FINAL CONTRACT REPORT

WET NIGHT VISIBILITY OF PAVEMENT MARKINGS: EXECUTIVE SUMMARY

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INTRODUCTION

Much of the visual information needed by a driver to navigate roads 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, or amount of light reflected back to the source, of conventional pavement markings is degraded under these conditions; water scatters light instead of returning it, making the marking less visible. This reduced visibility renders the driving task more challenging because drivers have less tracking information. The urgency of the problem was confirmed by a 1997 customer service survey conducted by VDOT in which Virginia drivers said that "nighttime visibility, especially in wet conditions" needed added attention. This issue has also been discussed a number of times by the Traffic Research Advisory Committee of the Virginia Transportation Research Council (VTRC).

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. Snow plowable raised pavement markers may be viewed as a benchmark, as they are the primary means currently used by VDOT to provide wet night retroreflectivity. Methods for testing these and other road markings, including a bucket method and a spray method, are being developed to enable field personnel to evaluate the retroreflective properties of wet, in-service pavement marking materials, but the applicability of the tests is unknown.

PURPOSE AND SCOPE

The research sought to answer the following questions: what level of retroreflectivity do drivers need under rain conditions and what levels of retroreflectivity are current pavement markings and markers capable of producing under various rain conditions? The rain conditions include the period during rainfall of various intensities within a defined range and the recovery period (drying) after rain has stopped. The research also sought to test the suitability of the American Society for Testing and Materials (ASTM) measurement methods for wet pavement marking retroreflectivity. The findings should then be used to develop performance measures for evaluating wet night retroreflectivity of pavement delineation devices and a performance-based specification that is based on the visibility needs of motorists during wet night conditions, perhaps even one for inclusion in VDOT's Road and Bridge Specifications.

PHASE 1—RAINFALL CHARACTERIZATION

Methods and Materials

Two sets of rain data were purchased for this portion of the project from the National Climatic Data Center (NCDC): a set of hourly weather records from 424 weather stations across Virginia and a second set with data that were recorded every 15 min from 54 weather stations across Virginia. Through an analysis of the reliability of the data, it was found that the data from the 15 min set, which measured in hundredths of 1 in of rain, provided the closest representation of typical Virginia 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 (the data from the beginning and end periods of rain were excluded).

Results and Discussion

The following rain event rates were chosen as possibilities for the simulated rain used in the experiment:

1) 0.8 in per hr (95th 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).

High rain rates can cause inadequate retroreflectivity performance in some of the pavement marking technologies tested in the simulation phase, such as large beads in paint and thin thermoplastics, making it desirable to minimize the rain rate in order to fairly test all of the products. Therefore the value of 0.8 in per hr was selected, which is also close to the minimum rain amount available on the Virginia 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 rainfall condition. The second task evaluated the pavement markings during a recovery or drying period. The third established the performance of the measured pavement marking technologies during the wet conditions at non-typical geometries, including measurement of the pavement markings using the ASTM methods and measurement in the simulated rain.

Equipment

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, and it includes rain-making capabilities. For this experiment, an auxiliary pavement section was paved to the side of the main Smart Road facility. This pavement section was 1,200 ft long with a constant grade of 2 percent. The experimental area was also paved flat, meaning it had no central crown. The pavement type was bituminous asphalt.

Pavement Markings

Six different types of pavement markings were viewed by the participants during the experiments. 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). A spacing of 40 ft was used between the raised retroreflective pavement markers (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 1.

Experimental Vehicles

The two experimental vehicles used were a sedan and a truck tractor, both with standard halogen headlamps, which were the sole sources of illumination during the experimental sessions. The sedan was a 1998 Ford Crown Victoria, and the truck was a 1997 Volvo VN series class 8 tractor.

Measurement Equipment

Three instruments were used in the experiment: a Minolta T-10 illuminance meter, a Radiant Imaging CCD photometer, and an external beam Mechatronic FRT 01 retroreflectometer.

Saturated Evaluation

The evaluation of the saturated pavement markings required human observers to view and evaluate the markings in the rain and for instruments to measure the markings' visibility.

Experimental Design

The experimental design is a 6 X 2 X 2 partial factorial design; only the conditions of dry sedan, wet sedan, and wet truck were evaluated for the experiment. The conditions are shown in Table 2.

Table 1. Pavement marking technology summary.

