marking Luminance for each line type by distance for the wet truck condition.

Figures 52 through 54 show the results for the calculated retroreflectivity for each of the skip mark locations measured above. Line A was omitted from the analysis.

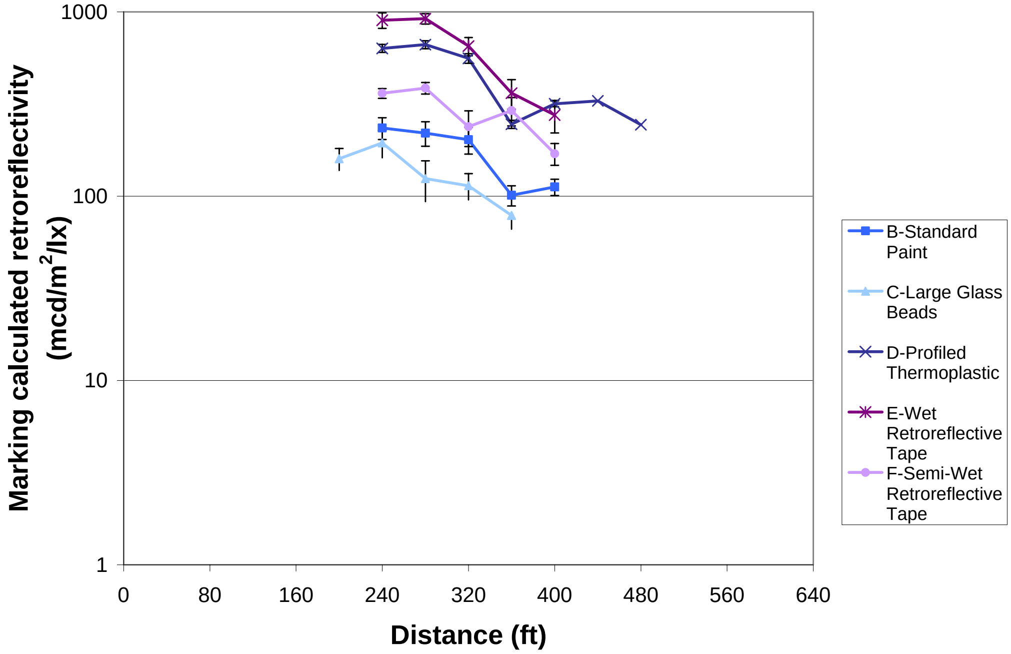


Figure 52. Calculated Retroreflectivity for each line type by distance for the dry sedan condition.

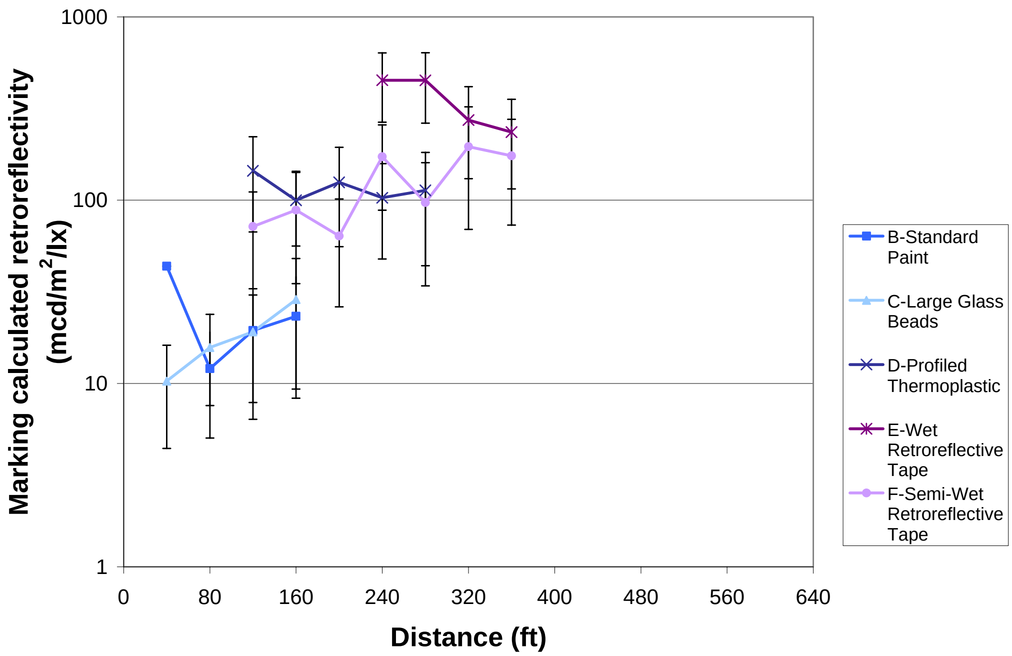


Figure 53. Calculated retroreflectivity for each line type by distance for the wet sedan condition.

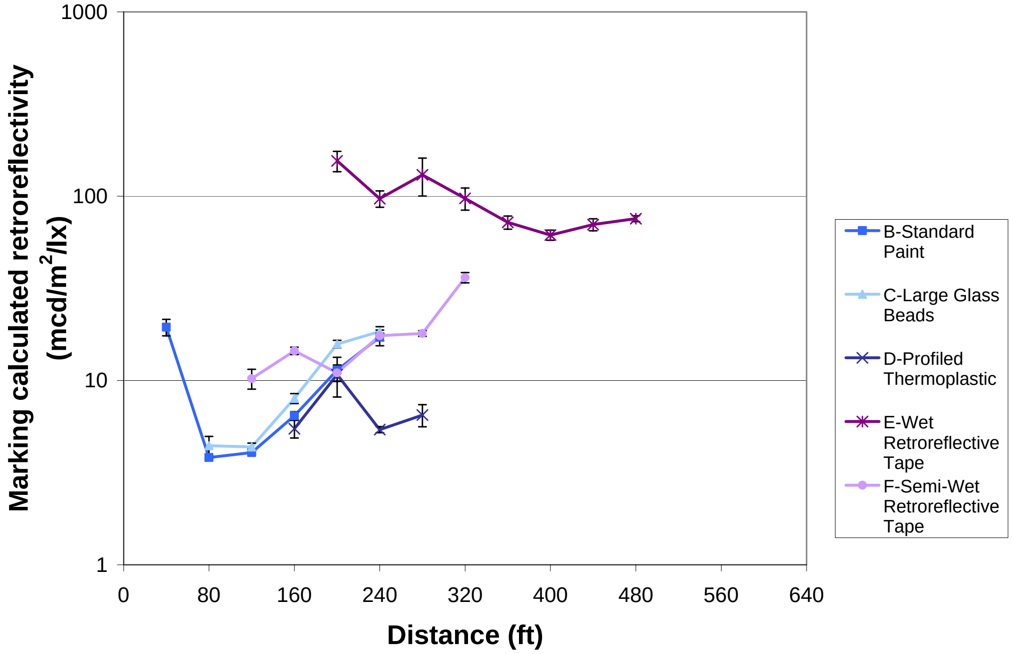


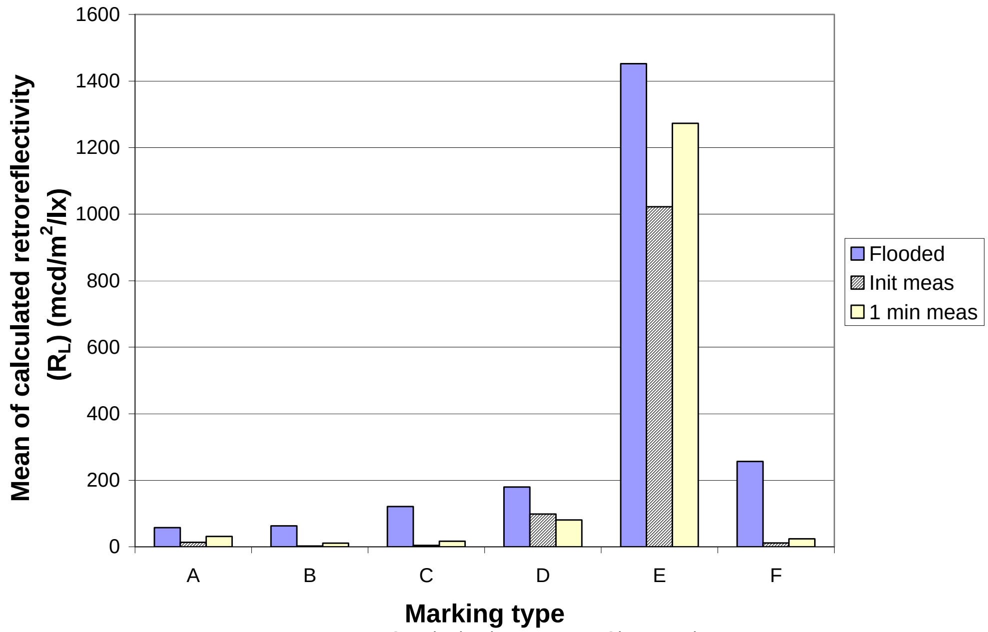
Figure 54. Calculated retroreflectivity for each line type by distance for the wet truck condition.

The measurements behave as one would expect. The greater the distance from vehicle the lower the luminance of the pavement marking. This is primarily because the change in headlamp illuminance striking the pavement marking. The change in the geometry between the vehicle headlamps, the observed marking, and the observer may also play a part. These results will be used to further provide information with respect to the limits of the visibility of the pavement markings.

ASTM Measurement Methods

The second set of measurements performed on the pavement markings were the wet retroreflectivity measurements made with the ASTM methods. These measurements were made with both the flooded (E2177-01) and the continuous (E2176-01) measurement methods. The results from the two methods were analyzed separately.

The ASTM flooded measurement is designed to represent a situation when the pavement marking is wet but the rain has stopped. Data from the recovery evaluations were included for comparison to the measurement method (Figure 55). As the ASTM flooding method requires the measurement to be made 45 s after flooding, both the initial data, made immediately after the rain is turned off, and the 1 min data can be used for comparison. Note that the measured retroreflectivity was the only measurement set used so that the same measurement instrument was used for all of the compared results.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 55. Calculated retroreflectivity for each line type by distance for the wet truck condition.

In order to remove issues of calibration and scaling, a correlation analysis was used to compare the three measurement sets (Table 20). This correlation was performed with an n of 5.

Table 20. Correlation summary for the ASTM flooded measurement method and the evaluation results.

	ASTM Flooded	1 min Measurement	Initial Measurement
ASTM Flooded	1		
1 min Measurement.	0.993	1	
Initial Measurement	0.992	0.999	1

The ASTM continuous measurement method is designed to represent the pavement markings in the rain. This is comparable to the saturated evaluation condition from the participant evaluations (Figure 56). The correlation analysis between these measurement sets showed a Pearson *r* value of 0.992.

The correlation between these methods seems very high. This can be a result of the magnitude of line E measurement. The correlation results recalculated without Line E are shown in Table 21 for the continuous wetting method.

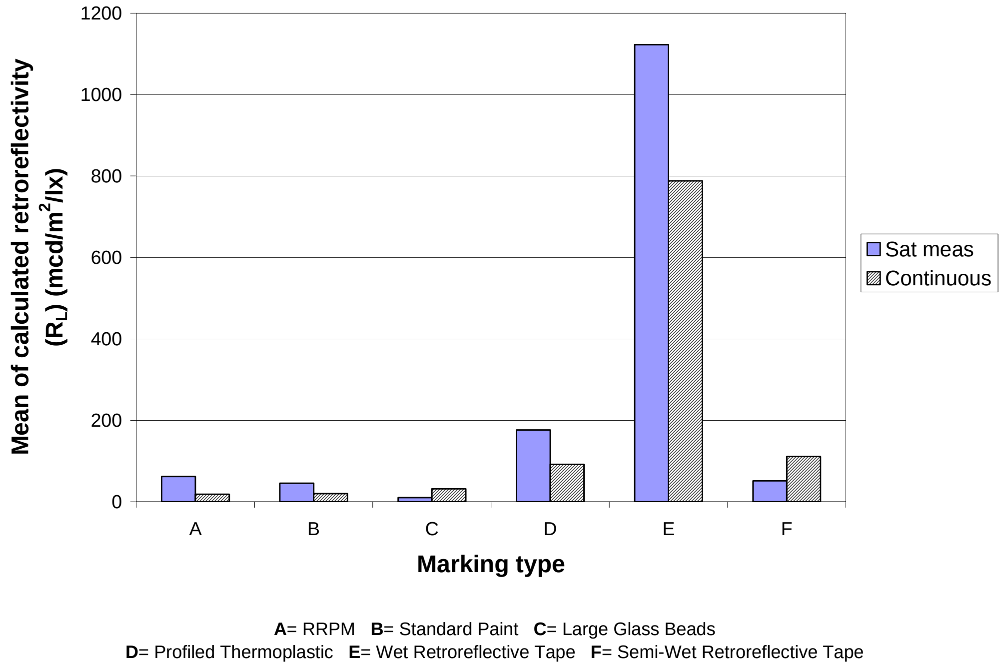


Figure 56. Calculated retroreflectivity for each line type by distance for the wet truck condition.