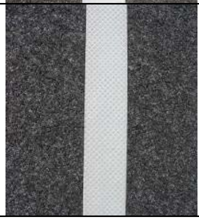
Marking	Technology	Supplier/Trade Name	Image
A	Standard Latex Paint with Standard Glass Beads and Raised Retroreflective Markers	The Paint and Beads Conform with VDOT Road & Bridge Specification 2002 Section 246 RRPMs Are 3M PSA 290 Type Self Adhesive Markers with Red and White Lenses	
B	Standard Latex 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	

Table 2. Experimental design.

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

Independent Variables

The independent variables in this evaluation included the pavement marking types, which were selected to provide the widest range of marking retroreflectivity possible.

The second variable, marking condition, was whether or not the Smart Road's simulated rain system was running (at a rate of 0.8 in per hr) and wetting the marking or if the marking was dry.

The final factor, vehicle type, provided two different angular views of the roadway. The standard geometry used for the evaluation of the retroreflectivity of pavement marking is for a sedan-style vehicle, specified by the American Society for Testing and Materials (ASTM) as 30 m geometry. The second view was from a truck, which provided a much higher viewing angle.

Dependent Variables

Participants were asked to count the number of skip marks visible from the passenger seat of the experimental vehicles. This count, representing the visibility distance, was measured for each marking in each of the experimental conditions.

As the participants performed the count, the luminance of the third skip mark in the series, which was 30 m from the experimental vehicle, was measured by a CCD photometer. Similarly, the retroreflectivity of the first marking in the sequence was measured using a standard 30 m geometry instrument (FRT-01 Retroreflectometer) placed in front of the vehicle.

The last dependent variables were subjective. Participants were asked to rank their preference for each marking type and their comfort level while driving in various rain conditions.

Participants

Sixteen males and 17 females, all 60 years old and over, were selected to participate and were paid. Data were taken on their vision and comfort levels in driving at night and in the rain.

Method

One by one, the participants were held outside in the dark for at least one minute to allow for dark adaptation. They were then seated in the experimental vehicle and asked to count the number of skip marks visible through a slit in a windshield baffle, which limited the view to one pavement marking material only. Participants verbally told the count to the experimenter in the rear seat of the vehicle. 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. At the same time, experimenters recorded the luminance and retroreflectivity of the pavement markings. Participants had a maximum of one minute to make their count. After completing the count, the participants filled out the rating sheets. The process repeated for each pavement marking material type.

Recovery Evaluation

The recovery evaluations were made using a similar methodology as that of the saturated measurements. In this case though, the sedan was the only experimental vehicle. All six pavement markings were used, the same in-vehicle setup was used, and the dependent variables for the 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 evaluation.

Method

The procedure was the same as in the saturated evaluation, including the visibility distance measurement, luminance measurement, and retroreflectivity measurement. However, after taking these measurements with the simulated rain turned on (a repeat of the rain evaluation), the measurements were also taken just after the rain was turned off and again every minute for 10 min. This additional time period represented the time from the moment without falling rain, when the marking was still saturated, through 10 min of drying. The procedure was repeated for each pavement marking.

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. Measurements were performed in two steps: a retroreflectivity by distance measurement and the evaluation of the markings using the ASTM methods.

Retroreflectivity by Distance Measurements

During saturated and recovery evaluations, the luminance, measured retroreflectivity, and calculated retroreflectivity were evaluated with 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. However, 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 and the illuminance of each pavement marking on the experimental area from the experimental vehicle.

For each condition used in the evaluation (wet sedan, wet truck, and dry sedan), an image of the roadway was taken with a CCD photometer that showed all of the pavement markings of interest, using the maximum and minimum number of skip marks seen by all of the participants as limits. Pavement marking luminance and illuminance were measured from this image. This allowed for the calculation of the actual retroreflectivity at all markings, not just those at 30 m geometry.

ATSM Measurement Methods

The ASTM Measurement Methods for retroreflectivity consisted of two types of methods: the flooded (bucket) method and the continuous (sprayer) method. Both methods were performed using the same retroreflectometer. The flooded method produced a condition of wetness like that found just after rainfall; retroreflectivity measurements were taken 45 s after a gallon of water was poured on the pavement marking. The continuous method produced wetness like that found during rainfall with a sprayer, set to spray 0.8 L of water per minute, 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. As the ASTM measurement method produce similar conditions to those in the recovery evaluation, these results can be compared.

Results

Saturated Evaluation

A Pearson *r* correlation matrix was generated for both marking conditions, saturated and dry, and both vehicle types, sedan and truck. The analysis showed good correlation between the Rank Count and Preference Ranking (0.903), between the Marking Luminance and Measured Retroreflectivity (0.0933) and between Marking Luminance and Visibility Distance (0.857). The remaining comparisons did not have strong correlations. A Pearson *r* correlation matrix was generated for wet data only, including both the sedan and the truck. In this analysis, the correlation between Preference Ranks and Visibility Distance stood out as especially high (0.988). However, since luminance and retroreflectivity are responded to psychophysically, a further correlation analysis was performed for the visibility distance and the logarithm of the luminance and the retroreflectivity (Table 3). In this analysis, it was found that the correlation coefficients of the visibility distance increased to 0.977 and 0.935 for the luminance and the retroreflectivity respectively.

An analysis was performed for the interaction of pavement marking technology (Line) and the wet/dry condition. Results are shown in Figure 1.

Table 4 shows the mean visibility distances measured in the evaluation.

Table 3. Correlation coefficients for 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

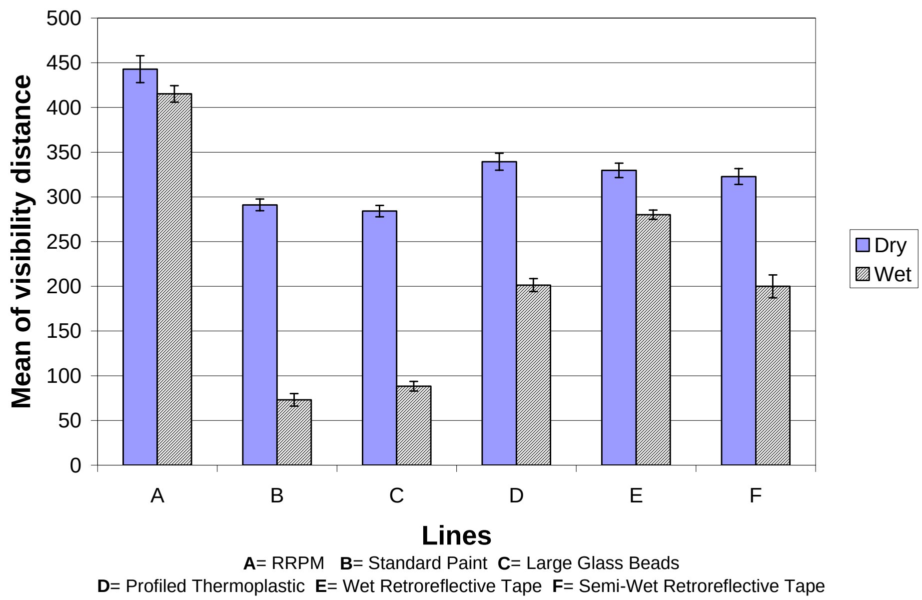


Figure 1. Sedan: results of the visibility distance for the condition x line interaction.

Table 4. Visibility distance summary (in ft).

Technology	Dry Condition	Wet 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

After the evaluation of each of the pavement marking materials, participants answered subjective measure questionnaires on how comfortable they thought they would be with the different pavement markings if the road was dry and if the road was wet, with different windshield wiper speeds for the latter. They were asked to make these ratings twice, once while observing dry pavement markings and once while observing wet markings. The results showed that participants were not consistent in their ratings; that is, when the pavement markings were wet, their comfort levels changed dramatically from what their expected comfort levels had been during the dry observation.

The visibility distance results show that the truck provided greater distance than does the sedan (Table 5). On average, this seems to show an improvement in the visibility distance of approximately one additional skip mark. The analysis showed that there was no interaction of vehicle type and line type.

Table 5. 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 2 shows the results of participants' preference ranking of pavement markings for the wet truck condition.