Table 21. Recalculated correlation summary for the ASTM flooded measurement method and the evaluation results without line E.

	Flooded	1 min Meas.	Init. Meas.
Flooded	1		
1 min. Meas.	0.355	1	
Init. Meas.	0.281	0.996	1

The recalculated correlation results for the continuous method and the saturated evaluation shows a Pearson *r* value of 0.526. The correlation results, and those between the flooded method and the measured values (illustrated in Table 21), show that the methods do not correlate with measurements made in the simulated rain.

Discussion

As stated, the experimental questions investigated in this project were:

1) What level of retroreflectivity do drivers need under rain conditions?

2) What levels of retroreflectivity are current pavement markings and markers capable of producing under various rain conditions? The rain conditions include 1) the period during rainfall of various intensities within a defined range, and 2) the recovery period (drying) after rain has stopped.

3) What is the suitability of the ASTM Wet Retroreflectivity measurement Methods?

Each of these questions will be assessed individually.

Drivers' Needs in Wet Conditions

In order to establish the needs of the driver in wet night conditions, two things must be considered. The first is the threshold of luminance and retroreflectivity that the participants use to determine the visibility of a skip line. The second is the safe distance at which they must gather information to maintain their performance of the driving task.

Threshold Analysis

The luminance of the pavement marking determines whether or not a marking can be seen. Figure 57 uses the data from the recovery evaluation, plotting luminance of the markings at the 30 m point compared to the marking count. Again, as the luminance is experienced physiologically, it is represented as a logarithm.

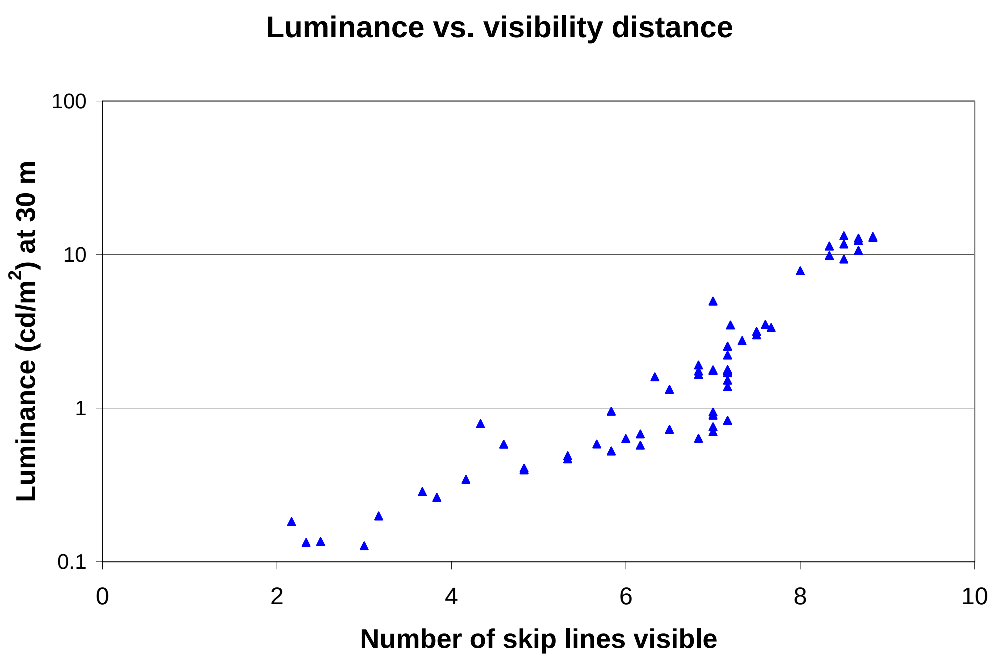


Figure 57. Pavement luminance versus skip mark count.

The limit of our vision is determined by some threshold luminance, which allows an object to be just perceivable. It should be noted that visibility is determined by contrast. In this experiment however, the background luminance used to calculate the contrast is typically the same for all measurements, which means that the luminance of the marking determines the visibility. The threshold luminance of pavement markings at the limit of visibility can be used to determine the requirements of the retroreflectivity of the pavement markings.

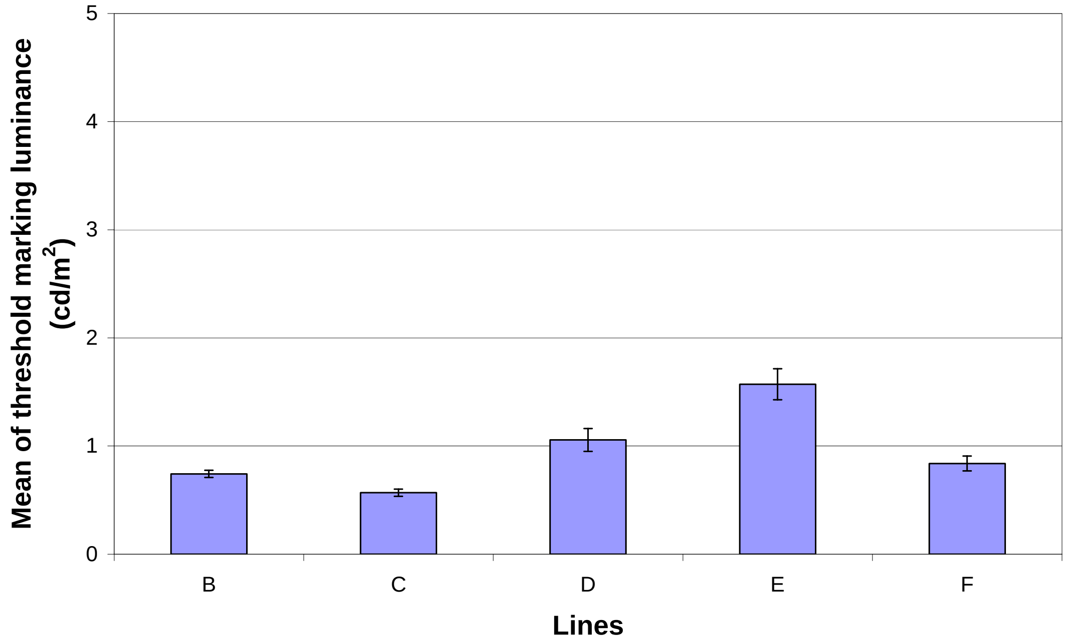
The two dependent variables investigated were the pavement marking luminance and the calculated retroreflectivity. The results for each of these variables were considered below in terms of the rain condition and in terms of the vehicle type.

In these analyses, the threshold values were determined at the limits of vision. If a participant was able to see 6 pavement marking skip lines, the luminance and calculated retroreflectivity of the 6^{th} skip line was used as the threshold values for that participant and evaluated pavement marking combination. In order to establish this value, the retroreflectivity by distance relationship made from the measurements of each pavement marking were combined with the saturated data measured in the participant evaluation. From these measurements, the mean of the threshold luminance and threshold retroreflectivity for all participants was calculated and analyzed.

The threshold luminance is lower for the rain condition than for the dry condition. From this analysis, it is clear that the participants require a lower luminance threshold in the rain than in the dry condition. Figure 58 shows the influence of the line on the threshold and Figure 59 shows the line x condition interaction for the same data. The line effects show that a different threshold luminance is used based on the line type. This is similar to information in the interaction graph. An interesting outcome of this is that the lines that can be seen the farthest away (Line E) seem to have a higher threshold luminance than the lines that are seen closer. This indicates that the contrast requirements are greater the farther the object is from the driver. This is a well-known phenomenon, in that the visual size of an object is reduced when it is farther from the observer. As the object appears smaller, it requires a greater contrast with the background in order to be seen.

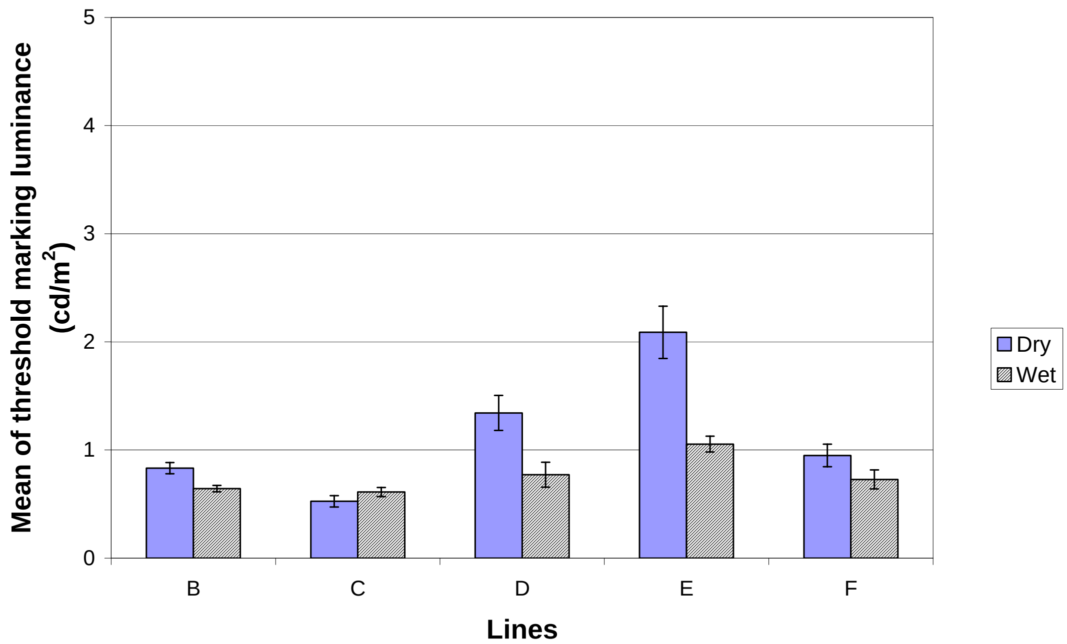
Figures 60 and 61 show the impact of the line type and the line and condition, respectively, on the calculated retroreflectivity at the limit of visibility (threshold luminance). The threshold retroreflectivity is lower in the rain condition than it is in the dry condition. As with the luminance data, the threshold retroreflectivity is higher for lines observed at a greater distance. This again indicates the visual size versus distance relationship and the requirement to have a higher luminous contrast the further an object is from the observer.

The next analysis considered the impact of the vehicle on the threshold. A lower luminance threshold was required by the participants in the truck than in the sedan. This is likely due to the change in perspective from the truck, as compared to the sedan. Figures 62 and 63 show the impact of the line and the line x vehicle interaction. These charts show similar trends as those in the previous analysis. Here again a lower luminance threshold is required for lines with shorter visibility distances.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 58. Threshold sedan: Results of threshold marking luminance for the line main.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 59. Threshold sedan: Results of threshold marking luminance for the condition X line interaction.