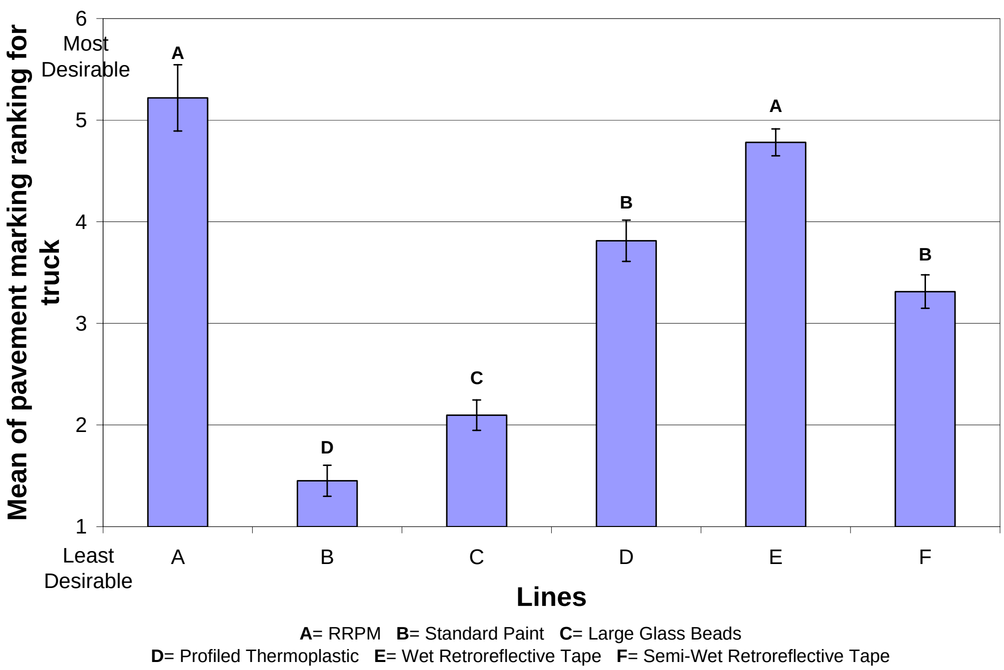


Figure 2. Truck: results of pavement marking ranking for the line main effect (means with the same letter are not significantly different).

Recovery Evaluation

Figure 3 shows the mean of the participants' results for the number of pavement skip marks identified during the recovery evaluation.

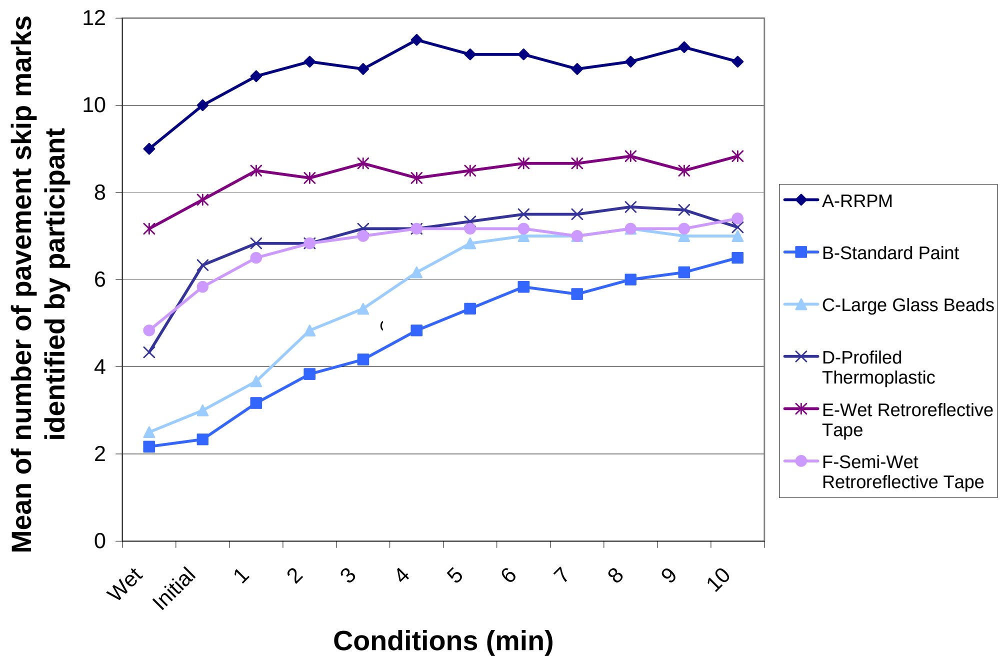


Figure 3. Recovery across participants: results of number of pavement skip marks identified by participant.

The recovery time was selected as the time when the material returned to stable performance. Table 6 summarizes the mean recovery time for each of the marking technologies.

Table 6. Mean 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

Recovery times were much shorter in terms of when the participants could count a stable number of skip marks than in terms of measured retroreflectivity, as can be seen in Figures 4 and 5. This means that although the markings were not at their full performance the driver was still able to have full visual performance.

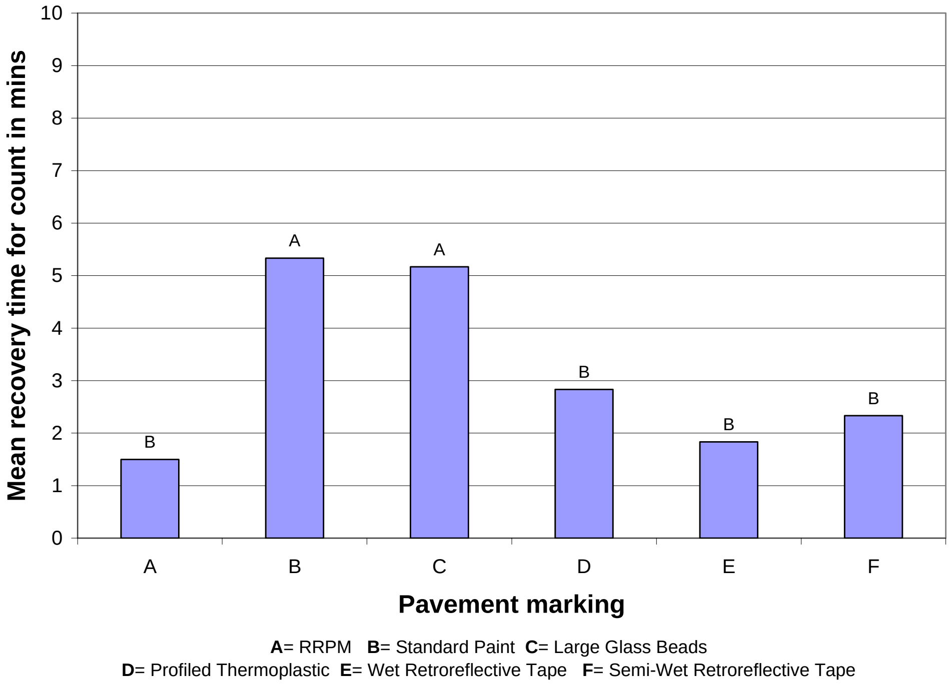


Figure 4. Main effects of line on the mean recovery time for count.

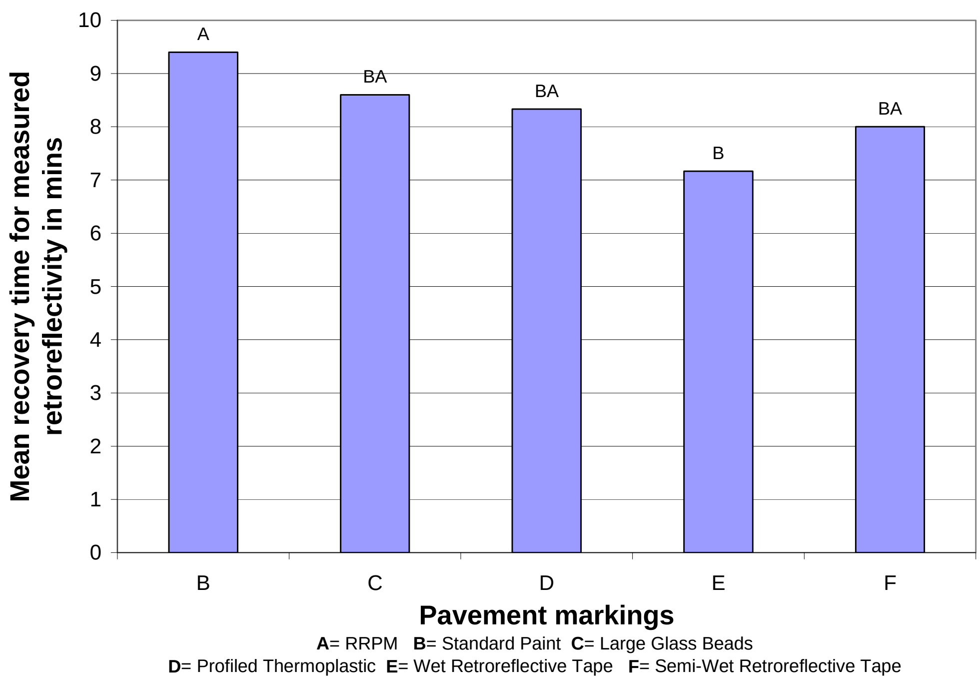


Figure 5. Main effects of line on the mean recovery time for measured retroreflectivity.