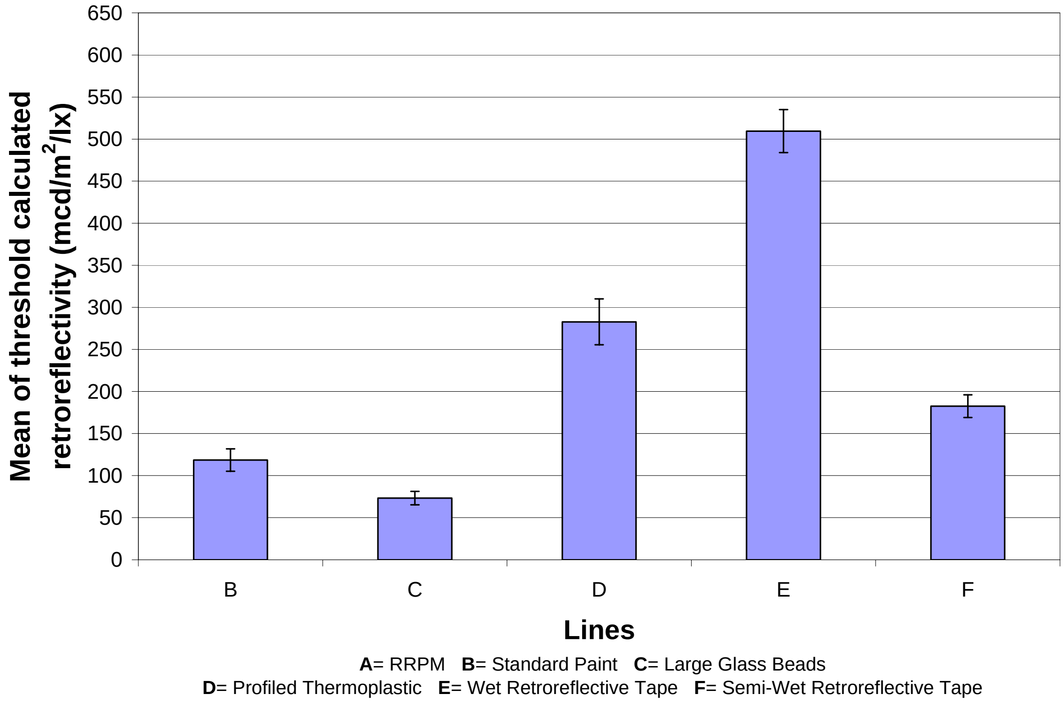


Figure 60. Threshold sedan: SNK post-hoc results of threshold calculated retroreflectivity for the line main effect (means with the same letter are not significantly different).

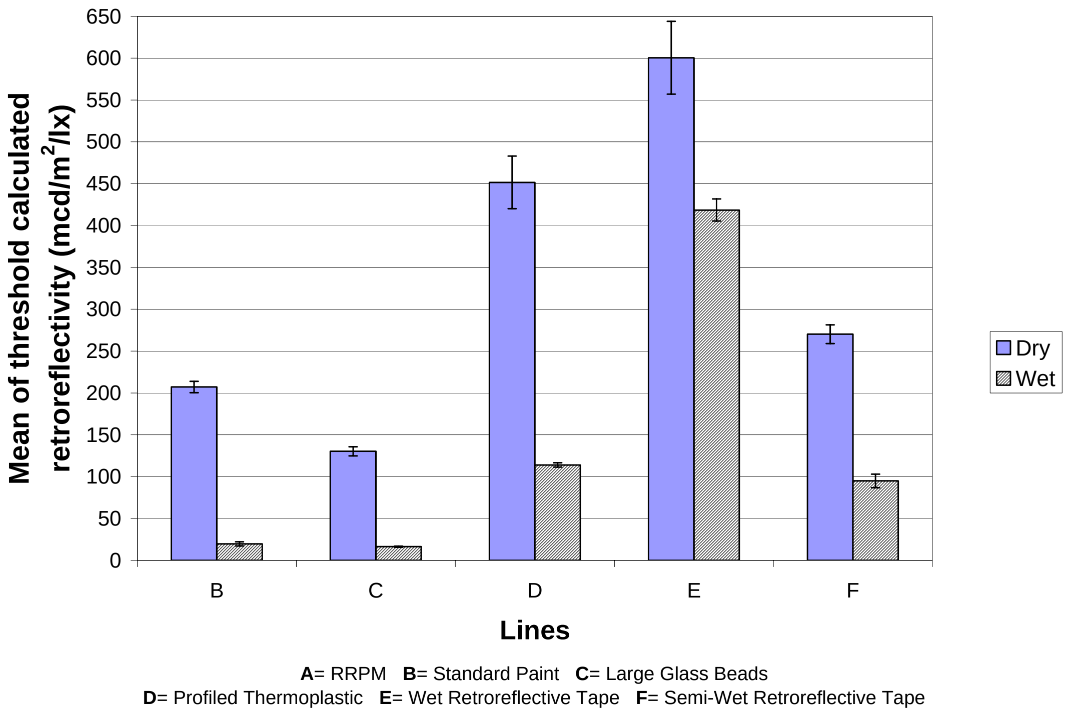
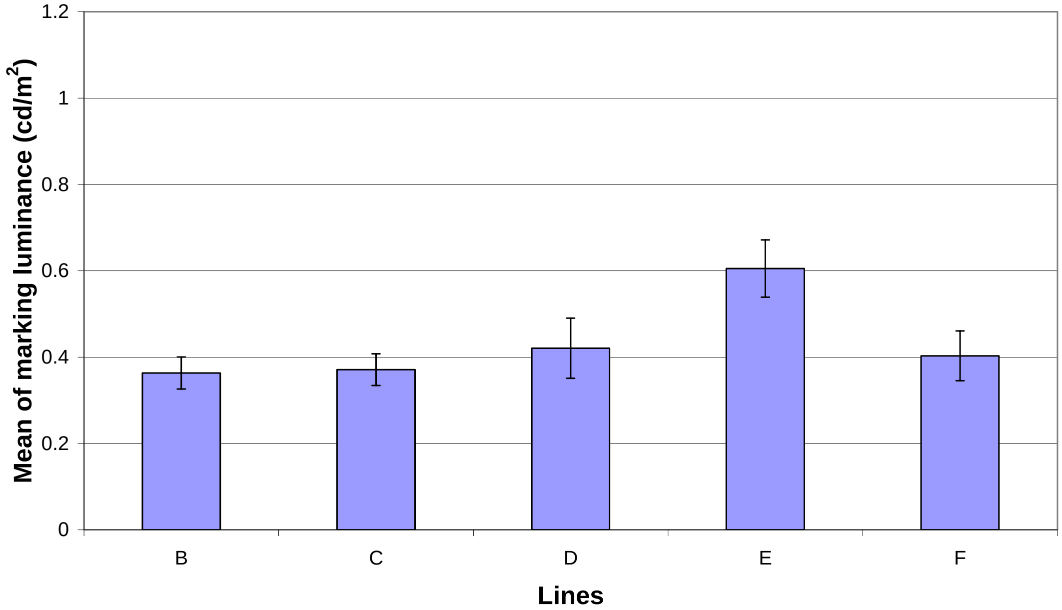
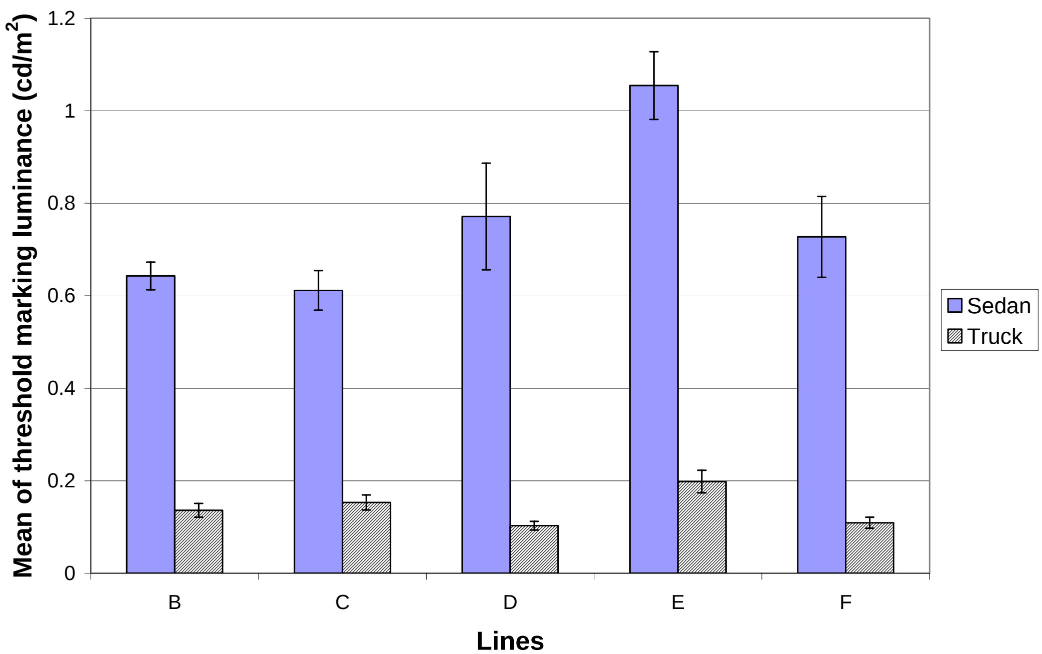


Figure 61. Threshold sedan: Results of threshold calculated retroreflectivity for the condition X line interaction.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 62. Threshold wet: SNK post-hoc results of threshold marking luminance for the line main effect (means with the same letter are not significantly different).



A= RRPM **B**= Standard Paint **C**= Large Glass Beads
D= Profiled Thermoplastic **E**= Wet Retroreflective Tape **F**= Semi-Wet Retroreflective Tape

Figure 63. Threshold wet: Results of threshold marking luminance for the vehicle X line interaction.

It is interesting to note that the results for the truck do not show as much variation between marking technologies as those for the sedan. This could be a result of the higher observation angle in the truck.

Finally, the required retroreflectivity to achieve a given visibility distance is much higher in the sedan than in the truck. The line main effect and line x vehicle interaction are shown in Figures 64 and 65. As expected, the threshold value changes with the distance at which a line is observed.

It would be expected that a participant would require the same threshold luminance for all marking technologies, and be able to see the materials providing high values of retroreflectivity at even farther distances, but this does not seem to be the case. The luminance that a person requires at the visibility threshold seems to be related to the maximum visibility distance: longer distances require higher threshold values. Line B, for example, has a lower value of retroreflectivity, resulting in a shorter detection distance from Line E. The threshold luminance for Line B, however, defined as the luminance measured at the detection distance, is lower than that for Line E, which as a much longer detection distance.

To investigate this further, a dosage factor was calculated. The dosage factor is the threshold luminance multiplied by the visual solid angle (steradians) of the threshold skip mark. This technique can be applied to the retroreflectivity measurement. Figure 66 shows the relationship of the threshold luminance dosage factor by line type for the rain conditions. This figure shows that the dosage from line types D, E, and F require equivalent dosages, whereas B and C both require higher dosages.

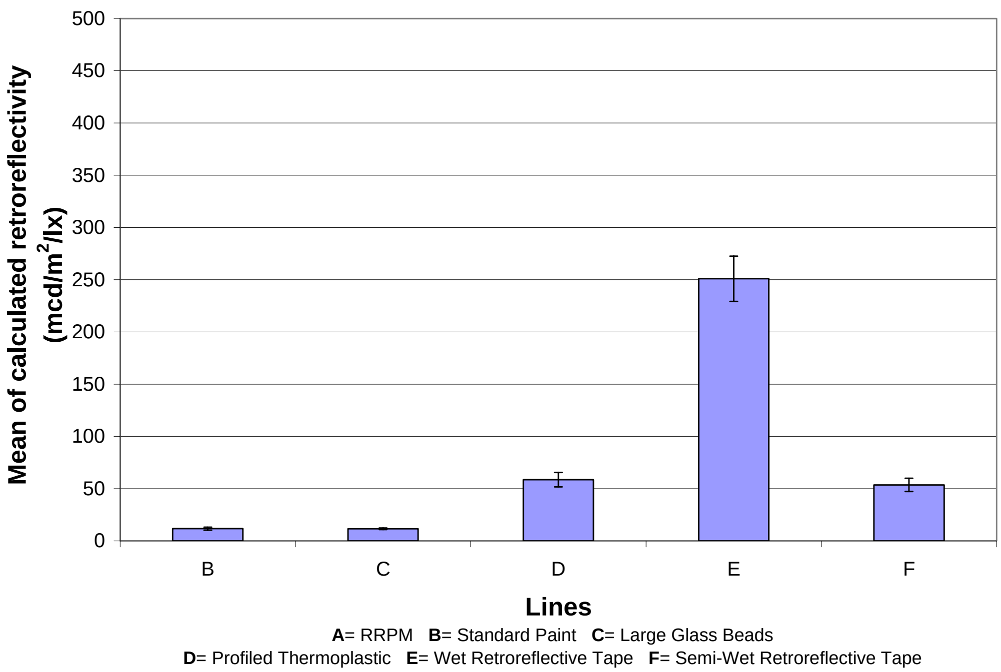


Figure 64. Threshold wet: Threshold calculated retroreflectivity for the line main effect.

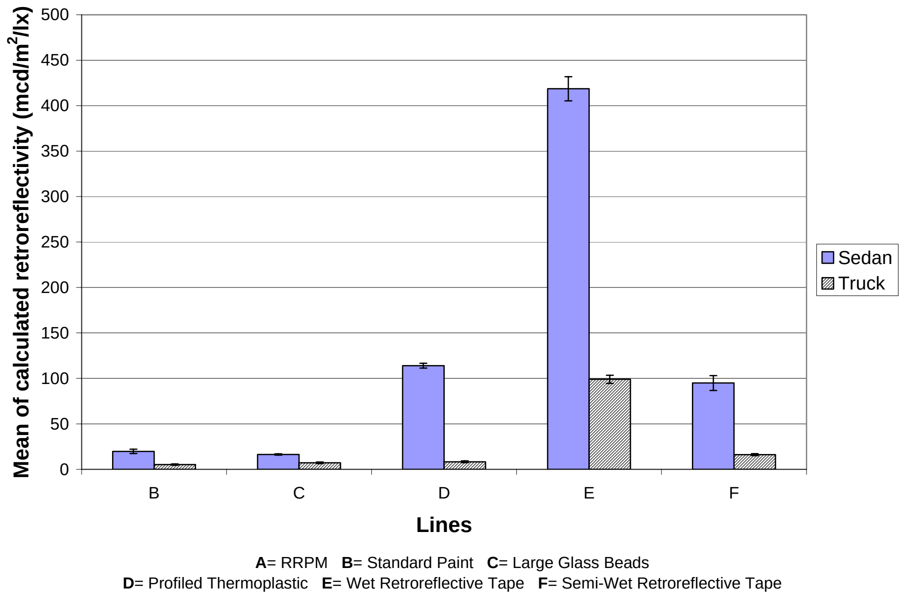


Figure 65. Threshold wet: Results of threshold calculated retroreflectivity for the vehicle X line interaction.

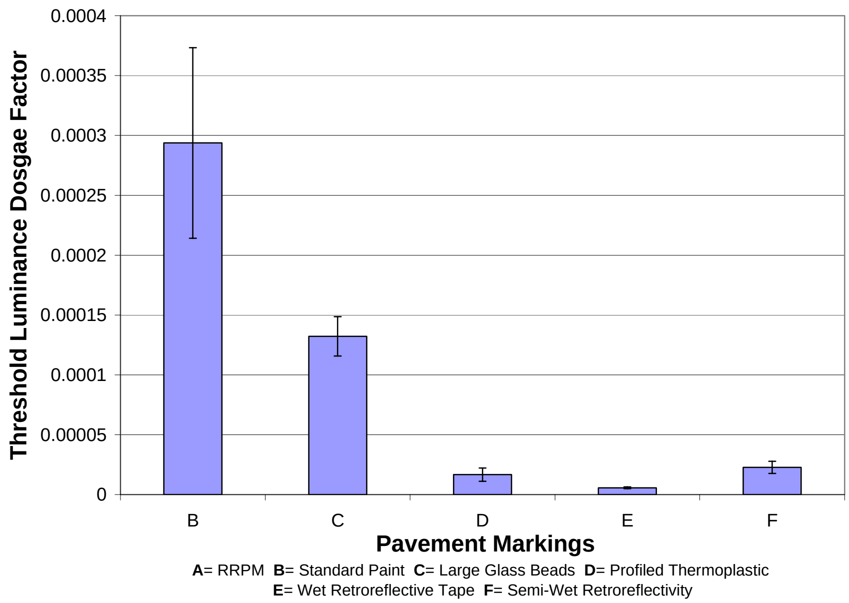


Figure 66. Threshold wet: Results of the Threshold Luminance Dosage Factor

Figure 67 shows the retroreflectivity dosage factor by line type. As with the luminance factor, Lines D, E, and F are similar and Lines B and C are higher. It is not clear from this investigation why the dosage factor for lines B and C are higher. It is noteworthy, however, that these lines have the shortest visibility distance and, therefore, the largest solid visual angle. This increase may represent a critical point where an increase in the size of the object no longer represents an increase in detectability. This would represent the transition to the Weber's Law portion of the visual sensitivity function. The exact nature of this relationship will have to be investigated further. However, this relationship does show that the required retroreflectivity at a distance can be determined from the visual size of the line.

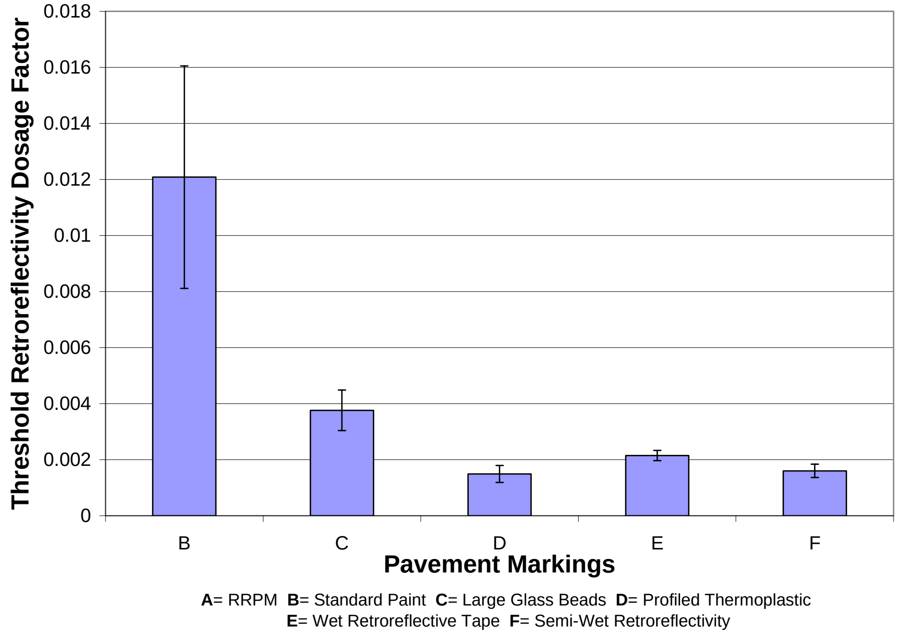
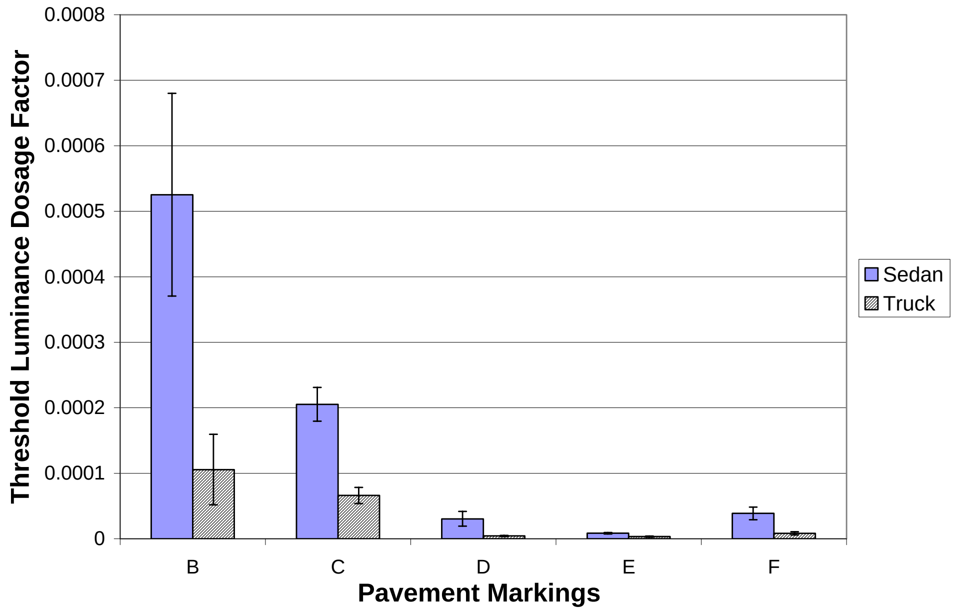


Figure 67. Threshold wet: Results of the Threshold Retroreflectivity Dosage Factor.

In Figures 68 and 69, the threshold luminance dosage and the retroreflectivity dosage are shown by line type and by vehicle. These relationships are less clear in that the numbers vary greatly by the vehicle type. This is not expected, as the vehicle type should not influence the dosage required for visibility. It is possible that two events are occurring to generate this changing threshold. The first is the change in visual perspective, and the second is the change in visual adaptation.

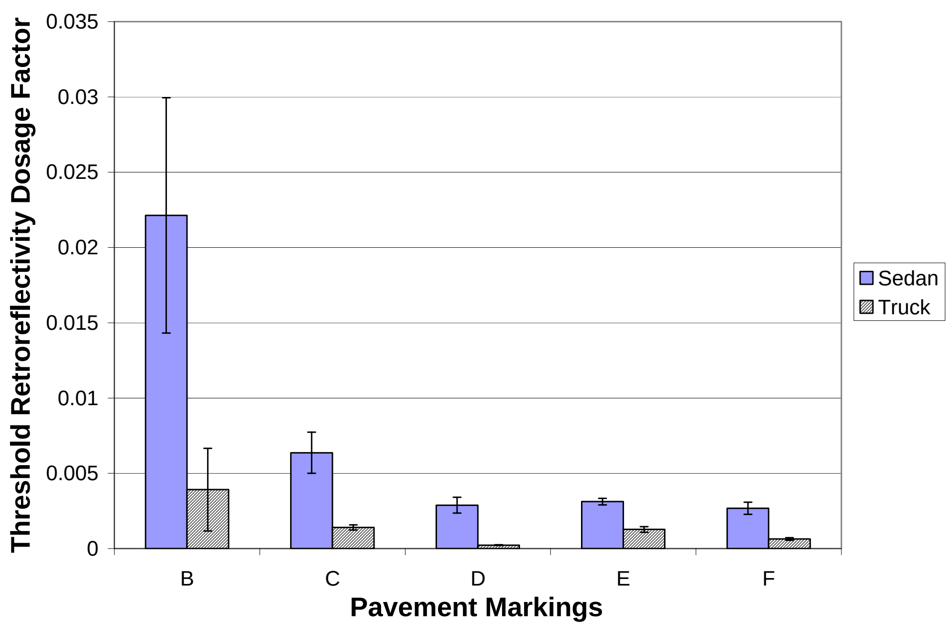
As a driver sits in a vehicle, the skip marks are stretched out in front of the vehicle. In order to perceive a skip, the participant must be able to see the blank in the line. This becomes increasingly more difficult the farther the line is from the vehicle. Because of visual perspective, the detection of the blank is much more difficult, and the skip line begins to look like a solid line. This can be seen in the results for the truck, as the threshold value does not have as much variation as in the sedan. The higher perspective provided by the truck allows the participant to see more of the line. At the point where the participant can no longer separate line and space, the measure is not the luminance threshold but rather their inability to determine a skip and space in the line. This is a potential problem with the methodology used in this investigation. A true measure of the visibility distance with a solid line is required to remove the perspective issue.