Retroreflectivity Measurements

Retroreflectivity by Distance Measurements

The measurements behaved as one would expect. The greater the distance from the vehicle, the lower the luminance of the pavement marking. This was a result of the changing geometry of the vehicle headlamps and the observer. These results will be used to provide further information with respect to the limits of the visibility of the pavement markings. The threshold of the visibility for each of the markings was different and no standout requirement could be found.

ASTM Measurement Methods

The results of these measurements showed that the ASTM flooded method, which flooded the pavement marking, was highly correlated to the initial measurement and the 1 minute measurement of the recovery evaluation, as seen in Table 7.

Table 7. Correlation summary for the ASTM flooded measurement method and the experimental 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 correlation analysis between the ASTM continuous method and the saturated measurement showed a correlation coefficient of Pearson *r* value of 0.992.

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?

More research is needed to give conclusive results for the first question, which addresses the limit of vision as determined by some threshold luminance at which an object is just perceptible. It would be expected that a participant would require the same threshold luminance, regardless of the detection distance. In actuality, the threshold is related to the distance that a person can see. 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. In order to investigate this, a dosage factor, calculated as the product of the visual size of the object in solid angle (steradians) and the retroreflectivity of the pavement marking was generated. Figure 6 shows the mean of this dosage factor by material type. It is unclear why there appear to be two groups; Lines B and E with one dosage factor and Lines C, D, and F with a different dosage factor. This relationship also seemed to vary by the vehicle type. While the dosage factor concept requires further investigation to fully identify the relationship, it has the possibility of being used to develop a performance based specification for the wet visibility of the pavement markings. By varying the required detection distance, and therefore the object size, a required retroreflectivity can be calculated.

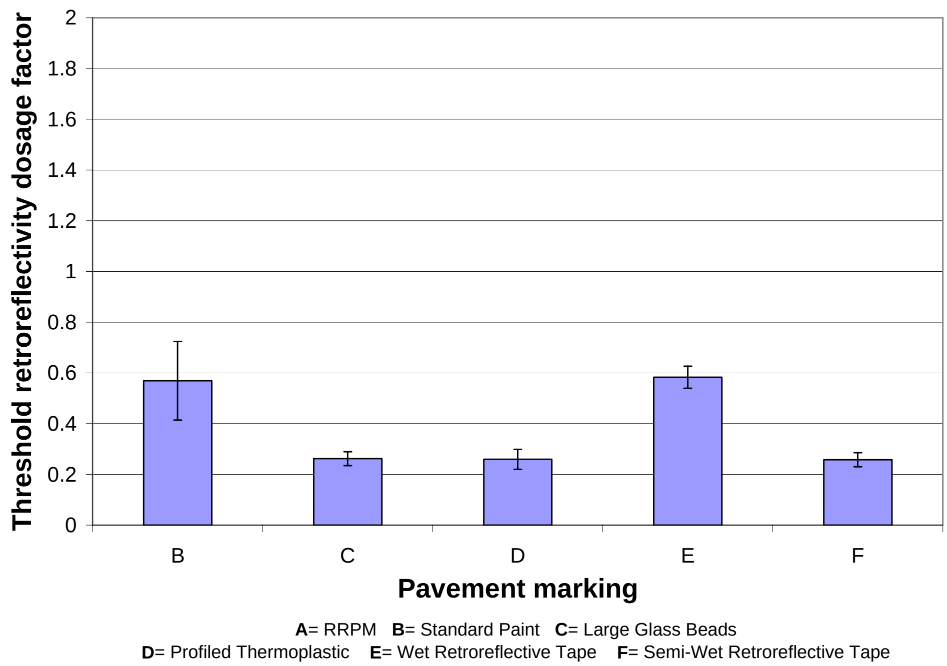


Figure 6. Mean threshold retroreflectivity dosage factor by material type.