To perceive an object, visual science has shown that a lower adaptation luminance level results in a lower threshold luminance level. In the case of a rain event, the driver adaptation luminance is typically lower due to darker pavement and sky. To achieve the same visibility distance, the driver requires a lower threshold. Because the same pavement type and vehicle lighting were used in this investigation, this effect cannot be determined.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads **D**= Profiled Thermoplastic
E= Wet Retroreflective Tape **F**= Semi-Wet Retroreflectivity

Figure 68. Threshold wet: Results of the Threshold Luminance Dosage Factor.



A= RRPM **B**= Standard Paint **C**= Large Glass Beads **D**= Profiled Thermoplastic
E= Wet Retroreflective Tape **F**= Semi-Wet Retroreflectivity

Figure 69. Threshold wet: Results of the Threshold Retroreflectivity Dosage Factor.

Required Retroreflectivity

In order to analyze the required retroreflectivity, the retroreflectivity dosage relationship found earlier can be used to determine the level required. Using the general relationship (Figure 67), which is the mean of the sedan and truck measurements, the required retroreflectivity can be calculated from the required visibility distance.

As pavement markings are primarily used for tracking, the required visibility distance is one that will allow the driver to react to an event in the roadway. The Roadway Delineation Practices Handbook [7] specifies 2 to 3 s of visibility for pavement markings. Using 2 s as the minimum required time, the required visibility distance for a driver can be calculated for several speeds (Table 22).

Table 22. Required visibility distance by speed.

Speed (mph)	Required Reaction Distance (ft)
65	190
55	161
45	132
35	102
25	73

The data from Table 14 show that the RRPMs (line A), the wet retroreflective tape (line E), the profiled thermoplastic (line D) and the semi-wet retroreflective tape (line F) provide adequate visibility in both wet and dry conditions at all speeds. In wet conditions, the paint with large beads (line C) and the paint with standard glass beads (line B) are only adequate to 25 mph.

The suggested retroreflectivity for these speeds can be calculated for a skip marking using a 4 in. by 10 ft marking size. By calculating the apparent solid angle of the pavement marking skip line at the required distance from Table 22, the retroreflectivity can be calculated by dividing that solid angle into the dosage value from Figure 67. These results are shown in Table 23. These values were calculated using the higher result from Line B and E (0.57).

Table 23. Required retroreflectivity by speed

Speed (mph)	Suggested Retroreflectivity $mcd{\cdot}m^2{\cdot}lux^{-1}$
65	115
55	70
45	39
35	18
25	7

Further work is required to fully investigate this relationship and the required retroreflectivity. It is noteworthy that the visibility measurements made in this investigation are static measurements only. True visibility distance for these technologies must be assessed in a dynamic environment to include the impact of driver workload in the assessment of the visibility distance.

Wet Retroreflectivity of Current Pavement Marking Technology

As taken from the experimental results, the performance of the pavement markings can be summarized by the marking technology.

Line A – Raised Retroreflective Pavement Markers

Of all of the technologies considered, this marking technology was the best performing. The response during the saturated and the recovery evaluations showed the best response. The participants in both vehicles also found this line to be the most comfortable during all of the reviewed rain conditions. Finally, this technology was ranked by the participants as the most desirable for roads in Virginia, both in dry and wet conditions. Table 24 shows the summary of the results for line A.

Table 23. Summary of results for RRPM.

RRPM			
	Dry Sedan	Wet Sedan	Wet Truck
Count	10.62	10.98	11.33
Visibility Distance (in ft)	443 ft	415 ft	485 ft
Recovery Time Count (in min)		1.5 min	
Recovery Time Visibility Distance (in min)		1.5 min	

It should be noted that the line used in this experiment was not the typical configuration for this marking technology. It was decided that the markers would be spaced 40 ft apart in order to match the paint and tape technology. In a typical installation however, the markers would be spaced 80 ft apart. This change might impact the acceptance of the technology by the participants and in turn, requires further investigation. The other aspect of this marking technology is that it is cost prohibitive to install these markings on non-interstate or non high volume high speed roadways.

Line B – Latex Paint with Standard Glass Beads

Latex paint with standard glass beads is the marking used on most of the roads in Virginia. Table 25 shows a summary of the variables measured and calculated for this technology.

Table 24. Summary of results for standard paint and beads.

Standard Paint and Beads			
	Dry Sedan	Wet Sedan	Wet Truck
Count	6.31	1.69	2.88
Visibility Distance (in ft)	291	73	114
Measured Retroreflectivity (in $mcd \cdot m^2 \cdot lux^{-1}$)	450.4	3.9	6.2
Calculated Retroreflectivity (in $mcd \cdot m^2 \cdot lux^{-1}$)	128.5	4.4	3.8
Contrast	15.91	0.54	0.79
Luminance (in cd/m^2)	3.225	0.109	0.092
Recovery Time Count (in min)		5.3	
Recovery Time Visibility Distance (in min)		5.3	
Recovery Time Measured Retroreflectivity (in min)		9.4	
Recovery Time Calculated Retroreflectivity (in min)		9.0	

In terms of participant ranking, this technology provided as much comfort as most of the other the technologies for a dry road but dropped significantly for the rain conditions. The participants also ranked this technology as the least desirable in wet conditions, and it tied for the least desirable in dry conditions.

Line C – Latex Paint with Large Glass Beads

Like the paint with standard glass beads, this technology was a poor performer in the wet conditions. It was generally grouped with the standard paint in terms of performance. Table 26 summarizes the performance for this technology. In the recovery evaluation, the mean recovery time for the marking was slightly faster than that of the paint and standard bead technology. This is likely because of the larger glass beads.

Table 25. Summary of results for paint and large glass beads.

Paint and Large Glass Beads			
	Dry Sedan	Wet Sedan	Wet Truck
Count	5.83	2.17	3.23
Visibility Distance (in ft)	284	88	126
Measured Retroreflectivity(in $mcd \cdot m^2 \cdot lux^{-1}$)	440.3	4.4	6.7
Calculated Retroreflectivity(in $mcd \cdot m^2 \cdot lux^{-1}$)	123.9	5.3	4.8
Contrast	13.43	0.89	1.12
Luminance (in cd/m^2)	3.11	0.131	0.115
Recovery Time Count (in min)		5.2	
Recovery Time Visibility Distance (in min)		5.2	
Recovery Time Measured Retroreflectivity (in min)		8.6	
Recovery Time Calculated Retroreflectivity (in min)		8.7	

The participants selected this technology along with the standard bead technology as the least comfortable in all of the rain conditions. Similarly, this technology was grouped with latex paint with standard beads as the least desirable on Virginia roads in dry conditions and the second least desirable in wet conditions next to the latex paint with standard beads.

This material is considered to be a solution to improve wet retroreflectivity, but the results here do not show this improvement. It should be noted that the 0.8 in. per hr rain rate used for this evaluation is typically too high for this technology. As a 95th percentile rate was selected for the rain rate, it is likely that the marking flooded, and the performance was degraded. An investigation of the performance at a wider range of rain rates is desirable to fully investigate this effect.

Line D – Profiled Thermoplastic

This material performed very similarly to the semi-wet retroreflective tape. Both of these technologies were typically grouped in the same categories for all of the analyses. Table 27 summarizes the performance for the profiled thermoplastic technology.

Table 26. Summary of results for profiled thermoplastic.

Profiled Thermoplastic			
	Dry Sedan	Wet Sedan	Wet Truck
Count	8.34	6.22	6.97
Visibility Distance (in ft)	339	201	233
Measured Retroreflectivity (in mcd·m^2·lux^{-1})	761.7	87.8	95.9
Calculated Retroreflectivity (in mcd·m^2·lux^{-1})	238.4	30.4	32.2
Contrast	28.99	10.36	14.94
Luminance (in cd/m^2)	5.983	0.748	0.775
Recovery Time Count (in min)		2.8	
Recovery Time Visibility Distance (in min)		2.8	
Recovery Time Measured Retroreflectivity (in min)		8.3	
Recovery Time Calculated Retroreflectivity (in min)		7.7	

The participants did express that they were slightly more comfortable with this technology in the rain than technologies B, C, or F in both the sedan and the truck in wet conditions, and they were equally comfortable with all of the technologies in the dry condition. The participants also ranked this material as the second most desirable for Virginia roads in dry conditions and grouped it with F as the third most desirable in wet conditions.

Line E – Wet Retroreflective Marking Tape

Of the line technologies (non-marker), this material performed the best. It generally stood out in categories measured. It had the unique feature of increasing in retroreflectivity in the wet condition. The results for this tape are shown in Table 28.

Table 27. Summary of results for wet retroreflective tape.

Wet Retroreflective Tape			
	Dry Sedan	Wet Sedan	Wet Truck
Count	8.17	6.12	9.22
Visibility Distance (in ft)	329.66	280	316.25
Measured Retroreflectivity (in $mcd \cdot m^2 \cdot lux^{-1}$)	1332.62	878.58	694.17
Calculated Retroreflectivity (in $mcd \cdot m^2 \cdot lux^{-1}$)	241.39	142.68	111.93
Contrast	29.7	48.1	44.13
Luminance (in cd/m^2)	6.06	.351	2.7
Recovery Time Count (in min)		1.8	
Recovery Time Visibility Distance (in min)		1.8	
Recovery Time Measured Retroreflectivity (in min)		7.2	
Recovery Time Calculated Retroreflectivity (in min)		6.2	

The recovery time for this material was grouped with the raised retroreflective markers for performance. The participants also expressed comfort with this material in all conditions of rain and dry. This material was ranked second with the profiled thermoplastic for desirability in the dry condition and first with the RRPMs in the wet conditions.

Line F – Semi–Wet Retroreflective Marking Tape

As stated, this material was generally grouped with the profiled thermoplastic in terms of performance. Table 29 summarizes the results for this material.

Table 28. Summary of results for semi-wet retroreflective tape.

Semi-Wet Retroreflective Tape			
	Dry Sedan	Wet Sedan	Wet Truck
Count	7.76	6.17	6.36
Visibility Distance (in ft)	323	200	216
Measured Retroreflectivity (in $mcd \cdot m^2 \cdot lux^{-1}$)	499.4	5.1	17.4
Calculated Retroreflectivity (in $mcd \cdot m^2 \cdot lux^{-1}$)	124.2	22	22.5
Contrast	15.22	8.42	9.2
Luminance (in cd/m^2)	3.119	0.541	0.542
Recovery Time Count (in min)		2.3	
Recovery Time Visibility Distance (in min)		2.3	
Recovery Time Measured Retroreflectivity (in min)		8	
Recovery Time Calculated Retroreflectivity (in min)		5.6	

The participants ranked this material in the middle groups in terms of comfort for all rain conditions and vehicle types. The material was grouped with lines B and C as the least desirable in the dry conditions and ranked with the profiled thermoplastic as the third most desirable in the wet conditions.

Suitability of the ASTM Measurement Methods

Both the continuous and flooded ASTM measurement methods showed a high correlation to the experimental methods used in the simulated rain when line E was included in the analysis and less when line E was left out. The relationship of the measurement methods to the response of the participants is an issue that requires consideration.

The relationship of these measurement methods to the human response is shown in Figure 70. The participant response is for the saturated and the initial counts from the recovery evaluation. Here, the retroreflectivity is presented in a logarithmic scale to represent the psychophysical nature of the measurement.

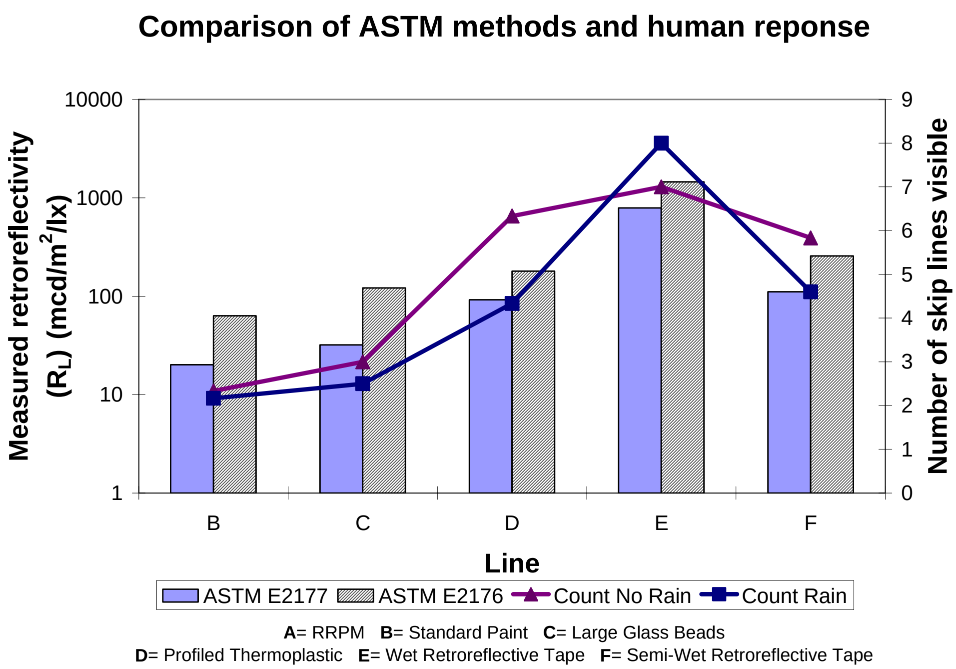


Figure 66. Relationship of human response to the ASTM measurement method results.

The correlation of the methods and the human response was performed. Table 30 shows the results with the flooded method. Table 31 shows the results with the continuous method. It should be noted that these correlations are calculated with an n of 5.

Table 29. Correlation results of the flooded ASTM measurement method to the human response.

	ASTM Flooded	Initial Measured Retro	1 min Measured Retro	Initial Count	1 min Count
ASTM Flooded	1				
Initial Measured Retro	0.97	1			
1 min Measured Retro	0.995	0.98871	1		
Initial Count	0.645	0.76647	0.68175	1	
1 min Count	0.75938	0.85663	0.78982	0.98651	1

Table 30. Correlation results of the continuous ASTM measurement method to the human response.

	ASTM Continuous	Saturated Measured Retro	Saturated Count
ASTM Continuous	1		
Saturated Measured Retro	0.988	1	
Saturated Count	0.932	0.915	1

The high correlation values indicate that the ASTM methods correlate with the participant counts as well as the simulated rain method used in the experiment. The correlation for the continuous measurement is much higher than that for the flooded wetting method.

The correlation was recalculated using the logarithm of the retroreflectivity versus the count value with the results shown in Table 32 and 33. In this case, the correlation values were even higher than the non-log calculation. Again, an n of 5 is used in this calculation.

Table 31. Correlation results of the logarithm of the flooded ASTM measurement method to the human response.

	Log ASTM Flooded	Log Initial Measured Retro	Log 1 min Measured Retro	Initial Count	1 min Count
Log ASTM Flooded	1				
Log Initial Measured Retro	0.885	1			
Log 1 min Measured Retro	0.953	0.984	1		
Initial Count	0.828	0.97	0.941	1	
1 min Count	0.901	0.991	0.982	0.987	1

Table 32. Correlation results of the logarithm of the continuous ASTM measurement method to the human response.

	Log ASTM Continuous	Log Saturated Measured Retro	Saturated Count
Log ASTM Continuous	1		
Log Saturated Measured Retro	0.96908	1	
Saturated Count	0.99724	0.9808	1

It should also be noted that the sprayed rate of water flow on the pavement marking was not varied from the ASTM standard measurement method and may impact the measured results.

However, the correlation analysis from the saturated evaluation does show that the calculated retroreflectivity and the measured retroreflectivity are correlated. The comparison of the values shows that the two values have relatively good correlation between the range of 10 and 100, but the correlation breaks down outside of this range. Figure 71 shows a comparison of the measured and calculated results from the recovery evaluation. Note that logarithmic scales are used for clarity.

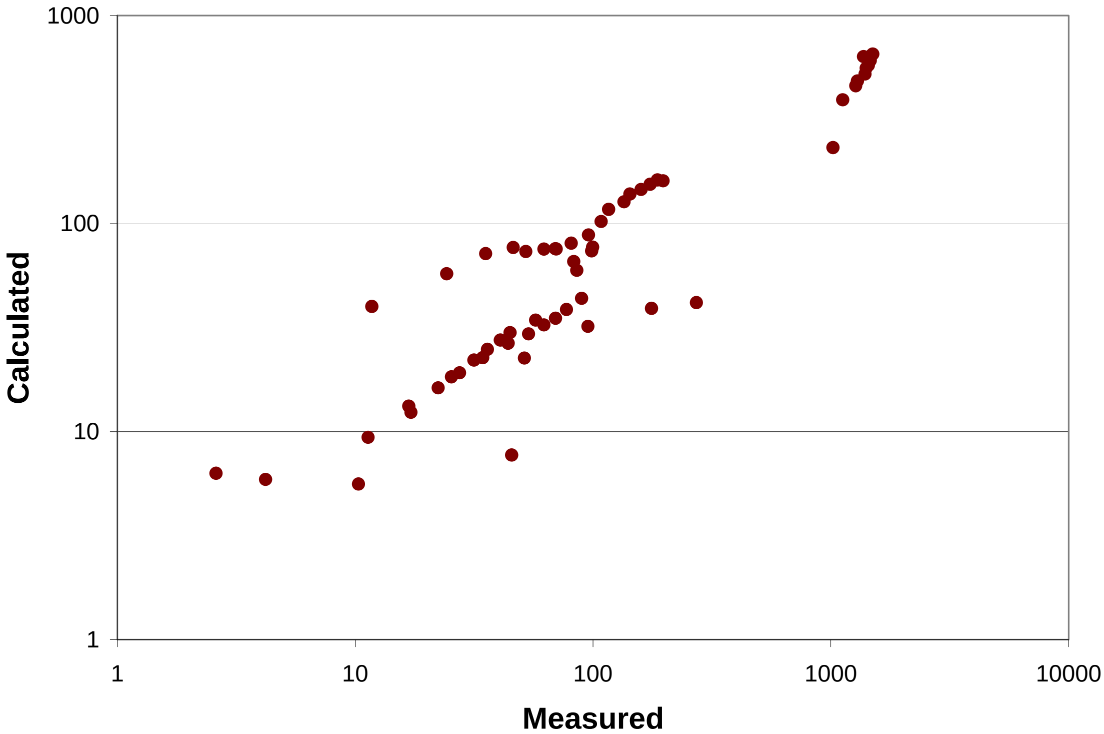


Figure 67. Relationship of measured and calculated retroreflectivity.

There are two issues that may contribute to this breakdown in the correlation. The first is the attenuation by the rain of the measuring instrument's light beam with the distance from the vehicle. The second is the use of two headlamps as light sources in the participant evaluations rather than a single light source as in the measurement process.

In the measurement of the retroreflectivity with the Mechatronic Instrument, a 3 m measurement distance is used to simulate the 30 m geometry. In the rain event, light traveling through the space will collide with the rain drops, which will cause scattering of the light beam. This will reduce the intensity of the light beam both as it travels to the pavement marking and as the luminance returns to the system. This effect can be measured using the headlamp illuminance measurements made for the retroreflectivity by distance. The ratio of the clear and the rain events represents the attenuation of the light intensity. This effect is shown in Figure 72.

The attenuation of the beam varies by distance. This means that the intensity is significantly more attenuated when the measurement is made at the full 30 m rather than at 3 m with the instrument. For the measured retroreflectivity, the calibration of the retroreflectometer requires that an assumption be made about the amount of light leaving the instrument, and therefore hitting the pavement marking surface. If this light is attenuated, the calibration of the instrument is no longer valid and the measured values would be higher than the actual values. For the calculated retroreflectivity, the illuminance was measured at the pavement marking so that the attenuation occurred only on one pass of the light through the rain rather than two as with the retroreflectometer. This means that the error, because of the attenuation, is greater for the measured retroreflectivity than for the calculated retroreflectivity.

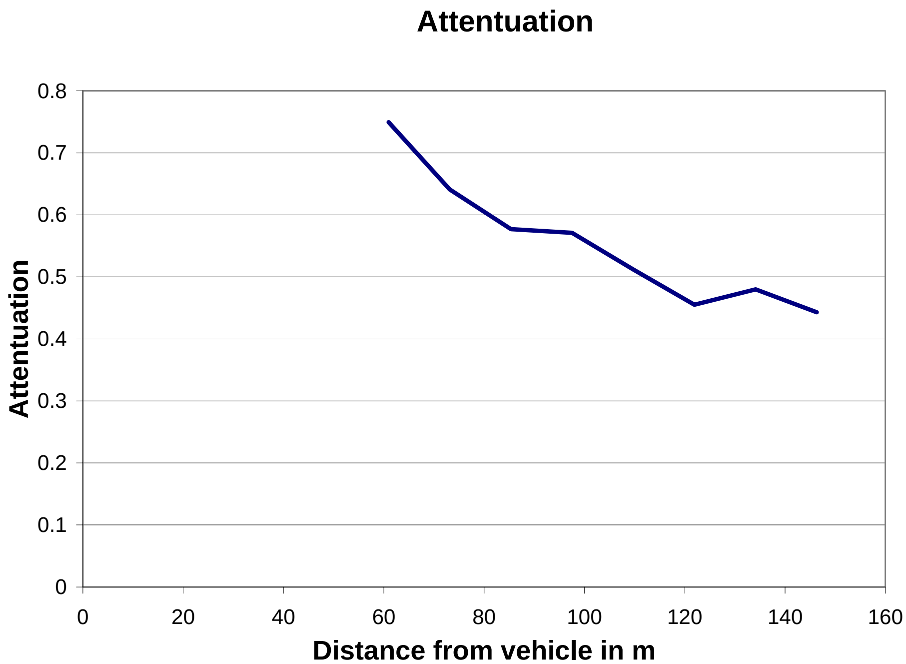


Figure 68. Attenuation of light intensity by distance.

The other difficulty with the measurement method used for the retroreflectivity is that a single light source is used for the instrument where two headlamps are used in the participant evaluations. In order to investigate this effect, a series of measurements were made with the sedan. In this series, the luminance of the pavement markings and the calculated retroreflectivity were measured for both headlamps and each headlamp individually. The measurements were made both at the third skip mark from the vehicle and the sixth skip mark. Figure 73 shows the luminance results for this measurement process. Figure 74 shows the calculated retroreflectivity. The vehicle is positioned such that the right headlamp is lined up with the pavement marking.

It is noteworthy that the calculated retroreflectivity is reduced with two headlamps even though the luminance of the pavement marker is higher. Although there is higher illuminance striking the pavement marking with both headlamps, the ratio of the luminance provided by the illuminance from the left headlamp is lower than that for the right headlamp because of the directionality of the light source and the greater observation angle. Thus, the calculated retroreflectivity for both headlamps is lower than the value would be for just the right headlamp.

In order to provide accurate measurements, both of these issues must be resolved and accounted for in the measurement procedure.