With regard to the differences in the dosage factor by vehicle type, it is possible that two events generate this changing threshold. The first is a potential problem with the measurement methodology concerning visual perspective. To count the number of skip lines, and thereby obtain visibility distances, participants have to be able to see the blank lines in between them, and at a certain distance those blanks are no longer visible, even if the pavement marking, appearing as a solid line, is visible beyond this point.

The second event has to do with visual adaptation. Visual science has shown that a lower adaptation luminance level requires a lower threshold luminance level to perceive an object. In the case of a rain event, the driver adaptation luminance is typically lower because of darker pavement and sky. This would result in a lower threshold being used by the driver to achieve the same visibility distance. As the same pavement type and vehicle lighting were used in this investigation, this effect cannot be determined.

The second question asks about the performance of various pavement markings in wet and dry nighttime conditions. Overall, the RRPMs are the best performing of all of the lines evaluated, showing the best human response during the saturated and recovery evaluations, although it should be noted that the markers were spaced 40 ft apart in order to match the paint and tape technology, whereas they are normally 80 ft apart. The participants also found this marker to be the most comfortable during all of the rain conditions reviewed and with both vehicles. Finally, this technology was ranked by the participants as the most desirable for roads in Virginia, both in the dry condition and in the wet condition. Of the line technologies (non-marker), the wet retroreflective marking tape performed the best. It generally stood out in categories measured and had the unique feature of increasing in retroreflectivity in the wet condition. The semi-wet retroreflective tape and the profiled thermoplastic were next in terms of performance with the paint with both regular and large beads being the worst performers in the experiment.

As for the suitability of the ASTM measurement methods, both the continuous and flooded ASTM methods show a high correlation to the experimental results. The correlation results are shown in Tables 8 and 9 and the performance is shown in Figure 7. A logarithm was used as the retroreflectivity is a psychophysical measurement and is responded to in a logarithmic manner.

Table 8. 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 9. 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

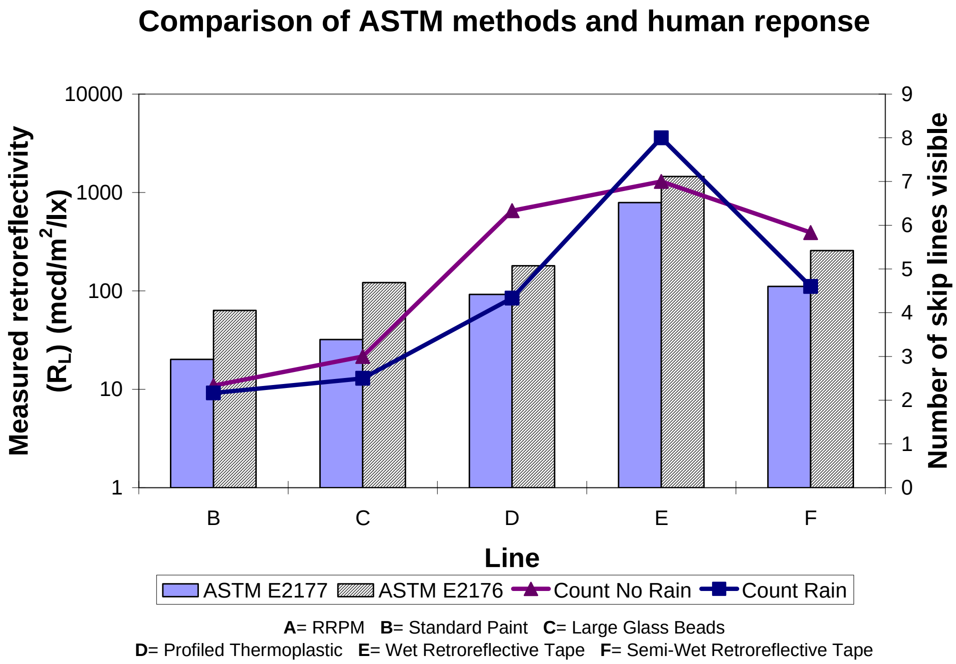


Figure 7. Relationship of human response to the ASTM measurement method results.

CONCLUSIONS

The conclusions from this study 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.