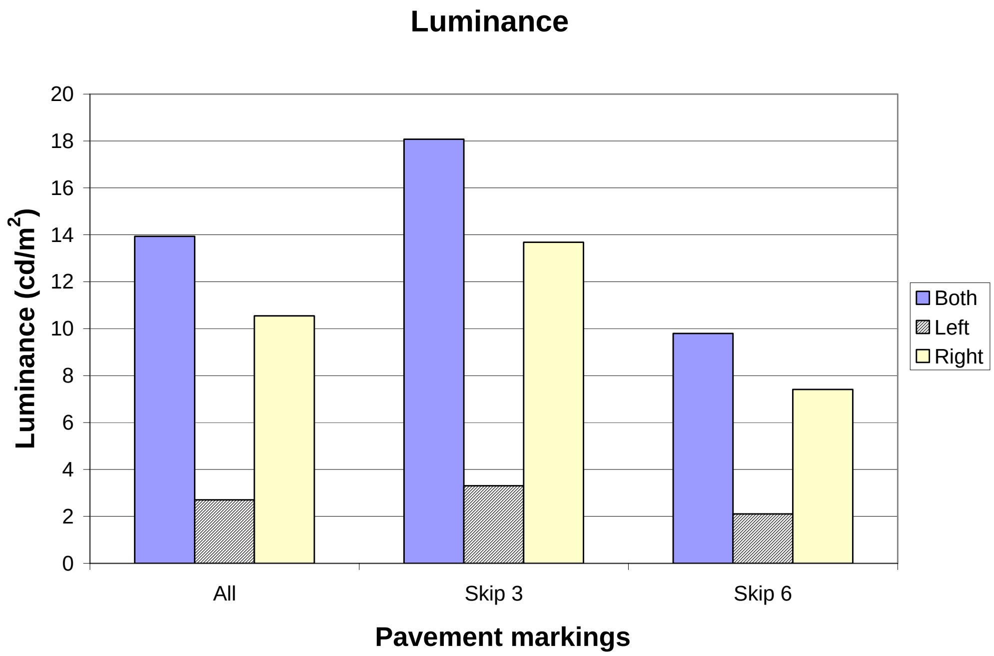


Figure 69. Pavement marking luminance for both and single headlamps.

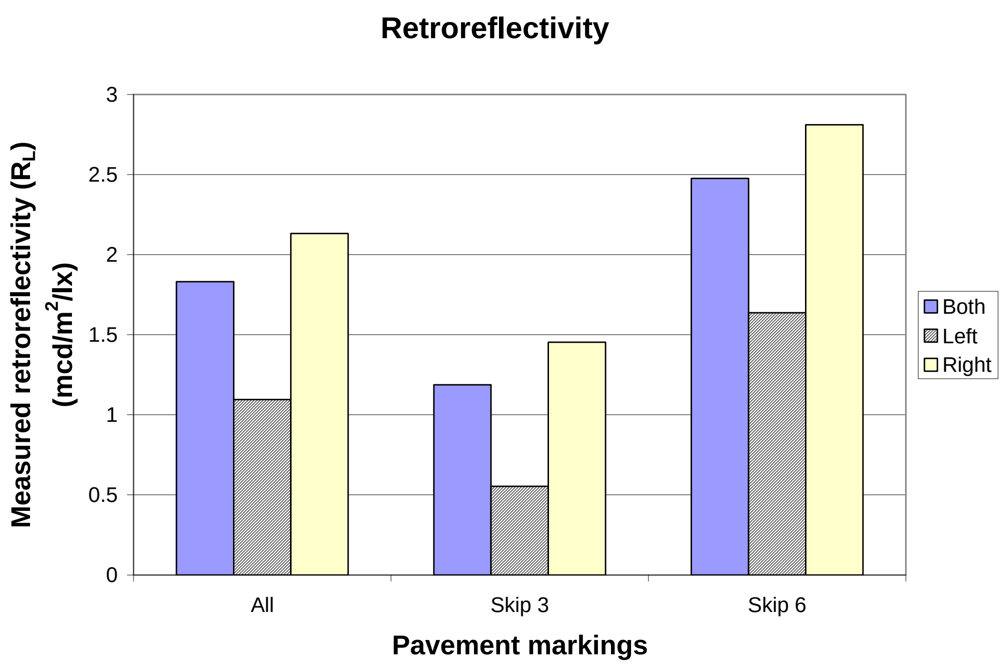


Figure 70. Attenuation of light intensity by distance.

CONCLUSIONS

The conclusions from this experiment are as follows:

1) The participant measures (visibility distance) are correlated most highly with the pavement marking luminance and moderately with the measured retroreflectivity.

2) The visibility distance is influenced by the condition of wetness of the pavement marking, the vehicle type and by the material. The presence of falling rain also influences the visibility through attenuation of the light reaching the observer.

3) The drivers' visual performance is highly correlated with their feelings of comfort and the desirability of the pavement marking technology. This is shown through the strong relationship of the participant measurement results with their rankings and ratings of the marking technology. It should be noted that these evaluations were a relative comparison of markings. It is likely that the relationship between comfort and performance would be less strong for a single marking type.

4) The recovery time for visibility distance varies by material and is shorter than the recovery time of other measured aspects of the pavement markings.

5) The threshold that a participant requires as the extent of their vision seems to change with the availability of marking luminance. This is related to the visual size of the object at the extent of vision. This appears to be influenced by the vehicle type, which can be a result of a change in driver perspective and adaptation luminance. Further investigation into the required luminance, and therefore retroreflectivity, is required.

6) Several of the measured pavement marking technologies provide adequate retroreflectivity to provide the required visibility distance. More investigation is required into some technologies at different rain rates. This must also be investigated in a dynamic situation to establish a true required visibility distance.

7) The ASTM methods seem to be highly correlated to the performance of the participants and to calculated retroreflectivity from the pavement marking luminance. The results from the measurements have a wide range, and after removal of the high performing materials, the correlation is not as high. The absolute values of the measurements are also not equivalent. The issues of using two headlamps and the attenuation of the luminous intensity of the light source must be accounted for in the measurement.

RECOMMENDATIONS

In order to more fully understand the visibility distance and the threshold of the retroreflectivity, which is necessary to generate a performance-based specification for pavement marking devices, further study is required. A further experiment must include a solid line and a true measure of visibility distance. The experiment should also use two different pavement types in order to study the impact of the visual adaptation luminance on visibility. Two vehicle heights must also be used in order to investigate the impact of perspective on the visibility.

Further study must also be given to the required visibility distance for a driver. An experiment can be combined with the one above using a dynamic driving situation and the monitoring of driver performance using measures such as lane tracking.

Further study must also be undertaken with the RRPM technology at standard spacing (80 ft) to further measure the effectiveness of the technology. Similarly, further research using the large bead technology at different rain rates is required to review manufacturer performance claims.

These recommendations will be used to define the next phases of the wet visibility project and the ongoing evaluation of the requirements of drivers in wet night conditions.

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APPENDIX A – QUESTIONNAIRES FOR PARTICIPANT RATING AND RANKINGS

Participant Number ___________

Pre-Evaluation Questionnaire

1. Please indicate approximately how often you drive at night: *(Please check only one.)*
   - O Every night.
   - O Three times per week.
   - O Once per week.
   - O Less often that one time per week.

2. When driving at night, do you mostly wear… *(Please check only one.)*
   - O Single vision eyeglasses?
   - O Bifocal eyeglasses?
   - O Trifocal eyeglasses?
   - O Contact lenses?
   - O Do not wear corrective lenses when driving.

3. Would you say you drive at night with: *(Please circle only one.)*

no difficulty	*little difficulty*	*moderate difficulty*	*extreme difficulty*

4. In general, how do you feel about driving at night in good weather? *(Please circle only one.)*

very comfortable	*somewhat comfortable*	*neither comfortable nor uncomfortable*	*somewhat uncomfortable*	*very uncomfortable*

5. In general, how do you feel about driving at night in typical rain conditions? *(Please circle only one.)*

very comfortable	*somewhat comfortable*	*neither comfortable nor uncomfortable*	*somewhat uncomfortable*	*very uncomfortable*

6. What vehicle do you most often drive at night?

   Make _______________

   Model _______________

   Year _____________

7. What is the minimum visible distance in front of the vehicle in feet that you would need while driving at night?

   Dry Clear Conditions ______________

   Light Rain Conditions ______________

   Medium Rain Conditions ______________

   Heavy Rain Conditions ______________

8. What are you <u>most</u> concerned about when driving in bad weather at <u>nigh</u>t?

Participant Number ___________ Marking A B C D E F

Sedan Dry Sedan Wet Truck Wet

Pavement Marking Rating

Rate the following statements:

How comfortable would you be driving on a highway at night under the following conditions?

1	2	3	4	5
Very Uncomfortable		Neither		Very Comfortable

Dry Road	1	2	3	4	5
Raining enough to set the wipers on an intermittent setting	1	2	3	4	5
Raining enough for the wipers on regular speed	1	2	3	4	5
Raining enough for the wipers on high Speed	1	2	3	4	5

Participant Number ___________ Sedan Dry Sedan Wet Truck Wet

Pavement Marking Ranking

Rank which markings you would like to see on Virginia’s Roads.

1 should be the marking you most want to see on the road and 6 is the marking you would least like to see on the road.

A ______________

B ______________

C ______________

D ______________

E ______________

F ______________

Participant Number ___________ Sedan Dry Sedan Wet Truck Wet

Post-evaluation Questionnaire

1) What is the minimum number of visible skip lines you would need while driving at night?

Dry Clear Conditions ______________

Light Rain Conditions ______________

Medium Rain Conditions ______________

Heavy Rain Conditions ______________

2) Do you have any other comments about the pavement markings you have seen tonight?

APPENDIX B – PARTICIPANT TRAINING PRESENTATION

Wet Visibility of Pavement Markings

~ Driving Transportation With Technology ~

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TRANSPORTATION INSTITUTE

Goal of the Study

- We will be evaluating the Visibility of Pavement Markings under Wet Night Conditions
- We are establishing the visual needs of drivers during Rainy Conditions
- This will evaluation will be in two vehicles and in two rain conditions.

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Virginia Tech
TRANSPORTATION INSTITUTE

Process

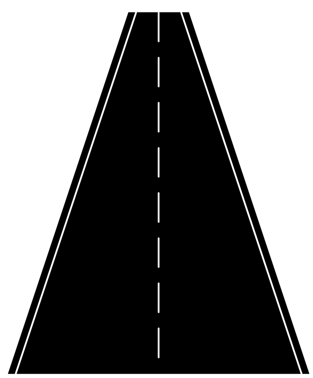
- One at a time, we will be counting the number of skips lines visible for a variety of pavement marking technologies

~ Driving Transportation With Technology ~

Virginia Tech TRANSPORTATION INSTITUTE

What is a skip line?

- It is the “dash”



~ Driving Transportation With Technology ~

Virginia Tech TRANSPORTATION INSTITUTE

Process

- You will be looking through a baffled slot on the windshield
- You will need to move your head from side to side to view the entire line
- The goal is to align a red marker at one end of the line with the sign at the start of the line

~ Driving Transportation With Technology ~

Virginia Tech
TRANSPORTATION INSTITUTE

Alignment

Correct | Incorrect

~ Driving Transportation With Technology ~

TRANSPORTATION INSTITUTE

Counting

- Count the number of skip lines or Markers you see and tell it to the experimenter in the back seat
  - You can count out loud or silently
  - Other equipment will be clicking making noise beside you
    - It is to accurately record the state of the pavement marking
- You can leave the vehicle after you have finished counting

~ Driving Transportation With Technology ~

Virginia Tech TRANSPORTATION INSTITUTE

Rating

- After you have evaluated the pavement marking, we will have you fill out a rating form for each of the technologies
  - This will be performed at a table on the road
- Always rank the markings with respect to the vehicle you were tested (Truck or Sedan)

~ Driving Transportation With Technology ~

Virginia Tech TRANSPORTATION INSTITUTE

Rating Sheet

Pavement Marking Rating

Rate the following statements:

How comfortable would you be driving on a highway at night under the following conditions:

1	2	3	4	5
Very Uncomfortable		Neither		Very Comfortable

Dry Road	1	2	3	4	5
Raining enough to set the wipers on an intermittent setting	1	2	3	4	5
Raining enough for the wipers on regular speed	1	2	3	4	5
Raining enough for the wipers on high Speed	1	2	3	4	5

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Aid

- We will be using a Truck or a Sedan
  - A set of stairs has been provided to aid in getting into the truck
  - A rotating seat has been provided in the sedan if required to aid in access

~ Driving Transportation With Technology ~

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Process

- This cycle of evaluation and rating will continue for six different technologies
- While the other participants are evaluating
  - Refreshments are available
  - The bus is available for shelter
- Please do not discuss your results with other participants
- One of the Experimenters will be with you and let you know when you will be needed

~ Driving Transportation With Technology ~

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Ranking

- After we have completed all of the pavement marking evaluations, We will be asking you to review and rank all of the pavement markings simultaneously
- Always rank the markings with respect to the vehicle you were tested (Truck or Sedan)

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Ranking Sheet

Pavement Marking Ranking

Rank which markings you would like to see on Virginia's Roads?

1 should be the marking you most want to see on the road and 6 is the marking you would least like to see on the road.

A ______________
B ______________
C ______________
D ______________
E ______________
F ______________

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Safety

- Please be careful of the edge of the asphalt
  - a sharp drop off can exist
- Do not cross the white line across the pavement unescorted
  - The vehicles may be in motion

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Other Issues

- If you need to come back to the building for any reason, we will be providing a vehicle to shuttle you

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APPENDIX C – WET/DRY CONDITION - ANOVA SUMMARY TABLES

Table 33. ANOVA for the number of pavement marking skips identified by the participant.

Number of Pavement Marking Skips Identified by the Participant

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	399.7	12.9			
Within						
Condition	1	1056.0	1056.0	1467.7	<.0001	*
Participant_Number*Condition	25	18.0	0.7			
Line	5	1795.9	359.2	227.7	<.0001	*
Participant_Number*Line	155	244.5	1.6			
Line*Condition	5	304.0	60.8	41.6	<.0001	*
Participant_Number*Line*Condition	125	182.5	1.5			
Total	347	4000.6				

* p < 0.05 (significant)

Table 34. ANOVA for the measured retroreflectivity.

Measured Retroreflectivity under Standard 30 m Geometry

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	26	183627.7	7062.6			
Within						
Condition	1	6869657.2	6869657.2	784.4	<.0001	*
Participant_Number*Condition	12	105090.1	8757.5			
Line	4	21011824.0	5252956.0	2587.1	<.0001	*
Participant_Number*Line	100	203048.5	2030.5			
Line*Condition	4	232251.9	58063.0	27.4	<.0001	*
Participant_Number*Line*Condition	41	86764.6	2116.2			
Total	188	28692264.0				

* p < 0.05 (significant)

Table 35. ANOVA for the contrast.

Contrast Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	2003.7	64.6			
Within						
Condition	1	3701.2	3701.2	77.9	<.0001	*
Participant_Number*Condition	25	1188.5	47.5			
Line	4	39892.3	9973.1	287.1	<.0001	*
Participant_Number*Line	124	4308.1	34.7			
Line*Condition	4	10295.5	2573.9	74.2	<.0001	*
Participant_Number*Line*Condition	100	3467.3	34.7			
Total	289	64856.5				

* p < 0.05 (significant)

Table 36. ANOVA for the calculated retroreflectivity.

Calculated Retroreflectivity Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	57122.1	1842.6			
Within						
Condition	1	1148253.7	1148253.7	674.7	<.0001	*
Participant_Number*Condition	25	42545.9	1701.8			
Line	4	713576.9	178394.2	327.2	<.0001	*
Participant_Number*Line	124	67606.7	545.2			
Line*Condition	4	105592.9	26398.2	48.1	<.0001	*
Participant_Number*Line*Condition	100	54927.7	549.3			
Total	289	2189625.8				

* p < 0.05 (significant)

Table 37. ANOVA for the pavement marking rating under dry road condition.

Pavement Marking Rating under Dry Road Condition

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	120.5	3.9			
Within						
Condition	1	35.1	35.1	25.5	<.0001	*
Participant_Number*Condition	25	34.4	1.4			
Line	5	70.5	14.1	29.7	<.0001	*
Participant_Number*Line	155	73.6	0.5			
Line*Condition	5	20.1	4.0	8.4	<.0001	*
Participant_Number*Line*Condition	124	59.5	0.5			
Total	346	413.6				

* p < 0.05 (significant)

Table 38. ANOVA for the pavement marking rating under intermittent wipers setting.

Pavement Marking Rating with Wipers on Intermittent Setting

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	110.3	3.6			
Within						
Condition	1	50.9	50.9	38.6	<.0001	*
Participant_Number*Condition	25	32.9	1.3			
Line	5	104.3	20.9	44.1	<.0001	*
Participant_Number*Line	155	73.3	0.5			
Line*Condition	5	19.3	3.9	9.2	<.0001	*
Participant_Number*Line*Condition	125	52.8	0.4			
Total	347	443.8				

* p < 0.05 (significant)

Table 39. ANOVA for the pavement marking rating under regular wipers setting.

Pavement Marking Rating with Wipers on Regular Setting

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	115.3	3.7			
Within						
Condition	1	67.4	67.4	59.1	<.0001	*
Participant_Number*Condition	25	28.5	1.1			
Line	5	107.1	21.4	40.9	<.0001	*
Participant_Number*Line	155	81.2	0.5			
Line*Condition	5	28.0	5.6	11.4	<.0001	*
Participant_Number*Line*Condition	125	61.6	0.5			
Total	347	489.1				

* $p < 0.05$ (significant)

Table 40. ANOVA for the pavement marking rating under high wipers setting.

Pavement Marking Rating with Wipers on High Setting

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	142.2	4.6			
Within						
Condition	1	49.3	49.3	39.5	<.0001	*
Participant_Number*Condition	25	31.2	1.2			
Line	5	108.0	21.6	40.0	<.0001	*
Participant_Number*Line	155	83.7	0.5			
Line*Condition	5	28.0	5.6	12.2	<.0001	*
Participant_Number*Line*Condition	125	57.5	0.5			
Total	347	499.9				

* $p < 0.05$ (significant)

APPENDIX D – SATURATED - ANOVA SUMMARY TABLES

Table 41. ANOVA for the number of pavement marking skips identified by the participant.

Number of Pavement Marking Skips Identified by the Participant

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	198.8	6.4			
Within						
Vehicle	1	84.0	84.0	34.9	<.0001	*
Participant_Number*Vehicle	28	67.4	2.4			
Line	5	3508.8	701.8	692.1	<.0001	*
Participant_Number*Line	155	157.2	1.0			
Line*Vehicle	5	7.7	1.5	1.7	0.1484	
Participant_Number*Line*Vehicle	140	129.2	0.9			
Total	365	4153.0				

* $p < 0.05$ (significant)

Table 42. ANOVA for the measured retroreflectivity.

Measured Retroreflectivity under Standard 30 m Geometry

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	23	117078.4	5090.4			
Within						
Vehicle	1	87670.8	87670.8	11.9	0.0029	*
Participant_Number*Vehicle	18	133007.9	7389.3			
Line	4	16879039.7	4219759.9	2057.0	<.0001	*
Participant_Number*Line	80	164109.9	2051.4			
Line*Vehicle	4	152278.9	38069.7	12.9	<.0001	*
Participant_Number*Line*Vehicle	30	88721.8	2957.4			
Total	160	17621907.3				

* $p < 0.05$ (significant)

Table 43. ANOVA for the contrast.

Contrast Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	1387.5	44.8			
Within						
Vehicle	1	9.2	9.2	0.1	0.7086	
Participant_Number*Vehicle	28	1807.2	64.5			
Line	4	84550.7	21137.7	568.1	<.0001	*
Participant_Number*Line	124	4614.2	37.2			
Line*Vehicle	4	528.5	132.1	2.9	0.0243	*
Participant_Number*Line*Vehicle	112	5066.7	45.2			
Total	304	97964.1				

* $p < 0.05$ (significant)

Table 44. ANOVA for the calculated retroreflectivity.

Calculated Retroreflectivity Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	3027.5	97.7			
Within						
Vehicle	1	2523.3	2523.3	18.6	0.0002	*
Participant_Number*Vehicle	28	3798.3	135.7			
Line	4	630855.7	157713.9	1920.9	<.0001	*
Participant_Number*Line	124	10180.8	82.1			
Line*Vehicle	4	11138.8	2784.7	33.2	<.0001	*
Participant_Number*Line*Vehicle	112	9391.2	83.9			
Total	304	670915.6				

* $p < 0.05$ (significant)

Table 45. ANOVA for the pavement marking rating under dry road condition.

Pavement Marking Rating under Dry Road Condition

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	32	195.5	6.1			
Within						
Vehicle	1	0.1	0.1	0.1	0.7485	
Participant_Number*Vehicle	28	19.2	0.7			
Line	5	153.6	30.7	39.1	<.0001	*
Participant_Number*Line	155	121.7	0.8			
Line*Vehicle	5	3.0	0.6	1.6	0.1764	
Participant_Number*Line*Vehicle	140	54.2	0.4			
Total	366	547.3				

* $p < 0.05$ (significant)

Table 46. ANOVA for the pavement marking rating under intermittent wipers setting.

Pavement Marking Rating with Wipers on Intermittent Setting

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	32	149.6	4.7			
Within						
Vehicle	1	0.6	0.6	1.0	0.3357	
Participant_Number*Vehicle	28	16.4	0.6			
Line	5	194.7	38.9	52.2	<.0001	*
Participant_Number*Line	155	115.7	0.7			
Line*Vehicle	5	3.9	0.8	2.2	0.0607	
Participant_Number*Line*Vehicle	140	50.1	0.4			
Total	366	530.9				

* $p < 0.05$ (significant)

Table 47. ANOVA for the pavement marking rating under regular wipers setting.

Pavement Marking Rating with Wipers on Regular Setting

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	32	147.0	4.6			
Within						
Vehicle	1	3.3	3.3	5.4	0.0274	*
Participant_Number*Vehicle	28	17.2	0.6			
Line	5	208.8	41.8	56.6	<.0001	*
Participant_Number*Line	155	114.4	0.7			
Line*Vehicle	5	4.6	0.9	2.8	0.018	*
Participant_Number*Line*Vehicle	140	45.9	0.3			
Total	366	541.2				

* $p < 0.05$ (significant)

Table 48. ANOVA for the pavement marking rating under high wipers setting.

Pavement Marking Rating with Wipers on High Setting

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	32	134.7	4.2			
Within						
Vehicle	1	0.3	0.3	0.6	0.4452	
Participant_Number*Vehicle	28	16.2	0.6			
Line	5	225.8	45.2	66.2	<.0001	*
Participant_Number*Line	155	105.8	0.7			
Line*Vehicle	5	4.7	0.9	2.4	0.0412	*
Participant_Number*Line*Vehicle	140	55.2	0.4			
Total	366	542.7				

* $p < 0.05$ (significant)

APPENDIX E – PAVEMENT MARKING RANKING FOR DRY SEDAN AND TRUCK - ANOVA SUMMARY TABLES

Table 49. ANOVA for the pavement marking rating for dry sedan.

Pavement Marking Rating for Dry Sedan

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	28	29.529	1.055			
Within						
Line	5	202.994	40.599	20.63	<.0001	*
Participant_Num*Line	140	275.506	1.968			
Total	173	508.029				

* $p < 0.05$ (significant)

Table 50. ANOVA for the pavement marking rating for saturated truck.

Pavement Marking Rating for Truck

Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	31	6.047	0.195			
Within						
Line	5	337.972	67.594	45.55	<.0001	*
Participant_Num*Line	153	227.028	1.484			
Total						

* $p < 0.05$ (significant)

APPENDIX F – RECOVERY TIME - ANOVA SUMMARY TABLES

Table 51. ANOVA for recovery time of count.

Count Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	5	6.33333333	1.26666667			
Within						
Line	5	84.33333333	16.86666667	5.83	0.0011	*
Participant_Number*Line	25	72.33333333	2.89333333			

* p < 0.05 (significant)

Table 52. ANOVA for recovery time of measured retroreflectivity.

Count Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	5	2.49217741	0.49843548			
Within						
Line	4	15.72551075	3.93137769	4.11	0.0209	*
Participant_Number*Line	14	13.40782259	0.95770161	.	.	

* p < 0.05 (significant)

Table 53. ANOVA for recovery time of calculated retroreflectivity.

Count Source	DF	SS	MS	F value	P value	Sig
Between						
Participant_Number	5	8.915	1.783			
Within						
Line	4	51.215	12.80375	8.17	0.0005	*
Participant_Number*Line	19	29.785	1.56763158	.	.	

* p < 0.05 (significant)